Tunnel spectroscopy of the electron-electron interaction in disordered aluminum films

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The method of tunnel spectroscopy was used in a study of the energy dependences of the one-particle density of states $\nu(\varepsilon)$ in disordered aluminum films which were two- and three-dimensional in respect of the interaction effects. The experimental dependences of the tunnel conductance on the bias voltage V, reflecting the singularities of $\nu(\varepsilon)$, were described quantitatively by the theory of Al'tshuler, Aronov, and Lee [Sov. Phys. JETP **50**, 968 (1979); **59**, 415 (1984); JETP Lett. **37**, 175 (1983); Phys. Rev. Lett. **44**, 1288 (1980); in: Electron-Electron Interaction in Disordered Systems, (E. L. Efros and M. Pollak, eds.) North-Holland, 1985] in a wide range of values of the parameters eV/kT. The results demonstrated that a study of the tunnel conductance anomalies can provide information on the distribution of impurities across the thickness of a film.

§I. INTRODUCTION

Enhancement of the electron-electron interaction because of the diffusive nature of the motion of electrons in disordered metals modifies greatly the properties of quasiparticle excitations of energies $|\varepsilon| \lesssim \hbar/\tau$ (ε is the energy of a quasiparticle measured from the Fermi level μ and τ is the momentum relaxation time).[1–5] Contributions dependent on the quasiparticle energy appear in all the transport and thermodynamic quantities. In particular, the energy spectrum of quasiparticles is modified on a scale of $|\varepsilon| \lesssim \hbar/\tau$ and a singularity appears in the one-particle density of states $\nu(\varepsilon)$ at the Fermi level.[1–5]

The most direct method for investigating the energy dependence of the density of states in metals is tunnel spectroscopy (see, for example, Ref. 6). The dependence of the differential conductance $G = dI/dV$ of a metal-insulator-metal tunnel contact on the voltage V applied to it reflects — in the absence of inelastic tunneling processes — the dependences $\nu(\varepsilon)$ at the electrodes forming such a contact. Therefore, according to the theory of Refs. 1–5, tunnel experiments on disordered metals should exhibit singularities of the dependence $G(V)$ at $V = 0$. In fact, such singularities (known as the zero-bias anomalies of the tunnel conductance) have been reported for the last twenty years (see, for example, Refs. 6–8). The voltage dependences of the tunnel conductance have either a maximum or a minimum at $V = 0$. A peak of the dependence $G(V)$ at $V = 0$ is usually attributed to the scattering by magnetic impurities,[9] whereas a minimum of G at $V = 0$ can be explained only by the Fermi liquid theory of disordered metals.

The appearance of the theory of Al'tshuler, Aronov, and Lee[1–5] has stimulated experimental studies of the characteristics of the electron-electron interaction in disordered conductors, including studies by tunnel spectroscopy.[10–16] Strongly disordered systems are of special interest and observations of the critical behavior of $\nu(\varepsilon = 0)$ exhibited by these systems have demonstrated the major importance of the electron-electron interaction effects in the vicinity of the Anderson metal-insulator transition.[10–12] The case of weakly disordered conductors has been studied less thoroughly and a quantitative agreement with the theory of Refs. 1–5, developed on the assumption that $k_F l \gg 1$ (k_F is the Fermi wave vector and l is the mean free path of electrons), has been reported only so far in Ref. 15. Therefore, our principal aim was to study singularities of the density of states resulting from the electron-electron interaction in weakly disordered metal films. In contrast to preceding experiments, measurements were carried out in a sufficiently strong (for the demonstration of the spin effects) magnetic field, which made it possible to determine the contributions of the various types of interaction to the observed dependences $\nu(\varepsilon)$. It was found that the experimental results obtained for films with thicknesses and resistivity varying within wide limits can be described quantitatively by the theory of Refs. 1–5 throughout the investigated range of temperatures and bias voltages. Preliminary results of this study were published earlier.[17]

The present paper is organized as follows. The necessary theoretical results are obtained in §2. The methods used in the preparation of the samples and in low-temperature measurements of the tunnel conductance are described in §3. The experimental results are presented and discussed in §4.

§2. THEORETICAL ASPECTS

Singularities of the density of states in disordered metals appear because of the interactions between: a) an electron and a hole with similar energies and a small combined momentum; b) two electrons with similar energies and a small combined momentum. In the former case we shall speak of the diffusion interaction channel and we shall describe the latter as the Cooper channel. The corrections to the density of states are proportional to the values of the corresponding interaction constants and to the probability of a second encounter of two interacting particles character-

