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(54) **ELECTRON SOURCE, ELECTRON GUN AND USE OF ELECTRON SOURCE**

(57) The present application provides an electron source, an electron gun, and use of the electron source. The electron source includes an optical fiber, a conductive connection layer, and an electron emission layer. The conductive connection layer is disposed on an outer surface of the optical fiber. The electron emission layer includes an electron excitation layer electrically connected to the conductive connection layer. The

electron excitation layer includes a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof. The electron excitation layer is disposed on a laser output path of the optical fiber, and a laser output from the optical fiber can directly irradiate the electron emission layer, such that the electron excitation layer is excited by the laser to emit electrons.

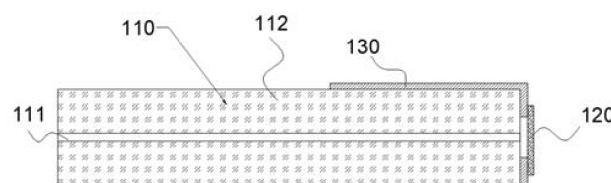


FIG. 1

Description

RELATED APPLICATIONS

[0001] This application claims priority to Chinese patent applications with the following application Nos.: 2023118662886, 202311869450X, 2023118659205, 202311865833X, 2023118694478, 2023118663111, 2023118662693, 2023118663041, 2023118694209, 2023118662763, 2023118659173, and 202311865921X, all filed on December 29, 2023. The contents of the above identified applications are hereby incorporated herein in their entireties by reference.

TECHNICAL FIELD

[0002] The present application relates to the technical field of electron sources, and in particular to an electron source, an electron gun, and use of the electron source.

BACKGROUND

[0003] An electron source is a device that generates electrons in vacuum. Conventional electron sources are mainly classified into thermionic emission electron sources, field emission electron sources, and photoemission electron sources according to excitation methods. The thermionic emission electron sources are mainly made of metallic materials, and when the metallic materials are heated to several thousand degrees Celsius, electrons are thermally excited to escape from the material surface, thereby forming electrons in vacuum. The field emission electron sources typically employ metallic tips, and under the action of a strong external electric field, electrons are emitted from the tips. The photoemission electron sources use metallic materials as photocathodes, and electrons are generated by irradiating the photocathode materials with laser beams.

[0004] However, conventional electron sources cannot balance emission efficiency and stability. How to provide an electron source with both high electron emission efficiency and good stability has become a pressing technical issue to be addressed.

SUMMARY

[0005] According to various embodiments of the present application, an electron source, an electron gun, and use of the electron source are provided.

[0006] In a first aspect, the present application provides an electron source, the electron source includes an optical fiber, a conductive connection layer, and an electron emission layer, and the conductive connection layer is disposed on an outer surface of the optical fiber;

the electron emission layer includes an electron excitation layer electrically connected to the conductive connection layer, and the electron excitation layer includes a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof;

the electron excitation layer is disposed on a laser output path of the optical fiber, and a laser output from the optical fiber is capable of directly irradiating the electron emission layer such that the electron excitation layer is excited by the laser to emit electrons.

[0007] In some embodiments, a thickness of the electron excitation layer is in a range from 0.1 nm to 100 nm.

[0008] In some embodiments, the electron emission layer further includes an auxiliary layer, and the auxiliary layer is stacked on a side of the electron excitation layer adjacent to the optical fiber; or the auxiliary layer is stacked on a side of the electron excitation layer away from the optical fiber.

[0009] In some embodiments, the auxiliary layer includes a conductive support layer, a heat dissipation support layer, or a combination thereof.

[0010] In some embodiments, the auxiliary layer has a thickness in a range from 0.1 nm to 100 nm and a light transmittance greater than or equal to 10%.

[0011] In some embodiments, the auxiliary layer includes a conductive support layer, and the conductive support layer is electrically connected to the conductive connection layer.

[0012] In some embodiments, a material of the conductive support layer includes a conductive metal, and in the optical fiber, the laser has a wavelength in a range from 200 nm to 2000 nm and a pulsed power in a range from 1 nW to 1 W.

[0013] In some embodiments, the electron excitation layer includes a zero-dimensional material.

[0014] In some embodiments, a number density of the zero-dimensional materials in the electron excitation layer is in a range from $10/\text{mm}^2$ to $10^{12}/\text{mm}^2$.

[0015] In some embodiments, there is no spatial gap between two adjacent zero-dimensional material particles.

[0016] In some embodiments, an average particle size of the zero-dimensional materials is in a range from 1 nm to 100 μm .

[0017] In some embodiments, the electron excitation layer includes a one-dimensional material.

[0018] In some embodiments, a diameter of the one-dimensional material is in a range from 1 nm to 20 nm.

[0019] In some embodiments, the electron excitation layer includes a plurality of one-dimensional materials, and axial directions of any two one-dimensional materials are parallel to each other.

[0020] In some embodiments, the electron excitation layer includes a plurality of one-dimensional materials, and along a radial direction of the one-dimensional materials, there is no spatial gap between two adjacent one-dimensional materials.

[0021] In some embodiments, an angle between an axial direction of the one-dimensional material in the electron excitation layer and an output direction of the laser is in a range from 0° to 90° .

[0022] In some embodiments, the axial direction of the one-dimensional material in the electron excitation layer is the same as the output direction of the laser, and a length of the one-dimensional material is in a range from 0.1 μm to 1 μm .

[0023] In some embodiments, the angle between the axial direction of the one-dimensional material in the electron excitation layer and the output direction of the laser is greater than 0° and less than or equal to 90° , and a length of the one-dimensional material is in a range from 1 μm to 200 μm .

[0024] In some embodiments, the angle between the axial direction of the one-dimensional material in the electron excitation layer and the output direction of the laser is greater than 0° and less than or equal to 90° , and the length of the one-dimensional material is in a range from 10 μm to 30 μm .

[0025] In some embodiments, the angle between the axial direction of the one-dimensional material in the electron excitation layer and the output direction of the laser is in a range from 45° to 90° .

[0026] In some embodiments, the electron excitation layer includes at least one two-dimensional material.

[0027] In some embodiments, a thickness of the two-dimensional material is in a range from 0.1 nm to 50 nm.

[0028] In some embodiments, the electron excitation layer includes at least two two-dimensional materials stacked sequentially in the laser output direction of the optical fiber, and the two-dimensional materials are each an electrically conductive two-dimensional material; two adjacent two-dimensional materials are the same or different.

[0029] In some embodiments, an angle between crystal axes of two adjacent two-dimensional materials is in a range from 0° to 360° .

[0030] In some embodiments, the electron excitation layer is at least two two-dimensional materials joined together, the at least two two-dimensional materials are made of different materials, and the laser from the optical fiber is capable of irradiating a junction between adjacent two-dimensional materials.

[0031] In some embodiments, the electron excitation layer includes the one-dimensional material and the zero-dimensional material, the zero-dimensional material being disposed at an end and/or a lateral side of the one-dimensional material.

[0032] In some embodiments, a diameter of the one-dimensional material is in a range from 1 nm to 500 nm, and a length of the one-dimensional material is in a range from 10 nm to 1 mm.

[0033] In some embodiments, an average particle size of the zero-dimensional materials is in a range from 1 nm to 100 nm.

[0034] In some embodiments, the electron excitation layer includes the zero-dimensional material and the two-dimensional material, and the zero-dimensional material is disposed on a surface of the two-dimensional material.

[0035] In some embodiments, the electron excitation layer includes the one-dimensional material and the two-dimensional material, and the one-dimensional material is disposed on a surface of the two-dimensional material.

[0036] In some embodiments, the electron source further satisfies at least one of the following conditions:

(1) the zero-dimensional material includes a quantum dot, a fullerene, a nitrogen-vacancy (NV) center, a nanocrystal, or any combination thereof;

(2) the one-dimensional material includes a nanotube, a nanoribbon, a nanowire, or any combination thereof;

(3) the two-dimensional material includes graphene, black phosphorus, a transition metal chalcogenide, hexagonal boron nitride, or any combination thereof.

[0037] In some embodiments, the optical fiber is a solid-core optical fiber, a tapered optical fiber, a side-polished optical fiber, or a holey optical fiber.

[0038] In some embodiments, the optical fiber includes a fiber core and a cladding layer, the fiber core is configured for laser transmission, the cladding layer surrounds the fiber core, and an end face of a light-output end of the optical

fiber is aligned at an angle relative to an extending direction of the fiber core;

the electron emission layer is disposed on the end face of the light-output end of the optical fiber, the electron excitation layer covers the fiber core of the optical fiber, and a pulsed laser output from the fiber core is capable of directly irradiating the electron emission layer, such that the electron excitation layer is excited by the pulsed laser output from the fiber core to emit electrons.

[0039] In some embodiments, the optical fiber is a holey optical fiber, the holey optical fiber defining a light-guiding hole; the electron excitation layer is at least disposed on a sidewall of the light-guiding hole and extends along an extending direction of the light-guiding hole.

[0040] In some embodiments, the electron emission layer further includes an auxiliary layer; the auxiliary layer is stacked on a side of the electron excitation layer adjacent to the sidewall of the light-guiding hole; or

the auxiliary layer is stacked on a side of the electron excitation layer away from the sidewall of the light-guiding hole.

[0041] In some embodiments, the electron excitation layer includes a first portion and a second portion, the first portion completely covers the sidewall of the light-guiding hole, and the second portion is disposed on an end face of a light-output end of the holey optical fiber; and

the second portion is connected to the first portion and is electrically connected to the conductive connection layer.

[0042] In some embodiments, the conductive connection layer includes a first conductive portion and a second conductive portion, the first conductive portion is disposed on the end face of the light-output end of the holey optical fiber, and the second conductive portion is disposed on a circumferential side surface of the holey optical fiber; and the first conductive portion is connected to the second conductive portion and overlaps with the second portion of the electron excitation layer.

[0043] In some embodiments, the optical fiber is a holey optical fiber, the electron emission layer is disposed on an end face of a light-output end of the holey optical fiber, and the electron excitation layer covers an end of a light-guiding hole at the end face of the light-output end; a pulsed laser output from the holey optical fiber is capable of directly irradiating the electron emission layer, such that the electron excitation layer is excited by the pulsed laser output from the holey optical fiber and to emit electrons.

[0044] In some embodiments, a light-output end of the optical fiber has a tip portion, the electron excitation layer covers a surface of the tip portion of the optical fiber.

[0045] In some embodiments, the electron excitation layer includes a first portion;

a projection of the first portion on a target plane perpendicular to an extending direction of the fiber core covers a projection of the fiber core on the target plane; and
the first portion is electrically connected to the conductive connection layer.

[0046] In some embodiments, the electron excitation layer further includes a second portion connected to the first portion, a projection of the second portion on the target plane is located around the projection of the first portion on the target plane, and the second portion overlaps with the conductive connection layer.

[0047] In some embodiments, the conductive connection layer includes a first conductive portion and a second conductive portion, the first conductive portion is disposed on the tip portion of the optical fiber, and the second conductive portion is connected to the first conductive portion and disposed on a circumferential side surface of the optical fiber; the first conductive portion overlaps with the second portion.

[0048] In some embodiments, in an extending direction of the fiber core, a size of the tip portion is L1, and a size of the electron excitation layer is L2, wherein L1 is greater than L2.

[0049] In some embodiments, the size of the tip portion and the size of the electron excitation layer satisfy: $L2 > 1/2 \times L1$.

[0050] In some embodiments, the optical fiber includes a fiber core and a cladding layer, the fiber core is configured to transmit the laser, and the cladding layer surrounds the fiber core;

a light-leakage notch is defined at a light-output end of the optical fiber, and the light-leakage notch extends in a radial direction of the optical fiber;

the electron emission layer is disposed on a bottom wall of the light-leakage notch, the bottom wall of the light-leakage notch is a flat surface, and a projection of the electron excitation layer on the bottom wall covers a projection of the fiber core on the bottom wall;

the electron excitation layer further extends to the light-output end of the optical fiber.

[0051] In a second aspect, the present application provides an electron gun, including a housing, a grid electrode, an anode, and the electron source as described in the first aspect;

the electron source is fixed in the housing, and the grid electrode and the anode are sequentially disposed on an electron emission side of the electron source.

[0052] In a third aspect, the present application provides use of the electron source as described in the first aspect. The use of the electron source includes at least one of an electron microscope, an electron beam exposure machine, an X-ray tube, a free-electron laser, or a display.

[0053] In a fourth aspect, the present application provides a four-dimensional electron microscope for scanning a sample, including:

a light source assembly configured to emit a pulsed laser;
 the electron source as described in the first aspect, including an excitation optical fiber and an electron emission layer, the excitation optical fiber being coupled to the light source assembly, wherein the electron emission layer at least includes an electron excitation layer, the electron excitation layer is disposed on a pulsed laser output path of the excitation optical fiber, enabling the electron excitation layer to emit an electron beam upon excitation by the pulsed laser; the electron excitation layer includes a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof;
 an electron optical assembly disposed on an electron beam emission side of the electron source, wherein the electron optical assembly is configured to adjust a deflection direction of the electron beam to allow the electron beam to be incident onto the sample; and
 a detector disposed on a side of the sample and configured to collect a reflected electron signal of the electron beam incident onto the sample or a transmitted electron signal of the electron beam passing through the sample.

[0054] In some embodiments, the light source assembly includes a light source and a first optical fiber, an end of the first optical fiber is coupled to the light source, and another end of the first optical fiber is connected to the excitation optical fiber;

the light source is configured to emit the pulsed laser, and the first optical fiber is configured to transmit the pulsed laser emitted by the light source to the excitation optical fiber.

[0055] In some embodiments, the light source assembly further includes a first optical fiber beam splitter, a second optical fiber, and a first optical fiber time delay;

the first optical fiber beam splitter has a first input end and a first output end, the first input end is coupled to the light source, the first output end is opposite to the first input end, and the first output end is separately connected to the first optical fiber and the second optical fiber;

an end of the second optical fiber away from the first optical fiber beam splitter extends toward the sample;

the first optical fiber time delay is coupled to the second optical fiber to introduce a time delay to a light beam propagating in the second optical fiber.

[0056] In some embodiments, the reflected electron signal includes a secondary electron signal or a backscattered electron signal;

the sample has an incident surface disposed opposite to the electron beam emission side of the electron source;
 the detector includes a backscattered electron detector or a secondary electron detector, and the backscattered electron detector or the secondary electron detector is directed toward the incident surface of the sample, allowing the secondary electron detector to receive a secondary electron signal or allowing the backscattered electron detector to receive a backscattered electron signal.

[0057] In some embodiments, the reflected electron signal includes a cathodoluminescence signal;

the sample has an incident surface disposed opposite to the electron beam emission side of the electron source;
 the detector includes a cathodoluminescence analysis system, and the cathodoluminescence analysis system is directed toward the incident surface of the sample to receive the cathodoluminescence signal.

[0058] In some embodiments, the sample has an incident surface and an exit surface, the incident surface is disposed opposite to the electron beam emission side of the electron source, and the exit surface is disposed opposite to the incident surface;

the detector includes a receiving screen, and the receiving screen is directed toward the exit surface of the sample to receive the electron beam passing through the sample.

[0059] In some embodiments, the light source assembly further includes a second optical fiber beam splitter, a third optical fiber, and a second optical fiber time delay;

the second optical fiber beam splitter has a second input end and a second output end, the second input end is

coupled to the light source, the second output end is opposite to the second input end, and the second output end is separately connected to the first optical fiber and the third optical fiber;
 an end of the third optical fiber away from the second optical fiber beam splitter extends toward the sample;
 the second optical fiber time delay is coupled to the third optical fiber and configured to introduce a time delay to a light beam propagating in the third optical fiber.

[0060] In some embodiments, the four-dimensional electron microscope further includes a housing,

wherein the housing defines a vacuum chamber, and the electron source and the electron optical assembly are sequentially disposed in the vacuum chamber;
 the housing has an opening in communication with the vacuum chamber, and a light-input end of the excitation optical fiber of the electron source is exposed out from the opening and coupled to the light source assembly.

[0061] In some embodiments, an outer circumferential wall of the excitation optical fiber is sealingly connected to an inner sidewall of the opening.

[0062] In some embodiments, the electron source further includes an anode, the anode defines a first electron channel, and the electron optical assembly defines a second electron channel in communication with the first electron channel;

a preset electric field is adapted to be provided between the anode and the electron excitation layer, such that the electron beam is driven by the preset electric field to pass through the first electron channel and the second electron channel and is incident onto the sample.

[0063] In a fifth aspect, the present application provides an electron beam exposure machine for exposing a sample, including:

a light source configured to emit a laser;
 the electron source as described in the first aspect, including an optical fiber and an electron emission layer, the optical fiber being coupled to the light source, wherein the electron emission layer at least includes an electron excitation layer, the electron excitation layer is disposed on a laser output path of the optical fiber, enabling the electron excitation layer to emit an electron beam upon excitation by the laser; the electron excitation layer includes a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof; and
 an electron optical assembly disposed on an electron beam emission side of the electron source, wherein the electron optical assembly is configured to adjust focusing and a deflection direction of the electron beam to allow the electron beam to be incident onto the sample to form a preset exposure pattern on the sample.

[0064] In some embodiments, the electron beam exposure machine further includes a housing;

wherein the housing defines a vacuum chamber, and a light-output end of the optical fiber of the electron source and the electron optical assembly are spaced apart from each other and disposed in the vacuum chamber;
 the electron excitation layer is disposed on the light-output end of the optical fiber and located on the laser output path of the optical fiber.

[0065] In some embodiments, the housing has an opening in communication with the vacuum chamber, and a light-input end of the optical fiber of the electron source is exposed out from the opening and coupled to the light source;
 an outer circumferential wall of the optical fiber is sealingly connected to an inner sidewall of the opening.

[0066] In some embodiments, the light-input end of the optical fiber of the electron source extends out of the vacuum chamber through the opening and coupled to the light source; or

an end face of the light-input end of the optical fiber of the electron source is flush with a plane of the opening.

[0067] In some embodiments, the electron source further includes an optical modulator, the optical modulator is connected between the light source and the optical fiber, and is configured to control whether the laser propagates to the optical fiber.

[0068] In some embodiments, the electron optical assembly includes a focusing magnetic lens and a deflection coil, and the focusing magnetic lens and the deflection coil are spaced apart from each other along an emission direction of the electron beam and disposed at an electron beam emission side of the electron source.

[0069] In some embodiments, the optical modulator includes an electro-optic modulator or an optical switch.

[0070] In some embodiments, the electron source further includes an anode, the anode defines a first electron channel, and the electron optical assembly defines a second electron channel in communication with the first electron channel;

a preset electric field is adapted to be provided between the anode and the electron excitation layer, such that the electron beam is driven by the preset electric field to pass through the first electron channel and the second electron channel and is incident onto the sample.

[0071] In a sixth aspect, the present application provides an optical fiber multi electron beam exposure machine for exposing a sample, including:

a light source configured to emit a laser;

the electron source as described in the first aspect, including an optical fiber assembly and an electron emission layer, the optical fiber assembly being coupled to the light source, wherein the electron emission layer at least includes an electron excitation layer, the optical fiber assembly includes a plurality of fiber cores for transmitting laser beams, the electron excitation layer is disposed on a laser output path of the fiber cores, enabling the electron excitation layer to emit an electron beams upon excitation by the laser beams; the electron excitation layer includes a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof;

the electron source further includes an optical modulator, wherein an end of the optical modulator is connected to the light source, another end of the optical modulator is correspondingly and separately connected to the plurality of fiber cores of the optical fiber assembly, and the optical modulator is configured to control whether the laser emitted from the light source separately propagates to corresponding fiber cores; and

an electron optical assembly disposed on an electron beam emission side of the electron source, wherein the electron optical assembly is configured to adjust focusing and a deflection direction of the electron beam, to allow the electron beam to be incident onto the sample to form a preset exposure pattern on the sample.

[0072] In some embodiments, the optical fiber assembly includes a plurality of optical fibers arranged in an array, and the electron excitation layer is disposed on an end face of a laser output end of each optical fiber, such that the electron excitation layer is disposed on a laser output path of a fiber core of a corresponding optical fiber.

[0073] In some embodiments, the optical modulator includes a spatial optical modulator, an optical switch, or an electro-optic modulator.

[0074] In some embodiments, the electron optical assembly includes a focusing magnetic lens and a deflection coil, and the focusing magnetic lens and the deflection coil are spaced apart from each other along an emission direction of the electron beam and disposed at an electron beam emission side of the electron source.

[0075] In some embodiments, the optical fiber multi electron beam exposure machine further includes a housing;

wherein the housing defines a vacuum chamber, and the electron source and the electron optical assembly are sequentially disposed in the vacuum chamber;

the housing has an opening in communication with the vacuum chamber, and a light-input end of the optical fiber assembly of the electron source is exposed out from the opening and coupled to the light source;

an outer circumferential wall of the optical fiber assembly is sealingly connected to an inner sidewall of the opening.

[0076] In some embodiments, the electron source further includes an anode, the anode has a first electron channel, and the electron optical assembly has a second electron channel in communication with the first electron channel; a preset electric field is provided between the anode and the electron excitation layer, and the electron beam is driven by the preset electric field to pass through the first electron channel and the second electron channel and is incident onto the sample.

[0077] In a seventh aspect, the present application provides an X-ray tube, including:

a tube body defining a vacuum chamber therein;

the electron source as described in the first aspect, including an optical fiber and an electron emission layer, wherein a light-output end of the optical fiber is located in the vacuum chamber, the electron emission layer is disposed at the light-output end of the optical fiber, and the electron emission layer at least includes an electron excitation layer, the electron excitation layer is disposed on a laser output path of the optical fiber, enabling the electron excitation layer to emit electrons upon excitation by the laser; and

an anode target disposed in the vacuum chamber and disposed opposite to and spaced apart from the light-output end of the optical fiber, the anode target being configured to collect the electrons emitted from the electron excitation layer to emit X-rays;

wherein the tube body has an output window toward the anode target, and the output window is configured to guide the X-rays out from the vacuum chamber;

the electron excitation layer includes a zero-dimensional material, a one-dimensional material, a two-dimensional

material, or any combination thereof.

[0078] In some embodiments, along an extending direction of the optical fiber, the electron source is spaced apart from the anode target.

[0079] The anode target has a reflective target surface facing the light-output end, and the reflective target surface is aligned at an angle relative to the extending direction of the optical fiber.

[0080] The output window is disposed on a sidewall of the tube body and directed toward the reflective target surface.

[0081] In some embodiments, the anode target includes a transmission anode;

in a longitudinal extending direction of the tube body, the electron source and the output window are disposed at two opposite ends of the tube body, and the transmission anode is located between the electron source and the output window.

[0082] In some embodiments, along the extending direction of the optical fiber, the anode target is spaced apart from the light-output end of the optical fiber, and a preset electric field is adapted to be provided between the anode target and the electron excitation layer, such that the electrons emitted from the electron excitation layer are linearly accelerated along the extending direction of the optical fiber.

[0083] In some embodiments, the tube body surrounds both the optical fiber and the anode target.

[0084] In some embodiments, the tube body has a first port in communication with the vacuum chamber; the light-output end of the optical fiber extends into the vacuum chamber through the first port, and an outer circumferential wall of the optical fiber is sealingly connected to an inner circumferential wall of the first port.

[0085] In some embodiments, the tube body further has a second port disposed opposite to the first port, and a side of the anode target away from the light-output end extends out from the vacuum chamber through the second port; an outer circumferential wall of the anode target is sealingly connected to an inner circumferential wall of the second port.

[0086] In some embodiments, the X-ray tube further includes an external electrode, and the external electrode is disposed between the outer circumferential wall of the anode target and the inner circumferential wall of the second port;

in the longitudinal extending direction of the tube body, an end of the external electrode is located in the vacuum chamber, and another end of the external electrode extends out from the vacuum chamber.

[0087] In some embodiments, the optical fiber has a light-input end disposed opposite to the light-output end, and an end face of the light-input end is flush with a plane of the first port; or the light-input end extends out from the vacuum chamber through the first port.

[0088] In some embodiments, the tube body includes an inner tube and an outer tube, the inner tube surrounds the optical fiber and the anode target, and the outer tube surrounds the inner tube, the outer tube has an opening, and part of the inner tube is exposed from the opening to form the output window; a material of the inner tube includes an X-ray transmitting material, and a material of the outer tube includes an X-ray blocking material.

[0089] In some embodiments, an outer diameter of the tube body is in a range from 125 μm to 2000 μm , and a length of the tube body is in a range from 3 cm to 9 cm.

[0090] Details of one or more embodiments of the present application are set forth in the accompanying drawings and description below. Other features, objectives, and advantages of the present application will become apparent from the description, drawings, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0091] To illustrate the technical solutions in the embodiments of the present application more clearly, the accompanying drawings used in the embodiments are briefly described below. Apparently, the following described drawings are merely for some embodiments of the present application, and other drawings can be derived by those of ordinary skill in the art based on these drawings without any creative effort.

FIG. 1 is a schematic structural view of an electron source according to an embodiment of the present application. FIG. 2 is a schematic structural view of an electron source including an auxiliary layer according to an embodiment of the present application.

FIG. 3 is a schematic structural view of an electron source including zero-dimensional materials distributed in a high density according to an embodiment of the present application.

FIG. 4 is a schematic view of a high-density distribution of zero-dimensional materials according to an embodiment of the present application.

FIG. 5 is a schematic structural view of an electron source including zero-dimensional materials in combination

with an auxiliary layer according to an embodiment of the present application.

FIG. 6 is a schematic view of a low-density distribution of zero-dimensional materials according to an embodiment of the present application.

FIG. 7 is a schematic structural view of an electron source including one-dimensional materials according to an embodiment of the present application.

FIG. 8 is a schematic sectional view taken along line A-A in FIG. 7 of the present application.

FIG. 9 is a schematic structural view of an electron source including one-dimensional materials in combination with an auxiliary layer according to an embodiment of the present application.

FIG. 10 is a schematic sectional view taken along line B-B in FIG. 9 of the present application.

FIG. 11 is a schematic structural view of an electron source including one-dimensional materials arranged obliquely according to an embodiment of the present application.

FIG. 12 is a partially enlarged view of position A in FIG. 11 of the present application.

FIG. 13 is a schematic sectional view taken along line B-B in FIG. 11 of the present application.

FIG. 14 is a schematic structural view of an electron source including one-dimensional materials arranged obliquely in combination with an auxiliary layer according to an embodiment of the present application.

FIG. 15 is a schematic sectional view taken along line C-C in FIG. 14 of the present application.

FIG. 16 is a schematic structural view of an electron source including two stacked layers of different two-dimensional materials according to an embodiment of the present application.

FIG. 17 is a schematic structural view of another electron source including two stacked layers of different two-dimensional materials according to an embodiment of the present application.

FIG. 18 is a schematic structural view of an electron source including a two-dimensional material in combination with an auxiliary layer according to an embodiment of the present application.

FIG. 19 is a schematic structural view of an electron source including a planar heterojunction two-dimensional material according to an embodiment of the present application.

FIG. 20 is a schematic top view of a planar heterojunction two-dimensional material according to an embodiment of the present application.

FIG. 21 is a schematic structural view of another electron source including a two-dimensional material in combination with an auxiliary layer according to an embodiment of the present application.

FIG. 22 is a schematic structural view of an electron source including two-dimensional materials with an interlayer twist angle according to an embodiment of the present application.

FIG. 23 is a schematic structural view of an electron source including a two-dimensional material stacked inside a holey optical fiber according to an embodiment of the present application.

FIG. 24 is a schematic structural view of an electron source including a combination of zero-dimensional materials and one-dimensional materials according to an embodiment of the present application.

FIG. 25 is a schematic structural view of another electron source including a combination of zero-dimensional materials and one-dimensional materials according to an embodiment of the present application.

FIG. 26 is a schematic structural view of yet another electron source including a combination of zero-dimensional materials and one-dimensional materials according to an embodiment of the present application.

FIG. 27 is a schematic structural view of still another electron source including a combination of zero-dimensional materials and one-dimensional materials according to an embodiment of the present application.

FIG. 28 is a schematic structural view of another electron source according to an embodiment of the present application.

FIG. 29 is a schematic structural view of an electron source including a side-polished optical fiber according to an embodiment of the present application.

FIG. 30 is a schematic structural view of an electron source including a holey optical fiber according to an embodiment of the present application.

FIG. 31 is a schematic sectional view taken along line A-A in FIG. 30 of the present application.

FIG. 32 is a partially enlarged view of position B in FIG. 30 of the present application.

FIG. 33 shows a block circuit diagram of an anode and an electron source including a holey optical fiber according to an embodiment of the present application.

FIG. 34 is a schematic structural view of another electron source including a holey optical fiber according to an embodiment of the present application.

FIG. 35 is a partially enlarged view of position C in FIG. 34 of the present application.

FIG. 36 is a schematic structural view of an electron source including a tapered optical fiber according to an embodiment of the present application.

FIG. 37 is a partially enlarged view of position A in FIG. 36 of the present application.

FIG. 38 shows a block circuit diagram of an anode and an electron source including a tapered optical fiber according to an embodiment of the present application.

FIG. 39 is a schematic structural view of another electron source including a tapered optical fiber according to an embodiment of the present application.

FIG. 40 is a partially enlarged view of position A in FIG. 39 of the present application.

FIG. 41 is a schematic structural view of an electron gun according to an embodiment of the present application.

FIG. 42 is a schematic structural view of a four-dimensional electron microscope for detecting secondary electron signals according to an embodiment of the present application.

FIG. 43 is a schematic structural view of a four-dimensional electron microscope for detecting cathodoluminescence signals according to an embodiment of the present application.

FIG. 44 is a schematic structural view of a four-dimensional electron microscope for detecting electron beams passing through a sample according to an embodiment of the present application.

FIG. 45 is a partially enlarged view of position A in FIGS. 42 to 44 of the present application.

FIG. 46 is a schematic structural view of an electron beam exposure machine according to an embodiment of the present application.

FIG. 47 is a partially enlarged view of position A in FIG. 46 of the present application.

FIG. 48 shows a schematic structural diagram of a multi electron beam exposure machine according to an embodiment of the present application.

FIG. 49 is a partially enlarged view of position A in FIG. 48 of the present application.

FIG. 50 is a schematic structural view showing focusing of electron beams from the optical fiber multi electron beam exposure machine in FIG. 48 of the present application onto a sample, forming multiple focused electron beam spots.

FIG. 51 is a schematic structural view of an array of fiber cores in an optical fiber assembly of a multi electron beam exposure machine according to an embodiment of the present application.

FIG. 52 is a schematic structural view of closely packed fiber cores forming a pixel-based optical fiber in an optical fiber assembly of a multi electron beam exposure machine according to an embodiment of the present application.

FIG. 53 is a schematic structural view of an X-ray tube according to an embodiment of the present application.

FIG. 54 is an enlarged schematic view of position A in FIG. 53 of the present application.

FIG. 55 is an enlarged schematic view of position B in FIG. 53 of the present application.

FIG. 56 is a schematic structural view of another X-ray tube according to an embodiment of the present application.

FIG. 57 is an enlarged schematic view of position F in FIG. 56 of the present application.

[0092] 100: electron source, 110: optical fiber, 111: fiber core, 112: cladding layer, 113: annular light-guiding tube, 1101: light-input end, 1102: light-output end, 11021: end face, h: light-leakage notch, h1: bottom wall, h2: sidewall, k: sidewall of light-guiding hole, j: tip portion, j1: surface, 120: electron emission layer, 121: electron excitation layer, 121a: first material layer, 121b: second material layer, 1211: first portion, 1212: second portion, 122: auxiliary layer, 130: conductive connection layer, 131: first conductive portion, 132: second conductive portion, 200: grid electrode, 210: second electron channel, 300: anode, 310: first electron channel.

[0093] 10A: four-dimensional electron microscope, 110A: excitation optical fiber, 2A: light source assembly, 29A: light source, 21A: first optical fiber, 22A: second optical fiber, 23A: third optical fiber, 24A: first optical fiber beam splitter, 25A: second optical fiber beam splitter, 26A: first optical fiber time delay, 27A: second optical fiber time delay, 28A: optical switch, 3A: electron optical assembly, 31A: magnetic lens, 32A: intermediate lens, 33A: projection lens, 4A: detector, 41A: receiving screen, 42A: recording chamber, 5A: sample, 6A: housing, 20A: temporary substrate, 30A: perforated glass slide, 40A: annular heating sheet.

[0094] 10B: electron beam exposure machine, 200B: light source, 300B: housing, 310B: vacuum chamber, 400B: sample stage, 410B: sample, 500B: optical modulator, 600B: electron optical assembly, 610B: focusing magnetic lens, 620B: deflection coil, 20B: temporary substrate, 30B: perforated glass slide, 40B: annular heating sheet.

[0095] 10C: optical fiber multi electron beam exposure machine, 101C: optical fiber assembly, 200C: light source, 300C: housing, 310C: vacuum chamber, 400C: sample stage, 410C: sample, 500C: optical modulator, 600C: electron optical assembly, 610C: focusing magnetic lens, 620C: deflection coil, 20C: temporary substrate, 30C: perforated glass slide, 40C: annular heating sheet.

[0096] 10D: X-ray tube, 200D: anode target, 210D: reflective target surface, 220D: transmission anode, 300D: tube body, 310D: inner tube, 311D: output window, 320D: outer tube, 321D: opening, 301D: vacuum chamber, 302D: first port, 303D: second port, 400D: external electrode, 20D: temporary substrate, 30D: perforated glass slide, 40D: annular heating sheet.

DETAILED DESCRIPTION

[0097] The present application is further described in detail below in conjunction with embodiments and examples.

These embodiments and examples are only used to illustrate the present application and are not intended to limit the scope of the present application. These embodiments and examples are provided for the purpose of enabling a more thorough and comprehensive understanding of the content of the present application. It should be understood that the present application can be realized in many different forms, and is not limited to the embodiments and examples described herein. The person skilled in the art can make various changes or modifications without departing from the concept of the present application, and the equivalent forms obtained also fall within the protection scope of the present application. Furthermore, in the description below, a great deal of details is given in order to provide a comprehensive understanding of the present application, and it should be understood that the present application can be implemented without one or more of these details.

[0098] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by those skilled in the art of the present application. The terms used in the specification of the present application are for the purpose of describing exemplary examples only and are not intended to limit the present application.

[0099] In the present application, terms such as "optionally," "optional," and "option" mean that the specified feature is not mandatory, indicating either of the two parallel options: "present" or "absent" of the feature. If the term "optionally" or the like appears multiple times in a same technical solution, unless specifically stated otherwise, and there are no contradictions or mutually exclusive conditions, each "optional" choice is considered independently.

[0100] In the present application, in phrases such as "first aspect", "second aspect" and the like, the terms "first", "second", etc., are used solely for descriptive purposes and should not be interpreted as indicating or implying relative importance or quantity, nor as implying the importance or quantity of the indicated technical features. In addition, "first", "second", and the like only serve the purpose of non-exhaustive enumeration, and it should be understood that they do not constitute a closed-ended limitation on the quantity.

[0101] In the present application, an open-ended description for the technical features includes not only a closed-ended technical solution consisting of the recited technical features, but also an open-ended technical solution including the recited technical features.

[0102] In the present application, unless otherwise specified, when a numerical interval (i.e., a numerical range) is referred to, the suitable values are considered as continuously distributed within this numerical interval and include both endpoints of the numerical interval (i.e., the minimum value and the maximum value), as well as every value between the two endpoints. Unless otherwise specified, when a numerical interval is referred to as encompassing only integers within the numerical interval, it includes the integers at both endpoints of the numerical interval, and every integer between the endpoints, being equivalent to directly listing each integer. When multiple ranges are provided to describe a feature or a characteristic, these ranges can be combined. In other words, ranges disclosed herein are to be construed to include any or all sub-ranges subsumed therein, unless otherwise specified. The "value" in the numerical interval can be any quantitative value, such as a number, a percentage, a ratio, etc. The "numerical interval" can broadly include percentage intervals, ratio intervals, proportion intervals, and other types of numerical interval.

