

### [54] ELECTRON EMITTERS

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313/354

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[58] Field of Search ..... 250/49.5 A, 49.5 TE, 306,  
250/307, 308, 309, 310, 311; 313/336, 354

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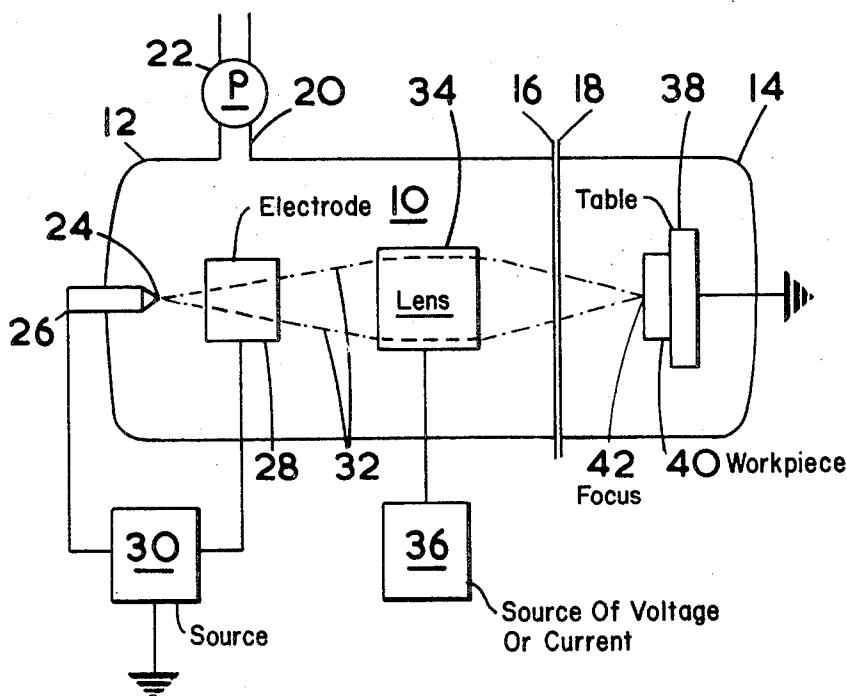
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### [57] ABSTRACT

A carbon filament such as a carbon fibre or graphite whisker is used as a source of field emission electrons in an electronic device such as an electron microscope or an electron beam machining device. A vacuum of only  $10^{-7}$  torr is required, and electrical noise in the beam may be reduced by momentarily heating the source in vacuum before use, and/or by using an electrical current stabilisation circuit.

