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(71) Applicant: **VA TECH Transmission & Distribution GmbH & Co. KEG**
1141 Wien (AT)

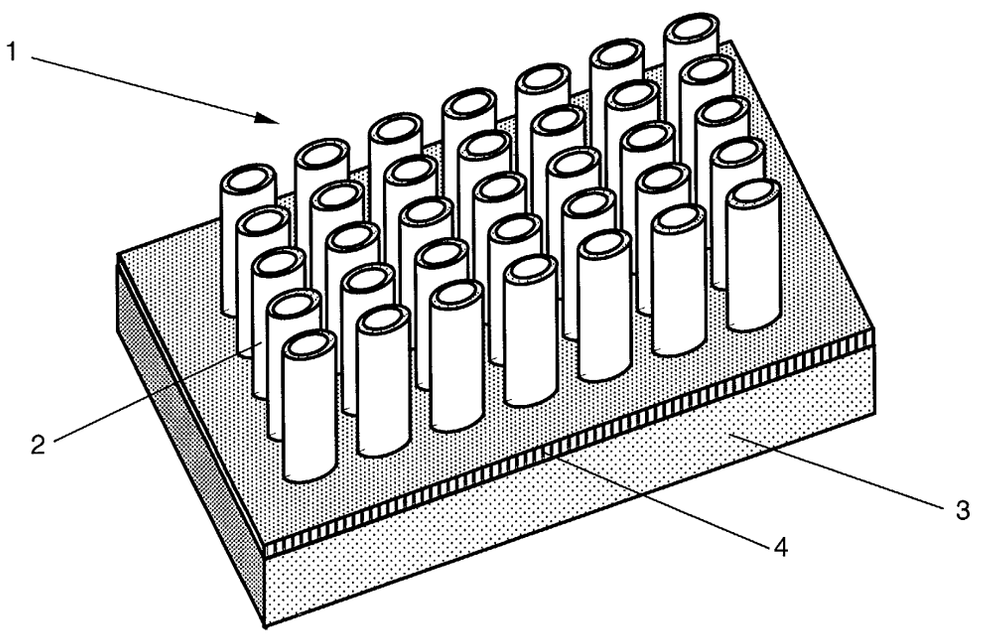
(72) Inventors:
- **Taylor, Gareth Andrew, Dr.**
  Newcastle upon Tyne, NE6 5AL (GB)
- **Chhowalla, Manish Dr.**
  Rockaway, NJ 07866 (US)
- **Amaratunga, Gehan Anil Joseph**
  Cambride CB2 2RW (GB)

(74) Representative: **VA TECH Patente GmbH & Co**
Penzinger Strasse 76
1141 Wien (AT)

(54) Method and device for collecting electrons

(57) In vacuum electron devices one of the main sources of voltage drop is the energy lost in transferring electrons from the vacuum state back into the solid electrical conductor, i.e. the anode electron collector. Such losses manifest in the form of thermal energy developed at the anode which must be managed. In devices that are intended to carry kilo-amperes, even a modest voltage drop, which at minimum is equivalent to the work function of the anode material, associated with the transfer of electrons back into the solid state results in kilo-watts of heat being generated. It is therefore the object of this invention to provide a more effective device for collecting electrons by forming small three dimensional geometrical structures on the collector base surface said geometrical structures being oriented outwardly away from the collector base and of a size smaller than 50 μm in width and/or height.

Fig. 1



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Description

[0001] The invention relates to an electron collector having a surface made of a material exhibiting a high melting temperature and preferably a low secondary electron emission coefficient, as well as a method for collecting electrons utilising an electron collector according to the invention.

[0002] Advances in surface and vacuum microelectronics are now creating the possibility of realising cold cathode electron emitters that are capable of producing currents which are up to several kilo-amperes, greater diameter electron beam widths and potentially higher current densities. Hence this new generation of devices have applications in power switching, with the ability to simultaneously switch high currents and voltages. This would make such devices useful in many applications where operation at electrical utility distribution and transmission voltages would bring significant advantages.

In order to compete with solid state devices, such as thyristors, transistors and their derivatives, switches based on vacuum electron technology must exhibit not only the ability to isolate and switch high currents at high voltages, but must also exhibit low on-state forward voltage drop characteristics. One of the main sources of voltage drop in a vacuum electron device is the energy lost in transferring electrons from the vacuum state back into the solid electrical conductor, i.e. the anode electron collector. Such losses manifest in the form of thermal energy developed at the anode which must be managed. In devices that are intended to carry kilo-amperes, even a modest voltage drop, which at minimum is equivalent to the work function of the anode material, associated with the transfer of electrons back into the solid state results in kilo-watts of heat being generated.

In addition, high currents can also result in a space charge build-up in the vacuum adjacent to the anode due to secondary electron emission from inelastic collisions of the primary electrons with the anode surface. This further increases the forward voltage drop attributable to the anode and again is manifested as higher thermal load to be managed.

[0003] In the US 4,417,175 collector plates of pyrolytic graphite are roughened by ion sputter texturing and show low secondary emission yields and reduced numbers of reflected primary electrons. The described collector plates are used as anode collector plates in high efficiency electron tube devices.