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ized by an energy difference $\Delta\varepsilon$ ($\Delta\varepsilon\sim\varepsilon$) in a time $t\lesssim\hbar/\Delta\varepsilon$ during which the coherence of their wave functions is retained.[18] This probability α_d depends strongly on the effective dimensionality of a sample governed by the ratio of its geometric dimensions and the diffusion length $L_\varepsilon = (\hbar D/\varepsilon)^{1/2}$ representing the distance traveled in the characteristic time $t = \hbar/\varepsilon$. Reduction in the dimensionality increases the value of α_d, which should enhance the interaction effects. The interaction constant can be represented in the form[5]

$$\lambda_d=\lambda_d{}^D(j=0)+3\lambda_d{}^D(j=1)-\lambda_d{}^C, \quad (1)$$

where d is the dimensionality of a conductor in relation to the interaction effects; the first two terms describe the interaction in the diffusion channel between particles with total spins $j=0$ and $j=1$; λ_d^C represents the interaction in the Cooper channel and the coefficient 3 is due to the multiplicity of the state with $j=1$. Since the constant $\lambda_d^D(j=0)$ is universal and depends only on the dimensionality of a conductor, the corrections to the density of states should be governed by the value of α_d and two Fermi liquid constants: $\lambda_d^D(j=1)$ and λ_d^C. At $T=0$ the corrections to the one-particle density of states are[1,2,5]:

$$\frac{d\nu_d(\varepsilon)}{\nu_d}\infty\frac{\lambda_d}{\nu_d(\hbar D)^{d/2}}\begin{cases}|\varepsilon|^{1/2}, & d=3\\ \ln(|\varepsilon|\tau/\hbar), & d=2,\end{cases} \quad (2)$$

where ν_2 is the number of states per unit energy interval and per unit area of a film of thickness $a\ll L_\varepsilon$. The expressions for $\delta\nu(\varepsilon)$ and $\delta G(V)$ given here and below are valid in the case of two-dimensional systems if the length L_ε is much less than the electron localization radius, whereas in the case of three-dimensional systems they are valid if electrons are delocalized and there is no spatial dispersion of the diffusion coefficient over distances $\sim L_\varepsilon$.

The following two points should be borne in mind in going over from expressions for $\delta\nu_d(\varepsilon)$ to the dependences of the tunnel conductance of the bias voltage. Firstly, in the process of tunneling the important states are those located at the distances $L\ll L_\varepsilon$ from the metal-insulator interface, i.e., the anomaly of the tunnel conductance is associated with a local density of states of interacting electrons near the surface of a sample. The presence of a boundary of a three-dimensional film enhances (near this boundary) the local density of states by a factor of 2 compared with the exchange mechanism.[4] Consequently, in the presence of a contact formed by a pure bulk electrode and a three-dimensional disordered film the dependence $\delta G(V)$ due to the singlet part of the diffusion interaction channel should have the following form[4] at voltages $V\gg kT/e$:

$$\frac{\Delta G(V)}{G}=\frac{e^2\rho}{2^{1/2}\pi^2\hbar}\left(\frac{eV}{\hbar D}\right)^{1/2}, \quad (3)$$

where $\rho=(e^2\nu D)^{-1}$ is the resistivity of the disordered electrode. Secondly, the image forces have the effect that the electron-electron interaction in a two-dimensional film forming a tunnel contact with a pure three-dimensional electrode is of the dipole nature at distances much greater than the thickness of an insulating layer δ or the thickness of the film a (Ref. 4). Therefore, for such a structure the dependence $\Delta G(V)$ associated with the correction $\delta\nu_2(\varepsilon)$ due to the singlet part of the diffusion interaction channel has the following form[4] if $V\gg kT/e$ and $\varkappa^2 a\delta\gg 1$:

$$\frac{G(V,T)-G(0,T)}{G(0,T)}=\frac{\lambda_\nu e^2R_\square}{4\pi^2\hbar}\ln\frac{eV}{kT}, \quad (4)$$

where

$$\lambda_\nu=\ln(\varkappa^2 a\delta)=\ln(4\pi\delta/DR_\square), \quad (5)$$

$\varkappa^{-1}=(4\pi e^2\nu)^{-1/2}$ is the Debye radius. The logarithm described by Eq. (5) represents the truncation of the Coulomb potential at distances exceeding δ.

Equations (2)–(4) are valid if $\varepsilon, eV\gg kT$. The density-of-states singularities are broadened at finite temperatures. For an arbitrary ratio of kT to eV, the expressions for $\Delta G(V)$ due to the interaction in the diffusion channel between particles with a total spin $j=0$ can be represented in the following form, which is convenient for comparison with the experimental results[5]:

$d=2$;

$$\frac{G(V,T)-G(0,T)}{G(0,T)}=\frac{e^2R_\square}{8\pi^2\hbar}\ln\left(\frac{4\pi\delta}{DR_\square}\right)\times\left[\Phi_2\left(\frac{eV}{kT}\right)-\Phi_2(0)\right], \quad (6)$$

$d=3$;

$$\frac{G(V,T)-G(0,T)}{G(0,T)}=\frac{e^2\rho}{8\sqrt{2}\pi^2\hbar}\left(\frac{kT}{\hbar D}\right)^{1/2}\times\left[\Phi_3\left(\frac{eV}{kT}\right)-\Phi_3(0)\right], \quad (7)$$

where

$$\Phi_d(A)=\int_{-\infty}^{\infty}dx\frac{\operatorname{ch}(x+A)-1}{\operatorname{ch}^2(x/2)}\times\int_0^\infty\frac{\operatorname{sh}y\,dy}{[\operatorname{ch}y+\operatorname{ch}(x+A)](1+\operatorname{ch}y)y^{2-d/2}},$$

