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Operation of Tunnel-Emission Devices

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The operation of a new class of devices employing the principle of tunnel emission is discussed. It is shown that a controlled electron source may be obtained with the use of a metal-insulator-metal diode structure where the second metal layer is very thin. A triode geometry may be secured by the addition of an additional insulator and a metal collector layer. Limitations on the operating frequency, current density, and current transfer ratio of such devices are discussed. Experimental results on diode and triode are discussed. Experimental results on diode and triode structures which employ several materials are presented. Successful triodes and vacuum emitters have been realized with the use of Al_2O_3 insulating films. Experiments using Ta_2O_5 are described, and the results are discussed.

TUNNEL EMISSION

Tunnel emission is the phenomenon occurring at a metal-insulator interface when a high electric field is present within the insulator.[1] The phenomenon is most easily studied with reference to a diode structure consisting of two metal plates separated by a thin insulating layer, a potential being applied between the two metal plates. When the field is increased to a sufficiently high value, electrons in the metal impinging upon the interface may "tunnel" through the insulator forbidden region into the conduction band. The mechanism by which this tunneling occurs is shown schematically in Fig. 1. The wave function for a stream of electrons near the Fermi level in the metal traveling to the right is a sine wave as shown. The insulator forbidden region does not permit propagating wave solutions. The problem is very much like that of an electromagnetic wave in a waveguide beyond cutoff, yielding exponentially damped solutions. In the conduction band, propagating solutions are again possible and the wavelength decreases as energy is gained from the electric field. Upon entering the left-hand metal, the wavelength abruptly decreases still farther because of the metal-insulator work function.

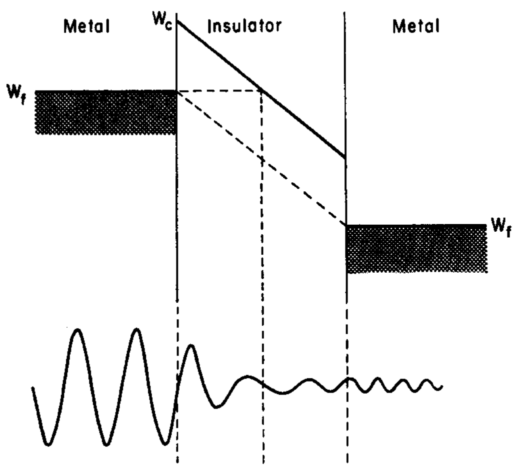

FIG. 1. Energy band structure of metal-insulator-metal diode with applied electric field showing wave function of tunneling electron (schematic).

An excellent survey of the theoretical work done on this problem and a complete list of references has been given by Chynoweth.[2] In general, a solution to the problem gives a current-voltage characteristic of the form

$$\frac{J}{J_0}=\left(\frac{E}{E_0}\right)^2 \exp(-E_0/E), \tag{1}$$

where J and E are the current density and electric field, respectively. In the expression given by Chynoweth,

$$E_0\approx\frac{4\phi^{\frac{3}{2}}(2m^*)^{\frac{1}{2}}}{3\hbar q},$$

and

$$J_0\approx 2q\phi^2 m^*/9\hbar\pi^2,$$

where ϕ is the metal-insulator work function, m^* is the effective mass of the electron, and q is the charge of the electron. The conditions given for the validity of these expressions are that the electron image force be not too strong and that the energy gap of the insulator be large compared with the metal-insulator work function. Also unstated is the condition that the applied voltage be greater than the work function, another way of stating that the electrons are tunneling into the conduction band of the insulator and not directly into the second metal.

Typical values for ϕ are of the order of 1 ev, making E_0 nearly 10^8 v/cm and J_0 of the order of 10^{10} amp/cm^2. A plot of the v-amp characteristic is shown in Fig. 2. It can be seen that the current density increases extremely rapidly with increasing electric field. In most cases the electric field required for significant current density is many times that required for avalanche breakdown in the bulk insulator. Such breakdown, however, requires a large number of electronic mean free paths and in the present case is averted by making the insulating layer very thin, i.e., less than one mean free path. The energy distribution of the tunneling is plotted against the electron wave number in Fig. 3. It can be

[1] C. A. Mead, Proc. Inst. Radio Engrs. 48, 359, 1478 (1960).