[0004] It is an object of the present invention to provide a more effective device for collecting electrons, and a method therefore, with low collection energy losses, low voltage drop and a low secondary electron emission and which can easily be manufactured.

[0005] To achieve the above object for the electron collector and the method to collect electrons, according to an aspect of the present invention, the textured surface is formed of three dimensional geometrical structures smaller than 50μm in width and/or height and oriented outwardly away from the collector base surface. By geometrically texturing the surface of the electron collector a very high collection area is achieved, which results in a low probability of secondary electron emission and hence in lower energy losses. This makes such devices very efficient and applicable for high current/voltage electron vacuum device, like switches as required in power switching.

[0006] To achieve good electron collection performances it is advantageous when the ratio of the height to width of the microstructure is at least 10:1 and the sum of the area of the microstructures exposed to the incoming electrons is less than 50% of the overall electron collector area.

[0007] The electron collection capability is advantageously evenly distributed along the collector surface when the three dimensional geometrical structures are substantially regular.

[0008] The required material properties to get good electron collection performances can be achieved using carbon, in particular graphite, diamond and the like as material for the textured surface.

[0009] A specially useful form of the surface textures are nanotubes or nanorods with a width between 10nm and 1μm, preferably between 20nm and 500nm, and a height between 100nm and 50μm, preferably between 500nm and 20μm. This shape of the textures optimises the electron collection abilities of an electron collection device according to the present invention.

[0010] The production of such a nanotube is simple and therefore cheap if at least one nanotube is made of graphite and is grown on or adhered to a substrate surface, preferably a metal, for example Ni, Co or Fe. Graphite exhibits some important properties, like a high melting temperature, low secondary electron emission and a moderate work function, which makes it very suitable to be used as material for electron collection devices. Moreover it can be easily processed using mechanical, low pressure chemical or plasma assisted techniques, making it very versatile in the production of the nanoscale structures.

The production can even be simplified more by arranging the nanotubes orthogonally on the substrate surface.

[0011] The collection effect can further be improved when the textured surface is built of a plurality of nanotubes or nanorods, which are located side by side in either a randomly or uniformly distributed manner and which have their longitudinal axis basically aligned in parallel, with a package density between $10^6 cm^{-2}$ and $10^{14} cm^{-2}$, preferably between $10^7 cm^{-2}$ and $10^{12} cm^{-2}$. This effect is increased further when the exposed free end of at least one nanotube forms an opening because the nanotube free ends are initially sealed with a piece of growth catalyst after the growth process. Open tubes have significantly higher collection area due to the utilisation of at least part of the inner nanotube wall surface

area.

Still another improvement of the collection capabilities of an electron collector, for example by reducing secondary electron emission, by improving conduction or by enhancing surface area, can be achieved when the microstructures are at least partially coated with electrically conductive thin films, preferably thinner than 50nm, of an electron collection improving material, such as different types of amorphous carbon, preferably tetrahedral amorphous carbon, hydrogenated amorphous carbon, amorphous carbon containing carbon nanoparticles, diamond or metallic substances possessing a low work function. These thin films are best deposited on the nanotube or nanorods free ends.

[0012] One easy and cheap method of making an electron collector comprises the steps of providing a material having a low secondary electron emission coefficient and a high melting temperature, depositing a thin layer of this material on a substrate surface and structuring the layer of this material using a suitable surface engineering technique in order to form three dimensional geometrical structures smaller than 50μm in width and/or height. Suitable surface engineering techniques are low pressure chemical, plasma assisted or mechanical surface engineering techniques.

Another method of making an electron collector comprises the steps of providing a material having a high melting temperature and preferably a low secondary electron emission coefficient and growing three dimensional geometrical structures smaller than 50μm in width and/or height of this material either directly on a substrate surface or growing it separately and adhering the grown structures onto a substrate surface.

Still another advantageous method of making an electron collector according the present invention comprises the steps of providing a electrically insulating material, such as Silica (SiO_2), Alumina (Al_2O_3), Zirconia or Zeolite, forming a microporous substrate built of three dimensional geometrical structures smaller than 50μm in width and/or height of this material using suitable techniques either directly on a substrate surface or forming it separately and adhering the formed structures onto a substrate surface and coating the microporous substrate with an electrically conducting layer, such as graphitic carbon, amorphous carbon, tetrahedral amorphous carbon, nanodiamond, Ti, Ta, W, Si or Ge, such that the front and back surface of the microporous substrate are connected through a electrically conducting coating layer which covers the inside of at least one micropore. The electron collection capabilities of such an electron collector can improved further when the opposite end to that from which collected electrons can enter the coated micropores of at least one of the micropores is partially filled with an electrically conducting material.

[0013] Such electron collection surfaces, according to the present invention, can be used as electron collector in vacuum or low pressure electron devices, making such devices very effective with very low energy losses, low voltage drop and a very low secondary electron emission. Electron vacuum devices utilising an electron collector according the invention may be used in high current/voltage application. With such an electron vacuum device voltages up to 50kV (and higher), compared to a maximum 10kV when using presently available thyristors or 4.5kV when using presently available transistors, and current densities up to 100Acm^{-2} can be switched. Moreover these devices are more robust than solid state devices, even momentary overloading of the device would not destroy it, whereas a thyristor or a transistor would be destroyed immediately when overloaded.