$x=\varepsilon/kT$, and $A=eV/kT$. Thermal broadening of the singularities of ΔG is of the same order of magnitude as the characteristic value $eV=5.4kT$ taken as the limit of resolution of the tunnel spectroscopy method when applied to normal metals.[6]

The influence of a magnetic field on the interaction in the diffusion channel is governed by the spin effects.[3,19] In a sufficiently strong magnetic field $H\gg H_S=\pi kT/g\mu_B$ (g is the Landé factor for the conduction electrons and μ_B is the Bohr magneton) the states with a total spin $j=1$ are split in respect of the spin projection along the field direction $M=0, \pm 1$. This should result in a Zeeman splitting of the triplet part of the contribution of the diffusion interaction channel to the density of states: singularities of ν corresponding to the projections of the total spin of the interacting particles $M=\pm 1$ are shifted on the energy scale by $\Delta\varepsilon=\pm g\mu_B H$ relative to the Fermi level (Ref. 3).[1] The singularities of ν due to the triplet part of the diffusion interaction channel are smeared not only at finite temperatures, but also in the case of spin scattering and they disappear for $\hbar/t_S \gg g\mu_B H$. [The total spin relaxation time $t_S = 3/4(\tau_S^{-1} + \tau_{SO}^{-1})^{-1}$ represents the spin-spin (τ_S) and spin-orbit (τ_{SO}) scattering processes.] It should be pointed out that neither the magnetic field nor the spin scattering should affect the interaction in the diffusion channel between particles with a total spin $j = 0$.

The application of a magnetic field suppresses the interaction in the Cooper channel because of the orbital effects if the field intensity is $H \gg H_c = \pi ckT/eD$. In the case of three-dimensional samples or two-dimensional films oriented at right-angles to the magnetic field, which are the objects of our study, the spin effects in the Cooper interaction channel are unimportant because $H_c \ll H_S$. The total spin of the particles interacting in the Cooper channel is always zero so that the spin-orbit scattering does not affect this channel and the spin-spin scattering broadens the singularities of ν due to the Cooper channel if $\hbar/\tau_s \gg kT$.

§3. EXPERIMENTAL METHOD

Aluminum films were formed by thermal deposition of 99.999% pure Al on glass substrates kept at room temperature. The film thickness and the rate of evaporation were determined by a quartz thickness meter to within 1 Å and 0.1 Å/sec. The density-of-states singularities were studied for two types of sample: a) thin (a = 30–50 Å) films deposited at a residual pressure of $P \approx 2\times 10^{-6}$ mbar at a rate of $v \approx 10$ Å/sec; b) thicker (a = 50–2000 Å) films which were evaporated in an oxygen atmosphere ($P_{O_2} \approx 1\times 10^{-4}$ mbar) at a rate of v = 5–10 Å/sec in order to ensure the necessary degree of disorder. In the latter case it was essential to maintain a constant evaporation rate in order to ensure a uniform thickness of the films. The homogeneity of the oxygen distribution across the film thickness was monitored by the method of Auger spectroscopy in the course of etching of the films by ion bombardment.[2)]

The temperature of the transition of the investigated aluminum films to the superconducting state depended strongly on their electrical resistivity: the values of T_c increased from ~1.3 K to 2–2.2 K when ρ increased from 10^{-6} Ω·cm to ~10^{-4} Ω·cm, and remained approximately constant on further increase in ρ to 10^{-2} Ω·cm. [Similar $T_c(\rho)$ dependences were observed earlier for aluminum films, as reported in Refs. 10 and 20.] Table I lists properties of some of the investigated films. The electron diffusion coefficient D was deduced from measurements of the upper critical field H_{c2} carried out in the range $T \ll T_c$, using the formula[21]

$$D = 0{,}87\frac{ckT_c}{eH_{c2}(T)}\left[1-2{,}1\left(\frac{T}{T_c}\right)^2\right]. \qquad (8)$$

The width of the transition $R(H)$ for samples with $\rho \lesssim 10^{-3}$ Ω·cm did not exceed 30% of H_{c2} corresponding to $R = \frac{1}{2}R(T > T_c)$.

Disordered aluminum films served as the lower electrode for tunnel contacts formed between films with very different values of the diffusion coefficient D. The tunnel contact area (~0.1 mm²) was governed by the size of a cut in a thermally deposited SiO layer of thickness 700–2000 Å, which separated the electrodes. Oxidation of the lower electrode took place in air over a period of several hours and then the upper electrode was deposited at a residual pressure of $P = (0.1\text{–}2)\times 10^{-6}$ mbar at a rate of 30–50 Å/sec. The aluminum films used as the upper electrode had the following properties: a = 1500–2000 Å, $l > 1000$ Å, $T_{c2} \approx 1.3$ K. At temperatures $T > T_{c1}, T_{c2}$ the resistance of the tunnel contacts was G^{-1} = 2–100 kΩ and it was always much higher than the resistance $R_\square$ per unit square of the films forming the contacts. The high quality of the investigated contacts was demonstrated by the low values of the leakage current.

