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3,105,166

ELECTRON TUBE WITH A COLD EMISSIVE CATHODE

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2 Sheets-Sheet 1

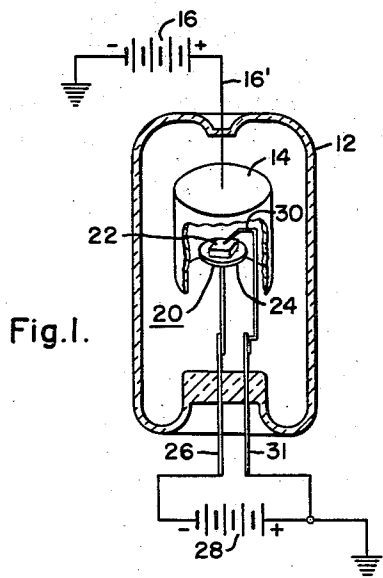


Fig. 1.

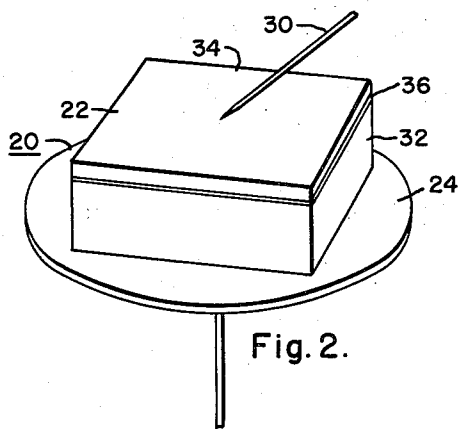


Fig. 2.

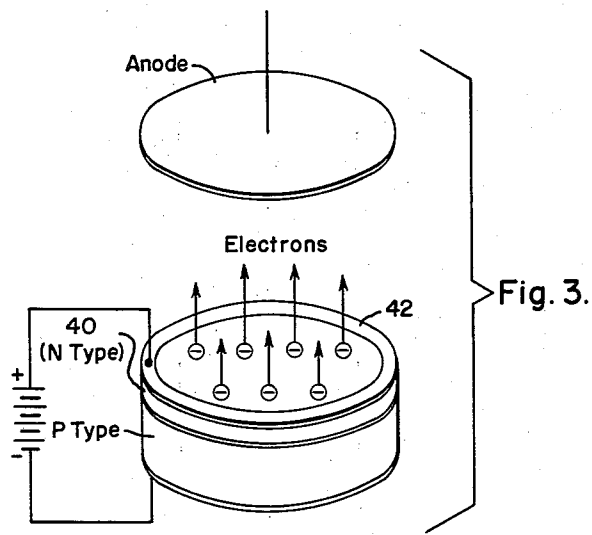


Fig. 3.

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Fig. 4.

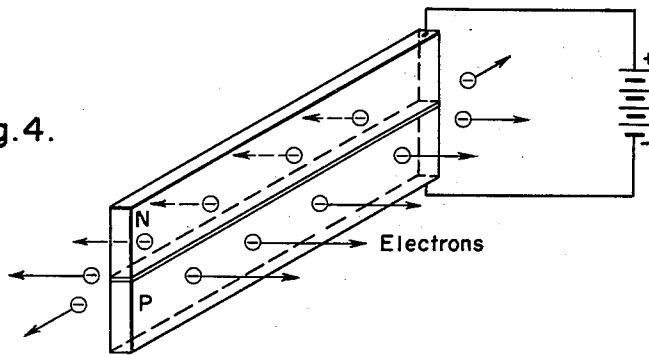


Fig. 5.

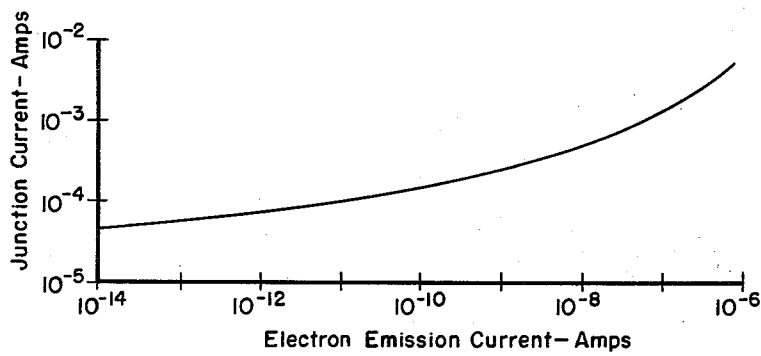
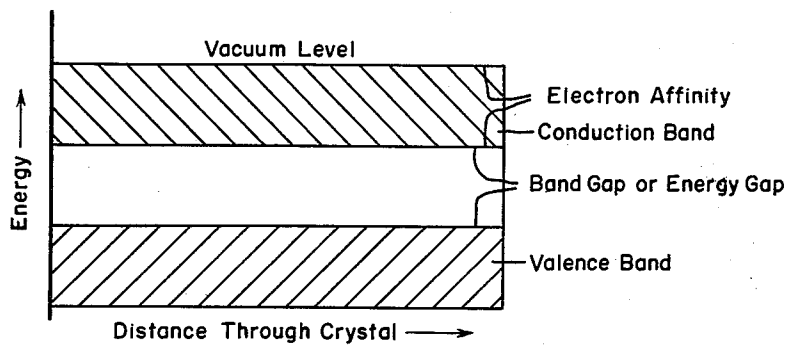


