

Nov. 15, 1960

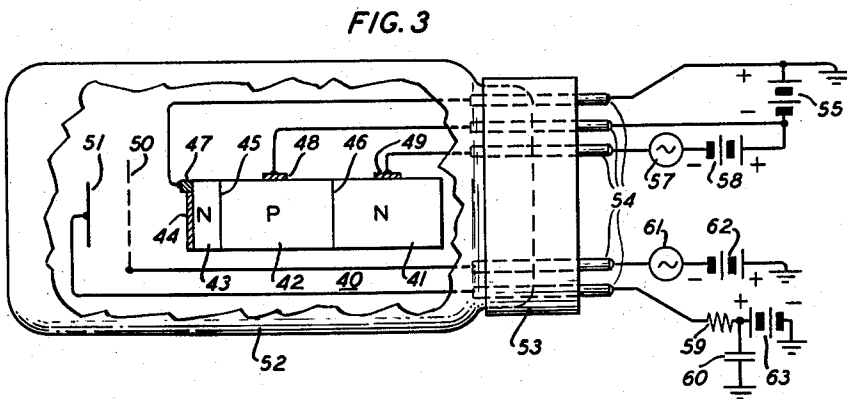
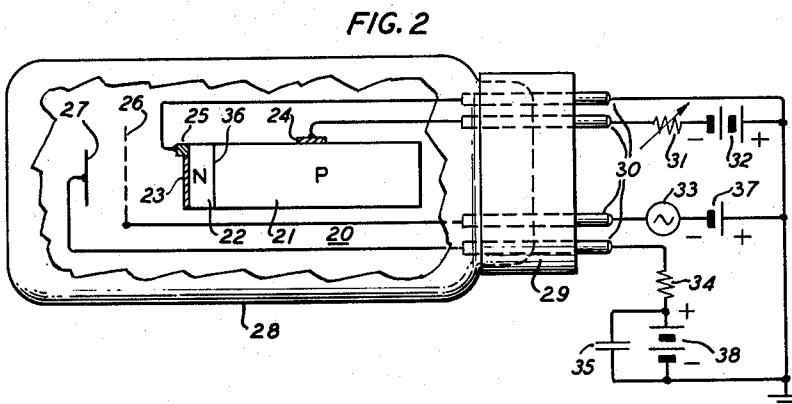
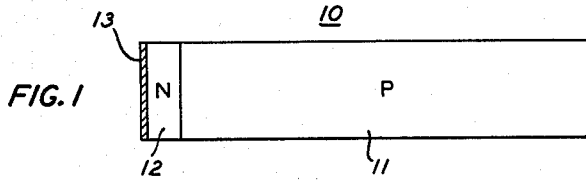
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SEMICONDUCTIVE ELECTRON SOURCE

Filed Sept. 1, 1955

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

FIG. 4

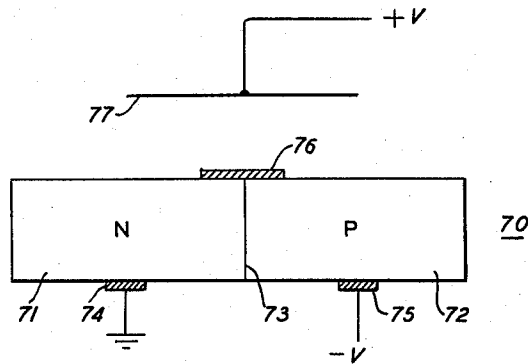


FIG. 5

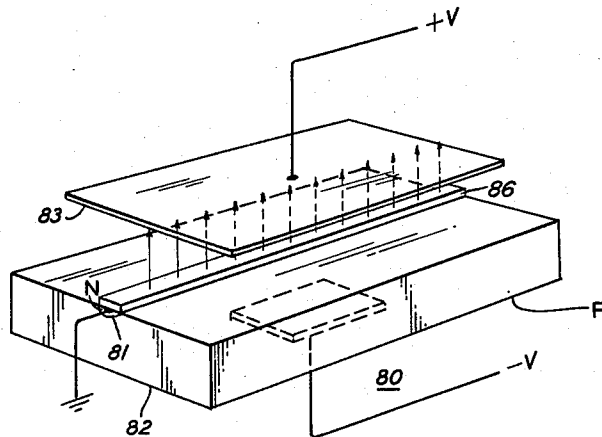
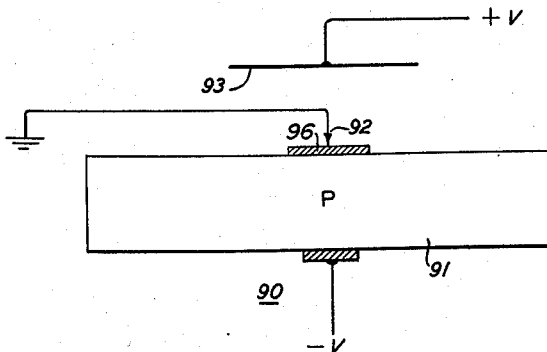