**11 Claims, 5 Drawing Figures**



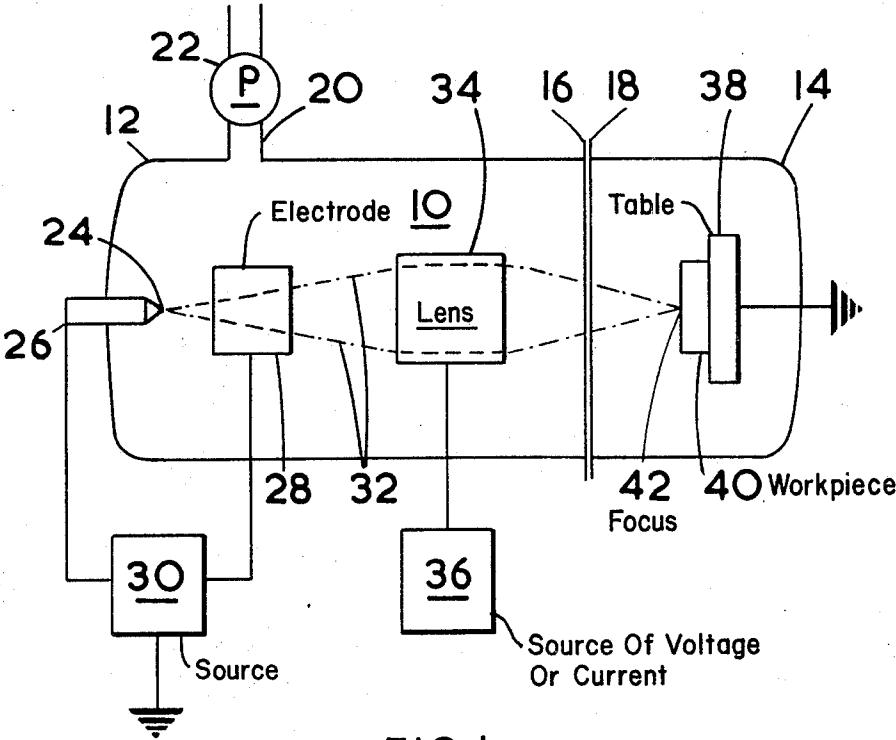


FIG. 1

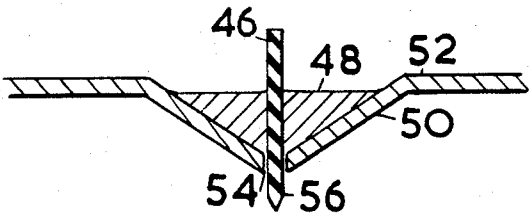
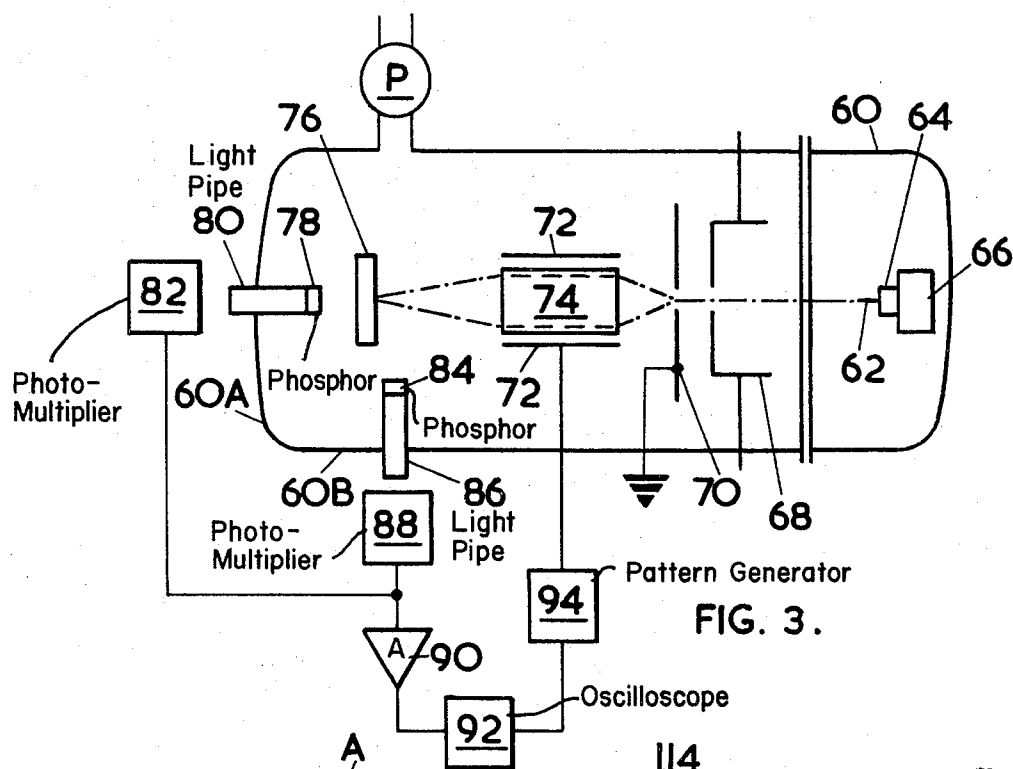
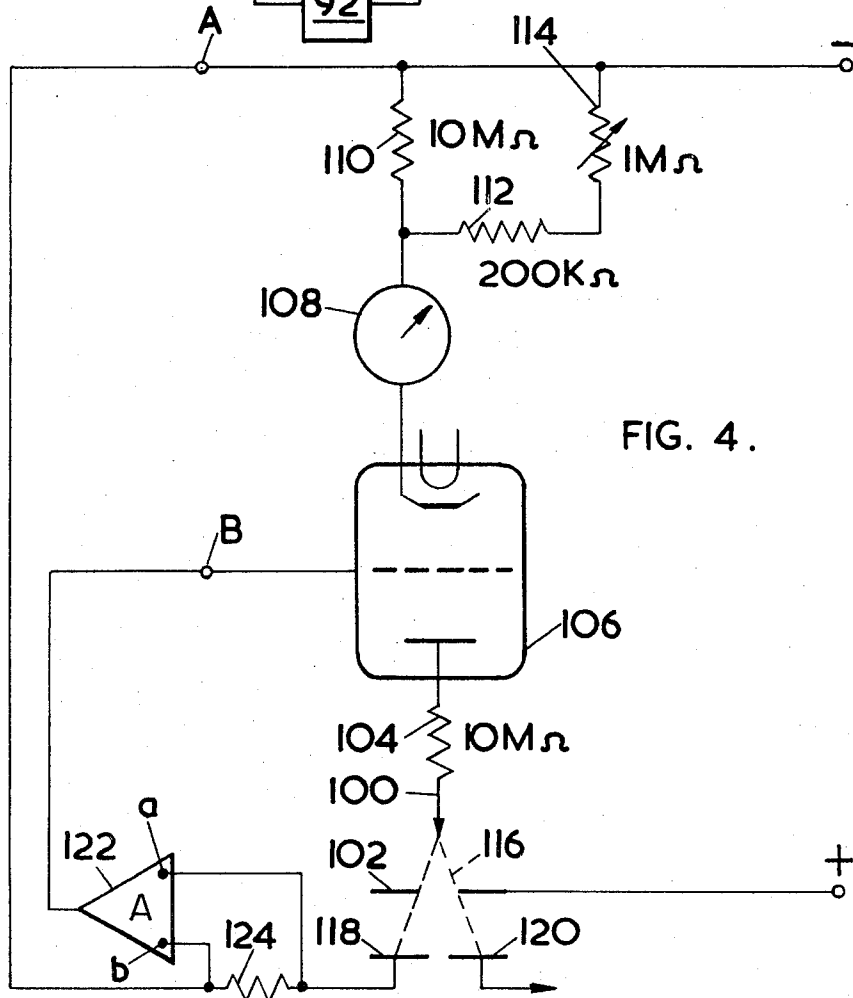


