Emission of energetic electrons from tunnel junctions

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Energetic (hot) electrons can be emitted from $Al-Al_2O_3-Au$ tunnel junctions. This emission supports a recently proposed hot-electron picture for light emission from tunnel junctions. A transfer ratio curve shows that a fraction approaching 1% of the injected, hot tunneling electrons retain sufficient normal energy to surmount the Au-vacuum surface barrier and be collected if the Au work function is lowered by the evaporation of 3—4 monolayers of cesium. Fitting tunneling junction *I-V* curves by two different methods gives a tunneling barrier 2—4 eV high and 15—19 Å thick. These barrier parameters are comparable to those of light-emitting tunnel junctions.

INTRODUCTION

Recently, Kirtley *et al.*[1] have proposed a hot-electron picture of light emission from tunnel junctions. They suggest that the emission process is dominated by radiative decay of surface plasmons generated by energetic (hot) electrons at the metal-vacuum interface rather than by inelastic interactions in the barrier region of the tunnel junction.

In this paper, we report experimental observations which support the hot-electron picture of light emission from tunnel junctions. We have observed electron emission from $Al-Al_2O_3-Au$ tunnel junctions. Our measurements are on junctions with insulators less than 20 Å thick that emit electrons at bias voltages as low as 2 V. In these junctions, the dominant mechanism of current flow is electron tunneling. The *I-V* characteristics are linear at low bias voltages (<1 V) and show Fowler-Nordheim behavior at higher bias voltages (>2.5 V). Earlier work on electron emission from metal-insulator-metal junctions[2–16] used thicker insulators (typically 100 Å thick) and high bias voltages (typically 5—12 V). Our work uses the same range of barrier thicknesses and bias voltages used in present light-emitting tunnel junctions.

The electron emission process can perhaps be characterized in a manner similar to the light-emission process. A majority of the electrons tunnel elastically. Although this hot-electron distribution relaxes via phonon emission and electron-electron scattering, a fraction of the electrons reach the metal-vacuum interface with sufficient energy to either excite surface electromagnetic waves for light emission or surmount the surface barrier and be emitted into vacuum in our current experiments.

We present a curve of transfer ratio (transfer ratio identically equals collected emission current/tunnel current) versus junction bias. This curve shows that for $Al-Al_2O_3-Au$ tunnel junctions with 3—4 monolayers of evaporated Cs on the Au film, a fraction approaching 1% of the tunneling electrons retain sufficient normal energy to be emitted into vacuum and collected.

EXPERIMENTAL

The Al strips were evaporated into cleaned glass substrates from W filaments in an oil diffusion pumped vacuum of order 3×10^{-6} Torr. The Al films were oxidized in air at 22 °C for ~20 min. The Au films were evaporated from an alumina coated W basket in a cryopumped vacuum of order 6×10^{-7} Torr. During the Au evaporation, the sample was cooled with liquid nitrogen. Film thicknesses measured with a quartz-crystal thickness monitor were of order 1000 Å for the Al films and 100 Å for the Au films.

After the evaporation, the samples were heated to room temperature in vacuum. Upon exposure to room air, junction resistances rose from as little as a few hundred ohms to as much as a few hundred kilohms in the time necessary to apply indium solder pads and transport the samples to the UHV chamber. The samples were mounted on the cold finger of a closed-cycle refrigerator.

Once in UHV, the samples were baked lightly overnight at approximately 80 °C. The cesium sources (SAES Getters) were outgassed during pumpdown. The chamber was allowed to cool to room temperature and the pressure would drop to 6×10^{-9} Torr before the refrigerator was turned on.

Emission measurements were carried out approximately 90 min. later at chamber pressures of 1×10^{-9} Torr. During Cs evaporation, the pressure rose to 5×10^{-8} Torr and returned to 1×10^{-9} Torr after the Cs source cooled off. The Cs evaporations were masked so that only one junction at a time was cesiated. Each junction was coated with an average thickness of 3—4 monolayers of Cs as measured with a quartz-crystal thickness monitor. Figure 1 shows the apparatus used for measuring the emission

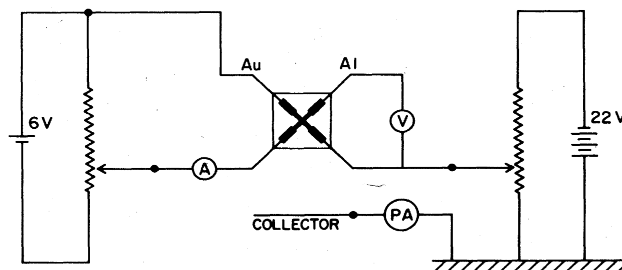

FIG. 1. Circuit for measuring tunnel junction *I-V* curves and emission current. The electrons are collected by a flat plate which is connected to ground through a picoammeter.

