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SCHOTTKY EMISSION THROUGH THIN INSULATING FILMS

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With the discovery of observable tunnel emission through thin insulating films, much attention has been focused on this mechanism of current transfer. The importance of space-charge limited current in somewhat thicker films has also been recognized. We have recently observed a third mechanism of current transfer, namely, the high-field emission of hot electrons from a metal into the conduction band of an insulator in contact with it; this process is identical with Schottky emission into the vacuum.[1]

The system consists of a thin insulating layer I between two metals M_1 and M_2, a voltage V being maintained between the metals (see Fig. 1). The work function between I and M_1 is ϕ_1; the actual potential seen by an electron passing from M_1 to I is shown by the dashed line; it differs from the conduction band level by virtue of the image forces between the electron in the insulator and the metal. An electron in the metal with a forward energy greater than the potential maximum can enter the conduction band of the insulator, and hence give rise to a current between the two metals.

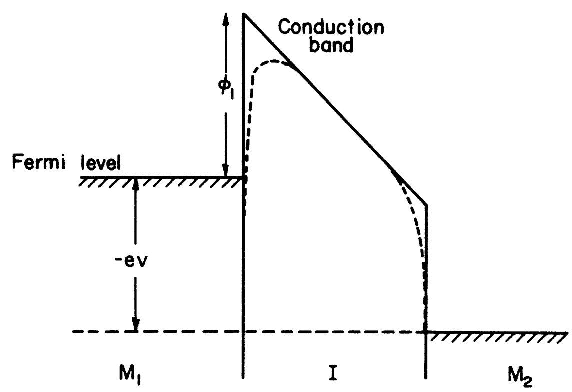

FIG. 1. Energy level diagram of system described in text.

The current-voltage and current-temperature relationships for the three transfer mechanisms mentioned above are given in Table I.

The constants in the expression for Schottky currents are

$$\beta = (q^3/Ka)^{1/2}/kT, \quad \alpha = AT^2 e^{-\phi/kT},$$

where q is the charge on the electron, a is the

Table I. Current-voltage and current-temperature dependences for the three transfer mechanisms.

Mechanism	Current-voltage dependence	Current-temperature dependence
Space-charge limited	$I \propto V^2$	$I \propto \mu$, the mobility of electrons in the insulator
Tunnel emission	$I \propto V$ for $V < \phi$ $I \propto V^2 \times e^{-\text{const}/V}$ for high V	None
Schottky emission	$I = \alpha \exp(\beta V^{1/2})$	$I \propto T^2 e^{-\text{const}/T}$

thickness of the insulator, K is its relative dielectric constant, and A is the Richardson constant. On the elementary theory $A = 120$ amp cm^{-2} $°C^{-2}$, but divergences from this value are common.

The characteristic of Schottky emission is its high temperature dependence; at room temperature and with film thicknesses of the order of 100 Å, the currents found are of the same general magnitude as tunneling currents, but Schottky emission is favored over tunnel emission by thicker films and higher work functions. There have been many instances of apparent tunnel emission reported in which the current-voltage relationships fail to fit a Fowler-Nordheim plot properly, and in which temperature dependence is observed; we suggest that these may occur because some or all of the current arises from Schottky emission.[2]

Our first observation of Schottky emission was in a film of polymerized silicon oil (PSO) on gold; the film was prepared by a method similar to that described by Christy.[3] The current-voltage dependence is shown in Fig. 2; the plot of logI vs $V^{1/2}$ is a very good straight line, the intercept on the axis of logI giving the value of α. The original results have been checked with a variety of PSO films of different thicknesses, with similar results. Schottky emission has also been found in the systems Al-Al_2O_3-Al and Al-GeO_2-Al; the estimated thicknesses were PSO, 100 Å; Al_2O_3, 50 Å; GeO_2, unknown. At room temperature, the entire current in these films appeared to come from Schottky emission.

