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July 11, 1967 J. M. LAVINE ETAL 3,330,991
NON-THERMIONIC ELECTRON EMISSION DEVICES
Filed July 12, 1963

FIG. 1

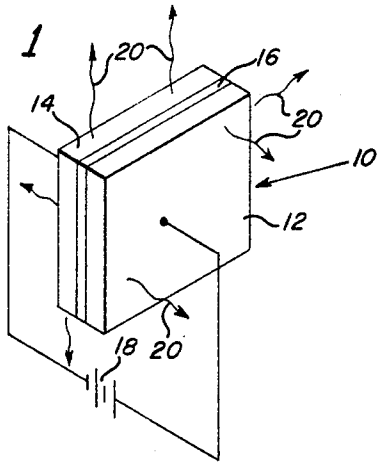
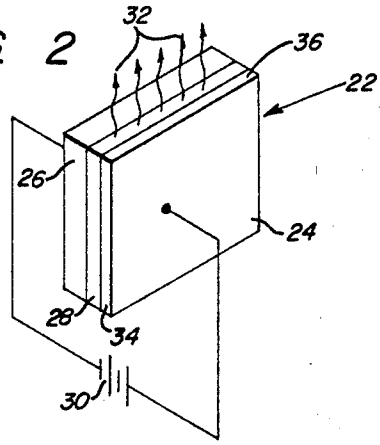


FIG. 2



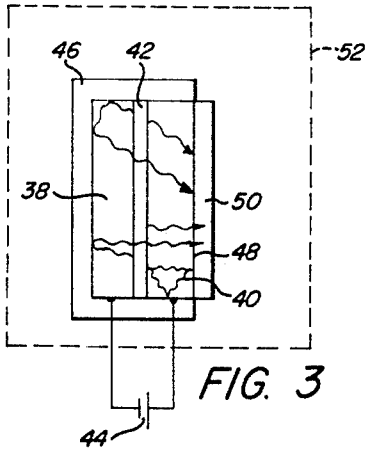


FIG. 3

reflective coating

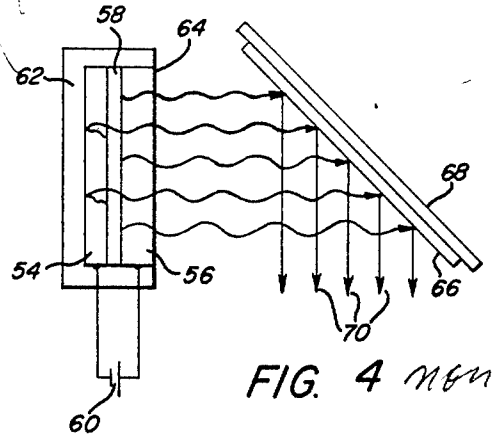


FIG. 4 non transmissive

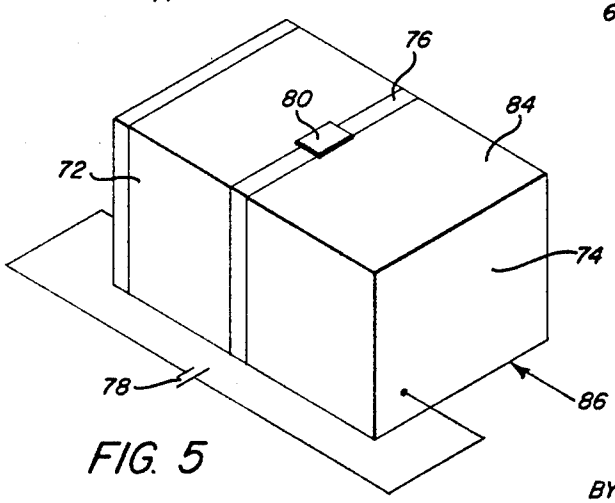


FIG. 5

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3,330,991

Patented July 11, 1967

3,330,991

NON-THERMIONIC ELECTRON EMISSION DEVICES

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Filed July 12, 1963, Ser. No. 294,554
6 Claims. (Cl. 315—94)

This invention pertains generally to electron emission devices, and more particularly to electron emission devices of the "cold-cathode" or non-thermionic type.

Thermionic cathodes are well known in the electron tube art employing, in the most common form a heater element and a surrounding sleeve having an electron emissive coating thereon. As the heater raises the temperature of the cathode sleeve, electrons are emitted, usually in vacuo, from the sleeve. Oxide-coated thermionic emitters of this type are reasonably efficient, commonly yielding ten to two hundred milliamperes per watt. However, the energy spectrum of the output of such emitters is quite broad, and noise also results from high-temperature operation. The presence of a high temperature source also has deleterious effects upon other components of a vacuum tube.

