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(54) **Electron tube device**

(57) An electron tube device (100) comprises an electron emitter (10), which is adapted for a release of electrons, an electron collector (20), which is adapted for a collection of the electrons, wherein the electron collector (20) and the electron emitter (10) are spaced from each other by a gap (1), and a gate electrode (30), which is arranged between the electron emitter (10) and the electron collector (20), wherein the gate electrode (30) is adapted for subjecting the electrons in the gap (1) to

an electrical potential, wherein the gate electrode (30) comprises at least one membrane-shaped, electrically conductive or semiconductive electrode layer (31), which is at least partially transparent for the electrons, and the at least one electrode layer (31) has at least one of a plurality of through-holes and at least one electron absorption reducing dopant. Furthermore, methods of using the electron tube device (100) are disclosed.

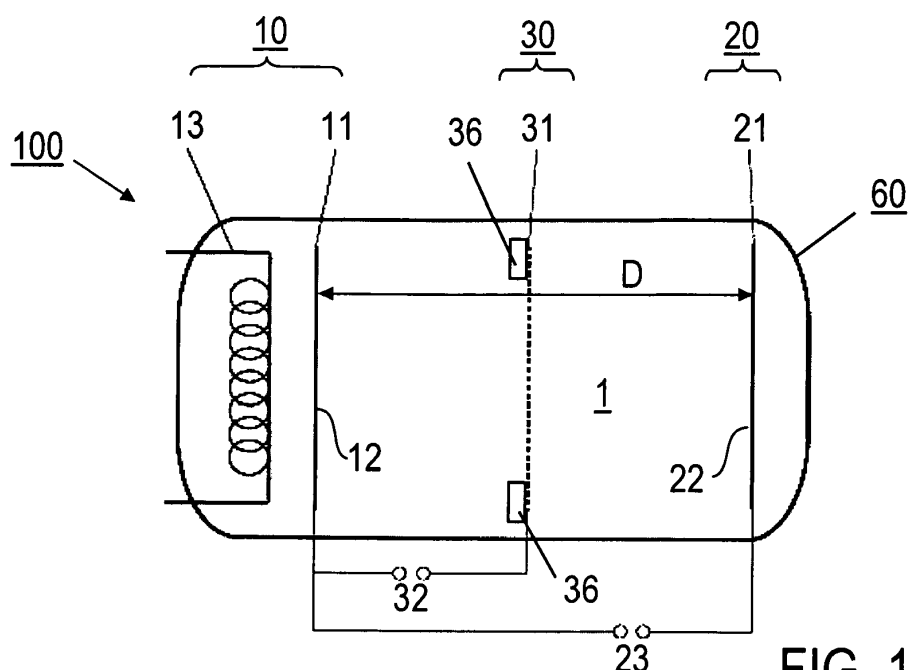


FIG. 1

Description

[0001] The present invention relates to an electron tube device comprising at least one electron emitter, at least one electron collector and at least one gate electrode. The electron tube device is adapted for controlling electric current between the at least one electron emitter and at least one of the at least one electron collector and the at least one gate electrode. Furthermore, the present invention relates to a method of controlling electric current, wherein the electron tube device is used. Applications of the invention are available in the fields of actively controlling electric currents, or operating display devices.

[0002] For illustrating background art relating to two-dimensional materials, like e.g. graphene, and electron tube devices, reference is made to the following prior art documents:

- [1] WO 2014/019594;
- [2] S. Meir, C. Stephanos, T. H. Geballe, J. Mannhart, Highly-efficient thermoelectronic conversion of solar energy and heat into electric power, *Journal of Renewable and Sustainable Energy* 5, 043127 (2013);
- [3] S. Meir, Highly-Efficient Thermoelectronic Conversion of Heat and Solar Radiation to Electric Power, Doctoral thesis (2012);
- [4] C. Stephanos, Thermoelectronic Power Generation from Solar Radiation and Heat, Doctoral thesis (2012);
- [5] J.-N. Longchamp, T. Latychevskaia, C. Escher, H.-W. Fink, Low-energy electron transmission imaging of clusters on free-standing graphene, *Applied Physics Letters* 101, 113117 (2012);
- [6] B. Guo, L. Fang, B. Zhang, J. R. Gong, Graphene Doping: A Review, *Insciences Journal* 1 (2), 80 (2011);
- [7] H. Liu, Y. Liu and D. Zhu, Chemical doping of graphene, *Journal of Materials Chemistry* 21, 3253 (2011);
- [8] C. Li, M. T. Cole, W. Lei, K. Qu, K. Ying, Y. Zhang, A. R. Robertson, J. H. Warner, S. Ding, X. Zhang, B. Wang, W. I. Milne, Highly Electron Transparent Graphene for Field Emission Triode Gates, *Advanced Functional Materials* 24, 1218 (2014);
- [9] C. Lee, X. Wei, J. Kysar, J. Hone, Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene, *Science* 321, 385 (2008);
- [10] A. Balandin, S. Ghosh, W. Bao, I. Calizo, D. Teweldebrhan, F. Miao, C. N. Lau, Superior Thermal Conductivity of Single-Layer Graphene, *Nano Letters* 8, 902 (2008); and
- [11] J. Schwede, I. Bargatin, D. C. Riley, B. E. Hardin, S. J. Rosenthal, Y. Sun, F. Schmitt, P. Pianetta, R. T. Howe, Z.-X. Shen, N. A. Melosh, Photon-enhanced thermionic emission for solar concentrator systems, *Nature Materials* 9, 762 (2010).

[0003] Electron tubes are active electronic compo-

nents, which are used for e. g. the generation, amplification, rectification, modulation and/or control of electric current. Typical applications are known in the fields of radar and radio technique, magnetrons, plasma generation, X-ray generation (X-ray tubes), cathode ray generation (cathode ray tube, e. g. in an oscilloscope) or vacuum fluorescence displays.

[0004] A conventional electron tube 100' comprises an electron emitter 10' (cathode), an electron collector 20' (anode) and a gate electrode 30' in a vessel 60', which is evacuated or filled with a working gas (see Figure 7, prior art). Electrons are created at the electron emitter 10' e. g. by thermoionic emission from a hot filament or a cathode 11' indirectly heated with a heater filament 13'. The gate electrode 30' is connected with a gate voltage source 32'. The electric current through the electron tube 100' can be controlled in dependency on the voltage V_g of the gate voltage source 23'. The voltage V_g generally is a negative voltage relative to the emitter electrode 10', or with special applications (so called "space charge grids") a positive voltage can be used. With a modified conventional electron tube 100', multiple gate electrodes 30' can be provided, which are connected with specific voltage sources.

