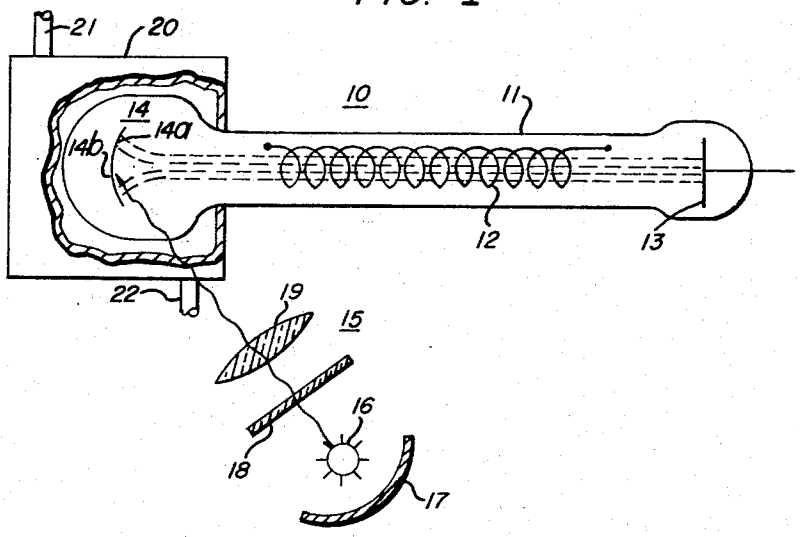
Sept. 27, 1966 W. M. FEIST 3,275,869

LOW NOISE ELECTRON EMITTERS

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FIG. 1



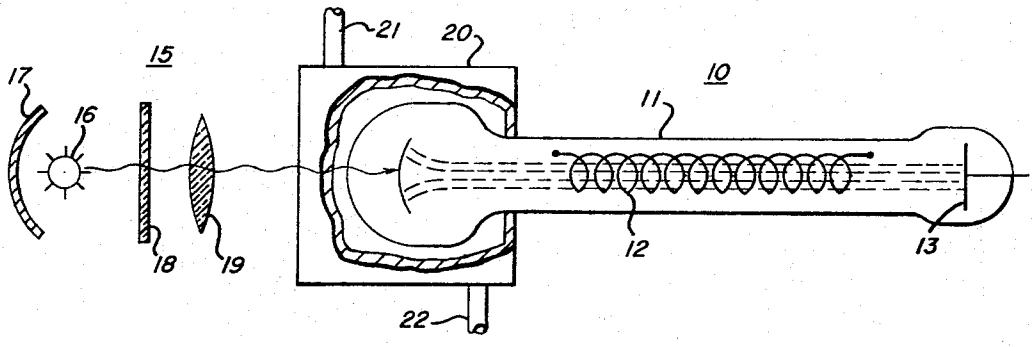


FIG. 2

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LOW NOISE ELECTRON EMITTERS

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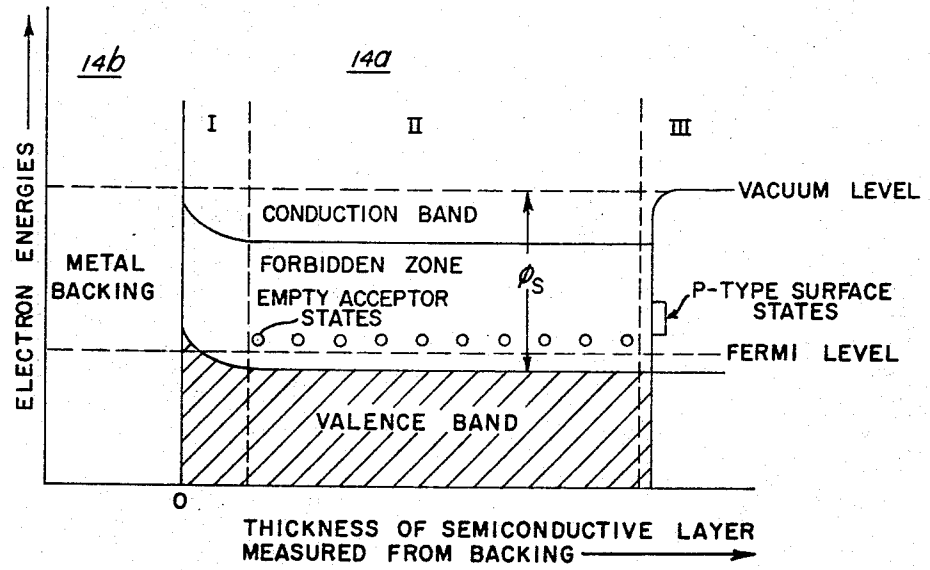


