Effect of electron-electron interaction on state density in 2*D* aluminum films

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Tunnel spectroscopy has been used to study the effect of the electron-electron interaction on the density of electron states in 2*D* aluminum films. The experimental data, obtained over broad ranges of the temperature and the magnetic field, can be described quantitatively by the theory of the electron-electron interaction in disordered metals.

The single-particle state density ν in a disordered metal should depend strongly on the quasiparticle energy ϵ in the interval $kT \ll \epsilon \ll \hbar/\tau$ (τ is the momentum relaxation time).[1–4] The appearance of energy-dependent contributions $\Delta\nu$ is attributed to two types of electron-electron interactions: 1) an interaction between particles with similar momenta and energies ($\Delta\epsilon \lesssim kT$) (the so-called diffusion interaction channel) and 2) an interaction between particles with a small net momentum and with energies $\epsilon \lesssim kT$ (the so-called Cooper interaction channel). At a tunnel junction in which one of the electrodes is a disordered metal film, these contributions should be seen as structural features in the tunnel conductivity G at low bias voltages V (the so-called zero-bias anomaly[5]). The shape of these structural features depends on the effective dimensionality of the film, which is determined by the ratio of the film thickness a to the scale length $L_\epsilon = \sqrt{\hbar D / max\,\{kT, eV\}}$, where D is the electron diffusion coefficient.

The method of tunnel spectroscopy has recently been used to study the energy dependence of ν in disordered films of metals and semimetals.[6-11] These studies have been carried out in weak magnetic fields $H \lesssim kT/g\mu$ (g is the Landé factor of the conduction electrons, and μ is the Bohr magneton), where spin effects are negligible. The data have been interpreted as resulting from the manifestation of the interaction in the diffusion channel, but only in Ref. 10 was a quantitative agreement with the theory found.

In this letter we report a study of the structural features in the state density which result from the electron-electron interaction in the particular case of $2D$ aluminum films, over broad ranges of T and H, including fields $H \gg kT/g\mu$. The experimental data can be described quantitatively by the theory, and they agree with the results obtained in a study of the effect of the interaction on the conductivity of $2D$ aluminum films.[12]

We studied the conductivity of tunnel junctions formed by two aluminum films, a thin film ($a \simeq 30$–50 Å) and a thick one ($a \simeq 2000$ Å), synthesized by vapor deposition of 99.999%-pure aluminum at a residual pressure $P = (0.1$–$2) \times 10^{-6}$ mbar. The thin films (the lower electrode in each case) are deposited at a rate of 10 Å/s and have a surface resistivity $R_{\square} = 40$–600 Ω. The area of the tunnel junctions (~ 0.1 mm^2) is determined by the size of the aperture in the 500-Å SiO layer that separates the electrodes. The aluminum films are oxidized in air for several hours, and then the upper electrode is deposited. The lower and upper electrodes go superconducting at $T_{c1} \simeq 2$ K and $T_{c2} \simeq 1.3$ K, respectively. At $T > 2$ K, the resistance of the tunnel junction is 2–10 kΩ. The low leakage currents testify to the high quality of these junctions. The measurements are carried out at $T = 0.4$–300 K and $H = 0$–40 kOe. In parallel with the differential conductivity G of the tunnel junction, determined by a synchronous-detection arrangement, we measure curves of $R(T)$ and $R(H)$ for the thin aluminum film serving as the lower electrode.

At sufficiently low temperatures ($T \lesssim 20$–40 K), a minimum appears at $V = 0$ on the curve of the conductivity of the tunnel junction versus the voltage. The thermal width of this minimum corresponds to the limiting resolution of tunnel spectroscopy of normal metals, $eV \simeq 5.4$ kT (Ref. 5). At $T < T_{c1}$, T_{c2} and $H = 0$, a gap structural feature—typical of tunnel contacts between two superconductors—appears against the background of this minimum. This new feature has a far greater amplitude than the minimum. As the magnetic field (perpendicular to the plane of the junction) is increased, first the upper electrode (the thicker one) goes into the normal state (at $H < 500$ Oe), and then the lower one does; the inset in Fig. 1 shows $R(H)$ for one of the films studied. The typical structural features on the curves of $\Delta G(V)/G$ due to the superconducting gap in the thin film disappear at fields $H > H^*$, where H^* corresponds to the upper boundary of the $R(H)$ transition of the film to the normal state (Fig. 1). [In series with the tunnel junction there is a part of the thin aluminum films with $R \simeq (1/2) R_{\square}$ ($G^{-1} \gg R$), so that the curves of $\Delta G(V)$ shift vertically upon the suppression of superconductivity in this film.] The peak observed in the resistance of the tunnel junction at $T > T_{c1}$ or at $H > H^*$ is associated with the *minimum* of the state density at the Fermi level in the thin aluminum film. [If both of the films forming the tunnel junction are thick enough, no structural feature is found on the $G(V)$ curve at $V = 0$.]