[0103] All documents referred to in the present application are incorporated by reference in the present application as if each document is individually incorporated by reference. Unless there is a conflict with the objectives and/or the technical solutions of the present application, the cited documents involved in the present application are incorporated in their entireties and for all purposes. When the present application cites documents, the definitions of relevant technical features, terms, norms, phrases, and the like in the cited documents are also cited. When the present application cites documents, the examples and preferred embodiments of the related technical features that are cited can also be incorporated into the present application by reference, provided that the present application can be implemented. It should be understood that when the cited contents conflict with the description of the present application, the present application should prevail or the cited contents shall be adaptively modified according to the description of the present application.

[0104] In conventional art, thermionic emission electron sources are mainly made of metallic materials such as tungsten wires and lanthanum hexaboride. When these materials are heated to thousands of degrees Celsius, electrons are thermally excited to escape from the material surface, forming electrons in vacuum. Field emission electron sources typically employ metallic tips, such as tungsten tips, and under the action of a strong external electric field, electrons are emitted from the tips. The electron beams generated by the thermionic electron sources can operate in a relatively low vacuum environment, offer good environmental adaptability and good stability, but exhibit low brightness and poor coherence. The electron beams generated by the field emission electron sources have high brightness and good coherence, but require a high vacuum environment and are very sensitive to vibration. Both the thermionic emission electron sources and the field emission electron sources provide limited controllability on electron emission properties and can hardly simultaneously achieve high coherence, pulse characteristics, emission efficiency, and stability.

[0105] Photoemission electron sources adopt metallic materials, such as Au, as a material of an electron emission layer with a thickness equal to or greater than 50 nanometers (nm), even up to hundreds of nanometers. However, the

inventors of the present application have found through research that the metallic electron emission layer is relatively thick, and in the electron emission layer, the distance between the surface at the laser acting side (the bottom layer of the electron emission layer) and the surface at the electron emission side (the surface layer of the electron emission layer) is relatively large (from 50 nm to hundreds of nanometers). Electrons excited from the bottom layer are prone to scattering by the metal lattice when passing through the electron emission layer, thereby affecting the emission efficiency. Moreover, metallic materials are susceptible to damage under high-power laser irradiation, affecting the service life of the electron emission layer and thus affecting the electron emission efficiency and stability. In some electron sources, laser irradiation is from a lateral side to excite elections. Compared with the laser irradiation from the back side, the lateral side laser irradiation requires modification of the vacuum chamber, and the irradiation process is difficult to operate, resulting in issues such as unstable excitation conditions.

[0106] In addition, graphene is used as a saturable absorber in conventional art. Having broadband saturable absorption characteristics and fast recovery time, graphene is used in Q-switching and mode-locking of lasers, or used to adjust the laser spectrum for sensing and detection. However, there is a difference between graphene-based laser modulation and graphene-based electron emission. The present graphene-based photoexcitation electron source relies on the photoelectric effect to excite and emit electrons. In contrast, the graphene-based laser modulation relies on the principle of light absorption to regulate laser output parameters. Specifically, there is a significant difference between graphene-based laser modulation and graphene-based electron emission. The graphene-based electron emission relies on the photoelectric effect, while the graphene-based laser modulation relies on the principle of light absorption. In laser modulation, the graphene saturable absorber mainly uses the phenomenon that the absorbance (or transmittance) of graphene increases (or decreases) and finally reaches a saturation threshold as the incident light power increases, and is mainly used in laser apparatuses to generate laser pulses. For example, in a fiber ring resonator of a fiber laser, when light circulates in the resonator and the power of light passing through the graphene saturable absorber exceeds its saturation absorption threshold, the light intensity in the resonator instantly drops below the saturation absorption threshold due to the saturable absorption effect, and this part of dropped optical energy is output as a pulse from the beam splitter of the resonator.

[0107] In view of this, there is a need to provide an electron source that can balance electron emission efficiency and stability.

[0108] The present application adopts a low-dimensional material such as a zero-dimensional material, a one-dimensional material, or a two-dimensional material as the material of the electron emission layer. Upon laser irradiation, the low-dimensional material emits electrons due to the photoelectric effect. The low-dimensional material has an atomic-level thickness, is free of dangling bonds, and possesses stable properties, thereby offering excellent stability and long service life. Moreover, the low-dimensional material can be directly integrated with an optical fiber, and the optical fiber can provide a stable excitation source with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios.

[0109] A first aspect of the present application provides an electron source. As shown in FIGs. 1 to 41, the electron source 100 includes an optical fiber 110, a conductive connection layer 130, and an electron emission layer 120. The conductive connection layer 130 is disposed on an outer surface of the optical fiber 110.

[0110] The electron emission layer 120 includes an electron excitation layer 121 electrically connected to the conductive connection layer 130, thereby connecting the low-dimensional material to an external circuit, forming a complete loop to realize charge replenishment and electric field control. The electron emission layer 120 can be excited to emit electrons under laser irradiation, forming an electron beam.

[0111] The electron excitation layer 121 includes a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof.

[0112] The electron excitation layer 121 is disposed on a laser output path of the optical fiber 110, and a laser output from the optical fiber 110 is capable of directly irradiating the electron emission layer 120 such that the electron excitation layer 121 is excited by the laser to emit electrons.

[0113] It should be noted that, in the electron source of the present application, laser is transmitted through the optical fiber to the electron emission layer material to excite electrons, which is a back side irradiation approach with advantages of being convenient, fast, simple, and easy to operate, and is significantly different from the lateral side laser irradiation to the tips.

[0114] It should be noted that the low-dimensional material in the present application refers to a zero-dimensional material, a one-dimensional material, or a two-dimensional material.

[0115] The present application adopts the low-dimensional material, such as the zero-dimensional material, the one-dimensional material, or the two-dimensional material, as the material of the electron excitation layer. The low-dimensional material has an atomic-level thickness, and thus electrons generated by the back side irradiation can be emitted without traveling through the bulk of the material, resulting in high electron emission efficiency. Moreover, the low-dimensional materials are free of dangling bonds and have stable properties and high melting points, which are less prone to damage and suitable for high-power excitation scenarios, with the advantages such as good stability and long

service life.

[0116] In addition, the low-dimensional material can be directly integrated with the optical fiber. The optical fiber can transmit laser while serving as a carrier for the low-dimensional material, thereby providing a stable excitation source with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios, does not require a complex optical path, and possesses the characteristics of small volume and high integration.

[0117] The zero-dimensional material has typical discrete energy levels. Under laser excitation, electrons are mainly excited via tunneling effect from the discrete energy levels without metal lattice scattering. Consequently, the excited electrons exhibit very high monochromaticity, and the emitted electrons have concentrated energy and low energy spread. In addition, the zero-dimensional material has an atomic-level thickness, and the excited electrons in the electron excitation layer can be emitted without long-distance traveling, resulting in high electron emission efficiency. Moreover, the zero-dimensional material is free of dangling bonds and has stable properties and a high melting point, which is less prone to damage and suitable for high-power excitation scenarios, with the advantages such as good stability, long service life, and low working vacuum degree.

[0118] The one-dimensional material has a small (nanoscale) radius of curvature, which can enhance light-matter interaction and provide a large field enhancement factor, ensuring multiphoton emission, optical field emission, etc., and can be applied to scenarios requiring high-brightness electron sources. The two-dimensional material has an atomic-level thickness, and hardly affects the optical transmission mode during the interaction with the laser, exhibiting high stability; moreover, the excited electrons can be directly emitted without scattering within the material, ensuring the purity in the properties of the emitted electrons and an extremely narrow pulse width.

[0119] In the present application, the zero-dimensional material refers to a material whose all three spatial dimensions are confined to the nanoscale, in which electrons cannot move freely. The one-dimensional material refers to a material in which electrons can move freely only in one dimension that is outside the nanoscale. The two-dimensional material refers to a material in which electrons can move freely only in two dimensions that are outside the nanoscale (i.e., planar motion). The term "nanoscale" herein refers to a range from 0.1 nm to 100 nm. The zero-dimensional material, one-dimensional material, and two-dimensional material can be excited to emit electrons under laser excitation.

[0120] It should be noted that the light output path of the optical fiber in the present application refers to a path that is irradiated by the laser from the optical fiber. Taking a solid-core optical fiber as an example, the laser is output from the solid-core optical fiber at an end face of the fiber core, and thus the electron emission layer can be disposed at the fiber core. Taking a side-polished optical fiber as an example, the laser is output from the side-polished optical fiber at the side-polished portion, and thus the electron emission layer can be disposed at the side-polished portion. It can be understood that, in the present application, the electron emission layer can be in direct contact with the laser output surface of the optical fiber, or can be supported by other structural layers, provided that the laser output from the optical fiber is capable of irradiating the electron emission layer.

[0121] It should also be noted that the purpose of electrically connecting the conductive connection layer to the electron emission layer in the present application is provide a connection between the low-dimensional material and an external circuit, forming a complete loop to realize charge replenishment and electric field control. As an embodiment, in the present application, the conductive connection layer can be directly connected to the electron emission layer. In some other embodiments, the conductive connection layer can be connected to the electron emission layer through other electrically conductive structures. For example, taking a solid-core optical fiber as an example, the conductive connection layer is disposed on a lateral surface of the solid-core optical fiber, the electron emission layer is disposed at the fiber core of the solid-core optical fiber, the conductive connection layer is electrically connected to the electron emission layer, and no conductive connection layer is disposed at the fiber core.

[0122] In some embodiments, the zero-dimensional material, the one-dimensional material, or the two-dimensional material each independently includes a doping element.

[0123] The low-dimensional material is doped with elements to improve the electrical conductivity, change the work function, and regulate the electron emission performance of the low-dimensional material. For example, alkali metal and alkaline earth metal elements can improve the electrical conductivity of the low-dimensional material while reducing the work function of the low-dimensional material, thereby increasing the emitted beam current. Elements such as B, C, N, O, F, and rare earths can create discrete energy levels to produce narrow energy electron beams.

[0124] Optionally, the doping element includes at least one selected from the group consisting of an alkali metal element, an alkaline earth metal element, a transition metal element, a rare earth element, a halogen element, and a light element. The light element includes at least one selected the group consisting of B, C, N, or O.

[0125] In some embodiments, the conductive connection layer is provided with an electrode. Optionally, the conductive connection layer can completely cover the outer surface of the optical fiber or partially cover the outer surface of the optical fiber, while no conductive connection layer is disposed on the laser output path. Further optionally, a thickness of the conductive connection layer is in a range from 10 nm to 1 μm , for example, can be 10 nm, 100 nm, 200 nm, 300 nm, 400 nm, 500 nm, 600 nm, 700 nm, 800 nm, 900 nm, or 1 μm .

[0126] In some embodiments, a thickness of the electron excitation layer is in a range from 0.1 nm to 100 nm, for example, can be 0.1 nm, 0.5 nm, 1 nm, 5 nm, 10 nm, 20 nm, 30 nm, 40 nm, 50 nm, 60 nm, 70 nm, 80 nm, 90 nm, or 100 nm. The thickness of the electron excitation layer within the above range is beneficial to further reducing the traveling distance of the excited electrons between the two opposite surfaces of the electron excitation layer, thereby further improving the electron emission efficiency.

[0127] In some embodiments, as shown in FIG. 2, the electron emission layer 120 further includes an auxiliary layer 122. The auxiliary layer 122 is stacked on a side of the electron excitation layer 121 adjacent to the optical fiber 110.

[0128] Alternatively, the auxiliary layer 122 is stacked on a side of the electron excitation layer 121 away from the optical fiber 110.

[0129] In the present application, the auxiliary layer can be additionally introduced. When the electron excitation layer requires structural support, the auxiliary layer is adopted to provide structural support for the electron emission layer; that is, the electron excitation layer is disposed on the auxiliary layer. Alternatively, when the electron excitation layer is not directly conductively connected with the conductive connection layer, the auxiliary layer, which is electrically conductive, is adopted to connect the electron excitation layer to the conductive connection layer, thereby realizing electron conduction between the electron excitation layer and the conductive connection layer via the auxiliary layer.

[0130] Optionally, the auxiliary layer includes a conductive support layer, a heat dissipation support layer, or a combination thereof.

[0131] Optionally, a thickness of the auxiliary layer is in a range from 0.1 nm to 100 nm, for example, can be 0.1 nm, 0.5 nm, 1 nm, 5 nm, 10 nm, 20 nm, 30 nm, 40 nm, 50 nm, 60 nm, 70 nm, 80 nm, 90 nm, or 100 nm.

[0132] Optionally, a light transmittance of the auxiliary layer is greater than or equal to 10%, for example, can be 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, or 100%. It can be understood that the "light transmittance" in the present application refers to the transmittance of the auxiliary layer to the laser. By controlling the thickness and light transmittance of the auxiliary layer, the laser can be ensured to pass through the auxiliary layer and irradiate the electron excitation layer.

[0133] In some embodiments, the auxiliary layer includes a conductive support layer, and a material of the conductive support layer includes a conductive metal. Optionally, the laser in the optical fiber has a wavelength in a range from 200 nm to 2000 nm, for example, can be 200 nm, 400 nm, 600 nm, 800 nm, 1000 nm, 1200 nm, 1400 nm, 1600 nm, 1800 nm, or 2000 nm, and a pulsed power in a range from 1 nW to 1 W, for example, can be 1 nW, 100 nW, 1 μ W, 10 μ W, 100 μ W, 1 mW, 10 mW, 100 mW, or 1 W. In the present application, the auxiliary layer can include a conductive metal, and the laser parameters are controlled, which avoids melting of the conductive metal caused by laser irradiation, ensuring that the auxiliary layer maintains its support and conducting functions.

[0134] In some embodiments, the auxiliary layer is disposed on an electron emission side of the electron excitation layer. The thickness of the auxiliary layer is in a range from 0.1 nm to 10 nm, reducing the influence of the auxiliary layer on the electron emission effect.

[0135] In some embodiments, as shown in FIGs. 3 to 6, the material of the electron excitation layer 121 includes zero-dimensional materials.

[0136] In some embodiments, an average particle size of the zero-dimensional materials is in a range from 1 nm to 100 μ m.

[0137] In some embodiments, a number density of the zero-dimensional materials in the electron excitation layer is in a range from 10/mm² to 10¹²/mm².

[0138] In some embodiments, there is no spatial gap between two adjacent zero-dimensional material particles.

[0139] It should be noted that when the zero-dimensional materials are in a high-density distribution in the electron excitation layer, the electron excitation layer can, partially or completely, directly cover the fiber core on the end face of the optical fiber to realize electrical connection between the electron excitation layer and the conductive connection layer. As shown in FIG. 4, "high-density distribution" means that no spatial gap exists between two adjacent zero-dimensional material particles. The high-density distributed zero-dimensional materials are beneficial to further increasing the quantity and energy concentration of the emitted electrons.

[0140] Furthermore, when the electron excitation layer is not able to be directly conductively connected to the conductive connection layer, for example, in the case that the zero-dimensional materials are in a low-density distribution in the electron excitation layer, the electron excitation layer is connected to the conductive connection layer via the electrically conductive auxiliary layer, thereby realizing electron conduction between the electron excitation layer and the conductive connection layer via the auxiliary layer. In addition, the auxiliary layer can further assist the electron excitation layer in heat dissipation, improving the heat dissipation effect. As shown in FIG. 6, "low-density distribution" means that there is a spatial gap between two adjacent particles of the zero-dimensional material in the electron excitation layer.

[0141] In some embodiments, as shown in FIGs. 7 to 15, the electron excitation layer 121 includes a one-dimensional material.

[0142] In some embodiments, a diameter of the one-dimensional material is in a range from 1 nm to 20 nm. For example, the diameter can be 1 nm, 3 nm, 5 nm, 7 nm, 10 nm, 13 nm, 15 nm, 17 nm, or 20 nm.

[0143] It can be understood that the electron excitation layer can include a plurality of one-dimensional materials. In this case, the axial directions of different one-dimensional materials can be at different angles with respect to an output direction of the laser. For example, the electron excitation layer includes a total of ten one-dimensional materials, among which three one-dimensional materials have their axial directions at an angle of 45° with respect to the output direction of the laser, two one-dimensional materials have their axial directions at an angle of 60° with respect to the output direction of the laser, and five one-dimensional materials have their axial directions at an angle of 80° with respect to the output direction of the laser. Considering the difficulty in the preparation process, the angles between the axial directions of the one-dimensional materials in the electron excitation layer and the output direction of the laser are the same. In some embodiments, the electron excitation layer includes a plurality of one-dimensional materials, and the axial directions of any two of the one-dimensional materials are parallel to each other.

[0144] In some embodiments, the electron excitation layer includes a plurality of one-dimensional materials, and there is no spatial gap between two adjacent one-dimensional materials in a radial direction of the one-dimensional materials.

[0145] In some embodiments, the angle between the axial directions of the one-dimensional materials in the electron excitation layer and the output direction of the laser is in a range from 0° to 90°, for example, can be 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, or 90°.

[0146] In some embodiments, as shown in FIGs. 7 to 10, the axial directions of the one-dimensional materials are the same as the output direction of the laser, thereby achieving dot emission of the electron source with high resolution. When the one-dimensional materials are in a low-density distribution, the emitted electrons have low energy spread and high brightness. When the one-dimensional materials are in a high-density distribution, a high beam current from the electron source can be realized. Herein, the density refers to the number of one-dimensional materials per unit area. For example, the low density refers to a density of less than 1/nm², while the high density refers to a density greater than 1/nm².

[0147] In the above-described electron excitation layer, the axial directions of the one-dimensional materials are the same as the output direction of the laser, which can achieve dot emission of the electron source with high resolution. During working of the above-described electron source, the laser is directly transmitted through the optical fiber without involving complex and unstable external spatial optical paths, which greatly improves the structural simplicity and operational convenience of the electron source, and reduces the interference of external space on the stability of the electron beam. Consequently, the electron source has ultra-high stability and integration. The one-dimensional material has an atomic-level diameter, and the electrons under the back-side irradiation can be emitted into vacuum without traveling through the bulk of the material, resulting in high electron emission efficiency, which is very suitable for ultrafast electron sources with narrow pulse width. Moreover, the one-dimensional material is free of dangling bonds and has stable properties and a high melting point, which is less prone to damage and is suitable for high-power excitation scenarios. The above-described electron source includes, but is not limited to, a high beam current electron source, an ultrafast electron source, or a high-coherence electron source.

[0148] In some embodiments, the one-dimensional materials in the electron excitation layer are in a low-density distribution. The low density refers to the case that adjacent one-dimensional materials in the electron excitation layer are not in contact with each other and thus cannot achieve electron conduction. For example, the low density refers to the number of one-dimensional materials per unit area being less than 1/nm². In this case, the electrons emitted from the electron excitation layer have low energy spread and the electron source has high brightness.

[0149] In some embodiments, the one-dimensional materials in the electron excitation layer are in a high-density distribution. The high density refers to the case that adjacent one-dimensional materials in the electron excitation layer are in contact with each other and thus can achieve electron conduction. For example, the high density refers to the number of one-dimensional materials per unit area being greater than 1/nm². Thus, a high beam current electron source can be formed.

[0150] In some embodiments, the axial directions of the one-dimensional materials in the electron excitation layer are the same as the output direction of the laser, and the one-dimensional material has a length in a range from 0.1 μm to 1 μm and a diameter in a range from 1 nm to 20 nm. For example, the length of the one-dimensional material can be 0.1 μm, 0.2 μm, 0.3 μm, 0.4 μm, 0.5 μm, 0.6 μm, 0.7 μm, 0.8 μm, 0.9 μm, or 1 μm. The diameter and length of the one-dimensional material are within the above ranges, which can further improve the emission efficiency and stability of the electron source. If the diameter is too large, the one-dimensional material has a small field enhancement factor and weak interaction with light. If the length is too short, the one-dimensional material exhibits the properties of a zero-dimensional material and is difficult to prepare under control. If the length of the one-dimensional material is too long, light traveling through the one-dimensional material suffers from significant scattering or other energy losses, thereby weakening the interaction between light and the one-dimensional material.

[0151] In some embodiments, as shown in FIGs. 11 to 15, the axial directions of the one-dimensional materials have

an angle with respect to the output direction of the laser. The angle can be a right angle or an acute angle. The one-dimensional materials can be excited by the laser to form a linear-shaped electron source.

[0152] In some embodiments, the angle between the axial directions of the one-dimensional materials in the electron excitation layer and the output direction of the laser is greater than 0° and less than or equal to 90° .

[0153] In the above-described electron source, the angle between the axial directions of the one-dimensional materials and the output direction of the laser is greater than 0° and less than or equal to 90° , which achieves linear emission of the electron source and improves the emission area and efficiency. During working of the above-described electron source, the laser is directly transmitted through the optical fiber without involving complex and unstable external spatial optical paths, which greatly improves the structural simplicity and operational convenience of the electron source, and reduces the interference of external space on the stability of the electron beam. Consequently, the electron source has ultra-high stability and integration. The one-dimensional material has an atomic-level diameter, having strong interaction with the optical field and electric field, resulting in high electron emission efficiency, which is very suitable for ultrafast electron sources with narrow pulse width. Moreover, the one-dimensional material is free of dangling bonds and has stable properties and a high melting point, which is less prone to damage and suitable for high-power excitation scenarios.

[0154] In some embodiments, the angle between the axial directions of the one-dimensional materials in the electron excitation layer and the output direction of the laser is greater than 0° and less than or equal to 90° , and the length of the one-dimensional material is in a range from $1\ \mu\text{m}$ to $200\ \mu\text{m}$, for example, can be $1\ \mu\text{m}$, $2\ \mu\text{m}$, $3\ \mu\text{m}$, $4\ \mu\text{m}$, $5\ \mu\text{m}$, $6\ \mu\text{m}$, $7\ \mu\text{m}$, $8\ \mu\text{m}$, $9\ \mu\text{m}$, $10\ \mu\text{m}$, $20\ \mu\text{m}$, $30\ \mu\text{m}$, $50\ \mu\text{m}$, $70\ \mu\text{m}$, $100\ \mu\text{m}$, $130\ \mu\text{m}$, $150\ \mu\text{m}$, $180\ \mu\text{m}$, or $200\ \mu\text{m}$, and optionally, in a range from $10\ \mu\text{m}$ to $30\ \mu\text{m}$. If the length is too long, preparation of the one-dimensional material may be difficult. If the length is too short, the emission length of the one-dimensional material is short, resulting in low electron emission efficiency, and it is difficult for the one-dimensional material in the electron excitation layer to be in contact with the conductive connection layer.

[0155] In some embodiments, the angle between the axial directions of the one-dimensional materials in the electron excitation layer and the output direction of the laser is in a range from 45° to 90° . As such, not only strong interaction between the laser and the one-dimensional materials can be ensured, but also electrons can be ensured to be emitted from the lateral side of the one-dimensional materials, which can further improve the emission efficiency and stability of the electron source.

[0156] In some embodiments, as shown in FIGs. 16 to 23, the electron excitation layer includes at least one two-dimensional material.

[0157] In the present application, at least one two-dimensional material can be adopted as the electron excitation layer. The two-dimensional material has an atomic-level thickness, and thus excited electrons generated from the laser irradiation surface can be emitted into vacuum without traveling through the layer of the material, which is very suitable for ultrafast electron sources with narrow pulse width. The two-dimensional material is free of dangling bonds, stable, and has a high melting point, which is less prone to damage and thus suitable for high beam current electron sources under high-power excitation. Moreover, the rich variety of the two-dimensional materials, along with the homogeneous and heterogeneous structures, brings ultra-high freedom in electron emission properties, enabling, for example, pulsed emission and linear emission of the electron sources. In addition, in the present application, the two-dimensional material can be directly integrated with the optical fiber. The optical fiber transmits laser while serving as a carrier for the low-dimensional material, thereby providing a stable excitation source with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios, does not require a complex optical path, and possesses the characteristics of small volume and high integration.

[0158] In some embodiments, a thickness of the two-dimensional material is in a range from $0.1\ \text{nm}$ to $50\ \text{nm}$, for example, can be $0.1\ \text{nm}$, $0.5\ \text{nm}$, $1\ \text{nm}$, $5\ \text{nm}$, $10\ \text{nm}$, $20\ \text{nm}$, $30\ \text{nm}$, $40\ \text{nm}$, $50\ \text{nm}$, $60\ \text{nm}$, $70\ \text{nm}$, $80\ \text{nm}$, $90\ \text{nm}$, or $100\ \text{nm}$.

[0159] In some embodiments, the electron excitation layer includes at least two two-dimensional materials stacked sequentially in an output direction of the laser, or the electron emission layer includes at least two two-dimensional materials of different materials connected to each other in the same plane.

[0160] In some embodiments, at least two two-dimensional materials are stacked with each other, or at least two two-dimensional materials are joined together to form a same plane. Further, two adjacent two-dimensional materials can be made of different materials, thereby forming a vertical heterojunction or a planar heterojunction. The heterojunction structure can enhance the interaction between light and the two-dimensional materials, realizing high-efficiency electron emission at a low laser power. Moreover, the heterojunction structure allows tunable interface energy bands; through material design and twist angle regulation, special interface states can be obtained, realizing electron emission with high brightness and low energy spread.

[0161] In some embodiments, as shown in FIG. 16, the electron excitation layer 121 includes at least two two-dimensional materials stacked sequentially in the laser output direction of the optical fiber, and the two-dimensional materials are each an electrically conductive two-dimensional material; adjacent two-dimensional materials are the

same or different. As shown in FIG. 21, the electron excitation layer 121 includes a first material layer 121a and a second material layer 121b stacked sequentially with each other. In the present application, the stacked two-dimensional materials can be all electrically conductive, providing rapid charge transfer with high stability between the layers of two-dimensional materials. If the stacked two-dimensional materials include an insulating material, the insulating material may block electron transmission, which not only requires an additional control electrode but also causes additional scattering issues during electron transfer, resulting in low emission efficiency and high energy spread.

[0162] In some embodiments, as shown in FIG. 22, the angle between crystal axes of two adjacent two-dimensional materials is in a range from 0° to 360° . By stacking multiple two-dimensional materials, vertical heterojunctions or vertical homojunctions between two adjacent two-dimensional materials can be formed. The heterojunction structure can enhance interaction between light and the two-dimensional materials, realizing high-efficiency electron emission at low laser power. Moreover, the heterojunction structure allows tunable interface energy band; through material design and twist angle regulation, special interface states can be obtained, realizing electron emission with high brightness and low energy spread.

[0163] In some embodiments, as shown in FIGs. 19 and 20, the electron excitation layer is formed by piecing at least two two-dimensional materials of different materials together, and the laser output from the optical fiber irradiates a junction between the adjacent two-dimensional materials. Optionally, the electron emission layer includes a two-dimensional material layer formed by a graphene layer and a molybdenum disulfide layer joined together. The junction between graphene and molybdenum disulfide forms a one-dimensional interface. This one-dimensional interface has different response to light compared with either graphene or molybdenum disulfide, thereby realizing one-dimensional emission of an interface state.

[0164] In some embodiments, the electron excitation layer is formed by at least two two-dimensional materials of different materials joined together, and the thicknesses of adjacent two-dimensional materials are the same or different. In the present application, the thicknesses of the two-dimensional materials joined together can be different, thereby realizing different electron excitation forms. As shown in FIG. 20, the electron excitation layer 121 includes a first material layer 121a and a second material layer 121b joined together in a same plane.

[0165] In some embodiments, the auxiliary layer includes a transparent support layer.

[0166] Optionally, the material of the transparent support layer includes boron nitride, mica, diamond, or any combination thereof.

[0167] In the present application, the transparent support layer can be made of the transparent material, which does not affect the interaction between the laser and the two-dimensional material.

[0168] In some embodiments, a thickness of the transparent support layer is in a range from 0.1 nm to 1000 nm, for example, can be 0.1 nm, 0.5 nm, 1 nm, 5 nm, 10 nm, 100 nm, 200 nm, 300 nm, 400 nm, 500 nm, 600 nm, 700 nm, 800 nm, 900 nm, or 1000 nm.

[0169] In some embodiments, a light transmittance of the transparent support layer is greater than or equal to 10%, for example, can be 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, or 100%.

[0170] In some embodiments, at least one of the zero-dimensional material or the one-dimensional material is further disposed on a surface of the two-dimensional material. Optionally, the one-dimensional material is disposed on the surface of the two-dimensional material, and the angle between the axial direction of the one-dimensional material and the plane of the two-dimensional material is in a range from 0° to 90° . In the present application, the zero-dimensional material or the one-dimensional material can be disposed on the surface of the two-dimensional material, thereby modifying the surface of the two-dimensional material, realizing electron source emission in different modes.

[0171] In some embodiments, as shown in FIGs. 24 to 27, the material of the electron excitation layer includes one-dimensional materials and zero-dimensional materials, and the zero-dimensional materials are disposed at an end and/or a lateral side of the one-dimensional materials. It can be understood that when the one-dimensional material is a solid structure, the zero-dimensional material can be disposed at an end and/or an outer wall of the one-dimensional material. When the one-dimensional material is a hollow structure, the zero-dimensional material can be disposed at an end and/or an inner or outer wall of the one-dimensional material. For example, as shown in FIG. 24, the zero-dimensional materials are disposed on the ends of the one-dimensional materials. As shown in FIG. 25, the zero-dimensional materials are disposed on the sidewalls of the one-dimensional materials.

[0172] In the present application, the zero-dimensional material can be combined with the one-dimensional material, and the zero-dimensional material can be disposed at the end or lateral side of the one-dimensional material, that is, modifying the surface structure of the one-dimensional material with the zero-dimensional material. Both the zero-dimensional material and the one-dimensional material have typical discrete energy levels. Under laser irradiation, electrons are mainly excited via tunneling effect from the discrete energy levels, rendering the emitted electrons with the characteristics of concentrated energy, low energy spread, and high emission efficiency.

[0173] In the electron source provided by the present application, the laser can be transmitted through the fiber core of the optical fiber to the end face of the optical fiber and then irradiate the electron excitation layer. The electron

excitation layer can include the one-dimensional material and the zero-dimensional material. Under photoexcitation, since the one-dimensional material and the zero-dimensional material each have an atomic-level thickness, electrons excited from the electron excitation layer can be emitted without long-distance traveling, resulting in high electron emission efficiency. Furthermore, the one-dimensional material and the zero-dimensional material are free of dangling bonds and have stable properties and high melting points, which are less prone to damage and suitable for high-power excitation scenarios, with the characteristics of good stability, long service life, and low working vacuum degree. In addition, the one-dimensional material and the zero-dimensional material can be directly integrated with the optical fiber. The optical fiber is configured to transmit the laser, which can effectively reduce laser scattering and effectively reduce the energy loss of the emitted laser, improving the excitation efficiency. Moreover, the optical fiber serves as a carrier for the one-dimensional material and the zero-dimensional material, thereby providing a stable excitation source with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios, does not require a complex optical path, and possesses the characteristics of small volume and high integration. In addition, the one-dimensional material and zero-dimensional material can create more electron energy levels and increase the electron density, realizing higher electron emission efficiency.

[0174] In the present application, the zero-dimensional material can be disposed on the one-dimensional material, and composited with the zero-dimensional material. As such, more electron energy levels can be created and the electron density can be increased. In addition, the one-dimensional material can be modified with the zero-dimensional material, achieving an increased electron emission efficiency, thereby further improving the electron emission efficiency and stability.

[0175] In some embodiments, the axial direction of the one-dimensional material modified with the zero-dimensional material has an angle relative to the laser output path of the optical fiber; that is, an angle between the axial direction of the one-dimensional material and the output direction of the laser is in a range from 0° to 90°. While exciting the one-dimensional material to form a linear-shaped electron source, the laser can also excite the zero-dimensional material to form a dot-shaped electron source, which can enhance the excited electron source and effectively improve the electron emission efficiency.

[0176] In some embodiments, the axial direction of the one-dimensional material in the electron excitation layer is parallel to the laser output path of the optical fiber. The axial direction of the one-dimensional material in the electron excitation layer is parallel to the laser output path of the optical fiber, meaning that the axial direction of the one-dimensional material is the same as the output direction of the laser. In addition, the zero-dimensional material is disposed on the one-dimensional material, thereby achieving high resolution dot emission of the electron source.

[0177] In some embodiments, the electron excitation layer includes a plurality of one-dimensional materials, and the axial directions of any two of the one-dimensional materials are parallel to each other. In the electron excitation layer, the axial directions of the one-dimensional materials are parallel to each other, and the zero-dimensional materials are disposed on the one-dimensional materials, which is beneficial to obtaining an electron beam with consistent orientation, thereby further enhancing the energy concentration.

[0178] In some embodiments, the electron excitation layer includes a plurality of one-dimensional materials, and there is no spatial gap between two adjacent one-dimensional materials in the radial direction of the one-dimensional materials. It should be noted that when the one-dimensional materials in the electron excitation layer are in the high-density distribution in the electron excitation layer, the electron excitation layer can, partially or completely, directly cover the fiber core on the end face of the optical fiber to realize electrical connection between the electron excitation layer and the conductive connection layer. As shown in FIG. 24, "high-density distribution" means that no spatial gap exists between adjacent one-dimensional materials in the electron excitation layer in the radial direction of the one-dimensional materials.

[0179] In some embodiments, when the axial directions of the one-dimensional materials in the electron excitation layer are parallel to the laser output path of the optical fiber, and there is a spatial gap between two adjacent one-dimensional materials in the radial direction of the one-dimensional materials, the emitted electrons have low energy spread and high brightness, which can achieve a high beam current electron source.

[0180] In some embodiments, as shown in FIG. 24, the axial directions of the one-dimensional materials in the electron excitation layer 121 are parallel to the laser output path of the optical fiber 110, and there is no spatial gap between two adjacent one-dimensional materials in the radial direction of the one-dimensional materials, which is beneficial to further improving the energy concentration of the emitted electrons.

[0181] In some embodiments, a diameter of the one-dimensional material is in a range from 1 nm to 500 nm, and a length of the one-dimensional material is in a range from 10 nm to 1 mm. It can be understood that when the one-dimensional material is a hollow structure, the diameter of the one-dimensional material refers to its outer diameter. An average particle size of the zero-dimensional materials is in a range from 1 nm to 100 nm.

[0182] In some embodiments, the one-dimensional material includes a nanotube, a nanorod, a nanowire, a nanoribbon, a coaxial nanocable, or any combination thereof. Optionally, the one-dimensional nanomaterial includes a carbon nanotube, a silicon nanowire, a germanium nanowire, a silver nanowire, a gold nanopillar, a boron nitride

nanotube, or any combination thereof. It can be understood that in the present application, the nanorod refers to a solid cylindrical (or with a polygonal cross-section) one-dimensional nanomaterial with a relatively short length and a relatively straight longitudinal shape; the nanowire refers to a solid one-dimensional nanomaterial with a relatively great length and with a straight or curved morphology; and the nanoribbon refers to a structure having a quadrilateral cross-section with a width-to-thickness ratio generally in a range from several to over ten.

[0183] In some embodiments, the electron excitation layer includes the zero-dimensional material and the two-dimensional material, and the zero-dimensional material is disposed on the surface of the two-dimensional material. By disposing the zero-dimensional material on the surface of the two-dimensional material, the two-dimensional material serves as a support layer for carrying the zero-dimensional material. In addition, as the two-dimensional material is electrically conductive, an additional conductive layer can be avoided. That is, the two-dimensional material can serve as the auxiliary layer for the zero-dimensional material, achieving the functions of support and electrical conduction.

[0184] In some embodiments, the electron excitation layer includes the one-dimensional material and the two-dimensional material, and the one-dimensional material is disposed on the surface of the two-dimensional material. Optionally, an angle between the axial direction of the one-dimensional material and the surface of the two-dimensional material is in a range from 0° to 90°. By disposing the one-dimensional material on the surface of the two-dimensional material, the two-dimensional material can serve as a support layer for carrying the one-dimensional material. In addition, as the two-dimensional material is electrically conductive, an additional conductive layer can be avoided. That is, the two-dimensional material can serve as the auxiliary layer for the one-dimensional material, achieving the functions of support and electrical conduction.