[2] A. G. Chynoweth, Progr. in Semiconductors 4, 97 (1959).

seen that the electrons are concentrated very close to the Fermi level ($k/k_f=1$).

TUNNEL-EMISSION AMPLIFIER

A very significant feature of the tunnel-emission process is that it constitutes a controlled source of majority carriers. Suppose we make the right-hand metal layer thin compared with an electronic mean free path in the metal. A typical electron tunneling from the left-hand metal will now pass through the thin metal layer and out through the surface. Such a device may in principle be operated at very high current densities and may well constitute the most practical high current density "cathode" for many conventional and microwave tube applications. In order for the electrons to

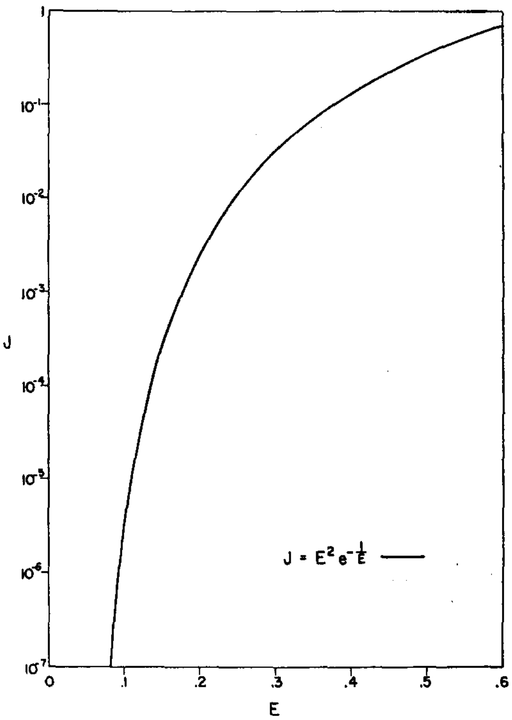

FIG. 2. Theoretical v-amp characteristic of diode as given by Eq. (1).

appear in the vacuum, the electron energy (corresponding to the voltage applied between the metal layers) must be greater than the right-hand metal-vacuum work function. A triode structure may also be constructed by adding another insulating layer to the right of the thin metal region and then a third metal layer, the purpose of which is to collect electrons emitted from the surface of the thin metal layer. The energy band representation of such a structure is shown in Fig. 4. The device thus formed is similar to a transistor, and the same terminology is applied to the metal layers. Three major areas which should be investigated with respect to this device concern (a) frequency limitations, (b) current density and area limitations, and (c) current

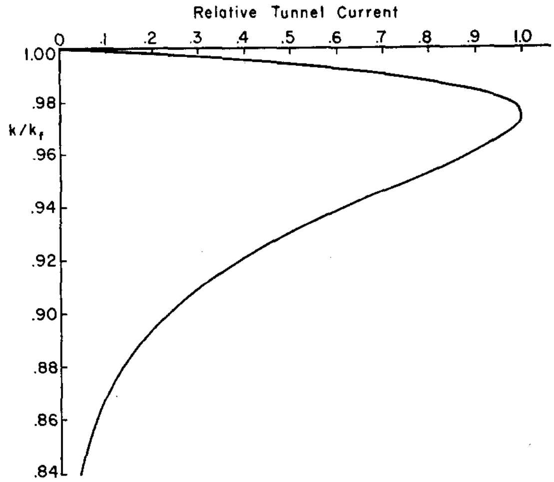

FIG. 3. Momentum distribution of tunnel electrons (normalized to Fermi momentum).

transfer ratio limitations. These areas will now be considered in detail.

Frequency Limitations

Since the actual emitter-base tunneling takes place in an extremely short time, we should expect the major limitations on the gain bandwidth to be input capacitance and base-collector transit time.

The capacitance limitation is very similar to that of an ordinary vacuum tube. A high-frequency figure of merit M may be defined as follows:

$$M=1/RC,$$

where R is the incremental common base input resistance and C is the emitter-base capacitance. This figure of merit is independent of the area of the device unless the current density is not uniform, a condition which will be discussed shortly.

