Temperature dependence of the two-dimensional electronic density of states in disordered metal films

J. M. Valles, Jr., R. C. Dynes, and J. P. Garno
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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We present measurements of the temperature dependence of the conductance of a tunnel junction of the form Al/oxide/disordered-granular-Ag-film at low temperatures. From these measurements we deduce that the logarithmic corrections to the two-dimensional density of states due to disorder-enhanced Coulomb interactions depend on temperature. Specifically, for sheet resistances $1.35\ \text{k}\Omega/\square < R_\square < 6.12\ \text{k}\Omega/\square$ and temperatures $0.07\ \text{K} < T < 6.0\ \text{K}$ the logarithmic singularity in the density of states centered on the Fermi energy is sharp at low temperatures and smears out as the temperature increases. Our data are consistent with a model which attributes the temperature dependence of the density of states to a redistribution of the zero-temperature energies of the quasiparticle states over an energy range of the order of $k_B T$.

When the amount of static disorder in a metallic system is increased, the effects of electron-electron interactions become enhanced. Physically, the disorder-induced reduction in the electron diffusion constant leads to poorer screening and stronger spatial correlations between electrons with closely spaced energies. Consequently, Coulomb interactions extend over longer length scales than in a clean metal and depend on the energy difference between the quasiparticles. Altshuler, Aronov, and Lee showed that one manifestation of these enhanced Coulomb interactions is to give rise to singular corrections to the density of states at the Fermi energy.[1] They predicted logarithmic corrections for two-dimensional disordered systems and these have been observed.[2,3] They also predicted that the correction to the density of states should be temperature dependent.

In this paper, we present the first systematic study of the temperature dependence of these *corrections* to the density of states. Specifically, we have measured the temperature dependence of the conductance of Al/Al_2O_3/granular-Ag tunnel junctions for Ag-film sheet resistances $1.35\ \text{k}\Omega/\square < R_\square < 6.12\ \text{k}\Omega/\square$. As one raises the temperature of the Ag film, the logarithmic singularity (centered on the Fermi energy, E_F in the tunneling density of states) fills in and becomes smeared out. This filling in proceeds in such a way that the total number of states remains constant. That is, the increase in the density of states at E_F is compensated for by a decrease in the density of states at energies a few $k_B T$ away from E_F. The measured increase in the number of states at E_F is in rough agreement with an approximate theory of Altshuler and Aronov.[4] Preliminary data indicate that our basic results also hold true for films which are uniform on an atomic scale. We emphasize that this is a change in the density of states, not simply the trivial change in occupation of states brought about by temperature.

The granular Ag films were quench condensed at 4 K onto fire polished glass substrates using an ultrahigh-vacuum cryogenic evaporator.[5] Prior to cooling down the substrate, we evaporated gold contacts for four-terminal resistance measurements of the 2.5-mm-wide Ag film and a 0.1-mm-wide conventional Al film which we oxidized in air for the tunnel junction counterelectrode. The data we present in this paper were obtained for a series of Ag evaporations onto a single substrate and Al counterelectrode. Hence, all variations in the tunnel junction resistance with sheet resistance can be solely attributed to changes in the Ag film properties. These films became electrically continuous at an equivalent mass deposited thickness of approximately 3 nm. Using a free electron model and the Boltzmann equation for the conductivity we deduce that for this series of films, $1.0 < k_F\lambda < 5.5$ where k_F is the Fermi wave vector and λ is the elastic mean free path.

This junction and the others that we have measured satisfied the criterion $R_j(2.5\ \text{mm}/0.1\ \text{mm}) \gg R_\square$, where R_j is the junction resistance. This ensured that the voltage drop across the junctions far exceeded any lateral drops in the finite resistance films. In addition, we are confident that the junction used in this experiment was of high quality. Similarly fabricated junctions with a superconducting film in place of the Ag film consistently showed sharp phonon structure in the junction conductance. Although we present data from a single series of films we have performed the experiment many times with reproducible results.

The tunnel junction resistances, dV/dI, were measured using standard ac lock-in techniques at a frequency of 27 Hz and inverted to give conductances. Typical modulation levels were on the order of 20 μV_{rms} and frequent checks were made to ensure that no significant distortion of the derivative due to overmodulation or heating was taking place. The primary noise source was 60 Hz pick-up which produced $< 2\ \mu V_{\text{rms}}$ across the junction.