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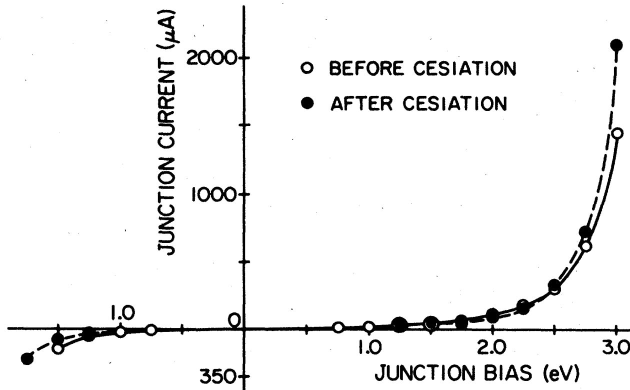

FIG. 2. Tunnel junction I-V curves.

current and junction I-V curves. Later, a Au plated Cu Faraday cage with an aluminum shield was used to collect the emitted electrons, but there was no systematic change from the data obtained with the flat plate collector shown in the figure.

RESULTS

A pair of tunnel junction I-V curves is shown in Fig. 2. This particular pair shows very little change in the I-V characteristic due to the cesium overlayer. Other pairs, however, had up to 15 times as much current at voltages >2.7 V after cesium deposition.

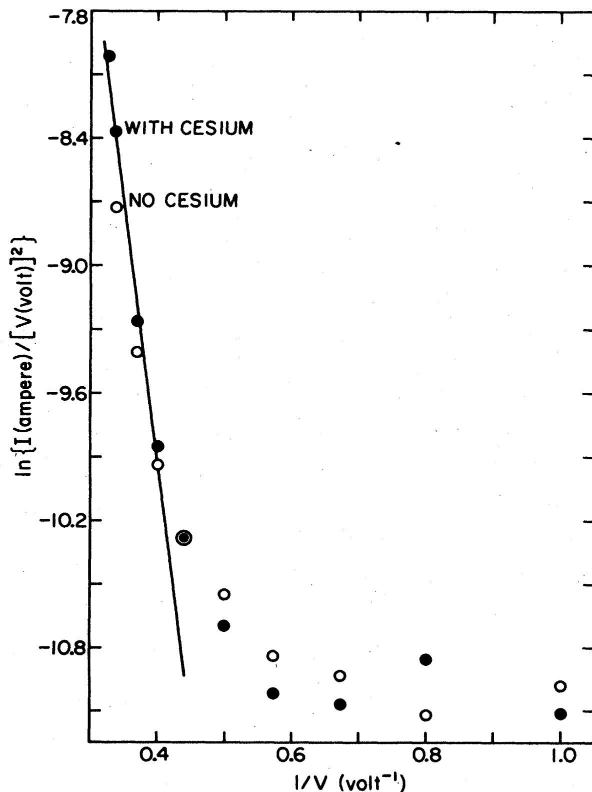

FIG. 3. Fowler-Nordheim plots for the tunnel junctions of Fig. 2. Note the asymptotic straight-line dependence for high bias voltage.

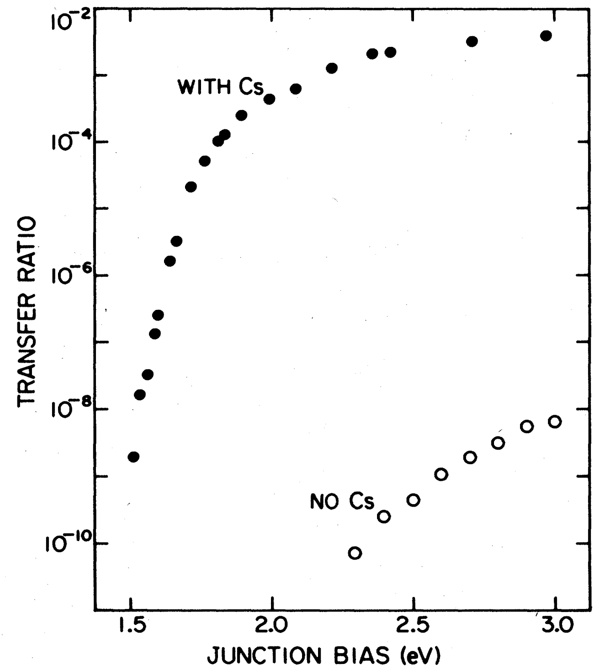

FIG. 4. Transfer ratio (collected emission current/tunnel current) versus junction bias for the tunnel junction of Fig. 2.

