United States Patent

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[54] **COLD CATHODE STRUCTURE COMPRISING SEMICONDUCTOR WHISKER ELEMENTS**
9 Claims, 6 Drawing Figs.

[52] **U.S. Cl.** **317/234,** 317/235
[51] **Int. Cl.** **H01l 3/00,** H01l 5/00
[50] **Field of Search** 313/346, 108; 317/234, 235, 7, 8, 25, 25.1, 30, 31

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ABSTRACT: Cold cathode structures comprise a plurality of semiconductor whisker elements each including an electronic barrier near the free end. Electron emission is enhanced by a high external field that is concentrated at the tip of each whisker element.

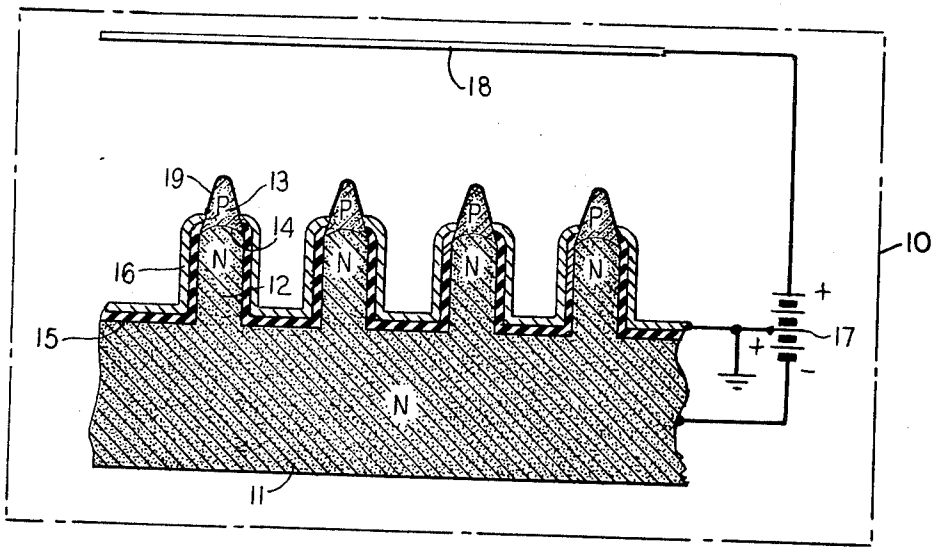


FIG. 1

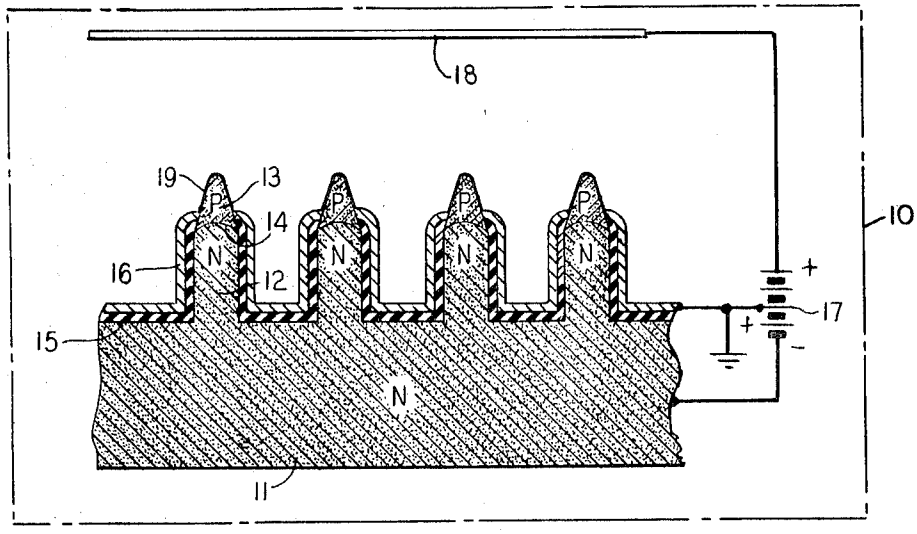


FIG. 2

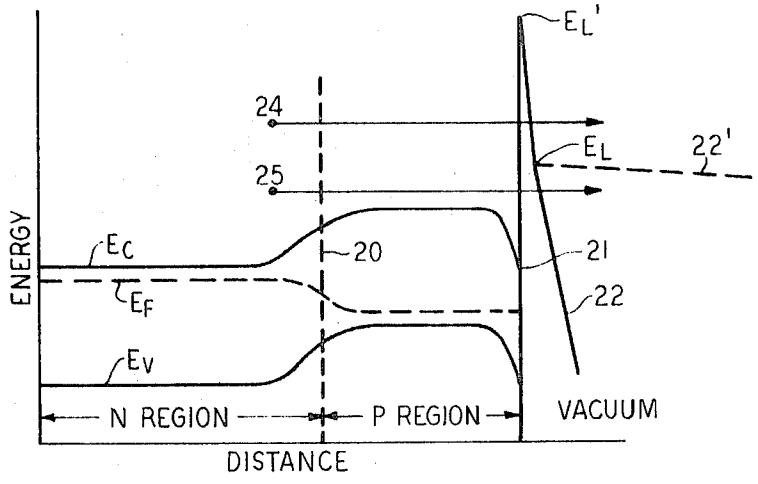
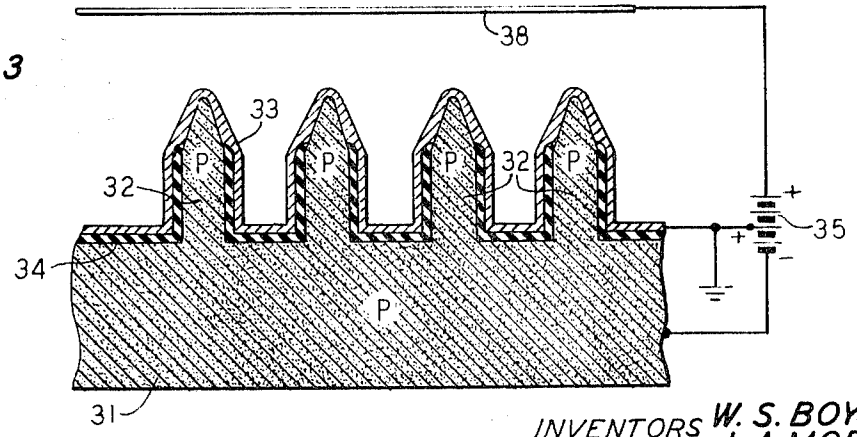


FIG. 3



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FIG. 4

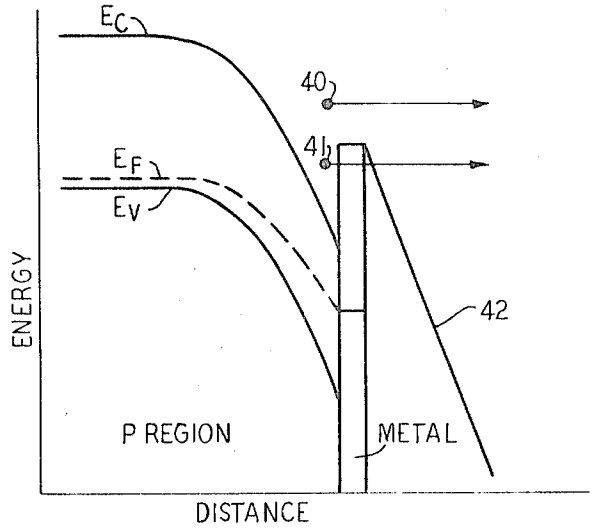


FIG. 5

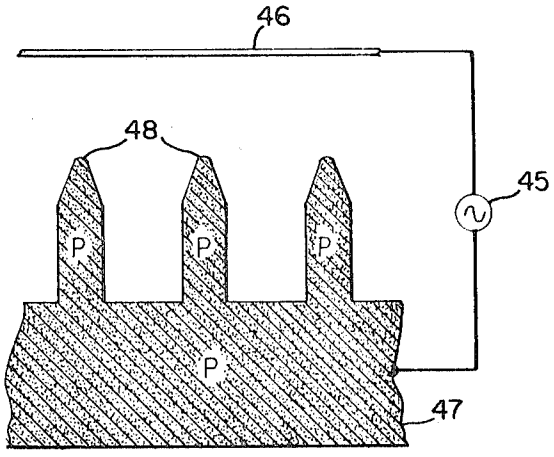
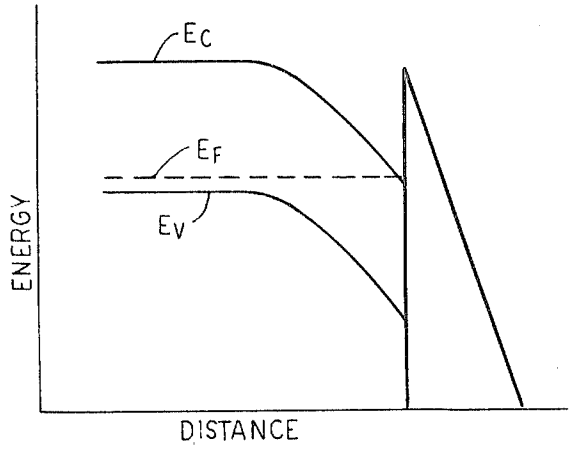


