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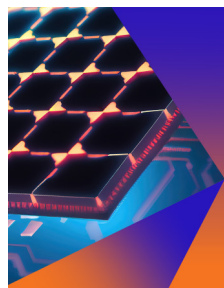


J. Appl. Phys. 41, 3229–3236 (1970)

<https://doi.org/10.1063/1.1659405>



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are in close agreement with the work of Pong and Norris who determined the yield over a narrower range of energy. The yield curve now clearly exhibits a change in slope at 7.8 eV, corresponding to a maximum in the imaginary dielectric constant. The photoemission threshold is obtained by using a threshold law derived by Kane, $Y = C(E - E_t)^n$, where Y is the yield, E and E_t are the photon energy and threshold energy, and C and n are constants. The yield data up to 8 eV are best represented by

$$Y^{2/5} = (0.07030 \pm 0.00035) E - (0.4118 \pm 0.0023),$$

resulting in an extrapolated photoemission threshold

of 5.86 eV in good agreement with a value of 5.74 eV obtained by Mort and Lakatos in photoinjection experiments.

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Voltage-Current Characteristics for Electrical Conduction Through Thin MgO Films*

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(Received 28 October 1969; in final form 27 March 1970)

The voltage-current characteristics of Au-MgO-Au thin-film emission diodes formed by electron beam evaporation of Au and MgO are consistent with an expression derived for Schottky field emission into the conduction band of the oxide. These results however indicate a potential barrier height of about 0.72 eV when determined from the zero-field intercept of the straight line $\log I$ vs $V^{1/2}$ plot and about 0.33 eV when obtained from an Arrhenius plot. These apparent barrier heights were different for devices fabricated by depositing the MgO film in an oxygen atmosphere. The apparent barrier height determined from the zero-field intercept went up for increasing oxygen pressure and the barrier height determined from the Arrhenius plot went down. Emission of electrons into vacuum was observed from each device at very low sample biases indicating that preferential emission through pinholes in the Au overlayer was occurring.

INTRODUCTION

A number of possible current flow mechanisms from metal to metal have been proposed for metal-insulator-metal sandwich devices. The simple band picture was used by Simmons^{1,2} to analyze the electron injection process in terms of tunneling, where the insulator presents a potential barrier to conduction electrons in the metals. The experiments of Nelson and Anderson³ with Al-Al₂O₃-Al and Au devices, in which internal photoemission measurements were used to deduce the height and the bias dependence of the insulator potential-energy barrier, were found to be in good agreement with Simmons' model.

A number of other people have also analyzed the current flow mechanism in terms of tunneling.⁴⁻⁷ Savoye and Anderson⁸ used a modification of this analysis known as internal TF emission to explain their results. In these processes the electrons must penetrate the barrier, however, if the barrier is low enough some electrons will have enough thermal energy to surmount the barrier and give rise to a Schottky current when a field is applied. Emtage and Tantraporn⁹ and Pollack¹⁰ attributed their results to a Schottky process. The Poole-Frenkel¹¹ effect gives rise to a current-voltage relationship nearly the same as the Schottky equation

and is another possible mechanism which must be considered. A discussion of these and other possible current flow mechanisms in thin oxide films is given by Jonscher.¹² These processes could all be modified by space charge.¹³⁻¹⁵ Thus, the electron processes of importance in these devices are in some doubt and must surely depend on the materials used and the method of fabrication. Under appropriate conditions a fraction of these electrons, accelerated by the electric field in the insulator, can be emitted into vacuum and collected by an anode.

In order to minimize impurity levels in the deposited films and at the interfaces, and to produce a symmetrical potential energy barrier the devices were fabricated and studied *in situ* in an ultrahigh vacuum system. To determine the dependence of the results on the insulating film composition, oxygen gas was admitted to various pressures during deposition of the MgO film. All measurements of device I - V characteristics were done at a number of different temperatures.

EXPERIMENTAL PROCEDURES

The samples were fabricated by evaporation of the Au and MgO to form films on a glass substrate, 1×0.6 in. which had been thoroughly cleaned by ultrasonic

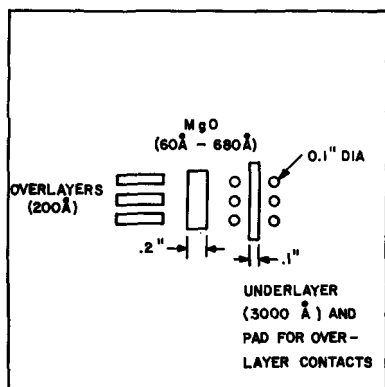


FIG. 1. Mask for deposition of Au-MgO-Au diodes.

agitation and immediately placed in the uhv system. The system was then evacuated and baked to a temperature of 150°C which brought the pressure to a typical value of 6×10^{-11} Torr. The substrates were then heated to a temperature of 400°C by means of a W filament and each evaporation source was thoroughly outgassed before deposition began. The vacuum was again allowed to reach its base pressure, 6×10^{-11} Torr, and sample fabrication was then begun. During deposition of the metal layers the pressure rose to 10^{-9} Torr and during deposition of the MgO layer to 10^{-8} Torr. The entire fabrication process took less than 30 min, the gold overlayer deposition began within 5 min of the finish of the MgO deposition.