[0185] In some embodiments, the zero-dimensional material includes a quantum dot, a fullerene, an NV center, a nanocrystal, or any combination thereof. The NV center refers to a nitrogen-vacancy center. The quantum dot includes a carbon quantum dot, a CdSe colloidal quantum dot, a GaAs semiconductor quantum dot, or any combination thereof. For example, the zero-dimensional material includes one or more selected from the group consisting of fullerene, carbon black, a nanodiamond, an NV center of a diamond, a metal nanoparticle, a perovskite quantum dot, a graphene quantum dot, a CdZnSe/ZnS quantum dot, and a CdZnS quantum dot. Optionally, the zero-dimensional material is a metal nanoparticle and/or a graphene quantum dot.

[0186] In some embodiments, the one-dimensional material includes a nanotube, a nanoribbon, a nanowire, or any combination thereof. Optionally, the nanotube includes at least one selected from the group consisting of a carbon nanotube, a Si nanotube, a Se nanotube, a Te nanotube, a Bi nanotube, a BN nanotube, a BCN nanotube, a WS nanotube, a MoS₂ nanotube, and a TiO₂ nanotube. Optionally, the nanowire includes an elemental nanowire such as a Si nanowire or a Ge nanowire, an oxide nanowire such as a SnO nanowire or a ZnO nanowire, a nitride nanowire such as a GaN nanowire or a Si₃N₄ nanowire, a sulfide nanowire such as a CdS nanowire or a ZnS nanowire, or a ternary compound nanowire such as a BaTiO nanowire or a PbTiO nanowire. The nanoribbon includes a ZnO nanoribbon, an SnO nanoribbon, etc. The coaxial nanocable refers to a core/shell quasi-one-dimensional structure with a nanoscale radial dimension, such as a C/BN/C/Si/SiO₂ coaxial nanocable, a SiC/SiO₂ coaxial nanocable, etc. Thus, the emission efficiency and stability of the electron source can be further improved.

[0187] In some embodiments, the two-dimensional material includes graphene, a transition metal chalcogenide, a two-dimensional perovskite, a two-dimensional diamond, boron nitride, or any combination thereof. Optionally, the transition metal chalcogenide includes WS₂, WSe₂, NbSe₂, or any combination thereof.

[0188] In some embodiments, the optical fiber is a solid-core optical fiber, a tapered optical fiber, a side-polished optical fiber, or a holey optical fiber.

[0189] In some embodiments, as shown in FIG. 28, the optical fiber 110 includes a fiber core 111 and a cladding layer 112, the fiber core 111 is configured for transmitting laser, and the cladding layer 112 surrounds the fiber core 111. An end face of a light-output end of the optical fiber 110 is aligned at an angle relative to an extending direction of the fiber core.

[0190] The electron emission layer is disposed on the end face of the light-output end of the optical fiber. The electron excitation layer covers the fiber core of the optical fiber, and a pulsed laser output from the fiber core is capable of directly irradiating the electron emission layer, such that the electron excitation layer is excited by the pulsed laser output from the fiber core to emit electrons.

[0191] In some embodiments, as shown in FIG. 29, the optical fiber is a side-polished optical fiber. In the present application, the low-dimensional material can be disposed on a side-polished surface of the side-polished optical fiber, and an evanescent wave leaking from the fiber core interacts with the low-dimensional material in a horizontal direction. For example, when the low-dimensional material is the two-dimensional material, an edge state similar to a one-dimensional material is obtained at the side-polished position, forming a novel electron emission structure to achieve high brightness, low energy spread, and narrow pulse width. When the low-dimensional material is the one-dimensional material, an edge state similar to a zero-dimensional material is obtained at the side-polished position, forming a novel electron emission structure to achieve high brightness, low energy spread, and narrow pulse width. When the

low-dimensional material is a combination of the two-dimensional material, the one-dimensional material, and the zero-dimensional material, the energy band of the two-dimensional material can be modulated through doping with the one-dimensional material and the zero-dimensional material, thereby improving light-matter interactions and achieving electron emission with high brightness, low energy spread, and narrow pulse width.

[0192] In some embodiments, as also shown in FIG. 29, a light-leakage notch h is defined at the light-output end 1102 of the optical fiber 110, the light-leakage notch h extending in the radial direction of the optical fiber 110. The electron excitation layer 121 is disposed on a bottom wall h1 of the light-leakage notch h, and the bottom wall h1 of the light-leakage notch h is a flat surface. A projection of the electron excitation layer 121 on the bottom wall h1 covers a projection of the fiber core 111 on the bottom wall h1. The electron excitation layer 121 further extends to the light-output end 1102 of the optical fiber 110.

[0193] Optionally, the light-leakage notch h further has a sidewall h2 extending in the radial direction of the optical fiber 110. The bottom wall h1 and the sidewall h2 collectively define the light-leakage notch h.

[0194] Optionally, the bottom wall h1 of the light-leakage notch h is a flat surface, and the bottom wall h1 of the light-leakage notch h extends along the extending direction of the optical fiber 110.

[0195] The bottom wall h1 of the light-leakage notch h can be spaced apart from the fiber core 111, and the bottom wall h1 of the light-leakage notch h is parallel to a tangent plane of the outer surface of the fiber core 111. Alternatively, the bottom wall h1 of the light-leakage notch h is tangent to the outer surface of the fiber core 111. As another alternative, the bottom wall h1 of the light-leakage notch h is a flat surface intersects the fiber core 111. For example, the fiber core 111 and the cladding layer 112 are simultaneously sectioned by a sectioning method to form the light-leakage notch h, so that a part of the bottom wall h1 of the light-leakage notch h is formed in the fiber core 111, and another part of the bottom wall h1 of the light-leakage notch h is formed in the cladding layer 112.

[0196] As such, the laser transmitted in the fiber core 111 of the optical fiber 110 can generate an evanescent wave at the bottom wall h1 of the light-leakage notch h. Since the electron excitation layer 121 is disposed on the bottom wall h1 of the light-leakage notch h and the projection of the electron excitation layer 121 on the bottom wall h1 covers the projection of the fiber core 111 on the bottom wall h1, the laser transmitted in the fiber core 111 of the optical fiber 110 can interact with the electron excitation layer 121 through the evanescent wave, causing electrons in the electron excitation layer 121 to absorb the energy of the evanescent wave, resulting in electron transitions. These electrons can escape from the electron excitation layer 121, thereby realizing electron excitation.

[0197] In some embodiments, the optical fiber is a holey optical fiber. In the present application, the holey optical fiber refers to a microstructured optical fiber or a hollow-core optical fiber, such as a photonic crystal optical fiber, an anti-resonant optical fiber, a capillary optical fiber, etc. The low-dimensional material can be disposed within the hole or disposed on the wall of the hole of the holey optical fiber, allowing a relatively long interaction distance between the laser and the low-dimensional material, thereby realizing electron emission with high brightness. Since the holey optical fiber itself possesses a special light transmission mode, different type of material or different dimensional material can be further grown or transferred into the hole or on the wall of the hole which has already been grown or filled with a low-dimensional material to form a heterojunction, thereby realizing multi-functional electron emission.

[0198] In some embodiments, the optical fiber is a holey optical fiber having a light-guiding hole. The electron excitation layer is disposed at least on a sidewall of the light-guiding hole and extends in an extending direction of the light-guiding hole.

[0199] As shown in FIGs. 30 to 35, the optical fiber 1110 is a holey optical fiber having a light-guiding hole. The holey optical fiber serves as a medium for transmitting the laser and as a carrier for the low-dimensional material. The holey optical fiber can be a hollow-core holey optical fiber. The hollow-core holey optical fiber can be a single-hole or multi-hole hollow-core optical fiber. Alternatively, the holey optical fiber can be a solid-core holey optical fiber. The solid-core holey optical fiber can be a single-hole or multi-hole solid-core optical fiber, which is not specifically limited herein. FIG. 30 shows an embodiment in which the holey optical fiber is a single-hole hollow-core optical fiber.

[0200] Specifically, in the embodiment shown in FIG. 30, the fiber core 111 composed of air is disposed in the light-guiding hole. The holey optical fiber further includes a cladding layer 112 surrounding the fiber core 111. The cladding layer 112 is an annular light-guiding tube. The sidewall k of the light-guiding hole is the inner sidewall of the annular light-guiding tube. Specifically, the material of the annular light-guiding tube can be high borosilicate, glass, quartz, etc.

More specifically, the holey optical fiber is a capillary optical fiber.

[0201] The holey optical fiber has a light-input end 1101 and a light-output end 1102 disposed opposite to each other. The light-input end 1101 is configured to couple to a laser source, so that the laser emitted by the laser source can be transmitted through the holey optical fiber. The laser source can be a laser generating device. The electron excitation layer 121 can be entirely disposed on the sidewall k of the light-guiding hole; alternatively, the electron excitation layer 121 can be partially disposed on the sidewall k of the light-guiding hole, which is not specifically limited herein.

[0202] In this way, in use of the electron source 100, during transmission of the laser in the holey optical fiber, an evanescent wave can be generated at the sidewall k of the light-guiding hole. Since the electron excitation layer 121 is

disposed on the sidewall k of the light-guiding hole, the laser can interact with the electron excitation layer 121 through the evanescent wave, causing electrons in the electron excitation layer 121 to absorb the energy of the evanescent wave, resulting in electron transitions. These electrons can escape from the electron excitation layer 121, thereby realizing electron excitation.

[0203] It should be noted that, both the hollow-core holey optical fiber and the solid-core holey optical fiber can allow the laser emitted by the laser source to be transmitted through the holey optical fiber 110 to reach the light-output end 1102 of the holey optical fiber 110. During transmission of the laser in the holey optical fiber 110, an evanescent wave can be generated at the sidewall k of the light-guiding hole. The laser can interact with the electron excitation layer 121 through the evanescent wave, causing electrons in the electron excitation layer 121 to absorb the energy of the evanescent wave, resulting in electron transitions. These electrons can escape from the electron excitation layer 121, thereby realizing electron excitation.

[0204] In some embodiments, the holey optical fiber is a hollow-core holey optical fiber, and a light-guiding medium is disposed in the light-guiding hole. The light-guiding medium includes air or a rare gas. The light-guiding medium can be air or a rare gas. Using a rare gas can generate nonlinear optical effects, thereby converting single-wavelength light pulses output from the holey optical fiber 110 to light pulses in a band covering from ultraviolet to infrared, or even the terahertz band, or even to generate an ultra-broadband supercontinuum spectrum, which is also beneficial to better exciting the electron excitation layer 121 to emit electrons.

[0205] In some embodiments, at least part of the electron excitation layer 121 completely covers the sidewall k of the light-guiding hole. The electron excitation layer 121 can completely cover the sidewall k of the light-guiding hole, or a part of the electron excitation layer 121 can completely cover the sidewall k of the light-guiding hole, which is not specifically limited herein. In this way, the laser transmitted in the holey optical fiber 110 can better interact with the electron excitation layer 121 and excite the electron excitation layer 121 to emit electrons.

[0206] In some embodiments, the electron emission layer further includes the auxiliary layer. The auxiliary layer is stacked on a side of the electron excitation layer adjacent to the sidewall of the light-guiding hole, or the auxiliary layer is stacked on a side of the electron excitation layer away from the sidewall of the light-guiding hole.

[0207] In some embodiments, the electron excitation layer includes a first portion and a second portion, the first portion completely covers the sidewall of the light-guiding hole, and the second portion is disposed on an end face of the light-output end of the holey optical fiber. The second portion is connected to the first portion and is electrically connected to the conductive connection layer. In this way, by electrically connecting the conductive connection layer 130 to the second portion 1212 of the electron excitation layer 121, on the one hand, the conductive connection layer 130 can replenish electrons to the electron excitation layer 121, which facilitates the electron excitation layer 121 in continuously emitting electrons under laser excitation. On the other hand, since the second portion 1212 is disposed on the light-output end 1102 of the holey optical fiber 110, during the transmission of the laser in the holey optical fiber 110 toward the light-output end 1102, the laser not only can interact with the first portion 1211 of the electron excitation layer 121 through the evanescent wave but also can interact with the second portion 1212 on the light-output end 1102, causing electrons in the electron excitation layer 121 to absorb the energy of photons and undergo electron transitions. These electrons can escape from the electron excitation layer 121, thereby realizing high-efficiency emission of electrons in an axial direction of the holey optical fiber 110.

[0208] In some embodiments, the conductive connection layer includes a first conductive portion and a second conductive portion, the first conductive portion is disposed on the end face of the light-output end of the holey optical fiber, and the second conductive portion is disposed on the circumferential side surface of the holey optical fiber. The first conductive portion is connected to the second conductive portion and overlaps with the second portion of the electron excitation layer. In this way, the conductive connection layer 130 can cover more surfaces of the holey optical fiber 110, improving the bonding strength between the conductive connection layer 130 and the holey optical fiber, and also facilitating the electron replenishment to the electron excitation layer 121 through the conductive connection layer 130. Since the first conductive portion 131 overlaps with the second portion 1212, the first conductive portion 131 is in electrical contact with the second portion 1212, and the orthographic projection of the first conductive portion 131 on the light-output end 1102 is located around the sidewall k of the light-guiding hole, allowing the conductive connection layer 130 to replenish electrons to the electron excitation layer 121 without affecting the interaction between the laser and the electron excitation layer 121.

[0209] In some embodiments, the first portion 1211 and the second portion 1212 are both of annular structures. The inner diameter of the first portion 1211 is less than or equal to the inner diameter of the second portion 1212, which is beneficial for the laser to interact with the first portion 1211 of the electron excitation layer 121 through the evanescent wave, and also interact with the second portion 1212 on the light-output end 1102. As such, electrons in the electron excitation layer 121 can absorb the energy of the evanescent wave and undergo electron transitions. These electrons can escape from the electron excitation layer 121, thereby realizing high-efficiency emission of electrons in the axial direction of the holey optical fiber 110.

[0210] In some embodiments, the conductive connection layer 130 includes a first metal layer and a second metal

layer that are stacked with each other. The adhesion of the first metal layer is greater than that of the second metal layer. For example, the material of the first metal layer is titanium, palladium, or chromium, and the material of the second metal layer is gold. In this way, the first metal layer with higher adhesion can make the conductive connection layer 130 better adhere to the holey optical fiber 110, improving the bonding strength between the conductive connection layer 130 and the holey optical fiber 110, and also improving the service life of the conductive connection layer 130.

[0211] In some embodiments, the optical fiber is a holey optical fiber, the electron emission layer is disposed on the end face of the light-output end of the holey optical fiber, and the electron excitation layer covers the end of the light-guiding hole located at the end face of the light-output end. The pulsed laser output from the holey optical fiber is capable of directly irradiate the electron emission layer, such that the electron excitation layer is excited by the pulsed laser output from the holey optical fiber to emit electrons.

[0212] In some embodiments, the optical fiber is a tapered optical fiber. In the present application, the low-dimensional material can be disposed on the tapered optical fiber, and due to the tapered geometry of the tapered optical fiber, the field emission enhancement factor is improved, resulting in a high-brightness electron source. The low-dimensional material can be the two-dimensional material. Furthermore, at least one of the zero-dimensional material or the one-dimensional material can be further disposed on the two-dimensional material, thereby achieving high brightness, low energy spread, and narrow pulse width.

[0213] In some embodiments, as shown in FIGs. 36 to 40, the light-output end of the optical fiber has a tip portion. The electron excitation layer covers the surface of the tip portion of the optical fiber. The electron excitation layer 121 can directly cover the surface j1 of the tip portion j of the optical fiber 110, or can indirectly cover the surface j1 of the tip portion j of the optical fiber 110, which is not specifically limited herein.

[0214] In use of the electron source 100, the laser in the fiber core 111 of the optical fiber 110 can be transmitted toward the light-output end 1102 of the optical fiber 110. The light-output end 1102 has the tip portion j, the electron excitation layer 121 covers the surface j1 of the tip portion j of the optical fiber 100, and the electron excitation layer 121 is located on the light output path of the fiber core 111. Thus, when the laser transmitted in the fiber core 111 of the optical fiber 110 propagates to the tip portion j and outputs from the tip portion j, this part of laser can interact with the electron excitation layer 121, such that electrons in the electron excitation layer 121 absorb photons of the laser and undergo energy transition to escape from the electron excitation layer 121, thereby realizing electron excitation. The laser can be transmitted along the fiber core 111 of the optical fiber 110, allowing the laser transmitted in the fiber core 111 to propagate to the light-output end 1102, exit the optical fiber 110, and interact with the electron excitation layer 121, such that electrons in the electron excitation layer 121 absorb photons of the laser and undergo energy transition, thereby escaping from the electron excitation layer 121 and realizing electron excitation. The electron source 100 adopts the low-dimensional material such as the zero-dimensional material, one-dimensional material, or two-dimensional material, as the material of the electron excitation layer 121, and the electron excitation layer 121 is disposed on the optical fiber 110 to realize electron excitation, eliminating a complex spatial optical coupling structure for external lasers and also abandoning a high-magnification microscope for solving the alignment problem of a metallic needle tip, thus reducing the process cost of the electron gun and improving the stability.

[0215] In the approach that a metal layer is disposed on the tip portion of the optical fiber and the laser transmitted through the optical fiber interacts directly with the metal layer to excite electrons, the electrons may be easily scattered by the metal lattice when passing through the metal layer, resulting in low electron emission efficiency. In addition, the conduction band of metallic materials is a half-filled, resulting in a wide energy distribution of the electrons emitted from the excited metal layer. Compared with this approach, in the present application, the material of the electron excitation layer 121 adopts the low-dimensional material, such as the zero-dimensional material, one-dimensional material, or two-dimensional material. The low-dimensional material has an atomic-level thickness, and thus electrons generated upon the back side irradiation can be emitted without traveling through the bulk of the material, resulting in high electron emission efficiency. Moreover, the low-dimensional material is free of dangling bonds and has stable properties and a high melting point, which is less prone to damage and suitable for high-power excitation scenarios, with the characteristics such as good stability and long service life. In addition, the low-dimensional material also has high optical nonlinearity and abundant electron band gaps, allowing the laser to interact more effectively with the electron excitation layer 121 to generate energy resonance and excite electrons in the electron excitation layer 121. These electrons are excited and then escape into the vacuum, forming an electron beam. The electron beam emitted via tunneling effect from the electron excitation layer 121 has concentrated energy and low energy spread. Furthermore, the low-dimensional material can be directly integrated with the optical fiber 110. The optical fiber can transmit the laser while serving as a carrier for the low-dimensional material, thereby providing a stable excitation source with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios, does not require a complex optical path, and possesses characteristics of small volume and high integration.

[0216] Optionally, along the extending direction of the fiber core 111, the radial size of the tip portion j gradually decreases. In the present application, the electron excitation layer 121 of can be disposed on the tip portion j of the

optical fiber 110 and cover the surface j1 of the tip portion j of the optical fiber 110. The tip portion j of the optical fiber 110 has a needle-tip shaped geometric structure, which improves the field emission enhancement factor, thereby achieving a high-brightness electron source 100.

[0217] In some embodiments, the electron excitation layer includes a first portion. A projection of the first portion on a target plane perpendicular to the extending direction of the fiber core covers a projection of the fiber core on the target plane. The first portion is electrically connected to the conductive connection layer.

[0218] In some embodiments, the electron excitation layer further includes a second portion connected to the first portion. A projection of the second portion on the target plane is located around the projection of the first portion on the target plane. The second portion overlaps with the conductive connection layer. As such, the conductive connection layer 130 is electrically connected to the second portion 1212 of the electron excitation layer 121, while the projection of the second portion 1212 on the target plane is located around the projection of the first portion 1211 on the target plane. As such, the conductive connection layer 130 can replenish electrons to the electron excitation layer 121 without affecting the interaction between the fiber core 111 and the electron excitation layer 121, which facilitates the electron excitation layer 121 in continuously emitting electrons under laser excitation.

[0219] In some embodiments, the conductive connection layer includes a first conductive portion and a second conductive portion, the first conductive portion is disposed on the tip portion of the optical fiber, and the second conductive portion is connected to the first conductive portion and disposed on a circumferential side surface of the optical fiber. The first conductive portion overlaps with the second portion. In this way, the conductive connection layer 130 can cover more surfaces of the optical fiber 110, improving the bonding strength between the conductive connection layer 130 and the optical fiber, and also facilitating the electron replenishment to the electron excitation layer 121 through the conductive connection layer 130.

[0220] In some embodiments, along the extending direction of the fiber core, the size of the tip portion is L1, and the size of the electron excitation layer is L2, wherein L1 is greater than L2.

[0221] In some embodiments, the size of the tip portion and the size of the electron excitation layer satisfy the following relationship: $L2 > 1/2 \times L1$. The electron excitation layer 121 covers the surface j1 of the tip portion j, and the electron excitation layer 121 is disposed around the tip portion j. Since $L2 > 1/2 \times L1$, the contact area between the electron excitation layer 121 and the surface j1 of the tip portion j can be increased, improving the bonding strength between the electron excitation layer 121 and the optical fiber 110, and also facilitating the laser transmitted by the fiber core 111 to excite the electron excitation layer 121 to emit electrons.

[0222] In some embodiments, the optical fiber is a solid-core optical fiber. In the present application, the low-dimensional material can be disposed at the fiber core of the solid-core optical fiber. The evanescent wave leaking from the fiber core can interact with the low-dimensional material surrounding the optical fiber. In this system, a relatively long distance for interaction between light and the material can be realized, achieving high brightness electron emission. In addition, micro-nano optical fibers with different diameters can be drawn, allowing light of different modes and different intensities to interact with the low-dimensional material, so as to achieve electron emission with precisely regulated parameters. In addition, different types or dimensional materials can be further grown or transferred onto the already grown or transferred low-dimensional material to form heterojunctions, thereby realizing multifunctional electron emission.

[0223] It should be noted that there is no specific requirement or special limitation on the size of the optical fiber in the present application. Those skilled in the art can reasonably select the size of the optical fiber according to actual use requirements.

[0224] In some embodiments, the electron excitation layer is prepared by using at least one of a dry transfer method, a wet transfer method, or a direct growth method.

[0225] In some embodiments, the electron excitation layer is prepared by using a dry transfer method, and the preparation method includes: transferring a zero-dimensional material, a one-dimensional material, or a two-dimensional material to an adhesive tape by mechanical exfoliation, and then transferring the zero-dimensional material, the one-dimensional material, or the two-dimensional material to a laser emission side of the optical fiber via the adhesive tape.

[0226] In some embodiments, the electron excitation layer is prepared by using a wet transfer method, and the preparation method includes: directly preparing a zero-dimensional material, a one-dimensional material, or a two-dimensional material in a solution and allowing the material to float on the liquid surface, contacting the material on the liquid surface with an optical fiber, and drying.

[0227] In some embodiments, the electron excitation layer is prepared by using a direct growth method, and the preparation method includes: directly preparing the electron emission layer on a laser emission side of the optical fiber by at least one of chemical vapor deposition, physical vapor deposition, molecular beam epitaxy, or liquid filling.

[0228] A second aspect of the present application provides an electron gun. As shown in FIG. 41, the electron gun includes a housing, a grid electrode 200, an anode, and the electron source as described in the first aspect. The electron source is fixed in the housing. The grid electrode and the anode are sequentially disposed on an electron

emission side of the electron source.

[0229] For example, the electron source 100 is applied in the electron gun, and the electron gun further includes an anode 300. The anode 300 defines a first electron channel 310 allowing electrons emitted from the electron excitation layer 121 to pass through. A preset voltage is provided between the anode 300 and the conductive connection layer 130, so that a preset electric field is formed between the anode 300 and the conductive connection layer 130, and the electrons emitted from the electron excitation layer 121 can be driven by the preset electric field to transport toward the first electron channel 310 of the anode 300 and exit through the first electron channel 310. Specifically, the electron excitation layer 121 is electrically connected to a negative electrode of a power supply through the conductive connection layer 130, and the anode 300 is electrically connected to a positive electrode of the power supply, so that a preset voltage is provided between the anode 300 and the conductive connection layer 130. The electron excitation layer 121 and the anode 300 are spaced apart and arranged in the extending direction of the holey optical fiber 110. Thus, with the anode 300, a uniform electric field in the axial direction of the holey optical fiber 110 can be formed, and the electrons can be linearly accelerated along the axial direction of the holey optical fiber 110 and pass through the first electron channel 310.

[0230] In the present application, the grid electrode 200 is configured to limit the shape of the electron beam, and the anode 300 is configured to accelerate the electrons. The electrons excited and emitted from the electron source 100 will interact with the electrostatic field established by the grid electrode 200 and the space charges of the electrons themselves to form an electron beam with a specific shape. The electron beam passes through a second electron channel 210 of the grid electrode 200, and then through the first electron channel 310 of the anode 300 to exit the electron gun for use.

[0231] A third aspect of the present application provides use of the electron source as described in the first aspect, wherein the use of the electron source includes at least one of an electron microscope, an electron beam exposure machine, an X-ray tube, a free-electron laser device, or a display.

[0232] A fourth aspect of the present application provides a four-dimensional electron microscope 10A for scanning a sample. Referring to FIG. 42 and in combination with FIGs. 43 to 45, the four-dimensional electron microscope 10A provided by the present application includes a light source assembly 2A, an electron source 100, an electron optical assembly 3A, and a detector 4A. The light source assembly 2A can emit a pulsed laser. The pulsed laser propagates to the electron source 100 to excite the electron source 100, forming an electron beam. The electron beam is modulated by the electron optical assembly 3A and then projected onto a sample 5A to excite a corresponding signal. The detector 4A receives the corresponding signal to obtain information of the sample 5 according to the corresponding signal. The electron source 100 includes an excitation optical fiber 110A and an electron emission layer 120. The excitation optical fiber 110A includes a light-input end 1101 coupled to the light source assembly 2A and a light-output end 1102 opposite to the light-input end 1101. That is, the excitation optical fiber 110A is coupled to the light source assembly 2A. The electron emission layer 120 at least includes an electron excitation layer 121. The electron excitation layer 121 is disposed on an output path of the pulsed laser output from the excitation optical fiber 110, enabling the electron excitation layer 121 to emit an electron beam upon excitation by the pulsed laser. In other words, the excitation optical fiber 110A includes a fiber core 111 for transmitting the pulsed laser, and the electron emission layer 120 is disposed on the output path of the pulsed laser output from the fiber core 111. Upon excitation by the pulsed laser transmitted through the fiber core 111, the electron excitation layer 121 of the electron emission layer 120 can emit an electron beam in a direction outward from the light-output end 1102. It can be understood that, under the pulsed laser excitation, the emitted electron beam is a pulsed beam. That is, the electron source 100 itself can emit a pulsed electron beam, which enables a four-dimensional detection without the need of an optical window on the housing 6A at the position adjacent to the electron source 100 in the four-dimensional electron microscope 10A for introducing the pulsed electron beam, avoiding damage to the chamber resulting from the damage to the housing 6A.

[0233] It can be understood that the electron source of the four-dimensional electron microscope 10A can include any one of the above-described electron sources, and the optical fiber in the electron source is the excitation optical fiber.

[0234] Referring to FIGs. 42 to 44, in some embodiments, the four-dimensional electron microscope 10A further includes a housing 6A. The housing 6A defines a vacuum chamber. The electron source 100 and the electron optical assembly 3A are sequentially disposed in the vacuum chamber. The electron source 100 extends through an end of the housing 6A in a longitudinal direction thereof. In other words, the housing 6A has an opening in communication with the vacuum chamber. The light-input end 1101 of the excitation optical fiber 110A of the electron source 100 is exposed out from the opening and coupled to the light source assembly 2A. An outer circumferential wall of the excitation optical fiber 110A is sealingly connected to an inner sidewall of the opening, thereby ensuring the sealing of the chamber and improving the overall quality of the chamber. The electron source 100 of the present application can emit a pulsed electron beam without the need to open an optical window at the position of the housing 6A adjacent to the electron source 100 for introducing the pulsed electron beam, avoiding damage to the chamber of the electron microscope, so as not to affect the performance of the electron microscope. Furthermore, the present application

allows for retrofitting of an existing electron microscope. During retrofitting, only the electron source 100 needs to be replaced to output the pulsed electron beam, without the need to open an optical window at the position of the housing 6A adjacent to the electron source 100, thus avoiding damage to the chamber of the existing electron microscope. The retrofitting is simple and has a low cost, with the detection performance improved after retrofitting.

[0235] In some embodiments, a third optical fiber 23A can extend into the housing through an opening on the housing 6A adjacent to the sample 5A, irradiating the sample with excitation light, which cooperates with the electron beam to jointly characterize the sample.

[0236] It can be understood that the excitation optical fiber 110A serves as both a medium for transmitting the laser and a carrier for the low-dimensional material of the electron emission layer 120. The excitation optical fiber 110A can be a single-mode optical fiber, a multi-mode optical fiber, a polarization-maintaining optical fiber, a holey optical fiber, a multi-core optical fiber, etc. It should be noted that, no matter which type of excitation optical fiber 110A is used, the electron emission layer 120 is located in the vacuum chamber.

[0237] Referring to FIGs. 42 to 44, the electron optical assembly 3A is disposed on an electron beam emission side of the electron source 100. The electron optical assembly 3A is configured to adjust the deflection direction of the electron beam to allow the electron beam to be incident onto the sample 5A. In some embodiments, the electron optical assembly 3A includes structures such as a magnetic lens 31A, which is mainly configured to modulate the deflection direction of the electron beam, so that the electron beam can be projected onto the sample 5A. The detector 4A is disposed on a side of the sample 5A and configured to collect reflected electron signals of the electron beam incident on the sample 5A or to collect transmitted electron signals of the electron beam passing through the sample 5A. That is, through the arrangement of the detector 4A, the four-dimensional electron microscope 10A of the present application can function as both a scanning electron microscope and a transmission electron microscope.

[0238] In some embodiments, the electron source 100 further includes an anode. A preset electric field is provided between the anode and the electron emission layer 120. The electron beam driven by the preset electric field can be incident onto the sample 5A. That is, the electron emission layer 120 emits an electron beam upon excitation by the pulsed laser and forms a cathode opposite to the anode. Under the action of the electric field between the anode and the electron emission layer 120, the electrons can move toward the sample 5. In addition, the electron optical assembly 3A is disposed on the electron beam emission side of the electron source 100 and configured to adjust the deflection direction of the electron beam. Thus, the electron beam emitted from the electron emission layer 120 can be incident onto the sample 5A, and then the detector 4A can receive the corresponding signal from the sample 5A to detect and obtain information of the sample 5A.

[0239] In some embodiments, the anode defines a first electron channel, and the electron optical assembly 3A defines a second electron channel in communication with the first electron channel, so that the electron beam driven by the preset electric field can pass through the first electron channel and the second electron channel and reach the sample 5A. That is, the electron beam is driven by the electric field to pass through the first electron channel, and is regulated by the electron optical assembly 3A when passing through the second electron channel, resulting in direction deflection of the electron beam. Finally, the electron beam is incident onto the sample 5A, after which the detector 4A receives the reflected electron signals or transmitted electron signals from the sample 5A. It can be understood that the anode can be configured as an annular hollow structure, and the center of the annular anode is the first electron channel for the electron beam to pass through. Thus, the anode can cooperate with the electron emission layer 120 to form an electric field that drives the electron beam without affecting the passage of the electron beam.

[0240] In some embodiments, the four-dimensional electron microscope 10A further includes a sample stage. The electron source 100, the electron optical assembly 3A, and the sample stage are spaced apart and sequentially disposed in a propagation direction of the electron beam. The sample stage is configured to carry the sample 5A. In some embodiments, a channel is defined in the middle of the sample stage to allow the electron beam passed through the sample 5A to propagate. That is, the electron beam passing through the sample 5A will not be blocked by the sample stage and can continue to propagate, thereby enabling the four-dimensional electron microscope 10A to realize transmission scanning detection.

[0241] In some embodiments, the light source assembly 2A includes a light source 29A and a first optical fiber 21A. The light source 29A is configured to emit a pulsed laser. The first optical fiber 21A is connected between the light source 29A and the excitation optical fiber 110A and is configured to transmit the pulsed laser emitted by the light source 29A to the excitation optical fiber 110A. In other words, an end of the first optical fiber 21A is coupled to the light source 29A, and the other end of the first optical fiber 21A is connected to the excitation optical fiber 110A. In some embodiments, a device such as an optical switch 28A can be disposed between the first optical fiber 21A and the excitation optical fiber 110A to control the open or close of the optical path.

[0242] The four-dimensional electron microscope 10A of the present application can perform surface scanning and detection on a sample, that is, can realize the function of a scanning electron microscope. Referring to FIG. 42, in some embodiments, the reflected electron signals include secondary electron signals or backscattered electron signals; that is, the four-dimensional electron microscope 10A of the present application can detect secondary electrons

and backscattered electron signals excited from the surface of the sample. In these embodiments, the light source assembly 2A further includes a first optical fiber beam splitter 24A, a second optical fiber 22A, and a first optical fiber time delayer 26A. The first optical fiber beam splitter 24A is capable of dividing the pulsed laser into two parts: one part is used to excite an electron beam, and the other part, after time-delay modulation, irradiates the surface of the sample 5A to realize time-resolved imaging analysis, thereby realizing the presentation of characteristics in the time dimension. It can be understood that the first optical fiber beam splitter 24A can include a first input end and a first output end, the first input end is coupled to the light source 29A, and the first output end is opposite to the first input end. The first output end is separately connected to the first optical fiber 21A and the second optical fiber 22A. That is, the first optical fiber beam splitter 24A splits the pulsed laser emitted by the light source 29A into two parts, and respectively transmits to the first optical fiber 21A and the second optical fiber 22A.

[0243] Referring to FIG. 42, the sample 5A has an incident surface disposed opposite to the electron beam emission side of the electron source 100. The end of the second optical fiber 22A away from the first optical fiber beam splitter 24A extends toward the incident surface of the sample 5A, so that the light transmitted through the second optical fiber 22 can irradiate the sample 5A. The incident surface of the sample 5A can be disposed obliquely relative to the propagation direction of the electron beam, or can be perpendicular to the propagation direction of the electron beam, which is not limited herein. In some embodiments, the first optical fiber time delayer 26A is coupled to the second optical fiber 22A and is configured to apply a time delay to the light beam propagating in the second optical fiber 22A, so that the light in the second optical fiber 22A has a preset time delay with respect to the electron beam exciting light in the first optical fiber 21A. It can be understood that, based on the photoelectric effect, in the related art, imaging by electron microscopes involves forming an image contrast by different photoelectron yields at different spatial positions of the sample. The present application, in combination with ultrafast optical pump-probe technology, can provide high temporal resolution for the electron microscopes. In these embodiments, the electron beam excited by the pulsed laser from the first optical fiber 21A is used to excite the sample 5A, and the time-delayed pulsed laser from the second optical fiber 22A is used as probe light to irradiate the sample 5A, thereby exciting the material and causing changes in the reflection or transmission behavior of the electron beam incident on the sample 5A, forming the required secondary electron signals or backscattered electron signals with time-resolved characteristics. When the time-delayed pulsed laser in the second optical fiber 22A is used as probe light, the time delay of the pulsed laser in the second optical fiber 22A can be adjusted by the first optical fiber time delayer 26A, thereby observing changes at different time points after the material is excited by the laser, so as to realize time-resolved electron beam imaging, enabling real-time detection of ultrafast dynamic processes on the surface of the sample 5A at ultra-high spatiotemporal resolution. In these embodiments, the detector 4A includes a backscattered electron detector or a secondary electron detector. The backscattered electron detector or the secondary electron detector is disposed toward the incident surface of the sample 5A to receive the secondary electron signals for imaging.

[0244] Referring to FIG. 43, in the embodiment conducting surface scan and detection of the sample, cathodoluminescence signals from the sample 5A can also be detected and analyzed. The cathodoluminescence signals can be excited from the surface of the sample 5A by the electron beam. The detector 4A includes a cathodoluminescence analysis system, and the cathodoluminescence analysis system is directed toward the incident surface of the sample 5A to receive the cathodoluminescence signals from the surface of the sample 5A. The cathodoluminescence analysis system can be configured as a time-correlated single-photon counting system (TCSPC). The cathodoluminescence analysis system performs time-resolved cathodoluminescence analysis on the cathodoluminescence signals through the time-resolved single-photon counting system, which is not repeated herein.