The conductance of a bulk-metal–insulator–dirty-metal tunnel junction at a voltage V and temperature T is given by

$$G(V,T)=dI/dV=C\int_{-\infty}^{+\infty}N(E,T)\frac{df(E+V,T)}{dV}dE\ , \tag{1}$$

where E is the single particle energy measured relative to the Fermi energy, $N(E,T)$ is the density of states of the dirty metal which we have given an explicit temperature dependence, and $f(E+V,T)$ is the Fermi distribution function. C is proportional to the density of states in the bulk metal and the tunneling probability, both of which we assume to be energy and temperature independent. If $N(E,T)$ does not depend on temperature, then it follows that $G(V,T)$ is given by

$$G(V,T)=\int_{-\infty}^{+\infty}G(V',T')\frac{df(V'+V,T)}{dV}dV'\ , \tag{2}$$

where $T'\ll T$. By measuring the tunnel junction conductance at a low temperature, $G(V,T')$, calculating $G(V,T)$ using (2) and examining deviations of a measured $G(V,T)$ with this result, we can obtain a qualitative description of the temperature dependence of the density of states in the dirty metal.

In Fig. 1 we plot $G(V)$ versus $\log_{10}(V)$ for $T<0.08$ K for four different sheet resistance films. $G(V)$ for the two lowest $R_\square$ depended logarithmically on the voltage over more than a decade. The higher $R_\square$ films showed roughly logarithmic behavior with some concave downward curvature. This curvature may be due to a crossover from two- to three-dimensional behavior as the diffusion length, $(\hbar D/E)^{1/2}$, approaches the film thickness, where D is the electronic diffusion constant.[2] These results are consistent with earlier measurements done on indium oxide[2] and tin films.[3] We will use these data in Eq. (2) as $G(V',T')$.

As one raises the temperature the sharp feature in the tunneling conductance near the Fermi energy becomes smeared as shown in Fig. 2. That is, relative to $G(V,T')$, the zero-bias conductance increases and the conductances at voltages on the order of $5k_BT$ decreases. Comparing

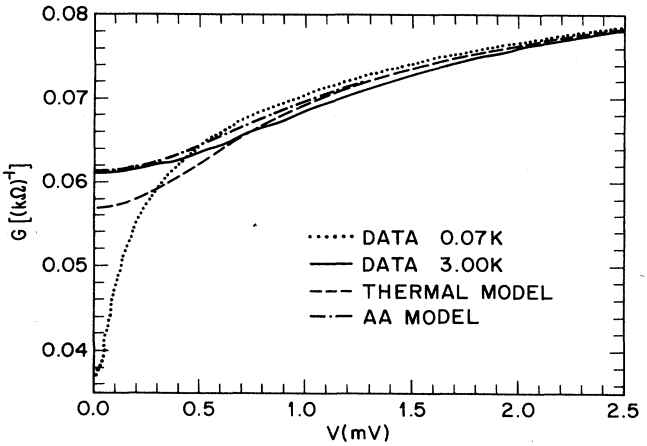

FIG. 2. Tunnel junction conductance for the 3.82-kΩ/□ film at $T=0.07$ K (dotted line) and 3.0 K (solid line). The dashed line corresponds to the simple thermal model which assumes a temperature-independent density of states. The dashed-dotted line uses the Altshuler and Aronov form, Eq. (3), for the temperature dependence of the density of states.

the data to the prediction of Eq. (2) we find that this smearing can be partially accounted for by assuming that the quasiparticles in the system are thermally distributed among the states which were in the system at the lowest temperature, T'. This model predicts an increase in the zero-bias conductance and a decrease in $G(V=5k_BT)$ with temperature which are both smaller than that observed (dashed line in Fig. 2). From this comparison we can conclude that the density of states increases in the vicinity of the Fermi energy, and decreases at higher energies as the temperature increases.