FIG. 3

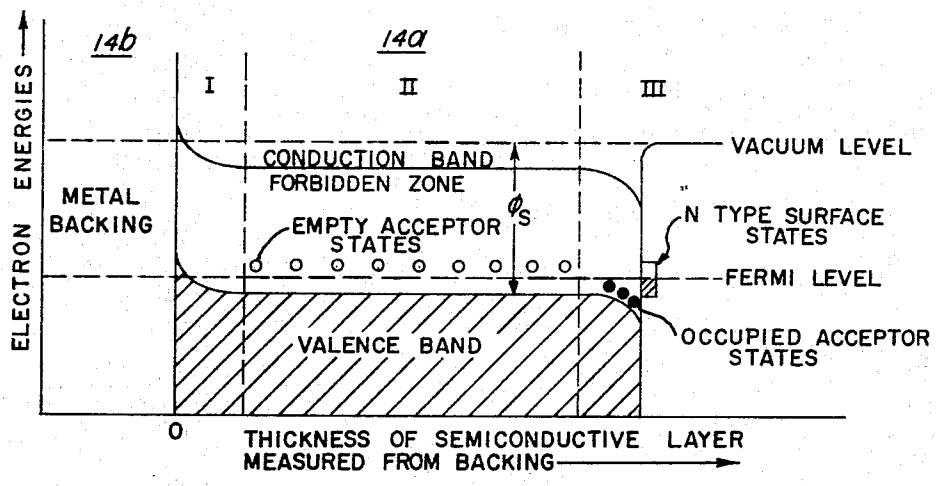


FIG. 4

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LOW NOISE ELECTRON EMITTERS

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Filed July 12, 1963, Ser. No. 294,555
8 Claims. (Cl. 313—65)

The present invention is concerned with an electron emissive device and, more particularly, with an electron emissive device for producing a stream of electrons having a narrow range of energies.

While the invention may be applied to electron tubes in general, it is particularly useful in a travelling wave tube, an electron tube in which an electron beam of very low noise content is especially desirable.

Presently, the large majority of electron tubes utilize thermionic cathodes wherein a stream of electrons is emitted by heating a cathode to high temperatures (e.g. 1500° K.). The kinetic energies or velocities of electrons produced by thermionic emission vary over a wide range of values which, theoretically has no upper limit, i.e. a Maxwellian distribution. Such a wide spread of electron energies manifests itself as undesirable noise in the output signal of a travelling wave tube or similar device.

It is therefore an object of the present invention to provide a low noise source of electrons which is suitable for use in a variety of electron tubes, including travelling wave tubes.

A low noise electron emitter constructed in accordance with the present invention comprises a cathode having a surface layer of material which responds to electromagnetic radiation by emitting electrons. The material is substantially insensitive to radiation at wave-lengths above a threshold wavelength λ_0. The electron emitter further comprises a source of electromagnetic radiation aligned with the cathode surface, the radiation from the source extending over a range of wavelengths beginning at a lower wavelength limit $\lambda_{lim.}$ which is less than, but close to, the threshold wavelength λ_0 of the cathode surface material.

In accordance with a further aspect of the invention, means are also provided for cooling the cathode to temperatures substantially below room temperature so as to aid in reducing the energy spread of electrons emitted from the cathode.