The differential conductance of these tunnel contacts was determined employing the usual lock-in detection method. A current I increasing linearly with time (the rise time of I from zero to its maximum value was 10 min) and an alternating current $I_\sim$ of frequency 1 kHz was applied via a contact connected to the current source. The amplitude of an alternating voltage $U_\sim$ on the contact satisfied the condition $U_\sim \ll kT/e$ throughout the investigated temperature range. We measured $G = dI/dV$ and determined the current-voltage characteristic of the contact, as well as the dependences $R(T)$ and $R(H)$ for the disordered aluminum film. The measurements were carried out at temperatures T = 0.4–300 K in magnetic fields H = 0–40 kOe.

§4. EXPERIMENTAL RESULTS

At room temperature the investigated tunnel contacts exhibited a weak quadratic dependence of $G(V)$ associated with the barrier effects (see, for example, Ref. 6). However, the tunnel contacts formed by strongly disordered films ($\rho \approx 10^{-3}$ Ω·cm) exhibited an anomalous tunnel conductance minimum at $V = 0$, which was observed even at T = 300 K against the background of the quadratic depen-

TABLE I.

Film No.	$R_\square$, Ω	a, Å	ρ, Ω·cm	D, cm²/sec
1	40	50	$2\cdot10^{-5}$	3,9
2	100	50	$5\cdot10^{-5}$	2,1
3	300	30	$9\cdot10^{-5}$	0,8
4	760	100	$7{,}6\cdot10^{-4}$	1,1
5	10,8	500	$5{,}4\cdot10^{-5}$	4,2
6	22	1350	$2{,}9\cdot10^{-4}$	0,65
7	31	2000	$6{,}2\cdot10^{-4}$	0,56
8	260	400	$1\cdot10^{-3}$	0,58
9	350	500	$1{,}75\cdot10^{-3}$	0,44

dence $G(V)$. Cooling increased the depth of this minimum in the dependences $G(V)$ and at temperatures $T < T_{c1}$, T_{c2} a gap singularity of much greater amplitude, typical of tunnel contacts between two superconductors, appeared against the background. An increase in the magnetic field intensity oriented at right-angles to the planes of the films resulted in a transition to the normal state first of the upper "purer" electrode (in fields $H < 500$ Oe), followed by suppression of the superconductivity in the lower disordered electrode. Characteristic features of the dependences $G(V)$ associated with the appearance of the superconducting gap in the disordered film disappeared in fields $H > H^*$, where H^* was the upper limit of the transition $R(H)$ of the film to the normal state (Fig. 1). [It was found that a region of the disordered aluminum film characterized by $R \approx \frac{1}{2} R_\square$ $(G^{-1} \gg R_\square)$ was connected in series with the tunnel contact so that suppression of the superconductivity in this field shifted vertically the $\Delta G(V)$ curves.] The dip in the dependence $G(V)$ observed at $V=0$ at temperatures $T > T_{c1}$ or in fields $H > H^*$ was associated with a minimum of the density of states at the Fermi level of the disordered aluminum film. [If both films forming the tunnel contact had sufficiently high values of the electron diffusion coefficient, there was no singularity at $V=0$ in the dependence $G(V)$.] We shall now analyze the form of the dependences of the differential tunnel conductance on the voltage applied to a contact in those ranges of T and V where disordered films can be regarded as two- and three-dimensional in repsect of the electron-electron interaction effects.

Two-dimensional case

We shall consider the form of the dependences $G(V)$ observed under conditions when the superconductivity was suppressed completely in the upper and lower electrodes: $T \gg T_{c1}$ or $H \gg H^*$ when $T < T_{c1}$. Then, in the case of the contacts formed by sufficiently thin $[a \ll L_T = (\hbar D / kT)^{1/2}]$ disordered films a logarithmic dependence $\Delta G(V)$ typical of the two-dimensional case (see Figs. 2 and 3) is observed in a wide range of bias voltages $kT/e \ll V \ll \hbar D/ea^2$. The lower limit of the range of bias voltages V where $\Delta G(V) \propto \ln V$ is obeyed is set by the finite temperature, whereas the upper limit is associated with an increase in the effective dimensionality of the disordered film when its thickness becomes greater than the characteristic scale length $L_V = (\hbar D / eV)^{1/2}$, of the interaction effects between particles characterized by an energy difference $\Delta\varepsilon = eV \gg kT$. (The condition for the change from the two- to the three-dimensional case is discussed in greater detail below.)

A comparison with the theory shows that the dependences $\Delta G(V)/G$ observed in the case $a \lesssim L_V$ are described quantatively by Eq. (6), which allows only for the singlet contribution of the diffusion interaction (Fig. 3). It should be stressed that in comparing the experimental results with Eqs. (4) and (6) the only uncontrolled quantity is the insulator thickness δ, selected to be ~ 20 Å. According to Eq. (5), variation of δ within reasonable limits of 10–40 Å alters the theoretical values of $\Delta G/G$ by no more than 10%. Therefore, we can say that the quantitative agreement with Eq. (6) is obtained without recourse to fitting parameters.