FIG. 6



COLD CATHODE STRUCTURE COMPRISING SEMICONDUCTOR WHISKER ELEMENTS

BACKGROUND OF THE INVENTION

The most commonly used electron source is the thermionic cathode which has the well-recognized disadvantage of requiring a power source to heat an appropriate semiconductor emissive coating. As a result, input power is dissipated, a "warm up" period is required for heating the cathode to its required temperature, a cooling period is required before emission stops, and the high operating temperature and temperature cycling limit the longevity of the device. Accordingly, considerable effort has been expended in attempting to develop a lower temperature (preferably room temperature) cathode electron source that can generate usefully large electron current densities.

In the field emission cathode, a large external electric field is applied to an N-type semiconductor or a metal for drawing off conduction band electrons from the surface. In addition to requiring a high-voltage source, the high field requirement necessitates a high vacuum to prevent cathode damage by high momentum gas ions. While the field requirement can be reduced somewhat by treating the surface of the cathode with a low work function material such as barium oxide, the device at present has only limited commercial utility.

Various junction devices have been proposed as cold cathodes which operate on the broad principle that a suitable voltage across a semiconductor junction will, like applied high temperatures, produce enough hot electrons having a sufficiently high energy to escape from the surface. Although in theory these devices can be made with a very low work function, that is, a low potential barrier at the surface, imperfections in surface preparation and formation nearly always result in a fairly high work function that contains the electrons and prevents them from being emitted. Surface treatment with a low work function coating usually results in chemically unstable material systems and has only partially alleviated the problem.

SUMMARY OF THE INVENTION

It is an object of this invention to provide an efficient cold cathode electron emitter.

To obtain enhanced cold emission of electrons from a solid, certain conditions must be satisfied; these are:

a. The temperature of the electrons must be much higher than the temperature of the lattice.
b. The potential barrier at the interface between the solid and the vacuum must be made as small as possible.
c. In order to avoid destructive heating of the lattice, the thermal heat transport from the electron gas to the lattice must be kept small.

Various means may be used for obtaining electron distributions which differ from thermal equilibrium. These are, for example, production of minority carriers either (1) by forward injection across a suitable P-N potential barrier junction, or (2) by using high electric field for avalanche pair production within the material such as in a reverse bias potential barrier. The barriers can be obtained with a metal-semiconductor barrier, a Bardeen surface states barrier, a metal-oxide-semiconductor barrier, by a rapid change in conductivity type from P to N in the body of the semiconductor material as by chemical or physical imperfections, or merely by the application of an external AC field as will be described in detail later. The electronic barriers used for giving forward injection or reverse-bias avalanche breakdown should not be confused with the surface barrier at the interface of the solid and the vacuum.

In accordance with our invention, the height and penetrability of the barrier at the interface of the solid and the vacuum are reduced by the application of a high field to the surface of the semiconductor. by using whiskerlike structures it is possible to increase the field at the tips of the whiskers while also producing hot electrons in regions near the tips by any of the means discussed in (1) and (2) above.

The optimum mechanism for obtaining hot electrons at the tips of cold semiconductor whisker elements depends on the specifc semiconductor properties. In any case, it is advantageous to use a semiconductor because the carrier concentrations can be kept sufficiently small that the total heat carried to the crystal lattice is also small.

DRAWING DESCRIPTION

These and other objects, features and advantages of our invention will be better appreciated from the following detailed description taken in conjunction with the accompanying drawing in which:

FIG. 1 is a schematic view of one embodiment of the invention;

FIG. 2 is an energy band diagram which illustrates electron mechanisms in the device of FIG. 1;

FIG. 3 is a schematic view of another embodiment of the invention;

FIG. 4 is an energy band diagram which illustrates electron mechanisms in the device of FIG. 3;

FIG. 5 is a schematic view of another embodiment of the invention; and

FIG. 6 is an energy band diagram which illustrates electron mechanisms in the device of FIG. 5.

