

March 5, 1968

T. E. HARTMAN

3,372,315

ELECTRON TUNNEL EMISSION DEVICE EXHIBITING  
APPROXIMATELY 0.9 CURRENT TRANSFER RATIO

Original Filed Aug. 4, 1965

4 Sheets-Sheet 1

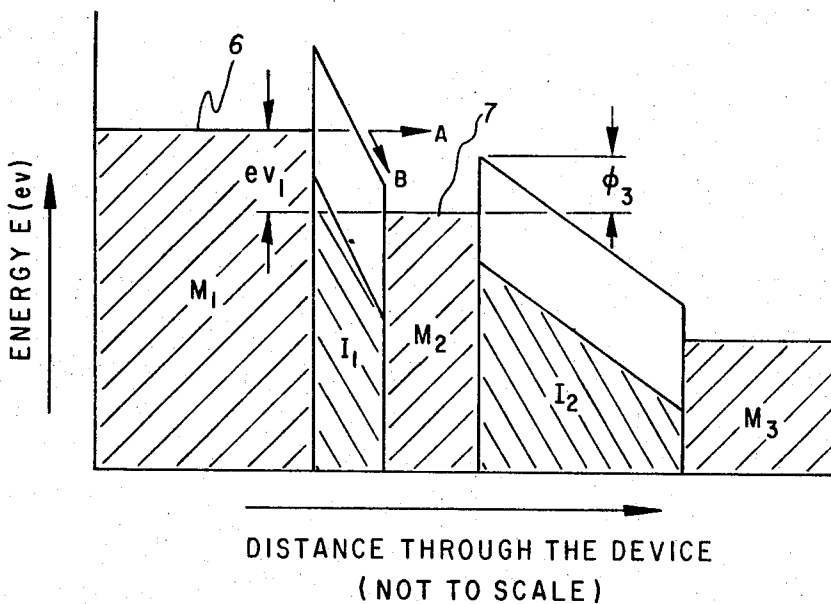


*Fig. 1*