The invention will now be further described with reference to the accompanying drawings in which:

FIG. 1 is a schematic representation of a first embodiment of the invention as applied to a travelling wave tube;

FIG. 2 is a schematic representation of a second embodiment of the invention as applied to a travelling wave tube;

FIG. 3 is an energy level diagram of a cathode having a semiconductive electron emitting layer with p-type surface states which may be employed in the FIG. 1 or FIG. 2 embodiments of the invention; and

FIG. 4 is an energy level diagram of a cathode having a semiconductive electron emitting layer with n-type surface states which may be employed in the FIG. 1 or FIG. 2 embodiments of the invention.

Referring to FIG. 1, a schematic representation of a travelling wave tube, indicated generally by the reference numeral **10**, comprises an evacuated glass envelope **11**, a slow wave structure shown as a helix **12**, a collector electrode **13** and an electron emissive cathode **14**. Additional elements of a conventional travelling wave tube such as the input and output waveguides, the electron accelerating anode and electric and magnetic beam focusing means have been omitted since they are not essential

to an understanding of this invention. In accordance with the invention, cathode **14** is sensitive to electromagnetic radiation over a given range of wavelengths, beginning at a threshold wavelength λ_0, for emitting electrons. While the invention is not restricted to cathodes sensitive to radiation at wavelengths in the visible spectrum, the invention will be further described with reference to such a cathode since materials sensitive to radiation at such wavelengths are well known. Cathode **14** may comprise either one of the commonly known photoemissive metals or, as will be described hereinafter, cathode **14** comprises an electron emitting layer of semiconductive material **14***a* adhered to a metallic backing layer **14***b*. Preferably, emitting layer **14***a* comprises a layer of an alkali antimonide such as the intermetallic compound of cesium and antimony Cs_3Sb to which additional p-type acceptor impurities have been added as wil lbe more fully explained below in connection with FIGS. 3 and 4.

A source of electromagnetic radiation, indicated generally by reference numeral **15**, is disposed external to envelope **11** and optically aligned with emitting layer **14***a* of cathode **14**. Source **15** comprises a light source **16**, a reflector **17**, a low-pass filter **18** and a focusing lens **19**. Low-pass filter **18** serves to block radiation at wave-lengths less than a limiting wavelength $\lambda_{lim.}$, where $\lambda_{lim.}$ is close to but less than the threshold wavelength λ_0 of cathode **14**. From the standpoint of efficiency, the upper wavelength limit of source **16** is also preferably close to λ_0. However, this latter limit is not essential to the invention. Radiation source **15** may, in the alternative, comprise any other type of device which provides radiation having a sharply defined lower wavelength limit. For example, an essentially monochromatic source of radiation such as a gaseous discharge device or a laser may be used to provide the desired radiation or illumination.

A means for cooling cathode **14**, shown as a refrigerating enclosure **20**, is disposed around the outside of glass envelope **11** at the end thereof which contains cathode **14**. An inlet conduit **21** and an outlet conduit **22** are attached to refrigerating enclosure **20** to permit entry and discharge of a cooling medium. Refrigerating enclosure **20**, or at least that part thereof which lies along the optical path between cathode **14** and radiation source **15**, is transparent to radiation at wavelengths between the lower wavelength limit $\lambda_{lim.}$ of source **15** and the threshold wavelength λ_0 of cathode **14**.

Referring now to FIG. 3 of the drawing, an energy level diagram is shown for a cathode having an electron emitting layer of semiconductive material constructed in accordance with the invention. Electron energy is plotted along the axis of ordinates, while the thickness of semiconductive layer **14***a* measured from metallic backing **14***b* is plotted along the axis of abscissae.

In the diagram of FIG. 3, the metallic backing layer **14***b* of cathode **14** is shown to the left of the axis of ordinates, while the emitting layer of semiconductive material **14***a* is shown to the right of the axis of ordinates. The semiconductive layer is divided into three regions in FIG. 3. The three regions are designated as the region of contact between the metallic backing and the semiconductive layer (I), the bulk region (II) and the surface region (III). Furthermore, three discrete energy level bands are shown, the highest being the conduction band which defines the energy levels normally occupied by some conduction electrons when the material is at temperatures above absolute zero (i.e. greater than 0° K.), the lowest being the valence band which defines the energy levels occupied by the more tightly bound valence electrons and the intermediate being the forbidden energy gap or zone which separates the allowable