Fig. 6.



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ELECTRON TUBE WITH A COLD EMISSIVE CATHODE

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7 Claims. (Cl. 313-310)

This invention relates to an electron device and, more particularly, to an electron source.

It is an object of this invention to provide a cathode or an electron source for an electron device that does not depend on thermionic emission.

It is an object to provide an improved unheated electron source which depends on the creation of energetic electrons within a material such that the energy of the electrons is greater than the electron affinity of the material and thereby electrons are emitted from the surface.

It is another object to provide a small area electron source of low beam current.

It is another object to provide a cathode which operates at room temperature and does not depend on thermionic emission.

It is another object to provide an improved cathode in which the response is substantially instantaneous, thereby enabling one to modulate the beam directly and at a high frequency rate.

It is another object to provide an improved cathode that does not require complicated activation techniques.

It is another object to provide a cathode which will operate at low temperatures.

It is another object to provide a cathode having a substantially longer lifetime than present thermionic emissive-type cathodes.

These and other objects are effected by our invention as will be apparent from the following description taken in accordance with the accompanying drawing throughout which like reference characters indicate like parts, and in which:

FIGURE 1 is a schematic showing of a vacuum tube incorporating our invention;

FIG. 2 is an enlarged view of the cathode shown in FIG. 1;

FIG. 3 is an illustration of a modified cathode in accordance with the teachings of our invention;

FIG. 4 is an illustration of another modification of a cathode in accordance with the teachings of our invention;

FIG. 5 is a curve indicating the electron emission plotted against junction current of a cathode embodying the teaching of our invention; and

FIG. 6 is a showing of simple energy band diagram for a semiconductor crystal.

Referring in detail to FIG. 1 there is shown an electron device and more specifically a diode-type receiving tube incorporating a cathode in accordance with the teaching of our invention. The diode includes a vacuum-tight container 12 which may be of any suitable material, such as glass. A cup-shaped anode member 14 of a suitable material such as Inconel, which is an alloy of about 79.5% Ni, 13.0% Cr, 6.5% Fe and lesser amounts of Mn, Si, C and Cu, is positioned within the envelope 12. The anode 14 may be supported by a lead member 16 sealed through the top of the container 12 to which a positive voltage is applied by a battery 16. A cathode 20 is positioned in the lower portion of the envelope 12 near the opening in the cup-shaped anode 14.

The cathode 20 consists of a body 22 of suitable semiconductive material mounted on a support plate or elec-

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trode contact 24 of suitable material such as Inconel. A lead 26 is connected to the plate 24 and sealed through the lower portion of the container 12 to support the cathode 20 within the container 12. The lead 26 is connected to the negative terminal of a battery 28. A second contact 30 is provided to the cathode 20 which in the specific embodiment shown consists of a tungsten wire contact. The contact 30 contacts the upper surface of the body 22 of material and is connected by a lead-in 31 to the exterior of the envelope 12 to the positive terminal of the battery 28.

The body 22 of material, as shown in detail in FIG. 2, consists of a layer 32 of P-type material in contact on one surface with the base contact 24 and a layer 34 of N-type material adjacent the other surface P-type layer with an intermediate junction region 36. The contact member 30 is in contact with the N-type layer 34. By providing a potential of from 7 to 40 volts by means of the battery 28 across the body 22 of material and collecting potential of 135 volts to the anode 14 by the battery 16, an electron current was obtained which ranged from 10^{-12} to 10^{-6} amperes.

The cathode body or wafer 22 in one specific embodiment was silicon carbide formed with a thickness of the layer 34 of N-type material of less than 10 microns and the layer 32 of P-type material of a thickness of about 1000 microns. The silicon carbide junction cathode may be prepared in several methods, one of which is disclosed in an article entitled "Electrical Contacts to Silicon Carbide" by R. N. Hall in the June 1958 issue of the Journal of Applied Physics. Another method of preparing the silicon carbide junction is disclosed in a copending application Serial No. 738,631, filed May 29, 1958 and now Patent 2,937,323, entitled "Fused Junctions in Silicon Carbide," by L. J. Kroko et al.