DETAILED DESCRIPTION

Referring now to FIG. 1 there is shown schematically a cold cathode structure in accordance with an illustrative embodiment of the invention comprising an N-type semiconductor substrate **11** upon which is formed a plurality of semiconductor projections or whisker elements **12**. The free end or tip of each whisker element is a thin P-type semiconductor **13** which forms with the major part of the whisker element a P-N junction **14**. Overlaying the entire upper surface of the substrate and the N-conductivity part of each whisker is an insulator coating **15**. A conductive coating **16** overlays the insulator and forms an ohmic contact with each P-type region **13** without contacting any N-type region.

a voltage source **17** biases the conductive coating and the P-type regions **13** positively with respect to the N-type semiconductor. It also biases an external anode electrode **18** at a high positive voltage with respect to the P-type regions. Because the whisker elements extend toward electrode **18**, the electric field between the cathode electrode and the anode electrode is concentrated at the tips of the cathode whiskers; that is, at P-type regions **13**. The tips are preferably made with sharp ends as shown to enhance field concentration and may be coated with a thin film **19** of low work function material such as barium oxide. The cold cathode structure and the electrode **18** are maintained in a vacuum by a suitable envelope **10**, which is shown schematically in phantom.

In the energy band diagram of FIG. 2, E_C is the lower boundary of the conduction band of one of the whiskers of FIG. 1, E_V is the upper boundary of the valence band, and E_F is the Fermi level. Line **20** represents the junction of the N-type and P-type regions, and line **21** represents the upper surface of the whisker tip. E_L is the vacuum level of the semiconductor; that is, the energy level electrons must attain to surmount the potential barrier at the surface for free emission into the vacuum. The energy difference between E_L and E_C is known as the electron affinity and the energy difference of E_L and E_F is the work function of the P-type whisker tip. The thin film **19** reduces the vacuum level of the whisker tip surface from E_L' to E_L.

Since the N-type region contains electrons in the conduction band, the applied bias voltage reduces the junction barrier at **20** and allows representative electrons **24** and **25** to diffuse across the junction **20**. Electron **24** is shown as having a higher energy than the vacuum level E_L at surface **21**; and so, if the P-region is short enough to permit the electron to drift across it without recombination, it will be emitted from the surface into the vacuum. The distance from the junction to the whisker tip is preferably smaller than one diffusion length to

minimize recombination. In theory, emission of electrons such as electron 24 should give a substantial usable current because the work function of P-type material, especially if the surface has been treated with barium oxide, can theoretically be made so small that most of the conduction band electrons have energies above E_L. In practice, however, most of the electrons, like electron 25, have a lower energy than E_L and in the absence of any modification of the surface barrier would be reflected by the surface barrier.

The application of the high field intensity at the whisker tip, however, makes it possible for electron 25 to tunnel through the surface potential barrier. The surface potential barrier is reduced in thickness as shown graphically by line 22 sloping downwardly from the vacuum level E_L. Line 22 may be considered as a representation of the variation of the vacuum level E_L with distance; as such, the distance between line 22 and surface 21 at any given energy level is an inverse function of the probability that an electron at that energy level will tunnel through the barrier. Furthermore, although not shown here, the top of the barrier is lowered and this is also advantageous.

The phenomenon of electron tunneling through potential barriers involves quantum mechanical concepts which are well understood by workers in the art but which are difficult to explain qualitatively and concisely. Due to its wave nature, the location of an electron cannot be predicted with certainty, but rather must be expressed in terms of its probability of existence at a location within a specified distribution. As a result, the distance between surface 21 and vacuum level line 22 at a particular electron energy is indicative of the inverse probability that a semiconductor electron of that energy will exist at the vacuum side of the potential barrier rather than being reflected by the barrier. The slope of line 22 is proportional to the applied electric field; the greater the field, the greater the proportion of electrons between energies E_C and E_L that will tunnel through the surface barrier.

In prior art junction emitters, an external anode voltage and the cathode bias voltage give a typical vacuum level slope shown by line 22'. The probability of electron tunneling is so small that the only realizable currents result from hot electrons such as electron 24 which are of higher energy than the vacuum level at the surface. However, with an intense field at the surface, the slope of vacuum level 22 is increased to give a small effective distance between the surface 21 and line 22, thereby inducing substantial emission by electron tunneling. In fact, it can be shown that the tunneling current density is an exponential function of applied electric field.