[0005] Space charges, which are created at the electrodes and in the space between the electrodes, reduce the current between the electron emitter 10' and the electron collector 20', thus restricting the efficiency of the tube operation. For compensating the effect of the space charges, a positive voltage V_a can be applied to the electron collector 20'. The positive voltage V_a increases the current density. However, an undesired increase of dissipation loss is created simultaneously.

[0006] Alternatively, the effect of the space charges and dissipation losses could be reduced by a longitudinal magnetic field between the electron emitter 10' and the electron collector 20' in combination with a positive gate voltage V_g , as it is known from thermoelectronic generators [1-4]. With a small distance between the electrodes (e.g. $< 100 \mu\text{m}$), the effect of the space charges can be substantially reduced and increased current densities could be obtained even at a relatively low gate voltage (e. g. $< 20 \text{ V}$). However, creating the magnetic field with a sufficient field strength (typically 0.1 to 1 T) represents a disadvantage for most of the applications of electron tubes. In particular, single electronic tubes being adapted for creating the magnetic field would have a complex structure and increased size. Furthermore, with the use of the magnetic field device, the range of available materials of the remaining tube components is restricted as the remaining components should not include magnetic materials.

[0007] Typically, the gate electrode 30' is a grid electrode made of filaments forming a lattice, wherein the electrons pass the meshes of the lattice. As an alternative, C. Li et al. have proposed a field emission triode tube with a gate electrode made of graphene (see [8]). Graphene forms a continuous membrane-shaped layer,

which is semi-transparent for the electrons. The electrons pass the layer material as such. As a disadvantage, a relatively large portion of the electrons can be absorbed by the gate electrode, thus reducing the operation efficiency of the electron tube. As a further alternative, gate electrodes can be made of carbon nano-tubes (see [11-13]). However, nano-tube based gate electrodes have disadvantages in terms of an inhomogeneous density and electron transmission in longitudinal direction (perpendicular to the emitter and collector surfaces) and a complex manufacturing process.

[0008] The objective of the present invention is to provide an improved electron tube device, which is capable of avoiding disadvantages and limitations of conventional electron tubes. It is a particular objective of the invention to provide the electron tube device having reduced dissipation losses, increased current density, reduced weight and size, reduced costs, improved operation efficiency, and/or improved variability in terms of materials for manufacturing the electron tube. It is a further objective of the invention to provide an improved method of controlling an electric current using an electron tube.

[0009] The above objectives are solved with an electron tube device and a method of using thereof, comprising the features of the independent claims, respectively. Preferred embodiments and applications of the invention are defined in the dependent claims.

[0010] According to a first general aspect of the invention, an electron tube device is provided, which comprises an electron emitter (cathode), an electron collector (anode) and a gate electrode. The electron tube device is a vacuum tube (valve) for the generation, amplification, rectification, modulation and/or control of electric current. The electron emitter and the electron collector are arranged with a mutual gap (spacing), wherein emitter and collector surfaces point to the gap, resp.. The electron collector preferably is made of a material having a work function, which is larger compared with the work function of the electron emitter material. The electron emitter is adapted for a release of electrons by direct heating (thermoionic emission) or indirect heating and the effect of an accelerating voltage applied to the electron tube. The electron collector is adapted for a collection of the electrons. The gate electrode is arranged between the electron emitter and the electron collector for subjecting the electrons emitted from the electron emitter to an electrical potential, e. g. a negative potential, an electron accelerating electrical potential, an alternating potential and/or a switched potential sequence.

[0011] The gate electrode comprises at least one membrane-shaped, electrically conductive or semiconductive electrode layer, which is at least partially transparent for the electrons (semi-transparent electrode layer). The at least one membrane-shaped, partially or completely transparent electrode layer (or: electrode layer) is capable of creating the electric field, while the electrons can pass the gate electrode material. A free-standing thin membrane of a material with electron transmission (or

low electron absorption) can be passed by the electrons with only small or negligible energy loss, so that it can be used as a homogeneous, negatively or positively charged gate electrodes. The material and/or thickness of the at least one electrode layer are selected such that electrons traveling towards the collector electrode are transmitted through the layer material, i.e. the electrons pass through a continuous section of the material layer. The electrons pass through the layer material as such.

[0012] The at least one electrode layer is partially transparent, i.e. it has at least 20 %, preferably at least 25 %, particularly preferred at least 50 % electron transmission probability. Preferably, the at least one membrane-shaped, partially transparent electrode layer consists of a two-dimensional material (graphene-like material). Particularly preferred, the two-dimensional material is at least one atomic monolayer.

[0013] According to the invention, the at least one electrode layer of the gate electrode has a plurality (at least two) through-holes and/or includes at least one dopant. The through-holes are openings in the at least one electrode layer. The electrode layer is formed as a grid, e. g. a regular or irregular grid. Preferably, the regular grid is a hexagonal grid. The through-holes may have a circular or non-circular, e. g. elliptic, rectangular or triangular shape. The dopant is a substance included in the material of the at least one electrode layer, wherein the dopant has an electron absorption reducing effect, in particular by changing the Fermi energy of the layer material and/or a reduction of energy losses by adjusting a plasmon frequency in the layer material.

[0014] The inventors have found that conductive or semiconductive, two-dimensional materials, like graphene or graphene-like materials, have further advantages as they allow a reduction of electron absorption by changing the Fermi energy of the layer material and/or a reduction of energy losses by adjusting a plasmon frequency in the layer material by adding the at least one dopant (at least one doping substance) to the layer material. Advantageously, the doping allows a shifting of the Fermi energy (see e.g. [6, 7]), so that the absorption of electrons can be reduced, in particular in predetermined electron energy intervals. In case a two-dimensional material is used that conducts electricity only poorly, this conduction can be enhanced by doping the two-dimensional material or by adding one or more ultrathin conducting layers onto the two-dimensional material. Furthermore, when the electrons pass graphene or similar materials, they can excite plasmons, thus losing energy. The plasmon frequency, e.g. in graphene, can be changed by doping, so that energy losses of the electrons are reduced.

[0015] Advantageously, an increased electron transmission probability can be obtained compared e. g. with the graphene gate of [8] as the electron absorption is further reduced by the through-holes and/or doping, while the mechanical stability of the at least one electrode layer is kept. The electrons pass through the layer material of the at least one electrode layer or through the holes.

[0016] Furthermore, with the gate electrode used according to the invention, the efficiency of the current control with the electron tube can be improved. The invention proposes new electron tubes with reduced volume, weight and material requirements. Moving or vibrating mechanical parts are avoided, so that the inventive electron tube device is capable of a noise-free and vibration-free operation. As the electron tube device does not require external magnetic fields, the creation of magnetic stray fields is avoided.