The films were deposited through a mask as shown in Fig. 1, each film was deposited after moving the substrate to the new position. The thicknesses of the films were determined by precalibrating deposition rate vs electron beam power using a quartz crystal monitor.^{16,17} This method had to be used rather than continuous monitoring during deposition as a consequence of the lack of space and electrical feedthroughs into the vacuum system. After device fabrication was completed the substrate was moved to the measurements position and the devices were brought into contact with eight W springs, mounted on an insulating disk, which made electrical contact to the three devices. Figure 2 shows a schematic of the measurements structure within the vacuum. Measurements of the I - V characteristics were made using a four-terminal method on a slowly varying dc basis and using a 10-msec ramp. The emission into vacuum was measured only with the 10-msec ramp. A filament was mounted in the vacuum system about 10 in. from the measurements position and the tem-

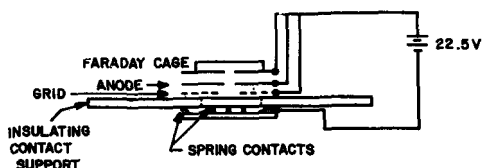


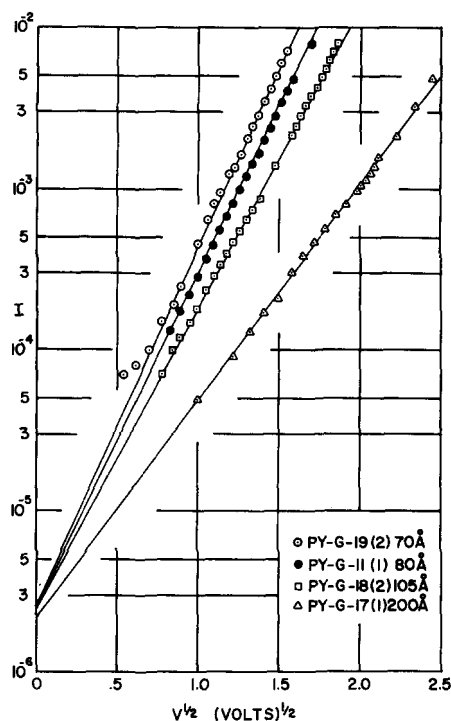
FIG. 2. Schematic of measurements apparatus in vacuum.

perature of the device was monitored by a Pt-Pt 10% Rh thermocouple.

EXPERIMENTAL RESULTS

These studies have involved fabrication and study of 60 thin-film sample sets each of which contained three overlayer films. Of these, 13 devices were studied in detail.

The I - V characteristics of these devices did not plot as a straight line on a $\ln(I/V^2)$ vs I/V plot. Thus, the Fowler-Nordheim¹⁸ equation does not hold for these

FIG. 3. Comparison of results of devices with thin (<200 Å) oxide films.

devices. The other injection process which is possible is Schottky field emission^{9,10} and the equation applied to a metal-oxide-metal device is given by van der Ziel¹⁹ and is

$$J = AT^2 \exp(-\phi_R/kT) \exp(bV^{1/2}), \quad (1)$$

where

$$b = (q^3/4\pi\epsilon_r\epsilon_0s)^{1/2}(kT)^{-1}. \quad (2)$$

In these expressions A is Richardson's constant, ϵ_r is the relative dielectric constant of the oxide, s is the oxide thickness, and k is Boltzmann's constant. From these expressions it is obvious that a plot of $\ln I$ vs $V^{1/2}$ should be a straight line for the Schottky process. Figure 3 is a plot of the data for four devices on a Schottky, $\ln I$ vs $V^{1/2}$, plot. It can be seen from this figure that the functional dependence of I upon V is the same as for Schottky emission.

At this point, however, one must be careful not to

assume Schottky emission just because a plot of $\ln I$ vs $V^{1/2}$ is a straight line. The Poole-Frenkel effect¹¹ gives rise to a similar I - V characteristic. The equation describing the dependence of I upon V for the Poole-Frenkel effect is given by:

$$J = G_0 V \exp(bV^{1/2} - \Psi/kT), \quad (3)$$

where G_0 is a constant with the dimensions of conductivity, Ψ is the energy difference between the trap level and the bottom of the conduction band, and the other symbols have already been defined. As can be seen, this mechanism may also plot as a straight line on a $\log I$ vs $V^{1/2}$ plot.