valence and conduction electron energy levels. The "Fermi level" is indicated by a dashed line and is that energy level at which the probability of occupation by an electron is ½. A plurality of unoccupied acceptor states which may, for example, be produced by diffusion of excess cesium atoms or other p-type impurities within the semiconductive layer **14***a*, are arranged at an energy level in the forbidden zone close to the upper limit of the valence band. The presence of unoccupied acceptor states close to the valence band serves to shift the Fermi level of the material from a level approximately midway in the forbidden gap to a level close to the upper limit of the valence band. A shift of the Fermi level of this nature is indicative of the fact that fewer electrons are available for emission from energy levels above the valence band when such acceptor states are present.

The operation of the FIG. 1 apparatus utilizing a cathode **14** which has an energy level characteristic as shown in FIG. 3 will now be described.

Light source **16**, in conjunction with reflector **17** and focusing lens **19**, produces a beam of light which falls upon emitting layer **14***a* of cathode **14**. Low-pass filter **18** serves to limit the light falling upon emitting layer **14***a* to a band of wavelengths having a lower wavelength limit $\lambda_{lim.}$ which is within the range of wavelengths to which emitting layer **14***a* is sensitive. Furthermore, the lower wavelength limit $\lambda_{lim.}$ is close to but less than the threshold wavelength λ_0 of emitting layer **14***a* as will be more fully explained below. Light impinging upon emitting layer **14***a* causes electrons to be emitted from layer **14***a* towards helix **12** and collector **13**. In accordance with the well-known operation of a travelling wave tube, the electrons are focused into a beam by focusing fields (not shown). The beam of electrons passes through the center of helix **12**, giving up energy to electromagnetic waves which are coupled to helix **12** by means of a waveguide or similar device (not shown). The amplified electromagnetic wave is coupled out of helix **12** by means of a second waveguide (not shown) and the electrons are collected by collector **13**.

The emission of electrons from cathode **14** will now be considered in greater detail. The maximum energy or velocity of the electrons emitted from emitting layer **14***a* depends upon

(1) The wavelength (or frequency) of the incident light, and

(2) The difference between the potential energy of the electron within the layer **14***a* and the potential energy of an electron at the vacuum level outside the layer **14***a* (the latter difference being the photoelectric work function ϕ_{ph} where the emitted electron occupied the highest energy level occupied by electrons within the layer **14***a*).

Specifically, the maximum energy of an emitted electron is given by the expression

$$E=h\upsilon-\phi$$

where

E is the energy of the emitted electron,
h is Planck's constant,
υ is the frequency of incident light, and
ϕ is the energy required to raise the electron from an energy level inside the material to the vacuum level.

The threshold wavelength λ_0 of emitting layer **14***a* is related to the work function ϕ_{ph} thereof by the expression

$$\lambda_0=12.395/\phi_{ph}$$

where λ_0 is measured in thousands of Angstrom units and ϕ_{ph} is measured in electron volts.

Furthermore, the maximum energy difference between photo-emitted electrons is given by the expression

$$(\Delta E)_{max.}=12.395\frac{(\lambda_0-\lambda_{lim.})}{\lambda_0\,\lambda_{lim.}}$$

where

$\lambda_{lim.}$=minimum wavelength of the incident light in thousands of Angstrom units,
λ_0=threshold wavelength in thousands of Angstrom units, and
$(\Delta E)_{max.}$=maximum energy difference of emitted electrons in electron volts.