In Fig. 3 is shown a measurement of the temperature dependence of the current through a PSO film at constant voltage; if the current were entirely thermionic, the plot of $\log(I/T^2)$ vs $1/T$ would be a straight line of slope $(\phi - \gamma V^{1/2})/k$,

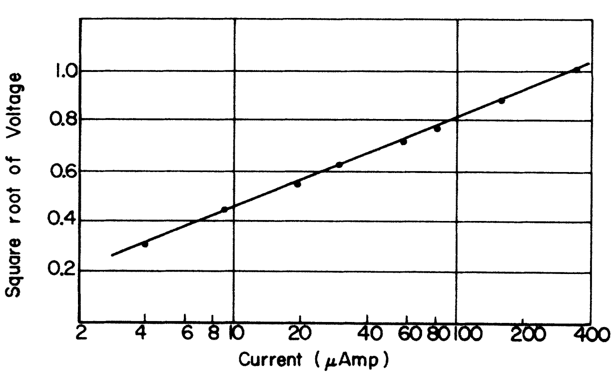

FIG. 2. Verification of the relationship $\log I \propto V^{1/2}$ for Au-PSO-Au system at 300°K.

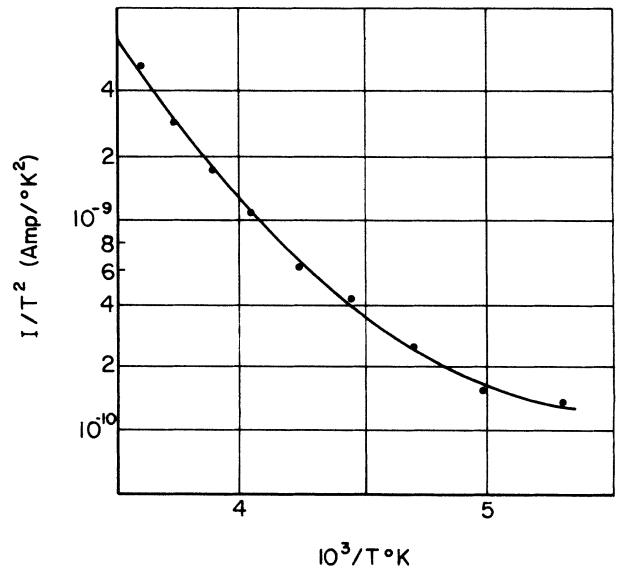

FIG. 3. Temperature dependence of current through PSO film at fixed applied voltage.

where $\gamma = \beta/T$. The deviation of the line from linearity probably arises from a constant tunneling current of about 4 μa superimposed on the thermionic current, the tunneling current becoming dominant at -70°C.

The above results provided two ways of estimating metal-insulator work functions. The first method is from the observed values of α, using an assumed value for A of 120 amp cm^{-2} $°C^{-2}$; ϕ may then be calculated directly. The best method should be from the temperature dependence of the current, but a small tunneling current can make it difficult to obtain a good value. Since a factor of 10 in A gives an error of only 0.06 ev in ϕ, the first method is probably more reliable, unless measurements can be made at high temperatures without film breakdown.

The values obtained for ϕ were:

System	Au-PSO	Al-Al_2O_3	Al-GeO_2
ϕ (ev)	0.78; 0.50*	0.74	0.90

The value denoted by an asterisk was obtained from a temperature-dependence measurement.

[1]F. Seitz, Modern Theory of Solids (McGraw-Hill Book Company, New York, 1940), pp. 161-8.

[2]See, e.g., C. A. Mead, J. Appl. Phys. 32, 646 (1961). The curves given for current-voltage dependence in Al-Al_2O_3 and Ta-Ta_2O_5 systems fit Schottky plots well; in the latter case, this occurs even at 77°K (see Mead's Fig. 11), giving an estimated work function for Ta-Ta_2O_5 of 1.2 ev.

[3]R. W. Christy, J. Appl. Phys. 31, 1680 (1960).