If one assumes Schottky emission to be the controlling mechanism for these devices the slopes of the curves in Fig. 3 are b , which can be written as

$$b = \gamma \epsilon_r^{-1/2} s^{-1/2} T^{-1}. \quad (4)$$

The device temperature during measurement was 313°K and the precalibrated oxide thickness was 80 Å. The slope of the curve then results in a dielectric constant $\epsilon_r = 10.9$ which is fairly close to the low-frequency dielectric constant of MgO which is 9.8.²⁰ Since there is no *a priori* reason for assuming the high-frequency dielectric constant for Schottky emission, the Schottky mechanism cannot be ruled out.

If one plots $\ln(I/V)$ vs $V^{1/2}$ one does not obtain a straight line as should occur for the Poole-Frenkel mechanism. This result is not surprising since this is a bulk effect. It thus appears that the conduction mechanism is not the Poole-Frenkel effect.

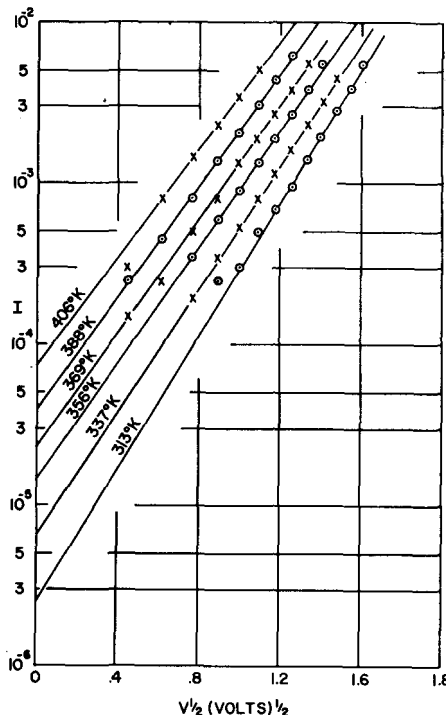


FIG. 4. $\ln I$ vs $V^{1/2}$ as a function of temperature for device PY-G-11, overlayer 1.

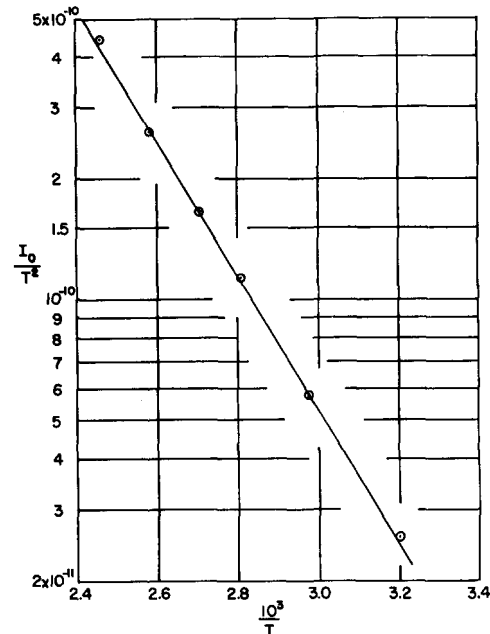


FIG. 5. $\ln(I_0/T^2)$ vs $10^3/T$ for device PY-G-11, overlayer 1.

Devices were studied with oxide thicknesses in the range of 60–680 Å. In all cases, in which no oxygen gas was admitted during deposition of the MgO film the I - V characteristics plotted as a straight line on a $\ln I$ vs $V^{1/2}$ plot and were not straight lines on a $\ln(I/V^2)$ vs $1/V$ plot nor on a $\ln(I/V)$ vs $V^{1/2}$ plot. As can be seen from Fig. 3 the zero-field intercept is independent of oxide thickness.

From the Richardson-Schottky equation with zero field:

$$I_0 = aA^*T^2 \exp(-\phi_R^*/kT), \quad (5)$$

where a is the device area, A^* is the apparent Richardson's constant and ϕ_R^* the apparent barrier. From this expression ϕ_R^* can be obtained. The barriers obtained in this manner range from 0.69 to 0.72 eV. This determination of the barrier height may not be accurate because of the questionable value of the Richardson constant. However, as Hartman *et al.*²¹ point out, a change in this constant by an order-of-magnitude would only change the barrier determined in this way by about 10%.

A number of other features of the I - V characteristics which became evident during measurements on these devices should be mentioned. No aging effect was noted during measurements of the I - V characteristics of these devices. The I - V characteristics were identical with the overlayer biased positive or negative, indicating a symmetrical barrier if the conduction mechanism is electrode controlled. No hysteresis effects were noted using the slowly varying dc measurement technique indicating that neither charge trapping^{22,23} nor device heating occurred during measurement. Finally, the characteristics were the same for dc and pulse measurements.