The fact that the corrections to the density of states due to the interaction in the Cooper channel are negligibly small far from the superconducting transition is not surprising because the magnetic fields required for the destruction of the superconductivity in a film (H_{c2}) and suppression of the interaction in the Cooper channel because of the orbital effects (H_c) are of the same order of magnitude at temperatures $T \ll T_{c1}$. The absence of a contribution associated with the triplet part of the interaction amplitude in the diffusion channel is a less trivial observation. The smallness of the contribution of the triplet part of the diffusion interaction channel is manifested not only by a quantitative comparison with the theory, but also by the qualitative behavior of the dependences $\Delta G(V)$ in the case of magnetic fields $H \gg H_S$

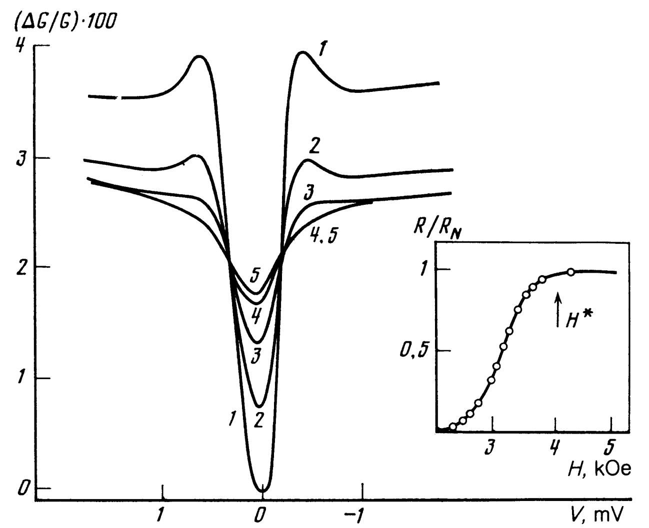

FIG. 1. Dependences $\Delta G(V)/G$ obtained at $T = 0.4$ K for tunnel contacts in which the disordered electrode was film No. 1. The intensities of the magnetic field oriented at right-angles to the film plane were (kOe): 1) 0.9; 2) 3.5; 3) 9.0; 4) 17.5; 5) 35. The inset shows the dependence $R(H)/R_N$ for film No. 1 at $T = 0.4$ K.

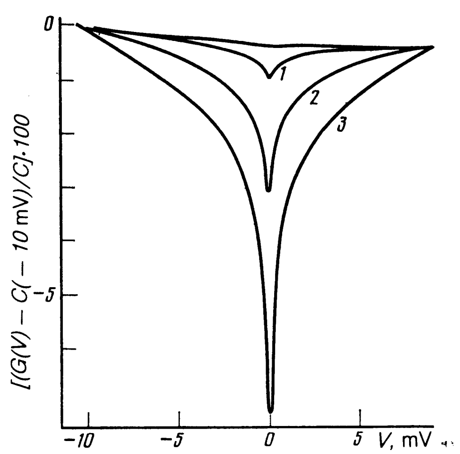

FIG. 2. Dependences $\Delta G(V)/G$ obtained at $T = 0.4$ K in $H = 35$ kOe for tunnel contacts with two-dimensional disordered electrodes. The numbers of the samples are given alongside each curve. The highest curve was obtained for a tunnel contact formed by films of thickness $l > 1000$ Å.

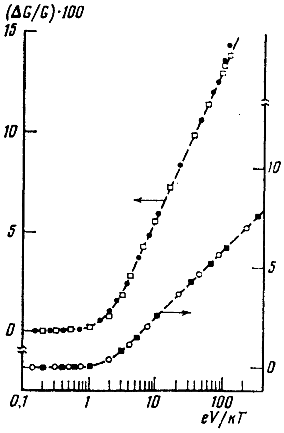

FIG. 3. Dependences of $\Delta G/G$ on eV/kT for tunnel contacts in which the disordered electrodes were films Nos. 3 (○ and ■) and 4 (● and □), obtained in $H = 35$ kOe at various temperatures: ○) 0.4 K; □) 0.6 K; ●), ■) 4.2 K. The dashed curves are the theoretical dependences represented by Eq. (6).

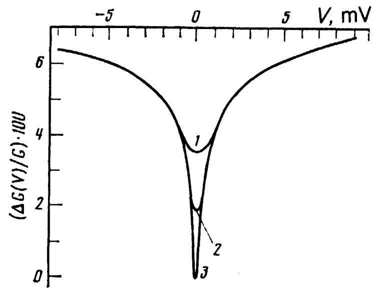

FIG. 4. Dependences $\Delta G(V)/G$ obtained for tunnel contacts in which the disordered electrode was film No. 3, obtained in $H = 35$ kOe at the following temperatures: 1) 4.2 K; 2) 1.3 K; 3) 0.4 K.

sufficiently strong for suppression of the spin effects (Fig. 2). A magnetic field which does not influence the singlet part of the contribution of the diffusion interaction channel should cause a Zeeman splitting of the triplet contribution and should give rise at $V = g\mu_B H/e$ to singularities of G of amplitude proportional to the interaction constant $\lambda_2^D(j=1)$ (Refs. 3 and 19). The rate of spin relaxation in the investigated aluminum films was not sufficiently high for the broadening of the Zeeman singularities [the total spin relaxation time $t_S = (1\text{–}2)\times 10^{-11}$ sec (Ref. 22) obtained under the experimental conditions satisfy the inequality $\hbar/t_s \ll g\mu_B H$], so that the absence of the Zeeman singularities in the dependences $\Delta G(V)$ recorded in the range $H \gg H_S, \hbar/t_S$ is evidence of the weakness of the diffusion interaction between particles with a total spin $j = 1$.