One solution to the foregoing problems is the utilization of so-called cold-cathodes or non-thermionic emitters. As may be inferred from the name, cold-cathode emitters do not depend upon thermal activation in order to achieve electron emission. Instead, other modes of energy conversion may be employed to effect the desired electron emission. For example, one common form of non-thermal electron emission is characterized by photoelectric effects. That is to say, non-thermal electron emission may be achieved by means of a suitable photon source which illuminates a photoemissive body or coating. Since the electron emission in such a device is a result of photoelectric, rather than thermal activity, the energy-spread of the emitted elecrons can be made relatively narrow, thus affording, among other things, low-noise operation.

It would seem then that photoelectric emission of electrons might well provide the answer to the problem of low-noise monoenergetic operation. However, photoelectric cathodes have not been widely used as a general source of electrons, and this lack of general acceptance stems mostly from a rather drastic shortcoming of the photoelectric emitters employed heretofore; viz., the maximum output has been quite low, especially in comparison to that obtained with thermionic cathodes. More specifically, the over-all efficiency in converting input power into vacuum electrons obtained in the photoelectric emitters of the prior art is several orders of magnitude less than that of thermionic devices.

Thermionic emitters often necessitate thermal insulation and comparatively fragile mounting elements to reduce heat transfer. Thermionic cathodes present out-gassing and other problems such that the useful life is restricted. Further, thermionic emission is slow-starting, necessarily involving a warm up period prior to efficient operation and precluding fast modulation of the emission.

It is accordingly a primary object of the present invention to provide a photoelectric emission source with improved properties.

A more specific object of this invention is to provide an electron emission source which provides an output comparable in density with that of representative thermionic emitters, while avoiding the necessity of employing heater means and the like.

A further object of the invention is to provide a photoelectric electron emitter which is capable of providing an emission current far surpassing that of the photoelectric emitters of the prior art.

An ancillary object of the invention is to provide an electron emission source characterized by a substantially monoenergetic output.

Other objects of this invention are to provide a low-noise electron source, eliminate thermal insulation in the device, provide rigid mounting of the cathode on the envelope of the tube itself, thereby eliminating fragile mounting parts. The invention further eliminates the need of out-gassing and thermionic emission and leakage, and further provides incident starting and emission that may be modulated at very high frequencies.

In accordance with the present invention, the above and other objects are achieved by means of the combination of a semiconductor junction and a photoemissive body. The semiconductor junction is suitably biased to effect the emission of photons therefrom, and the illumination of the photoemissive body by such photons results in the emission of electrons. The junction bias is, in the preferred embodiment set forth herein, a forward bias, and the photon emission is a manifestation of recombination-radiation. Recombination-radiation is herein defined to include incoherent radiation produced by recombination, coherent or laser action produced by recombination effects and super-radiance which includes coherent radiation and incoherent radiation.

With the above considerations and objects in mind, the invention itself will now be described in connection with a preferred embodiment thereof given by way of example and not of limitation, and with reference to the accompanying drawings, in which:

FIG. 1 is a perspective representation of a semiconductor junction device exhibiting recombination-radiation;

FIG. 2 is a perspective representation of a semiconductor junction device exhibiting laser radiation;

FIG. 3 is a schematic representation of one preferred form of the electron emitter of the present invention;

FIG. 4 is a schematic representation of an alternative preferred form of the electron emitter of the present invention; and

FIG. 5 is a perspective representation of a third form of the electron emitter of the present invention.

Referring now particularly to FIG. 1, the principle of recombination-radiation is illustrated therein by means of a semiconductor device indicated generally at **10** and comprising two elements **12** and **14** of opposite conductivity type, forming therebetween a semiconductor junction **16**. A forward bias is applied across junction **16** by means of voltage source **18**, the opposite poles of which are connected to respective elements **12** and **14**. As is well known to those skilled in the art, when a suitably prepared junction in a material such as gallium-arsenide is forward biased, photons are produced by the radiative recombination of electrons with holes within the semiconductor material. This recombination-radiation generally emerges in all directions, mostly perpendicular to the junction, unless blocked or reflected by metal contacts or supports as is indicated by the plurality of arrows **20** in FIG. 1.