FIG. 6



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1

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SEMICONDUCTIVE ELECTRON SOURCE

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This invention relates to electron systems, and more particularly to arrangements in which electron emission is obtained from the surface of a semiconductive body having a p-n junction therein.

Conduction occurs in electronic semiconductors by means of two types of charge carriers: electrons and holes. Generically, those conductors wherein conduction is in the main by electrons are called n-type, while those wherein conduction occurs by holes are called p-type. The conductivity transition region between two contiguous zones of opposite conductivity type is known as a p-n junction.

There are two main types of electron sources, or cathodes, now known in the art, i.e., hot thermionic cathodes and so-called "cold" cathodes.

Hot thermionic cathodes are now generally used to provide an electron beam in the common forms of electron discharge devices. However, cathodes of this type have certain disadvantages. In particular, these cathodes require a heating element having a power source in order to warm the cathode to the elevated temperature necessary to obtain useful electron emission, and this heating element serves no other useful purpose, so that the power used by it is essentially wasted. Moreover, a "warming up" period is required after the electron tube is turned on, due to the heating period for the cathode, and, after the current is turned off, the cathode delivers a diminishing electron current until the cathode has cooled sufficiently to prevent further emission. Additionally, a thermionic cathode generally is characterized by a coating of a metal oxide, which is the main source of the electron emission. Due to the evaporation of this coating at the elevated temperatures required for operation, the life of the cathode and therefore of the electron discharge device itself is limited.

Other types of cathodes, such as "cold" cathodes, are sometimes used in some forms of electron discharge devices in place of hot cathodes. These "cold" cathodes fundamentally operate by the application of a strong external electric field which pulls electrons from a pointed unheated cathode. However, since these cathodes require a high external potential for operation, the extent of their usefulness is thereby limited.

A broad object of the applicant's invention is to provide an electron source of a novel type suitable for use in electron discharge devices.

An important feature of the present invention is a semiconductive element, advantageously of silicon or germanium, containing a p-n junction and having a coating of an alkali metal such as cesium on its surface near the p-n junction. It has been known hitherto that alkali metals such as cesium, when coated on a metallic surface, decrease the electron work function and thereby increase the rate of electron emission. In accordance with the present invention, a coating of an alkali or alkaline earth metal is used on the surface of a semiconductive body to reduce the electron work function at the semiconductor surface.

2

Moreover, to obtain copious electron emission from a cathode surface it is necessary to produce large numbers of electrons with a high energy. In previously known electron emitters, this is achieved in several ways. In thermionic emitters, electrons acquire energy by heat. In photoelectric emitters, the electrons receive their energy by absorption of light quanta. For "cold" cathode emission the potential barrier at the pointed cathode is lowered by applying a very strong external electric field, and thereby even low energy electrons can be pulled through the barrier.

In contradistinction, in accordance with the present invention, the electron emitter is a semiconductive body which includes a suitably biased p-n junction therein. Several arrangements of this type which are particularly advantageous are described herein.

An illustrative embodiment of the invention comprises a semiconductive body, the main portion of which is of p-type conductivity and a surface layer of which is of n-type conductivity. The conductivity, electrical potential, and geometry of the p-type and n-type regions are chosen in such a manner as to accelerate electrons to high kinetic energies near the n-type surface layer. Some of these high energy electrons escape from the semiconductor surface into the surrounding space and form useful electron emission. By providing an alkali coating in the region of the n-type surface layer, the escape of such electrons is facilitated, so that a usefully large electron emission may result. Such a semiconductor body, therefore, may be used as a cathode in a great variety of electron discharge devices. Moreover, such cathodes may be associated with electrodes to control the escaping electrons in a manner quite analogous to those used with conventional thermionic cathodes.