The above conclusion is supported by the results obtained in a study of the quantum corrections to the conductance of two-dimensional $[a \ll L_T = (\hbar D/kT)^{1/2}]$ aluminum films. In the case of the investigated films subjected to a magnetic field sufficiently strong for suppression of the temperature dependence of the contributions of the Cooper channel and of weak localization, the temperature dependence of the conductance obtained in the range $T = 0.4 - 15$ K is well approximated by the expression $\Delta\sigma(T) = A(e^2/2\pi^2\hbar)\ln T$, where $A = 1\text{–}1.1$. The fact that the values of A are close to unity for $H^* < H < H_S$ and $kT > \hbar/t_S$ again demonstrates that the contribution of the triplet part of the diffusion interaction is small (see, for example, Ref. 5).

The dependences $\Delta G(V)/G$ determined for a specific sample in a wide range of temperatures $T = 0.4\text{–}20$ K and plotted as a function of the parameter eV/kT coincide when the condition $H \gg H^*$ is satisfied (Fig. 3). A one-parameter dependence of the relative change in the tunnel conductance has been reported earlier[16] for two-dimensional bismuth films. The fact that ΔG is a function of one dimensionless parameter eV/kT is in agreement with the theory and it follows from Eq. (6). Thermal broadening of the tunnel conductance anomaly is close to the limit of resolution of the tunnel spectroscopy of normal metals,[6] which is eV $\approx$ 5.4 kT (Fig. 4). The coincidence of the dependences $\Delta G(\mathrm{eV/kT})/G$ obtained for kT $< \hbar/t_S$ confirms the theoretical prediction that the spin scattering should not affect the singlet part of the diffusion interaction channel.

The quantitative agreement with the theory is observed throughout the investigated range of values of the surface resistance of two-dimensional films $R_\square = 40\text{-}800\ \Omega$. Similar results, but in a very much narrower range of V, were obtained earlier[15] in a study of the singularities of the density of states in two-dimensional tin films. Investigations of the conductance of tunnel contacts between two-dimensional films of semimetals [In_2O_{2-x} (Refs. 13) and Bi (Ref. 16)] and pure superconductor films gave values of $\Delta G(V)/G$ exceeding the theoretical estimates given by Eqs. (4) and (6).[3]

A sufficiently strong magnetic field $H \gg H^* \approx H_{c2}$, oriented at right-angles to the plane of a film suppresses the interaction in the Cooper channel because of the orbital effects. On approach to the superconducting transition because of reduction in the magnet field ($H \to H_{c2}$, $T_{c1} > T = \mathrm{const}$) the tunnel conductance decreases at low voltages V and this is due to a manifestation of the Cooper channel contribution. The corresponding correction to G is localized in the range $|V| \lesssim kT_{c1}/e$ (curves 4 and 5 in Fig. 1), in agreement with the theoretical predictions[5]: the values of $\delta\nu_d^c(\varepsilon)$ should decrease on increase in V and T proportionally to $\ln(\max\{eV, kT\}/kT_c)$. If $H \lesssim H^*$, the contribution of the Cooper interaction channel, which can be regarded as a precursor of the superconducting gap, is transformed into a gap singularity typical of superconductors.

Three-dimensional case

In the case of the tunnel contacts in which the thickness of the disordered electrode obeys $a \ll L_T$ an increase in the bias voltage should in principle alter the form of the dependences $\Delta G(V)$ from logarithmic to square-root. This behavior, first reported in Ref. 13, corresponds to an increase in the effective dimensionality of a disordered film when the condition $a \ll L_V$ is no longer obeyed. Figure 5 shows the values of $\Delta G(V)$ for sample No. 4 as a function of $V^{1/2}$ and ln V. The transition to the square-root dependence $\Delta G(V)$ typical of the three-dimensional case is observed at values of V_c corresponding to the condition $L_V \approx a/3$. The condition for the change in the dimensionality given in earlier investigations[13,16] is $L_V = a/2\pi$, which corresponds to the values

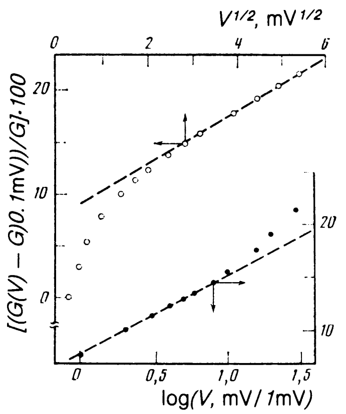

FIG. 5. Dependences of $\Delta G(V)/G$ on $V^{1/2}$ (○) and on $\ln(V, \mathrm{mV}/1\ \mathrm{mV})$ (●), obtained at $T = 0.4$ K in $H = 35$ kOe for tunnel contacts in which the disordered electrode was film No. 4.

