# Effect of electron-electron interaction on tunneling conductivity of bismuth films

V. N. Lutskiĭ, A. S. Rylik, and A. K. Savchenko
*Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR*

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The conductivity $G$ of a tunnel structure Bi film-Bi oxide-Pb film exhibits a symmetric minimum when there is no voltage ($V$) across the junction. The zero anomaly of $G(V)$ and its temperature dependence are interpreted in terms of the theory of electron-electron interaction in disordered systems.

We know that the conductivity of thin bismuth films at low temperatures is caused by electron-electron interaction and trapping of electrons in slightly disordered systems.[1,2] Theory shows that an intensification of electron-electron interaction due to the diffusion of electrons gives rise to special features in the single-particle state density at the Fermi level and to a change in the conductivity associated with this process.[3] The special features of the electronic state density of a tunneling structure containing a thin film can be studied directly by measuring the differential conductivity of the film, $G = \partial I / \partial V$.

In this letter we report the results of a measurement of the dependence of the differential conductivity $G$ of a Bi-Bi oxide-Pb tunnel junction on the voltage $V$ across the junction. A bismuth film of thickness $a = 400$–$1500$ Å was obtained by thermal deposition on a mica substrate in a vacuum of $10^{-6}$–$10^{-5}$ torr and by oxidation at 100 °C in dry $O_2$. A thick Pb film ($a \sim 3000$ Å) was then deposited. The surface resistivity of Bi films was in the range 35–150 $\Omega$ and the resistivity of tunnel junctions was in the range 0.5–5 k$\Omega$. The quality of the junctions was determined from the change in the value of $G$ ($V = 0$) upon the transition of a Pb film to the superconducting state.

  

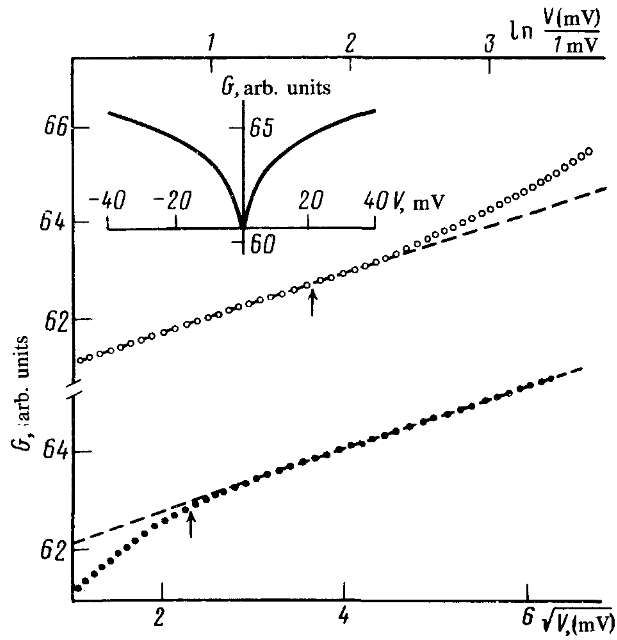


FIG. 1. Tunneling conductivity versus the voltage at $T = 4.2$ K for a 1200-Å-thick Bi film with $R_\square = 35\ \Omega$ [○—$G(\ln V)$; ●—$G(\sqrt{V})$]. The arrow corresponds to the condition $L_V = a/2\pi$. The original $G(V)$ curve is shown in the inset.

At $V = 0$, we see a minimum on the $G(V)$ curves for all the films studied. The symmetrically shaped zero anomaly is described by the function $\Delta G \sim \ln V$ when the voltage across a junction is low and by the function $\Delta G \sim \sqrt{V}$ when the voltage across a junction is high (Fig. 1). The magnetic field $H \leqslant 60$ kOe had no effect on the zero anomaly.

The particular features of the tunneling-conductivity minimum indicated above cannot account for the tunneling conductivity in terms of the mechanisms described in the review by Zeller and Geaver.[4] The change from a logarithmic dependence of $G(V)$ to a square-root dependence is, on the other hand, a typical result of a theory in which the effect of an electron-electron interaction on the electronic state density is considered.