It has been observed that the recombination of electrons with holes in a diffused semiconductor diode made of gallium-arsenide is mostly radiative. That is to say, most of the electrons which are injected by forward biasing the diode cause the emission of a photon upon recombination. In the case of gallium-arsenide, this photon has an energy slightly less than the bandgap, so that the gallium-arsenide is relatively transparent to the resultant radiation. It follows that most of the radiation must pass

out of the crystal, since the absorption of photons at this energy level is small. Similar effects have been observed in the following materials:

GaSb	Ge-Si alloys
InP	InGaAs
GaP	SiC
InAs	CdTe
Ge	GaAs-GaP alloys
Si	

as well as other alloys of the materials listed. Apparently, one of the basic requirements for a high percentage of radiative recombinations is that there be a fairly large bandgap and a correspondence of the conduction band minimum and valence band maximum to the same point in the reciprocal lattice or *k* space. Unfortunately, in material such as germanium and silicon, in which the band edges do not occur in the same position of *k* space, the efficiency, measured by the number of photons emitted per unit of current, is significantly less. Accordingly, the gallium-arsenide combination referred to herein is a preferred material. However, it will be understood that the use of other materials, with equivalent properties are within the scope of the invention disclosed and claimed herein.

While the photon energy emitted in incoherent recombination-radiation as illustrated in FIG. 1 tends to be reasonably monochromatic, the radiation is not directional, and the use of a reflecting or other directing means is generally necessary in order to achieve some degree of direction in the output from such a device. In contrast to this characteristic of the recombination-radiation, the photon energy output from laser action is substantially more monochromatic and highly directional, as is illustrated in FIG. 2. Super-radiance which is intermediate between the two is also possible.

Referring particularly now to FIG. 2, a similar semiconductive device indicated generally at **22** comprises a pair of semiconductive elements **24** and **26** of opposite conductivity type, with a diffused semiconductor junction **28** lying therebetween. A voltage source **30** is employed to bias the semiconductor junction **28** to cause the latter to lase, the opposite terminals of the source **30** being connected, respectively, to the semiconductor elements **24** and **26** as shown.

As to the laser mode of operation, the output is not only highly directional, but substantially included in the plane of the semiconductor junction **28**, as is indicated by the plurality of arrows **32** in FIG. 2. This output energy is substantially monochromatic, as is typical of laser operation. As will be understood by those skilled in the art, in order to achieve the energy buildup associated with the stimulated emission of radiation characteristic of laser action, the lower surface **34** of the semiconductor device **22** will be suitably flat to provide a reflective internal surface, and the upper surface **36** will be flat in a manner which renders this surface semi-reflective so as to provide a pair of opposed reflective surfaces which form an optical chamber for the multiple reflections involved in laser operation, along with a means of egress in the form of the semi-reflective or more transparent surface.

One preferred form of the non-thermionic electron emitter of the present invention is shown in FIG. 3, wherein the two semiconductor bodies **38** and **40** of opposite conductivity type have a diffused junction **42** therebetween which is biased in the forward direction by means of a voltage source **44** connnected between the two semiconductor elements **38** and **40**. The magnitude of the current applied to the junction **42** determines the extent and nature of the radiation emitted from the junction; generally speaking, at lower current inputs the radiation is that of fluorescence, whereas at higher current inputs the radiation is predominantly laser activity. It is assumed for the purpose of the explanation of the structure and operation of FIG. 3 and FIG. 4 that the amplitude of current input is such as to provide a photon output that is primarily a result of recombination-radiation.

FIG. 3 also shows the use of a reflective coating **46** which is postioned around all of the surfaces of the emitter device except for the surface represented by the line **48**, it being understood that the stylized representation comprising FIGS. 3 and 4 illustrates cross-sectional characteristics of the devices shown. In other words, the recombination-radiation photons emitted from junction **42** in FIG. 3 will diverge in all directions from the semiconductor junction, but they will be collected and reflected by means of the reflective layer **46** so as to all be emitted from the interior of the semiconductor device through the surface **48**. This surface **48** is accordingly covered with a layer or body **50** of photoemissive material, so as to position the latter in the path of photon radiation.