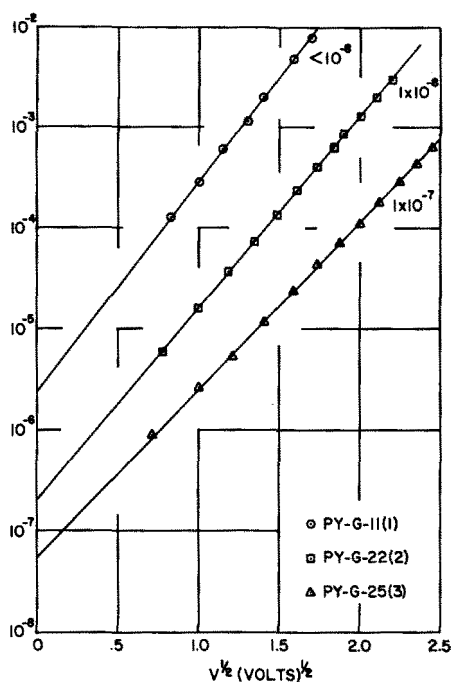


FIG. 6. Comparison of results with different pressures of oxygen present during fabrication.

Since the functional dependence of I upon V indicates a Schottky mechanism, which is very temperature dependent, the I - V characteristics were measured at a number of temperatures. Figure 4 is a plot of $\ln I$ vs $V^{1/2}$ over a temperature range of about 100°C . It can be seen that the I - V characteristics are temperature dependent. If a plot of the zero-field intercept current I_0 obtained from this figure, is made on a $\ln(I_0/T^2)$ vs $1/T$ plot the result should be a straight line and the slope of this line will again determine ϕ_R^* . A plot of this type is made in Fig. 5. It can be seen that the plot is a straight line although most of these plots were not. The slope of the straight line drawn in the figure gives a barrier of $\phi_R^* = 0.33$ eV.

In order to determine the effect of nonstoichiometry on the device characteristics a number of devices were fabricated by depositing the oxide film with oxygen gas present in the vacuum system. Since the pressure in the vacuum system normally rose to 10^{-8} Torr during oxide deposition, oxygen gas was admitted to the system to a pressure of 1×10^{-8} Torr and this device, PY-G-22(2) was studied. Oxygen gas was admitted to a pressure of 1×10^{-7} Torr during fabrication of the next device, PY-G-25(3). A summary of these two devices and one fabricated with no oxygen admitted is shown in Fig. 6. The zero-field intercept of the Schottky plots is a function of oxygen pressure with the lower intercept (higher barrier?) present for the devices fabricated with more oxygen present during MgO deposition, which could mean more stoichiometric oxide films. The characteristics still plot as a straight line on a $\ln I$ vs $V^{1/2}$ plot.

A number of devices were fabricated with the deposition of MgO done in an atmosphere of 10^{-6} Torr and higher of oxygen. None of these devices could be measured, they either broke down before any current was drawn or were initially shorts. One device, PY-G-38(1), which had an MgO film $120\text{-}\text{\AA}$ thick was fabricated by depositing the oxide film in an atmosphere of 10^{-5} Torr of O_2 to a thickness of $30\text{ }\text{\AA}$ and depositing the remaining $90\text{ }\text{\AA}$ after the O_2 had been pumped from the system. It took a higher bias to obtain the same current with the overlayer positive than with the overlayer negative. This would be expected if the current is limited by the interfacial barrier height. The fact that the barrier is higher for the overlayer positive would be expected since the more stoichiometric part of the oxide film is near the underlayer. These results are consistent with the hypothesis that admitting oxygen gas during deposition of the MgO film increases the stoichiometry of the film as seen by an increased barrier height. The data is plotted on a Fowler-Nordheim plot in Fig. 7 and it can be seen that the injection mechanism could now be tunneling, i.e., a higher barrier.

It was noted during the study of the I - V characteristics of these devices that at low fields, $\lesssim 10^4$ V/cm, the I - V characteristics were linear. The device resistance increased for increasing amounts of O_2 present during MgO deposition and was independent of oxide thickness.

The experiment was designed to permit simultaneous measurements of the I - V characteristics of the device and emission into vacuum from the device. The emission transfer ratios, $\alpha = I_e/(I_e + I_s)$, for a number of devices

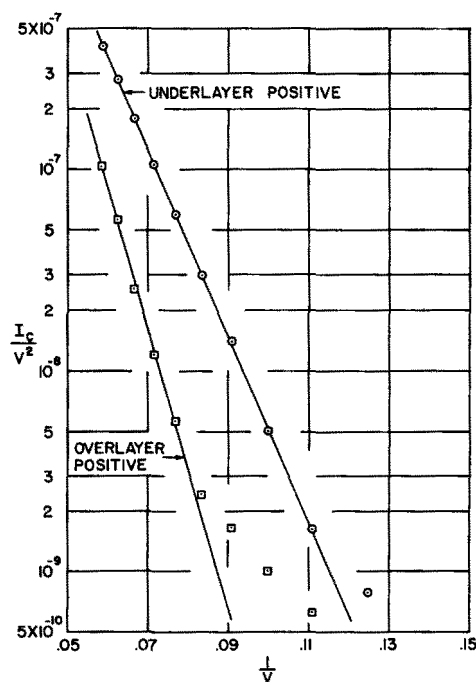


FIG. 7. Fowler-Nordheim plot of I - V characteristics of device PY-G-38(1).