However, cathodes in accordance with the invention have several advantages over thermionic cathodes. They require no heating and operate at room temperature. The electron emission may be turned on or off at will quite rapidly, merely by turning off the bias across the p-n junction. Furthermore, a saving of space and power results by dispensing with the heating element.

In a preferred embodiment, a semiconductive body contains a p conductivity type region having a thin n-type region on one surface thereof, and an adsorbed cesium film on the surface of the n-type region. The p-n junction between the p-type and n-type regions is biased in the reverse direction in the avalanche breakdown region to provide electrons which are able to escape and give rise to electron emission. Avalanche breakdown is the term given to the condition of copious electron flow which occurs when a p-n junction is biased in the reverse direction beyond a certain voltage, which depends on the parameters of the semiconductive body. Normally, a p-n junction biased in the reverse direction provides a high impedance to current flow. However, when the biasing voltage exceeds a value which is related primarily to the specific resistivities of the two zones defining the p-n junction, a large number of high velocity electrons cross the p-n junction. A detailed discussion of such principles is set forth in an article by K. G. McKay in the Physical Review, volume 94, pages 879 through 884, May 15, 1954, entitled "Avalanche Breakdown in Silicon."

In another embodiment, a semiconductive body is of the n-p-n type in which one n surface zone is thin and contains an adsorbed coating of an alkali or alkaline earth metal thereon. The p-n junction associated with the thin n-type zone is biased in the reverse direction. Electron emission in this embodiment is controlled by controlling the electrons injected across the other p-n junction which is biased in the forward direction.

The invention will be better understood from the fol-

3

lowing more detailed description taken in conjunction with the accompanying drawings, in which:

Fig. 1 shows a typical semiconductive body for use in the practice of the invention;

Fig. 2 shows an amplifier which utilizes an electron source in accordance with one embodiment of the invention;

Fig. 3 shows an amplifier which uses an electron source in accordance with another embodiment of the invention; and

Figs. 4, 5 and 6 show other arrangements of semiconductive bodies that may be employed to obtain controlled electron emission, in accordance with other embodiments of the invention.

In each of these figures, for clarity of exposition the drawing is not to scale.

In particular, Fig. 1 represents schematically a semiconductive body, advantageously of silicon, for serving as an electron source. The main portion 11 of the semiconductive body is of p-type conductivity. An n conductivity zone 12, typically about 10^{-6} to 10^{-3} centimeters thick, is formed on one surface of main portion 11. Typically, zone 12 can be formed by localized diffusion from a vapor state of a group V impurity, such as phosphorus, using the techniques of the kind described by C. S. Fuller in copending application Serial No. 414,272, filed March 5, 1954. Additionally, a thin film of an alkali or alkaline earth metal 13, typically cesium, is adsorbed on the n-type zone 12, advantageously by deposition from the vapor state. This layer 13 advantageously is about a monomolecular layer thick.

Fig. 2 shows a semiconductor body of the type shown in Fig. 1 incorporated into an electron discharge device which is connected in an amplifier circuit. The various elements of the electron discharge device are housed in a vacuum envelope 28, which typically will be of glass. In the interest of simplicity, there have been omitted from the drawing details such as support and spacer members. Leads from the various elements are connected to external circuitry through pins 39 in the base 29 of the housing. P-type zone 21 and n-type zone 22 have, respectively, electrodes 24 and 25 making low resistance connection thereto. Electrode 25 is made to the edge of the front face of the body and positioned not to impede appreciably electron emission from the n-type surface portion. P-type zone 21 is biased negatively with respect to the n-type zone 22 by means of a voltage supply 32. The voltage applied is of sufficient magnitude that avalanche breakdown occurs at junction region 36. As previously discussed, the avalanche breakdown voltage depends on the parameters of the semiconductive body, and typically is designed to be of the order of tens or hundreds of volts. The breakdown current is adjusted to a suitable value by means of the variable current-limiting resistance 31. The electrons produced by the ionization of junction region 36 are accelerated by the electric field associated with the junction toward the nearby surface of the body. Some of these electrons have sufficient kinetic energy to escape over the potential barrier at the surface into the surrounding area. The surface coating 23, of an alkali metal such as cesium, reduces the height of the potential barrier and permits a larger fraction of the electrons to escape at the front face of the body. These electrons form an electron stream which can be utilized in the manner analogous to the use of the electron stream provided by a thermionic cathode.