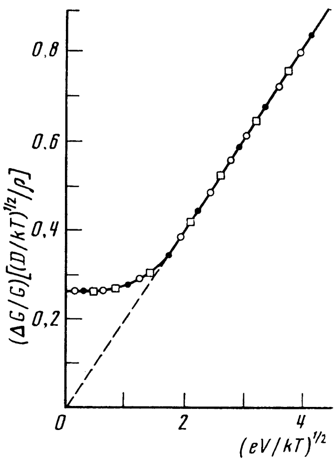

FIG. 7. Normalized dependences of $\Delta G/G$ on eV/kT for tunnel contacts in which the disordered electrode was film No. 6, obtained in $H = 35$ kOe at $T = 0.4$ K (●), 1.3 K (○), and 4.2 K (□). The continuous curve is the theoretical dependence represented by Eq. (7).

of V_c which are ~ 4 times greater, but the data on the electron diffusion coefficient (and, consequently, on the value of L_V for the semimetal films investigated in these cases) were approximate. (Moreover, the values of a and D given in Ref. 13 also indicate that the transition to the three-dimensional case occurs when $V < 4\pi^2\hbar D/ea^2$.) An increase in the thickness and/or the degree of disorder of the films reduces the values of V_c, and, in particular, films of thickness $a > L_T$ exhibit three-dimensional behavior for any value of V.

The dependences $\Delta G(V)$ obtained at $T = 0.4$ K in fields $H \gg H^*$ for three-dimensional films with different values of the resistivity are plotted in Fig. 6. For samples with $\rho < 5\times10^{-5}\ \Omega\cdot$cm it is difficult to observe the anomaly of the tunnel conductance at $V = 0$ and particularly to compare it quantitatively with the theory because of the barrier effects resulting in the asymmetry of the current-voltage characteristics typical of tunnel contacts with aluminum electrodes.[6] However, in the case of samples with $\rho = (0.5\text{–}5)\times10^{-4}\ \Omega\cdot$cm which still satisfy the condition $\Delta G(V)/G \ll 1$ it is possible to identify sufficiently accurately the dependence $\Delta G(V)$ associated with the interaction effect. Figure 7 shows the dependences $\Delta G(V)/G$ obtained for sample No. 6 at various temperatures. Throughout the investigated range of values of T and V, corresponding to a change in the dimensionless parameter eV/kT from 0 to ~ 100, the experimental dependences $\Delta G(V)$ agree quantitatively with Eq. (7) derived for the interaction in the diffusion channel between particles with a total spin $j = 0$. The conclusion of the smallness of the contribution of the triplet part of the diffusion channel made above in an analysis of the dependences $\Delta G(V)$ for two-dimensional samples remains valid also in the case of three-dimensional films. As in the two-dimensional case, this follows not only from the tunnel measurements, but also from the results of a study of the temperature dependences of the conductance of the films in a magnetic field $H_S > H > H_c$ sufficiently strong for the suppression of effects of weak localization and of the Cooper interaction. The experimental dependences $\Delta\sigma(T)$ determined in such fields at $T = 0.4$–10 K are in good agreement with the expression

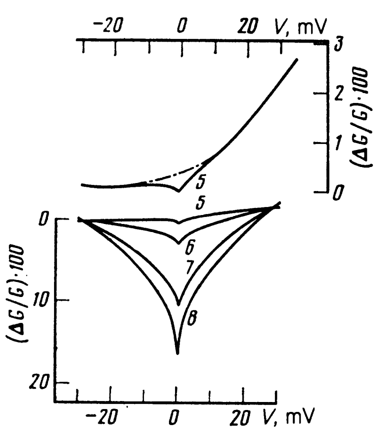

FIG. 6. Dependences $\Delta G(V)/G$ obtained for tunnel contacts with three-dimensional disordered electrodes at $T = 0.4$ K in $H = 35$ kOe. The numbers of the samples are indicated alongside the curves. The dash-dot curve is a parabolic dependence $\Delta G(V)/G$ observed for pure samples and associated with barrier effects.

$$\sigma(T_2) - \sigma(T_1) \approx 0.3(e^2/\pi^2\hbar)(k/\hbar D)^{1/2}(T_1^{1/2} - T_2^{1/2}), \qquad (9)$$

which describes the temperature dependence of the singlet part of the contribution of the diffusion channel to the conductance of three-dimensional conductors.[5]

An increase in the electrical resistivity of films manifests a growing anomaly of the behavior of the current-voltage characteristics of tunnel contacts. The dependences of the differential resistance dV/dI of a tunnel contact on the current I flowing through it are plotted in Fig. 8 for sample No. 8 with the resitivity $\rho = 1.04\times10^{-3}\Omega\cdot$cm. The form of the $\Delta G(V)/G$ curves is close to the square-root law when ρ is increased right up to $7\times10^{-3}\Omega\cdot$cm. [It should be pointed out that in the case of aluminum films evaporated thermally in an oxygen atmosphere the metallic type of conduction is observed for $\rho \lesssim 10^{-1}\Omega\cdot$cm (see, for example, Refs. 10 and 20).] Equation (7) obtained on the assumption that $\Delta G(V)/G \ll 1$, ceases formally to be valid in the case of such strongly disordered samples. Nevertheless, it is found that