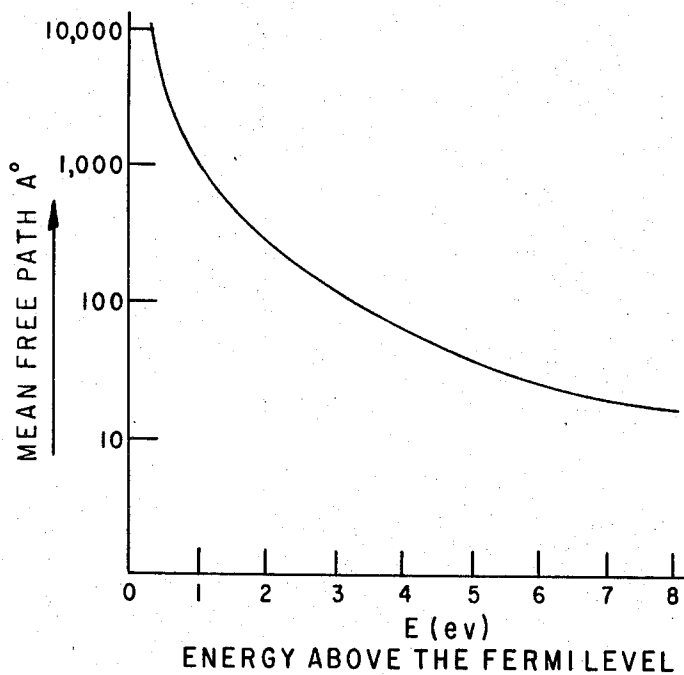


*Fig. 2*

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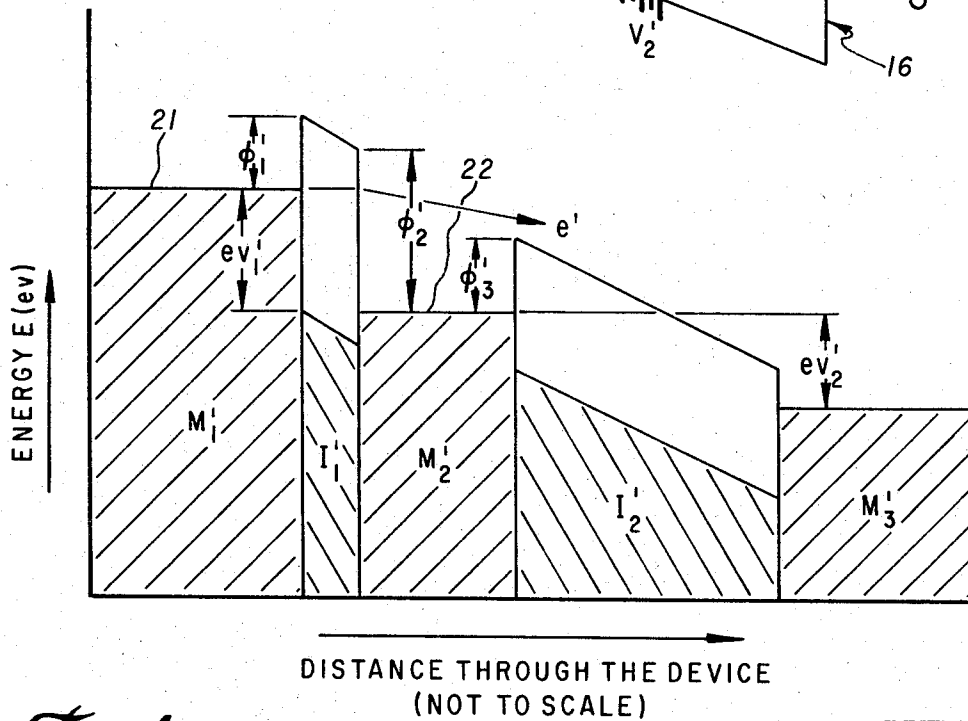
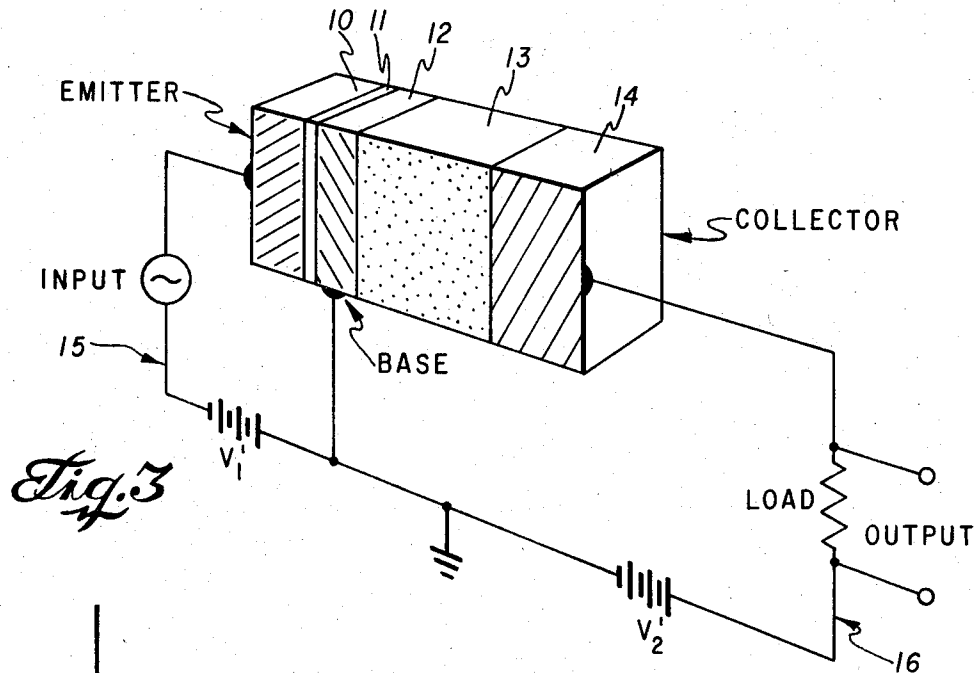
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4 Sheets-Sheet 3