[0017] According to a second general aspect of the invention, a method of using the electron tube device of the above first aspect of the invention is provided, wherein the electron tube device preferably is at least one of an active electronic component for current rectification, an active electronic component for current modulation and/or control, a vacuum fluorescence display, an active electronic component for ignition voltage reduction in fluorescent tubes, and an ion source.

[0018] Preferably, at least one of the following measures is provided, which have particular advantages for reducing the electron absorption in the gate electrode. Firstly, the at least one electrode layer may include at least 10 through-holes, preferably at least 100 through-holes, e. g. 1000 through-holes or more distributed over the area of the at least one electrode layer facing to the electron emitter. Furthermore, the total area of the through-holes may be at least 10 %, preferably at least 20 %, particularly preferred at least 40 %, e. g. 60 % or more, of an exposed surface of the gate electrode facing to the electron emitter.

[0019] The inventors have found that the number of electrons reaching the electron collector continuously increases as a function of decreasing hole diameter with constant gate electrode transparency (area of through-holes / area of the gate electrode) if the diameter of the holes is small compared with the distance between the electron emitter and the electron collector. With reducing the hole diameter, the homogeneity of the electric field is improved as transversal field components are reduced. Accordingly, a transversal deflection of electrons is reduced, thus decreasing the electron absorption at the gate electrode and increasing the electron current to the electron collector. Thus, according to particularly preferred features of the invention, the cross-sectional dimension, like the hole diameter, of the through-holes can be selected to be smaller than 500 μm , in particular smaller than 200 μm . Furthermore, in particular with an emitter collector distance of e.g. 10 μm , a hole diameter below 10 μm , in particular below 5 μm , e. g. 1 μm , can be preferred. The inventors have found that e. g. a structured graphene grid with a hole diameter of 1 μm and a lateral width of the layer sections between the holes of 5 nm has an electron absorption below 1 %. In particular this low electron absorption allows to omit a magnetic field, thus clearly showing the advantage compared with the conventional techniques.

[0020] Advantageously, the through-holes can be cre-

ated e.g. with electron beam lithography or optical lithography, combined with ion etching or chemical etching. An irregular grid of through-holes can be made e. g. by ion irradiation.

[0021] Contrary to the nano-tube based gate electrodes, the inventive gate electrode has an improved homogeneity and planarity. Graphene and similar materials can be structured easily, e.g. by electron beam lithography. Furthermore, the inventive gate electrodes allow the provision of three electrodes electron tubes, in particular with minimized size and weight, having an emitter-collector-distance below 10 μm , in particular below 5 μm . This distance cannot be obtained with conventional, grid-based gate electrodes, as the electric field in the lattice meshes would be very small, if the emitter-gate-distance would be substantially larger than the mesh diameter.

[0022] As further advantages of the invention, current densities of some A/cm^2 can be obtained by suppressing space charge effects. Contrary to semiconductor transistors, electron transport in electron tubes is a ballistic transport, and the heat transport is essentially reduced. Furthermore, a positive gate voltage in combination with low losses at the gate electrode offers the possibility to use field emission at the emitter, wherein a field strength of about $10^6 \text{ V}/\text{m}$ is used for Schottky field emission, or a field strength above $10^9 \text{ V}/\text{m}$ is used for Fowler-Nordheim emission. With an emitter-gate distance of about 100 μm , a gate voltage below 100 V, in particular below 10 V could be used for field emission. Due to the low gate voltage and the use of the inventive gate electrode, the gate dissipation loss can be drastically reduced compared with conventional field emission triodes. The gate voltage necessary for Schottky or Fowler-Nordheim field emission can be reduced by using an emitter provided with nanotubes, exploiting the strong electric field at the tips of the nanotubes.

[0023] The electron emitter and collector electrodes can be provided as filaments, plates or membranes spaced from each other, in particular having a linear or planar shape. The gate electrode may be provided, e. g. manufactured or deposited, on the emitter or on the collector electrode, provided it is electrically insulated from the emitter or collector electrode. The membrane structure of the electrodes allows the construction of the electron tube device with a compact structure. As the emitter and collector electrodes also may comprise thin films, foils, or membranes, the weight and/or the material demand of the electron tube can be further reduced. In particular, the emitter and collector electrodes may comprise two-dimensional, mono- or multilayer materials, in particular graphene-like materials, like the gate electrode.

[0024] According to a preferred embodiment of the invention, the at least one electrode layer of the gate electrode includes at least one of graphene, silicene, phosphorene, stanene, germanene, MoS_2 , C_3N_4 and boron nitride. Advantageously, graphene and the further preferred examples have a high electron transmission probability and heat conductivity (see e.g. [10]). As an exam-

ple, graphene has a transmission probability of 27 % for 66 eV electrons (see [5]).

[0025] According to a particularly preferred embodiment of the invention, the dopant of the at least one electrode layer comprises at least one of B, N, Bi, Sb, Au, NO₂, ammonia and polyethyleneimine. Preferred doping concentrations are e.g. 10¹⁰ to 10¹⁴ cm⁻².

[0026] With a further preferred feature of the invention, the at least one electrode layer of the gate electrode is made of a material, which is insensitive to ionizing radiation. Advantageously, this feature increases a long-term stability of the electron tube device operation, in particular under the effect of ionizing radiation. This advantage is important in particular for applications of the invention in space crafts. As a further advantage, two-dimensional membranes of the above materials are stable under the effect of ionizing radiation. This stability can even be improved if the at least one electrode layer is made of an isotope selected for a higher insensitivity compared with other isotopes. With a preferred example, the at least one electrode layer can consist of graphene, which is completely made of C¹² isotopes. According to a further preferred embodiment of the invention, the at least one electrode layer of the gate electrode is connected with a frame. The frame is arranged between the electron emitter and the electron collector. Preferably, the at least one electrode layer is spanned on the frame, so that a stable mechanical support of the at least one electrode layer is provided. The frame is electrically isolated with respect to the electron emitter and/or the electron collector, e.g. with ceramic spacers. With preferred examples, the spacers comprise aluminium oxide (sapphire, Al₂O₃) or yttrium-stabilized zirconoxide (ZrO₂).

[0027] According to a further advantageous modification of the invention, the gate electrode further comprises a supporting layer, which is connected with the at least one electrode layer. The supporting layer carries the at least one electrode layer. Advantageously, this increases the mechanical stability of the gate electrode and the positioning of the gate electrode with a distance relative to both of the electron collector and the electron emitter. Preferably, the supporting layer has a thickness in a range of 5 μm to 100 μm. With a particularly preferred example, the supporting layer is made of silicon, which has advantages in terms of mechanical stability and heat conductivity. Alternatively, the supporting layer is made of germanium or tungsten. The supporting layer is a grid with supporting layer through-holes having diameters in a range of e. g. 1 μm to 100 μm.