For example, in this embodiment of Fig. 2 the electron stream is used in a vacuum tube which is operated as an amplifier. To this end, there is associated with the semiconductive cathode an electron permeable control grid 26, and an anode or plate 27, in the manner characteristic of the usual form of thermionic cathode vacuum tube.

An input circuit is connected between the cathode and

4

control grid. This input circuit includes the grid bias voltage supply 37 and the signal source 33. Typically, the voltage supply 37 maintains a negative bias relative to zone 22 of the cathode.

The output circuit is connected between the cathode and anode. The output circuit includes an anode voltage supply 38 which maintains the anode suitably positive with respect to zone 22 of the cathode and a load 34, shown schematically as a resistor. A capacitor 35 is used to by-pass signal currents across the anode voltage supply 38.

The operation of an amplifier of this type is analogous to the operation of a thermionic vacuum tube amplifier. Input signals applied to the control grid 26 by the signal source 33 act to modify correspondingly the amount of current which arrives at the anode. The variations in anode current are made to establish signal potential variations across the load 34 in the anode circuit.

Other arrangements of focusing electrodes, control grids, suppressor grids and screen grids can also be used in much the same way as with conventional thermionic cathodes.

Another cathode structure is shown incorporated into the electron discharge device shown connected in the amplifier of Fig. 3. The various tube elements are housed in an evacuated glass envelope 52. The semiconductive body 40 comprises a p-type zone 42 which is inserted between two terminal n-type zones 41 and 43. Zone 43 is coated with a thin film of an electron work function reducing material 44. Zone 43 is also made very thin, preferably of the order of 10^{-6} to 10^{-3} centimeters to facilitate electron emission therefrom.

P-n junction 45 between p zone 42 and n zone 43 is biased in the reverse direction by means of the voltage supply 55, such that only a small saturation current flows across junction 45 in the absence of any injection of electrons from the junction 46 which exists between zones 41 and 42.

This junction 46 is biased in the forward direction by means of a voltage supply 58, which advantageously is variable, for the injection of electrons into the p zone 42. These electrons diffuse across the p zone 42, which also should be thin to minimize recombination therein, and are accelerated to high energies when they fall down the large potential drop across p-n junction 45. Since the n region 43 is very thin, and the presence of coating 44 reduces the potential barrier at the surface, some of these electrons escape into the vacuum space before losing energy to the lattice. The amount of such electron emission can be adjusted easily by varying the voltage of voltage supply 58 which controls the amount of electron current injected across p-n junction 46.

A cathode of this type may be utilized in several different fashions. First, it may be operated with a fixed setting of the voltage supply 58, and associated with a control grid for operation in the manner of the tube shown in the amplifier of Fig. 2, in which input signals are applied between the cathode and the control grid. Alternatively, it may be incorporated in a tube which does not include a control grid, and, for amplifier operation, the signal may be applied in series with the voltage supply 58 to vary correspondingly the amount of current injected across the p-n junction 46 and hence the amount of current emitted by the cathode. As still a third alternative, such a cathode may be associated with a control grid, as in the tube shown in Fig. 2, and input signals applied either to vary the voltage across p-n junction 46 or between the cathode and control grid; or separate signals may be applied in each of these fashions for mixing. Fig. 3 shows an arrangement corresponding to this third alternative.

Provision is made for including a first signal source 57 in series with the voltage supply 58, which fixes the voltage across the p-n junction 46. Provision is also made for including a second signal source 61 in series

5

with the control grid bias supply 62 in the circuit connected between the zone 43 of the cathode and control grid 50. Accordingly, this arrangement may be employed to amplify signals applied by either source 57 or source 61, or alternatively used to mix signals applied by the two sources.

Moreover, in arrangements of this kind, it is feasible to substitute for the rectifying p-n junction 46 a rectifying point contact electrode biased in the forward direction for the injection of electrons into the p-type zone 42 for diffusion thereacross to p-n junction 45 for the control of electron emission from the body.

Another useful embodiment of this invention is represented by the electron gun of Fig. 4. Semiconductive body 70 has an n-type zone 71 and a p-type zone 72 with p-n junction 73 therebetween. This p-n junction is biased in the reverse direction in the avalanche breakdown region, and the high energy electrons which escape from one edge of this junction in a direction substantially parallel to the junction are collected by an anode 77 positioned transverse to the direction of flow in the vacuum space. A thin layer of an electron work function reducing material 76 is placed across the p-n junction at the edge of the junction opposite to the anode. Relatively little emission results from the edges adjacent the p-n junction where no coating is provided. This arrangement gives a line source of emitted electrons and does not require either the n-type or p-type zones to be thin. It is, of course, feasible to introduce between the emissive surface of the body 70 and the anode 77 focusing and control electrodes in the manner previously discussed. This is also true of the embodiments shown in Figs. 5 and 6.