FIG. 2



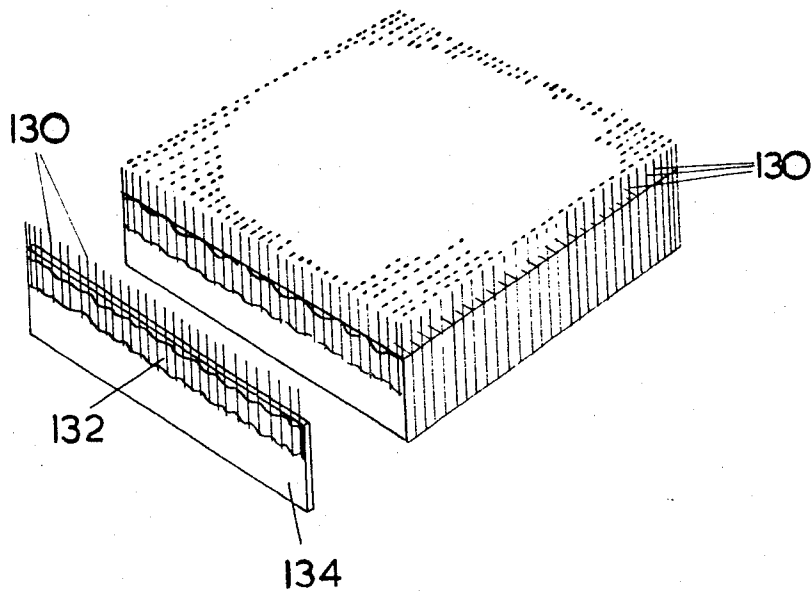


FIG. 5.

## ELECTRON EMITTERS

This invention relates to vacuum electronic devices comprising a source which can emit electrons and means for applying emitted electrons to a target or receiver so as to produce a desired effect thereon.