[0014] In another very useful application of an electron collector according to the present invention it is used as a secondary electron reducing device for example in a vacuum or low pressure electron device. Because of the very good electron collection capabilities of an electron collector according to the invention it is also very suitable to use it for collecting effectively disturbing secondary electrons.

[0015] The invention is described with the exemplary, non restrictive Fig.1 to 7. The figures show:

Fig.1, a sketch of an electron collector with cylindrical nanotubes according the present invention,
Fig.2, the basic principle of the invention,
Fig.3, a sketch of an electron collector with solid nanorods according the present invention,
Fig.4, a sketch of an electron collector with nanostructures with hexagonal cross section,
Fig.5, a sketch of an electron collector with microstructures with rectangular cross section,
Fig.6a and 6b, sketches of microporous ceramic matrixes according the present invention and
Fig.7, an electron microscope picture of a typical textured surface according the invention.

[0016] In Fig. 1 an electron collector 1 is shown which is built of a metal substrate plate 3 which may be subsequently coated with one or more thin layers of metallic material 4 to provide seeding and/or adhesion upon which a plurality of vertically aligned and uniformly or randomly distributed parallel graphite nanotubes 2 are grown.

[0017] Fig. 2 indicates the basic principle of the invention. An incoming primary electron 7 impinging upon the collector surface will travel into the microstructured tube 2 whose walls 9 are electrically conductive. Dependent upon the incident angle of the electron 7 it will either collide with the wall of the nanotube 2 or the substrate 3 (or the coating 4). In the event of a secondary electron or multiple secondary electrons 10 being emitted from the primary collision site 12, which are generally produced from the surface with a cosine probability distribution 11, the height and width of the nanotube 2 is such that such secondary electrons 10 are also generally captured within the constraints of the nanotube 2. Sim-

ilarly primary electrons 7 impinging upon the collector 1 that enter the interstitial spaces between nanotubes 2 will collide with either the outer of the nanotubes 2 or the substrate 3 (or the coating 4). Secondary electrons 10 resulting from primary collisions of primary electrons 7 impinging in the interstitial spaces between nanotubes 2 will have a high probability of colliding with outer walls 9 of the nanotubes 2 rather than readmission of those secondary electrons 10 into the surrounding vacuum. In the event that the tops 13 of the nanotubes 2 are closed, the outside nanotube walls 9 that define the interstices between the nanotubes 2 will be the primary electron collector surface. To ensure that the probability of a secondary electron 10 being readmitted from the textured surface back into the vacuum is kept below one percent, the ratio of the nanotube height to nanotube width should be at least 10:1.

[0018] Where higher current densities or greater thermal conductivity is required solid microstructured nanorods 14 rather than nanotubes could be used. In the exemplary, non restrictive Fig. 3 an electron collector 1 is shown which is built of a metal substrate plate 3 which may be optionally coated with one or more thin layers of metallic material 4 to provide seeding and/or adhesion upon which a plurality of vertically aligned and uniformly or randomly distributed parallel graphite nanorods 14 are grown. In this case the impinging electrons are collected at the substrate or by walls of the nanorods 14 or by the facing ends 15 of the nanorods 14.

[0019] Similar high density surface microstructures may also be realised through growth or removal of material to form more regular structures with properties similar to those outlined for nanotubes 2 or nanorods 14. These embodiments are described with the exemplary, non restrictive Figs. 4 and 5. In both figures an electron collector 1 is shown which is built of a metal substrate plate 3 which may be optionally coated with one or more thin layers of metallic material 4 to provide seeding and/or adhesion upon and upon which a further, thicker film 16 is deposited and subsequently modified to produce substantively regular holes or channels 17. The cross section of the holes 17 may be of any shape, for example hexagonal as in Fig. 4 or rectangular as in Fig. 5. In each case the film 16 would be manufactured from a conductive material such as graphite, highly doped p-type diamond or from a metallic substance possessing a low work function. The thickness of the thin film 16 can be up to 50μm. Ideally the wall thickness of the structures will be such that the sum of the area of solid facing the incoming electrons is less than 20% of the overall plane area. The dimensions of these structures have the same range of diameters and heights indicated for nanotube surfaces.

[0020] Secondary electron 10 emission may be further reduced by further coating the microstructures shown in Figs. 1, 3, 4 and 5 with a conformal thin film coating of a low secondary electron yield coefficient material such as platinum or gold. Such a coating would typically be less than 50nm in thickness.

[0021] In another embodiment a microporous ceramic matrix such as Silica (SiO_2), Alumina (Al_2O_3), Zirconia or Zeolite can be used as the base structure of the electron collector. The electron collecting surface is completed by covering the microporous ceramic structure with a high melting point, low secondary electron yield, electrically conducting thin film material such as, for example, graphitic carbon, amorphous carbon, tetrahedral amorphous carbon, nanodiamond, Ti, Ta or W. Such microstructures are illustrated in Fig. 6a and 6b. The thin film coverage may be accompanied by partial filling of the microporous structure through, for example, capillary action of the molten metal. The filled part of the microporous structure would be for the back contact of the electron collector while the hollow but microporous electrically conducting surface would form the front of the electron collector which forms the main interface with the vacuum from where the electrons are collected.