In the electron gun shown in Fig. 5, a semiconductive body 80, whose main portion 82 is p-type, has an n-type channel 81 of line configuration in one surface. The p-n junction between such n-type and p-type regions is biased in reverse in the avalanche breakdown region, and the high energy electrons produced escape through the n-type channel region 81. A coating 86 of a suitable material, such as cesium, is placed on the surface of the n-type channel 81 to facilitate electron emission. The electrons emitted are collected at the anode 83. This embodiment has the advantage of closely controlling the area of electron emission. The n-type channel 81 could be of any desired configuration, such as annular or circular, to obtain an electron stream whose cross-section has a corresponding configuration.

Another embodiment of the invention is shown by the electron gun of Fig. 6. A point contact electrode 92, typically of tungsten, is placed on one surface of a p-type semiconductor body 91. A suitable low work function coating 96 is provided adjacent to the region of contact. The point contact 92 is biased in reverse, and the high energy electrons produced by the high fields near the point contact are emitted into vacuum and are drawn to the anode 93. This arrangement gives an electron-emissive cathode which is very small in area, and is effectively a point source of electrons. The operation of this device may be improved by suitable "forming" treatments of the point contact electrode of the type familiar to workers in point contact transistors. Such "forming" treatment consists of passing a large current through the point electrode and body for a short time.

While the previous discussion has been limited primarily to the use of cesium as electron work function reducing material, other materials can be employed for this purpose. Other alkali metals including lithium, sodium, potassium, and rubidium can be used, as well as alkaline earth metals such as calcium, strontium and barium. Furthermore, it may be advantageous to oxidize partially the metal employed to give a low work function metal-metal oxide film. Additionally, thin alloy films such as cesium-antimony may also be used in this way.

Moreover, semiconductive materials other than germanium and silicon may be employed without departing

6

from the spirit and scope of the invention. Such other semiconductors include the germanium-silicon alloys and group III-group V compounds such as gallium arsenide, aluminum arsenide, gallium antimonide, aluminum antimonide and indium phosphide.

Moreover, electrode arrangements other than those described herein may be employed. Also, other semiconductor arrangements for providing electron emission from a surface thereof, such as by applying high forward voltages rather than reverse voltages to obtain electron emission, are within the scope and spirit of this invention.

Furthermore, cathodes of this type may be used to serve as the electron source in an electron gun for use in various known cathode ray devices. For example, they can be used as an electron source to provide electron beams for use in high frequency amplifiers such as travelling wave, backward wave, and klystron tubes. In such arrangements, it is advantageous to include adjacent the semiconductive body a beam-forming electrode which forms the electrons emitted into a well collimated beam. Moreover, it is feasible to include as part of the electron gun an electrode system which is capable of diverging or converging the electron beam formed.

Accordingly, it is to be understood that the specific embodiments shown are merely illustrative of the principles of the invention. Various modifications may be devised by a worker in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. Apparatus for providing an electron stream comprising a semiconductive body including a rectifying barrier, a coating of an electron work function reducing material deposited on a portion of said body's surface adjacent to the rectifying barrier, means including a voltage source for biasing the rectifying barrier in the reverse direction beyond the point of avalanche breakdown for inducing electron emission outwardly into free space from said body in the region of said coating, and means spaced from said body and said coating for forming the electrons emitted into a stream.
2. An electron source comprising a semiconductive body the main portion of which is of p conductivity type and an end surface layer of which is of n conductivity type, means for biasing the p-n junction between said main portion and said surface layer in the reverse direction beyond the point of avalanche breakdown, and a coating of electron work function reducing material on the surface of said surface layer for inducing electron emission from said surface into free space.
3. An electron source comprising a semiconductive body having a pair of terminal zones of n-type conductivity and an intermediate zone of p-type conductivity, one terminal zone being sufficiently thin to permit high velocity electrons to diffuse through it into free space with little energy loss, means for biasing the p-n junction between said p zone and said thin n zone in the reverse direction, a coating of electron work function reducing material on said thin terminal n zone for facilitating electron emission from said zone into free space, and means for biasing the p-n junction between said p zone and the other terminal n zone in the forward direction to control electron flow into said thin n zone.
4. A point source of electrons comprising a semiconductive body of p conductivity type, a point contact forming a rectifying junction on one surface of said body, a coating of an electron work function reducing material on said surface in the vicinity of said point contact, means for reverse biasing said point contact for inducing electron emission from the body into free space in the region of contact, and means spaced from said body and said coating for forming the electrons emitted into a beam.
5. An amplifier comprising an electron source having a semiconductive body the main portion of which is of p conductivity type and an end surface layer of which is of n conductivity type, said n-type surface layer hav-