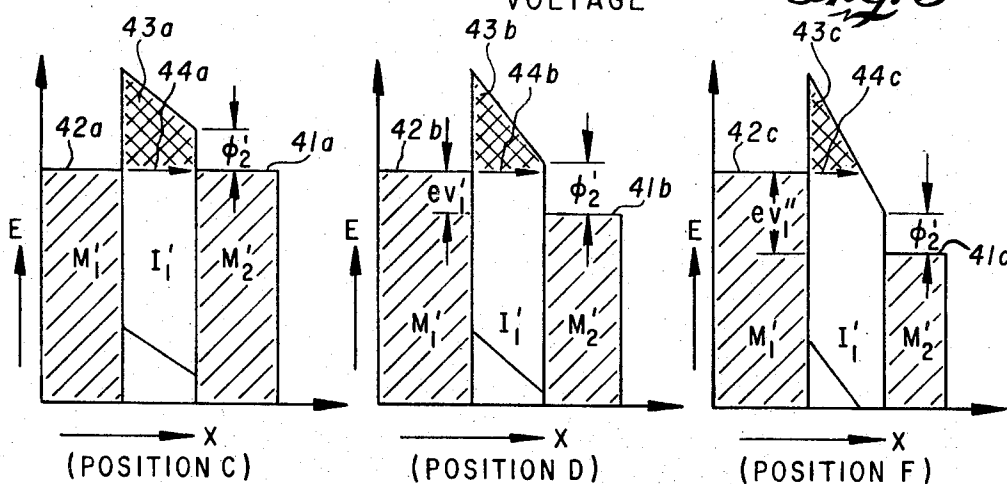
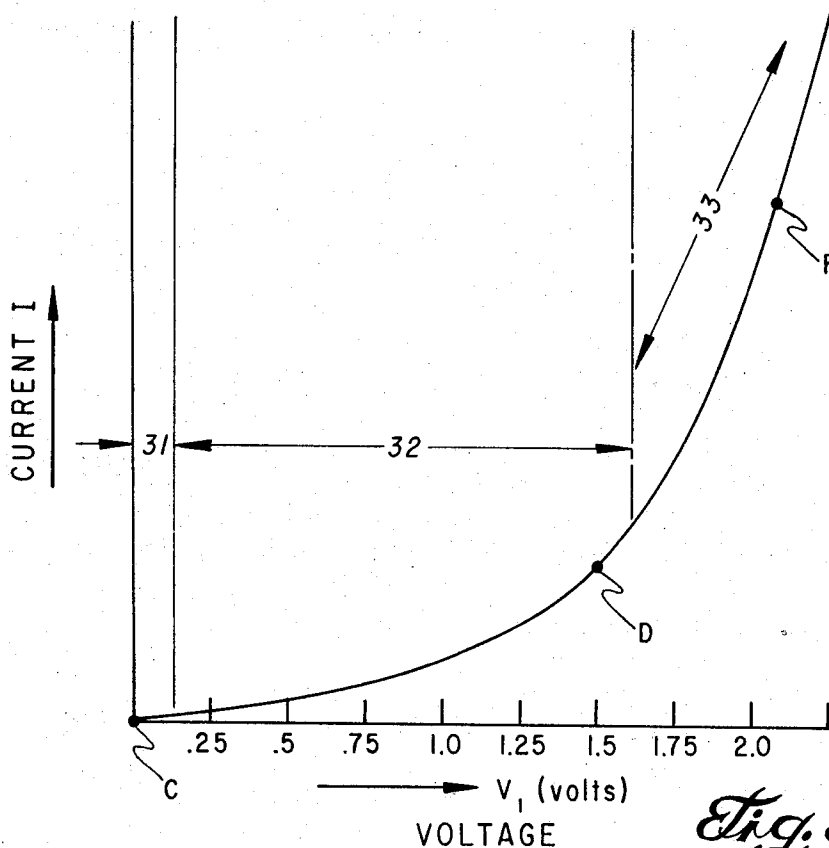


Fig. 6a.

Fig. 6b.

Fig. 6c. INVENTOR  
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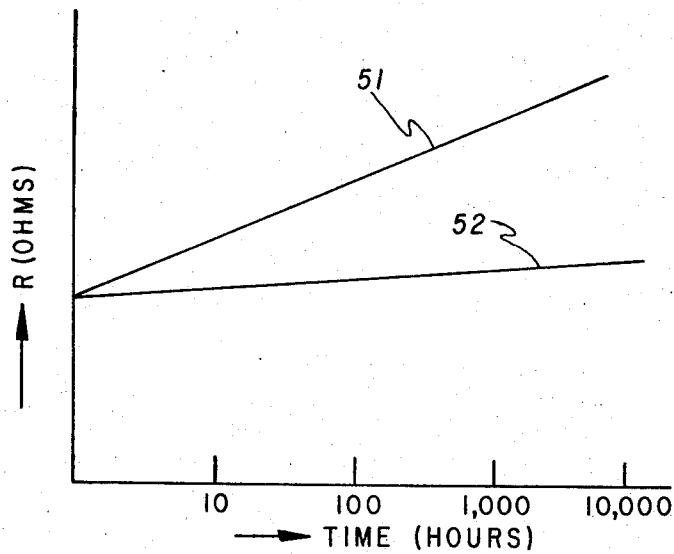


*Fig. 7*

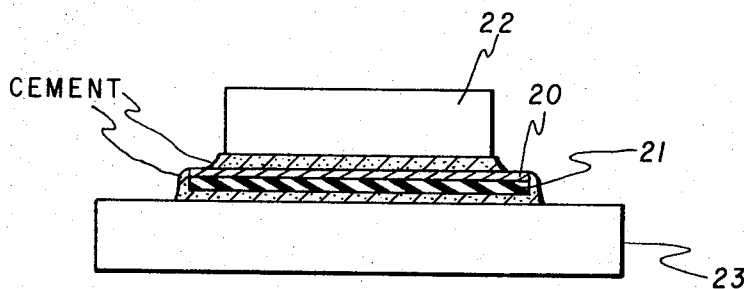


*Fig. 8*

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1

3,372,315

## ELECTRON TUNNEL EMISSION DEVICE EXHIBIT- ING APPROXIMATELY 0.9 CURRENT TRANSFER RATIO

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of Delaware

Continuation of application Ser. No. 477,274, Aug. 4,  
1965. This application Feb. 27, 1967, Ser. No. 619,074  
2 Claims. (Cl. 317-235)

This application is a continuation of patent application  
Ser. No. 477,274 filed Aug. 4, 1965, now abandoned.