[0022] It is of course also in the scope of the invention to adhere a carpet of nanostructures to the substrate surface or to fix it on the substrate surface in any other possible way as long as a conductive connection between substrate and nanostructure is ensured.

It is also possible to use metal substrates that are non-planar as electron collector shapes, for instance a hemisphere, pyramid, cone, cylinder, cube or any other shape. The principle of the orthogonally oriented microstructures collecting the incoming electrons remains the same whichever electrode shape is used.

[0023] Fig. 7 shows a carpet of nanotubes or nanorods where the regularity and the even distribution of the nanotubes or nanorods, made with one of the methods according the present invention, may be recognized.

Claims

1. An electron collector having a surface made of a material exhibiting a high melting temperature and preferably a low secondary electron emission coefficient, **characterised in that** the surface is formed of three dimensional geometrical structures smaller than 50μm in width and/or height and oriented outwardly away from the collector base surface.

2. An electron collector according to claim 1, **characterised in that** the ratio of the height to width of the structure is at least 10:1.

3. An electron collector according to claim 1 or 2, **characterised in that** the sum of the area of the structures exposed to the incoming electrons is less than 50%, preferably less than 20%, of the overall electron collector area.

4. An electron collector according to claim 1, 2 or 3, **characterised in that** the three dimensional geo-

metrical structures are substantially regular.

5. An electron collector according to one of claims 1 to 4, **characterised in that** the surface is made of carbon, in particular graphite, diamond and the like.

6. An electron collector according to one of claims 1 to 5, **characterised in that** the surface is formed of nanotubes with a width between 10nm and 1μm, preferably between 20nm and 500nm, and a height between 100nm and 50μm, preferably between 500nm and 20μm.

7. An electron collector according to one of claims 1 to 5, **characterised in that** the surface is formed of nanorods with a width between 10nm and 1μm, preferably between 20nm and 500nm, and a height between 100nm and 50μm, preferably between 500nm and 20μm.

8. An electron collector according to claim 6 or 7, **characterised in that** at least one nanotube or nanorod is made of graphite and is grown on or adhered to a substrate surface, preferably a metal surface, for example Ni, Co or Fe.

9. An electron collector according to claim 6, 7 or 8, **characterised in that** the longitudinal axis of at least one nanotube or nanorod is substantially orthogonal to the substrate surface.

10. An electron collector according to one of the claims 6 to 9, **characterised in that** the textured surface is built of a plurality of nanotubes or nanorods, which are located side by side in either a randomly or uniformly distributed manner and which have their longitudinal axis basically aligned in parallel, with a package density between $10^6 cm^{-2}$ and $10^{14} cm^{-2}$, preferably between $10^7 cm^{-2}$ and $10^{12} cm^{-2}$.

11. An electron collector according to one of the claims 6 to 10, **characterised in that** the exposed free end of at least one nanotube forms an opening.

12. An electron collector according to one of the claims 1 to 11, **characterised in that** the three dimensional geometrical structures are at least partially coated with electrically conductive thin films, preferably thinner than 50nm, of an electron collection improving material, such as different types of amorphous carbon, preferably tetrahedral amorphous carbon, hydrogenated amorphous carbon, amorphous carbon containing carbon nanoparticles, diamond or metallic substances possessing a low work function.

13. An electron collector according to claim 12, **characterised in that** only the free ends of nanotubes or nanorods are coated.

14. A method to collect electrons, **characterised in that** at least some electrons are collected by a microscopically textured surface comprising three dimensional geometrical structures, basically smaller than 50μm in width and/or height and which are oriented outwardly away from the collector base surface.

15. A method according to claim 14, **characterised in that** at least some electrons are collected by at least one nanotube with a width between 10nm and 1μm, preferably between 20nm and 500nm, and a length between 100nm and 50μm, preferably between 500nm and 20μm.

16. A method according to claim 15, **characterised in that** at least some electrons are collected by at least one nanorod with a width between 10nm and 1μm, preferably between 20nm and 500nm, and a length between 100nm and 50μm, preferably between 500nm and 20μm.

17. A method according to claim 15 or 16, **characterised in that** at least some electrons are collected by at least one carbon, preferably graphite, diamond or the like nanotube or nanorod which is substantially orthogonal grown on or adhered to a substrate surface, preferably a metal surface, for example Ni, Co or Fe.

18. A method according to one of the claims 15 or 17, **characterised in that** at least some electrons are collected by a plurality of nanotubes or nanorods located side by side in either a randomly or uniformly distributed manner and which have their longitudinal axis basically aligned in parallel, with a package density between $10^6 cm^{-2}$ and $10^{14} cm^{-2}$, preferably between $10^7 cm^{-2}$ and $10^{12} cm^{-2}$.