One specific method of fabricating the P-N junction in the silicon carbide is to fuse small pellets of silicon containing a few percent boron to an N-type silicon carbide crystal by heating to a temperature of 2000° C. for a period of 1 minute and then allowing the material to cool at a rate of 20° C. per second. The resulting ingot can be then treated with hydrofluoric acid and nitric acid so as to etch away most of the silicon and leave a P-type layer on the N-type silicon carbide crystal. Before inserting the cathode material into the vacuum tube, it is also found advantageous to submerge the material within a suitable etching solution, for example, hydrofluoric acid for one-half of an hour to insure that the surface is entirely clean. The material may then be washed in alcohol, mounted in the tube and then baked in a vacuum of 10^{-6} millimeters of mercury at a temperature of 270° C. for a period of twenty-four hours.

Although silicon carbide was used in the specific embodiment, other semiconductor and insulator materials are suitable. It is necessary that the material have an energy difference between the vacuum level and the bottom of the conduction band, which is referred to as electron affinity, equal to or less than about $\frac{3}{2}$ the band gap. The band gap is defined as the energy difference between the bottom of the conduction band and the top of the valence band. These terms are also defined in the energy band diagram shown in FIG. 6. In the case of silicon carbide, the electron affinity is about 4 electron volts and the band gap of silicon carbide is about 2.86 electron volts at room temperature. We have found that the material must have electron affinity less than three halves of the band gap of material. Such a relationship is most likely to be found in materials having a large band gap, by which we mean a band gap of more than 2 electron volts. Silicon, for example, which has been found to be a poor emitter, has a band gap of the order of 1 electron

volt and an electron affinity of 3 electron volts. It is, therefore, important that the material used have an electron affinity less than the hole-electron pair production threshold which is of the order of 1.5 times the band gap of the material. Other materials which may provide large band gap electron sources with suitable junctions and which will serve as external electron emitters are AlP, AuCs, GaP, ZnS, ZnSe, ZnO, NiO, Al₂O₃, TiO₂, and diamond.

We have measured the electron emission current from the reverse biased P-N junction in silicon carbide, and the emission there ranged from 10⁻¹² to 10⁻⁶ amperes. In each case, the emission depended strongly on the method of preparing the sample. It was found to be important that the samples be heated at 270° C. in a vacuum for several hours. By applying the reverse bias to the silicon carbide junction, a breakdown radiation originating in small blue spots about 1 micron in diameter was obtained. These blue spots are observed both within the junction area and at its periphery. It is believed that electrons are emitted primarily from those spots which are very near the crystal surface. The cathode was placed in a holder in such a way that the tungsten wire contact was placed on the highly conducting N-type surface which has a thickness of the order of 5 microns. It is at this surface that the blue spots appear. It was found after first applying the reverse voltage to the junction that the electron emission current was observed to increase several orders of magnitude during the first few minutes. Subsequently, the electron emission response to reverse bias was instantaneous and reproducible within a factor of 2 even after a long period of time. It was found that these so-called incubation periods are longer in those samples which were not baked in air or a vacuum. It is possible that a surface change caused by electron emission itself may be the reason for the great increase of emission during the incubation period. Because breakdown occurs at the junction at small spots, the reverse characteristic is too soft to define a specific breakdown voltage.

In FIG. 5, there is illustrated the electron emission from a silicon carbide junction plotted against the junction current. The reverse voltages range from 7 to 38 volts. It was found that the breakdown radiation first appears to a dark adapted eye at a single peripheral spot when the junction current is about the same as that at which electron emission begins. Other spots appear as the current is increased until about thirty were visible at the highest reverse currents. Perhaps only a few of these contribute an appreciable number of electrons. The total area of all spots was estimated to be 10⁻⁶ centimeter square and hence the maximum emission current density was about 1 ampere per square centimeter. The sample was also tested to show that the electron current was not caused by breakdown radiation through a photo-emission mechanism. It was found that several samples emitted more electrons than photons. Also, an oxide film on the surface would prevent electron emission but did not noticeably affect light emission. It was noticed that heating the sample in air at 800° C. for one hour also suppressed electron emission probably because of the formation of an oxide layer. At the reverse currents utilized, there was definitely very little, if any, heating of the silicon carbide crystal which might result in thermionic emission.