From Eq. (1) we may evaluate the incremental input resistance, assuming $E\ll E_0$:

$$R=dE^2/AJE_0,$$

where A is the area of the device and d is the emitter-base insulator thickness. The capacitance is that of a plane-parallel capacitor:

$$C=\epsilon A/d.$$

The figure of merit may thus be written as

$$M=JE_0/\epsilon E^2, \quad (2)$$

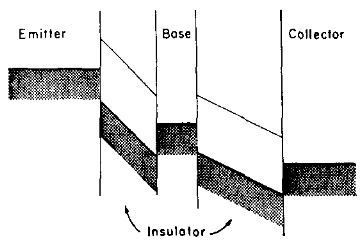

FIG. 4. Energy band representation of tunnel-emission triode (schematic).

and may be uniquely evaluated in terms of the normalized current density. It can be seen that the figure of merit is very nearly proportional to the current density, and the desirability of operating at relatively high current densities is quite obvious.

Base-collector transit time may become a problem if the collector insulating region is made too thick. Two cases will be considered:

(1) Collector insulating layer thick compared with electronic mean free path. In this case we may define an electron mobility μ in the insulator. The transit time t may then be expressed in terms of the collector base voltage V_{cb}:

$$t = d^2/\mu V_{cb}. \tag{3}$$

It should be pointed out that as the collector is made thicker the collector base capacitance is reduced, thus making possible higher gains at frequencies approaching the figure of merit. However, the transit time rapidly becomes important as d is increased.

(2) Collector insulating layer thin compared with electronic mean free path. In this case the transit time is determined only by the electronic velocity and insulator thickness, and for all reasonable thicknesses will be extremely short.

Current Density and Area Limitations

Equation (2) shows clearly the desirability of operation at the highest possible current density (or total current for a given area if the distribution of current is nonuniform). One limitation on the current density is that of space charge in the base-collector insulator. The space-charge limited value of current density is given by

$$J = 2.33\times10^{-6}\frac{\epsilon}{\epsilon_0}\cdot\frac{V^{\frac{3}{2}}}{d^2}\ \text{amp/cm}^2, \tag{4}$$

provided the film is thin compared with a mean free path. For film thicknesses of the order of the mean free path, the value will be somewhat smaller than indicated by this expression. In general, it is necessary to make the collector insulator region thin enough to prevent space-charge limitations at the highest current density to be encountered.

Another rather serious limitation of the *effective* current density is that of the self-bias effect. Since it is not possible to make the current transfer ratio of the device exactly unity, some current will be required to flow laterally in the thin metal base region. If the emitter-collector current transfer ratio $\alpha<1$, the lateral voltage drop resulting from this current decreases the emitter-base electric field near the center of the device and reduces the current density there. By this mechanism, current is effectively confined to a small strip along the edge of the emitter. The situation is very similar to that encountered in the junction transistor.[3] The "characteristic length" with which the current density decreases will now be determined. A two-dimensional structure is envisioned, a cross section of which is shown in Fig. 5. The lateral (x-directed) base current j per unit length of the structure is given by

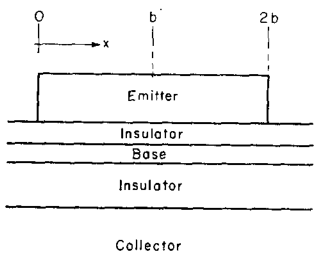

FIG. 5. Model for calculating the effects of lateral base current.