In the operation of the device illustrated in FIG. 3, the source **44** applies a current of selected magnitude to the semiconductor junction **42**, resulting in the recombination of holes and electrons within the semiconductor device comprising the elements **38** and **40** of opposite conductivity type, as well as the diffused junction **42** therebtween. As photons are generated as a result of this recombination-radiation, they are emitted both through the surface **48** and in the direction of the several surfaces of the reflective coating **46**. The latter photons are suitably reflected, and for the most part by multiple reflection, with the end result that practically all of the photons generated are emitted through the surface **48** and into the photosensitive layer **50**. As will be appreciated by those skilled in the art, this photoemissive layer **50** may comprise a layer or body of any suitable material which emits electrons upon being illuminated by photons; one illustrative example of a suitable material for this purpose is silver-oxygen-cesium. Obviously, other suitable materials may also be employed, which match the photoemissive layer to the photon energy output of the recombination diode for the desired application. It will also be understood by those skilled in the art that the non-thermionic electron emission device of the present invention will normally be enclosed within a vacuum envelope or the like as indicated by the line **52** in FIG. 3; this is the usual construction for most applications of electron emitters, so as to present a vacuum atmosphere both to preclude rapid decomposition of the photoemissive layer and to afford a suitable surrounding for efficient use of the electrons emitted.

A similar but somewhat modified structure shown in FIG. 4 illustrates a second form of the electron emitter of the present invention. In FIG. 4, a pair of semiconductive elements **54** and **56** of preferably opposite conductivity types, having a diffused junction **58** therebetween are connected to the opposite poles of a source **60** which supplies the forward bias current to the junction **58**. As was the case in connection with the structure of FIG. 3, the electron emitter device of FIG. 4 includes a reflective coating **62** which serves to reflect photons emitted from the junction **58** so that all photon radiation takes place through the surface **64**. In the structure of FIG. 4, the photoemissive layer **66** is spaced apart from the surface **64** through which the photons are emitted, with member or coating **66** being positioned on a suitable backing surface **68** or the like. It will be evident to those skilled in the art that the structure of FIG. 3 is suitable for the use of photoemissive layers which are transparent in nature, whereas the structure of FIG. 4 is a convenient modification to enable the use of photoemissive layers which are relatively non-transparent to the photon emission.

The operation of the device of FIG. 4 is substantially the same as that of the device illustrated in FIG. 3, with recombination-radiation taking place as a result of the forward biasing current applied to junction **58**

by means of the source **60**. The photons emitted from junction **58** are reflected and collected with the aid of the reflective coating **62** so that all of the photons that are emitted from the device pass through the surface **64** and impinge upon the photoemissive member **66**. The resultant electron emission is indicated by the arrows **70**.

It is now evident that one particularly advantageous feature of this invention is the ability to achieve a point source with substantial ease by means of the reflective coatings **46** and **62** in FIGS. 3 and 4, possibly in combination with suitable masking means (not shown) on the surfaces **48** and **64** so as to positively control the area through which photon emission takes place.

The device illustrated in FIG. 5 is illustrative of one preferred form of the electron emitter of this invention particularly adapted for laser operation. As shown, a pair of semiconductive elements **72** and **74** include a diffused junction **76** therebetween which is forward biased by the source **78**, the opposite terminals of which are connected, respectively, to the semiconductor elements **72** and **74**. The amplitude of current to be applied to the junction **76** by means of the source **78** is such in FIG. 5 as to result in laser operation, with the photon output taking place in the plane of the semiconductor junction **76**. Accordingly, the photoemissive material **80** is applied to the body only in the plane of the junction **76**, as shown. Correspondingly, a reflective coating is applied over all of the surfaces of the device of FIG. 5 except in the area of the photoemissive material **80**, such reflective coating **82** restricting the laser photon output to that portion of the plane of the junction **76** upon which the photosensitive material **80** is deposited.

The operation of the device in FIG. 5 is thus evident, with the forward bias current being applied by means of source **78** to semiconductor junction **76** to cause the junction to lase and emit photons in the plane of the junction, thus illuminating the photoemissive material **80** and causing the latter to emit electrons. Obviously, the size of the photoemissive element **80** can either be quite small as shown in FIG. 5 so as to effectively constitute a point-source cathode or could be extended in the plane of the semiconductor junction **76** so as to provide an electron emission surface of greater area. Obviously, the extent to which the reflective coating **82** covers the surface of the device will be correspondingly varied.

As was stated in connection with FIG. 2, in order to effectively achieve the laser operation with the device illustrated in FIG. 5, the upper surface **84** and the opposite or lower surface **86** are suitably prepared to form the optical cavity characteristic of laser devices, with the upper surface **84** being only semireflective, so as to permit egress of the photons.

With regard to each of the several configurations described herein, the general requirements for the photoemissive layer are that it exhibit a pohtoelectric threshold less than the energy of the recombination-created photons, and that it be of proper thickness for maximum efficiency. This latter requirement applies to both the semitransparent photo surface **50** of FIG. 3 and the relatively opaque photosurface **66** in FIG. 4. Additionally, since the light from the semiconductor junction is nearly monochromatic, high efficiency of the photocathode can be accomplished by employing light interference within the photoemissive material.