In fact, the change in the density of states with temperature conserves the number of states in the system. We show this in Fig. 3 where we have plotted the integral from $V=0$ to approximately $10k_BT$ of $G(V,T)$ from Eq. (2) and the data shown in Fig. 2. These integrals give the number of single particle states at $T'=0.08$ and 3.0 K, re-

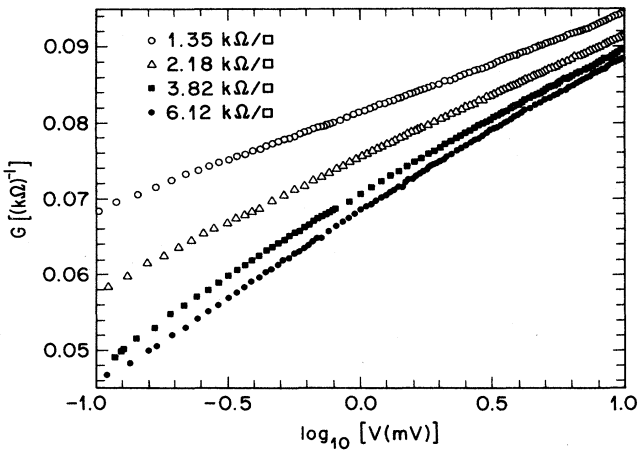

FIG. 1. Low temperature ($T<0.08$ K) tunnel junction conductance as a function of the $\log_{10}$ of the voltage for the four films studied.

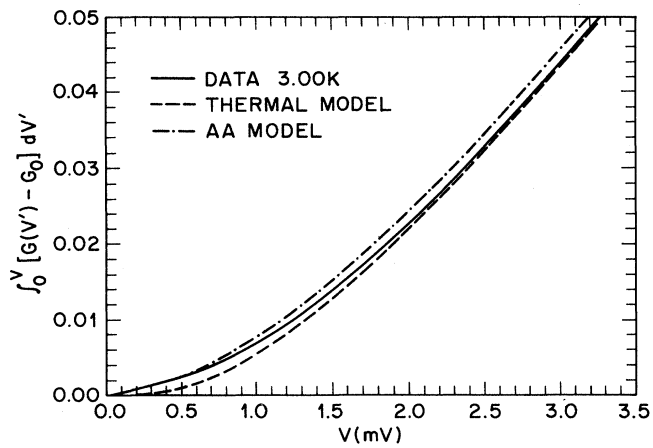

FIG. 3. The integral (minus a constant) of the measured and calculated conductances in Fig. 2. Note how the data and the simple thermal curves coalesce at high voltages.

spectively. To within the noise in our data, these integrals yield the same value. Thus, it appears that the single particle extended states are rearranged in energy by changes in temperature without loss of extended states.

Altshuler and Aronov[4] calculated the temperature dependence of the correction to the density of states due to enhanced Coulomb interactions in two-dimensional disordered electronic systems, and they found

$$\delta N(E)=\frac{-1}{8\pi^2\hbar D}\ln\left[\frac{x}{D^2\kappa_2^4\hbar\tau}\right]\ln\left[\frac{\tau x}{\hbar}\right], \quad (3)$$

where $x=\max\{E,T\}$, κ_2 is the inverse screening length, τ is the elastic scattering time, and D is the electronic diffusion constant.[4] The source of this temperature dependence is the dependence of the single particle energies on the energies of the other quasiparticles and their distribution among the energy states of the system. At very low temperatures the abrupt nature of the Fermi distribution function at the Fermi energy gives rise to the sharp singularities in the density of states. At higher temperatures the distribution becomes smeared over an energy range centered on the Fermi energy of roughly $k_B T$. On this basis, one expects the density of states to be smeared over this energy range as well. This form predicts that $N(E_F)$ increases with temperature. However, in this approximation, the total number of states increases with temperature. We know that this is not the case. This is illustrated in Fig. 3 where we compare the integral of this approximation (dashed line) with the data (solid line) and the simple thermal model (dotted line).

We compare the Altshuler and Aronov prediction with our data by using $G(x,T')$ in Eq. (2) and plotting the result as the dashed line in Fig. 2. This prediction agrees well with the data at zero bias but misses at higher voltages, hence the discrepancy in Fig. 3.

We have found a way to fit the temperature dependence of the data which conserves the number of states and provides some physical insight. In our model we assume that the essential effect of the temperature on the correction to the density of states is to cause a smearing of the energies of the zero-temperature states over some range, Γ. If we use a Lorentzian form to describe this smearing then the density of states as a function of temperature is given by

$$N(E,T)=\int_{-\infty}^{+\infty}N(E')\frac{\Gamma/\pi}{(E-E')^2+\Gamma^2}dE', \quad (4)$$

where Γ depends on temperature. Substitution of the above integral into the integrand of Eq. (1) yields the tunnel junction conductances as a function of Γ and temperature. We note that the choice of a Lorentzian is somewhat arbitrary. For instance, a Gaussian would probably serve the purpose equally well.