It can therefore be seen that the maximum energy difference between photo-emitted electrons may be controlled for a material having a given threshold wavelength by limiting the minimum wavelength of the incident light to a value close to the threshold wavelength λ_0. In a travelling wave tube such as is shown in FIG. 1, it is possible, in accordance with the present invention, to restrict the maximum energy spread of emitted electrons to values not presently attainable from a thermionic cathode itself. For example, in order to restrict the maximum energy spread of emitted electrons to a value of 0.1 ev. (electron volts), the lower wavelength limit $\lambda_{lim.}$ of source **15** is restricted to a wavelength which satisfies the expression

$$0<\lambda_0-\lambda_{lim.}\leq\frac{\lambda_0^2}{123.95}$$

where λ_0 and $\lambda_{lim.}$ are measured in thousands of Angstrom units. The threshold wavelength λ_0 for a cathode having a cesium-antimony surface may be, in round figures, of the order of 7000 A. (Angstrom units). In such a case, the above expression is satisfied if the lower frequency limit $\lambda_{lim.}$ of source **15** lies within the limits

$$7000\text{ A.}<\lambda_{lim.}<7395\text{ A.}$$

Further reduction in the energy spread between emitted electrons may be achieved by further limiting the lower wavelength limit $\lambda_{lim.}$ of source **15**.

In order to achieve practical levels of emission from a cathode illuminated by such a narrow band of wavelengths near the threshold wavelength λ_0, th photoelectric yield (i.e. unit of emission current per unit of incident illumination) of emitting layer **14***a* must rise sharply within the range of wavelengths between λ_0 and $\lambda_{lim.}$. The desired sharply rising photoelectric yield characteristic is obtained by insuring that a large number of electrons occupy energy levels close to the highest occupied energy level in emitting layer **14***a*. Since the majority of electrons within any material occupy energy levels in the valence band while only relatively few electrons are thermally excited to higher energy levels (e.g. in the conduction band or, as with p-type semiconductors, in defect level states in the forbidden gap), the desired large number of electrons within a narrow band of energies is best obtained by preventing electrons from occupying levels above the valence band. Ideally, the photoelectric work function ϕ_s will then be equal to the difference between the valence band upper limit and the vacuum level. Furthermore, the photo-emitted electrons will be supplied almost exclusively from valence band energy levels. In accordance with the invention, the desired sharply rising photoelectric yield over a narrow band of wavelengths close to the threshold wavelength λ_0 is obtained

(1) By cooling cathode **14** by means of refrigerating enclosure **20** so as to "freeze" electrons out of energy level states above the valence band, and

(2) By introducing p-type acceptor impurities having unoccupied energy levels near the upper limit of the valence band throughout emitting layer **14***a*.

A cooling medium such as a liquified gas (e.g. helium) is passed through refrigerating enclosure **20** by means of inlet conduit **21** and outlet conduit **22** so as to cool cathode **14** to a temperature substantially below room temperature (e.g. even approaching absolute zero) and thereby reduce the number of electrons occupying energy levels above the valence band energy levels.

The unoccupied p-type acceptor states (shown as circles in FIGS. 3 and 4 above the Fermi level) serve to decrease the probability that energy levels above the valence band are occupied by electrons. Sufficient acceptor states may even be added to depress the Fermi level below the upper limit of the valence band.

Referring now to FIG. 2, a second embodiment of the invention in a travelling wave tube is shown. Corresponding parts in FIG. 2 are indicated by the same reference numerals as in FIG. 1.

The FIG. 2 embodiment is generally similar to the FIG. 1 embodiment with the exception that cathode **14** comprises an electron emitting layer **14***a* and a semitransparent metallic backing layer **14***c*. In this case, the radiation from source **15** impinges upon semitransparent backing layer **14***c* and passes through semitransparent backing layer **14***c*, causing the emission of electrons from emitting layer **14***a* towards helix **12**. The thickness of emitting layer **14***a* is preferably approximately equal to the maximum escape depth for photoexcited electrons (e.g. about 200–300 Angstrom units for an alkali antimonide) so as to obtain a high photoelectric yield from cathode **14**. In all other respects, the embodiment shown in FIG. 2 corresponds to that shown in FIG. 1.