[0245] The four-dimensional electron microscope 10A of the present application can further perform transmission detection on the sample, that is, can realize the function of a transmission electron microscope. Referring to FIG. 44, the sample 5A further includes an exit surface opposite to the incident surface. In some embodiments, the detector 4A includes a receiving screen 41A. The receiving screen 41A is disposed on the side of the sample 5A away from the electron source 100 and is configured to receive the electron beam passing through the sample 5A. The receiving screen 41A can be a fluorescent screen. The electron beam passes through the sample and projects the information of the sample onto the fluorescent screen. An image recording chamber 42A then performs imaging and photographing to obtain experimental results, such as bright-field images, dark-field images, electron diffraction patterns, high-resolution images, and chemical information. In these embodiments, a high-angle annular dark-field detector, a low-angle annular dark-field detector, or an annular bright-field detector, etc., can also be correspondingly disposed facing the exit surface of the sample 5A to obtain high-angle annular dark-field images, low-angle annular dark-field images, or annular bright-field images of electrons passed through the sample 5A, thereby detecting the sample 5A and realizing the function of a transmission scanning electron microscope.

[0246] In some embodiments, the electron optical assembly 3A further includes an intermediate lens 32A and a projection lens 33A sequentially disposed between the sample 5A and the receiving screen 41A. The intermediate lens 32A is configured to converge the electron beam, and the projection lens 33A is configured to adjust the radial size of the electron beam to facilitate the image recording chamber 42A to image the electron beam projected on the

receiving screen 41A.

[0247] In some embodiments, the light source assembly 2A further includes a second optical fiber beam splitter 25A, a third optical fiber 23A, and a second optical fiber time delay 27A. The first optical fiber beam splitter 24A can split the pulsed laser into two parts: one part is used to excite an electron beam, and the other part is used as probe light and, after time-delay modulation, irradiates the surface of the sample 5A to realize time-resolved imaging analysis. The second optical fiber beam splitter 25A can include a second input end and a second output end, the second input end is coupled to the light source 29A, and the second output end is opposite to the second input end. The second output end is separately connected to the first optical fiber 21A and the third optical fiber 23A. That is, the second optical fiber beam splitter 25A splits the pulsed laser emitted by the light source 29A into two parts, and respectively transmits to the first optical fiber 21A and the third optical fiber 23A. The end of the third optical fiber 23A away from the second optical fiber beam splitter 25A extends toward the sample 5A, so that the light transmitted through the third optical fiber 23A can irradiate the sample 5A. The second optical fiber time delay 27A is coupled to the third optical fiber 23A and is configured to apply a time delay to the light beam propagating in the third optical fiber 23A, so that the light in the third optical fiber 23A has a preset time delay with respect to the electron beam exciting light in the first optical fiber 21A, thereby realizing time-resolved electron beam imaging.

[0248] The present application adopts the pulsed laser to excite the electron excitation layer 121 and form an electron beam, which eliminates a complex spatial optical coupling structure for an external laser, so that the four-dimensional electron microscope 10A is less affected by the environment and can provide a stably excited electron beam, thereby improving the scanning stability of the sample 5A to be tested. In addition, the electron source 100 of the present application adopts the low-dimensional material to emit electrons. The electron excitation layer 121 enables strong light-matter interaction and has abundant electron band gaps, allowing the pulsed laser to interact more effectively with the electron excitation layer 121 to excite electrons from the electron excitation layer 121. The electrons emitted from the interior of the electron excitation layer 121 via tunneling effect have low energy spread, high brightness, and high stability. Furthermore, the present application can form a pulsed electron beam by exciting the electron excitation layer 121 with the pulsed laser, without the need to open an additional window on the electron microscope for introducing the pulsed electron beam, avoiding damage to the electron microscope chamber, which is conducive to realizing a miniaturized design. Moreover, the electron beam can be modulated by modulating the pulsed laser through the electron optical assembly 3A, thereby reducing the influence on scanning quality during modulation of the electron beam, and thus enabling stable scanning of the sample 5A to be tested.

[0249] In a fifth aspect, the present application provides an electron beam exposure machine for exposing a sample, which can achieve the effects such as good stability, precise regulation, high exposure quality, and being adapted for miniaturized designs.

[0250] As shown in FIGs. 46 and 47, the electron beam exposure machine 10B includes a light source 200B, an electron source 100, an optical modulator 500B, and an electron optical assembly 600B. The light source 200B is configured to emit a laser for electron excitation. The laser propagates to the electron source 100 to excite the electron source 100, thereby forming an electron beam. The electron beam is modulated by the electron optical assembly 600B and irradiates the sample 410B to expose the sample 410B.

[0251] It can be understood that the electron source in the electron beam exposure machine can include any one of the above-described electron sources of the present application.

[0252] Referring to FIG. 46, the electron source 100B further includes the optical modulator 500B. The optical modulator 500B is connected between the light source 200B and the optical fiber 110, and is configured to control whether the laser propagates to the optical fiber 110. In some embodiments, the optical modulator 500B includes an electro-optic modulator or an optical switch. The optical switch can control whether the laser emitted by the light source 200B propagates to the optical fiber 110. The electro-optic modulator can regulate the phase of the laser emitted by the light source 200B while controlling whether the laser emitted by the light source 200B propagates to the optical fiber 110. Since the electron beam is controlled by controlling the laser via the optical modulator 500B, there is no need to include an electron beam blanker to modulate the electron beam. Moreover, the electron beam exposure machine 10B of the present application can be formed by retrofitting an existing electron microscope. During retrofitting, since the electron beam can be controlled via the optical modulator 500B, there is no need to add an electron beam blanker structure, or consider its corresponding effects on electric and magnetic field distributions and wiring issues. The electron source 100 of the present application allows directly adding an optical modulator 500B on the external optical path, such as on the optical fiber 110, thereby completing the hardware retrofitting for the electron exposure function.

[0253] The electron beam exposure machine 10B further includes an electron optical assembly 600B. The electron optical assembly 600B is disposed on an electron beam emission side of the electron source 100. The electron optical assembly 600B is configured to adjust the deflection direction of the electron beam to allow the electron beam to be incident onto the sample 410B.

[0254] In some embodiments, the electron optical assembly 600B includes a focusing magnetic lens 610B and a

deflection coil 620B. The focusing magnetic lens 610B and the deflection coil 620B are spaced apart from each other along an emission direction of the electron beam and disposed at the electron beam emission side of the electron source 100. The focusing magnetic lens 610B and the deflection coil 620B are mainly configured to modulate the deflection direction of the electron beam, thereby projecting the electron beam onto the sample 410B and forming a preset exposure pattern on the sample.

[0255] In some embodiments, the electron source 100 further includes an anode. A preset electric field is provided between the anode and the electron excitation layer 121. The electron beam driven by the preset electric field can be incident onto the sample 410B. That is, the electron excitation layer 121 emits an electron beam upon excitation by the laser and forms a cathode opposite to the anode. Under the action of the electric field between the anode and the electron excitation layer 121, the electrons can move toward the sample 410B. In addition, the electron optical assembly 600B is disposed on the electron beam emission side of the electron source 100 and configured to adjust the deflection direction of the electron beam. Thus, the electron beam emitted from the electron excitation layer 121 can be incident onto the sample 410B for exposure.

[0256] In some embodiments, the anode defines a first electron channel, and the electron optical assembly 600B defines a second electron channel in communication with the first electron channel, so that the electron beam driven by the preset electric field can pass through the first electron channel and the second electron channel and reach the sample 410B. That is, the electron beam is driven by the electric field to pass through the first electron channel, and is regulated by the electron optical assembly 600B when passing through the second electron channel, resulting in direction deflection of the electron beam. Finally, the electron beam is incident onto the sample 410B. It can be understood that the anode can be configured as an annular hollow structure, and the center of the annular anode is the first electron channel for the electron beam to pass through. Thus, the anode can cooperate with the electron excitation layer 121 to form an electric field that drives the electron beam without affecting the passage of the electron beam.

[0257] As shown in FIG. 46, in some embodiments, the electron beam exposure machine 10B further includes a sample stage 400B. The sample stage 400B is disposed on the side of the electron optical assembly 600B away from the electron source 100 along the propagation direction of the electron beam. The sample stage 400B is configured to carry the sample 410B. In some embodiments, the sample stage 400B is further provided with a Faraday cup for measuring the beam current of the electron beam, that is, measuring the intensity of the electron beam incident onto the sample 410B, so as to facilitate regulation of the electron beam, thereby controlling the exposure effect.

[0258] In some embodiments, the electron beam exposure machine 10B further includes a housing 300B. The housing 300B defines a vacuum chamber 310B. The light-output end 1102 of the optical fiber 110 of the electron source 100, the electron optical assembly 600B, and the sample stage 400B are spaced apart from each other and sequentially disposed in the vacuum chamber 310B. The electron excitation layer 121 is disposed on the light-output end 1102 of the optical fiber 110 and thus located on the output path of the laser output from the optical fiber 110, so that the electron source 100 emits an electron beam into the vacuum chamber 310B. In other words, the electron source 100 extends through an end of the housing 300B in a longitudinal direction thereof. The housing 300B has an opening in communication with the vacuum chamber 310B. The light-input end 1101 of the optical fiber 110 of the electron source 100 is exposed out from the opening and coupled to the light source 200B. The outer circumferential wall of the optical fiber is sealingly connected to the inner sidewall of the opening, thereby ensuring the sealing performance of the chamber and improving the overall quality of the chamber.

[0259] Furthermore, the present application allows for retrofitting of an existing electron microscope. During retrofitting, only the electron source 100 needs to be replaced to output the electron beam, without the need to open an optical window on the housing 300B adjacent to the electron source 100, thus avoiding the damage to the chamber of the existing electron beam exposure machine. The retrofitting is simple and has a low cost, with the detection performance improved after retrofitting.

[0260] In some embodiments, depending on the exposure pattern, multiple electron sources 100 can be combined for scanning exposure, which can improve the exposure efficiency. For a high-precision region of a preset pattern to be exposed, the optical fiber 110 can be a single-mode optical fiber, so that the electron beam emitted by the electron source 100 is a low-current electron beam. For a large-area scanning region, the optical fiber 110 can be a multi-mode optical fiber or other types of optical fibers, so that the electron beam emitted by the electron source 100 is a high-current electron beam. In actual use, the spot sizes or exposure times of the electron beams projected onto the sample, formed by the electron sources using different optical fibers, can also be calculated and adjusted according to the beam current intensity, thereby achieving fast and high-precision scanning exposure.

[0261] In some embodiments, as shown in FIGs. 46 to 47, the light-input end 1101 of the optical fiber 110 extends out of the vacuum chamber 310B through the opening to allow the optical fiber to be coupled to the light source 200B. Alternatively, the end face of the light-input end 1101 of the optical fiber 110 can be flush with the plane of the opening. In this way, the optical fiber 110 can be substantially encapsulated in the housing 300B, and the end face of the light-input end 1101 of the optical fiber 110 is exposed out from the opening, so that the light source 200B can be coupled to

the light-input end 1101 of the optical fiber 110, thereby effectively protecting the optical fiber 110 and also facilitating the transmission of the laser from the light source 200B to the optical fiber 110.

[0262] The present application adopts the laser to excite the electron excitation layer 121 to form an electron beam, which eliminates a complex spatial optical coupling structure for an external laser, so that the electron beam exposure machine 10B is less affected by the environment and can provide a stably excited electron beam, thereby improving the scanning stability of the sample 410B to be tested. In addition, the electron source 100 of the present application adopts the low-dimensional material to emit electrons. The electron excitation layer 121 enables strong light-material interaction and has abundant electron band gaps, allowing the laser to interact more effectively with the electron excitation layer 121 to excite electrons from the electron excitation layer 121. The electrons emitted from the interior of the electron excitation layer 121 via tunneling effect have low energy spread, high brightness, and high stability. Furthermore, the present application can form a pulsed electron beam by exciting the electron excitation layer 121 with the laser, without the need to open an additional window on the electron microscope for introducing a pulsed electron beam, thereby avoiding damage to the electron microscope chamber. Furthermore, there is no need to include an electron beam blanker to modulate the electron beam, further saving space and facilitating a miniaturized design. Moreover, the excited electron beam can be modulated by modulating the laser through the electron optical assembly 600B, thereby reducing the influence on scanning quality during modulation of the electron beam, and thus enabling stable exposure of the sample 410B to be tested.

[0263] In a sixth aspect, the present application provides an optical fiber multi electron beam exposure machine for exposing a sample, which can achieve the effects such as improved exposure efficiency, precise regulation, improved exposure quality, and being adapted for miniaturized designs.

[0264] As shown in FIGs. 48 to 52, the optical fiber multi electron beam exposure machine 10C includes a light source 200C, an electron source 100, and an electron optical assembly 600C. The light source 200C is configured to emit a laser for excitation. The laser propagates to the electron source 100 to excite the electron source 100, forming electron beams. The electron beams are modulated by the electron optical assembly 600C and then projected onto the sample 410C to expose the sample 410C.

[0265] The electron source 100 includes an optical fiber assembly 101 and electron emission layers 120. The optical fiber assembly 101 is coupled to the light source. The electron emission layers at least include electron excitation layers 121. The optical fiber assembly 101 has a light-input end 1101 coupled to the light source 200C and a light-output end 1102 opposite to the light-input end 1101. The laser emitted by the light source 200 enters the optical fiber assembly 101 from the light-input end 1101, propagates through the optical fiber assembly 101, and exits from the light-output end 1102. The optical fiber assembly 101 includes a plurality of fiber cores 111 for transmitting laser beams. The electron excitation layers 121 are disposed on the laser output paths of the fiber cores 111 of the optical fiber assembly 101, enabling the electron excitation layers 121 to emit electron beams upon excitation by the laser beams. In other words, the electron emission layers 120 are configured to emit electron beams outward from the light-output end 1102 upon excitation by the laser beams transmitted through the fiber cores 111. The laser propagates in the fiber cores 111 and exits from the light-output end 1102 onto the electron excitation layers 121, and the electron excitation layers 121 are excited to emit electron beams.

[0266] It can be understood that the electron source in the optical fiber multi electron beam exposure machine can include any one of the above-described electron sources of the present application.

[0267] Referring to FIG. 48, the electron source 100 further includes an optical modulator 500C. One end of the optical modulator 500C is connected to the light source 200C, and the other end of the optical modulator 500C is separately connected to the plurality of fiber cores 111 of the optical fiber assembly 101. The optical modulator 500C is configured to separately control whether the laser propagates to individual fiber cores 111. In some embodiments, the optical modulator 500C includes a spatial light modulator, an optical switch, or an electro-optic modulator. The optical switch can control whether the laser emitted by the light source 200C propagates to individual fiber cores 111 of the optical fiber assembly 101. The electro-optic modulator and the spatial light modulator can regulate the phase of the laser emitted by the light source 200C while controlling whether the laser emitted by the light source 200C propagates to individual fiber cores 111 of the optical fiber assembly 101. That is, the optical modulator 500C is configured to control whether the laser emitted by the light source 200C separately propagates to corresponding fiber cores 111, so as to separately control whether the light passes through individual fiber cores 111.

[0268] Since the electron beam is controlled by controlling the laser via the optical modulator 500C, there is no need to include an electron beam blanker to modulate the electron beam. Moreover, the optical fiber multi electron beam exposure machine 10C of the present application can be formed by retrofitting an existing electron microscope. During retrofitting, since the electron beam can be controlled via the optical modulator 500C, there is no need to add an electron beam blanker structure, or consider the corresponding effects on electric and magnetic field distributions and wiring issues. The electron source 100 of the present application allows directly adding an optical modulator 500C on the external optical path, such as on the optical fiber assembly 101, thereby completing the hardware retrofitting for the electron exposure function.

[0269] Referring to FIG. 48, the optical fiber multi electron beam exposure machine 10C further includes an electron optical assembly 600C. The electron optical assembly 600C is disposed on an electron beam emission side of the electron source 100. The electron optical assembly 600C is configured to adjust the focusing and deflection directions of the plurality of electron beams to allow the plurality of electron beams to be incident onto the sample 410C.

Referring to FIG. 50, the sample 410C can be divided into a plurality of regions in an array structure. The electron optical assembly 600C focuses the plurality of electron beams to the corresponding regions, respectively. The plurality of electron beams simultaneously expose the corresponding regions, thereby improving the overall exposure efficiency of the sample 410C.

[0270] In some embodiments, the electron optical assembly 600C includes a focusing magnetic lens 610C and a deflection coil 620C. The focusing magnetic lens 610C and the deflection coil 620C are spaced apart from each other along the emission direction of the electron beams and disposed at the electron beam emission side of the electron source 100. The focusing magnetic lens 610C and the deflection coil 620C are mainly configured to modulate the deflection directions of the electron beams, thereby projecting the electron beams onto different regions of the sample 410C.

[0271] FIG. 51 is a schematic structural view of an embodiment, showing fiber cores 101 arranged in an array in the optical fiber assembly 101 of the present application. Referring to FIG. 49, the optical fiber assembly 101 in the embodiment of FIG. 51 includes a plurality of optical fibers 110 arranged in an array. The electron excitation layer 121 is disposed on an end face of a light-output end of each optical fiber 110, so that the electron excitation layer 121 is located on the laser output path of the fiber core 111 of the corresponding optical fiber 110. In other words, in some embodiments, the optical fiber assembly 101 can be in form of an optical fiber array. The optical fiber array includes a plurality of optical fibers 110. One end of each optical fiber 110 is connected to the optical modulator 500C, and the other end of each optical fiber 110 is covered with one electron excitation layer 121. The optical modulator 500C is separately connected to the plurality of optical fibers 110 in the optical fiber array to separately control the propagation of the laser in each optical fiber 110, or in other words, to control whether the light passes through each fiber core 111 in each optical fiber 110. It can be understood that the optical modulator 500C simultaneously controls the light passing through the plurality of the fiber cores 111, exciting the electron excitation layers 121 to form multiple electron beams. Then, the electron optical assembly 600C controls the multiple electron beams to focus the multiple electron beams to different regions of the sample 410C, respectively. The multiple electron beams simultaneously expose the corresponding regions, realizing a dot-matrix exposure, thereby improving the overall exposure efficiency of the sample 410C.

[0272] Referring to FIG. 52, in the embodiment shown in FIG. 52, the optical fiber assembly 101 includes a plurality of fiber cores 111 and a cladding layer 112 surrounding the plurality of fiber cores 111. The radial directions of the plurality of fiber cores 111 are parallel to each other. The plurality of fiber cores 111 are closely packed in the axial direction of the fiber cores 111 to form a pixel-based optical fiber. In other words, the optical fiber assembly 101 of the present application can adopt the structure of a pixel-based optical fiber. The electron excitation layer 121 is disposed on the light-output end 1102 of the optical fiber assembly 101, and thus the electron excitation layer 121 is located on the laser output paths of the plurality of fiber cores 111. That is, one end of the pixel-based optical fiber is connected to the optical modulator 500C, and the other end of the pixel-based optical fiber is covered with the electron excitation layer 121. The optical modulator 500C simultaneously controls the light passing through multiple fiber cores 111 in the optical fiber assembly 101, exciting the electron excitation layer 121 to form multiple electron beams. Then, the electron optical assembly 600C controls the multiple electron beams to focus the multiple electron beams to different regions of the sample 410C, respectively. The multiple electron beams simultaneously expose the corresponding regions, realizing a dot-matrix exposure, thereby improving the exposure efficiency of the entire sample 410C.

[0273] The modulation of whether light passes through the plurality of fiber cores 111 in the pixel-based optical fiber by the optical modulator 500C can also achieve patterned exposure. It can be understood that the optical modulator 500C controls the corresponding fiber cores 111 in the optical fiber assembly 101 to be in either a light-transmitting state or a light-blocking state, such that the laser output from the optical fiber assembly 101 can form a corresponding spot pattern. The axial pattern of the electron beams excited by the laser irradiating the electron excitation layer 121 will also change correspondingly. The electron beams are then modulated by the electron optical assembly 600C and irradiate the sample 410C to finally form a corresponding exposure pattern, thereby realizing patterned exposure. The above configuration can directly form an exposure pattern without requiring a long-term exposure using a single electron beam to form the required exposure pattern, relatively improving the exposure efficiency. Moreover, in combination with the electron source 100 of the present application, the precision of the exposure pattern can be relatively improved.

[0274] The fiber cores in the pixel-based optical fiber are closely packed, meaning that the electron beams excited by the light output from the fiber cores of the pixel-based optical fiber cooperate with each other and are finally focused to form a closed pattern. Thus, the patterning can be achieved by controlling light passing through each fiber core, further enabling scanning with electron beams of different shapes to obtain a complete pattern.

[0275] In the embodiment shown in FIG. 52, for the pixel-based optical fiber embodiment, the electron excitation layer 121 can be disposed on the end face 11021 of the light-output end 1102 of the fiber assembly 101, and the end face 11021 of the light-output end 1102 of the fiber assembly 101 can form an angle relative to the extending direction of the fiber cores 111. The laser output from the fiber cores 111 can directly irradiate the electron emission layer 120, such that the electron excitation layer 121 can be excited by the laser output from the fiber cores 111 to emit electrons. In other words, for the pixel-based optical fiber, the end face 11021 of the light-output end 1102 can be disposed obliquely, i.e., at an angle, relative to the extending direction of the fiber cores 111. Thus, oblique incidence on the electron excitation layer 121 can be achieved, and a photoelectric field perpendicular to the end face 11021 of the light-output end 1102 can be realized. In some embodiments, the angle between the end face 11021 of the light-output end 1102 of the fiber assembly 101 and the extending direction of the fiber cores 111 is in a range from 0° to 90°. When the angle is 90°, the laser propagating in the fiber assembly 101 perpendicularly output from the end face 11021 of the light-output end 1102. Accordingly, the electron emission direction can be changed by changing the angle of the end face 11021 of the light-output end 1102. Moreover, the electron emission direction can also be adjusted by adjusting the polarization state of the laser in the fiber cores 111 of the fiber assembly 101, thereby improving the adjustment flexibility of the electron beams in the optical fiber multi electron beam exposure machine 10C and broadening the applications of the electron source 100.

[0276] Referring to FIG. 52, for the pixel-based optical fiber, in some embodiments, the light-output end 1102 of the optical fiber assembly 101 has a tip portion j. The electron excitation layer 121 covers the surface j1 of the tip portion j of the optical fiber assembly 101. The laser output from the fiber cores 111 of the optical fiber assembly 101 can directly irradiate the electron emission layer 120, such that the electron excitation layer 121 is excited by the laser output from the fiber cores 111 to emit electrons. In other words, the light-output end 1102 of the pixel-based optical fiber can be in a tapered form. It can be understood that the electron excitation layer 121 is located on the light output paths of the fiber cores 111, receiving the laser output from the fiber cores 111. The tip portion j has a needle tip shaped geometric structure, which improves the field emission enhancement factor, thereby achieving a high-brightness electron source 100 and relatively increasing the light-emitting area of the fiber cores 111, thus exciting a high-power electron beam.

[0277] In some embodiments, the electron source 100 further includes an anode and a grid electrode. A preset electric field is provided between the anode and the electron excitation layer 121. The electron beams can be driven by the preset electric field and incident onto the sample 410C. That is, the electron excitation layer 121 emits electron beams upon excitation by the laser and forms a cathode opposite to the anode. Under the action of the electric field between the anode and the electron excitation layer 121, the electrons can move toward the sample 410C. The grid electrode cooperates with the electron source 100 and the anode to form an optical fiber electron gun. The grid electrode is configured to control the direction of the electron beams. In addition, the electron optical assembly 600C is disposed on the electron beam emission side of the electron source 100 and configured to adjust the focusing and deflection directions of the electron beams. Thus, the electron beams emitted from the electron excitation layer 121 can be incident onto the sample 410C for exposure. In some embodiments, the anode defines a first electron channel, and the electron optical assembly 600C defines a second electron channel in communication with the first electron channel, so that the electron beams driven by the preset electric field can pass through the first electron channel and the second electron channel and reach the sample 410C. That is, the electron beams are driven by the electric field to pass through the first electron channel, and are regulated by the electron optical assembly 600C when passing through the second electron channel, resulting in direction deflection of the electron beams. Finally, the electron beams are incident onto the sample 410C. It can be understood that the anode can be configured as an annular hollow structure, and the center of the annular anode is the first electron channel for the electron beams to pass through. Thus, the anode can cooperate with the electron emission layer 121 to form an electric field that drives the electron beams without affecting the passage of the electron beams.

[0278] In some embodiments, the optical fiber multi electron beam exposure machine 10C further includes a sample stage 400C. The sample stage 400C is disposed on a side of the electron optical assembly 600C away from the electron source 100 along the propagation direction of the electron beams. The sample stage 400C is configured to carry the sample 410C. In some embodiments, the sample stage 400C is further provided with a Faraday cup for measuring the beam current of the electron beams, that is, measuring the intensity of the electron beams incident onto the sample 410C, so as to facilitate regulation of the electron beams, thereby controlling the exposure effect.

[0279] In some embodiments, the electron beam exposure machine 10 further includes a housing 300C. The housing 300C defines a vacuum chamber 310C. The light-output end 1102 of the optical fiber assembly 101 of the electron source 100, the electron optical assembly 600C, and the sample stage 400C are spaced apart from each other and sequentially disposed in the vacuum chamber 310C. The electron excitation layer 121 is disposed on the light-output end 1102 of the optical fiber 110 and thus located on the laser output path of the fiber cores 111, so that the electron source 100 emits electron beams into the vacuum chamber 310C. In other words, the electron source 100 extends through an end of the housing 300C in a longitudinal direction thereof. The housing 300C has an opening in commu-

nication with the vacuum chamber 310C. The light-input end 1101 of the optical fiber assembly 101 of the electron source 100 is exposed out from the opening and coupled to the light source 200C. The outer circumferential wall of the optical fiber is sealingly connected to the inner sidewall of the opening, thereby ensuring the sealing performance of the chamber and improving the overall quality of the chamber. The present application allows for retrofitting of an existing electron microscope. During retrofitting, only the electron source 100 needs to be replaced to output the electron beams, without the need to open an optical window on the housing 300C adjacent to the electron source 100, thus avoiding to the damage to the chamber of the existing electron beam exposure machine. The retrofitting is simple and has a low cost, with the detection performance after retrofitting is improved.

[0280] For example, after the electron source 100 is prepared, the electron beam exposure machine 10 can be manufactured by arranging structures such as the housing 300C and a control system. The vacuum chamber 310C inside the housing 300C is connected to an external vacuum system to keep the vacuum chamber 310C in a vacuum state. Along the axis direction of the vacuum chamber 310C of the housing 300C, from top to bottom, the electron source 100, a focusing magnetic lens 610C, and a deflection coil 620C are sequentially arranged in the vacuum chamber 310C. A sample stage 400C is then correspondingly provided, so that the electron beams emitted by the electron source 100 can be projected to the position of the sample stage 400C, facilitating exposure of the sample 410 on the sample stage 400. The sample stage 400 can be arranged on an electrically controlled displacement stage. The sample stage 400C can be driven through the electrically controlled displacement stage to move, thereby facilitating the loading and unloading of the sample 410C. After the hardware assembly is completed, the electron source 100, the focusing magnetic lens 610C, the deflection coil 620C, and the Faraday cup can be respectively connected to the control system, and thereby controlled by the control system.

[0281] The control system can realize the connection between the above components through software such as Labview. Patterned data for the exposure process is input into the control system. The control system converts the received patterned data into exposure units and automatically calculates the scanning paths of the electron beams and the on/off time of light for the electron source 100 based on the beam current intensity of the electron beams during exposure, the vacuum state of the vacuum chamber 310C inside the housing 300C, and the focusing effect of the electron beams, forming two sets of commands, one for focusing and deflection, and the other for electro-optic modulation. That is, the control system controls the focusing magnetic lens 610C and the deflection coil 620C to regulate the focusing and deflection states of the electron beams, and controls the optical modulator 500C to regulate the one/off of the laser in the optical fiber 110, thereby improving the exposure effect. The above two sets of commands for focusing and deflection and electro-optic modulation can also be calibrated to make them highly consistent in time, avoiding mismatch of the control system during exposure operation. Moreover, multiple optical switches or spatial light modulators can be correspondingly arranged on the optical fiber assembly 101C. The optical switches or spatial light modulators can be correspondingly connected to the control system to individually control the propagation of light in the multiple fiber cores 111.

[0282] The present application adopts the laser to excite the electron excitation layer 121 to form electron beams, which eliminates a complex spatial optical coupling structure for external lasers, so that the optical fiber multi electron beam exposure machine 10C is less affected by the environment and can provide stably excited electron beams, thereby improving the scanning stability of the sample 410C to be tested. In addition, the electron source 100 of the present application adopts the low-dimensional material to emit electrons. The electron excitation layer 121 exhibits high optical nonlinear effect and abundant electron band gaps, allowing the laser to interact more effectively with the electron excitation layer 121 to excite electrons from the electron excitation layer 121. The electrons emitted from the interior of the electron excitation layer 121 via tunneling effect have low energy spread, high brightness, and high stability. Furthermore, the present application can form pulsed electron beams by exciting the electron excitation layer 121 with laser, without the need to open an additional window on the electron microscope for introducing the pulsed electron beams, thereby avoiding damage to the chamber of the electron microscope, which is conducive to realizing a miniaturized design. Moreover, the electron beams can be modulated by modulating the laser through the electron optical assembly 600C, thereby reducing the influence on scanning quality during modulation of the electron beams, and thus enabling stable exposure of the sample 410C to be tested.

[0283] In a seventh aspect, the present application provides an X-ray tube. As shown in FIGs. 53 to 55, the X-ray tube includes an electron source 100, an anode target 200, and a tube body 300. It can be understood that the electron source of the X-ray tube 10D can be the electron source as described above in the present application.

[0284] The optical fiber 110 has a light-input end 1101 and a light-output end 1102. The light-input end 1101 is configured to couple to a laser source, so that the laser emitted by the laser source can be transmitted through the fiber core 111 of the optical fiber 110. The laser source can be a laser generating device.

[0285] The optical fiber 110 serves as a medium for transmitting the laser and as a carrier for the low-dimensional material of the electron excitation layer 121. The optical fiber 110 can be a single-mode optical fiber, a multi-mode optical fiber, a polarization-maintaining optical fiber, a holey optical fiber, a multi-core optical fiber, etc. It should be noted that, no matter which type of the optical fiber 110 is used, the electron emission layer 120 is located in the

vacuum chamber 301D.

[0286] The tube body 300D defines a vacuum chamber 301D. The light-output end 1102 of the optical fiber 110 is located in the vacuum chamber 301D. The electron excitation layer 121 is disposed on the light-output end 1102 of the optical fiber 110, and the electron emission layer 120 at least includes the electron excitation layer 121. The electron excitation layer 121 is disposed on the laser output path of the optical fiber 110, enabling the electron excitation layer 121 to emit electrons upon excitation by the laser. The electron excitation layer 121 includes the zero-dimensional material, the one-dimensional material, the two-dimensional material, or any combination thereof.

[0287] In this way, when the laser transmitted in the fiber core 111 of the optical fiber 110 propagates to the light-output end 1102 of the optical fiber 110 and outputs therefrom, this part of laser can interact with the electron excitation layer 121, such that electrons in the electron excitation layer 121 absorb photons of the laser and undergo energy transition to escape from the electron excitation layer 121, thereby emitting electrons from the light-output end 1102.

[0288] The anode target 200D is disposed in the vacuum chamber 301D. The anode target 200D is disposed opposite to and spaced apart from the light-output end 1102 of the optical fiber 110. The anode target 200D is configured to collect the electrons emitted from the electron excitation layer 121 to emit X-rays. The tube body 300D has an output window 311D directed toward the anode target 200D. The output window 311D is configured to guide the X-rays to exit out from the vacuum chamber 301D.

[0289] When the X-ray tube 10D is in use, the electron excitation layer 121 of the electron source 100 can emit the electrons toward the anode target 200D, which excites the anode target 200D to emit X-rays. These X-rays can then exit the vacuum chamber 301D through the output window 311D. In this way, the electron source 100 of the X-ray tube 10D can realize cold emission of electrons, which, unlike hot electrodes such as filaments, does not generate excessive heat, thus significantly alleviating heat accumulation of the anode target 200D. Moreover, since the electron excitation layer 121 is disposed on the optical fiber 110, space occupation in the vacuum chamber 301D can be reduced, thereby facilitating reduction in the volume of the X-ray tube 10D.

[0290] In some embodiments, along the extending direction of the optical fiber 110, the anode target 200D is spaced apart from the light-output end 1102 of the optical fiber 110, and a preset electric field is provided between the anode target 200D and the electron excitation layer 121, so that the electrons emitted from the electron excitation layer 121 can be linearly accelerated along the extending direction of the optical fiber 110.

[0291] Compared with using a grid structure as the accelerating electrode, in the X-ray tube 10 of the present application, a preset electric field is applied between the anode target 200D and the electron excitation layer 121 to form linear acceleration of electrons in the direction from the electron excitation layer 121 toward the anode target 200D, which greatly simplifies the structure of the X-ray tube 10D, and thus is beneficial to reducing the volume of the X-ray tube 10D.

[0292] In these embodiments, the electron excitation layer 121 is connected to a negative electrode of an external power supply through the conductive connection layer 130, and the anode target 200D is connect to a positive electrode of the external power supply, thereby establishing the preset electric field between the anode target 200D and the electron excitation layer 121. Moreover, since the anode target 200D is spaced apart from the light-output end 1102 of the optical fiber 110 along the extending direction of the optical fiber 110, the electrons emitted from the electron excitation layer 121 can be accelerated under the action of the preset electric field toward the anode target 200D along the extending direction of the optical fiber 110, thereby effectively exciting the anode target 200D, causing the anode target 200D to emit X-rays with relatively concentrated energy.

[0293] Optionally, the light-input end 1101 of the optical fiber 110 extends out of the vacuum chamber 301D through a first port 302D as described below. The second conductive portion 132 of the conductive connection layer 130 is disposed on the circumferential side surface of the optical fiber 110, and part of the second conductive portion 132 is located on the portion of the circumferential side surface of the optical fiber 110 that is outside the vacuum chamber 301D, thereby facilitating external connection of the conductive connection layer 130 to the negative electrode of the external power supply.

[0294] In some embodiments, the tube body 300D surrounds both the optical fiber 110 and the anode target 200D. For example, the inner circumferential wall of the tube body 300D can be bonded to the outer circumferential wall of the optical fiber 110, and the outer circumferential wall of the anode target 200D can be bonded to the inner circumferential wall of the tube body 300D. While realizing assembly of the X-ray tube 10, the outer circumferential wall of the optical fiber 110 and the outer circumferential wall of the anode target 200D respectively have sizes matching the inner circumferential wall of the tube body 300D, which can reduce the radial size of the X-ray tube 10, thereby reducing the volume of the X-ray tube 10D. Consequently, the X-ray tube 10D occupies less space and has higher material utilization rate, thus endowing the electron source 100 with a high integration.

[0295] In some embodiments, the tube body 300D has a first port 302D in communication with the vacuum chamber 301D. The light-output end 1102 of the optical fiber 110 extends into the vacuum chamber 301D through the first port 302D, and the outer circumferential wall of the optical fiber 110 is sealingly connected to the inner circumferential wall of the first port 302D. In this way, the sealing performance of the vacuum chamber 301D can be improved. The

electron excitation layer 121 can emit electrons outward from the light-output end 1102 upon excitation by the laser transmitted through the fiber core 111, and the electron excitation layer 121 can effectively emit electrons toward the anode target 200D within the vacuum chamber 301D, thereby improving the reliability of the X-ray tube 10D.

[0296] Specifically, the tube body 300D and the optical fiber 110 can be assembled in a vacuum environment. The inner circumferential wall of the tube body 300D can be sealingly connected to the outer circumferential wall of the optical fiber 110, thereby improving the sealing performance of the vacuum chamber 301D.

[0297] In some embodiments, the tube body 300D further has a second port 303D opposite to the first port 302D. A side of the anode target 200D away from the light-output end 1102 extends out of the vacuum chamber 301D through the second port 303D. The outer circumferential wall of the anode target 200D is sealingly connected to the inner circumferential wall of the second port 303D. In this way, on the one hand, the assembly of the anode target 200D with the tube body 300D is achieved by the sealed connection between the outer circumferential wall of the anode target 200D and the inner circumferential wall of the second port 303D, which is also beneficial to improving the sealing performance of the vacuum chamber 301D. On the other hand, the side of the anode target 200D away from the light-output end 1102 extends out of the vacuum chamber 301D, facilitating connection of the anode target 200D to the positive electrode of the external power supply.