[0028] According to a further advantageous embodiment of the invention, the gate electrode may comprise multiple membrane-shaped electrically conductive or semiconductive electrode layers spaced from each other. The gate electrode may include a stack of two-dimensional materials, preferably monolayers, each providing an electrode layer. The material thickness and through-holes of the electrode layers are selected such that the gate electrode has an electron transparency of at least

20 %, preferably at least 25 %, particularly preferred 50 % or more. Advantageously, multiple electrode layers can be manufactured by a growing process, wherein the electrode layers are deposited with sacrificial layers there between, which are removed subsequently. This allows the adjustment of distances of the electrode layers below 0.1 μm, in particular below 10 μm. Preferred examples of materials, which can be used for creating the sacrificial layers comprise Cu, Fe, Al, or oxides, like CaMnO₃, SrMnO₃, La₂CuO₄ or YBa₂C₃O₇, which can be etched with weak acids, or even frozen water, which can be removed after deposition of the electrode layers.

[0029] The application of the invention is not restricted to the three electrode embodiment with one electrode emitter, one gate electrode, having one or more electrode layers and being connected with one gate voltage source, and one electrode collector. It is alternatively possible to provide more electrodes, in particular to provide more gate electrodes, each being connected with a specific gate voltage source and including one or more electrode layers. The electrode layer of the second and each further gate electrode may comprise a continuous layer or a layer having through-holes as described above. The provision of multiple gate electrodes may provide advantages in terms of enhancing the possible spacing between the emitter and collector and reducing heat losses.

[0030] As a further advantage of the invention, the structure of the electron tube device can be adapted to the particular application thereof. Preferably, the electrodes of the electron tube device are arranged within an evacuated container. Alternatively, the electrodes can be arranged in a container, which includes a working gas. The working gas, like e.g. Cs vapor, Cs-O vapor or ionized Cs-vapor, is capable of reducing space charges in the gap between the electron emitter and the electron collector and/or influencing a work function of the electron emitter, the electron collector and/or the gate electrode. Further examples of working gases are gases based on other alkali metals, like Rb or K, or Ba, optionally mixed with oxygen.

[0031] Further details and advantages of the invention are described in the following with reference to the attached drawings, which show in:

Figure 1: a schematic cross-sectional illustration of an inventive electron tube device having one single gate electrode;

Figure 2: a more detailed illustration of the electron tube device according to Figure 1;

Figure 3: a schematic cross-sectional illustration of an inventive electron tube device having two gate electrodes;

Figure 4: a more detailed illustration of the electron tube device according to Figure 3;

Figure 5: a schematic illustration of a frame carrying a gate electrode;

Figure 6: a microscopy image of a supporting layer carrying a gate electrode; and

Figure 7: a schematic cross-sectional illustration of a conventional electron tube device (prior art).

[0032] Features of preferred embodiments of the invention are described in the following with particular reference to the design of the gate electrode of an electron tube device. Exemplary reference is made to graphene-based gate electrodes. The graphene membrane can be made on and/or optionally transferred to a frame and/or a supporting layer by chemical vapor deposition or any other procedure as conventionally known. The invention is not restricted to the use of graphene. It is emphasized that other two-dimensional materials, e.g. as mentioned above, can be used as alternatives.

[0033] Furthermore, exemplary reference is made to an electron tube device having one single electron emitter, one single electron collector and one or two gate electrodes. Alternatively, the electron tube device can have multiple gate electrodes and/or multiple pairs of electron emitters and collectors, each with a gap accommodating one or more gate electrode(s). Features of electron tube devices, like the function principle thereof, the particular application, the design of the electron emitter and electron collector, or the control of electric currents are not described as far as they are known from conventional techniques. In particular, the electron tube can include further components as it is known from conventional electron tubes. It is emphasized that the drawings are schematic illustrations only, which do not represent scaled versions of practical devices. With practical implementations of the invention, the skilled person will be able to select geometrical dimensions, structural properties, materials and the electric circuitry in dependency on the particular application requirements.

[0034] According to Figures 1 and 2, the electron tube device 100 for the vacuum tube application of the invention comprises an electron emitter 10, an electron collector 20 and a gate electrode 30. The electron emitter 10 comprises a straight electrode filament (or planar plate) 11, which is made of e. g. of a metal refractory metal, e. g. tungsten, in particular coated, doped or impregnated with a work-function-reducing material, e.g. Ba, BaO, La or LaO, and electrically connected with ground potential (earth potential). In practice, the electrode filament 11 may be supported by mechanical components, like a carrier 14 (see Figure 2). Furthermore, an electrode heater filament 13 is provided for indirect heating the electrode filament 11. According to alternatives (not shown), the electron emitter 10 could be directly heated and/or provided with nanotubes pointing towards the gap 1. The electron collector 20 comprises a straight electrode filament (or planar plate) 21 as well, which is made of e. g.

a metal or a refractory metal, e.g. tungsten, steel, copper, gold, silver, which can be coated or doped to enhance its properties like heat radiation absorption/reflection or work function, wherein an exposed surface 22 of the electron collector 20 is arranged with a distance D from an exposed surface 12 of the electron emitter 10. The distance D (width of gap 1) is e. g. 100 μm . The area of each of the exposed surfaces 12, 22 is selected in dependency on the particular application and operation parameters of the electron tube device. It is pointed out that the emitter and collector electrodes may be realized as thin films, foils, or membranes to reduce the weight and/or the material demand of the electron tube device 100.

[0035] The electron emitter 10, electron collector 20 and gate electrode 30 are accommodated in a vessel 60, which is evacuated or filled with a working gas. The vessel 60 is made of e. g. glass or plastic material, including feedthrough sections for supply lines connected with the electrode components. The shape and size of the vessel 60 are adapted to the shape and size of the electrodes.

[0036] The gate electrode 30 comprises at least one membrane-shaped electrode layer 31, having a planar, preferably two-dimensional shape and extending in the gap 1 parallel to the parallel planar exposed surfaces 12, 22 of the electron emitter 10 and the electron collector 20, respectively. A distance between the electron emitter 10 and the gate electrode 30 is e. g. 10 μm . The electrode layer 31 is e. g. a graphene mono- or multilayer having through-holes with a diameter of 400 μm covering e. g. 50 % or 70 % of the area of the electrode layer 31 facing to the electron emitter 10. It is supported by a frame 33 as shown in Figures 2 and 5. The application of the invention is not restricted to the use of graphene as the electrode layer material, but rather possible with the other material examples as cited above or even with further semi-transparent two-dimensional materials having electric conductivity or semi-conductivity.