7

ing a coating of electron work function reducing material thereon, and means for biasing the p-n junction between said main portion and said surface layer in the reverse direction beyond the point of avalanche breakdown for inducing electron emission from the body into free space; an anode spaced from and in target relation with said electron source, a control element spaced from said electron source and interposed along the path of electron flow between said electron source and said anode, an input circuit connected to said control element, and an output circuit connected to said anode.

6. An amplifier having an electron source comprising a semiconductive body having a pair of terminal zones of n conductivity type and an intermediate zone of p conductivity type, one terminal zone being coated with an electron work function reducing material, said one terminal zone having a thickness of 10^{-6} to 10^{-3} centimeters to be electron-emissive, means for biasing the p-n junction between said p zone and said one terminal zone in the reverse direction for inducing electron emission from said one terminal zone into free space, and means for biasing the p-n junction between said p zone and the other terminal n zone in the forward direction to control electron flow into said one terminal zone; an anode spaced from and in target relation with said electron source, an input circuit connected between said p zone and said other terminal n zone, and an output circuit connected to said anode.

7. Apparatus for providing an electron stream comprising a semiconductive body including a rectifying barrier, a coating of cesium deposited on a portion of said body's surface adjacent to the rectifying barrier, means including a voltage source for biasing the rectifying junction in the reverse direction beyond the point of avalanche breakdown for inducing electron emission outwardly into free space from said body in the region of said coating, and means spaced from said body and said coating for forming the electrons emitted into a stream.

8. An electron source comprising a semiconductive body having a succession of zones wherein each zone is of opposite conductivity type to that of the zone contiguous thereto, a coating of an electron work function reducing material on a surface zone of said body, means for applying a reverse bias across the junction between said surface zone and a zone of opposite conductivity type contiguous thereto, means forming a rectifying junction with said contiguous zone for the injection of minority carriers therein for diffusion to said reverse-biased junction, and means spaced from said body and said coating for forming electrons emitted from the surface zone of said reverse-biased junction into a stream.

9. An electron source as in claim 2 including means spaced from said body and said coating for forming the electrons emitted into a stream.

8

10. An electron source as in claim 3 including means spaced from said body and said coating for forming the electrons emitted into a beam.

11. An amplifier comprising an electron source having a semiconductive body the main portion of which is of p conductivity type and an end surface layer of which is of n conductivity type, said n-type surface layer having a coating of cesium thereon, and means for biasing the p-n junction between said main portion and said surface layer in the reverse direction beyond the point of avalanche breakdown for inducing electron emission from the body into free space, an anode spaced from and in target relation with said electron source, a control element spaced from said electron source and interposed along the path of electron flow between said electron source and said anode, an input circuit connected to said control element, and an output circuit connected to said anode.

12. An electron source comprising a semiconductive body having a succession of zones wherein each zone is of opposite conductivity type to that of the zone contiguous thereto, of which one terminal zone is adapted for emitting electrons, said terminal zone and the zone contiguous thereto having respective low impedance contacts for applying to said body a biasing potential to accelerate electrons within said body toward said terminal zone, the surface of said terminal zone including a thin layer of a material capable of reducing the electron work function of said surface to permit escape of electrons from said surface into free space, an anode spaced from and in target relationship with said electron source, and a control element spaced from and intermediate said electron source and said anode.

13. An electron source for obtaining the emission of electrons into free space comprising a semiconductive body including a rectifying barrier, means connected to said body for biasing said barrier and for providing high energy electrons within said body, and means for reducing the electron work function of a surface of said body to a value sufficiently low to assure emission of said high energy electrons from within said body outwardly into free space, said last-mentioned means comprising a thin layer of an electron work function reducing material, one surface of said layer being adhered to a portion of the surface of said body adjacent to said barrier and an opposed surface of said layer being effectively entirely bounded by free space.

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