[0298] Specifically, the anode target 200D and the optical fiber 110 can be assembled in a vacuum environment. The inner circumferential wall of the tube body 300D can be bonded to the outer circumferential wall of the anode target 200D with a sealant, thereby improving the sealing performance of the vacuum chamber 301D.

[0299] In some embodiments, the X-ray tube 10D further includes an external electrode 400D. The external electrode 400D is disposed between the outer circumferential wall of the anode target 200D and the inner circumferential wall of the second port 303D. Along the longitudinal extending direction of the tube body 300D, one end of the external electrode 400D is located in the vacuum chamber 301D, and the other end of the external electrode 400D extends out of the vacuum chamber 301D. As such, on the one hand, the anode target 200D can be connected to the positive electrode of the external power supply through the external electrode 400D; on the other hand, the external electrode 400D is disposed around the outer circumferential wall of the anode target 200D and is partially located in the vacuum chamber 301D, which can increase the contact area between the external electrode 400D and the anode target 200D, improving the bonding strength between the external electrode 400D and the anode target 200D and allowing the external electrode 400D to provide a preset voltage to the anode target 200D.

[0300] In some embodiments, referring to FIGs. 53 to 55, along the extending direction of the optical fiber 110, the electron source 100 is spaced apart from the anode target 200D. The anode target 200D has a reflective target surface 210D directed toward the light-output end 1102. The reflective target surface 210D is aligned at an angle β relative to the extending direction of the optical fiber 110. β is greater than 0° and less than 90° . The output window 311D is disposed on a side wall of the tube body 300D and is directed toward the reflective target surface 210D. Optionally, the anode target 200D having the reflective target surface 210D can be made of tungsten, silver, palladium, rhodium, molybdenum, copper, nickel, cobalt, iron, chromium, etc. In this way, the electron source 100 can emit electrons toward the reflective target surface 210D of the anode target 200D, exciting the anode target 200D to emit X-rays. The X-rays are reflected by the reflective target surface 210D and exit the vacuum chamber 301D through the output window 311D.

[0301] In some other embodiments, referring to FIGs. 56 and 57, the anode target 200D includes a transmission anode 220D. Along the longitudinal extending direction of the tube body 300D, the electron source 100 and the output window 311D are disposed at two opposite ends of the tube body 300D. The transmission anode 220D is located between the electron source 100 and the output window 311D.

[0302] The transmission anode 220D can include a substrate and a metal layer disposed on a side of the substrate facing the light-output end 1102. The thickness of the metal layer is less than 100 nm. The substrate can be made of an X-ray transmitting material as described below. For example, the material of the substrate is glass. The material of the metal layer can be tungsten, silver, palladium, rhodium, molybdenum, copper, nickel, cobalt, iron, chromium, etc. The metal layer can be a metal coating layer.

[0303] As such, the electron source 100 located on one end of the tube body 300D emits electrons toward the anode target 200D, exciting the anode target 200D to emit X-rays. The X-rays pass through the anode target 200D, and then exit through the output window 311D located on the other end of the tube body 300D. For example, as shown in FIGs. 53 and 56, the light-input end 1101 of the optical fiber 110 extends out of the vacuum chamber 301D through the first port 302D. In this way, part of the second conductive portion 132 disposed on the circumferential side surface of the optical fiber 110 can be located outside the vacuum chamber 301D, facilitating connection of the conductive connection layer 130 to the negative electrode of the external power supply.

[0304] Alternatively, the end face of the light-input end 1101 of the optical fiber 110 can be flush with the plane of the first port 302D (not shown). In this way, the optical fiber 110 can be substantially encapsulated in the tube body 300D, and the end face of the light-input end 1101 of the optical fiber 110 is exposed through the first port 302D, so that the laser source can be coupled to the light-input end 1101 of the optical fiber 110, which effectively protects the optical

fiber 110 while also facilitating the laser transmission from the laser source to the optical fiber 110.

[0305] In some embodiments, the tube body 300D includes an inner tube 310D and an outer tube 320D. The inner tube 310D surrounds both the optical fiber 110 and the anode target 200D. The outer tube 320D surrounds the inner tube 310D. The outer tube 320D has an opening 321D, and part of the inner tube 310D is exposed out through the opening 321D to form the output window 311D. The inner tube 310D is made of an X-ray transmitting material, and the outer tube 320D is made of an X-ray blocking material. Optionally, the X-ray transmitting material includes glass, beryllium, aluminum, titanium, or sapphire. Optionally, the X-ray blocking material includes lead or barium sulfate.

[0306] Specifically, in the embodiment shown in FIG. 53, the opening 321D is disposed on a lateral side of the outer tube 320D. Specifically, in the embodiment shown in FIG. 53, the opening 321D is disposed at one end of the outer tube 320D away from the electron source 100, so that the electron source 100 and the output window 311D can be disposed opposite to each other along the extending direction of the optical fiber 110. In this way, the outer tube 320D can block X-rays, and the inner tube 310D can be exposed through the opening 321D, i.e., the output window 311D, thereby outputting the X-rays. These arrangements reduce the possibility of X-rays escaping from other parts of the inner tube 310D except the output window 311D, improving the safety and reliability of the X-ray tube 10 while realizing concentrated emission of X-rays, and reducing the loss during emission of X-rays from vacuum to the external environment.

[0307] In some embodiments, the outer diameter of the tube body 300D is in a range from 125 μm to 2000 μm , and the length of the tube body 300D is in a range from 3 cm to 9 cm. The tube body 300D surrounds both the optical fiber 110 and the anode target 200D. As such, the radial size of the X-ray tube 10D is small, which can greatly reduce the volume of the X-ray tube 10D, allowing effective acceleration of electrons between the electron excitation layer 121 and the anode target 200D in a relatively small vacuum chamber 301D. This structure is beneficial to realizing high integration and miniaturization of the electron source 100 and the X-ray emission structure, and helps to realize portable applications of the X-ray tube 10D and metal flaw detection in confined spaces.

[0308] In some embodiments, along the extending direction of the optical fiber 110, a distance between the light-output end 1102 of the optical fiber 110 and the anode target 200D can be in a range from 3 cm to 5 cm. Certainly, the distance between the light-output end 1102 of the optical fiber 110 and the anode target 200D in the present application is not limited thereto. The range of 3 cm to 5 cm is merely taken as an example for description.

[0309] In the present application, the distance between the electron excitation layer 121 and the anode target 200D is relatively small, resulting in a more uniform electric field distribution between the electron excitation layer 121 and the anode target 200D, thereby allowing more electrons to be effectively accelerated and then incident onto the anode target 200D and excite the anode target 200D to emit X-rays, which is also beneficial to the miniaturization of the X-ray tube 10D.

[0310] Compared with the X-ray tube in the related art that uses a grid structure as the accelerating electrode, in the present application, a preset electric field is applied between the anode target 200D and the electron excitation layer 121, so that the electrons emitted from the electron excitation layer 121 can be accelerated toward the anode target 200D along the extending direction of the optical fiber 110 under the action of the preset electric field. Such a structure saves space in the vacuum chamber 301D, simplifying the optical system and the electrical system, and making it easier to form an integrated and miniaturized X-ray tube 10D.

[0311] Compared with conventional X-ray tubes, in the present application, a portion of the inner tube 310D of the tube body 300D serves as the output window 311D, which maximally simplifies the window structure and is more conducive to the miniaturization of the X-ray tube 10D. In addition, unlike the relatively macroscopic and complex mechanical structures in the prior art, the present solution adopts a highly integrated optical fiber structure, reducing the size of a miniature X-ray source from the existing centimeter scale to the micrometer scale while ensuring comparable power.

[0312] By assembling the electron source 100 and the anode target 200D within the tube body 300D having a relatively small diameter, electrons can be effectively accelerated between the electron excitation layer 121 and the anode target 200D within a compact vacuum chamber 301D, which is beneficial to realizing high integration and miniaturization of the electron source 100 and the X-ray emission structure, and helps to realize portable applications of the X-ray tube 10 and metal flaw detection in confined spaces.

[0313] The following examples are provided to specifically describe the embodiments of the present application. It should be understood that these examples are merely for illustration of the present application and are not intended to limit the scope of the present application. In the following examples, experimental methods not specifying specific conditions should primarily refer to the guidelines given in the present application, or can refer to experimental manuals or conventional conditions in the art, or can refer to the conditions recommended by manufacturers, or can refer to experimental methods known in the art.

(I) In the following examples, the conductive connection layer was a gold layer with a thickness of 60 nm, covering the lateral surface of the optical fiber. The conductive connection layer was in contact with and electrically

connected to the auxiliary layer or the electron emission layer.

Example A-1

[0314] A mixture of polypropylene carbonate (PPC) and anisole in a mass ratio of 1:8 was dropped onto a silicon wafer, spin-coated at 1500 r/min for 1 minute using a spin coater, and then baked at 60 °C for 2 minutes to obtain a PPC film on the silicon wafer.

[0315] Graphene was mechanically exfoliated from a bulk raw material using a first adhesive tape. The first adhesive tape with the graphene was then attached onto the PPC film. After pressing with a cotton swab to ensure sufficient contact between the low-dimensional material and the PPC film, the graphene to be transferred was selected under an optical microscope.

[0316] A second adhesive tape was taken, and a square hole of 3 mm×3 mm was formed in the middle of the second adhesive tape. The second adhesive tape was attached onto the PPC film, such that the graphene to be transferred was located at the hole of the second adhesive tape. The PPC film was pressed with a cotton swab to ensure full adhesion with the second adhesive tape. The second adhesive tape with the PPC film was then peeled off, separating the PPC film from the first adhesive tape, thereby transferring the graphene onto the PPC film.

[0317] The second adhesive tape and the PPC film were fixed on a glass slide with a central circular hole in a diameter of 5 mm. The square hole of the second adhesive tape was located at the center of the central circular hole. A heating sheet was placed on the side of the glass slide away from the PPC film, and the assembly was positioned under an optical microscope, with the graphene side of the PPC film facing downward. The glass slide was first heated at 40 °C to flatten the wrinkles of the PPC film. Then, the end face of a solid-core optical fiber coated with the conductive connection layer was directed toward the graphene side of the PPC film and attached to the PPC film. The heating temperature was raised to 60 °C and the optical fiber was moved upward by 50 μm to ensure full contact between the end face of the optical fiber and the PPC film. The temperature was then raised to 130 °C to melt the PPC film. The optical fiber was removed and immersed in acetone to clean the residual PPC film from the end face of the optical fiber. An electron excitation layer made of graphene with a thickness of 1 nm was thereby obtained on the end face of the solid-core optical fiber. The graphene was electrically connected to the conductive connection layer, yielding an electron source.

Example A-2

[0318] Graphene was grown on a substrate through the chemical vapor deposition (CVD) method. The substrate with the graphene was placed into a water tank containing deionized water, allowing the graphene to float on the water surface. The tip portion of a tapered optical fiber was brought into contact with the graphene from above the water surface. After sufficient contact, the tip portion was immersed in water, then removed from water and dried to obtain an electron excitation layer made of graphene with a thickness of 0.4 nm on the tip portion of the tapered optical fiber. A conductive connection layer was then formed on the tapered optical fiber such that the graphene was electrically connected to the conductive connection layer, yielding an electron source.

Example A-3

[0319] An auxiliary layer made of gold with a thickness of 10 nm was deposited on the end face of a solid-core optical fiber having a conductive connection layer. Then, carbon quantum dots were grown on the surface of the auxiliary layer through the CVD method to obtain an electron excitation layer on the surface of the auxiliary layer. The auxiliary layer was electrically connected to the conductive connection layer, yielding an electron source.

Example A-4

[0320] An auxiliary layer made of gold with a thickness of 10 nm was deposited on the end face of a hollow-core optical fiber having a conductive connection layer. Then, carbon nanotubes were grown on the surface of the auxiliary layer through the CVD method, with the axial directions of the carbon nanotubes being perpendicular to surface of the auxiliary layer, to obtain an electron excitation layer on the surface of the auxiliary layer. The auxiliary layer was electrically connected to the conductive connection layer, yielding an electron source.

Example A-5

[0321] Graphene with a thickness of 1 nm was grown through the CVD method on the end face of a solid-core optical fiber having a conductive connection layer. Then, carbon nanotubes were grown on the surface of the gra-

phene through the CVD method, with the axial directions of the carbon nanotubes being parallel to the surface of the graphene, to obtain an electron excitation layer on the end face of the solid-core optical fiber. The graphene was electrically connected to the conductive connection layer, yielding an electron source.

5 Example A-6

[0322] Graphene with a thickness of 1 nm was grown through the CVD method on the side-polished surface of a side-polished optical fiber. Then, molybdenum disulfide (MoS_2) quantum dots were formed on the surface of the graphene through the CVD method to obtain an electron excitation layer. A conductive connection layer was disposed on the side-polished optical fiber and was electrically connected to the graphene, yielding an electron source.

Example A-7

[0323] An auxiliary layer made of gold with a thickness of 10 nm was deposited on the end face of a solid-core optical fiber having a conductive connection layer. Then, carbon nanotubes were grown on the surface of the auxiliary layer through the CVD method, with the axial directions of the carbon nanotubes being perpendicular to the surface of the auxiliary layer, followed by growing molybdenum disulfide (MoS_2) quantum dots on the carbon nanotubes through the CVD method, thereby obtaining an electron excitation layer. The auxiliary layer was electrically connected to the conductive connection layer, yielding an electron source.

Example A-8

[0324] Graphene and black phosphorus were sequentially grown on the end face of a solid-core optical fiber having a conductive connection layer, where the thickness of the graphene was 1 nm, and the thickness of the black phosphorus was 1 nm, thereby obtaining an electron excitation layer composed of stacked graphene and black phosphorus. The graphene was electrically connected to the conductive connection layer, yielding an electron source.

Comparative Example A-1

[0325] An electron source was prepared according to the structure of Example A-1, except that the electron emission layer in Example A-1 was replaced with a gold layer having a thickness of 100 nm, where the gold layer was prepared by deposition.

Comparative Example A-2

[0326] An electron source was prepared according to the structure of Comparative Example A-1, except that the electron emission layer in Comparative Example A-1 was replaced with a gold layer having a thickness of 1 nm.

[0327] The electron sources prepared in the above examples and comparative examples were assembled into electron guns. Each electron gun further included a housing, a grid electrode, and an anode. The prepared electron guns were subjected to performance tests using the following test methods:

Stability test: At an excitation power equal to 50% of a damage power and a vacuum degree of 2×10^{-5} Pa, an electric current was continuously emitted for 1 hour. After removing outliers, a difference between the maximum current and the minimum current and an average current were calculated. The stability was defined as (maximum current - minimum current)/average current.

Lifetime test: At an excitation power equal to 50% of a damage power and a vacuum degree of 2×10^{-5} Pa, an electric current was continuously emitted until the current decayed to below 10% of the initial value, and this time period was defined as the lifetime.

Working vacuum degree test: At an excitation power equal to 50% of a damage power, an electric current was continuously emitted while the vacuum degree of the working environment of the electron gun was gradually increased until the current showed a rapid decay (where "rapid decay" was defined as the current decaying by more than 50% within 1 minute), and the vacuum degree at this point was defined as the working vacuum degree.

[0328] Herein, the damage power refers to the laser power at which the material is damaged under irradiation with a 100 femtosecond (fs) pulsed laser. For example, the damage power of graphene is 0.25 J/cm^2 , and the damage threshold of gold is 0.1 J/cm^2 .

[0329] The test results are shown in Table 1.

Table 1

No.	Stability	Lifetime	Working vacuum degree
Example A-1	1%	2100 h	10 Pa
Example A-2	3%	2000 h	10 Pa
Example A-3	4%	1000 h	10^{-3} Pa
Example A-4	3%	1200 h	10^{-3} Pa
Example A-5	3%	1300 h	10^{-3} Pa
Example A-6	4%	1500 h	10^{-3} Pa
Example A-7	4%	1000 h	10^{-3} Pa
Example A-8	1%	2300 h	10 Pa
Comparative example A-1	10%	100 h	10^{-5} Pa
Comparative example A-2	20%	20 h	10^{-5} Pa

[0330] From the above table, it can be seen that:

In the present application, the low-dimensional material such as the zero-dimensional material, the one-dimensional material, or the two-dimensional material has an atomic-level size, and thus the electrons generated by the back side irradiation can be emitted into vacuum without traveling through the bulk of the material, which is very suitable for an ultrafast electron source with narrow pulse width. Moreover, the low-dimensional material can be directly integrated with different types of optical fibers, providing ultra-high stability and integration. In addition, the low-dimensional material is free of dangling bonds, and has stable properties and a high melting point, which is less prone to damage and is suitable for high beam current electron sources obtained by high-power excitation. By integrating the low-dimensional material with a tapered tip, a very sharp optical fiber tip can be obtained, which possesses large optical field and electric field enhancement factor, providing a high emission beam current. The low-dimensional material offers numerous combinations and thus is suitable for photoelectronic sources with various properties. Finally, the integration of the optical fiber with the low-dimensional material for the electron source have significant advantages. The optical fiber can transmit laser while serving as a carrier for the low-dimensional material, thereby enabling a stable excitation source with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios, does not require a complex optical path, and possesses the characteristics of small volume and high integration. When the electron source is integrated with other equipment, stable integration can be achieved without refitting the vacuum electronic device disruptively.

[0331] (II) Preparation of electron sources using zero-dimensional materials as the electron excitation layers. Specifically, the optical fiber was a single-mode solid-core optical fiber, wherein the diameter of the fiber core was $8.2\ \mu\text{m}$ and the diameter of the optical fiber was $125\ \mu\text{m}$. The wavelength of the excitation laser transmitted in the optical fiber was $1550\ \text{nm}$. The conductive connection layer was a metal layer covering the lateral surface of the optical fiber and composed of a $4\ \text{nm}$ thick titanium layer a $50\ \text{nm}$ thick gold layer. The conductive connection layer was in contact and electrically connected with the auxiliary layer or the electron excitation layer.

Example B-1

[0332] Graphene quantum dots were grown on the end face of a solid-core optical fiber having a conductive connection layer through the CVD method, thereby forming an electron excitation layer with a thickness of about $20\ \text{nm}$. The electron excitation layer was electrically connected to the conductive connection layer, yielding an electron source. The graphene quantum dots in the electron excitation layer had an average particle size of $10\ \text{nm}$ and a number density of $10^{10}/\text{mm}^2$.

Example B-2

[0333] An optical fiber same as Example B-1 was adopted. An auxiliary layer made of gold with a thickness of $5\ \text{nm}$ and a light transmittance of about 80% was deposited on the end face of the solid-core optical fiber having a conductive connection layer. Then, graphene quantum dots were grown on the surface of the auxiliary layer through the CVD method, thereby forming an electron excitation layer with a thickness of about $20\ \text{nm}$. The electron excitation layer was electrically connected to the conductive connection layer, yielding an electron source. The graphene quantum dots in the electron excitation layer had an average particle size of $10\ \text{nm}$ and a number density of $10^{10}/\text{mm}^2$ (i.e.,

closely packed).

Example B-3

- 5 **[0334]** The preparation method was similar to that of Example B-1, except that the graphene quantum dots were replaced with gold nanoparticles.

Example B-4

- 10 **[0335]** The preparation method was similar to that of Example B-1, except that the average particle size of the graphene quantum dots was 20 nm.

Example B-5

- 15 **[0336]** The preparation method was similar to that of Example B-2, except that the material of the auxiliary layer was replaced with graphene, and the light transmittance of the auxiliary layer was about 98%.

Comparative Example B-1

- 20 **[0337]** An electron source was prepared according to the structure of Example B-1, except that the electron excitation layer in Example B-1 was replaced with a gold layer with a thickness of 200 nm, and the gold layer was prepared by deposition.

Comparative Example B-2

- 25 **[0338]** An electron source was prepared according to the structure of Example B-3, except that the electron excitation layer in Example B-3 was replaced with a gold layer with a thickness of 20 nm, and the gold layer was prepared by deposition.

- 30 **[0339]** The electron sources 100 prepared in the above examples and comparative examples were assembled into electron guns. The prepared electron guns were subjected to the stability test, lifetime test, and working vacuum degree test. The test results are shown in Table 2.

Table 2

No.	Stability	Lifetime	Working vacuum degree
Example B-1	7%	1000 h	10^{-3} Pa
Example B-2	6%	1000 h	10^{-3} Pa
Example B-3	9%	500 h	10^{-3} Pa
Example B-4	8%	1000 h	10^{-3} Pa
Example B-5	5%	1000 h	10^{-3} Pa
Comparative example B-1	11%	100 h	10^{-5} Pa
Comparative example B-2	21%	50 h	10^{-5} Pa

- 35 **[0340]** From the above table, by comparing the examples with comparative example B-1 and comparative example B-2, it can be seen that the performance of the examples is significantly superior to that of Comparative Example B-1 and Comparative Example B-2, indicating that the electron source using the zero-dimensional materials as the electron excitation layer in the present application has better performance than those using the conventional metal layer or metal nano-layer.

40 **[0341]** (III) Preparation of electron sources using one-dimensional materials as the electron excitation layers.

Example C-1

- 55 **[0342]**

(1) The coating layer at the end of a single-mode solid-core optical fiber was removed, and the end face of the

optical fiber was flattened by cut. The end of the fiber core was blocked with a polymer microsphere. The diameter of the polymer microsphere was between the diameter of the fiber core and the diameter of the cladding layer.

(2) Titanium and gold were sequentially deposited on the optical fiber by evaporation, ensuring that titanium and gold were firmly deposited sequentially on the end face and the uncoated end portion of the optical fiber, thereby forming a conductive connection layer with a thickness of 54 nm, wherein the thickness of the titanium layer was 4 nm and the thickness of the gold layer was 50 nm. The end of the fiber core blocked with the polymer microsphere was immersed in acetone to dissolve the polymer microsphere, causing the coating on the polymer microsphere to be peeled off, thereby exposing the fiber core at the end face of the optical fiber.

(3) Carbon nanotubes were grown on the end face of the optical fiber having the conductive connection layer through the CVD method, thereby forming an electron excitation layer made of carbon nanotubes. The carbon nanotubes were electrically connected to the conductive connection layer, yielding an electron source, wherein the diameter of the carbon nanotubes was 1 nm, the length of the carbon nanotubes was 0.1 μm , and the axial directions of the carbon nanotubes were all parallel to the axial direction of the optical fiber. The diameter of the fiber core of the optical fiber was 8.2 μm , and the diameter of the optical fiber was 125 μm .

Example C-2

[0343] The preparation method of the electron source in this example was substantially the same as that in Example C-1, except for step (3). Step (3) was as follows:

[0344] An auxiliary layer made of gold with a thickness of 10 nm was deposited on the end face of the optical fiber having the conductive connection layer. The auxiliary layer was electrically connected to the conductive connection layer. Then, carbon nanotubes were grown on the surface of the auxiliary layer through the CVD method, thereby forming an electron excitation layer made of carbon nanotubes. The carbon nanotubes were electrically connected to the conductive connection layer, yielding an electron source, wherein the diameter of the carbon nanotubes was 1 nm, the length of the carbon nanotubes was 0.1 μm , and the axial directions of the carbon nanotubes were all parallel to the axial direction of the optical fiber. The diameter of the fiber core of the optical fiber was 8.2 μm , and the diameter of the optical fiber was 125 μm . The electron excitation layer and the auxiliary layer constituted the electron emission layer.

Example C-3

[0345] The preparation method of the electron source was substantially the same as that in Example C-2, except that in step (3), the diameter of the carbon nanotubes was 10 nm.

Example C-4

[0346] The preparation method of the electron source was substantially the same as that in Example C-2, except that in step (3), the diameter of the carbon nanotubes was 20 nm.

Example C-5

[0347] The preparation method of the electron source was substantially the same as that in Example C-2, except that in step (3), the length of the carbon nanotubes was 1 μm .

Example C-6

[0348] The preparation method of the electron source was substantially the same as that in Example C-2, except that in step (3), the diameter of the carbon nanotubes was 0.5 nm.

Example C-7

[0349] The preparation method of the electron source was substantially the same as that in Example C-2, except that in step (3), the diameter of the carbon nanotubes was 21 nm.

Example C-8

[0350] The preparation method of the electron source was substantially the same as that in Example C-1, except that the carbon nanotubes in Example C-1 were replaced with gold nanowires.

Comparative Example C-1

[0351] An electron source was prepared according to the structure of Example C-1, except that the electron excitation layer in Example C-1 was replaced with a gold layer with a thickness of 100 nm, and the gold layer was prepared by deposition.

[0352] The electron sources prepared in the above examples and comparative examples were assembled into electron guns. Each electron gun further included a housing, a grid electrode, and an anode. The prepared electron guns were subjected to the performance tests.

Table 3

No.	Stability	Lifetime	Working vacuum degree
Example C-1	5.3%	1020 h	1.08×10^{-3} Pa
Example C-2	5.4%	1027 h	1.3×10^{-3} Pa
Example C-3	5.6%	1060 h	1.4×10^{-3} Pa
Example C-4	5.7%	1063 h	1.5×10^{-3} Pa
Example C-5	5.1%	1022 h	1.2×10^{-3} Pa
Example C-6	4.8%	1003 h	1.01×10^{-3} Pa
Example C-7	5.0%	1005 h	1.03×10^{-3} Pa
Example C-8	10.9%	510 h	1.8×10^{-3} Pa
Comparative example C-1	10%	100 h	1.01×10^{-5} Pa

[0353] It can be seen from the above table that compared with the electron gun of comparative Example C-1, the electron guns of Examples C-1 to C-8 have higher working vacuum degree, better stability, and longer lifetime, indicating that Examples C-1 to C-8 provided by the present application effectively improve the electron emission efficiency and stability of the electron source.

[0354] (IV) Preparation of electron sources using one-dimensional materials as the electron excitation layers. In the following examples, the conductive connection layer was a metal layer with a thickness of 60 nm, covering the lateral surface of the optical fiber. The conductive connection layer was in contact with and electrically connected to the auxiliary layer or the electron excitation layer. The material of the metal layer was gold.

Example D-1

[0355] Carbon nanotubes were grown on a silicon wafer through the CVD method and transferred onto a polypropylene carbonate film by acid etching.

[0356] The preparation method of the electron source included the following steps:

(1) The coating layer at the end of a single-mode solid-core optical fiber was removed, and the end face of the optical fiber was flattened by cut. The end of the fiber core was blocked with a polymer microsphere. The diameter of the polymer microsphere was between the diameter of the fiber core and the diameter of the cladding. The diameter of the fiber core of the single-mode optical fiber was 8.2 μm , and the diameter of the optical fiber was 125 μm .

(2) Gold was deposited on the optical fiber by evaporation, ensuring that gold was firmly deposited on the end face of the optical fiber and the uncoated end portion of the optical fiber, thereby forming a conductive connection layer made of gold with a thickness of 54 nm. The end of the fiber core blocked with the polymer microsphere was immersed in acetone to dissolve the polymer microsphere, causing the coating on the polymer microsphere to be peeled off, thereby exposing the fiber core at the end face of the optical fiber, so as to form a relatively flat annular electrode at the electron emission end.

(3) The carbon nanotubes on the polypropylene carbonate film were transferred to the front side of a perforated glass slide and suspended, enabling them to be observed under a microscope. An annular heating sheet was attached to the back side and was connected to a power supply. The perforated glass slide was fixed on the sample stage of the microscope, and the optical fiber with the electrode obtained in step (2) was fixed on the displacement stage under the sample stage, so that the objective lens, the center hole of the heating sheet, the glass slide, the carbon nanotubes, and the end face of the optical fiber with the electrode were collinear and

arranged sequentially from top to bottom.

(4) The position of the electrode was observed under the microscope and subjected to horizontal alignment. Voltage was applied for preheating, and the optical fiber displacement stage was moved such that the annular electrode came into contact with the carbon nanotubes, producing a Newton ring. The voltage was slowly increased to make the contact between the annular electrode and the carbon nanotubes tighter.

(5) After the annular electrode was completely attached to the carbon nanotubes, the heating voltage was further increased to completely melt the polypropylene carbonate film. The optical fiber was removed and immersed in acetone to dissolve residual polypropylene carbonate.

[0357] In the electron source prepared in this example, the electron excitation layer was made of the carbon nanotubes. The angle θ between the axial direction of each carbon nanotube and the output direction of the laser was 10° . The diameter of the carbon nanotubes was 1 nm, and the length of the carbon nanotubes was 200 μm .

Example D-2

[0358] Carbon nanotubes were grown on a silicon wafer through the CVD method and transferred onto a polypropylene carbonate film by acid etching.

[0359] The preparation method of the electron source included the following steps:

(1) The coating layer at the end of a single-mode solid-core optical fiber was removed, and the end face of the optical fiber flattened by cut. The end of the fiber core was blocked with a polymer microsphere. The diameter of the polymer microsphere was between the diameter of the fiber core and the diameter of the cladding. The diameter of the fiber core of the single-mode optical fiber was 8.2 μm , and the diameter of the optical fiber was 125 μm .

(2) Gold was deposited on the optical fiber by evaporation, ensuring that gold was firmly deposited on the end face and the uncoated end portion of the optical fiber, thereby forming a conductive connection layer made of gold with a thickness of 54 nm. The end of the fiber core blocked with the polymer microsphere was immersed in acetone to dissolve the polymer microsphere, causing the coating on the polymer microsphere to be peeled off, thereby exposing the fiber core at the end face of the optical fiber, so as to form a relatively flat annular electrode at the electron emission end. An auxiliary layer made of gold with a thickness of 10 nm was deposited on the end face of the optical fiber having the conductive connection layer. The auxiliary layer was electrically connected to the conductive connection layer.

(3) The carbon nanotubes on the polypropylene carbonate film were transferred to the front side of a perforated glass slide and suspended, enabling them to be observed under a microscope. An annular heating sheet was attached to the back side and was connected to a power supply. The perforated glass slide was fixed on the sample stage of the microscope, and the optical fiber with the electrode obtained in step (2) was fixed on the displacement stage under the sample stage, so that the objective lens, the center hole of the heating sheet, the glass slide, the carbon nanotubes, and the end face of the optical fiber with the electrode were collinear and arranged sequentially from top to bottom.

(4) The position of the electrode was observed under the microscope and subjected to horizontal alignment. Voltage was applied for preheating, and the optical fiber displacement stage was moved such that the annular electrode came into contact with the carbon nanotubes, producing a Newton ring. The voltage was slowly increased to make the contact between the annular electrode and the carbon nanotubes tighter.

(5) After the annular electrode was completely attached to the carbon nanotubes, the heating voltage was further increased to completely melt the polypropylene carbonate film. The optical fiber was removed and immersed in acetone to dissolve residual polypropylene carbonate.

[0360] In the electron source prepared in this example, the electron excitation layer was made of the carbon nanotubes. The angle θ between the axial direction of each carbon nanotube and the output direction of the laser was 10° . The diameter of the carbon nanotubes was 1 nm, and the length of the carbon nanotubes was 200 μm . The electron excitation layer and the auxiliary layer constituted the electron emission layer.

Example D-3

[0361] An electron source was prepared according to the structure of Example D-2, except that the angle between the axial directions of carbon nanotubes and the output direction of the laser was 90° .

Example D-4

[0362] An electron source was prepared according to the structure of Example D-2, except that the diameter of the carbon nanotubes was 3 nm.

Example D-5

[0363] An electron source was prepared according to the structure of Example D-1, except that the carbon nanotubes in Example D-1 were replaced with gold nanowires.

Comparative Example D-1

[0364] An electron source was prepared according to the structure of Example D-1, except that the electron excitation layer in Example D-1 was replaced with a gold layer with a thickness of 100 nm, and the gold layer was prepared by deposition.

[0365] The electron sources prepared in the above examples and comparative examples were assembled into electron guns. Each electron gun further included a housing, a grid electrode, and an anode. The prepared electron guns were subjected to the performance tests. The test results are shown in Table 4.

Table 4

No.	Stability	Lifetime	Working vacuum degree
Example D-1	5.2%	1021 h	1.1×10^{-3} Pa
Example D-2	5.4%	1026 h	1.3×10^{-3} Pa
Example D-3	3.1%	1008 h	1.05×10^{-3} Pa
Example D-4	5.5%	1032 h	1.4×10^{-3} Pa
Example D-5	10.1%	1002 h	1.04×10^{-3} Pa
Comparative example D-1	10%	100 h	1.01×10^5 pa

[0366] It can be seen from Table 4 that compared with the electron gun of the comparative example, the electron guns of the examples of the present application have higher working vacuum degree, better stability, and longer lifetime, indicating that the examples provided in the present application effectively improve the electron emission efficiency and stability of the electron source.

[0367] (V) Preparation of electron sources by combining one-dimensional materials and zero-dimensional materials. In the following examples, the optical fiber was a single-mode solid-core optical fiber, wherein the diameter of the fiber core was 8.2 μm and the diameter of the optical fiber was 125 μm . The wavelength of the excitation laser transmitted in the optical fiber was 1550 nm. The conductive connection layer was a metal layer covering the lateral surface of the optical fiber and composed of a 4 nm thick titanium layer and a 50 nm thick gold layer. The conductive connection layer was in contact and electrically connected with the auxiliary layer or the electron excitation layer.

Example E-1

[0368] Carbon nanotubes each with an outer diameter of about 20 nm and a length of about 5 mm were grown through the CVD method on the end face of a solid-core optical fiber having a conductive connection layer. The axial directions of the carbon nanotubes were parallel to the laser output path of the optical fiber. Subsequently, graphite quantum dots with an average particle size of about 5 nm were grown at the ends of the carbon nanotubes, thereby obtaining an electron excitation layer with a thickness of about 20 nm. The electron excitation layer was electrically connected to the conductive connection layer, yielding an electron source.

Example E-2

[0369] An auxiliary layer made of gold with a thickness of 5 nm and a light transmittance of 60% was deposited on the end face of a solid-core optical fiber having a conductive connection layer. Then, carbon nanotubes each with an outer diameter of about 20 nm and a length of about 5 μm were grown on the surface of the auxiliary layer through the CVD method. The axial directions of the carbon nanotubes were parallel to the laser output path of the optical fiber.

Subsequently, graphite quantum dots with an average particle size of about 5 nm were grown at the ends of the carbon nanotubes, thereby obtaining an electron excitation layer with a thickness of about 20 nm. The electron excitation layer was electrically connected to the conductive connection layer, yielding an electron source.

Example E-3

[0370] The preparation method was similar to that of Example E-1, except that the graphite quantum dots were replaced with gold nanoparticles.

Example E-4

[0371] The preparation method was similar to that of Example E-1, except that the carbon nanotubes were replaced with silicon nanowires.

Example E-5

[0372] The preparation method was similar to that of Example E-2, except that the material of the auxiliary layer was replaced with graphene, and the light transmittance of the auxiliary layer was 98%.

Comparative Example E-1

[0373] An electron source was prepared according to the structure of Example E-1, except that the electron excitation layer in Example E-1 was replaced with a gold layer with a thickness of 200 nm, and the gold layer was prepared by deposition.

Comparative Example E-2

[0374] An electron source was prepared according to the structure of Example E-3, except that the electron excitation layer in Example E-3 was replaced with a gold layer with a thickness of 20 nm, and the gold layer was prepared by deposition.

[0375] The electron sources prepared in the above examples and comparative examples were assembled into electron guns. The prepared electron guns were subjected to the stability test, lifetime test, and working vacuum degree test. The test results are shown in Table 5.

Table 5

No.	Stability	Lifetime	Working vacuum degree
Example E-1	6%	1000 h	10^{-3} Pa
Example E-2	5%	1000 h	10^{-3} Pa
Example E-3	7%	500 h	10^{-3} Pa
Example E-4	6%	1000 h	10^{-3} Pa
Example E-5	4%	1000 h	10^{-3} Pa
Comparative example E-1	11%	100 h	10^{-5} Pa
Comparative example E-2	21%	50 h	10^{-5} Pa

[0376] From table 5, by comparing the examples with the comparative examples, it can be seen that the performance of the examples is significantly superior to that of the comparative examples, indicating that the electron source using the one-dimensional material and the zero-dimensional material as the electron excitation layer in the present application has better performance than those using the conventional metal layer or metal nano-layer.