19. A method according to one of the claims 14 to 18, **characterised in that** at least some electrons are collected by three dimensional geometrical structures which are at least partially coated with thin films, preferably thinner than 50nm, of an electron collection improving material, for example by reducing secondary electron emission, by improving conduction or by enhancing surface area, such as different types of amorphous carbon, preferably tetrahedral amorphous carbon, hydrogenated amorphous carbon, amorphous carbon containing carbon nanoparticles, diamond or metallic substances possessing a low work function.

20. Method of making an electron collector, comprising the following steps:

- providing a material having a high melting temperature and preferably a low secondary electron emission coefficient,
- depositing a thin layer of this material on a substrate surface and
- structuring the layer of this material using a suitable surface engineering technique in order to form three dimensional geometrical structures smaller than 50μm in width and/or height.

21. Method of making an electron collector according to claim 20, **characterised in that** the surface engineering technique used is a low pressure chemical, a plasma assisted or a mechanical surface engineering technique.

22. Method of making an electron collector, comprising the following steps:

- providing a material having a high melting temperature and preferably a low secondary electron emission coefficient,
- growing three dimensional geometrical structures smaller than 50μm in width and/or height of this material either directly on a substrate surface or growing it separately and adhering the grown structures onto a substrate surface.

23. Method of making an electron collector, comprising the following steps:

- providing a electrically insulating material,
- forming of a microporous substrate built of three dimensional geometrical structures smaller than 50μm in width and/or height of this material using suitable techniques either directly on a substrate surface or forming it separately and adhering the formed structures onto a substrate surface,
- coating of the microporous substrate with an electrically conducting layer such that the front and back surface of the microporous substrate are connected through a electrically conducting coating layer which covers the inside of at least one micropore.

24. Method of making an electron collector according to claim 23, **characterised in that** the electrically insulating material is Silica (SiO_2), Alumina (Al_2O_3), Zirconia or Zeolite.

25. Method of making an electron collector according to claim 23 or 24, **characterised in that** the coating material is a high melting point metal such as Ti, Ta or W.

26. Method of making an electron collector according to claim 23 or 24, **characterised in that** the coating material is graphitic carbon, amorphous carbon, tetrahedral amorphous carbon or nanodiamond.

27. Method of making an electron collector according to claim 23 or 24, **characterised in that** the coating material is a semiconductor such as Si or Ge.

28. Method of making an electron collector according to one of the claims 23 to 27, **characterised in that** the opposite end to that from which collected electrons can enter the coated micropores of at least one of the micropores is partially filled with an electrically conducting material.

29. Use of the electron collector according to one of the claims 1 to 13 for a vacuum or low pressure device comprising an enclosure, for example made of glass, ceramic or metal, which is evacuated to less than 10^1 Pa, comprising an electron emitter, preferably a cold, a thermionic or a thermal electron emitter, optionally one or more control grids and an electron collector.

30. A vacuum or low pressure electron device according to claim 29, **characterised in that** the electron device is capable to switch high current densities in the range between $10mAcm^{-2}$ and $500Acm^{-2}$ at high voltages of up to 50kV.

31. Use of the electron collector according to one of the claims 1 to 13 as a secondary electron reducing device, for example in a vacuum or low pressure device.