This invention relates to solid-state electron devices.  
More particularly it relates to improvements in tunnel  
emission amplifiers and to a process for making such  
amplifiers.

It is an object of the invention to provide a tunnel emis-  
sion amplifier having a high current-transfer ratio, i.e.,  
efficiency.

It is another object to provide a tunnel emission am-  
plifier which operates in a low-voltage range.

It is still a further object to provide a process for mak-  
ing such a tunnel emission amplifier.

In accordance with these and other objects, features  
and improvements, the tunnel emission amplifier of the  
invention comprises three conductive metal layers sepa-  
rated by two insulating layers of which the first in-  
sulating layer must be an oxide of the material consti-  
tuting the second conductive metal layer. The first con-  
ductive metal layer forms the emitter, the second conduc-  
tive metal layer forms the base, and the third conduc-  
tive metal layer forms the collector of the tunnel emission  
amplifier of the invention. By using the combination of  
materials, and constructing the layers according to this  
invention, and by operating in the voltage range accord-  
ing to this invention, there is obtained an amplifier device  
with a high current transfer ratio, by which is meant  
that the ratio of the number of electrons that reach the  
collector to the number of electrons that leave the emitter  
is high.

The novel features believed characteristic of this in-  
vention are set forth in the appended claims. The in-  
vention itself, however, as well as other objects and ad-  
vantages thereof, may best be understood by reference  
to the following detailed description of illustrative em-  
bodiments, read in conjunction with the appended claims  
and the accompanying drawings, wherein:

FIGURE 1 is an energy-level diagram representing  
conditions within a prior art tunnel emission amplifier de-  
vice during its operation;

FIGURE 2 is a graph showing the relationship be-  
tween the energy of "hot" electrons and their mean-free  
path in aluminum (Al);

FIGURE 3 is a representation of one embodiment of  
the invention;

FIGURE 4 is an energy-level diagram representing con-  
ditions within the embodiment of the invention shown in  
FIGURE 3 during its operation;

FIGURE 5 is a graph showing the relationship between  
the operating voltage and the current across the first  
three layers of the device shown in FIGURE 3;

FIGURES 6a, 6b and 6c are energy-level diagrams for  
the first three layers of the device shown in FIGURE 3,  
illustrating the effect of three different applied voltages;

FIGURE 7 shows two graphs illustrating the relation-  
ship between time and resistance across the first three  
layers of the device for two different conditions, one

2

condition being that the three layers are encapsulated, the  
other condition being that the layers are not encap-  
sulated; and

FIGURE 8 is the representation of a device used in  
one process for fabricating the tunnel emission amplifier  
of the invention.

An amplifying device, consisting entirely of thin metal  
and insulator films, is shown in Patent No. 3,056,073 is-  
sued to C. A. Mead on Sept. 25, 1962. The device of the  
patent, called a tunnel emission amplifier, consists of three  
metal layers separated by two insulating layers. The struc-  
ture is somewhat analogous to a vacuum tube triode, with  
the insulating layers replacing the vacuum separating the  
metal electrodes. The physical phenomena assumed for  
controlling the emission and movement of electrons in  
the device are, however, considerably different from those  
involved in vacuum triode operation. In the tunnel emission  
amplifier, it is proposed to obtain a high-density electron  
current between the emitter and base metal layers by a  
field-induced tunnelling mechanism. Because of the posi-  
tive bias of the collector with respect to the base, electrons  
entering the conduction band of the second insulating layer  
will be driven to the collector. In operation, control of the  
electron current is effected by varying the emitter-to-base  
potential. In order to be effective as an amplifier, the  
tunnel emission device should have a current transfer  
ratio close to unity, i.e., in the vicinity of 0.9. However,  
a device constructed according to the teachings of the  
Mead patent has been found to have a current transfer  
ratio much smaller than this, more particularly to be  
somewhere between 0.1 and 0.5. Since current transfer  
ratio is the ratio of the number of electrons arriving  
at the collector to the number of electrons leaving the  
emitter, a small transfer ratio means that a large number  
of electrons are being removed at the base connection to  
the device.