[0377] (VI) Preparation of electron sources using two-dimensional materials. In the following examples, the conductive connection layer includes a Ti layer with a thickness of 5 nm and an Au layer with a thickness of 60 nm.

Example F-1

[0378] This example provides an electron source, including a solid-core optical fiber, an electron excitation layer,

and a conductive connection layer. The conductive connection layer covers the sidewall of the solid-core optical fiber and forms an annular layer on the end face of the light-output end of the solid-core optical fiber. The annular layer does not cover the fiber core of the solid-core optical fiber. The electron excitation layer is made of graphene with a thickness of 1 nm, and is disposed on the end face of the light-output end of the solid-core optical fiber. The electron excitation layer covers the fiber core of the solid-core optical fiber and overlaps with the annular layer, thereby being electrically connected to the conductive connection layer.

[0379] This example also provides a preparation method of the above electron source, including the following steps:

[0380] Graphite was pasted and exfoliated using a first adhesive tape. The graphene material on the first adhesive tape was exfoliated again using a second adhesive tape, and again using a third adhesive tape, until the thickness of the graphene is 1 nm.

[0381] The adhesive tape with the graphene was transferred onto a polypropylene carbonate film, and baked at 50 °C for 2 minutes. The adhesive tape was then peeled off, obtaining a polypropylene carbonate film with the graphene.

[0382] A conductive connection layer was evaporated onto the solid-core optical fiber to form an annular layer on the light-output end of the solid-core optical fiber. Then, the polypropylene carbonate film with the graphene was transferred to the light-output end of the solid-core optical fiber and attached to the annular layer, covering the fiber core of the solid-core optical fiber. The polypropylene carbonate was heated and melted, and residual polypropylene carbonate was removed by immersion in acetone to form the electron excitation layer, thereby obtaining the electron source.

Example F-2

[0383] An electron source was prepared according to the method of Example F-1, except that the electron source included a solid-core optical fiber, an electron excitation layer, and a conductive connection layer. The electron excitation layer included a first material layer and a second material layer sequentially arranged along the laser output direction, wherein the first material layer was a graphene layer with a thickness of 5 nm, and the second material layer was a molybdenum disulfide layer with a thickness of 2 nm.

Example F-3

[0384] An electron source was prepared according to the method of Example F-1, except that the electron source included a solid-core optical fiber, an electron excitation layer, a conductive connection layer, and a transparent support layer. The transparent support layer was disposed on the side of the electron excitation layer adjacent to the solid-core optical fiber, and the transparent support layer was a boron nitride layer with a thickness of 100 nm.

Example F-4

[0385] An electron source was prepared according to the method of Example F-1, except that the electron source included a solid-core optical fiber, an electron excitation layer, a conductive connection layer, and a conductive support layer. The electron excitation layer was a molybdenum disulfide layer with a thickness of 2 nm. The conductive support layer was disposed on the side of the electron excitation layer adjacent to the solid-core optical fiber. The conductive support layer was a gold layer with a thickness of 5 nm. The conductive support layer was in contact with and electrically connected to the conductive connection layer.

Example F-5

[0386] An electron source was prepared according to the method of Example F-1, except that the electron source included a solid-core optical fiber 110e, an electron excitation layer, and a conductive connection layer. The electron excitation layer was formed by a first material layer and a second material layer joined together. The first material layer was graphene with a thickness of 1 nm, the second material layer was molybdenum disulfide with a thickness of 3 nm. The junction between the first and second material layers was a straight line.

Example F-6

[0387] An electron source was prepared according to the method of Example F-1, except that the electron source included a solid-core optical fiber 110f, an electron excitation layer, a conductive connection layer, and a conductive support layer. The conductive support layer was disposed on the side of the electron excitation layer adjacent to the solid-core optical fiber, and the conductive support layer was electrically connected to the conductive connection layer. The electron excitation layer was a combination of a first material layer and a second material layer stacked along the laser output direction. Each of the first material layer and the second material layer were a perovskite layer with a

thickness of 2 nm. The angle between the crystal axes of the two perovskite layers was 90°.

Example F-7

[0388] An electron source was prepared according to the method of Example F-1, except that the electron source included a holey optical fiber, an electron excitation layer, and a conductive connection layer. The electron excitation layer was a combination of a first material layer and a second material layer disposed on the inner wall of the holey optical fiber. The first material layer and the second material layer were sequentially stacked along the direction away from the inner wall of the holey optical fiber. The first material layer was made of graphene with a thickness of 5 nm, the second material layer was a molybdenum disulfide layer with a thickness of 3 nm. The conductive connection layer was electrically connected to the first material layer.

Comparative Example F-1

[0389] An electron source was prepared according to the structure of Example F-1, except that the electron excitation layer in Example F-1 was replaced with a gold layer with a thickness of 60 nm, and the gold layer was prepared by deposition.

Comparative Example F-2

[0390] An electron source was prepared according to the structure of Comparative Example F-1, except that the electron excitation layer in Comparative Example F-1 was replaced with a gold layer with a thickness of 1 nm.

[0391] The electron sources prepared in the above examples and comparative examples were assembled into electron guns, which were then subjected to the stability test, lifetime test, and working vacuum degree test. The test results are shown in Table 6.

Table 6

No.	Stability	Lifetime	Working vacuum degree
Example F-1	1%	2000 h	10 Pa
Example F-2	1%	2000 h	10 Pa
Example F-3	1%	2000 h	10 Pa
Example F-4	2%	1000 h	10 ⁻² Pa
Example F-5	2%	1000 h	10 ⁻² Pa
Example F-6	2%	500 h	10 ⁻² Pa
Example F-7	2%	700 h	10 Pa
Comparative example F-1	10%	100 h	10 ⁻⁵ Pa
Comparative example F-2	20%	20 h	10 ⁻⁵ Pa

[0392] From the above table, it can be seen that:

In the present application, at least one two-dimensional material is adopted as the electron emission layer. The two-dimensional material has an atomic-level thickness, and thus excited electrons generated from the laser irradiation surface can be emitted into vacuum without traveling through the layer of the material, which is very suitable for ultrafast electron sources with narrow pulse width. The two-dimensional material is free of dangling bonds, stable, and has a high melting point, which is less prone to damage and thus suitable for high beam current electron sources with high-power excitation. Moreover, the rich variety of two-dimensional materials, along with homogeneous and heterogeneous structures, brings ultra-high freedom in electron emission properties, for example, enabling pulsed emission and linear emission of electron sources. In addition, in the present application, the two-dimensional material can be directly integrated with the optical fiber. The optical fiber transmits laser while serving as a carrier for the low-dimensional material, thereby providing a stable excitation source with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios, does not require a complex optical path, and possesses the characteristics of small volume and high integration.

[0393] (VII) Preparation of electron sources using holey optical fibers, including the following examples and comparative examples.

Example G-1

[0394] A capillary optical fiber tube was selected as the holey optical fiber. The diameter of the fiber core of the holey optical fiber was 10 μm , and the diameter of the holey optical fiber was 125 μm . The wavelength of the laser transmitted in the holey optical fiber was 1550 nm. The conductive connection layer included a titanium layer with a thickness of 4 nm and a gold layer with a thickness of 50 nm, which were located around the fiber core and stacked on the holey optical fiber. An electron excitation layer was formed on the sidewall of the light-guiding hole and on the end face of the light-output end of the holey optical fiber through the CVD method. The electron excitation layer was a two-dimensional material of graphene with a thickness of 0.3 nm. The first portion of the electron excitation layer completely covered the sidewall of the light-guiding hole, and the second portion of the electron excitation layer was disposed on the end face of the light-output end of the holey optical fiber.

Example G-2

[0395] A capillary optical fiber tube was selected as the holey optical fiber. The diameter of the fiber core of the holey optical fiber was 10 μm , and the diameter of the holey optical fiber was 125 μm . The wavelength of the laser transmitted in the holey optical fiber was 1550 nm. The conductive connection layer included a titanium layer with a thickness of 4 nm and a gold layer with a thickness of 50 nm, which were located around the fiber core and stacked on the holey optical fiber. An electron excitation layer was formed on the sidewall of the light-guiding hole through the CVD method. The electron excitation layer was a two-dimensional material of graphene with a thickness of 3 nm.

Example G-3

[0396] An auxiliary layer made of gold with a thickness of 50 nm was deposited through the CVD method on the sidewall of the light-guiding hole and on the end face of the light-output end of the holey optical fiber. Then, carbon nanotubes were formed on the surface of the auxiliary layer through the CVD method, with the axial directions of the carbon nanotubes perpendicular to the surface of the auxiliary layer, thereby forming the electron excitation layer. The auxiliary layer was electrically connected to the conductive connection layer, yielding an electron source. In this example, the auxiliary layer overlapped with the first conductive portion of the conductive connection layer, and the second conductive portion of the conductive connection layer was disposed on the circumferential side surface of the optical fiber.

Example G-4

[0397] Graphene with a thickness of 2 nm was grown through the CVD method on the sidewall of the light-guiding hole and on the end face of the light-output end of the holey optical fiber. Then, carbon nanotubes were coated on the surface of the graphene, with the axial directions of the carbon nanotubes parallel to the surface of the graphene, followed by growing multiple quantum dots on the carbon nanotubes through the CVD method, thereby forming the electron excitation layer. The graphene was electrically connected to the conductive connection layer, yielding an electron source.

Comparative Example G-1

[0398] An electron source was prepared according to the structure of Example G-1, except that the electron excitation layer in Example G-1 was replaced with a gold layer with a thickness of 100 nm, and the gold layer was prepared by deposition.

Comparative Example G-2

[0399] An electron source was prepared according to the structure of Comparative Example G-1, except that the electron excitation layer in Comparative Example G-1 was replaced with a gold layer with a thickness of 2 nm, i.e., the same as the thickness of the graphene.

[0400] The electron sources prepared in the above examples and comparative examples were assembled into electron guns. Each electron gun further included a housing, a grid electrode, and an anode. The prepared electron guns were subjected to the performance tests. The test results are shown in the table below.

Table 7

No.	Stability	Lifetime	Working vacuum degree
Example G-1	2%	1000 h	10^{-2} Pa
Example G-2	2%	1000 h	10^{-2} Pa
Example G-3	5%	5000 h	10^{-2} Pa
Example G-4	5%	5000 h	10^{-2} Pa
Comparative example G-1	10%	100 h	10^{-5} Pa
Comparative example G-2	20%	20 h	10^{-5} Pa

[0401] Through testing, it was found that, compared the electron sources prepared in the comparative examples, the electron sources prepared in the examples have longer lifetime and better stability.

[0402] In summary, in the present application, the low-dimensional materials such as the zero-dimensional materials, one-dimensional materials, and two-dimensional materials have atomic-level sizes, enabling the excited electrons to be emitted into vacuum without traveling through the bulk of the material, which is beneficial to improving the electron emission efficiency and emission power and thus is very suitable for ultrafast electron sources with narrow pulse width. Moreover, the electron sources of the present application adopt low-dimensional materials as the materials for emitting electrons. Since the low-dimensional materials have high optical nonlinearity and discrete electron energy levels, the laser can interact more effectively with the electron excitation layer to generate energy resonance and excite electrons in the electron excitation layer. These electrons are excited and then escape into vacuum, forming an electron beam. The electron beam emitted from the interior of the electron excitation layer via the tunneling effect has concentrated energy and low energy spread. In addition, the low-dimensional materials can be directly integrated with different types of optical fibers, providing ultra-high stability and integration. Furthermore, the nanoscale electron excitation layer can barely affect the optical transmission mode of the holey optical fiber, so that the optical transmission mode of the electron source is mainly determined by the holey optical fiber, enabling effective emission of electrons from the electron source along the extending direction of the holey optical fiber, which provides great convenience for controlling the transmission mode of the electron source. Furthermore, the low-dimensional materials are free of dangling bonds, stable, and have high melting points, which are less prone to damage and suitable for high current electron sources under high-power excitation. By integrating the low-dimensional materials with tapered tips, very sharp optical fiber tips can be obtained, which possess large optical fields and electric field enhancement factors, providing high emission beam currents. The low-dimensional materials offer numerous combinations and thus are suitable for photoelectronic sources with various properties. Finally, the integration of the optical fibers with the low-dimensional materials for the electron sources exhibits significant advantages. The optical fibers can transmit laser while serving as carriers for the low-dimensional materials, thereby enabling stable excitation sources with tunable wavelength, polarization, and optical mode, which is suitable for various application scenarios. The electron sources eliminate the complex spatial optical coupling structures for introducing external lasers, have small volumes and high integration, and can be assembled into the housings of electron guns conveniently. When the electron sources are integrated with other equipment, stable integration can be achieved without refitting the vacuum electronic devices disruptively.

[0403] (VIII) Preparation of electron sources using tapered optical fibers, including the following examples and comparative examples.

Example H-1

[0404] A single-mode optical fiber was selected as the optical fiber 110. The diameter of the fiber core was 8.2 μm , and the diameter of the optical fiber was 125 μm . The tip portion of the optical fiber was conical shaped, with the diameter gradually reduced to 500 nm. The wavelength of the excitation laser transmitted in the optical fiber was 1550 nm. Graphite was subjected to mechanical exfoliation by using an adhesive tape to obtain 6-layer graphene. Taking the 6-layer graphene as a graphene unit, multiple graphene units were suspended on a liquid surface. With the light-input end of the optical fiber clamped, the tip portion of the optical fiber was inserted downward below the liquid surface to dip the graphene units floating on the liquid surface 3 times, so that an electron excitation layer, which was 18-layer graphene with a thickness of about 6.12 nm, was formed on the tip portion of the optical fiber. Subsequently, a conductive connection layer was formed on the outer surface of the optical fiber, yielding an electron source.

Example H-2

[0405] A single-mode optical fiber was selected as the optical fiber. The diameter of the fiber core was 8.2 μm , and the diameter of the optical fiber was 125 μm . The tip portion of the optical fiber was conical shaped, with the diameter gradually reduced to 500 nm. The wavelength of the excitation laser transmitted in the optical fiber was 1550 nm. 5-layer graphene was grown on a copper substrate through the CVD method. The copper substrate was etched away in an etching solution, such as an ammonium persulfate solution, to obtain 5-layer graphene suspended on the liquid surface. Taking the 5-layer graphene as a graphene unit, multiple graphene units were suspended on the liquid surface. With the light-input end of the optical fiber clamped, the tip portion of the optical fiber was inserted downward below the liquid surface to dip the graphene units floating on the liquid surface twice, so that 10-layer graphene with a thickness of about 3.4 nm was formed on the tip portion of the optical fiber. Subsequently, a conductive connection layer was formed on the outer surface of the optical fiber, yielding an electron source.

Example H-3

[0406] On the basis of Example H-1, a layer of CdSe quantum dots was coated on the surface of the graphene to form a combination structure of graphene and quantum dots, thereby obtaining the electron excitation layer of this example. The quantum dots have strong interaction with light, which can improve the response of the overall structure to light, increase the beam current, and enhance the brightness of the electron source. Secondly, the energy levels of the quantum dots are concentrated, which can realize electron emission with narrow linewidth.

Example H-4

[0407] A single-mode optical fiber was selected as the optical fiber. The diameter of the fiber core was 8.2 μm , and the diameter of the optical fiber was 125 μm . The tip portion of the optical fiber was conical shaped, with the diameter gradually reduced to 500 nm. The wavelength of the excitation laser transmitted in the optical fiber was 1550 nm. An auxiliary layer made of graphene with a thickness of 1 nm was deposited on the tip portion of the optical fiber, and then multiple nanotubes were deposited on the auxiliary layer. The axial directions of the nanotubes were parallel to the extending direction of the fiber core to obtain an electron excitation layer. Finally, a conductive connection layer was formed on the outer surface of the optical fiber, yielding an electron source, wherein the first conductive portion of the conductive connection layer was disposed on the surface of the tip portion of the optical fiber and overlapped with the auxiliary layer, and the second conductive portion of the conductive connection layer was disposed on the circumferential side surface of the optical fiber.

Comparative Example H-1

[0408] An electron source was prepared according to the structure of Example H-1, except that the electron excitation layer in Example H-1 was replaced with a gold layer with a thickness of 100 nm, and the gold layer was prepared by deposition.

Comparative Example H-2

[0409] An electron source was prepared according to the structure of Comparative Example H-1, except that the electron excitation layer in Comparative Example H-1 was replaced with a gold layer with a thickness of 6.12 nm.

[0410] The electron sources prepared in the above examples and comparative examples were assembled into electron guns. Each electron gun further included a housing, a grid electrode, and an anode. The prepared electron guns were subjected to the performance tests. The test results are shown in the table below:

Table 8

No.	Stability	Lifetime	Working vacuum degree
Example H-1	3%	1000 h	10^{-3} Pa
Example H-2	5%	1000 h	10^{-3} Pa
Example H-3	5%	1000 h	10^{-3} Pa
Example H-4	5%	1000 h	10^{-3} Pa
Comparative example H-1	10%	100 h	10^{-5} Pa

(continued)

No.	Stability	Lifetime	Working vacuum degree
Comparative example H-2	20%	50 h	10 ⁻⁵ Pa

[0411] Through testing, it was found that, compared with the electron sources prepared in the comparative examples, the electron sources prepared in the examples have longer lifetime and better stability.

[0412] In summary, in the present application, the low-dimensional materials such as the zero-dimensional materials, one-dimensional materials, and two-dimensional materials have atomic-level sizes, enabling the electrons under the back-side irradiation to be emitted into vacuum without traveling through the bulk of the material, which is very suitable for ultrafast electron sources with narrow pulse width. Moreover, the low-dimensional materials can be directly integrated with different types of optical fibers, providing ultra-high stability and integration. In addition, the low-dimensional materials are free of dangling bonds, stable, and have high melting points, which are less prone to damage and suitable for high current electron sources under high-power excitation. By integrating the low-dimensional materials with tapered tips, very sharp optical fiber tips can be obtained, which possess large optical fields and electric field enhancement factors, providing high emission beam currents. The low-dimensional materials offer numerous combinations and thus are suitable for photoelectronic sources with various properties. Finally, the integration of the optical fibers with the low-dimensional materials for the electron source exhibits significant advantages. The optical fiber can transmit laser while serving as carriers for the low-dimensional materials, thereby enabling stable excitation sources with tunable wavelength, polarization, and optical mode, which are suitable for various application scenarios, do not require a complex optical path, and have small volumes and high integration. When the electron sources are integrated with other equipment, stable integration can be achieved without refitting the vacuum electronic devices disruptively.

[0413] The technical features of the above-mentioned embodiments can be combined arbitrarily. In order to make the description concise, not all possible combinations of the technical features are described in the embodiments. However, as long as there is no contradiction in the combination of these technical features, the combinations should be considered as in the scope of the present application.

[0414] The above-described embodiments are only several implementations of the present application, and the descriptions are relatively specific and detailed, but they should not be construed as limiting the scope of the present application. It should be understood by those of ordinary skill in the art that various modifications and improvements can be made without departing from the concept of the present application, and all fall within the protection scope of the present application. Therefore, the patent protection of the present application shall be defined by the appended claims.

Claims

1. An electron source, comprising an optical fiber, a conductive connection layer and an electron emission layer, the conductive connection layer being disposed on an outer surface of the optical fiber,

wherein the electron emission layer comprises an electron excitation layer electrically connected to the conductive connection layer, and the electron excitation layer comprises a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof;

the electron excitation layer is disposed on a laser output path of the optical fiber, and a laser output from the optical fiber is capable of directly irradiating the electron emission layer such that the electron excitation layer is excited by the laser to emit electrons.

2. The electron source according to claim 1, wherein a thickness of the electron excitation layer is in a range from 0.1 nm to 100 nm.

3. The electron source according to claim 1 or 2, wherein the electron emission layer further comprises an auxiliary layer, and

the auxiliary layer is stacked on a side of the electron excitation layer adjacent to the optical fiber; or
the auxiliary layer is stacked on a side of the electron excitation layer away from the optical fiber.

4. The electron source according to claim 3, wherein the auxiliary layer comprises a conductive support layer, a heat

dissipation support layer, or a combination thereof.

- 5 5. The electron source according to claim 3 or 4, wherein the auxiliary layer has a thickness in a range from 0.1 nm to 100 nm and a light transmittance greater than or equal to 10%.
- 10 6. The electron source according to any one of claims 3 to 5, wherein the auxiliary layer comprises a conductive support layer, and the conductive support layer is electrically connected to the conductive connection layer.
- 15 7. The electron source according to any one of claims 4 to 6, wherein a material of the conductive support layer comprises a conductive metal, and in the optical fiber, the laser has a wavelength in a range from 200 nm to 2000 nm and a pulsed power in a range from 1 nW to 1 W.
- 20 8. The electron source according to any one of claims 1 to 7, wherein the electron excitation layer comprises a zero-dimensional material.
- 25 9. The electron source according to claim 8, wherein a number density of the zero-dimensional materials in the electron excitation layer is in a range from $10/\text{mm}^2$ to $10^{12}/\text{mm}^2$.
- 30 10. The electron source according to claim 8 or 9, wherein no spatial gap exists between two adjacent zero-dimensional material particles.
- 35 11. The electron source according to any one of claims 8 to 10, wherein an average particle size of the zero-dimensional materials is in a range from 1 nm to 100 μm .
- 40 12. The electron source according to any one of claims 1 to 11, wherein the electron excitation layer comprises a one-dimensional material.
- 45 13. The electron source according to claim 12, wherein a diameter of the one-dimensional material is in a range from 1 nm to 20 nm.
- 50 14. The electron source according to claim 12 or 13, wherein the electron excitation layer comprises a plurality of one-dimensional materials, and axial directions of any two one-dimensional materials are parallel to each other.
- 55 15. The electron source according to any one of claims 12 to 14, wherein the electron excitation layer comprises a plurality of one-dimensional materials, and along a radial direction of the one-dimensional materials, no spatial gap exists between two adjacent one-dimensional materials.
16. The electron source according to any one of claims 12 to 15, wherein an angle between an axial direction of the one-dimensional material in the electron excitation layer and an output direction of the laser is in a range from 0° to 90° .
17. The electron source according to claim 16, wherein the axial direction of the one-dimensional material in the electron excitation layer is the same as the output direction of the laser, and a length of the one-dimensional material is in a range from 0.1 μm to 1 μm .
18. The electron source according to claim 16, wherein the angle between the axial direction of the one-dimensional material in the electron excitation layer and the output direction of the laser is greater than 0° and less than or equal to 90° , and a length of the one-dimensional material is in a range from 1 μm to 200 μm .
19. The electron source according to claim 18, wherein the angle between the axial direction of the one-dimensional material in the electron excitation layer and the output direction of the laser is greater than 0° and less than or equal to 90° , and the length of the one-dimensional material is in a range from 10 μm to 30 μm .
20. The electron source according to claim 16, 18, or 19, wherein the angle between the axial direction of the one-dimensional material in the electron excitation layer and the output direction of the laser is in a range from 45° to 90° .
21. The electron source according to any one of claims 1 to 20, wherein the electron excitation layer comprises at

least one two-dimensional material.

22. The electron source according to claim 21, wherein a thickness of the two-dimensional material is in a range from 0.1 nm to 50 nm.

23. The electron source according to claim 21 or 22, wherein the electron excitation layer comprises at least two two-dimensional materials stacked sequentially in the laser output direction of the optical fiber, and the two-dimensional materials are each an electrically conductive two-dimensional material; two adjacent two-dimensional materials are the same or different.

24. The electron source according to any one of claims 21 to 23, wherein an angle between crystal axes of two adjacent two-dimensional materials is in a range from 0° to 360°.

25. The electron source according to any one of claims 1 to 20, wherein the electron excitation layer is at least two two-dimensional materials joined together, the at least two two-dimensional materials are made of different materials, and the laser from the optical fiber is capable of irradiating a junction between adjacent two-dimensional materials.

26. The electron source according to any one of claims 1 to 25, wherein the electron excitation layer comprises the one-dimensional material and the zero-dimensional material, the zero-dimensional material being disposed at an end and/or a lateral side of the one-dimensional material.

27. The electron source according to claim 26, wherein a diameter of the one-dimensional material is in a range from 1 nm to 500 nm, and a length of the one-dimensional material is in a range from 10 nm to 1 mm.

28. The electron source according to claim 26 or 27, wherein an average particle size of the zero-dimensional materials is in a range from 1 nm to 100 nm.

29. The electron source according to any one of claims 1 to 28, wherein the electron excitation layer comprises the zero-dimensional material and the two-dimensional material, and the zero-dimensional material is disposed on a surface of the two-dimensional material.

30. The electron source according to any one of claims 1 to 29, wherein the electron excitation layer comprises the one-dimensional material and the two-dimensional material, and the one-dimensional material is disposed on a surface of the two-dimensional material.

31. The electron source according to any one of claims 1 to 30, further satisfying at least one of following conditions:

- (1) the zero-dimensional material comprises a quantum dot, a fullerene, a nitrogen-vacancy center, a nano-crystal, or any combination thereof;
- (2) the one-dimensional material comprises a nanotube, a nanoribbon, a nanowire, or any combination thereof;
- (3) the two-dimensional material comprises graphene, black phosphorus, a transition metal chalcogenide, hexagonal boron nitride, or any combination thereof.

32. The electron source according to any one of claims 1 to 31, wherein the optical fiber is a solid-core optical fiber, a tapered optical fiber, a side-polished optical fiber, or a holey optical fiber.

33. The electron source according to any one of claims 1 to 31, wherein the optical fiber comprises a fiber core and a cladding layer, the fiber core is configured for laser transmission, the cladding layer surrounds the fiber core, and an end face of a light-output end of the optical fiber is aligned at an angle relative to an extending direction of the fiber core;
the electron emission layer is disposed on the end face of the light-output end of the optical fiber, and the electron excitation layer covers the fiber core of the optical fiber, a pulsed laser output from the fiber core is capable of directly irradiating the electron emission layer such that the electron excitation layer is excited by the pulsed laser output from the fiber core to emit electrons.

34. The electron source according to any one of claims 1 to 31, wherein the optical fiber is a holey optical fiber, the

holey optical fiber defines a light-guiding hole, the electron excitation layer is at least disposed on a sidewall of the light-guiding hole and extends along an extending direction of the light-guiding hole.

35. The electron source according to claim 34, wherein the electron emission layer further comprises an auxiliary layer, and

the auxiliary layer is stacked on a side of the electron excitation layer adjacent to the sidewall of the light-guiding hole; or
the auxiliary layer is stacked on a side of the electron excitation layer away from the sidewall of the light-guiding hole.

36. The electron source according to claim 34 or 35, wherein the electron excitation layer comprises a first portion and a second portion, the first portion completely covers the sidewall of the light-guiding hole, and the second portion is disposed on an end face of a light-output end of the holey optical fiber; and
the second portion is connected to the first portion and is electrically connected to the conductive connection layer.

37. The electron source according to any one of claims 34 to 36, wherein the conductive connection layer comprises a first conductive portion and a second conductive portion, the first conductive portion is disposed on the end face of the light-output end of the holey optical fiber, and the second conductive portion is disposed on a circumferential side surface of the holey optical fiber; and
the first conductive portion is connected to the second conductive portion and overlaps with the second portion of the electron excitation layer.

38. The electron source according to any one of claims 1 to 31, wherein the optical fiber is a holey optical fiber, the electron emission layer is disposed on an end face of a light-output end of the holey optical fiber, and the electron excitation layer covers an end of a light-guiding hole at the end face of the light-output end; a pulsed laser output from the holey optical fiber is capable of directly irradiating the electron emission layer, such that the electron excitation layer is excited by the pulsed laser output from the holey optical fiber to emit electrons.

39. The electron source according to any one of claims 1 to 31, wherein a light-output end of the optical fiber has a tip portion, the electron excitation layer covers a surface of the tip portion of the optical fiber.

40. The electron source according to claim 39, wherein the electron excitation layer comprises a first portion;

a projection of the first portion on a target plane perpendicular to an extending direction of the fiber core covers a projection of the fiber core on the target plane; and
the first portion is electrically connected to the conductive connection layer.

41. The electron source according to claim 40, wherein the electron excitation layer further comprises a second portion connected to the first portion, a projection of the second portion on the target plane is located around the projection of the first portion on the target plane, and the second portion overlaps with the conductive connection layer.

42. The electron source according to any one of claims 39 to 41, wherein the conductive connection layer comprises a first conductive portion and a second conductive portion, the first conductive portion is disposed on the tip portion of the optical fiber, and the second conductive portion is connected to the first conductive portion and disposed on a circumferential side surface of the optical fiber; the first conductive portion overlaps with the second portion.

43. The electron source according to any one of claims 39 to 42, wherein in an extending direction of the fiber core, a size of the tip portion is L1, and a size of the electron excitation layer is L2, wherein L1 is greater than L2.

44. The electron source according to claim 43, wherein the size of the tip portion and the size of the electron excitation layer satisfy: $L2 > 1/2 \times L1$.

45. The electron source according to any one of claims 1 to 31, wherein the optical fiber comprises a fiber core and a cladding layer, the fiber core is configured to transmit the laser, and the cladding layer surrounds the fiber core;

a light-leakage notch is defined at a light-output end of the optical fiber, and the light-leakage notch extends in

a radial direction of the optical fiber;
 the electron emission layer is disposed on a bottom wall of the light-leakage notch, the bottom wall of the light-leakage notch is a flat surface, and a projection of the electron excitation layer on the bottom wall covers a projection of the fiber core on the bottom wall;
 the electron excitation layer further extends to the light-output end of the optical fiber.

46. An electron gun, comprising a housing, a grid electrode, an anode, and the electron source according to any one of claims 1 to 45;

wherein the electron source is fixed in the housing, and the grid electrode and the anode are sequentially disposed on an electron emission side of the electron source.

47. Use of the electron source according to any one of claims 1 to 45, wherein the use of the electron source comprises at least one of an electron microscope, an electron beam exposure machine, an X-ray tube, a free-electron laser, or a display.

48. A four-dimensional electron microscope for scanning a sample, comprising:

a light source assembly configured to emit a pulsed laser;

the electron source according to any one of claims 1 to 45, comprising an excitation optical fiber and the electron emission layer, the excitation optical fiber being coupled to the light source assembly, the electron emission layer at least comprising the electron excitation layer, the electron excitation layer being disposed on a pulsed laser output path of the excitation optical fiber, enabling the electron excitation layer to emit an electron beam upon excitation by the pulsed laser; the electron excitation layer comprising a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof;

an electron optical assembly disposed on an electron beam emission side of the electron source, the electron optical assembly being configured to adjust a deflection direction of the electron beam to allow the electron beam to be incident onto the sample; and

a detector disposed on a side of the sample and configured to collect a reflected electron signal of the electron beam incident onto the sample or a transmitted electron signal of the electron beam passing through the sample.

49. The four-dimensional electron microscope according to claim 48, wherein the light source assembly comprises a light source and a first optical fiber, an end of the first optical fiber is coupled to the light source, and another end of the first optical fiber is connected to the excitation optical fiber;

the light source is configured to emit the pulsed laser, and the first optical fiber is configured to transmit the pulsed laser emitted by the light source to the excitation optical fiber.

50. The four-dimensional electron microscope according to claim 49, wherein the light source assembly further comprises a first optical fiber beam splitter, a second optical fiber, and a first optical fiber time delayer;

the first optical fiber beam splitter has a first input end and a first output end, the first input end is coupled to the light source, the first output end opposite to the first input end, and the first output end is separately connected to the first optical fiber and the second optical fiber;

an end of the second optical fiber away from the first optical fiber beam splitter extends toward the sample;

the first optical fiber time delayer is coupled to the second optical fiber to introduce a time delay to a light beam propagating in the second optical fiber.

51. The four-dimensional electron microscope according to claim 50, wherein the reflected electron signal comprises a secondary electron signal or a backscattered electron signal;

the sample has an incident surface disposed opposite to the electron beam emission side of the electron source;

the detector comprises a backscattered electron detector or a secondary electron detector, and the backscattered electron detector or the secondary electron detector is directed toward the incident surface of the sample, allowing the secondary electron detector to receive a secondary electron signal or allowing the backscattered electron detector to receive a backscattered electron signal.

52. The four-dimensional electron microscope according to any one of claims 49 to 51, wherein the reflected electron

signal comprises a cathodoluminescence signal;

the sample has an incident surface disposed opposite to the electron beam emission side of the electron source;

the detector comprises a cathodoluminescence analysis system, and the cathodoluminescence analysis system is directed toward the incident surface of the sample to receive the cathodoluminescence signal.

53. The four-dimensional electron microscope according to any one of claims 49 to 52, wherein the sample has an incident surface and an exit surface, the incident surface is disposed opposite to the electron beam emission side of the electron source, and the exit surface is disposed opposite to the incident surface; the detector comprises a receiving screen, and the receiving screen is directed toward the exit surface of the sample to receive the electron beam passing through the sample.

54. The four-dimensional electron microscope according to claim 53, wherein the light source assembly further comprises a second optical fiber beam splitter, a third optical fiber, and a second optical fiber time delay;

the second optical fiber beam splitter has a second input end and a second output end, the second input end is coupled to the light source, the second output end is opposite to the second input end, and the second output end is separately connected to the first optical fiber and the third optical fiber;

an end of the third optical fiber away from the second optical fiber beam splitter extends toward the sample;

the second optical fiber time delay is coupled to the third optical fiber and configured to introduce a time delay to a light beam propagating in the third optical fiber.

55. The four-dimensional electron microscope according to any one of claims 48 to 54, further comprising a housing,

wherein the housing defines a vacuum chamber, and the electron source and the electron optical assembly are sequentially disposed in the vacuum chamber;

the housing has an opening in communication with the vacuum chamber, and a light-input end of the excitation optical fiber of the electron source is exposed out from the opening and coupled to the light source assembly.

56. The four-dimensional electron microscope according to claim 55, wherein an outer circumferential wall of the excitation optical fiber is sealingly connected to an inner sidewall of the opening.

57. The four-dimensional electron microscope according to any one of claims 48 to 56, wherein the electron source further comprises an anode, the anode defines a first electron channel, and the electron optical assembly defines a second electron channel in communication with the first electron channel;

a preset electric field is adapted to be provided between the anode and the electron excitation layer, such that the electron beam is driven by the preset electric field to pass through the first electron channel and the second electron channel and is incident onto the sample.

58. An electron beam exposure machine for exposing a sample, comprising:

a light source configured to emit a laser;

the electron source according to any one of claims 1 to 45, comprising an optical fiber and an electron emission layer, the optical fiber being coupled to the light source, the electron emission layer at least comprising the electron excitation layer, the electron excitation layer being disposed on the laser output path of the optical fiber, enabling the electron excitation layer to emit an electron beam upon excitation by the laser; the electron excitation layer comprises a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof; and

an electron optical assembly disposed on an electron beam emission side of the electron source, wherein the electron optical assembly is configured to adjust focusing and a deflection direction of the electron beam to allow the electron beam to be incident onto the sample to form a preset exposure pattern on the sample.

59. The electron beam exposure machine according to claim 58, further comprising a housing;

wherein the housing defines a vacuum chamber, and a light-output end of the optical fiber of the electron source and the electron optical assembly are spaced apart from each other and disposed in the vacuum

chamber;

the electron excitation layer is disposed on the light-output end of the optical fiber and located on the laser output path of the optical fiber.

60. The electron beam exposure machine according to claim 59, wherein the housing has an opening in communication with the vacuum chamber, and a light-input end of the optical fiber of the electron source is exposed out from the opening and coupled to the light source;
an outer circumferential wall of the optical fiber is sealingly connected to an inner sidewall of the opening.

61. The electron beam exposure machine according to claim 60, wherein the light-input end of the optical fiber of the electron source extends out of the vacuum chamber through the opening and coupled to the light source; or
an end face of the light-input end of the optical fiber of the electron source is flush with a plane of the opening.