are plotted in Figs. 8 and 9. The overlayers were all about 200-Å thick except for PY-G-19(2) which has an overlayer 133-Å thick. A number of features of these plots are very striking. The transfer ratio decreases with increasing sample bias, contrary to the results of other investigators^{8,24} electrons are emitted into vacuum for very low sample biases, and the emission ratio goes up for thicker oxide films at a given sample bias.

To be sure that the measurements made were really of electrons into vacuum and not leakage or capacitance effects, the polarity of the anode and/or the overlayer was reversed. The only way in which an emission cur-

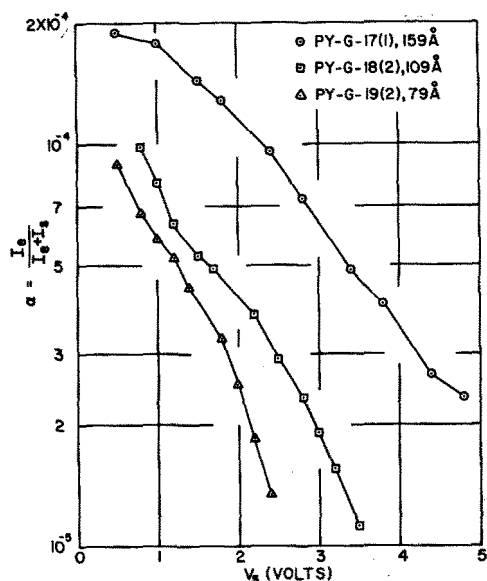


FIG. 8. Comparison of emission transfer ratio for devices with different oxide thicknesses, 10-msec pulse.

rent was observed was with both the overlayer and anode biased positively with respect to the underlayer.

Table I is a summary of the devices studied extensively.

ANALYSIS AND DISCUSSION OF RESULTS

Discussion of Injection of Electrons into the Oxide Film

Experimental results have been presented for the I - V characteristics of vacuum-deposited Au-MgO-Au emission diodes which are in agreement with an expression in which I_s is proportional to V_s at low fields and $\ln I_s$ is proportional to $V_s^{1/2}$ at high fields in the oxide. However, the results are not consistent with a Poole-Frenkel mechanism nor with the Richardson-Schottky equation modified for these devices by multiplying ϵ_0 by ϵ_r . The origin of the Richardson-Schottky equation was in connection with thermionic emission of electrons into vacuum from metals of high work function in which the work function is lowered by the electric field because of image force modification of the metal-vacuum interfacial barrier. The problem as

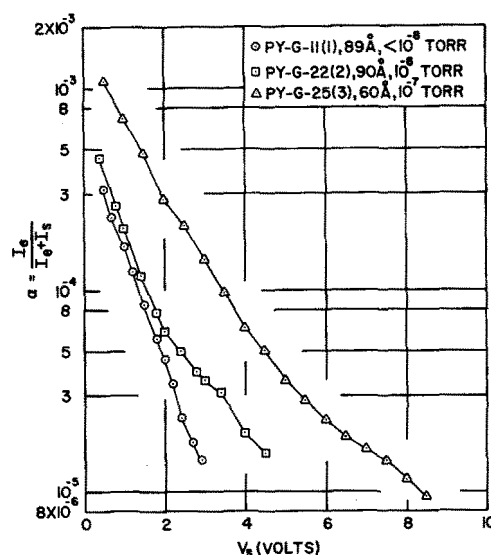


FIG. 9. Comparison of emission transfer ratio for devices with the MgO film deposited with different amounts of oxygen gas admitted, 10-msec pulse.

applied to these devices needs some modification since the multiple image force corrections to the barrier potential may become important.

The exact expression for the multiple-image correction to the potential energy of an electron in a medium with dielectric constant $\epsilon_r\epsilon_0$ between infinite parallel plane electrodes is derived by Simmons¹ who also gives an extremely good approximation to the multiple image correction [see Ref. 1, Eq. (33) and Fig. 4] which is

$$\phi_0(x) = -Ks^2/x(s-x). \quad (6)$$

As pointed out by Savoye and Anderson⁸ this approximation is closer to the true image correction at low fields than the single image correction but at high fields

TABLE I. Summary of device data.