In such devices it has been usual to provide the source which can emit electrons as a heatable filament, eg, of tungsten, or a heatable tube coated eg, with barium oxide, from which electrons may be caused to be emitted thermionically. Heating the source of electrons may consume an appreciable amount of energy, often very much greater than the energy involved in applying the emitted electrons to a useful task, so that such devices tend to be highly inefficient.

Efficiency can be improved by using a source of electrons which does not require heating and which provides a greatly increased current density, ie, by employing field emission. A conducting or semi conducting body can be made to act as an emitting source of electrons by applying a strong enough electric field, of correct sense, at the surface of the body; electrical fields of the order  $10^7$  to  $10^8$  volts per centimetre are required and conveniently such a field is obtained by applying a modest potential, eg, 500 to 5000 volts, to a source of very small radius, eg, the tip of a fine wire which has been sharpened by etching. For example, etched tungsten fibres have been used as field emitters, but for a long life of the source a very high vacuum, ie, about  $10^{-11}$  to  $10^{-12}$  torr has been required.

According to the present invention, an electronic device comprises an enclosure capable of enclosing a vacuum, a point source which can emit electrons arranged therein, which source consists essentially of at least one carbon filament having an emitting point, means for applying an electric field to the point source whereby electrons are emitted by field emission, and means for receiving said electrons, said carbon filament being a linearly extended body of carbonaceous material.

Optionally, said carbon filament is a "carbon fibre", ie a carbonised fibre of polyacrylonitrile prepared by the RAE process described in U.S. Pat. Spec. No. 3,412,062.

Alternatively said carbon filament may be a graphite whisker grown by conventional methods.

Carbon fibres prepared by the RAE method are found to have diameters generally in the range 1,000 to 100,000 Angstrom Units and radii at the tip, therefore, of as little as 500 Angstrom Units or even less. Such a small radius allows a field of the order of  $10^8$  volts per centimetre to be obtained at the tip with the application between the tip and an associated emission control electrode of a modest potential difference, about 500 to 5000 volts.

Elemental carbonaceous fibres have proved to be durable, resisting rupture by high electric forces applied to the tip and also resisting well the ion bombardment which occurs under relatively poor vacuum conditions, and such a fibre may be used as a field emitter at pressures of  $10^{-7}$  torr, or even at  $10^{-5}$  torr if long source life is not needed. Such operating pressures are substantially higher than has hitherto been practicable, so that less efficient and therefore cheaper vacuum apparatus can be used.

Moreover, it has been found that small radius fibres emit satisfactorily even without being etched in order

to reduce the tip radius of curvature, although large radius sources may preferably be etched to a point.

It is possible to enhance electron emission from an elemental carbonaceous body, working under conditions of field emission, by raising the temperature to a level at which thermionic emissions also takes place, but it is preferable to avoid this as it nullifies the advantages of field emission.

A field emission source of electrons has an advantage over a thermionic source in that the source is substantially a point source of very small size and the energy of the field emitted electrons has an appreciably smaller spread than that of thermionically emitted electrons. This advantage is particularly noticeable in electronic devices in which focusing of an electron beam is of importance, since the smaller the spread of energy the more precise is the focusing which can be obtained.

According to an important modification of the invention, optionally, focusing means are provided to focus electrons from the source onto said means for receiving the electrons.

Desirably the source which can emit electrons is at least one whisker or fibre of elemental carbonaceous material and may consist of an array of 10,000 or more elemental carbonaceous whiskers or fibres whereby the capacity of the source for emitting electrons may be greatly increased.

Preferably the whiskers or fibre of elemental carbonaceous material is supported in a mounting made of a material which does not attack the carbonaceous material. Such a material is preferably metallic so that the mounting can act as a heat sink. Suitably the carbonaceous material is held in a quantity of tin contained in a depression in a sheet of tantalum. Alternatively the carbonaceous material may be attached to a nickel tape mounting by means of colloidal graphite such as Aquadag (Registered Trade Mark) or other electrically conducting cement or adhesive.