62. The electron beam exposure machine according to any one of claims 58 to 61, wherein the electron source further comprises an optical modulator, the optical modulator is connected between the light source and the optical fiber, and is configured to control whether the laser propagates to the optical fiber.

63. The electron beam exposure machine according to claim 62, wherein the electron optical assembly comprises a focusing magnetic lens and a deflection coil, and the focusing magnetic lens and the deflection coil are spaced apart from each other along an emission direction of the electron beam and disposed at an electron beam emission side of the electron source.

64. The electron beam exposure machine according to claim 62 or 63, wherein the optical modulator comprises an electro-optic modulator or an optical switch.

65. The electron beam exposure machine according to any one of claims 58 to 64, wherein the electron source further comprises an anode, the anode defines a first electron channel, and the electron optical assembly defines a second electron channel in communication with the first electron channel;
a preset electric field is adapted to be provided between the anode and the electron excitation layer, such that the electron beam is driven by the preset electric field to pass through the first electron channel and the second electron channel and is incident onto the sample.

66. An optical fiber multi electron beam exposure machine for exposing a sample, comprising:

a light source configured to emit a laser;

the electron source according to any one of claims 1 to 45, comprising an optical fiber assembly and an electron emission layer, the optical fiber assembly being coupled to the light source, the electron emission layer at least comprising the electron excitation layer, the optical fiber assembly comprising a plurality of fiber cores for transmitting laser beams, the electron excitation layer being disposed on a laser output path of the fiber cores, enabling the electron excitation layer to emit electron beams upon excitation by the laser beams;
the electron excitation layer comprises a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof;

the electron source further comprising an optical modulator, an end of the optical modulator being connected to the light source, another end of the optical modulator being correspondingly and separately connected to the plurality of fiber cores of the optical fiber assembly, and the optical modulator being configured to control whether the laser emitted from the light source separately propagates to corresponding fiber cores; and
an electron optical assembly disposed on an electron beam emission side of the electron source, wherein the electron optical assembly is configured to adjust focusing and a deflection direction of the electron beam to allow the electron beam to be incident onto the sample to form a preset exposure pattern on the sample.

67. The optical fiber multi electron beam exposure machine according to claim 66, wherein the optical fiber assembly comprises a plurality of optical fibers arranged in an array, and the electron excitation layer is disposed on an end face of a light-output end of each optical fiber, such that the electron excitation layer is disposed on a laser output path of a fiber core of a corresponding optical fiber.

68. The optical fiber multi electron beam exposure machine according to claim 66 or 67, wherein the light modulation member comprises a spatial optical modulator, an optical switch, or an electro-optic modulator.

69. The optical fiber multi electron beam exposure machine according to any one of claims 66 to 68, wherein the electron optical assembly comprises a focusing magnetic lens and a deflection coil, and the focusing magnetic lens and the deflection coil are spaced apart from each other along an emission direction of the electron beam and disposed at an electron beam emission side of the electron source.

70. The optical fiber multi electron beam exposure machine according to any one of claims 66 to 69, further comprising a housing;

wherein the housing defines a vacuum chamber, and the electron source and the electron optical assembly are sequentially disposed in the vacuum chamber;
the housing has an opening in communication with the vacuum chamber, and a light-input end of the optical fiber assembly of the electron source is exposed out from the opening and coupled to the light source;
an outer circumferential wall of the optical fiber assembly is sealingly connected to an inner sidewall of the opening.

71. The optical fiber multi electron beam exposure machine according to any one of claims 66 to 70, wherein the electron source further comprises an anode, the anode defines a first electron channel, and the electron optical assembly defines a second electron channel in communication with the first electron channel;
a preset electric field is adapted to be provided between the anode and the electron excitation layer, such that the electron beam is driven by the preset electric field to pass through the first electron channel and the second electron channel and is incident onto the sample.

72. An X-ray tube, comprising:

a tube body defining a vacuum chamber therein;
the electron source according to any one of claims 1 to 45, comprising an optical fiber and an electron emission layer, a light-output end of the optical fiber being located in the vacuum chamber, the electron emission layer being disposed at the light-output end of the optical fiber, the electron emission layer at least comprising the electron excitation layer, the electron excitation layer being disposed on the laser output path of the optical fiber, enabling the electron excitation layer to emit electrons upon excitation by the laser; and
an anode target disposed in the vacuum chamber and disposed opposite to and spaced apart from the light-output end of the optical fiber, the anode target being configured to collect the electrons emitted from the electron excitation layer to emit X-rays;
wherein the tube body has an output window facing the anode target, and the output window is configured to guide the X-rays out from the vacuum chamber;

the electron excitation layer comprises a zero-dimensional material, a one-dimensional material, a two-dimensional material, or any combination thereof.

73. The X-ray tube according to claim 72, wherein along an extending direction of the optical fiber, the electron source is spaced apart from the anode target,

the anode target has a reflective target surface toward the light-output end, and the reflective target surface is aligned at an angle relative to the extending direction of the optical fiber, and
the output window is disposed on a sidewall of the tube body and directed toward the reflective target surface.

74. The X-ray tube according to claim 72 or 73, wherein the anode target comprises a transmission anode;
in a longitudinal extending direction of the tube body, the electron source and the output window are disposed at two opposite ends of the tube body, and the transmission anode is located between the electron source and the output window.

75. The X-ray tube according to any one of claims 72 to 74, wherein, along the extending direction of the optical fiber, the anode target is spaced apart from the light-output end of the optical fiber, and a preset electric field is adapted to be provided between the anode target and the electron excitation layer, such that the electrons emitted from the electron excitation layer are linearly accelerated along the extending direction of the optical fiber.

76. The X-ray tube according to any one of claims 72 to 75, wherein the tube body surrounds both the optical fiber and the anode target.

77. The X-ray tube according to any one of claims 72 to 76, wherein the tube body has a first port in communication with the vacuum chamber;
the light-output end of the optical fiber extends into the vacuum chamber through the first port, and an outer circumferential wall of the optical fiber is sealingly connected to an inner circumferential wall of the first port.

78. The X-ray tube according to claim 77, wherein the tube body further has a second port disposed opposite to the first port, and a side of the anode target away from the light-output end extends out from the vacuum chamber through the second port;
an outer circumferential wall of the anode target is sealingly connected to an inner circumferential wall of the second port.

79. The X-ray tube according to claim 78, wherein the X-ray tube further comprises an external electrode, the external electrode is disposed between the outer circumferential wall of the anode target and the inner circumferential wall of the second port,
in the longitudinal extending direction of the tube body, an end of the external electrode is located in the vacuum chamber, and another end of the external electrode extends out from the vacuum chamber.

80. The X-ray tube according to any one of claims 72 to 79, wherein the optical fiber has a light-input end disposed opposite to the light-output end, and an end face of the light-input end is flush with a plane of the first port; or the light-input end extends out from the vacuum chamber through the first port.

81. The X-ray tube according to any one of claims 72 to 80, wherein the tube body comprises an inner tube and an outer tube, the inner tube surrounds the optical fiber and the anode target, and the outer tube surrounds the inner tube, the outer tube has an opening, and part of the inner tube is exposed from the opening to form the output window;
a material of the inner tube comprises an X-ray transmitting material, and a material of the outer tube comprises an X-ray blocking material.

82. The X-ray tube according to any one of claims 72 to 81, wherein an outer diameter of the tube body is in a range from 125 μm to 2000 μm , and a length of the tube body is in a range from 3 cm to 9 cm.