FIGURE 1 is an energy-level diagram for the Mead de-  
vice in which the abscissa represents the distance through  
the device from the outer surface of the emitter and the  
ordinate represents the energy in electron volts (ev.) of  
an electron. In the diagram, region  $M_1$  is the first metal  
layer, region  $I_1$  is the first insulating layer, region  $M_2$  is  
the second metal layer, region  $I_2$  is the second insulating  
layer while region  $M_3$  is the third metal layer. Lines 6  
and 7 represent the Fermi level of  $M_1$  and  $M_2$ , respec-  
tively, and  $ev_1$  is the energy difference between these two  
levels due to an applied voltage  $V_1$  between  $M_1$  and  $M_2$ ,  
while  $\phi_3$  represents the energy an electron must have  
above the Fermi level of the metal layer  $M_2$  in order to  
pass into the conduction band of the second insulating  
layer  $I_2$ . Thus, referring to FIGURE 1, it can be seen that  
electrons, to be collected in  $M_3$ , must have sufficient en-  
ergy to clear the energy barrier  $\phi_3$ . All electrons which leave  
 $M_1$  (the emitter) by tunnelling, have at least the energy  
 $ev_1$  above the Fermi level 7 of  $M_2$ . The low current trans-  
fer ratio in the Mead device is thus caused by a large num-  
ber of electrons losing an amount of energy such that,  
upon reaching the second insulating layer  $I_2$ , they have in-  
sufficient energy to pass over the barrier  $\phi_3$ .

While it is not desired to be bound by any theories, it  
is believed that there are two primary reasons or explana-  
tions for the loss. One reason is that there are energy  
losses in the conduction band of  $I_1$ . In a device constructed  
according to the teachings of the Mead patent, an elec-  
tron, in tunnelling through  $I_1$ , enters the conduction band  
of  $I_1$ . Recent studies indicate that an electron loses a sig-  
nificant amount of energy in traveling through the con-  
duction band of  $I_1$ . See H. Kanter and W. Feibelman,

"Electron Emission From Thin Al-Al<sub>2</sub>O<sub>3</sub>-Au Structures," J. Appl. Phys., vol 32, pp. 3580-3588; December 1962, and R. E. Collins and L. W. Davies, "Energy Distribution of Hot Electrons in Aluminum," Appl. Phys. Letters, vol. 2, p. 213, June 1963. This energy loss means that an electron follows path B as shown in FIGURE 1, rather than path A, which means that the electrons enter the second metal layer M<sub>2</sub> with an energy less than  $\phi_3$ .

The second reason for the energy loss is electron-electron collisions in M<sub>2</sub>. The tunnel amplifier device as taught by Mead does not begin to operate until there is a bias between the first and second metal layers of approximately 8 volts. Recent studies by Sze et al. show that the mean-free path of hot electrons in metal is dependent upon the energy of the electrons. S. Sze, J. L. Moll, and T. Sugano, "Range-Energy Relation of Hot Electrons in Au," Solid State Electronics, vol. 7, pp. 509-524, 1964.

FIGURE 2 shows the relationship between the energy of an electron and its mean-free path in aluminum (Al) as determined by the formula given by J. J. Quinn, Phys. Rev., 126, p. 1453, 1962. In reference to this figure it can be seen that in the neighborhood of 8 ev. (the energy an electron in the M<sub>2</sub> region of the Mead device should have) an electron has a mean-free path of approximately 20 Å. Since the mean-free path is defined as the layer thickness at which 1/e of the electrons have not lost energy, then, in order to have only 10% of the electrons lose energy in the film, or to provide a device having a current transfer ratio of 0.9, the thickness of M<sub>2</sub> must be less than or equal to (0.105) $\lambda$  or approximately (1/10) $\lambda$ , where  $\lambda$  equals the mean-free path.

Mead teaches that the second metal layer must be of the thickness of 100 Angstrom units (100 Å.) in order to be continuous. For the voltage range in which the Mead device operates, it can be seen that this distance (100 Å.) is significantly greater than the mean-free path of the electron in said layer (20 Å.). This results in correspondingly more electron-electron collision energy losses. As a result of the two energy losses as described above, the current transfer ratio of the Mead device is significantly lowered.