Device No.	S^a	S_0^b	ϕ_1^c	ϕ_2^d	$P_{O_2}^e$
PY-G-11(1)	80	200	0.714	0.33	
PY-G-16(3)	105	...	0.721	...	...
PY-G-17(1)	200	194	0.721	0.33	...
PY-G-18(1)	105	...	0.694	0.34	...
PY-G-18(2)	105	222	0.700	0.35	...
PY-G-19(2)	70	133	0.710	0.33	...
PY-G-20(1)	680	...	0.695	...	...
PY-G-20(3)	680	...	0.695	...	...
PY-G-21(3)	90	...	0.732	0.34	...
PY-G-22(2)	90	209	0.780	0.21	10^{-8}
PY-G-25(3)	60	200	0.823	0.11	10^{-7}
PY-G-38(1)	120	...	1.9, 1.74 ^f	...	10^{-5} , ...

^a S = oxide thickness, in Å.

^b S_0 = overlayer thickness, in Å.

^c ϕ_1 = barrier obtained by zero intercept method, in eV.

^d ϕ_2 = barrier obtained from slope of Arrhenius plot, in eV.

^e P_{O_2} = pressure of admitted O_2 during MgO deposition, in Torr.

^f The barrier was obtained from the slope of the Fowler-Nordheim plot.

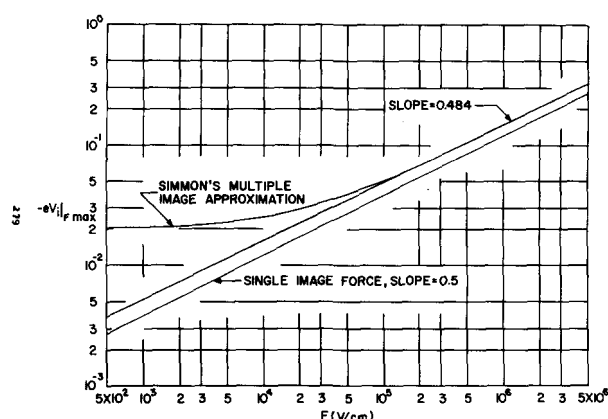


FIG. 10. Potential energy maximum of an electron in a dielectric with an applied field present, $S=100$ Å.

the opposite is true. Using this approximation to derive the Schottky equation one arrives at the expression:

$$I = aAT^2 \exp[-\phi_R/kT + f(V)/kT], \quad (7)$$

where $f(V)$ is a function of applied voltage. Figure 10 is a plot of the potential energy maximum of an electron in a dielectric separating two metal electrodes with an applied field present as a function of applied field. Two plots are made, one using the single image modification to the potential barrier at the emitting electrode and the other uses Simmon's multiple image approximation to the barrier. $f(V)$ is the function plotted using Simmon's approximation and is a function of electrode spacing (oxide thickness of 100 Å for this plot) and dielectric constant of the oxide as well as the applied voltage ($V=sF$, where F is the electric field). When the electrons coming from the other electrode are considered the equation becomes

$$I = aAT^2 \exp(-\phi_R/kT) \times \{\exp[f(V)/kT] - \exp[g(V)/kT]\} \quad (8)$$

or

$$I = aAT^2 \exp(-\phi_R/kT) \times \exp[f(V)/kT][1 - \exp(-eV/kT)], \quad (9)$$

where

$$g(V) = f(V) - eV. \quad (10)$$

Thus, at low voltages

$$I \cong (aATeV/k) \exp(-\phi_0'/kT) = V/G, \quad (11)$$

where

$$\phi_0' = \phi_R - f(V) \quad (12)$$

and $f(V)$ is nearly constant as a function of voltage.

Figure 11 is a comparison between the data of 3 devices and Eq. (9). The data points are circled and the solid line is Eq. (9). Thus, it can be seen that there is very good agreement between the data and Eq. (9) over 6 orders-of-magnitude of current and 5 orders-of-magnitude of voltage.

The values of resistance, $R = k \exp(\phi_0'/kT) / eaAT$,

at low voltages calculated and experimentally observed were in excellent agreement. For device PY-G-21(3) the calculated value was $1.3 \times 10^5 \Omega$ and experimentally it was $8 \times 10^4 \Omega$, for PY-G-22(2) the values are 3.9×10^5 and $4.3 \times 10^5 \Omega$ while for PY-G-25(3) they are 7.1×10^5 and $7.5 \times 10^5 \Omega$, respectively.