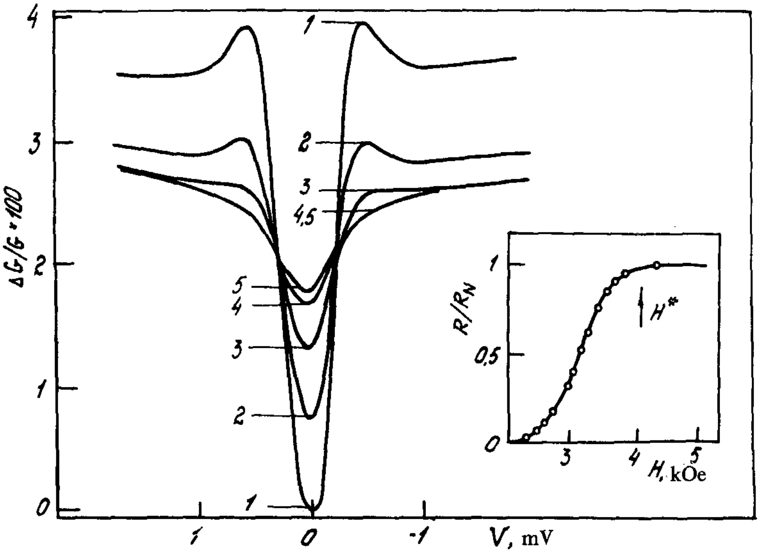

FIG. 1. Curves of $\Delta G(V)/G$ measured at $T=0.4$ K for a tunnel junction whose lower electrode is an aluminum film with $a\simeq 50$ Å and $R_\square = 40\ \Omega$. The inset shows the function $R(H)$ for this film at $T=0.4$ K. The magnetic field is directed perpendicular to the plane of the junction.

The region of greatest interest is the region of low temperatures, where the thermal width of the structural features in G is slight. At $T \ll T_{c1}$ and with the field oriented normal to the plane of the film, the typical value of H at which the Cooper interaction channel begins to be suppressed by orbital effects is on the order of the critical field $H_{c\perp} \simeq 0.87\,(ckTc_1/eD)[1-2,1(T/T_{c1})^2]$ which disrupts the superconductivity in the film.[13] Accordingly, in a sufficiently strong perpendicular field $H \gg H_{c\perp}$ all the structural features in the state density should be determined by the interaction in the diffusion channel. The diffusion interaction channel gives rise to corrections of two types to the state density, corresponding to total spins $J=0$ and $J=1$ of the interacting particles.[4] The contribution to the conductivity of a tunnel junction between a 2D film ($a \ll L_\epsilon$) and a pure bulk electrode which is made by the diffusion interaction channel with $J=0$ at $eV \gg kT$ is[3]

$$\frac{\Delta G(V)}{G} \equiv \frac{G(V_1)-G(V_2)}{G} = \frac{e^2 R_\square}{4\pi^2\hbar}\ln(2\kappa_2\delta)\ln\frac{V_1}{V_2}, \qquad (1)$$

where $\kappa_2 = 2\pi/DR_\square$ is the reciprocal of the screening length in the 2D case, and δ is the thickness of the insulator. We wish to emphasize that a magnetic field should not affect the diffusion interaction channel with $J=0$ (Ref. 4). Figure 2 shows the experimental results on $\Delta G(V)$ from various samples at $H \gg H_{c\perp}$. The observed logarithmic dependence of the conductivity of the tunnel junction on the applied voltage is characteristic of the 2D case. The solid lines in this figure are theoretical, plotted from (1). (The values of D were found from the measurements of $H_{c\perp}$; δ was assigned a value of 20 Å.) The good quantitative agreement with expression (1) is evidence that at $H \gg H_{c\perp}$

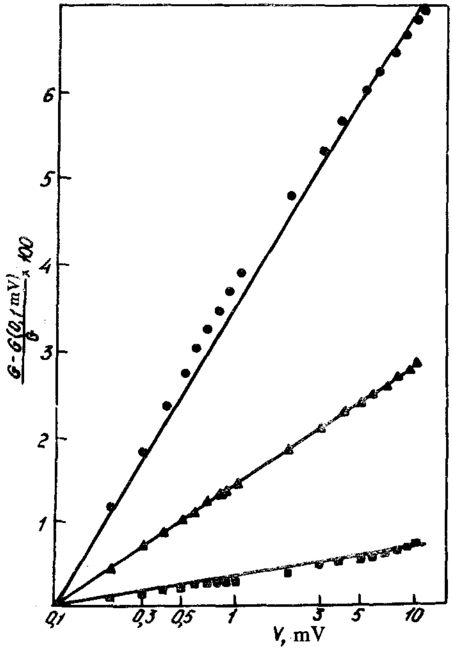

FIG. 2. Curves of $\Delta G(V)/G$ measured at $T = 0.4$ K and $H = 35$ kOe for tunnel junctions whose lower electrode has a surface resistivity $R_\square$ of (■) 40 Ω, (▲) 100 Ω, or (●) 300 Ω. The solid lines are theoretical, calculated from expression (1).

the gap in the tunnel conductivity reflecting the minimum of the state density is due to the diffusion interaction channel with $J = 0$.