It has been found that an electronic device according to the invention is electrically noisy. The noise may be reduced by heating the elemental carbonaceous material in vacuum for a few minutes before use as an electron source.

Alternatively there may be provided a current stabilisation circuit connectable to the means for receiving electrons and which can be arranged to control the magnitude of the current due to field emission electrons whereby electrical noise emitted by the source is reduced. For example, a valve arranged to act as a high impedance may be placed in series with the source. In another arrangement, the valve may be used to provide feedback from one portion of the emitted electron beam to control the emission control means, and reduce noise emitted by the source; this is possible since noise in the beam has been found to be spatially coherent.

In another arrangement a high value resistor may be connected in series with the source to reduce noise.

The invention will now be described by way of example only with reference to the drawing filed with the provisional specification in which:

FIG. 1 illustrates a device according to the invention and intended to be used for electron beam machining; and

FIG. 2 illustrates a carbon fibre in a suitable mounting;

and with reference to the drawing filed with this specification in which:

FIG. 3 illustrates schematically a scanning electron microscope according to the invention; and

FIG. 4 illustrates a current stabilisation circuit;

FIG. 5 illustrates an array of at least 1,000 filaments attached to a nickel tape mounting.

In FIG. 1, the device comprises an enclosure 10 consisting of two parts 12, 14 which can be sealed hermetically together by the mating flanges 16, 18. The enclosure 10 is evacuable through the pipe 20 by means of the vacuum pumping system 22. The source which can emit electrons is at least one carbon fibre 24, which has been prepared by heating a tensioned fibre of polyacrylonitrile to 500°C, the fibre being mounted on a mounting (not shown) connected to a conductor.

The means for applying an electric field to the point source is a cylindrical gun electrode 25. Both the gun electrode and the conductor 26 connected to the fibre 24 are connected to a source 30 of electrical energy. The source 30 can apply an electrical voltage between gun electrode 28 and the carbonaceous fibres 24 such that the electric field produced at the surface of the fibre 24 is strong enough and of the correct sense to draw electrons from the fibre at its tip which behaves as virtually a point source of electrons. The dotted lines 32 denote generally the flow of electrons from the source. Separation of the order of 1 millimetre to 1 centimetre between the electron source and the gun electrode is suitable with voltages in the range 500 to 5000 volts. Reference 34 represents diagrammatically the means for focusing the electrons. The means employed may be either electrostatic or electro-magnetic; if the former, 36 indicates diagrammatically a source of electric voltage; or if the latter, a source of electric current. Either electrostatic or electromagnetic means for focusing the electrons may be of the usual kind. At the right hand end of the enclosure 10, as shown in the drawing, is a table 38, arranged to be adjustable, by means not shown, from outside the enclosure, in two directions at right angles, both normal to the general direction of the electron beam 32. Reference 40 indicates a work piece which can be attached by any suitable means to the table 38, so that it may be machined by the electron beam 32 brought to a focus at 42, substantially at the surface of the work piece. It is desirable to provide means whereby the table 38 may also be moved in the same general direction as the electron beam 32, so that the surface of any work piece 40 may always be brought to coincide with the focus 42 of the beam without the necessity of adjusting the focusing means 34. Optimum focusing can then be maintained irrespective of the thickness of the work piece.

Desirably as high a degree of vacuum as possible should be maintained in the enclosure 10 while the source 24 is emitting electrons; but a pressure of the order of  $10^{-7}$  torr can be satisfactory for long periods of emission.

In FIG. 2 a single elemental carbonaceous fibre 46 is shown embedded in a quantity of tin 48 held in a cone-shaped depression 50 in a sheet of tantalum 52. The apex of cone 50 is pierced to form a hole 54 through which the fibre 46 protrudes. The tip of fibre 46 is etched to a point 56.

To make a mounting such as that shown in FIG. 2, a piece of tantalum sheet 52 0.006 inch thick is suitably supported and a cone-shaped depression 50 is made

with a metal tool; the cone may be 1/16 inch deep and 1/6 inch max diameter. A fine needle is forced through the cone apex, and the sheet 52 is washed with water, chromic acid, tap water and then distilled water. The sheet is dried, heated under vacuum to white heat for a few minutes to clean the surface, and cooled under vacuum.