The good agreement between Eq. (9) and the data indicates that the Schottky-type mechanism could be the dominant mechanism for injection of electrons into the oxide film. The low barrier would evidently be due to a high density of interface states at the metal-oxide junction. This same phenomena has been observed by other authors for metal-semiconductor interfaces.²⁵⁻²⁸

According to Fig. 5, the dependence of I upon temperature is not that of the Schottky process. Figure 12 is a plot of $\ln(I_0/T^2)$ vs $10^3/T$ for the two devices fabricated with O_2 gas present during oxide deposition and also for device PY-G-11(1). It can be seen that these curves do not plot as straight lines. From Eq. (5) one gets

$$\ln(I_0/T^2) = \ln(aA^*) - \phi_R^*/kT, \quad (13)$$

and the curves in Fig. 12 should be straight lines. However, if ϕ_R is a function of temperature:

$$\frac{d[\ln(I_0/T^2)]}{d(1/T)} = \frac{-\phi_R^*(T)}{k} - (kT)^{-1} \frac{d\phi_R^*(T)}{d(1/T)}. \quad (14)$$

Thus, the slope of these plots would not be proportional to the barrier height and would not be a straight line. If $d\phi_R^*(T)/dT$ is positive, i.e., if the barrier increases with increasing temperature, then $d\phi_R^*(T)/d(1/T)$ is negative and the slope of the $\ln(I_0/T^2)$ vs $1/T$ plots will give a number which is smaller than the actual barrier, this

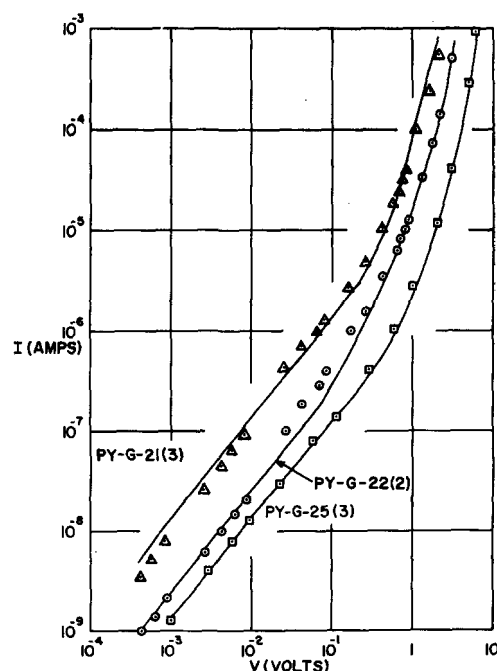


FIG. 11. Comparison between experimental data and Eq. 9 for three devices.

was seen here. These results were not checked with decreasing temperature so it is not known if a temperature transient exists, however after a day or more the measurements gave results the same as the original results.

Savoye⁸ found a contact potential difference of $\phi_{Au}-\phi_{Al}=0.8$ eV in his Al-Al₂O₃-Au samples. If the surface-state model holds, the barrier should be nearly the same for current flow in either direction, if it does not hold the barrier will be modified by the contact potential difference between the metals. A number of Au-MgO-Al devices were fabricated and the difference between barriers was $\phi_{R\ Au}-\phi_{R\ Al}=0.06$ eV. This value is much smaller than the difference in work functions of the two metals, but of about the same value as seen by Mead^{27,28} for different metals on CdSe. Thus, a model incorporating a high density of interface states to lower the expected barrier is consistent with the observed results.

Discussion of Emission into Vacuum

Figures 8 and 9 show the emission transfer ratio, $\alpha=I_e/(I_e+I_s)$, as a function of sample bias. Two features of these plots are very striking, one is that the transfer ratio decreases with increasing sample bias and the other is that for only one device, PY-G-25(3) does the sample bias exceed 5.45 V, the approximate necessary bias for electron emission through the gold overlayer film. Savoye and Anderson⁸ discuss the possibility of preferential emission of electrons through pinholes in the gold overlayer film. In order for electrons

to be emitted from these Au-MgO-Au devices the electrons must therefore be emitted through holes in the gold overlayer films.

None of the possible energy loss mechanisms are able to explain the decrease in transfer ratio with increasing sample bias if emission is taking place through holes in the Au overlayer films. The most probable explanation is that the oxide emitting surface becomes charged. When a sample current is first drawn, electrons arrive at the hole and those with enough energy are emitted into vacuum. The remaining portion are not collected by the overlayer immediately but lead to a space charge at the hole. Thus, the emitted current is dependent on sample current and time and in this manner indirectly dependent on the sample voltage. The total charged area is so slight, however, that it does not affect the sample current. The charging effect was noted, when the sample voltage was kept at maximum value for a few msec, the sample current remained constant but the emission current dropped as the pinhole charged up.

SUMMARY

This investigation was primarily concerned with the transport of electrons through vacuum-deposited thin-film emission diodes with subsequent emission into vacuum. The studies were specifically carried out on the evaporated Au-MgO-Au system.

A number of current flow mechanisms were ruled out since the functional dependence of I upon V was wrong for these mechanisms.

Using the multiple image correction to the potential barrier profile results in an I - V characteristic which is linear for low voltages. The expression derived in this analysis, Eq. (9), was plotted on log-log paper and fit the data over six orders-of-magnitude of current and four orders-of-magnitude of voltage. The conclusion drawn is that the electron flow in these devices could very well be that of emission of electrons over the potential barrier into the conduction band of the oxide by a Schottky-type process and subsequent acceleration by the strong electric field to the collection electrode.