Referring now to FIG. 4, an energy level diagram similar to the energy level diagram of FIG. 3 is shown. However, FIG. 3 indicates the effect on the energy level diagram of the presence of p-type surface states whereas FIG. 4 indicates the effect thereon of the presence of n-type surface states. Surface states having energy levels within the forbidden gap of a semiconductor result from the presence of impurities on the semiconductor surface. Where, as in FIG. 3, both the bulk region (region II) and the surface states (region III) are p-type, the surface states do not have any noticeable effect on the energy level diagram. However, where, as in FIG. 4, the bulk region (II) is of p-type material and the surface states are n-type, the upper limit of the valence band and the lower limit of the conduction band bend downward. This band bending takes place in the following manner. At equilibrium, the Fermi level must be the same within bulk region (II) as it is within the surface region (III). Therefore, the presence of n-type surface states requires a redistribution of negative charge from the surface states to unoccupied p-type acceptor states within the semiconductive material. As shown in FIG. 4, acceptor states near the surface are filled or occupied by electrons transferred from the n-type surface states. The electric fields set up by this redistribution of charge result in the downward bending of the energy bands (i.e. valence and conduction bands) near the surface of the semiconductive material. The occupied acceptor states in the surface region (III) might shift the threshold wavelengths λ_0 towards higher wavelengths. It is therefore desirable to minimize the effect of such n-type surface states. This objective may be accomplished by either absorbing a monolayer of molecules on the surface of emitting layer **14***a* so as to preclude the formation of n-type surface states or by providing sufficient p-type acceptor states close to the surface so as to minimize the distance over which the band bending occurs.

While this invention has been described with reference to cathode materials which are sensitive to radiation at wavelengths in the visible spectrum, it will be recognized that the invention contemplates use of radiation sources and emitting devices which operate at other wavelengths as well.

Furthermore, while it has been indicated that, in accordance with the invention, an electron beam having a maximum energy spread of 0.1 electron volts may be produced, practical beam currents (e.g. 20 microamperes) may be produced with a maximum energy spread of, for example, 0.02 electron volt using the type of cathode materials described above.

What is claimed is:

1. A low noise electron emitter comprising a cathode having a layer of material responsive to electromagnetic radiation for emitting electrons, said material being substantially non-responsive to radiation at wavelengths above a threshold wavelength, said electron emitter further comprising means for producing electromagnetic radiation over a range of wavelengths, said means being aligned with said cathode, the shortest wavelength produced by said means being less than said threshold wavelength of said layer of electron emitting material and said shortest wavelength being limited with respect to said threshold wavelength to limit the maximum energy difference between electrons emitted from said layer of electron emitting material.

2. A low noise electron emitter comprising a cathode having a layer of material responsive to electromagnetic radiation for emitting electrons, said material being substantially non-responsive to radiation at wavelengths above a threshold wavelength, said electron emitter further comprising means for producing electromagnetic radiation over a range of wavelengths, said means being aligned with said cathode, the shortest wavelength produced by said means being less than said threshold wavelength of said layer of electron emitting material and said shortest wavelength being limited with respect to said threshold wavelength to limit the maximum energy difference between electrons emitted from said layer of electron emitting material, said electron emitter still further comprising means for cooling said cathode to reduce the difference between said threshold wavelength and the shortest wavelength radiation produced by said means for producing electromagnetic radiation, whereby electrons having a narrow range of energies corresponding to the difference in wavelength between said threshold wavelength and said shortest wavelength are emitted from said cathode.

3. A low noise electron emitter comprising a cathode having a layer of material responsive to electromagnetic radiation for emitting electrons, said material being substantially non-responsive to radiation at wavelengths above a threshold wavelength, said electron emitter further comprising a source of electromagnetic radiation aligned with said cathode, means interposed between said cathode and said source for limiting the radiation impinging upon said cathode to a range of wavelengths having a lower limit, the lower wavelength limit being less than said threshold wavelength and selected with respect to said threshold wavelength to limit the maximum energy difference between electrons emitted from said layer of electron-emitting material, said electron emitter still further comprising means for cooling said cathode to decrease the difference between said threshold wavelength and said lower wavelength limit.

4. A low noise electron emitter comprising a cathode, said cathode comprising a layer of electron-emissive material responsive to electromagnetic radiation over a given range of wavelengths for emitting electrons, said material being substantially non-responsive to radiation above a threshold wavelength, the threshold, wavelength varying with the temperature of said material, said electron emitter further comprising a source of electromagnetic radiation, said source having a short wavelength limit which is within the range of wavelengths to which said material is responsive and which is close to the threshold wavelength for said material at a temperature of absolute zero, said electron emitter still further comprising means for directing radiation from said source of radiation to said cathode and means for cooling said cathode to reduce the difference between said threshold wavelength and said short wavelength limit whereby electrons having a narrow range of energies corresponding to the difference in wavelength between said threshold and said short wavelength limit are emitted from said cathode.