$$j(x) = \int_0^x (1-\alpha)J(x)dx. \tag{5}$$

The lateral voltage drop from the edge of the emitter $v(x)$ caused by this lateral current flowing through the base sheet resistance R_s is

$$-v(x) = \int_0^x j(x)R_s dx. \tag{6}$$

This voltage in turn affects the emitter-base electric field

$$E = \frac{V_{eb}-v(x)}{d}, \tag{7}$$

which in turn controls the total current density by Eq. (1). Substituting Eq. (7) into Eq. (1) and assuming $v\ll V_{eb}$, we arrive at the approximate result,

$$J(x)\approx J(0)\exp\left(-\frac{E_0}{E}\frac{v(x)}{V_{eb}}\right). \tag{8}$$

The three equations (5), (6), and (8) must now be solved simultaneously for $J(x)$. Fortunately, the equations are identical in form to those encountered in a similar calculation for junction transistors, and the solution has been found[4]:

$$J(x)\approx J(b)\sec^2[(b-x)/s], \tag{9}$$

where

$$s^2 = \frac{2V_{eb}(E/E_0)}{(1-\alpha)R_sJ(b)}. \tag{10}$$

The constant s has the dimensions of length and may be thought of as the "characteristic crowding distance," or distance from the edge of the emitter where the current density has fallen appreciably. It is quite clear that a heavy penalty in performance will be paid if the x dimension of the unit is large compared with this distance.

Current Transfer Ratio Limitations

The fraction of emitter current which actually reaches the collector will be referred to as the device current

[3] N. H. Fletcher, Proc. I. R. E. **43**, 551 (1955).
[4] C. A. Mead, Solid State Electronics **1**, 211, (1960).

gain α. This parameter is of major importance in the application of the device. As we have seen in the preceding section, higher values of α permit operation with less self-bias crowding. Also, it may be desired to operate the device in the common emitter connection where the current gain is a very sensitive function of α. Limitations on the current transfer ratio stem chiefly from two sources: traps in the insulators and base-insulator interfaces, and "collisions" in the base region and first insulating layer. It may be thought that electrons tunneling from the valence band of the emitter-base insulator into the base region would also constitute an important source of base current. This would be true if the insulator forbidden band were centered upon the metal Fermi level. The problem is very much like that of the emitter efficiency of a transistor, which is low if the Fermi levels in the two regions are equidistant from the center of the semiconductor forbidden regions. The problem is solved by moving the Fermi level in the emitter region nearer the edge of the band (by increasing the doping). Similarly, by making the metal-insulator work function less than half the forbidden gap, the base current tunneling from the valence band may be made much less than the emitter current. In the discussion which follows we will neglect base current from this source.

Traps in the insulating layers may be avoided by using insulating layers of high purity and good crystal structure. Traps at the interfaces may be more difficult to eliminate. It is anticipated that investigations in this area will prove to be a large part of the development of devices of this type.

As electrons traverse the thin base region, some will suffer "collisions" and lose enough x-directed energy that they are not able to surmount the work function into the vacuum or second insulator. It has already been stated that the mean free path in the first insulator should be large compared with the thickness of the layer. For reasonable current gain, the second metal "base" layer must also be thin compared with the mean free path l. It should be noted that this mean free path is a very different thing from that normally referred to in connection with the conductivity of the metal. Very little is known about the behavior of "hot" electrons with energies of only a few ev in a metal. However, two very significant experiments have recently been reported. It may be inferred from work done by Thomas[5] that the mean free path for electrons in potassium varies with electron energy as shown in Fig. 6. He attributes the very rapid decline in mean free path around 3 ev to the plasma resonance of the metal. The striking thing about his result is the *very long* mean free path at energies less than the plasma resonance energy. Since it is possible to make quite continuous metal layers under 100 A thick, such a film should in principle be capable of meeting the requirements of a control element for tunnel emission devices. Similar results indicating very long electron paths have also been reported for copper.[6]

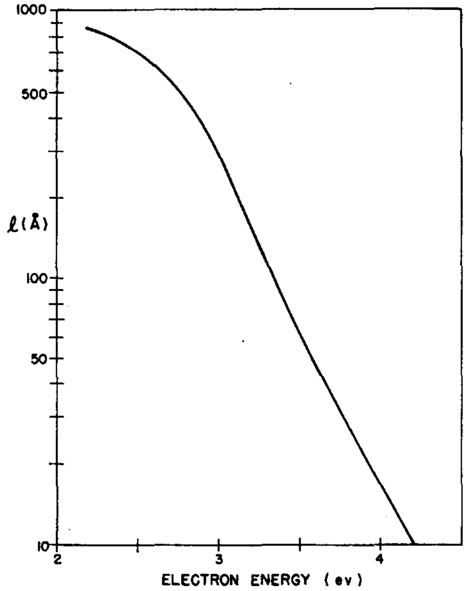

FIG. 6. Mean free path of electrons in potassium as a function of energy above Fermi level (after Thomas).