The purpose of the whisker configuration is of course to maximize the intensity of the electric field at the emitting tips. The determination of the optimum diameters, spacing and height of the whiskers to give maximum field concentration at the whisker tips under various conditions of voltage and electrode spacing are within the ordinary skill of workers in the art. It can be shown that the tunneling current component is dependent on the work function at the surface; thus, coating the whisker tips with barium oxide or the like will increase both the hot electron current emission and the tunneling current component.

A number of methods of fabricating the cathode of FIG. 1 are known in the art. The whiskers 12 may be grown by vapor-liquid-solid crystal growth on a silicon substrate by the general method described in the copending application Ser. No. 669,535 to J. R. Arthur, Jr., et al., filed Sept. 21, 1967 and assigned to Bell Telephone Laboratories, Incorporated. The oxide layer may then be deposited or grown over the entire surface and preferentially removed from the whisker tips by a directed electron beam or by a high voltage between a plasma and the semiconductor. Then, using the oxide layer as a mask, the tip can be made P-type by impurity diffusion or ion-implantation. Finally, the conductive coating 16 is applied, as by evaporation, with subsequent removal only from the whisker tips.

Rather than being considered an improvement on known junction emitters, the present invention can be considered as being an improvement on known field emission cathodes of the type which comprise a large number of N-type semiconductor whiskers. The junction mechanism permits electrons to be drawn from a P-type surface which can be made with a lower electron affinity than that of a corresponding N-type surface.

FIG. 3 shows another embodiment in which, as before, a plurality of whiskers 32 are formed on a semiconductor substrate 31. The entire semiconductor is of P-type conductivity and is overlayed with a conductive coating 33 which is insulated from the semiconductor at all locations except the whisker tips by an insulator coating 34. The surface of the semiconductor tip is carefully prepared such that conductive coating 33 forms a Schottky barrier junction with the semiconductor tip. A battery 35 biases an external electrode 38 positively with respect to the conductive coating 33. The battery also biases the conductive coating 33 at a positive voltage with respect to the semiconductor which is sufficient to cause avalanche breakdown in the semiconductor whisker near the conductive contact.

The high bias voltage required for avalanche breakdown gives an energy band characteristic as shown in FIG. 4. Although P-type material does not normally contain conduction band electrons, representative electrons 40 and 41 are generated in a manner characteristic of Schottky barrier diodes, which may be summarized as follows: The high bias voltage causes holes to tunnel from the metal layer into the valence band where they collide with valence band atoms to produce electron-hole pairs. These holes in turn collide with other atoms, as is characteristic of avalanche breakdown, and copious quantities of conduction band electrons are produced.

Some of these electrons such as electron 40 are at a higher energy level than the vacuum level 42 and they therefore escape from the metal surface. As is known, the conductive coating should be sufficiently thin to permit such electrons to tunnel through the metal and to be emitted rather than being transmitted to the battery. In addition, the high external field permits lower energy electrons such as electron 41 to tunnel through the potential barrier at the surface of the conductive coating. As before, the sharp tip of the whisker element causes an electric field concentration with high field intensity at the tip, giving a steep slope to the vacuum level 42, which results in substantial emission enhancement through electron tunneling.

Advantageously, the external field itself can be used to reverse-bias a P-type whisker tip to avalanche breakdown as shown in FIG. 5. An AC source 45 alternately biases an electrode 46 positively and negatively with respect to the P-type semiconductor cathode 47. During the positive portions of each cycle, the field concentrated at whisker tips 48 is sufficient to invert the conductivity of the whisker tip from P-type to N-type; that is, the field bends the conduction and valence bands at the semiconductor surface such that E_c is nearer the Fermi level E_F than is E_v, as shown in FIG. 6. Additionally, hot electrons are generated near the surface through avalanche multiplication and, as before, many of these electrons are either emitted directly into the vacuum or may tunnel through the surface barrier into the vacuum. During the negative portion of each cycle, the remaining minority carrier electrons are injected into the bulk of the P-type semiconductor.