Where gallium-arsenide is employed as the photon emitter, silver-oxygen-cesium (which exhibits an S–1 photoemissive response) will provide suitable electron emission. Where GaP is employed as the photon emitter, emitting well in excess of 1.5 ev., an efficient photoemissive material such as cesium antimonide may be used.

Where efficient emission is desired, and low beam noisiness is not a prerequisite, the photoemissive material may be chosen so that its maximum response falls near the frequency of the light radiated from the junction. Experimental efforts in this direction show that an over-all yield of 150 milliamperes per watt may be obtained. This compares quite favorably with the 10 to 200 milliamperes per watt with which oxide-coated thermionic cathodes are usually operated.

If a low-noise electron beam is desired, the photoemissive material may be chosen so that its threshold is as close to the frequency of the radiated light as is possible, and the entire system should be refrigerated. Under these conditions it should be possible to operate a sufficient current to operate a low-noise traveling wave tube with a beam temperature of 50° Kelvin with considerably less than 1 watt of D-C power applied to the cathode.

In many applications, cathodes with very high effective noise temperatures are desired as noise generators. This may be accomplished by selecting a photosurface whose threshold frequency is far below the frequency radiated below the junction. Accordingly, the energy spread of the emitted electrons will be large, resulting in a noise temperature which may approach several thousand degrees Kelvin.

The advantages of the electron emitter of the present invention make practical the combination of a highly efficient photoelectric emitter with a highly efficient photon emitter, so that nearly one vacuum electron may be obtained fo reach electron (or hole) crossing the PN junction. Since it can be demonstrated that currents far in excess of 1000 amperes per square centimeter can be injected into the PN junction, the cathode of this invention may provide a very high density source of electrons. Therefore, and as stated above, an extremely small cathode, approaching an actual point source of electrons, is feasible.

The invention has been described above in some detail, and particularly with reference to its application to a non-thermionic electron emitter for use in the vacuum tube art. However, it will be apparent to those skilled in the art that the invention is also applicable to other arts where there is a need for the generation of emitted electrons. Further, the description of the invention herein has referred to the use of a pair of semiconductor elements of opposite conductivity type; it will be, of course, apparent to those skilled in the art that whether there are two or more semiconductor elements of opposite conductivity, or, alternatively, a plurality of semiconductor elements of merely different, rather than oppostie, conductivity type, or two different semiconductor materials forming a heterojunction, or combinations of metal-semiconductor, metal-insulator semiconductor junctions which emit radiation efficiently, the invention claimed and disclosed herein is applicable with equal force. Hence, the invention is not to be considered as limited to the particular details given, nor to the specific application to which reference has been made during the description of the device, except insofar as may be required by the scope of the appended claims.

What is claimed is:

1. A non-thermionic electron emission device, comprising a semiconductor body having a semiconductor junction therein, means for forward biasing said junction to effect photon radiation therefrom, and photon-sensitive electron-emissive material on said body and in the path of such photon radiation for emitting electrons when impinged by said photon radiation.

2. A non-thermionic electron emission device, comprising a semi-conductor body having a PN junction therein, means for forward biasing said junction to effect photon radiation therefrom, and support means spaced from said body, photon-sensitive electron-emissive material on said support in the path of such photon radiation for emitting electrons when impinged by said photon radiation.

3. A non-thermionic electron emission device, comprising a body of semiconductor material having a semiconductor junction therein, means for biasing said junction to effect substantially monochromatic photon radia-

tion therefrom, and photon-sensitive electron-emissive material covering said junction and in the path of such photon radiation for emitting electrons when impinged by said radiation.

4. A non-thermionic electron emission device, comprising a body of semiconductor material having a semiconductor junction therein, means for biasing said junction to effect laser radiation of photons therefrom, and photon-sensitive electron-emissive material covering said junction and in the path of such photon radiation for emitting electrons, when impinged by said photon radiation.

5. A non-thermionic electron emission device, comprising a body of semiconductor material having a semiconductor junction therein, means for forward biasing said junction to produce fluorescent radiation of photons therefrom, and photon-sensitive electron-emissive material on said body and in the path of such photon radiation for emitting electrons when impinged by said photon radiation.

6. A non-thermionic electron emission device, comprising a body of semiconductor material having a semiconductor junction therein, means for biasing said junction to effect radiation of photons by means of both laser action and recombination-radiation fluorescence therefrom, and photon-sensitive electron-emissive materials on said body and in the path of such radiation for emitting electrons when impinged by said photon radiation.

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