The effect of a magnetic field on the diffusion interaction channel with $J = 1$ should result in a Zeeman splitting of this contribution and in the appearance at $V = \pm(g\mu H/e)$ of structural features in G, with an amplitude proportional to the interaction constant λ $(J = 1)$ (Ref. 4). The Zeeman structural features, in contrast with the main structure at $V = 0$, are broadened by not only the nonzero temperature but also the spin scattering of electrons. Since the total spin-relaxation time for these films, governed by spin-orbit and spin-spin scattering, is[12] $t_S = (1\text{–}2)\times 10^{-11}$ s, the absence of Zeeman structure from the curves of $G(V)$ observed at $g\mu H \gg kT, \hbar/t_S$ (Fig. 3) is evidence for $|\lambda(J = 1)| < 0.1$. We note that the tunnel measurements can be used to refine the estimate of λ $(J = 1)$ found earlier in a study of the conductivity of aluminum films.[12]

The increase in the tunnel conductivity at low V observed with increasing field at $H > H^*$ (Fig. 1) is apparently due to the suppression of the contribution of the Cooper interaction channel. This behavior is consistent with the theoretical conclusions, since the condition $2eD/c \gg g\mu$ holds for these films, and orbital effects should outweigh the spin effects in the Cooper interaction channel. In principle, the Zeeman splitting of the contribution of the Cooper interaction channel could be observed in the parallel orientation of the field, either at $T > T_{c1}$ (where the condition $kT/g\mu \ll H \ll c\hbar/eaL_\epsilon$ would have to hold) or at $T \ll T_{c1}$ (where, in addition, the parallel critical field of the film would have to be limited by the paramagnetic limit, $H_{c\parallel} \simeq 2.5\, kTc_1/g\mu \ll c\hbar/eaL_\epsilon$. In either case, fields $H > 50$ kOe would be required to observe this effect in films with $T_c \simeq 2$ K.

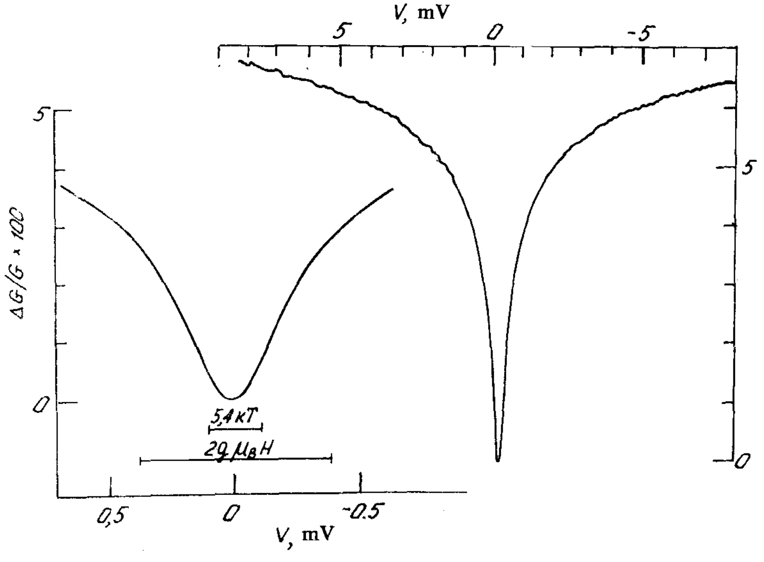

FIG. 3. Curves of $\Delta G(V)/G$ measured at $T = 0.4$ K and $H = 35$ kOe for a tunnel junction with a surface resistivity $R_\square = 300\ \Omega$ for the thin electrode. The slight asymmetry of the curves is a result of barrier effects.[5]

In summary, the structural feature observed in the state density in 2*D* aluminum films far from the superconductivity transition ($T \gg T_c$ or $H \gg H_{c\perp}$, $T < T_c$) is due to an interaction in the diffusion channel with $J = 0$, while that near the transition is due to the joint manifestation of the diffusion and Cooper interaction channels. It has been shown here, for the first time, that the feature observed in ν can be described quantitatively by the theory of Ref. 3 over a broad energy range. From measurements of the tunnel conductivity at $g\mu H \gg kT$, we find an estimate of λ ($J = 1$) which agrees with the results of a study of quantum effects in the conductivity of 2*D* aluminum films.

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