TRANSPORT OF HOT ELECTRONS IN THIN GOLD FILMS

C. A. Mead
California Institute of Technology, Pasadena, California
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Considerable interest has been expressed of late concerning the transparency of thin metal films to electrons with energies of a few electron volts above the Fermi level.[1–4] In the present experiments, information concerning the mean free path for loss of energy in gold is determined directly from measurements of electron transport. The technique used is that of tunnel emission[3,4] in which electrons are caused to tunnel from a metal substrate through a thin insulating layer into a thin metal electrode through which a certain number pass into a vacuum where they are collected. Measurement of the relative number transmitted through the thin metal layer as a function of the thickness of the layer yields a direct measurement of the energy mean free path.

In the present experiments, the metal substrate used was beryllium, prepared by vacuum evaporation onto a glass surface. A thin layer of beryllium oxide (produced thermally) served as the insulating layer. Thin layers of gold were evaporated on the oxidized surface in the form of small dots. The active areas used were of the order of 5×10^{-4} cm^2 in area.

The thickness of the thin gold layers was monitored by observing the sheet resistance of the gold on a glass monitor slide. The thickness of gold varies approximately as the inverse square root of the sheet resistance on a glass surface[5] for the range of thicknesses involved. Within each dot very continuous layers were formed on the beryllium oxide surface, sheet resistances being as much as an order of magnitude lower than for the same deposit on glass. (Holland's formula[6] gives a 400A thickness for $R^{-1/2} = 0.8$. Our measurements using multiple beam interferometry give 400 A at $R^{-1/2} = 0.95 \pm 10\%$. Considering the rather crude nature of the measurements, this agreement was considered acceptable.) Residual pressures during all evaporations were approximately 10^{-7} mm.

The ratio (α) of emitted current is plotted against the inverse square root of gold sheet resistance R (directly proportional to thickness) in Fig. 1 for two thicknesses of the insulating film. The energy mean free path obtained from the slope of this plot was 190 A for the lower curve and 180 A for the upper curve. The tunneling voltage was 7 volts for the lower curve and 10 volts for the upper curve. Data were taken at input currents of approximately 100 ma. It will be noted that the intercepts of the transfer ratio extrapolated to zero gold thickness are considerably less than unity, that for the 10-volt samples being larger than that for the 7-volt samples. This result is consistent with the assumption that the electrons lose some energy in the insulator before entering the metal. Only those which have energies larger than the work function when they enter the metal would be able to surmount the barrier into the vacuum, even if no energy were lost in the metal. If the electrons have energies distributed between the tunneling voltage and the bottom of the insulator conduction band due to energy loss in the insula-