[0037] Figure 1 schematically illustrates a gate heater unit 36, which is arranged for heating the gate electrode 30. The gate heater unit 36 is provided in direct contact with the electrode layer 31, and it contains e. g. a resistor heating for annealing (tempering) the electrode layer 31. Advantageously, this allows a removal of contaminations from the electrode layer 31. The gate heater unit 36 is a switchable component, so that the annealing can be conducted on request or in dependency on predetermined operation conditions of the electron tube device 100.

[0038] Figure 2 further shows a support structure 50, including a base plate 51 and electron collector spacers 53. The base plate 51 is made e.g. of Al_2O_3 with a through-hole 54. The electron emitter 10 is arranged for emitting electrons through the through-hole 54 to the electrode layer 31. The electron collector spacers 53 have a thickness defining the distance between the graphene electrode layer 31 and the electron collector 20. The electron collector spacers 53 are made of e. g. Al_2O_3 . The graphene electrode layer 31 is supported by the frame 33, which is arranged on an inner side of the

base plate 51 facing towards the electron collector 20. The frame 33 carries the electron collector spacers 53, and it is made of a metal, e. g. tungsten, or another conducting or semiconducting material, like silicon or boron nitride. Alternatively, the electron collector spacers 53 could be directly supported by the base plate 51, so that the distance between the graphene electrode layer 31 and the electron collector 20 would not be limited by the thickness of the electron collector spacers 53.

[0039] The graphene electrode layer 31 is arranged on the frame 33 in particular by one of the following procedures. Firstly, the graphene electrode layer 31 can be manufactured separately with a conventional method and subsequently transferred and fixed to the frame 33. Alternatively, the graphene electrode layer 31 can be grown on an auxiliary layer, which is connected with the frame 33 and subsequently removed. Furthermore, the graphene electrode layer 31 can be grown on a supporting layer 34 (see Figure 4).

[0040] With a preferred example, the electrode layer 31 could be electrically connected as follows. Firstly, the electrode layer 31, e.g. a graphene layer, is connected with an upper surface of the frame 33, wherein the upper surface of the frame 33 is not completely covered by the electrode layer 31. An outer section of the upper surface remains exposed. Subsequently, a thin metallic layer, e.g. a Pt layer, is deposited on the frame 33. The deposition is obtained using e.g. a sputtering or other thin film deposition process. The metallic layer creates the electric contact with the electrode layer 31, and the electrode layer 31 is fixed on the frame 33 by the metallic layer. Finally, the metallic layer is connected with a gate voltage source 32.

[0041] The electron tube device 100 is configured for a connection with voltage sources, including the gate voltage source 32 and a collector voltage source 23. The gate voltage source 32 provides a gate voltage V_g to be applied to the gate electrode 30. The collector voltage source 23 provides a collector voltage V_a to be applied to the electron collector 30. The voltages V_g , V_a are positive or negative or alternating voltages selected in dependency on the application of the electron tube device 100.

[0042] In an example of controlling an electric current, the electron emitter 10 is heated with the electrode heater filament 13. Electrons are released from the exposed surface 12 of the electron emitter 10. The electrons are accelerated e. g. by an accelerating electric potential created with the collector voltage source 23. Most of the electrons are transmitted through the electrode layer 31 of the gate electrode 30 to the electron collector 20. By the gate voltage V_g of the gate voltage source 32, the current to the electron collector 20 can be modulated. After passing the gate electrode 30, the energy of the electrons could be too low for reaching the collector electrode 20. This effect can be avoided by reducing the electric potential at the collector electrode 20, so that the electrons require less energy to reach the collector.

[0043] Figures 3 and 4 illustrate a modified embodiment of the electron tube device 100 which has two gate electrodes 30, 30A, each of which being designed like the gate electrode 30 of Figures 1 and 2. The electron emitter 10, the electron collector 20 and the vessel 60 are provided as described with reference to Figures 1 and 2. The gate electrodes 30, 30A are supported on frames 33, 33A, so that the electrode layers 31, 31A have a mutual distance of e. g. 10 μm in the gap 1 between the electron emitter 10 and the electron collector 20. Both frames 33, 33A are electrically isolated relative to each other, e.g. by an isolating layer 35 or by ceramic spacers. The voltage sources include two gate voltage sources 32, 32A creating a potential at the gate electrodes 30, 30A relative to the electron emitter 10 and the electron collector 20, resp..

[0044] According to Figure 4, the support structure 50 includes a base plate 51 and a cover plate 52. Both plates 51, 52 are made e.g. of Al_2O_3 with through-holes 54, 55, resp.. The electron emitter 10 and the electron collector 20 are arranged in the through-holes 54, 55, resp.. The graphene electrode layers 31, 31A of the gate electrodes 30, 30A are supported by the frames 33, 33A, which are arranged on inner sides of the base and cover plates 51, 52.

[0045] Figure 5 schematically shows a top view of the frame 33 having an outer shape, e.g. rectangular shape, which is adapted to the geometry of the support structure 50, and a through-hole with a shape, e.g. circular shape, which is adapted to the shape of the electron emitter 10. The frame 33 has a double function in terms of positioning the electrode layer 31 relative to the electron emitter 10 (see Figures 2, 4) and providing an electrical contact with the electrode layer 31. Accordingly, the frame 33 is made of or at least covered with a conductive, e.g. metallic, or semi-conductive material, which is electrically coupled with the gate voltage source (see Figure 1).

[0046] For increasing the mechanical stability, the electrode layer 31 can be grown on a supporting layer 34. An example of a supporting layer is shown with an REM image in Figure 6. The supporting layer 34 is made of, e.g., Si with a hexagonal structure having a mesh diameter of some 10 μm , e. g. by anisotropic etching. It is noted that the provision of the supporting layer 34 is not strictly necessary. Due to the tear strength of two-dimensional materials, e.g. graphene, the electrode layer 31 can be created with an area of some cm^2 without an additional supporting layer. Those skilled in the art will appreciate that also stacks of several supporting layers with different hole diameters may be used advantageously.

[0047] The features of the invention in the above description, the drawings and the claims can be of significance both individually as well in combination or sub-combination for the realization of the invention in its various embodiments.

Claims**1.** Electron tube device (100), comprising:

- an electron emitter (10), which is adapted for a release of electrons,
- an electron collector (20), which is adapted for a collection of the electrons, wherein the electron collector (20) and the electron emitter (10) are spaced from each other by a gap (1), and
- a gate electrode (30), which is arranged between the electron emitter (10) and the electron collector (20), wherein the gate electrode (30) is adapted for subjecting the electrons in the gap (1) to an electrical potential, wherein
- the gate electrode (30) comprises at least one membrane-shaped, electrically conductive or semiconductive electrode layer (31), which is at least partially transparent for the electrons,

characterized in that

- the at least one electrode layer (31) has at least one of a plurality of through-holes and at least one electron absorption reducing dopant.