The mechanism of hot electron production is essentially the same as that described in the copending application, Ser. No. 571,555 to C. N. Berglund, filed Aug. 10, 1966, which is directed to a metal-insulator-semiconductor (MIS) diode for producing light through radiative recombination. The minority carrier electrons required in the Berglund process are produced by a high field avalanche breakdown, and the field and carrier concentration requirements disclosed in that application are also descriptive of the FIG. 5 device. The field frequency used in the Berglund device is, however, restricted

by recombination considerations, and since in our cold cathode emitter we are unconcerned with radiative recombination, such restrictions do not apply. Notice that in our device, the concentrated external field, in addition to inverting the semiconductor conductivity and stimulating avalanche breakdown, also aids in tunneling emission as in the other embodiments.

Although the embodiment of FIG. 5 does not include a permanent junction at the whisker tips, the surface region of inverted conductivity, or inversion layer, constitutes an electronic barrier that may be considered a temporary P-N junction. The embodiment could alternatively be made more as the Berglund device by the use of a thin oxide film between the whisker surface and a thin conductive film to which the alternating bias voltage is applied. Hot electrons would then tunnel through the oxide and metal films much as in the FIG. 3 embodiment. The FIG. 5 device is, however, preferable because of its greater ease of fabrication.

In summary, various embodiments have been shown that illustrate how the combination of a whisker configuration with the use of an electronic barrier for generating hot electrons, either by forward injection or reverse bias avalanche multiplication, can be used to advantage as a cold electron source. The combination permits a high external field to be used to draw electrons from a P-type material and to give substantial emission by tunneling. Various other embodiments and modifications may, however, be made by those skilled in the art without departing from the spirit and scope of the invention.

I claim:

1. An electron source comprising: a semiconductor member including on one surface a plurality of elongated whisker elements;
means for forming an electronic barrier near a free end of each element;
means for biasing the free end of each element positively with respect to the remainder of the element;
and an electrode biased positively with respect to the free ends of each element for forming an intense electric field at the free end of each element;
said electrode being spaced from the whiskers and facing said free ends, thereby permitting electrons to be emitted into the space between the whiskers and the electrode.

2. The electron source of claim 1 wherein:
the major portion of each whisker element is of N-type conductivity;
the free end of each whisker element is of P-type conductivity;
and the biasing means includes a metal film in contact with the P-type portion and insulated from the N-type portion of each whisker element.

3. The electron source of claim 1 wherein:
the major portion of each whisker element is of P-type conductivity;
a metal film overlays each whisker element, is in contact with a free end of the P-type conductivity portion, and is insulated from the remaining portion, the contacted metal film and semiconductor whisker element end forming a Schottky barrier junction therebetween.

4. The electron source of claim 1 wherein:
the free end of each whisker element has a substantially conical configuration, thereby increasing electric field intensity thereat, and is coated with a low work function material.

5. An electron source comprising:
a P-type semiconductor including on one surface a plurality of elongated whisker elements;
means for producing an alternating electric field at the tips of the whisker elements;
alternate half-cycles of the field being of negative potential with respect to the whisker elements, and the remaining half-cycles being of sufficiently positive potential to invert the conductivity of the whisker element tips and cause avalanche multiplication thereat;
said alternating electric field producing means comprising an electrode spaced from the whisker elements and facing the whisker element tips, thereby permitting electrons to be emitted into the space between the whisker elements and the electrode.

6. In combination:
a positively biased anode electrode surrounded by a substantially evacuated space;
means for emitting electrons into said evacuated space toward the anode comprising a semiconductor member including on one surface facing the anode a plurality of elongated whisker elements spaced from the anode;
each of said whisker elements having a rectifying junction formed near a free end thereof;
an insulative film formed on a major portion of each whisker element;
means comprising a conductive film formed on the insulative film and overlaying each element for biasing the free end of each element positively with respect to the remainder of the element;
each of the free end surfaces of the whisker elements constituting a surface barrier which inhibits the free emission of electrons into said space; and
means comprising said positively biased anode for causing substantial electron tunneling through said surface barriers by forming an intense electric field at the free end of each element.

7. The combination of claim 6 wherein:
the major portion of each whisker element is of N-type conductivity;
the free end of each whisker element is of P-type conductivity;
and the rectifying junction of each whisker element is a P-N junction.

8. The combination of claim 6 wherein:
the major portion of each whisker element is of P-type conductivity;
the metal film overlaying each whisker element is in contact with the free end of the P-type conductivity portion;
and the rectifying junction is a Schottky barrier junction formed by the metal film and the free end of the semiconductor whisker element.

9. The combination of claim 6 wherein:
the free end of each whisker element has a substantially conical configuration, thereby increasing the electric field intensity thereat.