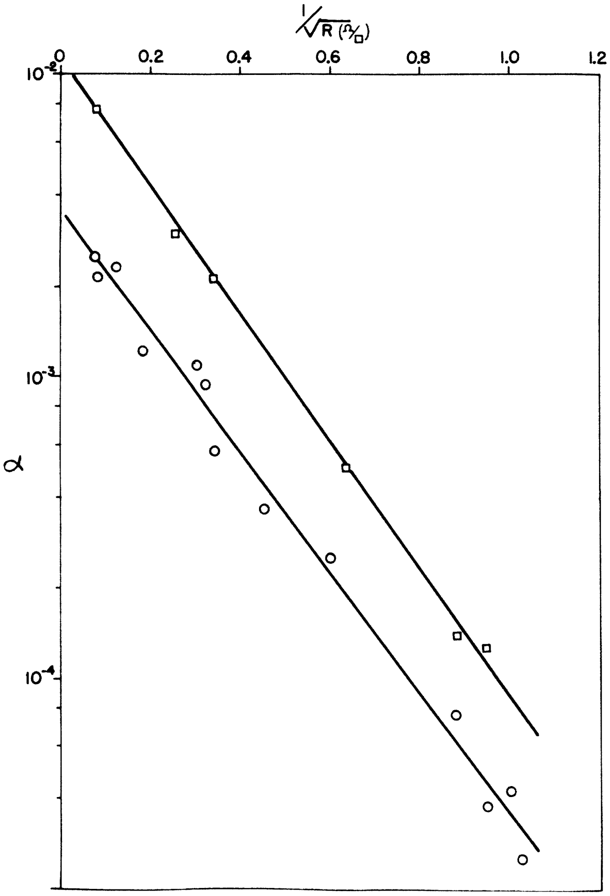

FIG. 1. Ratio of emitted current to input current vs gold film thickness (measured by sheet resistance). Upper curve for 10v and lower curve for 7v tunneling voltage.

tor, one would expect a larger number with energies above the gold work function if the tunneling voltage were higher. Also one would expect the higher tunneling voltage to yield a shorter mean free path, since the mean free path should decrease with electron energy.[6] However, the mean free path obtained from the present experiments is a weighted average over the energies from the gold work function up through the tunneling voltage and if a large fraction of the electrons were concentrated at energies near the bottom of the insulator conduction band, the change in apparent mean free path with tunneling voltage would be slight, as observed. If no energy were lost within the insulator, plots similar to those in Fig. 1 would all be expected to have an intercept of unity and slopes which corresponded closely to the true energy mean free path for energy corresponding to the tunneling voltage.

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MEAN FREE PATH OF PHOTOEXCITED ELECTRONS IN Au

W. G. Spitzer, C. R. Crowell, and M. M. Atalla
Bell Telephone Laboratories, Murray Hill, New Jersey

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At the present time there is considerable interest in the mean free path of hot electrons in metals.[1] Most of the work on photo-[2] and secondary emission[3] has dealt with electrons whose energy above the Fermi level exceeds the work function of the metal. In the present investigation the mean free path of electrons in Au has been investigated for electron energies between 0.8 and 1.1 ev. Au films of controlled thicknesses were evaporated on freshly cleaved Si surfaces and the spectral dependence of the photoresponse studied.

The samples were bars of 8 ohm cm *n*-type silicon covered with a 1-micron thick layer of SiO_2. At one end of the bar the oxide was removed and an Ohmic contact was made. The samples were cleaved in vacuum and the cleaved surface immediately covered by an evaporated Au layer. The above procedure is a modification of that employed by Archer and Atalla[4] to study metal-silicon surface barrier rectification. When such diodes are illuminated the silicon acts as a collector for photoexcited electrons in the metal layer. The effect of band-to-band transitions in the silicon is eliminated by restricting the photon energies to $E_{\text{ph}} < 1.1$ ev. In order to observe a photocurrent originating from electrons excited in the metal layer, the energy of these electrons must exceed the height of the Schottky barrier at the metal-semiconductor interface. That such a photocurrent can be detected has already been demonstrated for the case of electrochemically deposited metal films on CdS.[5] Figure 1 shows the square root of the response per incident photon as a function of the photon energy for five different thicknesses of Au. The extrapolation of the linear portion of these curves to zero response gives a photoelectric threshold of 0.79 ± 0.01 ev for all the samples. The same value was also obtained from a Fowler plot. This is in excellent agreement with the value 0.79 ev for the energy from the top of the barrier to the Fermi level as obtained from a study of the voltage dependence of the depletion layer capacitance.[4] The photoresponse is not due to scattered light of energy $E_{\text{ph}} > 1.1$ ev since the nature of the spectral response was not altered when silicon filters were placed in the spectrometer beam in front of the diode. For a threshold determination the response per absorbed photon rather than per incident photon should be used, but since the energy absorbed in each film was found to be nearly independent of E_{ph} in the region of interest, the data of Fig. 1 yield the correct threshold. The energy absorbed was determined from measurements of the spectral dependence of transmission and reflection of Au films evaporated on glass slides. Since the slides were positioned adjacent to the