2. Electron tube device according to claim 1, having at least one of the features

- the at least one electrode layer (31) includes monolayer or multilayer graphene, silicene, phosphorene, stanene, germanene, MoS₂, C₃N₄ or boron nitride, and
- the at least one dopant comprises at least one of B, N, Bi, Sb, Au, NO₂, ammonia and polyethyleneimine.

3. Electron tube device according to one of the foregoing claims, having at least one of the features

- the at least one electrode layer (31) includes at least 10 through-holes, and
- the total area of the through-holes is at least 10 % of a surface of the gate electrode (30) facing to the electron emitter (10).

4. Electron tube device according to one of the foregoing claims, wherein the through-holes have at least one of the features:

- the cross-sectional dimension of the through-holes is smaller than 500 μm , in particular smaller than 200 μm , and
- the through-holes are created by electron beam lithography or by optical lithography, combined with ion etching, reactive etching or chemical etching, and/or by ion irradiation.

5. Electron tube device according to one of the foregoing claims, having at least one of the features

- the at least one electrode layer (31) is made of a material which is insensitive to ionizing radiation, and
- the at least one electrode layer (31) is an atomic monolayer.

6. Electron tube device according to one of the foregoing claims, wherein

- the at least one electrode layer (31) is spanned on a frame (33), which is arranged between the electron emitter (10) and the electron collector (20).

7. Electron tube device according to claim 5, wherein

- the frame (33) is electrically isolated with respect to at least one of the electron emitter (10) and the electron collector (20) by a gap or a spacer.

8. Electron tube device according to one of the foregoing claims, wherein

- the gate electrode (30) further comprises a supporting layer (34), which carries the at least one electrode layer (31).

9. Electron tube device according to claim 8, wherein

- the supporting layer (34) is made of silicon, germanium or tungsten.

10. Electron tube device according to one of the foregoing claims, wherein

- the gate electrode (30) comprises multiple membrane-shaped electrically conductive or semi-conductive electrode layers.

11. Electron tube device according to one of the foregoing claims, wherein

- the gate electrode (30) is in thermal contact with a gate heater unit (36).

12. Electron tube device according to one of the foregoing claims, comprising

- at least one further gate electrode (30A) which includes at least one of an atomically monolayer-shaped electrode layer and an electrode grid.

13. Electron tube device according to one of the foregoing claims, having at least one of the features:

- the electron emitter (10), the electron collector (20) and the gate electrode (30) are arranged in an evacuated sealed tube,
- the electron emitter (10), the electron collector (20) and the gate electrode (30) are arranged in a sealed tube including an gas reducing space charges in the gap (2) or influencing a work function of at least one of the electron emitter (10), the electron collector (20) and the gate electrode (30),
- the electron tube device (100) does not include a magnetic field device.

14. Method of using the electron tube device (100) according to one of the foregoing claims, with at least one of the applications:

- active electronic component for current rectification,
- active electronic component for current modulation and/or control,
- vacuum fluorescence display,
- active electronic component for ignition voltage reduction in fluorescent tubes, and
- ion source.