The I-V curves in Fig. 2 were used to determine the barrier height and oxide layer thickness after the method of McBride, Rochlin, and Hansma.[17] The Fowler-Nordheim plots are reproduced in Fig. 3. Note the straight-line asymptotic dependence at high bias voltages. The barrier was determined to be 17 ± 2 Å thick and 1.9 ± 0.2 eV high both before and after cesiation. Junctions whose resistance was lowered by cesiation did not exhibit this straight-line asymptotic behavior and were not chosen for this analysis. Computer programs supplied by Hipps and Mazur[18] fit the I-V curves and gave barrier heights of $\phi_{Al}=4$ eV, $\phi_{Au}=3$ eV, and a barrier thickness of 15 Å. The difference in the results is perhaps due to the difference in the methods. The method of McBride *et al.* assumes a square barrier and is sensitive only to the high voltage, Fowler-Nordheim regime. Hipps and Mazur's computer fit assumes a trapezoidal barrier and fits the entire curve so that it is sensitive to the low-voltage ohmic part as well as the Fowler-Nordheim part of the curve.

Figure 4 shows a semilogarithmic plot of junction transfer ratio as a function of junction bias voltage. The transfer ratio is defined as the ratio of collected emission current to junction current. In the figure the largest transfer ratio corresponds to currents of less than 10 pA before cesium deposition and 10 μA after cesiation. The junction area was 0.2 mm^2.

DISCUSSION

At a junction bias of 3.0 eV, roughly 1% of the tunneling electrons are collected by the collector. It is not

surprising that this high percentage could be collected. (1) Simple tunneling theory suggests that the normal energy distribution of electrons injected into the top metal electrode is peaked near the bias energy for bias energies greater than the barrier height.[1] (2) The attenuation length of 3-eV electrons in Au is of order 100 Å,[16,19] so a large fraction of the electrons reach the metal-vacuum interface. (3) The transmission coefficient for electrons normally incident on a metal-vacuum interface with energies greater than the work function is greater than 90%.[20,21] The properties of evaporated Cs on thin evaporated Au films have been reported elsewhere. Cs forms a stoichiometric compound with Au, CsAu, with a work function of only 1.6—1.7 eV.[22] (4) Efficient electron collectors, such as Faraday cages, were used.

What limits the collected current to 1%? The steps in the overall process are tunneling, hot-electron transport in the Au film, emission, and collection. Each introduces losses that are not yet well understood. Important opportunities for both theoretical and experimental research on this system exist. For example, interesting theoretical problems include the following. (1) A calculation of the degradation of the tunneling electron normal energy distribution in transversing the Au film. This calculation could include the effects of velocity randomization due to small energy-loss electron-phonon collisions as well as the degradation of the overall hot-electron energy distribution due to large energy-loss electron-electron collisions. (2) A calculation of the transmission coefficient for electrons incident on a layered interface, such as the Au-CsAu-vacuum interface used in this research.

Further experimental investigations could include studies of the collected emission current as a function of both top electrode thickness and different top electrode combinations. Any experiments, however, are complicated by the difficulty of preparing and characterizing *smooth* thin films in this thickness range.

CONCLUSION

In summary, we conclude that a fraction approaching 1% of the hot tunneling electrons in an Al-Al_2O_3-Au tunnel junction with 3—4 monolayers of Cs evaporated on the Au film are emitted from the junction and collected. Clearly, this is an underestimate of the fraction of the electrons which reach the top of the Au electrode since both the transmission coefficient of the metal-vacuum interface and the collector efficiency are less than 100%. Thus, the present data support the hot-electron picture of light emission from tunnel junctions proposed by Kirtley[1] by demonstrating the presence of a substantial number of hot electrons at the metal-vacuum interface.

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