Small pieces of tin are heated on a carbon block under vacuum and melt to form beads which are allowed to cool under vacuum. A tin bead is placed in the tantalum cone 50 and heated under vacuum until the tin fuses to the tantalum surface, then cooled. A fine hole is drilled through the tin 48 in alignment with the needle hole 54 and a single fibre 46 is threaded through, then cut off close to the surface of the tin 48. The mounting is heated under vacuum until the tin 48 melts and flows round the fibre 46, is cooled and washed with water. The tip of fibre 46 is flame-etched to a point 56.

While tantalum and tin are suitable materials to use in the mounting, other metals which do not attack elemental carbonaceous material can be used.

In FIG. 5, an array of 1,000 filaments 132 attached to a nickel tape mounting 134 by a colloidal graphite or other cement or adhesive is shown.

In FIG. 3, a scanning electron microscope comprises an enclosure 60 evacuated by a pump P to about  $10^{-7}$  torr. A carbon fibre source 62 is mounted on a nickel tape support 64 attached to positioning means 66 which can be moved in three orthogonal directions and which can be inclined in any direction about the source 62 as centre by means of controls outside the enclosure 60. Adjacent to the source 62 is a cylindrical anode 68 having a small central aperture; the anode also forms the first electrode of an electron lens, the second electrode of the lens being an electrode 70 which also has a small central aperture. References 72 and 74 indicate x and y deflection electrodes and reference 76 indicates a specimen at the focus of the electron lens 68, 70.

A phosphor or scintillator 78 is arranged adjacent to the specimen 76 and is connected by a light pipe 80 through the end 60A of the enclosure to a photomultiplier or similar light detector 82 which can convert received light to an electrical signal. A similar phosphor 84, light pipe 86 and photomultiplier 88 are arranged with the light pipe 86 through the side 60B of enclosure 60.

The photomultipliers 82 and 88 are connected to an amplifier 90 which in turn is connected to a display oscilloscope 92 and which can amplify signals from photomultipliers 82 and which can amplify signals from photomultipliers 82 and 88 to make them compatible with the Z modulation input of the oscilloscope 92. The x and y deflection electrodes 72 and 74 are also connected to the oscilloscope 92 through a pattern generator 94 which causes an electron beam passing between the electrodes 72, 74 to scan the specimen 76, and which generates the same scan pattern on the oscilloscope 92.

In operation, electrons emitted by the carbon fibre source 62 pass through the electron lens 68, 70 and are deflected by electrodes 72, 74 to scan the specimen 76 in a pattern controlled by the pattern generator 94. Electrons transmitted by the specimen 76 are converted to visible light by phosphor 78, the light passes along light pipe 80 to photomultiplier 82 which con-

verts it to an electrical signal. Similarly, secondary electrons and electrons scattered by the specimen 76 are converted to an electrical signal by phosphor 84, light pipe 86 and photomultiplier 88. The electrical signals can be displayed on the oscilloscope 92 either simultaneously or separately.

Typically the carbon fibre source 62 is held at -10kv with reference to earth potential, anode 68 is held at -9kv and electrode 70 is earthed. In addition, positive voltages up to 10kv can also be applied to the phosphors 78 and 84 in order to accelerate low energy electrons to the phosphors.

A source may be heated before use by means of attaching a carbon fibre to a metal support and heating the support to a temperature of up to 1000°C for a few minutes in a vacuum better than  $10^{-8}$  torr. The emission current from the source will then be less noisy for several hours use thereafter.

In FIG. 4 a carbon fibre source 100 shown schematically and arranged adjacent to an anode 102 is connected through a  $10M\Omega$  resistor 104 to the anode of a triode valve 106 such as type 6BK4 valve. The valve grid is indicated at reference B. The cathode of valve 106 is connected through a microammeter 108 to a  $10M\Omega$  resistor 110 in parallel with a  $200k\Omega$  resistor 112 and a  $1M\Omega$  variable resistor 114 in series, the end of the parallel combination remote from the microammeter 108 being connected to a negative supply line A.