Another possible mechanism by which electrons may be lost in the base is the reflection of electronic wave functions from the metal-insulator interface. This problem has been dealt with[7] in connection with metal-vacuum interfaces which should exhibit similar characteristics. The result of such an investigation is that for electron energies in which we are interested, the reflection coefficient is very small compared with unity.

A note here is in order concerning the choice of base thickness. If it may be assumed for the moment that all electrons are lost because of collisions in the base and that the collector multiplication factor is unity, the current gain may be written

$$\alpha \approx \exp(-d/l).$$

An approximate expression for the base-sheet resistance is given by[8]

$$R_s \approx \frac{\rho}{d}\left(1+\frac{4L}{\pi d}\right),$$

where ρ is the bulk resistivity of the base material and L is the conductivity mean free path in the metal. For a given geometry and set of requirements on the device, d must be selected for a compromise between self-bias crowding and optimum α. If the electron mean free path in the first insulator is not long compared with the thickness, electrons may suffer collisions and lose sufficient x-directed momentum that they are not able to surmount the work function into the vacuum or second

[5] H. Thomas, Z. Physik **147**, 395 (1958).

[6] R. Williams and R. H. Bube, J. Appl. Phys. **31**, 968 (1960).

[7] L. A. MacColl, Phys. Rev. **56**, 699 (1939).

[8] L. Holland, *Vacuum Deposition of Thin Films* (John Wiley & Sons, Inc., New York, 1956), pp. 236, 347.

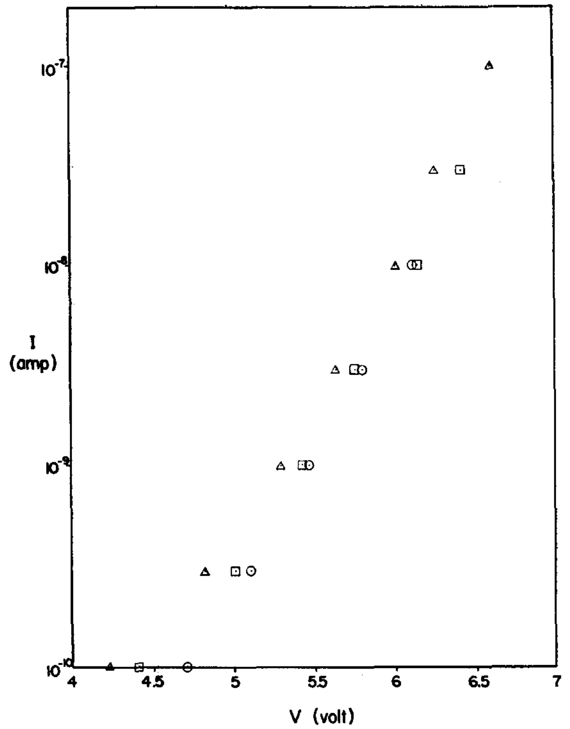

FIG. 7. Experimental v-amp characteristics of three similar Al-Al_2O_3-Al diodes.

insulator. For this reason it is desirable to make the first insulator thin compared with the conduction band mean free path. It should be noted in this connection that experimental information is available for only a very few semiconductors.

Finally, it should be pointed out that devices with a plurality of thin base layers are possible just as are vacuum tubes with several grids. Such arrangements may be found desirable for various applications as the state of the art advances.

EXPERIMENTAL RESULTS

Triode Structures

The first experimental tunnel-emission diodes were fabricated from aluminum because of the ease with which thin oxide films of known thickness may be formed on the surface by anodizing.[8] Initially, aluminum was evaporated on a glass substrate and anodized to the desired oxide thickness in a dilute ammonium citrate solution. More aluminum was evaporated through a mask on the surface of the oxide in the form of circular dots approximately 0.2 mm in diam. Additional diodes were prepared in a similar manner on the electropolished surface of an aluminium single-crystal substrate. The v-amp characteristics of three typical diodes anodized at 5 v (corresponding to approximately 70 A) is shown in Fig. 7.