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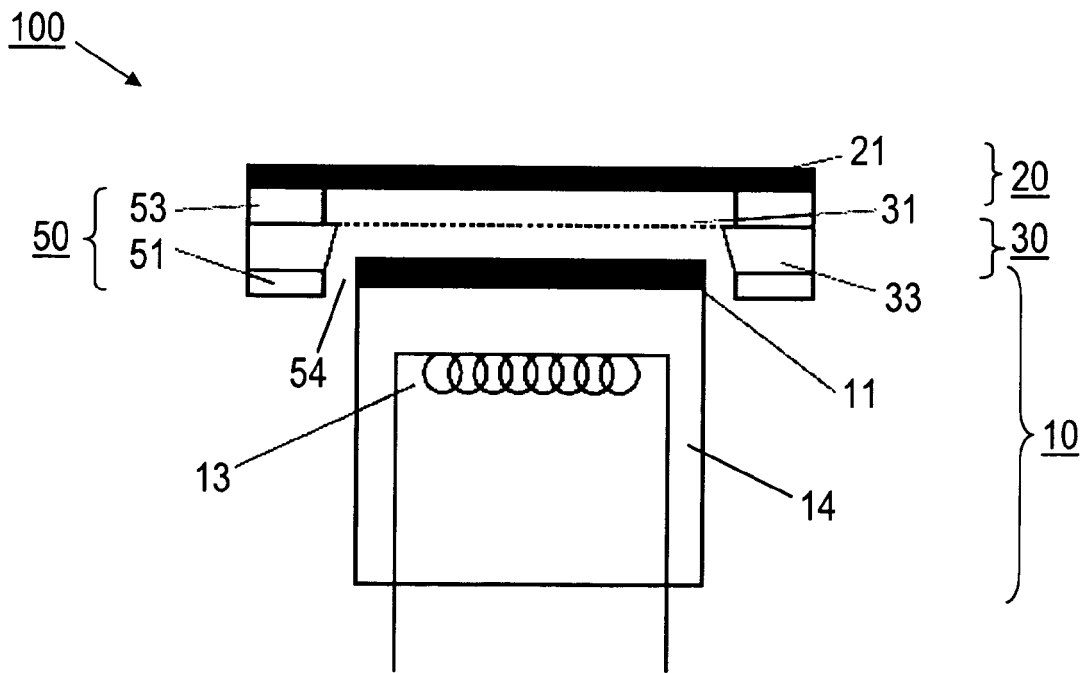
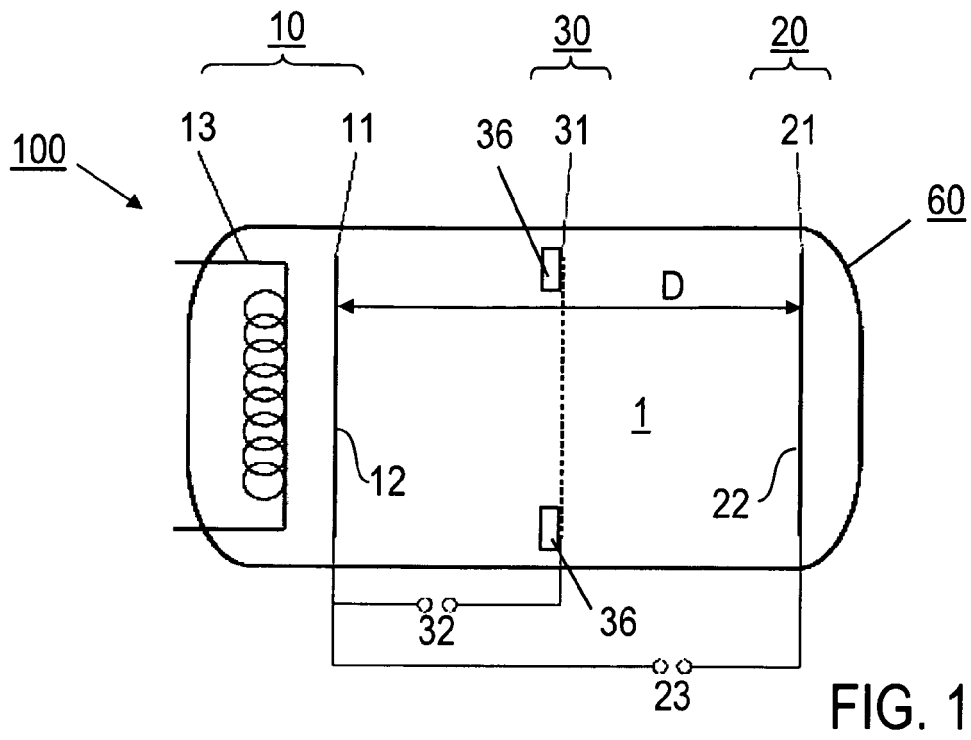
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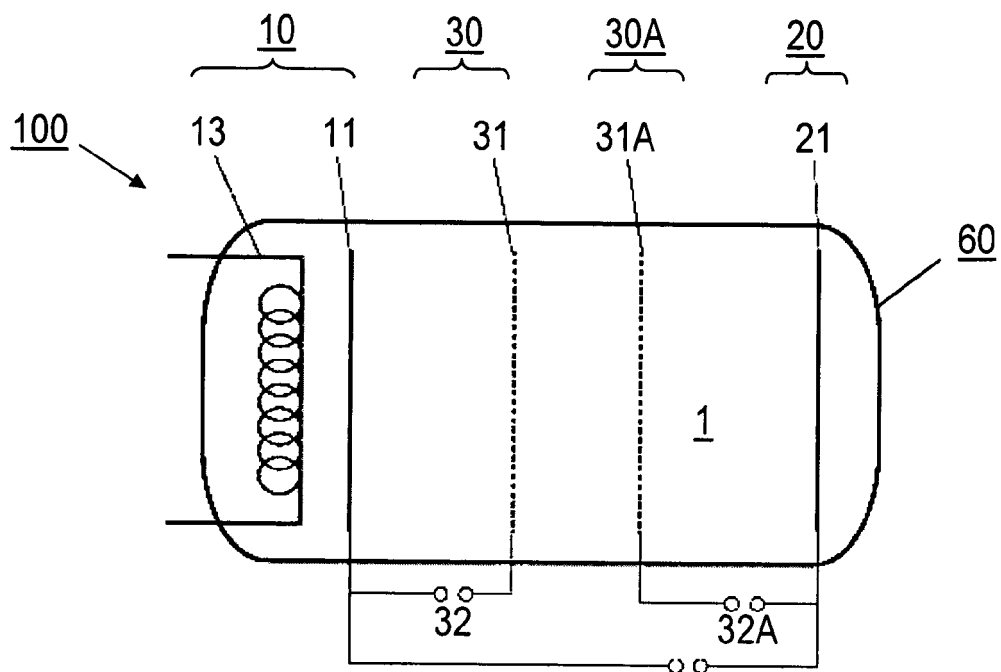