FIGURE 3 shows a solid state electron tunnel emission amplifier made in accordance with the invention. It comprises the following elements for which limitations on materials and size are important. Layer 10 is a first metal film which can be of any suitable metal, for example aluminum. Layer 11 is a very thin first insulating film. This film layer 11 should be composed of the oxide of a thin second metal film, layer 12. The material for layer 12 must be such that it can be anodized or oxidized and the oxide so formed consists of a compact continuous surface film on said metal film, suitable examples of materials being aluminum, beryllium, niobium, tantalum or titanium. An important feature of the invention is the formation of the insulating layer 11 by the growth of an oxide on the second metal layer. In this way, one is able to reduce the thickness of layer 12 below the thickness at which it can be deposited in a uniform and continuous state. In addition, good control can be obtained on the thickness of the oxide layer 11, thus making both layers 11 and 12 "ultra-thin." The thickness for layer 11 should be such that it is permeable to electrons, thus limiting its thickness from about 25 Å. to about 50 Å. Layer 12 should be on the order of 50-75 Å. thick. Layer 13 is a second insulating film and should preferably be a single crystal and of a material that has a low energy barrier  $\phi_3$  with respect to the Fermi level of layer 12. It should be from 100-10,000 Å. thick. Layer 14 is a third metal film which can be of any suitable metal, for example aluminum. Means 15 enables voltage V<sub>1</sub>' to be applied between elements 10 and 12. V<sub>1</sub>' is determined by the characteristics of the materials used for the various elements, as will be explained below. Means 16 enables voltage V<sub>2</sub>' to be applied between elements 12 and 14. V<sub>2</sub>' should be large enough to overcome any space charge limitations arising in the second insulating layer 13.

Tables I and II show suitable materials and thicknesses for the various layers of this device.

TABLE I

| Layer                    | Material               | Fabrication Technique            |
|--------------------------|------------------------|----------------------------------|
| M <sub>3</sub> (14)----- | Aluminum-----          | Evaporation.                     |
| I <sub>2</sub> (13)----- | Mica (ruby muscovite)- | Stripping from a native crystal. |
| M <sub>2</sub> (12)----- | Aluminum-----          | Evaporation.                     |
| I <sub>1</sub> (11)----- | Aluminum oxide-----    | Grown thermally (or anodically). |
| M <sub>1</sub> (10)----- | Aluminum-----          | Evaporation.                     |
| Encapsulation-----       | SiO <sub>2</sub> ----- | Do.                              |

TABLE II

| Layer:                    | Thickness range                                 |
|---------------------------|-------------------------------------------------|
| M <sub>3</sub> (14) ----- | >1000 Å.                                        |
| I <sub>2</sub> (13) ----- | 100-10,000 Å.                                   |
| M <sub>2</sub> (12) ----- | 100 Å. as deposited (80-70 Å. after oxidation). |
| I <sub>1</sub> (11) ----- | 25-35 Å.                                        |
| M <sub>1</sub> (10) ----- | >1000 Å.                                        |
| Encapsulation -----       | 1000-10,000 Å.                                  |

FIGURE 4 shows an energy level diagram for the device of the invention illustrated in FIGURE 3. The distance along the abscissa represents distance through the device from the outer surface of emitter 10 and distance along the ordinate represents the energy of an electron in the device. In the figure, region M<sub>1</sub>' represents the first metal layer 10 in FIGURE 3, region I<sub>1</sub>' represents the first insulating layer 11 in FIGURE 3, region M<sub>2</sub>' represents the second metal layer 12 in FIGURE 3, region I<sub>2</sub>' represents the second insulating layer 13 in FIGURE 3, while region M<sub>3</sub>' represents the third metal layer 14 in FIGURE 3. Lines 21 and 22 in FIGURE 4 represent the Fermi levels in layer M<sub>1</sub>' and M<sub>2</sub>', respectively, and the difference between them,  $eV_1'$ , is caused by the voltage V<sub>1</sub>' being applied between M<sub>1</sub>' and M<sub>2</sub>'.  $\phi_1'$  represents the energy barrier between the Fermi level of M<sub>1</sub>' and the conduction band of I<sub>1</sub>'.  $\phi_2'$  is the energy barrier between the conduction band of I<sub>1</sub>' and the Fermi level of M<sub>2</sub>'. The energy barrier between the Fermi level of M<sub>2</sub>' and the conduction band of I<sub>2</sub>' is  $\phi_3'$  and represents the energy that an electron in region M<sub>2</sub>' must have before it can pass into I<sub>2</sub>'. For the materials listed in Table I above,  $\phi_2'$  is about 1.6 ev. and  $\phi_3'$  is between 0.8 and 0.95 ev.

FIGURE 5 shows the voltage-current relationship for a Al-Al<sub>2</sub>O<sub>3</sub>-Al diode which has the same characteristics as M<sub>1</sub>'-I<sub>1</sub>'-M<sub>2</sub>' shown in FIGURE 4. The thickness of the insulating layer I<sub>1</sub>' determines to a large extent whether "tunnelling" will occur. For a layer 25-50 Å. thick, tunnelling will occur from the very outset of an application of any voltage across the diode. This is shown by region 31 in FIGURE 5. As the voltage increases, the current (caused by tunnelling) also increases at a fairly linear rate. As the voltage increases still further, the current increases more rapidly as shown by region 32. However, upon reaching a voltage about equal to  $\phi_2'$  or 1.6 volts, the current increases very rapidly with increasing voltage. This is a result of an increase in the probability for tunnelling.