5. A low noise electron emitter comprising a cathode having a surface of material responsive to electromagnetic radiation for emitting electrons, said material being substantially non-responsive to radiation at wavelengths above a threshold wavelength λ_0, said emitter further comprising a source of electromagnetic radiation aligned with said cathode, said source having a lower wavelength limit $\lambda_{lim.}$ which is related to said threshold wavelength λ_0 by the expression

$$0<\lambda_0-\lambda_{lim.}\leq\frac{\lambda_0^2}{123.95}$$

where $\lambda_{lim.}$ and λ_0 are measured in thousands of Angstrom units (A.) whereby the maximum energy difference between electrons emitted from said material is equal to or less than 0.1 electron volt.

6. A low noise electron emitter comprising a cathode, said cathode comprising a layer of semiconductive material responsive to electromagnetic radiation over a given wavelength range for emitting electrons, said material being substantially non-responsive to radiation at wavelengths above a threshold wavelength, said cathode further comprising p-type acceptor states diffused within said semiconductive material, the energy levels of said acceptor states being substantially closer to the upper limit of valence band energy levels than to the lower limit of conduction band energy levels of said semiconductive material, said electron emitter further comprising a source of electromagnetic radiation, said source having a short wavelength limit less than said threshold wavelength of said semiconductive material but limited with respect to said threshold wavelength to limit the maximum energy difference between electrons emitted from said layer of semiconductive material, said electron emitter still further comprising means for directing radiation from said source of electromagnetic radiation to said cathode and means for cooling said cathode whereby electrons having a narrow range of energies corresponding to the difference in wavelength between said threshold wavelength and said short wavelength limit are emitted from said layer of semiconductive material.

7. A low noise electron emitter comprising a cathode responsive to electromagnetic radiation over a range of wavelengths beginning at an upper threshold wavelength for emitting electrons, said cathode comprising a metallic backing layer and an electron emitting layer of semiconductive material, one surface of said emitting layer being in contact with one surface of said backing layer, said emitting layer including diffused p-type acceptor impurities having acceptor energy levels in the vicinity of the maximum valence band energy level of said emitting

layer, said emitting layer being substantially equal in depth to the maximum escape depth for photoexcited electrons from said emitting layer, said electron emitter further comprising a source of electromagnetic radiation, the radiation having a sharply defined short wavelength limit, said short wavelength limit being less than said threshold wavelength of said semiconductive material but limited with respect to said threshold wavelength to limit the maximum energy difference between electrons emitted from said semiconductive material, said electron emitter still further comprising means for directing radiation from said source of electromagnetic radiation to said cathode and means for cooling said cathode whereby electrons having a narrow range of energies corresponding to the difference in wavelength between said threshold wavelength and said short wavelength limit are emitted from the cathode.

8. A low noise electron emitter comprising a cathode, said cathode comprising a layer of semiconductive material responsive to electromagnetic radiation over a given wavelength range for emitting electrons, said material being substantially non-responsive to radiation at wavelengths above a threshold wavelength, said semiconductive material comprising a compound of compound alkali metals and antimony with p-type acceptor states diffused within said layer of semiconductive material, the energy levels of said acceptor states being substantially closer to the valence band energy level than to the conduction band energy level of said semiconductive material, said electron emitter further comprising a source of electromagnetic radiation aligned with said cathode, the shortest wavelength produced by said source being less than the threshold wavelength of said semiconductive material and limited with respect to said threshold wavelength to limit the maximum energy difference between electrons emitted from said semiconductive material, said electron emitter still further comprising means for cooling said cathode to a temperature in the vicinity of absolute zero whereby electrons having a narrow range of energies corresponding to the difference in wavelengths between said threshold wavelength and said shortest wavelength of said source are emitted from said semiconductive material.

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