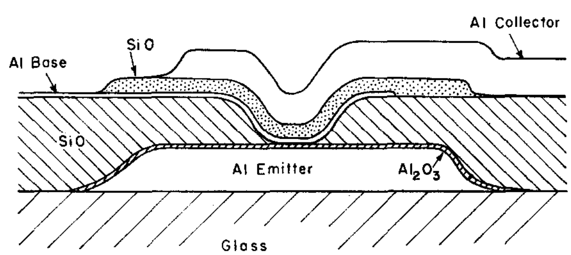

FIG. 8. Cross section of experimental tunnel-emission triode.

Early triodes were prepared as shown in Fig. 8. Aluminum was evaporated on a glass substrate in the form of a stripe approximately 5 mm wide, and was anodized to the desired oxide thickness (50–100 A). To avoid field concentrations at the edges, silicon monoxide was evaporated over all but a 1-mm stripe in the center. Thin aluminum base layer stripes approximately 1 mm wide were evaporated through a mask which allowed them to extend to the left so that contact could be made. The sheet resistance of the film was monitored during deposition, and was controlled to a value of approximately 10 ohms per square. Since the films began to show conductivity at greater than 100 kohm/square it is felt that at the thickness used, a reasonably uniform film was obtained. Judging from interferometer measurements and sheet resistance calculations, the film

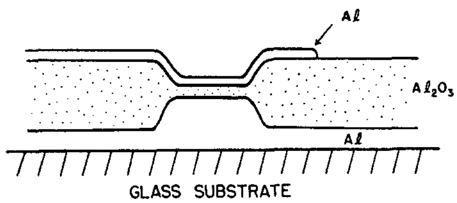

FIG. 9. Cross section of experimental vacuum emitter.

was estimated to be approximately 300 A thick. A very thin film of silicon monoxide (also of the order of 100 A thick) was then evaporated over the central part of the assembly, and finally thick aluminum collector stripes were evaporated in registry with the base stripes but extending to the right. Contact to all regions was made by means of pure indium solder, no difficulties being encountered even with the very thin base films. At current levels of a few μamp, units constructed by the technique just described showed current transfer ratios up to approximately 0.1.

Emission into a Vacuum

In order to study tunnel emission into a vacuum, diodes were constructed as shown in Fig. 9. Aluminum was first evaporated on a glass substrate. Circular areas approximately 0.1 mm in diam, which were to serve as the active area of the device, were masked by a photoresist process. All the remaining aluminum was anodized to 200 v (approximately 2500-A oxide thickness). The resist was then removed and the active areas were anodized to approximately 100-A oxide thickness. A very thin (10 ohms per square) aluminum film was then evaporated through a mask in the form of a rectangle which covered the active area completely and extended onto the thick oxide to provide a contact area. Contact was made by the use of indium solder. This technique allowed several dozen of the devices to be fabricated at once and minimized frustration caused by the destruction of one device. The entire assembly was mounted in a vacuum facing an anode plate spaced approximately 1 mm.

The emitter-base characteristic was observed on a v-amp curve tracer, while the average anode current was monitored by a sensitive oscilloscope. For some devices, current transfer ratios of the order of 0.01 have been observed; however, many are much lower and individual samples vary widely. The transfer ratio of one particular vacuum emitter is shown in Fig. 10 as a function of emitter current. The transfer ratio invariably increases rather rapidly with emitter current. The decrease in transfer ratio at low currents is thought to be caused by traps in the nearly amorphous insulator and at the insulator-metal interface.