Further evidence of Schottky emission into the oxide conduction band is found in the fact that emission into vacuum is seen from all the devices at low sample voltages. The sample biases are never large enough to allow emission of electrons into vacuum through the gold overlayer film. Thus, the electrons must be emitted through pinholes in the gold film, i.e., directly from the oxide film. The emitted electrons must still overcome a potential barrier at the oxide-vacuum interface which is the electron affinity of the MgO. If the electrons were not coming over the underlayer-oxide interfacial barrier they would not have enough energy to be emitted into vacuum until the sample bias had reached about 1.0 V or more. Emission into vacuum was seen from these devices at sample biases less than 0.5 V. Thus, if the electron affinity of MgO is about 0.8 eV,²⁹ the emission

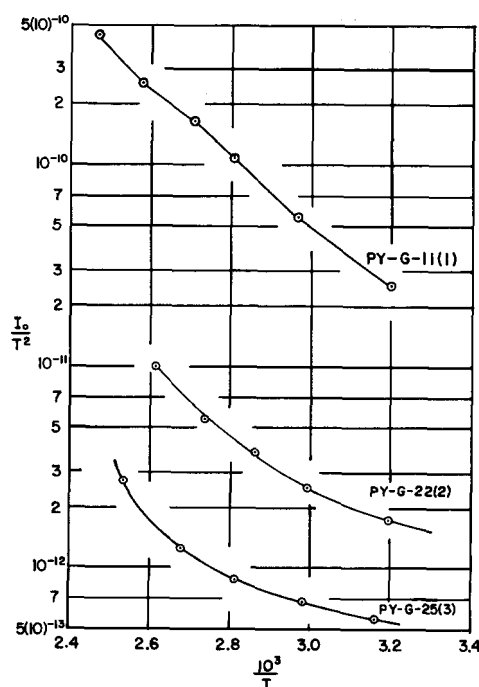


FIG. 12. $\ln(I_e/T^2)$ vs $10^3/T$ for devices fabricated with different amounts of oxygen present during MgO deposition.

current must be due to the electrons in the tail of the Fermi distribution above the energy level of the oxide conduction band. These electrons then have enough energy to be emitted into vacuum. The measurements of emission into vacuum are dominated by charging of the oxide at an emitting pinhole.

If the emission is Schottky emission the barrier height was a function of the amount of oxygen present in the vacuum system during deposition of the MgO film with a higher barrier for larger amounts of oxygen present. Raising the oxygen pressure during deposition of the MgO film probably leads to a more stoichiometric film. The barrier height also appeared to become higher with higher temperature.

The only evidence that the current flow mechanism in these devices is not Schottky emission is found in the temperature dependence of the I - V curves. This would still not rule out Schottky emission if the barrier is a function of temperature, becoming higher for higher temperatures. No direct evidence that this is happening was obtained so no definite conclusions as to the type of current flow mechanism present in these devices can be made.

* This work was supported by the Air Force Avionics Laboratory, Research and Technology Division, Wright-Patterson Air Force Base.

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Mechanisms Controlling the Positive Ion Emission from Heated Fe Filaments*

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(Received 28 May 1969; in final form 5 March 1970)

Positive ions emitted from heated iron filaments consist mainly of the alkali-metal atoms, such as lithium, sodium, and potassium, which are present in iron as trace impurities. Changes in the work function with different applied partial pressures of oxygen and hydrogen have been recorded. From the results of measurement it is concluded that the effect of oxygen on the work function of iron is much stronger than that of hydrogen. Kinetic data representing the emission of Na and K ions from Fe were obtained in the temperature range of 1050°-1350°K. Diffusion and ion desorption are discussed as possible rate-controlling processes. Activation energies, believed to represent the diffusion of Na and K atoms in Fe, are found to be approximately 38 kcal/mole (1.7 eV) and 53 kcal/mole (2.3 eV), respectively. The Richardson work function of iron varies from $\phi \approx 4.0$ eV at $P_{O_2} \approx 10^{-9}$ Torr to $\phi \approx 5.6$ eV at $P_{O_2} \approx 10^{-8}$ Torr. When a diffusion-controlled process is assumed, the difference between the activation energies, for the above two oxygen pressure conditions, is found to be the same as the difference ($I - \phi$); that is, the difference between the first ionization potential of the atom and the work function of the metal surface. The experimentally determined values of $(I - \phi)_{\text{exp}}$ for K and Na agree within experimental error with the calculated values.

INTRODUCTION

Up to the present time a large number of papers have been published on the subject of surface ionization (SI), and a review is given by Zandberg and

Ionov.¹ A thorough review of the experimental work on SI nearly up to date is given by Kaminsky.² Two papers have appeared recently describing studies of the positive ion emission arising from alkali-metal trace impurities supplied to the surface of a polymorphic