FIGURES 6a, 6b and 6c represent energy level diagrams for a Al-Al<sub>2</sub>O<sub>3</sub>-Al diode of the same characteristics as M<sub>1</sub>'-I<sub>1</sub>'-M<sub>2</sub>' layers in the diagram of FIGURE 4. The diagram shows the change in the position of the Fermi level in M<sub>2</sub>' shown by lines 41a, 41b and 41c due to a change in voltage applied between the two layers. FIGURE 6a has zero voltage applied, denoted by position C in FIGURE 5; FIGURE 6b has a voltage V<sub>1</sub>' which is less than  $\phi_2'/e$  or less than 1.6 volts, applied, denoted by position D in FIGURE 5, and FIGURE 6c has a voltage V<sub>1</sub>' which is greater than  $\phi_2'/e$  or 1.6 volts applied denoted by position F in FIGURE 5. In these diagrams, 41a, 41b and 41c represents the Fermi levels in M<sub>2</sub>'; 42a, 42b and 42c represent the Fermi levels in M<sub>1</sub>'. Regions 43a, 43b and 43c represent the areas of the forbidden region of the insulating layer I' which lie above the Fermi

level 42. Regions 44a, 44b and 44c represent the distances an electron must travel through the forbidden region of  $I_1'$  in tunnelling through the barrier presented by the forbidden region in  $I_1'$ .

The WKB approximation for the probability that an electron will tunnel shows that this probability is affected by two things. First, the larger area of the barrier above the Fermi level, region 43, the smaller the probability, and second, the shorter the distance the electron must travel through the forbidden area of  $I_1'$ , line 44, the larger the probability. However, the probability is affected to a much larger extent by tunnel distance, line 44, than it is by the area 43. Referring again to FIGURES 6a, 6b and 6c it can be seen that increasing the voltage affects the probability and thus the current. On increasing the voltage from 0 to  $V \leq \phi_2'/e$ , the only effect is to decrease the area 43, as can be seen by comparing FIGURES 6a and 6b. As stated above, this change in area affects the probability for tunnelling and causes the gradual increase in current represented by region 32 in FIGURE 5.

When the voltage applied is greater than  $\phi_2'/e$ , i.e., greater than 1.6 v. for the materials listed above, the barrier shape is changed so that the distance the electron travels through the forbidden area is decreased, as can be seen by comparing FIGURES 6b and 6c. As this change results in an exponential increase in the probability, the current increases rapidly, as seen by region 33 in FIGURE 5. This region where  $V > \phi_2'/e$  is commonly called the Fowler-Nordheim region and is the region in which it was proposed that the Mead device be operated.

The device of the present invention is designed to operate primarily in the voltage range of 0.8-1.6 volts for the materials listed above. This means that with reference to FIGURE 4,  $eV_1'$ , the difference between the Fermi level of the first metal layer and the Fermi level of the second metal layer, is greater than  $\phi_2'$ , the energy barrier between the Fermi level of the second metal layer and the conduction band of the second insulating layer, but less than  $\phi_2'$ , the energy barrier between the conduction band of the first insulating layer and the Fermi level of the second metal layer. It can be seen that for this operating range the electrons, in tunnelling, travel only through the forbidden area, and thus will not lose any energy in the conduction band of  $I_1'$ . Electron current will not start to flow to the collector of the device until  $eV_1' > \phi_3'$ , thus enabling the electrons to surmount the  $\phi_3'$  barrier.

Also as mentioned above for correct operation, a material must be chosen for  $I_2'$  so that  $\phi_3'$  is less than or about 1 ev. For proper operating conditions, an electron in  $M_2'$  will have an energy between 1 and 1.6 ev. Referring again to FIGURE 2, it can be seen that the mean-free path for an electron with this energy is approximately 700 Å. This means that the thickness of the second metal layer  $M_2'$  which is approximately 70 Å., as shown in Table II, would be equal to  $(1/10) \lambda$ , one necessary qualification for a device having a 0.9 efficiency.

Thus it can be seen that a device according to this invention includes a very thin first insulating layer  $I_1'$  and a very thin second metal layer  $M_2'$ , operated in such a voltage range that an electron tunnelling from the first metal layer  $M_1'$  to the second  $M_2'$  crosses only through the forbidden region of the first insulating layer  $I_1'$ , and whose energy, upon entering the second metal layer  $M_2'$ , is such that its mean-free path is approximately 10 times the thickness of said second metal layer. Such an embodiment results in low energy losses in both the first insulating layer and the second metal layer with the consequence that the current-transfer ratio is high.