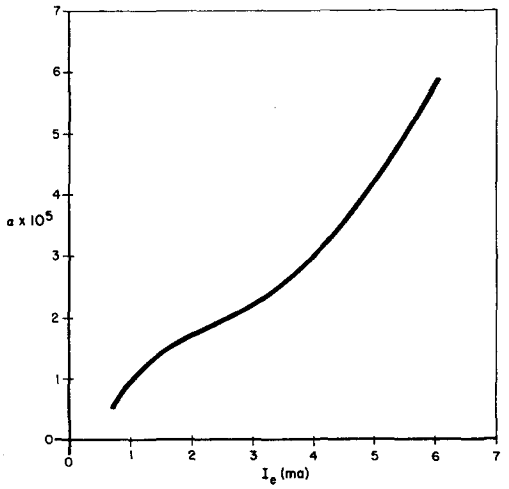

FIG. 10. Current transfer ratio of vacuum emitter as function of emitter current (emitter-base voltage was approximately 7 v).

Al_2O_3 Problem

In all of the experiments described thus far, the current obtained before the device was destroyed was quite low. The v-amp characteristics of the tunneling were sometimes quite noisy and erratic. It has been suggested that such difficulties are caused by the presence of hydroxide in the anodic Al_2O_3 film.[9] Some work has been done at various laboratories on thermally grown oxide films; however, one would not like to give up the controllability of the anodic process and the desirable property of producing a film in which the electric field is very uniform over the entire surface. For these reasons, a film was sought which would be very stable chemically but which could be formed by anodic techniques. These requirements were met by tantalum oxide.

[9] K. R. Shoulders (private communication).

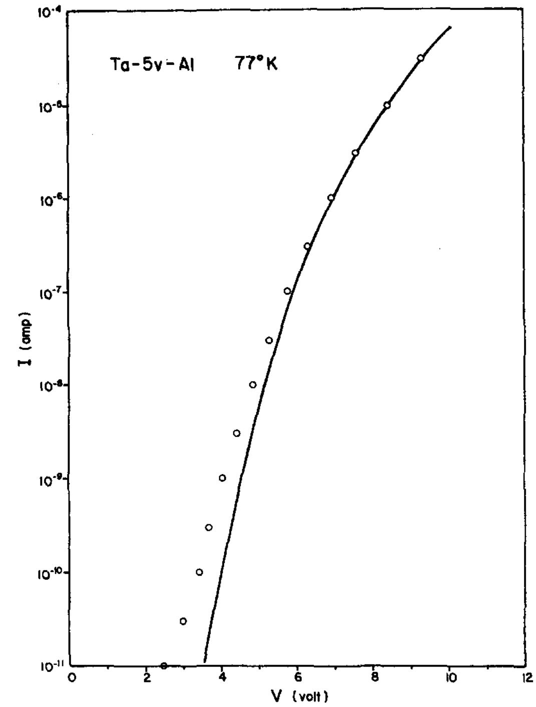

FIG. 11. Experimental v-amp characteristic of Ta-Ta_2O_5-Au diode at 77°K [solid line is a fit of Eq. (1)].

Results with Tantalum

Tantalum diodes were constructed in the same manner as the aluminum diodes already described. Since tantalum is very difficult to evaporate, the diode dots used were either gold or aluminum. For a given anodizing voltage, tunneling was found to occur at a considerably lower voltage than for the aluminum units. These diodes have been found to be remarkably stable, and currents of nearly an amp have been observed before destruction.

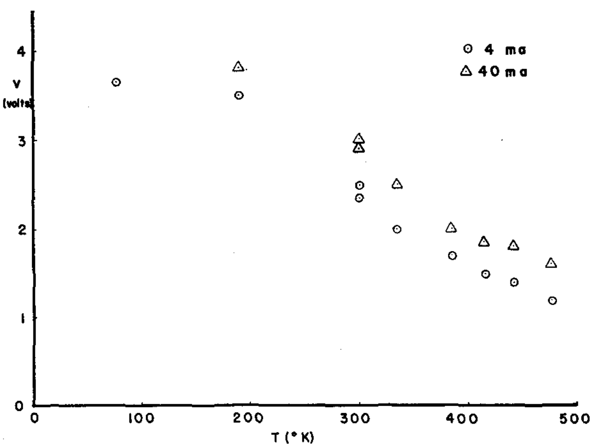

FIG. 12. Experimental temperature dependence of Ta-Ta_2-O_5-Au diode.