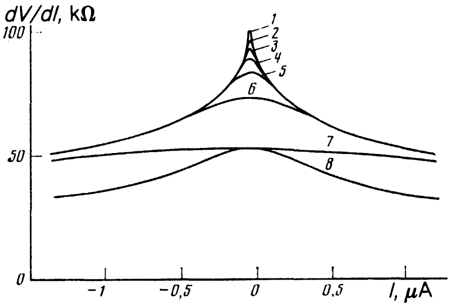

FIG. 8. Dependences $(dV/dI)(I)$ for tunnel contacts in which the disordered electrode was film No. 8, obtained at the following temperatures: 1) 0.4 K; 2) 4.2 K; 3) 10 K; 4) 20 K; 5) 40 K; 6) 90 K; 7), 8) 300 K. Curve 8 is plotted on a current scale different from the rest of the figure: one division represents $2 \mu A$.

the experimental dependences $\Delta G(V)$ are described satisfactorily by this equation even when $\Delta G(V)/G \sim 1$. This clearly demonstrates that, firstly, the range of validity of Eq. (7) can be extended right up to $\Delta G/G \sim 1$ and, secondly, in the case of films with resistivities $\rho \lesssim 10^{-3} \Omega \cdot$cm the spatial dispersion of the diffusion coefficient is still unimportant over distances $\sim L_V$ and $\xi(T)$ [$\xi(T)$ is the coherence length of a superconductor governing the critical field H_{c2}].

We have discussed above the dependences $\Delta G(V)$ for tunnel contacts formed by three-dimensional films with a uniform thickness. When aluminum is deposited thermally in an oxygen atmosphere, uniform films can be obtained if the rate of evaporation v is kept constant. Even slight relative changes in v ($\gtrsim 10\%$) produce a layer distribution of the oxygen concentration in the film (this is deduced by the Auger spectroscopy method) so that the diffusion coefficient of electrons varies across the thickness. Spatial variation of $D(x)$ (x is the distance to the film surface) is reflected in the form of the dependences $\Delta G(V)$ of tunnel contacts formed by films of this kind. In particular, the quantity $\Delta G(V)$ is no longer a single-valued function of

$$D = \frac{1}{a} \int_0^a D(x)\, dx,$$

which governs the thickness-average resistivity of a film $\rho = (e^2 \nu D)^{-1}$. For example, in the experiments on specially prepared aluminum films consisting of two layers—lower ($a_1 = 2000$ Å, $\rho_1 = 10^{-8} \Omega \cdot$cm) and upper ($a_2 = 60$ Å, $\rho_2 = 10^{-3} \Omega \cdot$cm), the surface of which carries a tunnel contact—we observed a tunnel conductance anomaly at $V \gtrsim 1$ mV ($L_V \lesssim a_2$) which was governed by the value of D in the upper layer. It therefore follows that experimental studies of the tunnel conductance anomaly can give information on the degree of disorder of three-dimensional conductors at distances $L \approx l - L_T$ from the surface. Variation of the bias voltage and, consequently, of the value of L_V, makes it possible to solve the inverse problem, i.e., to use the form of the $\Delta G(V)$ curve to reconstruct the dependence $D(x)$ in the range of x from a few tens to a few hundreds of angstroms.

§5. CONCLUSIONS

The tunnel experiments described above demonstrate that the observed dependences $\Delta G(V)$ reflect the energy dependence of the one-particle density of states governed by the electron-electron interaction in disordered aluminum films forming a tunnel contact. Far from the transition to the superconducting state (at temperatures $T \gg T_c$ or in fields $H \gg H_{c2}$ at $T < T_c$) the appearance of a minimum of $\nu(\varepsilon)$ at the Fermi level is due to the diffusion channel interaction between particles with a total spin $j = 0$. The dependences $\Delta G(V)$ for tunnel contacts formed by weakly disordered two- and three-dimensional aluminum films are described quantitatively by the theory of Refs. 1–5 in a wide range of values of eV/kT. The results of the tunnel experiments are in agreement with the data obtained from a study of the temperature dependence of the conductance of disordered films in strong magnetic fields. It is found that a study of the tunnel conductance anomaly in spatially inhomogeneous (layer) samples can provide information on the degree of disorder at distances from several tens to several hundreds of angstroms from the surface.

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[1]In metals with a large Stoner factor $(1 - I)^{-1} \gg 1$ (such as Pt or Pd) the singularities of ν corresponding to $M = \pm 1$ should be displaced more strongly: $\Delta\varepsilon \approx \pm g\mu H/(1 - I)$ (Ref. 19). However, it should be pointed out that observation of the Zeeman splitting of the singularity ν in such metals is difficult because of the characteristic strong spin-orbit scattering.

[2]The authors are grateful to D. V. Klyachko for an investigation of our samples by the Auger spectroscopy method.

[3]The investigation reported in Ref. 13 ignores the factor $\ln(4\pi\delta/DR_\square)$ in the expression for $\Delta G(V)/G$ given by Eq. (4). Its value for the investigated In_2O_{3-x} films is ~ 7. This refinement has the effect that the discrepancy between the experimental results and Eq. (4) decreases but does not disappear completely.

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