FIG. 3

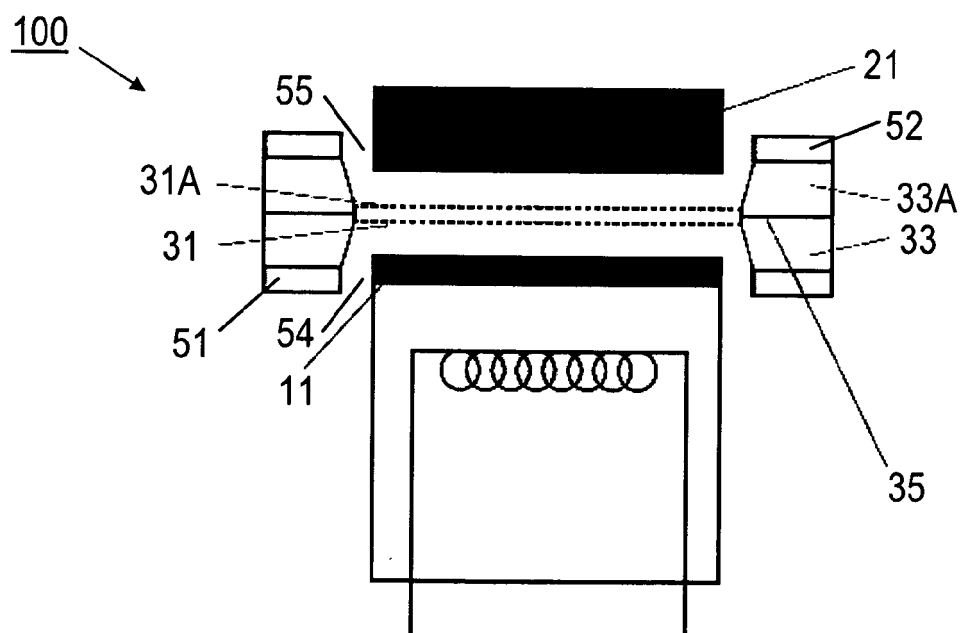


FIG. 4

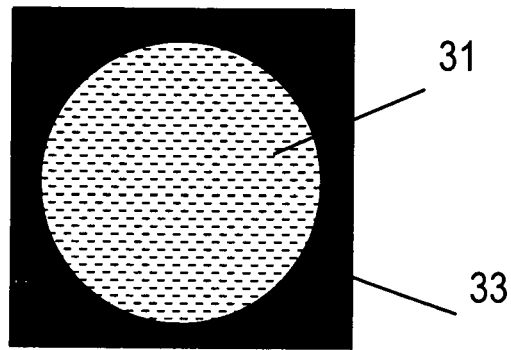


FIG. 5

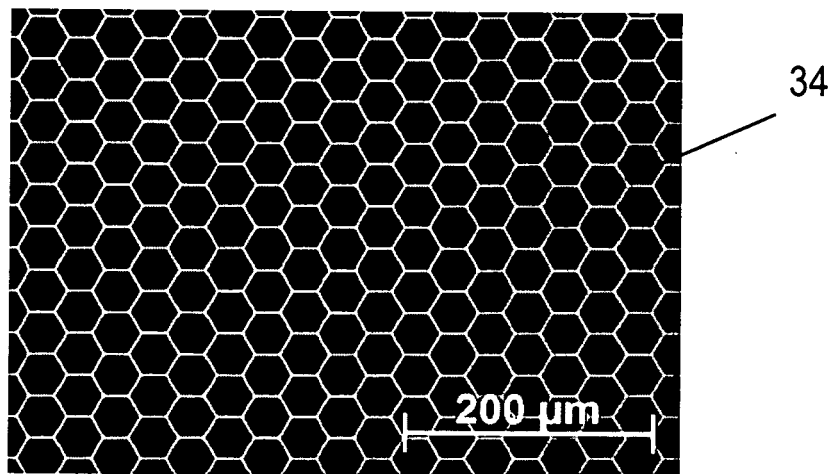


FIG. 6

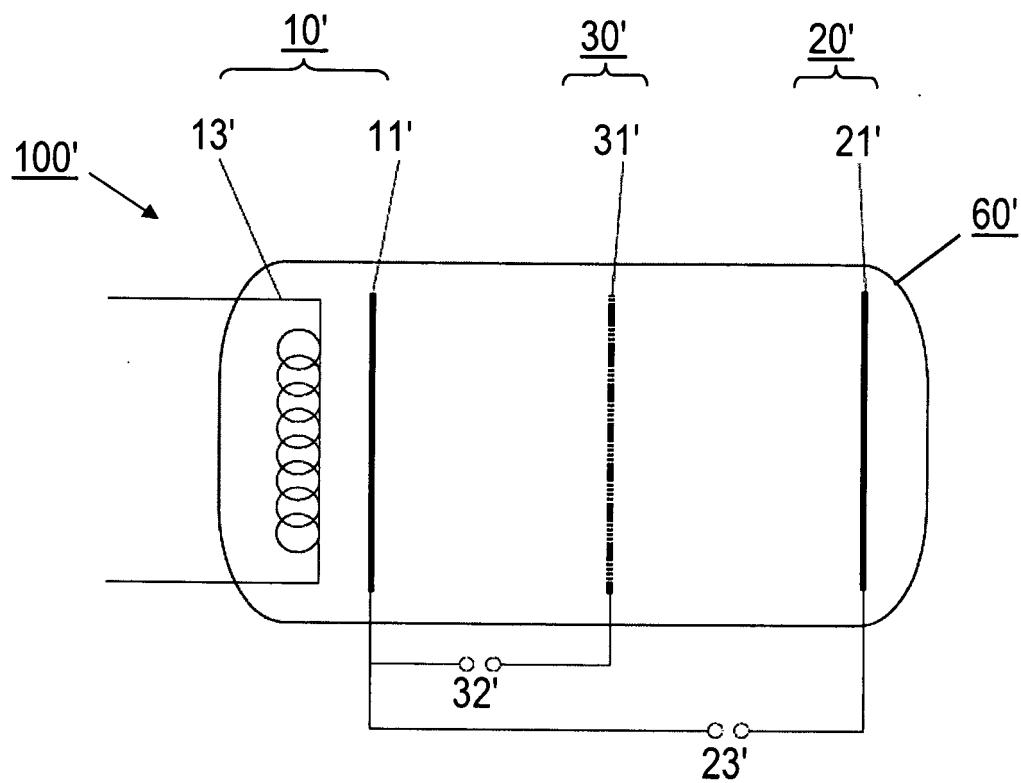


FIG. 7
(Prior Art)



EUROPEAN SEARCH REPORT

Application Number
EP 14 00 3487

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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 2013/169142 A1 (HYDE RODERICK A [US] ET AL) 4 July 2013 (2013-07-04)	1,2,5	INV. H01J3/02 H01J29/46 H01J29/48
Y	* paragraphs [0008], [0009], [0011], [0012], [0024] - [0051]; figures 1-8 *	2	
A	BEIDOU GUO ET AL: "Graphene Doping: A Review", INSCIENCES JOURNAL, 27 April 2011 (2011-04-27), pages 80-89, XP055175178, DOI: 10.5640/insc.010280 * abstract * * pages 81-84 *	2	
Y	HONGTAO LIU ET AL: "Chemical doping of graphene", JOURNAL OF MATERIALS CHEMISTRY, vol. 21, no. 10, 1 January 2011 (2011-01-01), pages 3335-3345, XP055175186, ISSN: 0959-9428, DOI: 10.1039/C0JM02922J * abstract * * page 3337 - page 3340 *	2	
The present search report has been drawn up for all claims			TECHNICAL FIELDS SEARCHED (IPC)
			H01J
Place of search		Date of completion of the search	Examiner
Munich		11 March 2015	Weisser, Wolfgang
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

EPO FORM 1503 03/82 (P04C01)



Application Number

EP 14 00 3487

CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing claims for which payment was due.

☐ Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due and for those claims for which claims fees have been paid, namely claim(s):

☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

☐ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

☐ As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

☒ None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

1, 2(completely); 5(partially)

☐ The present supplementary European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims (Rule 164 (1) EPC).



LACK OF UNITY OF INVENTION
SHEET B

Application Number

EP 14 00 3487

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. claims: 1, 2(completely); 5(partially)

Electron tube device according to present claim 1, further specifying the material of the membrane shaped gate electrode layer and the dopant material.

2. claims: 3, 4

Electron tube device according to present claim 1, further specifying the through-holes of the membrane shaped gate electrode layer and the method of formation thereof.

3. claims: 10, 12(completely); 5(partially)

Electron tube device according to present claim 1, further specifying the layer structure of the gate electrode or gate electrodes.

4. claims: 6-9

Electron tube device according to present claim 1, further specifying (a) spanning of the membrane shaped gate electrode layer on a frame or (b) the support thereof on a supporting layer.

5. claim: 11

Electron tube device according to present claim 1, further specifying that the gate electrode is in thermal contact with a gate heater unit.

6. claim: 13

Electron tube device according to present claim 1, further specifying the filling of the electron tube (evacuated sealed tube or sealed tube including an gas reducing space charges in the gap or influencing a work function of at least one of the electron emitter, the electron collector and/or the gate electrode).

7. claim: 14

Method of using an electron tube device according to present claim 1, further specifying various applications (active electronic component for current rectification, current



**LACK OF UNITY OF INVENTION
SHEET B**

Application Number
EP 14 00 3487

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The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

modulation and/or control; vacuum fluorescent display;
active electronic component for ignition voltage reduction
in fluorescent tubes; ion source).

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 14 00 3487

5 This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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11-03-2015

10	Patent document cited in search report	Publication date	Patent family member(s)	Publication date
	US 2013169142 A1	04-07-2013	NONE	
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

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