A typical v-amp characteristic of one of these diodes is shown in Fig. 11. The solid line is the theoretical curve of Eq. (1) where the effective area and metal-insulator work function have been adjusted to make the slope fit at the upper end of the curve. Such a procedure seems quite artificial, since the areas obtained are of the order of 10^{-4} of the true area. It was speculated that perhaps emission was occurring only at localized very small areas. To test this hypothesis, diodes were constructed as shown in Fig. 9 with a very thin gold film as the front electrode. The v-amp characteristic was monitored on a curve tracer and the diode was observed through a microscope. As the thin gold film was heated by the tunneling electrons, it eventually melted and presumably formed very small globules on the surface, resulting in a marked black color. In every case this effect started at the center of the diode and grew larger until it covered the whole active area. During this process no singularities were observable which could be attributed to high current points. The v-amp characteristic showed no change except that resulting from the change in area until the dark area reached the outer edge of the active area, at which time the diode became an open circuit. From this result it may be concluded that there were no *macroscopic* singularities in the tunnel emission current. However, the tunneling may proceed by means of impurities in the film, which could be considered microscopic singularities.

Effect of Crystal Orientation

One would expect the metal-insulator work function to be a function of crystal face, as in normal field emission. Diodes were built on ordinary rolled tantalum sheet (Fansteel capacitor grade), on sheet recrystallized at approximately 2800°C in argon [diodes made on (111) faces and also on crystal boundaries], and on sputtered tantalum films furnished by N. Schwartz at the Bell Telephone Laboratories. When anodized at the same voltage, the reproducibility between diodes was approximately 5% in voltage, and within this tolerance *no measurable difference in the diode characteristics was observed*. Additional diodes were made on different crystal faces of niobium with the same result.

Temperature Dependence

The voltage necessary for a given tunnel current is a reasonably sensitive function of temperature, as shown in Fig. 12. It is believed that this temperature dependence is caused by a corresponding change in the metal-insulator work function. Although no direct evidence is available on this point, it has been shown[10] that a very similar temperature dependence of the tunnel voltage in thin germanium *p-n* junctions is attributable to the change in band gap with temperature.

[10] A. G. Chynoweth, Phys. Rev. **118**, 425 (1960).

Tantalum Triode Experiments

Both triodes and vacuum emission diodes have been constructed with the use of tantalum in a manner similar to that discussed for aluminum. Some triodes showed feeble transfer characteristics but were not very reproducible. Tantalum diodes similar to that shown in Fig. 9, with thin aluminum front films, were tested for tunnel emission into a vacuum. Emitter currents up to 100 ma were used, and the anode meter was sensitive to 10^{-9} amp. From this experiment it was concluded that the transfer ratio, if any, was less than 10^{-7}. Since the front film was aluminum of the same thickness as that used in the aluminum oxide experiments, it is highly unlikely that all the electrons are being lost in the metal film. It is believed that the mean free path in the tantalum oxide film is sufficiently short that essentially all tunneling electrons suffer at least one collision from the time they enter the conduction band until they reach the metal. This prevents them from overcoming the aluminum-vacuum work function even if they successfully negotiate the metal film. However, in a triode structure the base metal-collector insulator work function is presumably much lower than the corresponding vacuum work function, and electrons may pass over even after losing some of their energy. In summary, anodically grown tantalum oxide films are chemically very stable and show interesting tunneling characteristics; however, the electronic mean free path appears to be so short that they are essentially useless for triodes or vacuum emitters.

CONCLUSIONS

It should be emphasized that the work reported here is certainly in its very early stages. The most serious limitations at present are our almost total lack of knowledge of the pertinent properties of materials, both metals and insulators, and the great need for suitable techniques for fabricating the desired structures. The effects of such basic parameters as crystal structure and orientation, metal-insulator interface structure, and impurities in the various layers are all totally unknown. Many basic questions are brought to mind which have not yet been given even superficial consideration. Hence the results given here must be treated as preliminary. Nonetheless, the feasibility of a new class of devices operating on the principle of tunnel emission has been demonstrated and hence this brief report is given in the hope that it will aid other investigators in the field.

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