Using the above, we produced good fits to the data by adjusting Γ for each film. Examples of such fits are shown in Fig. 4. Here we see that with suitable choice of Γ an extremely good fit results. In Fig. 5 we plot Γ for each film as a function of temperature for all of the films. To within the uncertainty, we find that Γ is *independent*

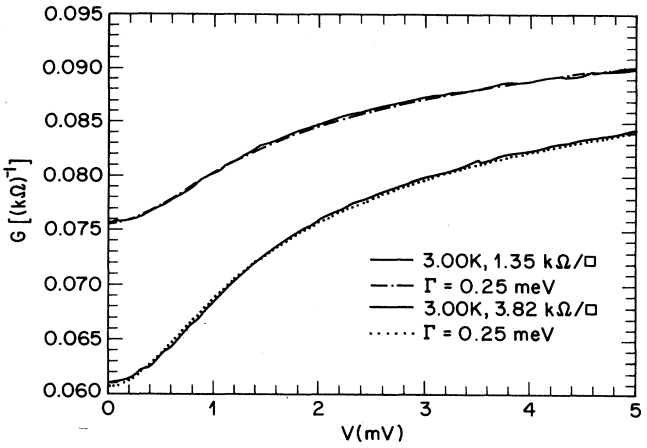

FIG. 4. Tunnel junction conductance at $T=3.0$ K for the 1.35- and 3.82-kΩ/□ films (solid lines) compared to fits using Eqs. (4) and (2).

of sheet resistance and therefore depends only on temperature. In addition, we find that Γ is roughly equal to the temperature.

Explicitly, these results show that, regardless of the amount of disorder in the system, one can obtain the renormalized density of states at a given temperature by "smearing" the zero-temperature density of states over an energy range given roughly by the temperature. Again, the correction to the density of states comes from energy-dependent electron-electron interactions. As the distribution of the quasiparticles among the energy states in the system changes, the interaction contributions to the energies of these states change. Redistributions due to temperature changes must occur over energies on the order of the temperature. We emphasize that the individual quasiparticle states are sharp relative to the temperature.

Thus, the "smearing" of the zero-temperature density

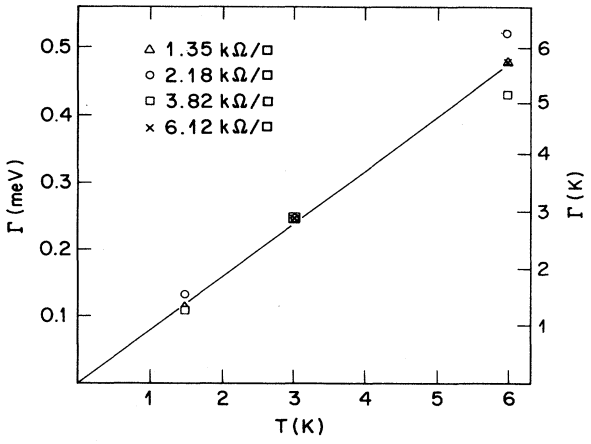

FIG. 5. The fitting parameter Γ as a function of temperature for the four films studied.

of states is not due to a decreased lifetime of the quasiparticles. If it were, then we would expect the parameter Γ to depend on sheet resistance (disorder). In fact, there is no dependence of Γ on sheet resistance whatsoever. We believe that this is a general result.

In summary, we have presented a systematic study of the temperature dependence of the conductance of a tunnel junction in which one of the electrodes is a disordered metal film. For 1.35 $k\Omega/\Box < R_\Box < 6.12$ $k\Omega/\Box$ we find that the corrections to the density of states due to enhanced Coulomb interactions in the disordered film are temperature dependent. The sharp logarithmic singularity in the density of states at the Fermi energy fills in as one raises the temperature of the metal. We can fit the observed temperature dependence by convoluting the zero-temperature density of states as a function of energy with a Lorentzian which has a width on the order of $k_B T$. That is, the renormalized quasiparticle energies are redistributed over an energy scale set by the temperature.

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