FIGURE 7 shows the relationship between time and resistance for a tunnel junction. Curve 51 is for an unprotected junction and curve 52 is for a junction which has been encapsulated. As can be seen, the resistance across the unprotected junction increases more rapidly with time than the resistance across the protected junction. Thus by encapsulating the tunnel junction, the de-

vice is stabilized and its useful lifetime is considerably lengthened.

One way to fabricate the device of the invention is as follows: In the first step, the second insulator  $I_2'$  and third metal layer  $M_3'$  (elements 13 and 14, respectively, in FIGURE 3) are joined and formed to their proper dimensions by a stripping process. Such a process, following the method described by Kazan and Foote, Tech. Doc. Rpt. No. ASD-TDR-63-640, Aug. 17, 1963, AF 33(657)-8989 by Electro-Optical Systems Inc., Pasadena, Calif., allows one to obtain a thin film of single crystal insulating material. A proper insulator must be chosen; in particular it must be a layered material. In a layered material the atomic bonds within the layer are very strong while the bonds between layers are relatively weak, thus allowing the material to be stripped into layers. The insulating material must also be chosen so that the barrier height  $\phi_3$  between it and the second metal layer is less than or about 1 ev. Mica (ruby or green muscovite) is one such suitable material. Its barrier height as determined by M. McColl and C. A. Mead, Transactions of the Metallurgical Soc. of AIME, vol. 233, p. 502, March 1965, is between 0.80 and 0.95 ev.

FIGURE 8 shows the method of stripping. A metal layer 20 is first evaporated onto a single crystal layered material 21 that will form the second insulator, said layer being approximately 0.001" thick. This combination is then cemented to a pair of blocks 22 and 23. The mounting block 23 is maintained in a fixed position and a torque applied to the stripping block 22, causing the cement, the metal film 20 and a thin layer of the layered insulator 21 to be left on the stripping block 22.

Referring to FIGURE 3, a thin layer of metal 12 is then deposited by any conventional technique, for example by evaporation, on the layered insulator 13, opposite the other metal film 14. Layer 12 should be as thin as possible and yet be continuous, which means that the layer will probably have a thickness on the order of magnitude of 100 Å. This layer must be formed of some metal, such as aluminum, that can be anodized or whose oxide forms a compact film on its surface. The oxide is grown to form the first insulating layer 11. In so doing, the thickness of both the oxide (first) insulating layer 11 and the second metal layer 12 can be controlled. As forming the oxide 11 thins the metal layer 12, it enables one to form said second metal layer 12 thinner than the minimum thickness which can be deposited in a continuous state. For proper operation, the oxide layer should be from 25-50 Å. thick, preferably about 30 Å.

A metal layer 10 is then deposited on the surface of insulating layer 11 opposite metal layer 12. Aluminum forms a suitable material for said metal layer 10. A protective layer of insulation is then deposited over 10, 11 and 12 as an encapsulation. Areas are left exposed on each metal film for the purpose of making electrical contacts, as shown in FIGURE 3.

The above-described process is a practical way of fabricating the tunnel emission amplifier of the invention. It should be noted that the materials listed above are not the only materials that can be used. Any material meeting the limitations previously listed is suitable for the device.

Various modifications of the disclosed embodiment, as well as other embodiments of the invention, will become apparent to persons skilled in the art without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A solid-state electron device comprising first, and second conductive metal layers separated by a first insulating layer, said second conductive metal layer being aluminum and having a thickness of about 70 Angstrom units, said first insulating layer being aluminum oxide and having a thickness from about 25 to about 50 Angstrom units, a layer of mica adjacent said second con-

ductive metal layer, said layer of muscovite having a thickness from about 100 to about 10,000 Angstrom units, a third conductive metal layer adjacent said layer of muscovite and opposite said second conductive metal layer, and bias means on said first and second metal layers for producing a current transfer of approximately 0.9.

2. The device according to claim 1 wherein said third metal layer is aluminum having a thickness greater than 1,000 A.

## References Cited

## UNITED STATES PATENTS

3,258,608 6/1966 Pollock ----- 307—88.5

JOHN W. HUCKERT, *Primary Examiner*.

M. H. EDLOW, *Assistant Examiner*.

UNITED STATES PATENT OFFICE  
CERTIFICATE OF CORRECTION

Patent No. 3,372,315

March 5, 1968

Thomas E. Hartman

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 6, line 75, for "mica" read -- muscovite --.

Signed and sealed this 1st day of July 1969.

(SEAL)

Attest:

Edward M. Fletcher, Jr.

Attesting Officer

WILLIAM E. SCHUYLER, JR.

Commissioner of Patents