The electron beam 116 emitted by the source 100 is received by two receiving means 118 and 120. Receiving means 120 is arranged to receive about three quarters of the electron beam and forms the receiving means of an electronic device according to the invention (not shown). Receiving means 118 is arranged to receive about one quarter of beam 116 and is connected to the first input 122(a) of an amplifier 122, and through a resistor 124 to the second input 122(b) of the amplifier 122 and to point A. The output of amplifier 122 is connected to point B.

In operation, the current due to electrons collected by electron receiving means 118 is amplified by amplifier 122 and applied between the cathode and grid of valve 106 so that current is stabilised, and the noise in electron beam 116 is reduced. The current due to electrons collected by collecting means 120 is fed to the electronic device and the noise in that device is substantially reduced.

The circuit of FIG. 4 may be modified by short circuiting points A and B. The valve 106 then merely acts as a series current stabiliser for the electron beam 116 and noise in the beam is reduced.

A valve current stabilisation circuit has a protective function in that it acts as a current limiter. However, the voltage at source 100 may vary and this may be a disadvantage for an electronic device which is sensitive to voltage. For example an electron gun may be brought out of focus by a large voltage variation.

In another modification the circuit of FIG. 4 may be replaced by a  $100M\Omega$  resistor which acts as a series stabiliser and reduces noise in the electron beam.

A single elemental carbonaceous fibre, produced by heating a tensioned fibre of polyacrylonitrile to 500°C, is capable of emitting, as a source of electrons, up to about 100  $\mu$  Ampere continuously for about 500 hours or 10  $\mu$ A for 100 days. If the field tending to extract electrons from the source is applied as a short high voltage pulse a peak current of up to 0.5 Ampere can be

produced. If the source which can emit electrons, instead of being a single fibre is an array of fibres which may number many thousands, eg, over 10,000, very substantial currents may be drawn from the source by the electric field. It is an important advantage of a field emission source of electrons over a thermionic source that the former can give rise to current densities of  $10^6$  to  $10^8$  Amperes per square centimetre whereas the latter is limited to densities of the order of 100 Amperes per square centimetre.

The invention has been described specifically with reference to a device and to an electron microscope, both devices using a focused beam of electrons. The invention may similarly be applied to an x-ray generator, a high resolution or high brightness cathode ray tube, a colour television tube, a low-light-level television camera, a vacuum gauge, an information storage and retrieval device, or microcircuit fabrication device.

A device using an unfocused beam of electrons may be a vacuum indicator, a vacuum gauge, a triode valve, an x-ray generator or a microwave generator.

We claim:

1. An electronic device consisting of an enclosure capable of enclosing a vacuum, a point source which can emit electrons arranged therein, which source consists essentially of at least one carbon filament having an emitting point, emission control means which can cause electrons to be emitted from the source by field emission, and means for receiving said electrons.

2. An electronic device according to claim 1 in which said carbon filament consists of a carbon fibre.

3. An electronic device according to claim 1 in which said carbon filament consists of a graphite whisker.

4. An electronic device according to claim 1 in which focusing means are provided to focus electrons from the source onto the means for receiving the electrons.

5. An electronic device according to claim 1 having a current stabilisation circuit connectable to the means for receiving electrons and which can be arranged to control the emission control means whereby electrical noise emitted by the source is reduced.

6. An electronic device according to claim 1 having a high electrical resistance in series with the source whereby electrical noise emitted by the source is reduced.

7. An electronic device according to claim 1 in said filaments have been heated in high vacuum before use, whereby electrical noise emitted by the source is reduced.

8. An electronic device according to claim 1 wherein the source comprises an array of at least 1,000 carbon filaments.

9. An electronic device according to claim 1 arranged as an electron beam machining device.

10. An electronic device according to claim 1 arranged as an electron microscope.

11. An electronic device consisting of an enclosure capable of enclosing a vacuum, a point source which can emit electrons arranged therein, which source consists essentially of at least one carbon filament having an emitting point said carbon filament being chosen from the group consisting of graphite whisker and carbon fiber, emission control means which can cause electrons to be emitted from the source by field emission, and means for receiving said electrons.

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