Fig. 1

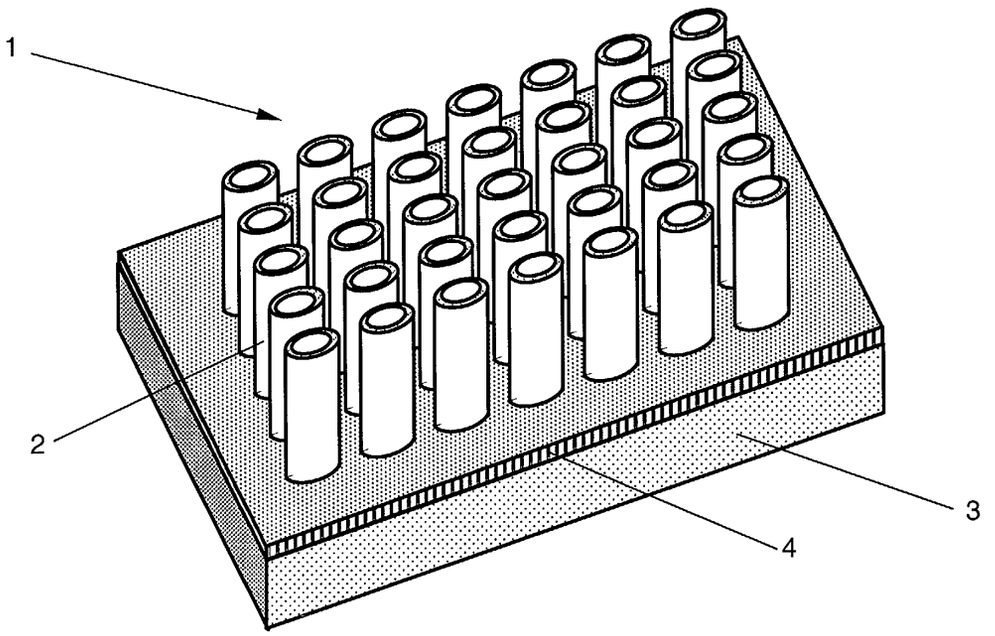


Fig. 2

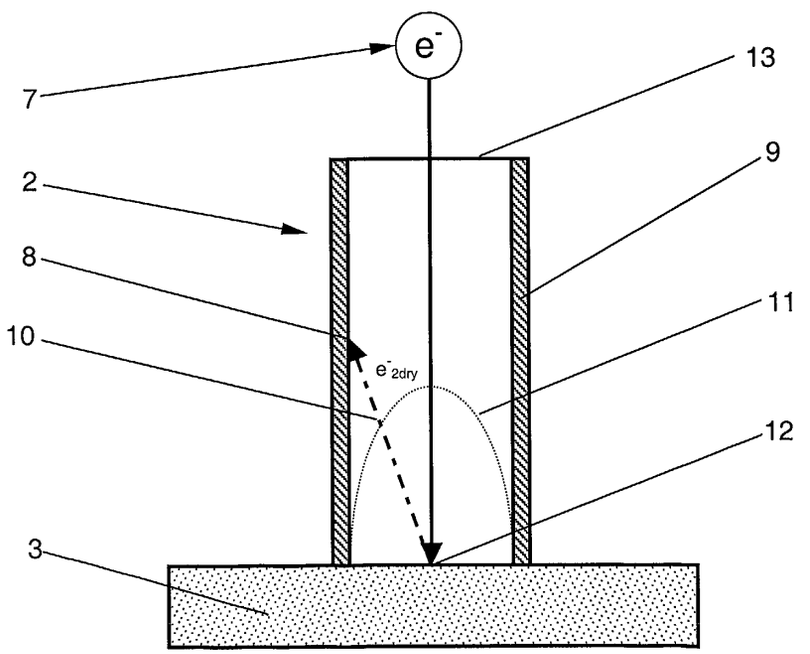


Fig. 3

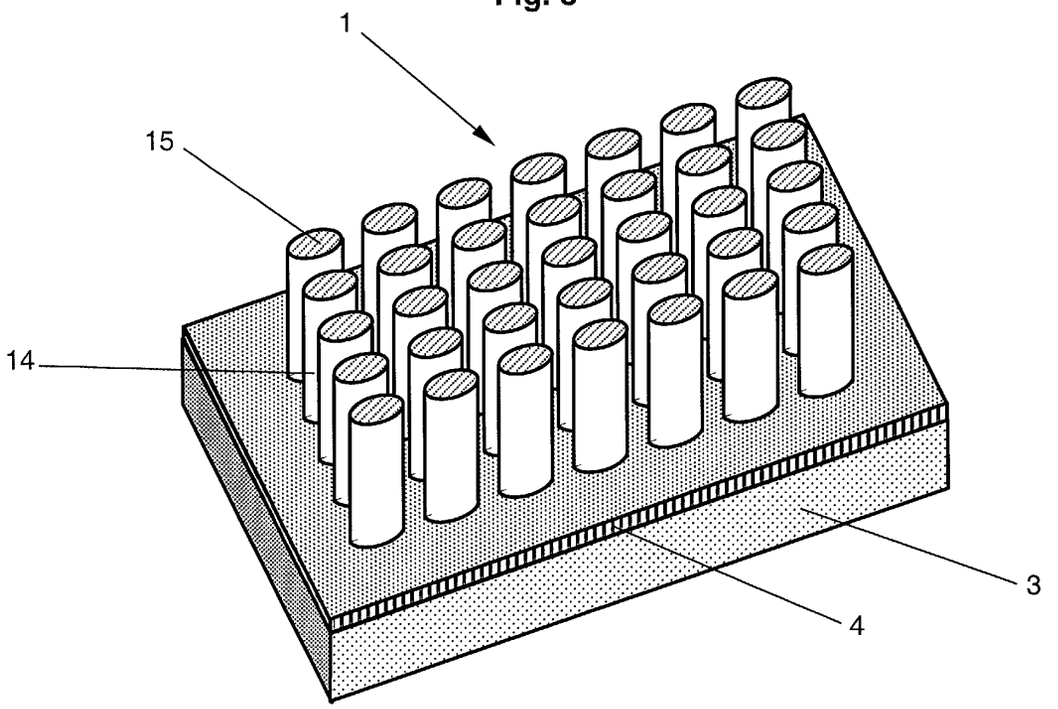


Fig. 4

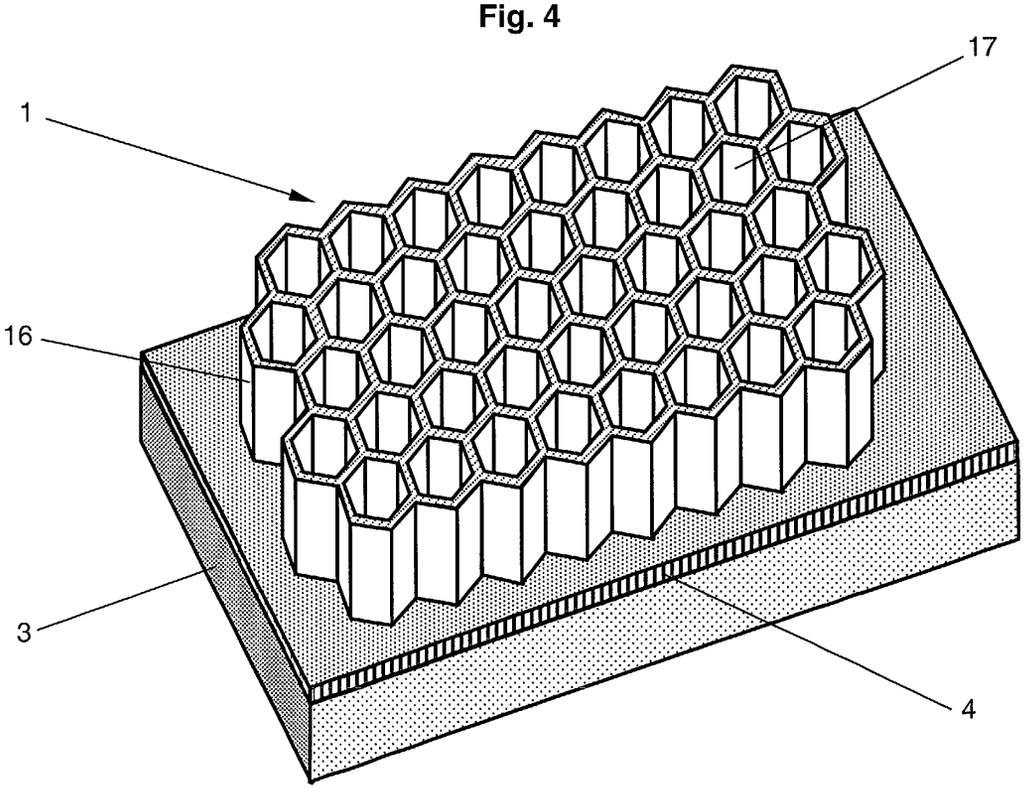


Fig. 5

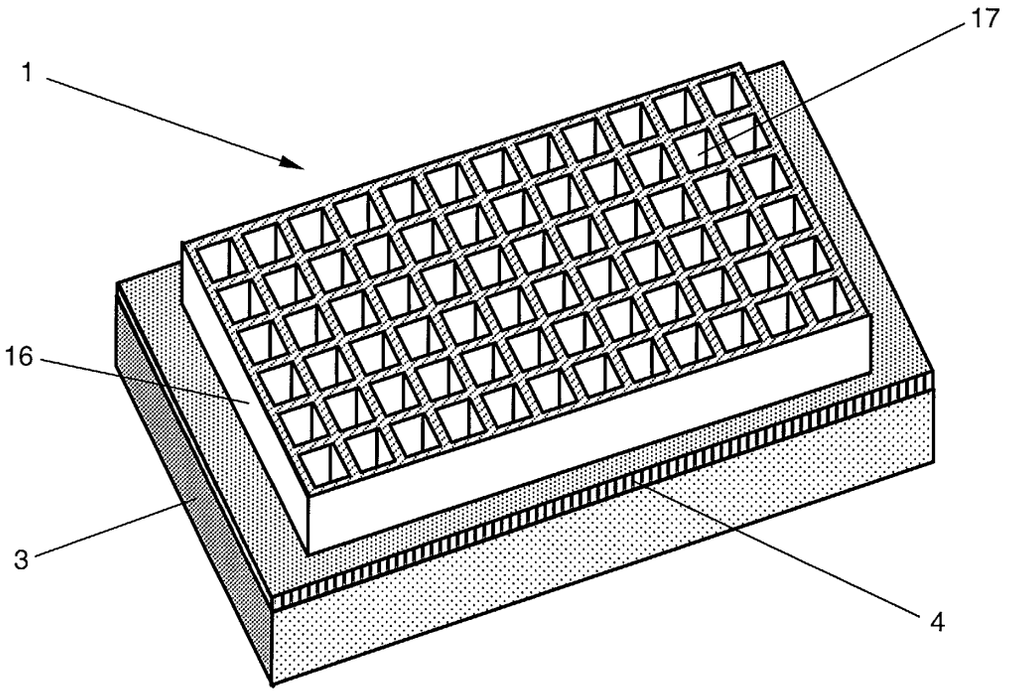


Fig. 6a

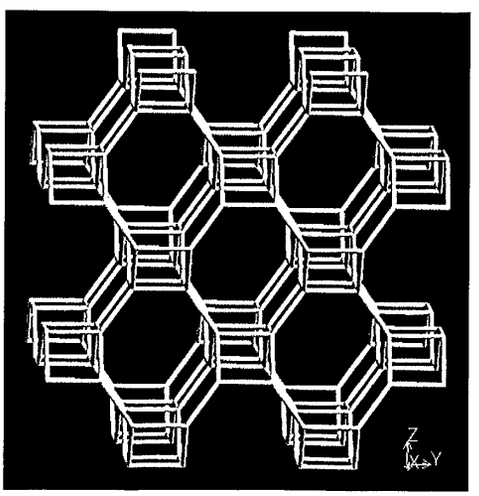


Fig. 6b

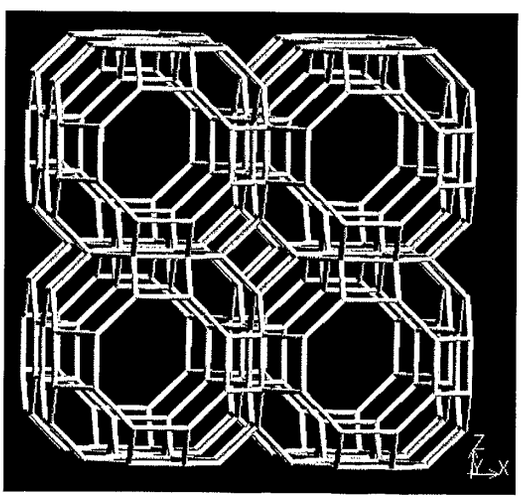
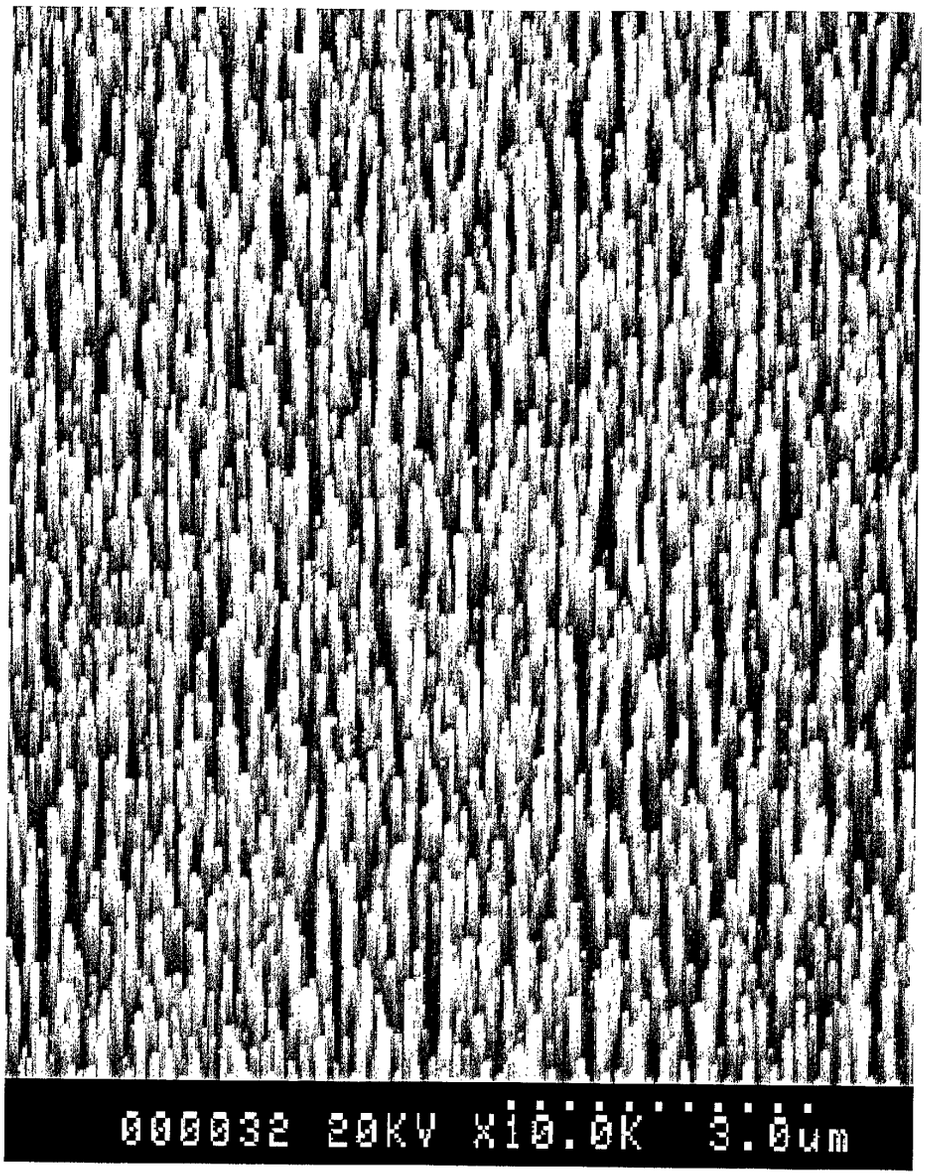


Fig. 7



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EUROPEAN SEARCH REPORT

Application Number
EP 01 30 5940

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
D,X	US 4 417 175 A (CURREN ARTHUR N ET AL) 22 November 1983 (1983-11-22) * column 1, line 19 - line 24 * * column 1, line 40 - line 43 * * column 2, line 63 - line 65 * * column 3, line 4 - line 16 * * column 4, line 13 - line 16 * * column 5, line 20 - line 27 * * column 5, line 57 - column 6, line 1; figure 3 *	1,2,5, 14,20-23	H01J23/027 H01J1/38
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	5 December 2001	Colvin, G

CATEGORY OF CITED DOCUMENTS

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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 01 30 5940

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