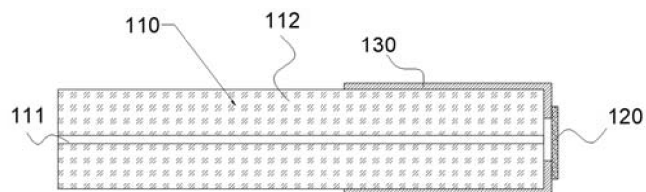


FIG. 1

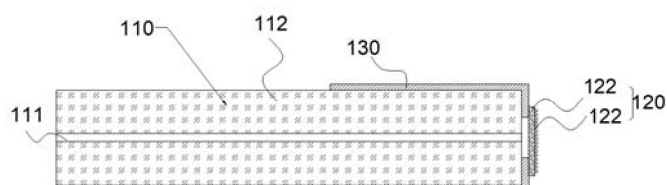


FIG. 2

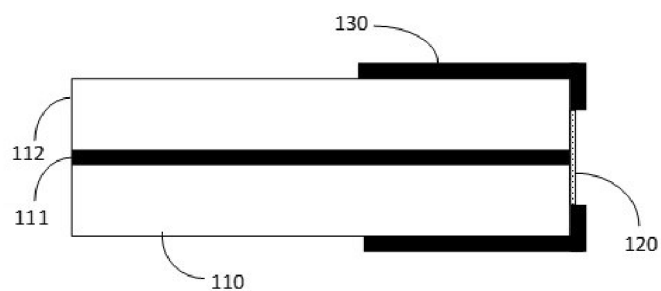


FIG. 3

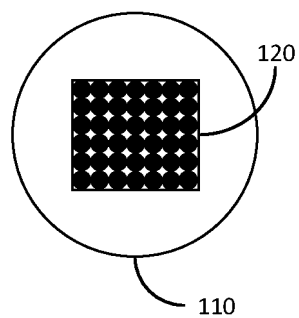


FIG. 4

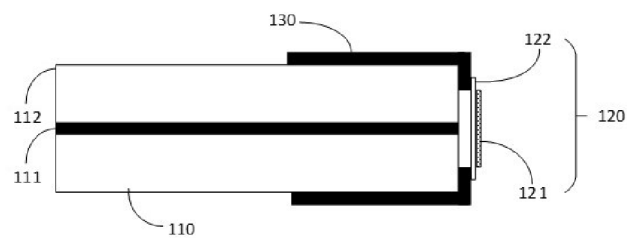


FIG. 5

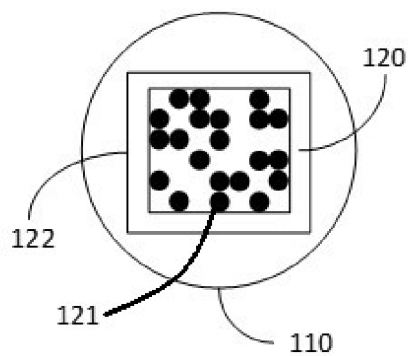


FIG. 6

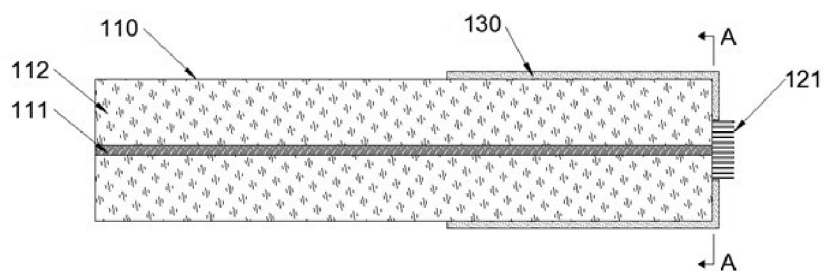


FIG. 7

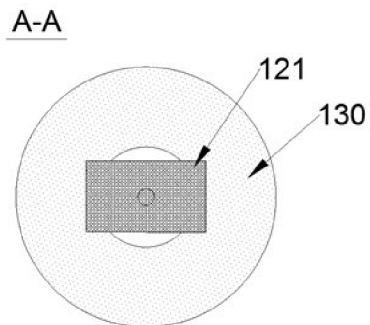


FIG. 8

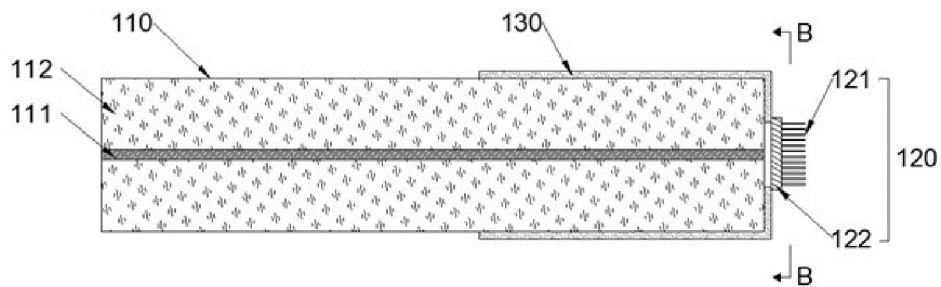


FIG. 9

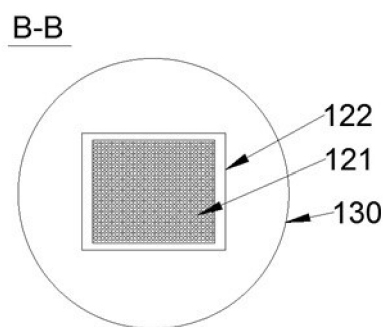


FIG. 10

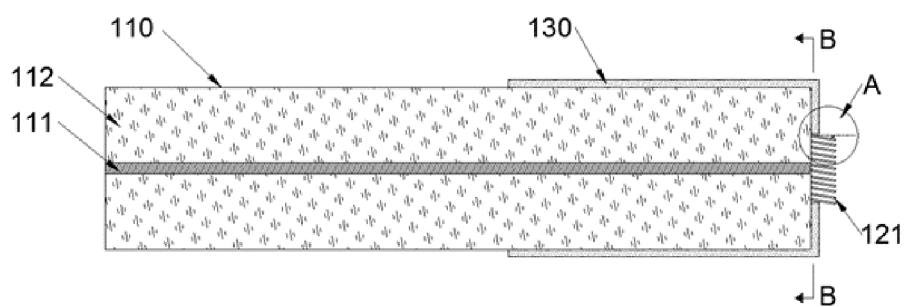


FIG. 11

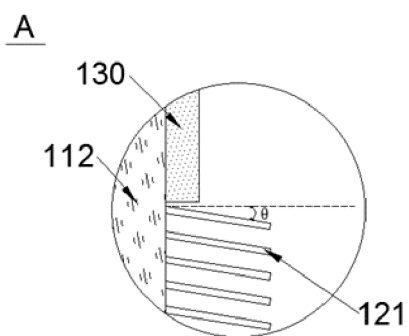


FIG. 12

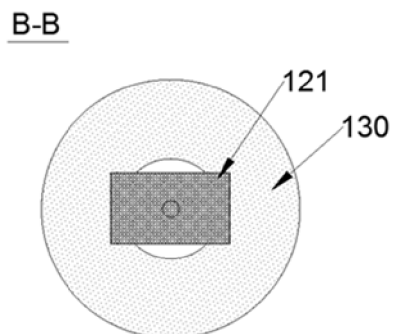


FIG. 13

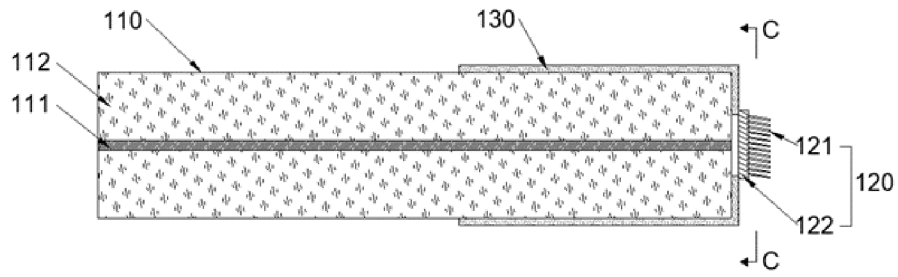


FIG. 14

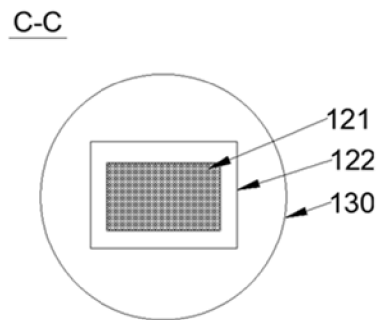


FIG. 15

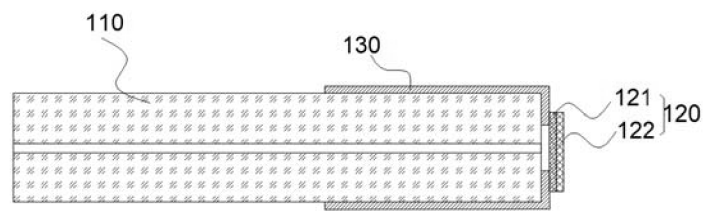


FIG. 16

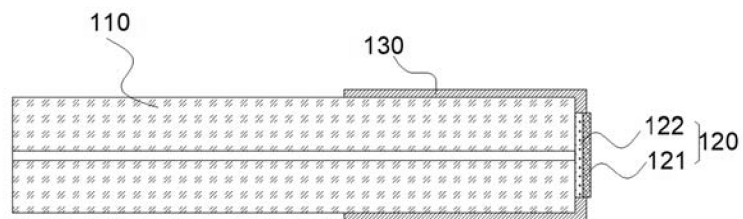


FIG. 17

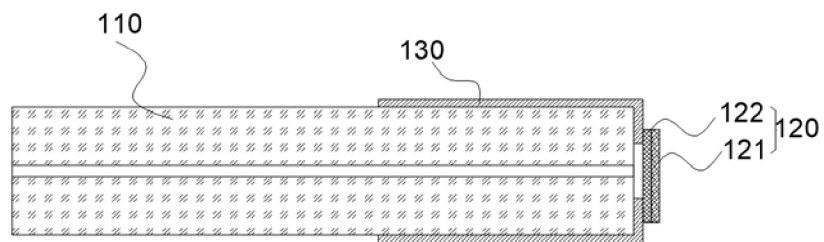


FIG. 18

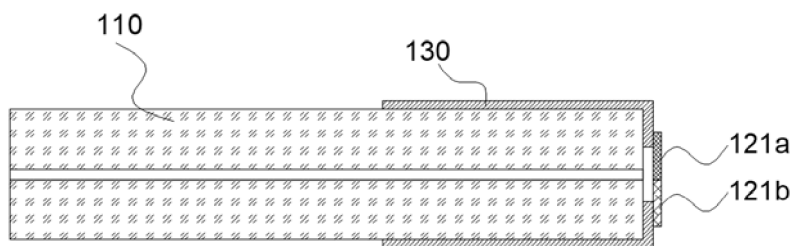


FIG. 19

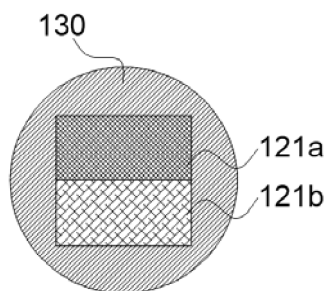


FIG. 20

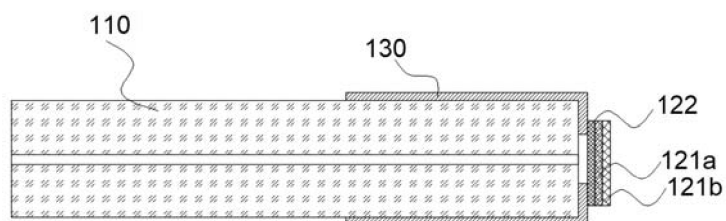


FIG. 21

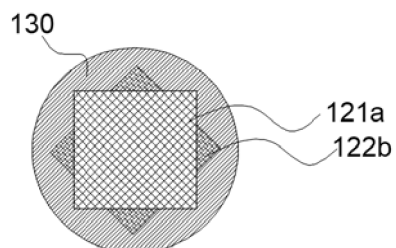


FIG. 22

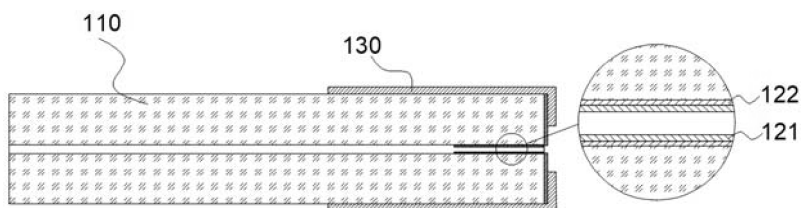


FIG. 23

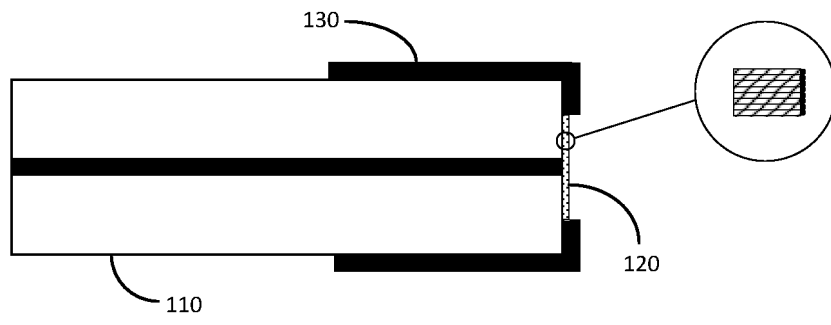


FIG. 24

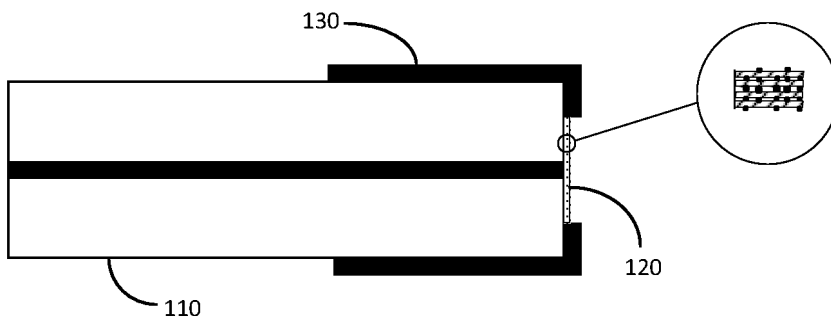


FIG. 25

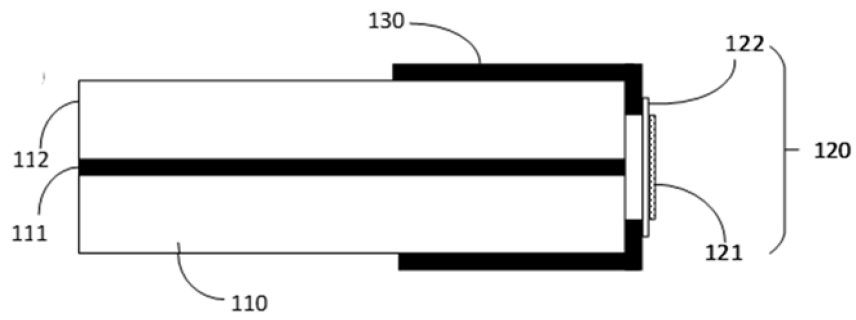


FIG. 26

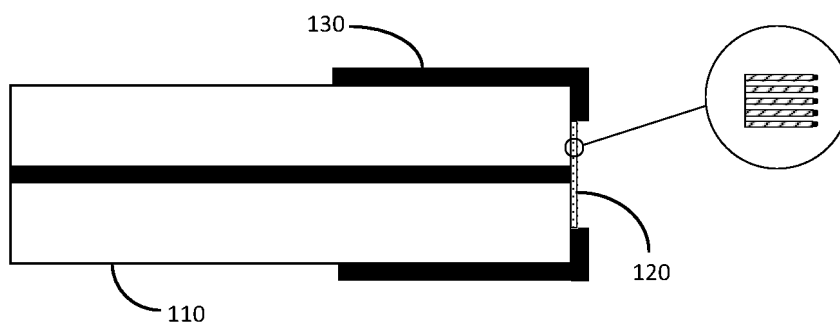


FIG. 27

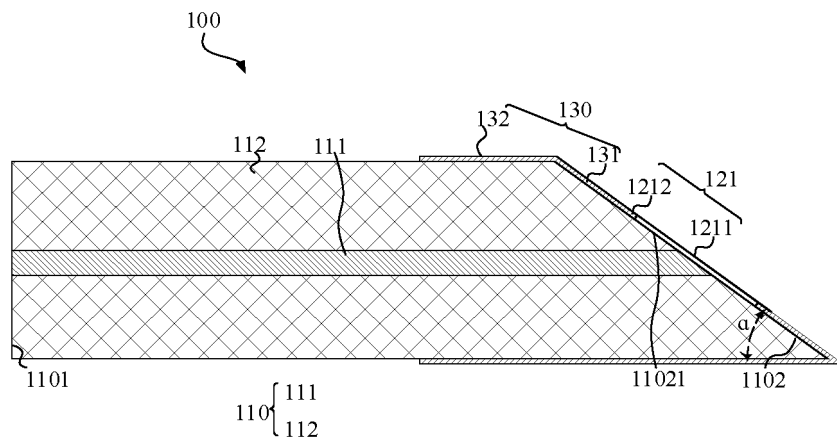


FIG. 28

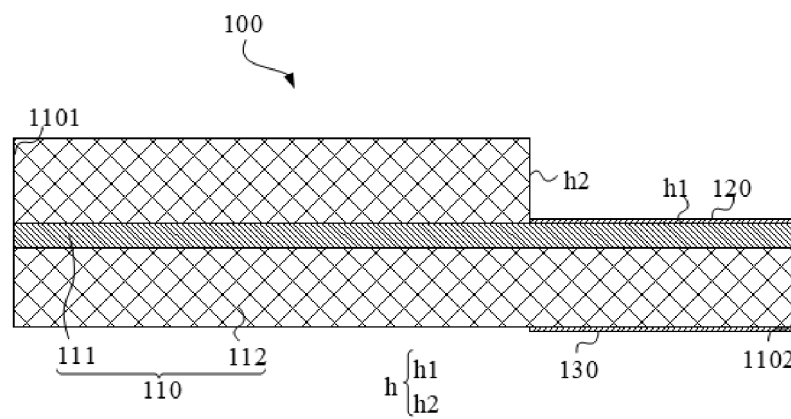


FIG. 29

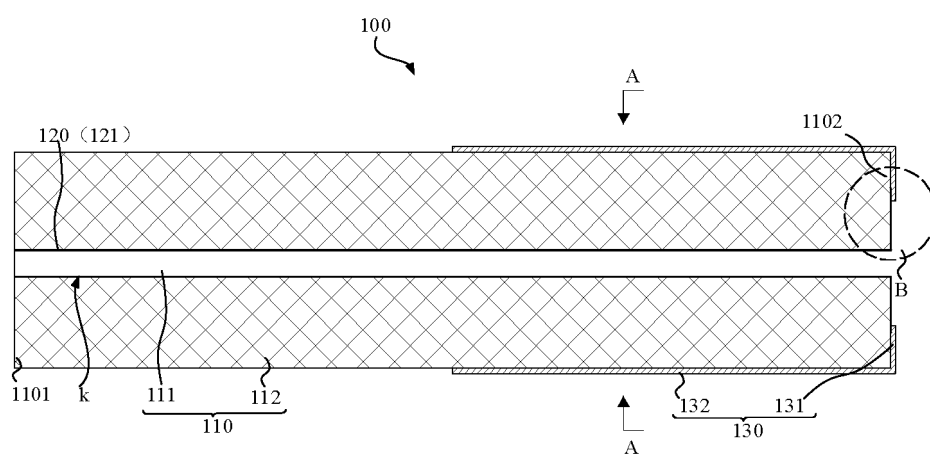


FIG. 30

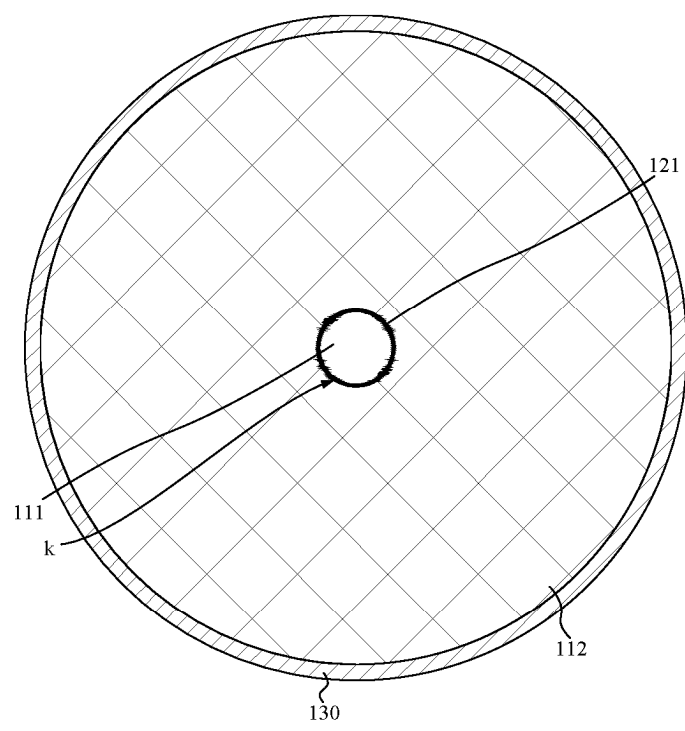


FIG. 31

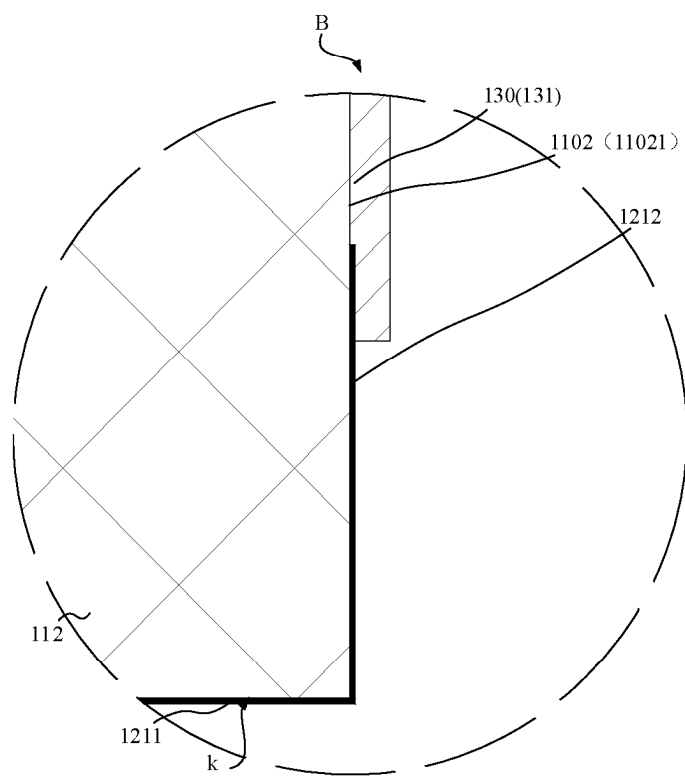


FIG. 32

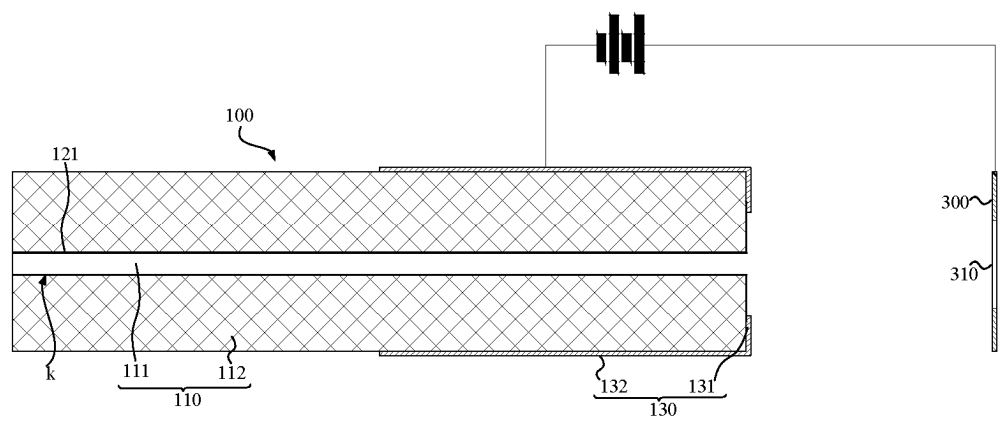


FIG. 33

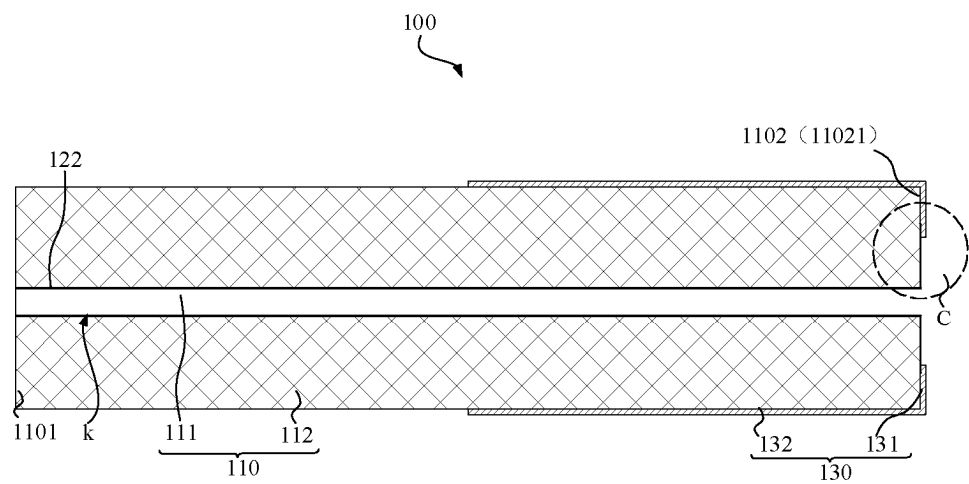


FIG. 34

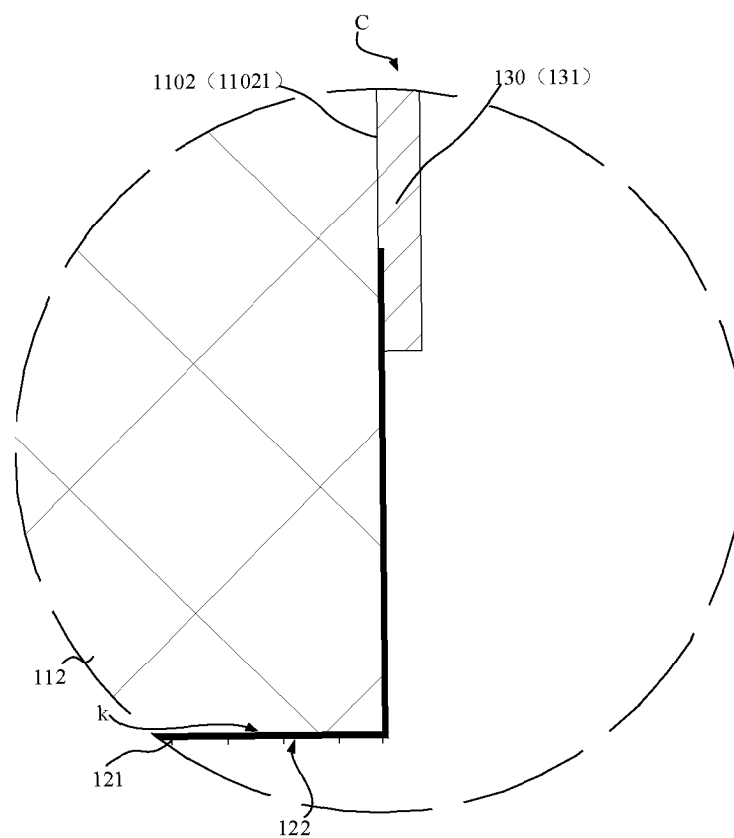


FIG. 35

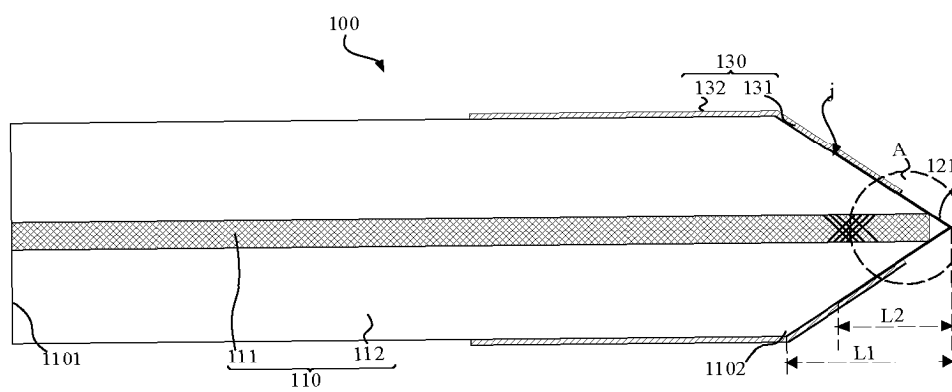


FIG. 36

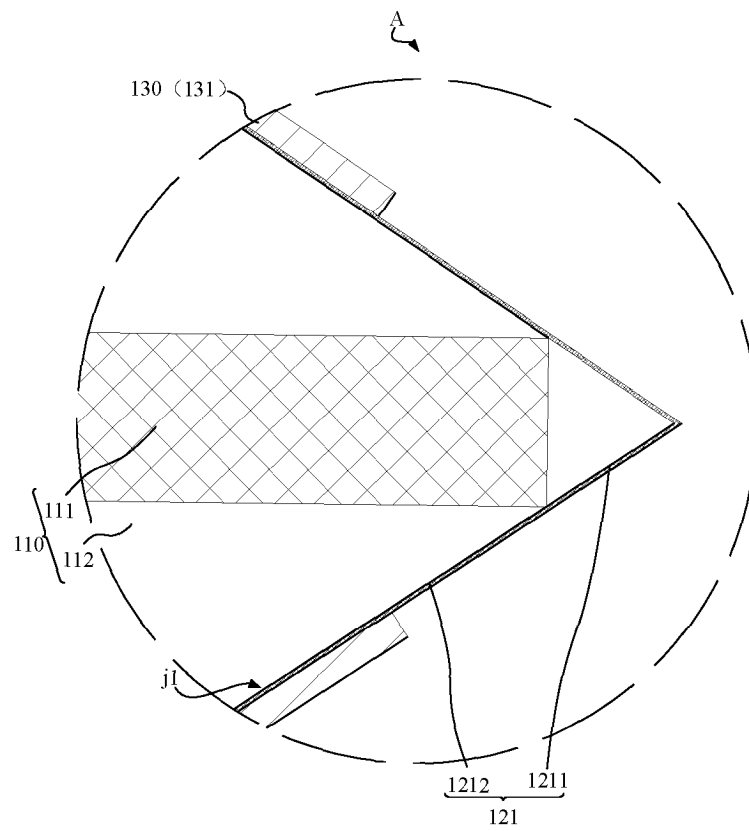


FIG. 37

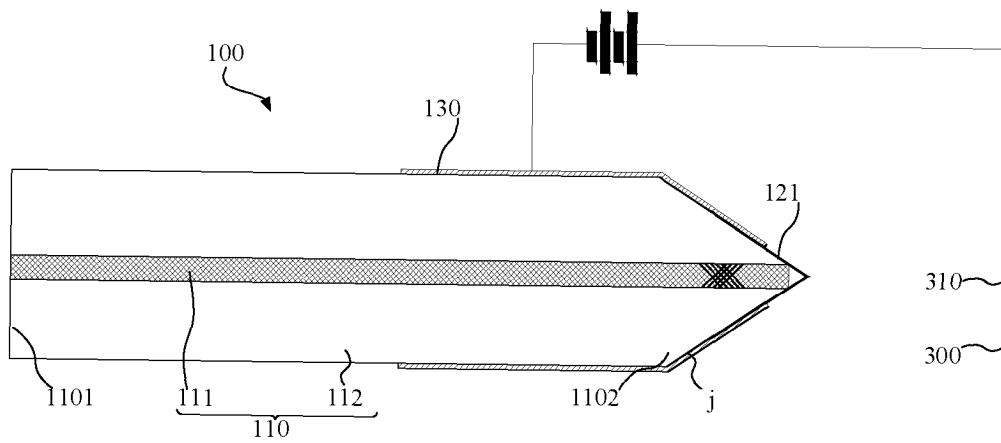


FIG. 38

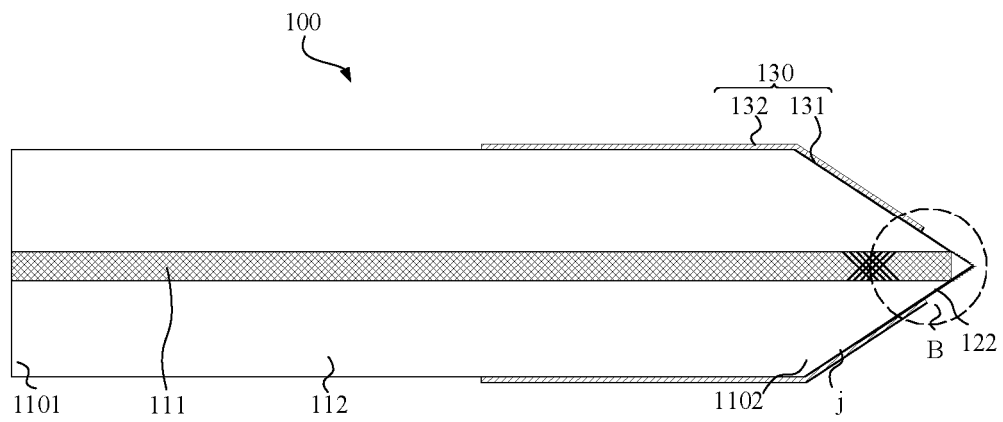


FIG. 39

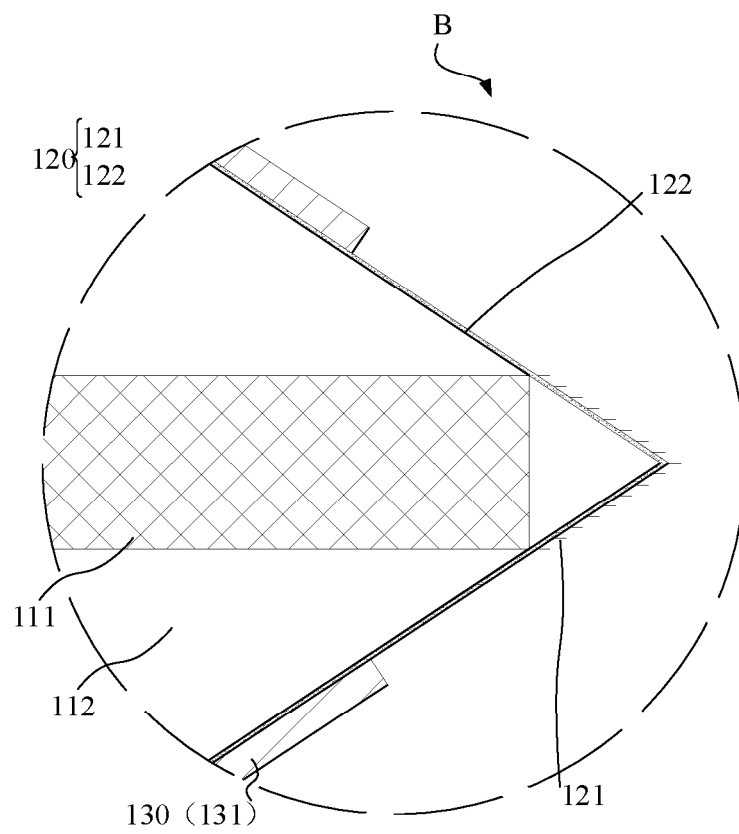


FIG. 40

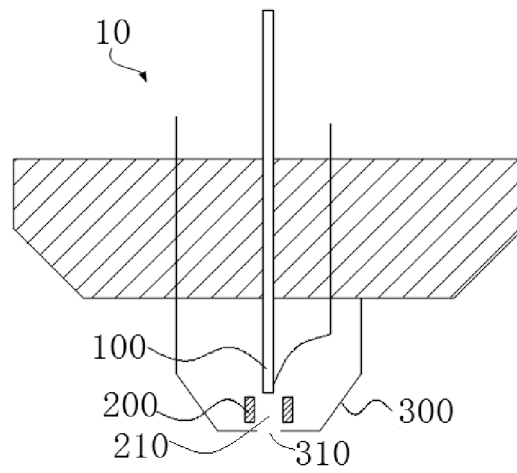


FIG. 41

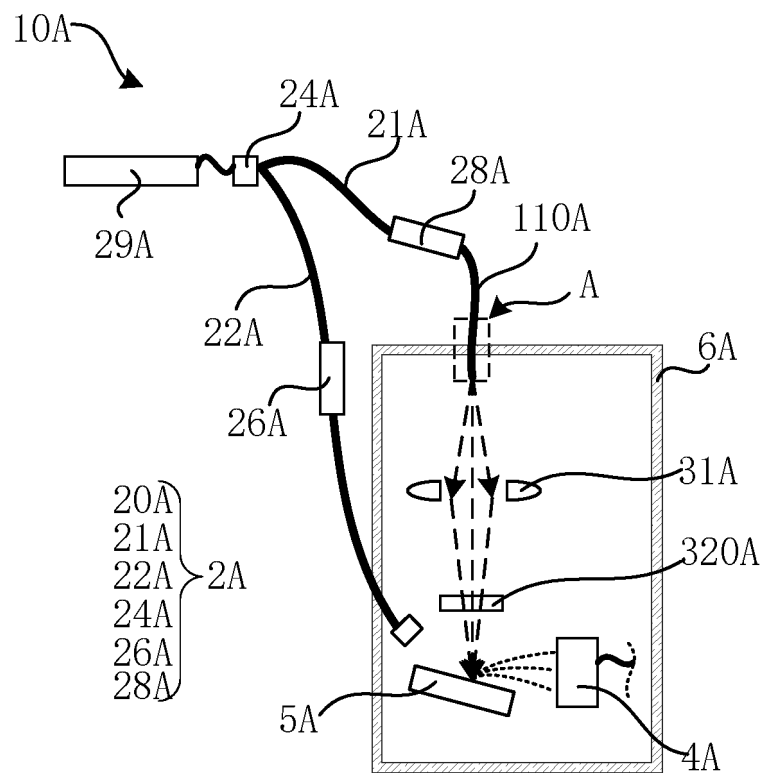


FIG. 42

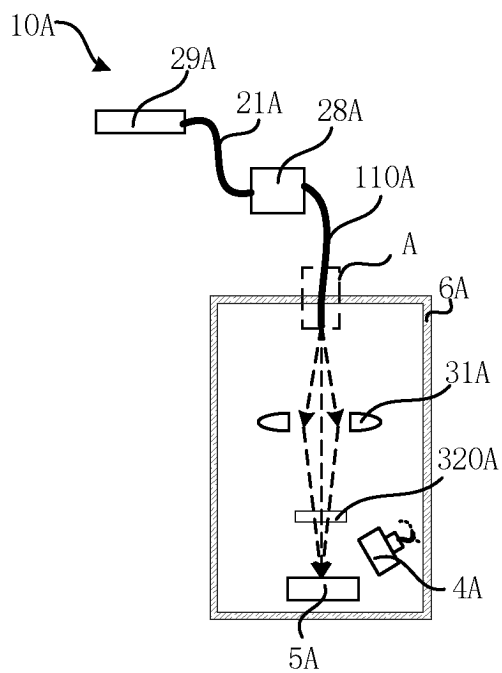


FIG. 43

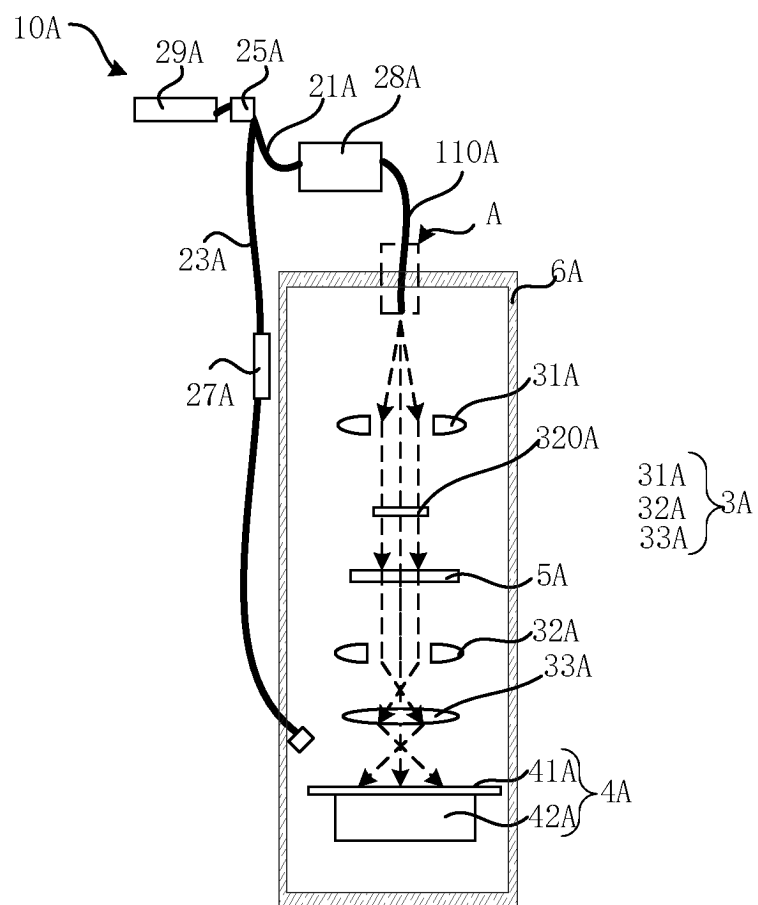


FIG. 44

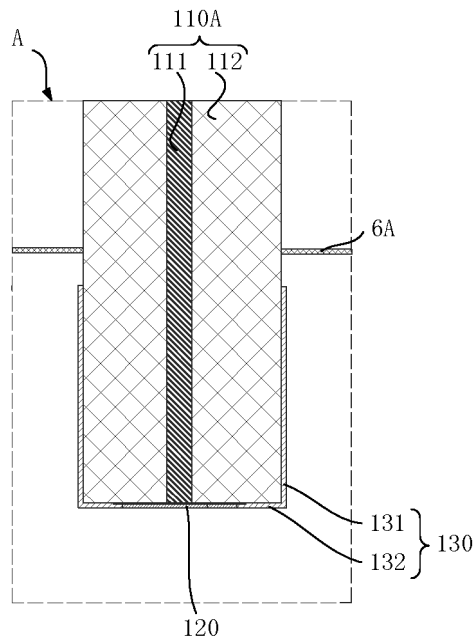


FIG. 45

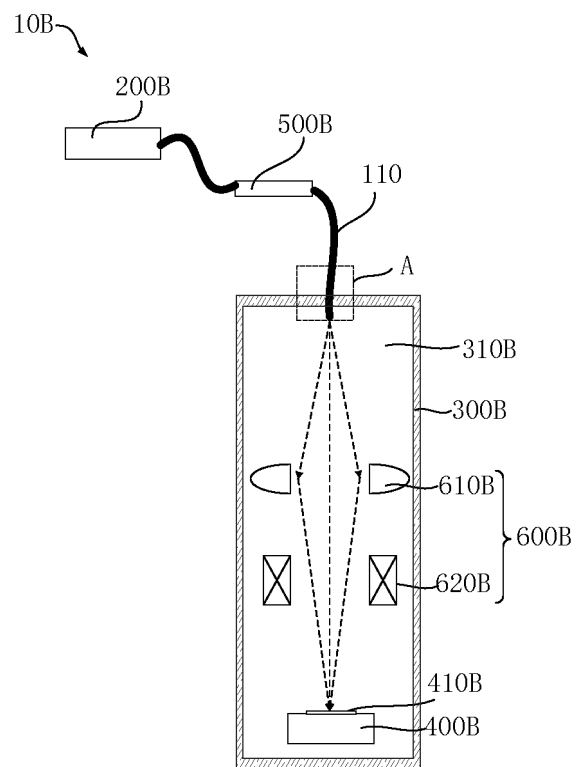


FIG. 46

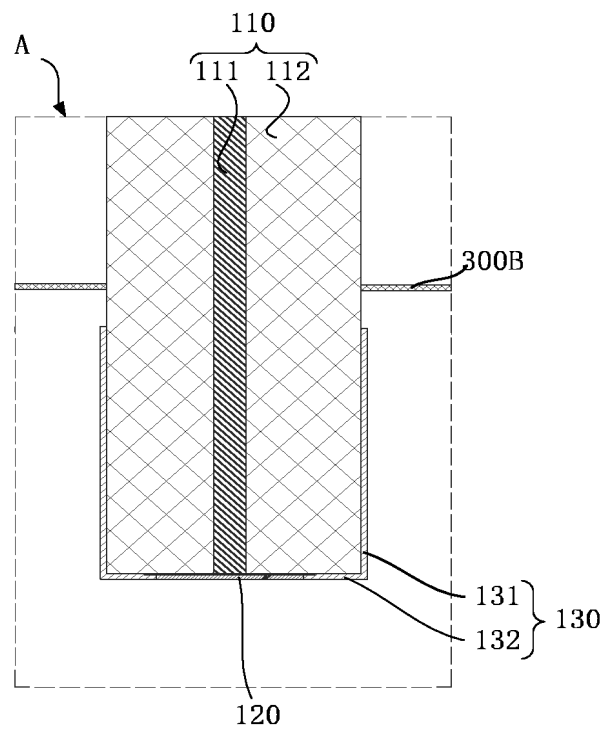


FIG. 47

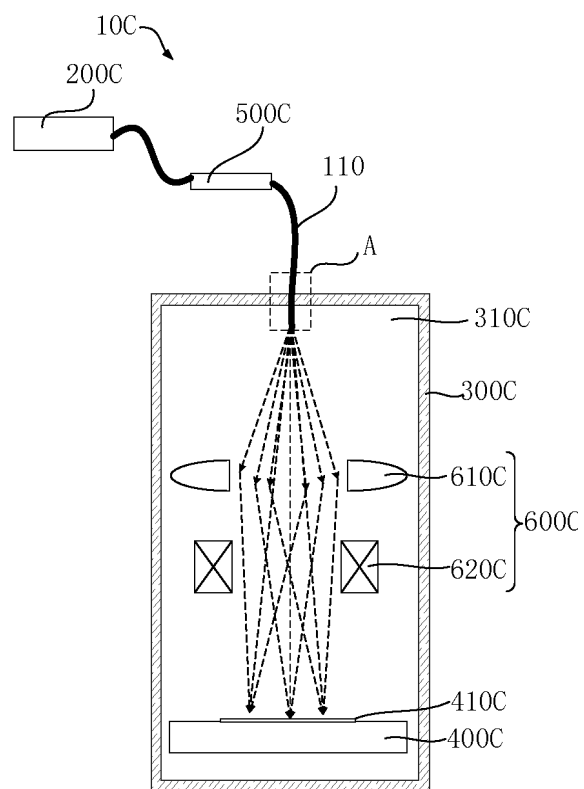


FIG. 48

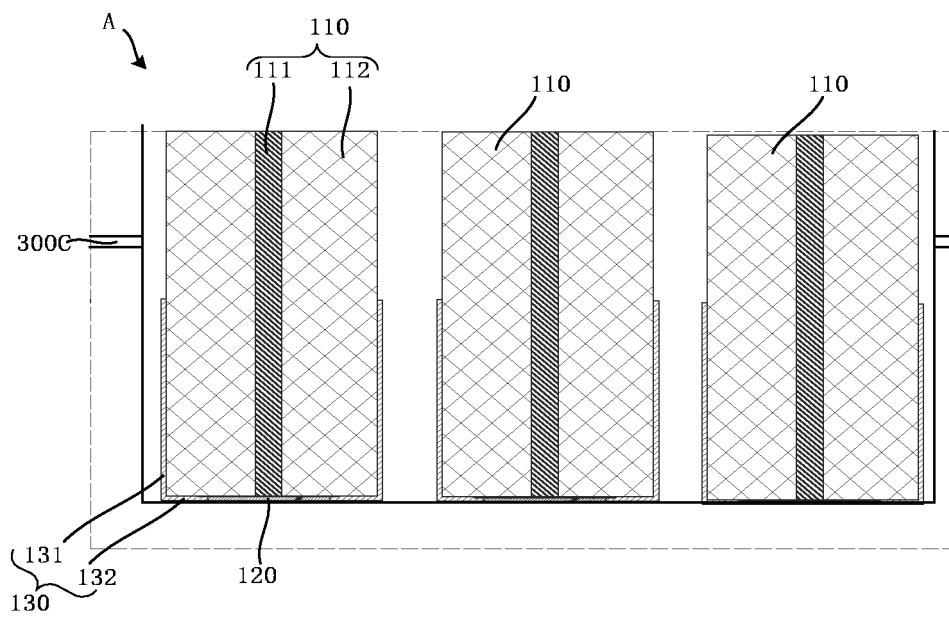


FIG. 49

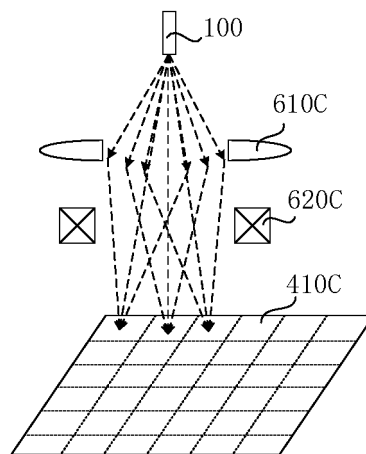


FIG. 50

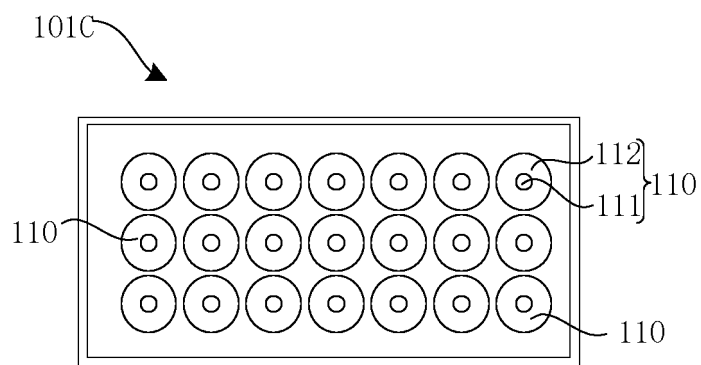


FIG. 51

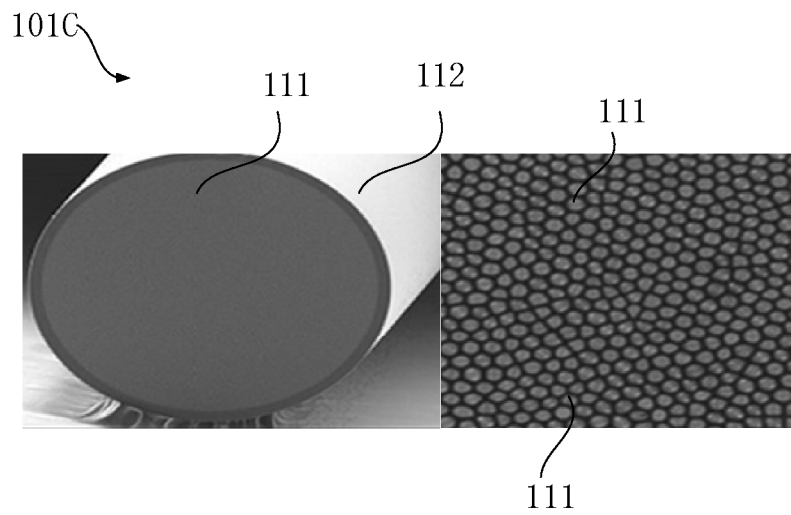


FIG. 52

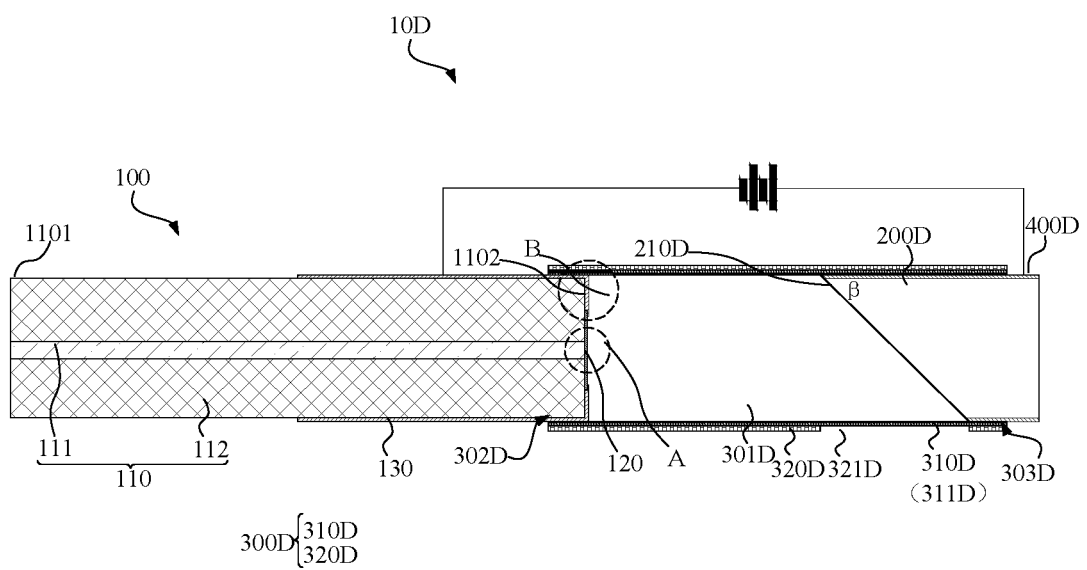


FIG. 53

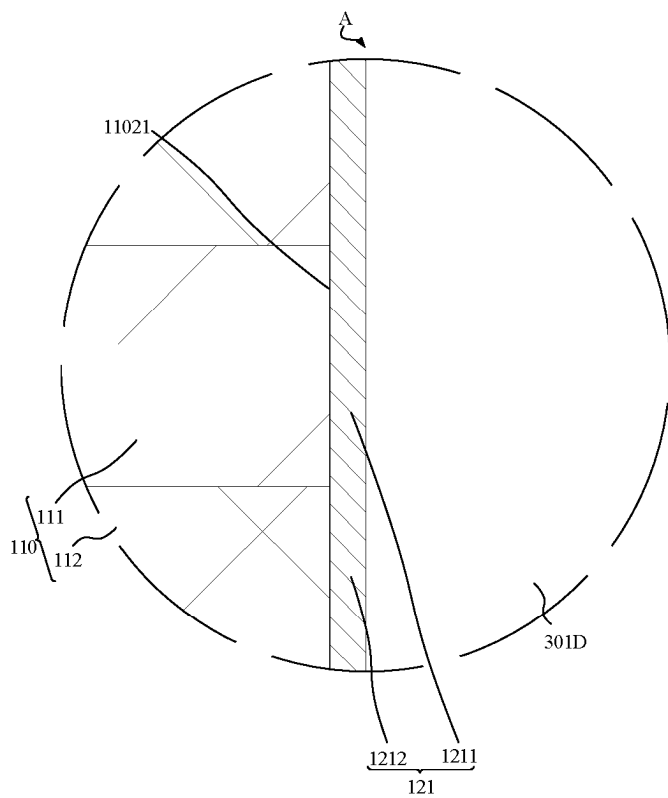


FIG. 54

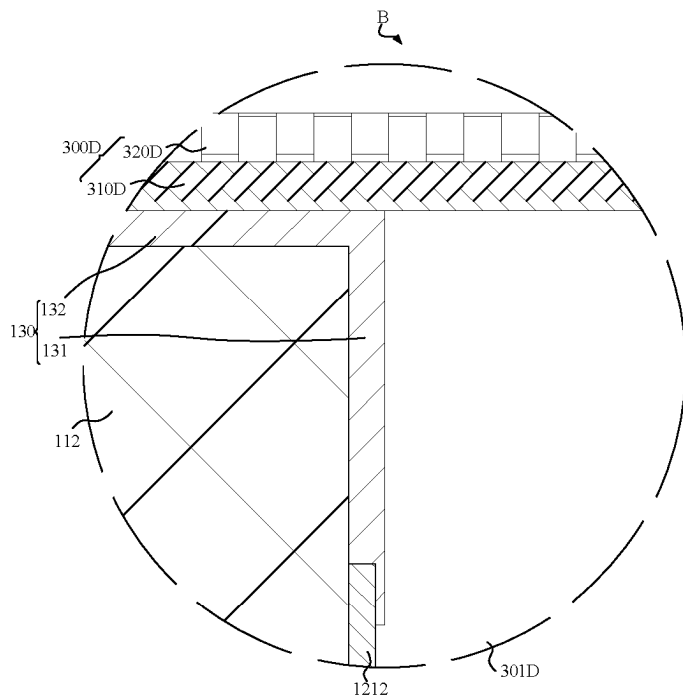


FIG. 55

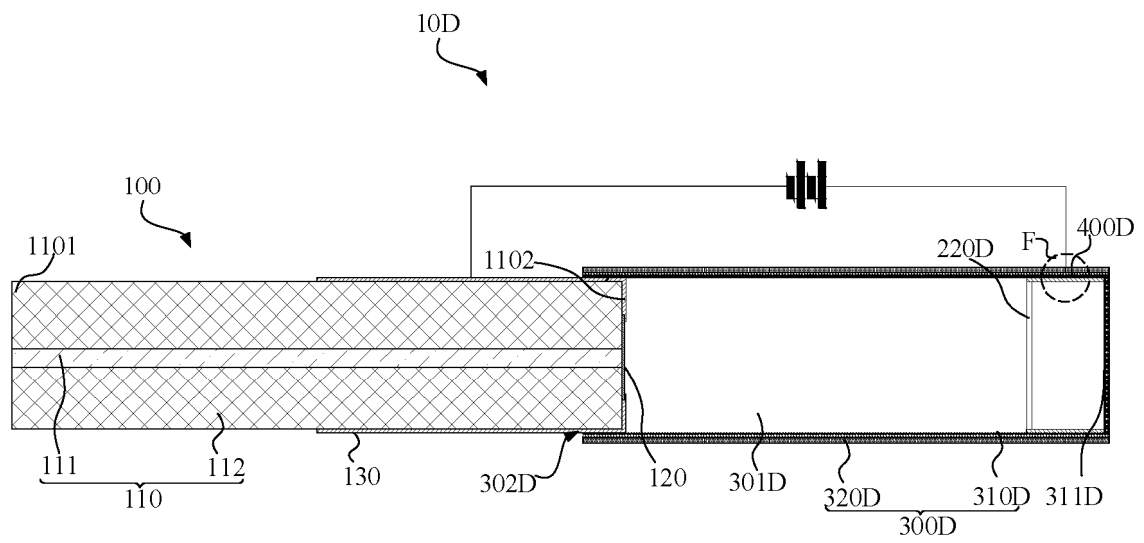


FIG. 56

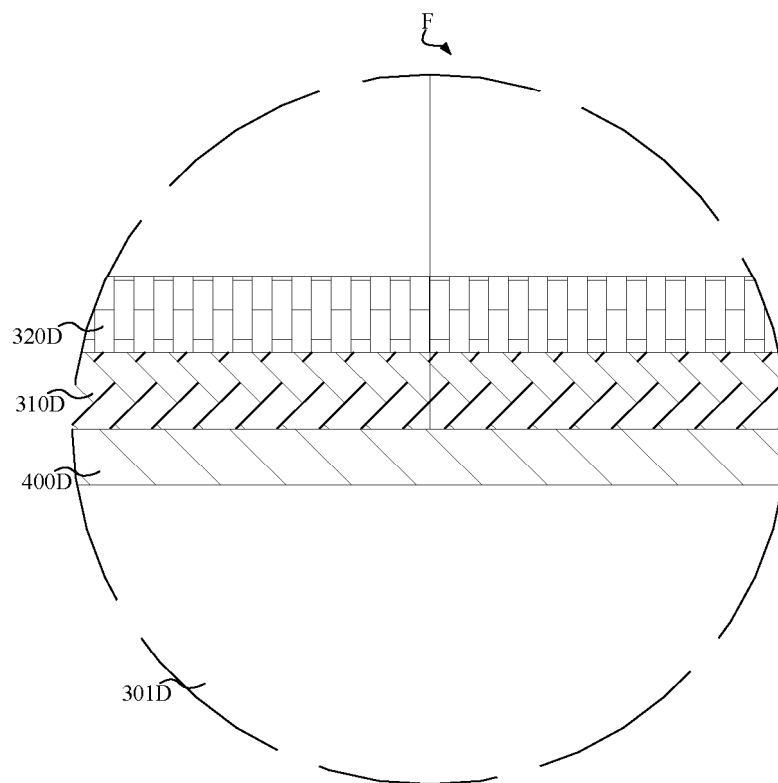


FIG. 57

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2024/142675

A. CLASSIFICATION OF SUBJECT MATTER

H01J1/304(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC:H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

VEN, CNABS, CNTXT, WOTXT, EPTXT, USTXT, CNKI, IEEE: 电子源, 光纤, 导电, 连接, 激光, 零维, 一维, 二维, 量子点, 富勒烯, 纳米线, 石墨烯, 端面, 漏光, 电子显微镜, 电子束, 曝光, electron, source, fiber, conductive, connect, laser, zero dimensional, one dimensional, two dimensional, quantum dot, fullerene, nanowire, graphene, end, light leakage, electron microscope, electron beam, exposure

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005213709 A1 (DINSMORE, M. T. et al.) 29 September 2005 (2005-09-29) description, paragraphs [0002]-[0049], and figures 1-3	1-2, 8-29, 31-32, 34-44, 46-47, 72-82
Y	US 2005213709 A1 (DINSMORE, M. T. et al.) 29 September 2005 (2005-09-29) description, paragraphs [0002]-[0049], and figures 1-3	3-7, 30, 33, 45, 48-71
Y	US 2006126788 A1 (CARL-ZEISS-STIFTUNG) 15 June 2006 (2006-06-15) description, paragraphs [0033]-[0057], and figures 1-4	3-7
Y	CN 106158553 A (UNIVERSITY OF SCIENCE AND TECHNOLOGY BEIJING) 23 November 2016 (2016-11-23) description, paragraphs [0005]-[0035]	30
Y	US 2003010905 A1 (LUO, Xin Simon) 16 January 2003 (2003-01-16) description, paragraphs [0003]-[0124], and figures 1-18	33
Y	JP 2005265434 A (TAMA TLO K.K.) 29 September 2005 (2005-09-29) description, paragraphs [0002]-[0046], and figures 1-3	45

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"D" document cited by the applicant in the international application	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E" earlier application or patent but published on or after the international filing date	"&" document member of the same patent family
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search 05 March 2025	Date of mailing of the international search report 13 March 2025
Name and mailing address of the ISA/CN China National Intellectual Property Administration (ISA/CN) China No. 6, Xitucheng Road, Jimenqiao, Haidian District, Beijing 100088	Authorized officer Telephone No.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2024/142675

C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	JP 2019200277 A (NUFLARE TECHNOLOGY, INC.) 21 November 2019 (2019-11-21) description, paragraphs [0002]-[0066], and figures 1-4	58-65
Y	JP 2009237490 A (FUJIFILM CO., LTD.) 15 October 2009 (2009-10-15) description, paragraphs [0002]-[0136], and figures 1-8	66-71
X	EP 0348611 A2 (INTERNATIONAL BUSINESS MACHINES CORP.) 03 January 1990 (1990-01-03) description, column 1, line 1 to column 7, line 42, and figures 1-6	1-2, 8-29, 31-32, 34-44, 46-47, 72-82
A	JP 2000173446 A (TOHOKU UNIVERSITY) 23 June 2000 (2000-06-23) entire document	1-82

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2024/142675

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				EP	0348611	A3	31 October 1990		
				EP	0348611	B1	20 July 1994		
				JPH	0298028	A	10 April 1990		
JP	2000173446	A	23 June 2000	None					

Form PCT/ISA/210 (patent family annex) (July 2022)

REFERENCES CITED IN THE DESCRIPTION

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