It is necessary to provide a high internal electric field in the material, to obtain energetic electrons. The term energetic electrons means those having a greater energy than the electron affinity of the material. In this embodiment the high electric field was obtained by the formation of a P-N junction within the silicon carbide. It is also necessary that the junction be close to the emission surface. In the case of silicon carbide, the material between the junction and the crystal surface should be less than 10 microns and, in general, less than 50 microns in

thickness. It is also believed that the electron emission can be enhanced by the adsorption of a monomolecular layer of alkali metal, such as cesium, at the junction so as to further reduce the electron affinity of the material.

Therefore, in those cases where copious external emission is more important than stability, an alkali metal monolayer may be adsorbed on a suitable wide gap material. This additional activation must be carried out under high vacuum conditions. Other materials that might be suitable for depressing the electron affinity are Ca, Sr, Ba, Ce and Th.

In FIG. 3, a modified cathode is illustrated in which a thin layer 40 of N-type material of less than 50 microns is provided on the surface facing the anode, and the electrode connection to the N-type layer 40 is made by an annular conductive ring 42 of a material such as platinum around the outer periphery of the N-type surface layer.

In FIG. 4, we have illustrated a body of material from which the emission is directly from the periphery of the junction rather than through the N-type material.

In order to provide a small electron emissive area the surrounding area may be masked off by providing a coating such as a suitable synthetic alkyd resin available under the proprietary name Glyptal.

While we have shown our invention in only a few forms, it will be obvious to those skilled in the art that it is not so limited, but is susceptible of various other changes and modifications without departing from the spirit and scope thereof.

We claim as our invention:

1. An electron tube comprising an electron emissive source, a collecting electrode for collecting electrons emitted from said electron emissive source, said electron emissive source comprising a semiconductive body with a bulk material having an electron affinity less than three halves of the band gap of the material, means for providing a high internal electric field in said body of material such that electrons are excited to energies greater than the electron affinity of said material, and means for establishing a potential between said electron emissive source and said collecting electrode for deriving an electrical output from said electron device.

2. An electron emissive cathode comprising a body of semiconductive silicon carbide, said body of semiconductive silicon carbide including a P-N type junction, means for providing a reverse bias on said junction to provide a high electric field in the region of said junction such that said electric field is of sufficient value to excite conduction band electrons in the region of said junction to energies greater than the electron affinity of said semiconductive silicon carbide such that electrons are emitted from the surface of said cathode near said junction.

3. An electron emissive cathode comprising a semiconductor body with a semiconductive bulk material having an electron affinity less than three halves of the band gap of the material, said semiconductive bulk material including a P-N type junction located near an exposed surface of the N-type region, means for providing a reverse bias on said junction to provide a high electric field in the region of said junction such that said electric field is of sufficient value to excite conduction band electrons in the region of said junction to energies greater than the electron affinity of said semiconductive bulk material such that electrons are emitted from said exposed surface of said N-type region.

4. The method of fabricating an electron emissive cathode comprising the steps of forming a P-N junction within a body of semiconductive silicon carbide having the property of an electron affinity less than three halves of the band gap of said material, cleaning the surface of said body, mounting said body in a vacuum system and baking said body at a temperature to 270° C. for a period of twenty-four hours.

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5. An electron device comprising a collecting electrode and an electron emissive source, said electron emissive source comprising a wafer of silicon carbide, said wafer including a layer of P-type conductivity and a layer of N-type conductivity separated by a junction region, said N-type layer facing said collecting electrode and having a thickness of less than 10 microns, means for establishing a reverse bias across said junction to provide a high electric field in the region of said junction such that said electric field is of sufficient value to excite conduction band electrons in the region of said junction to energies greater than the electron affinity of silicon carbide such that electrons are emitted from the surface of said N-type layer facing said collecting electrode.

6. An electron tube comprising an electron emissive source, a collecting electrode for collecting electrons from said electron emissive source, said electron emissive source comprising a body of material selected from the group consisting of silicon carbide, aluminum phosphide, gold-cesium, gallium phosphide, zinc sulfide, zinc selenide, zinc oxide, nickel oxide, aluminum oxide, titanium dioxide and diamond, means for providing a high internal electric field in said body of material such that electrons are excited to energies greater than the electron affinity of said material to cause emission of said excited electrons from said body of material, and means for establishing a potential between said electron emissive source and said collecting electrode to collect said excited electrons for deriving an electrical output from said electron device.

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7. An electron device comprising a collecting electrode and an electron emissive source, said electron emissive source comprising a wafer with a semiconductive bulk material having an electron affinity of less than three halves the band gap of the material, said bulk material including a layer of P-type material and a layer of N-type material separated by a junction, said N-type layer having an exposed surface facing said collecting electrode and having a thickness of less than 50 microns, means for establishing a field across said junction of sufficient value to excite conduction band electrons in the region of said junction to energies greater than the electron affinity of said bulk material so that electrons are emitted from the exposed surface of said N-type layer facing said collecting electrode.

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