According to Refs. 5 and 6, at $T = 0$ we can write in the two-dimensional case the correction

$$\frac{\delta\nu(\epsilon)}{\nu_0} = \frac{\lambda_\nu e^2 R_\square}{2\pi^2 \hbar} \ln \frac{|E|\tau}{\hbar} \tag{1}$$

to the state density at the Fermi level for samples of different effective sizes and in the three-dimensional case we can write the correction

$$\delta\nu(\epsilon) = \frac{\lambda_\nu}{4\sqrt{2}\pi^2} \frac{\sqrt{|E|}}{(D\hbar)^{3/2}}, \tag{2}$$

where $D$ is the diffusion coefficient, $\tau$ is the momentum-relaxation time, and $\lambda_\nu$ is the electron-electron interaction constant. The effective size of a sample, which depends on the voltage $V$ across a tunnel junction, is determined by the ratio of the film thickness $a$ to the scale length $L_V = \sqrt{D\hbar/eV}$: $a \gg L_V$ in the three-dimensional case and $a \ll L_V$ in the two-dimensional case.

In the case of the films we have studied, the transition from a logarithmic dependence of $G(V)$ to a square-root dependence corresponds (to within 50%) to the condition under which a transition from a $2d$ to a $3d$ case occurs: $L_V = a/2\pi$ (this criterion was used in Ref. 7).

The ratio $\Delta G/G_0 = \delta\nu/\nu_0$, which holds if $\nu_0 = \text{const}$ in the energy range $E_F \pm eV$, was used to determine the correction to the electronic state density. This ratio can be used for Bi films, because the state density of films with low-mobility current carriers becomes diffuse in comparison with that of a bulk crystal, as can be seen from the symmetric shape of the anomaly in $G(V)$ observed in the $\pm$ 50-mV range. In the three-dimensional case, the unperturbed state density was estimated from the equation $\nu_0 = (2e^2 D\rho)^{-1}$, and we took into account that at the surface of the sample the value of $\delta\nu$ is, according to Ref. 6, twice as large as that in the bulk of the crystal, given by expression (2).

In the case of the exchange part of the diffusion-interaction channel, which determines the conductivity of Bi films,[1] the effective interaction constant is[6] $\lambda_\nu^{3d} = 2$ in the three-dimensional case. In the two-dimensional case, we have $\lambda_\nu^{2d} = 0.5 \ln E/(Da^2\kappa_2^4 \hbar)$, where $\kappa_2 = \kappa^2 a/2$, and $\kappa$ is the reciprocal of the screening length. If the effect of the second electrode of the structure on the interaction of electrons in the film is taken into account, we can write the interaction constant as[6] $\lambda_\nu^{2d} = \ln 2\kappa_2\Delta$ in the two-dimensional case if $\kappa_2\Delta > 1$ ($\Delta$ is the thickness of the dielectric) and we can write the interaction constant as $\lambda_\nu^{2d} = \ln \kappa a$ if $\kappa_2 a < 1$. The use of the expressions given above to estimate the values of $\lambda_\nu$ yields a value on the order of unity. In the two- and three-dimensional cases, however, the interaction constant $\lambda_\nu$ obtained experimentally turned out to be an order of magnitude greater than that predicted theoretically.

According to the theory,[3] the zero anomaly resulting from electron-electron interaction at a finite temperature is described by the expression

$$\frac{\Delta G}{G}(V,T) = \frac{1}{4kT}\int_{-\infty}^{\infty} dE \frac{\delta\nu}{\nu_0}\cosh^{-2}\frac{E-eV}{2kT}, \tag{3}$$

in which for the two-dimensional case we have

$$\frac{\delta\nu(x)}{\nu_0} = -\frac{\lambda_\nu e^2 R_\square}{\pi^2\hbar}\int_0^\infty \frac{dy}{y}\frac{\sinh y}{\cosh y + \cosh x}, \qquad x = \frac{E}{kT}.$$

A characteristic feature in (3) is that the quantity $G(V,T) - G(V=0,T)$ is a function of the ratio $eV/kT$. The zero anomaly is identical in the two limiting cases, $eV \gg kT$ and $eV \ll kT$: We have accordingly $\Delta G \sim \ln V$ and $\Delta G \sim \ln T$ if the coefficients multiplying the logarithms are the same.

Figure 2 is an example of some experimental curves for the tunneling anomaly $G(V,T) - G(V=0,T)$ measured in a Bi film at various temperatures and plotted in the

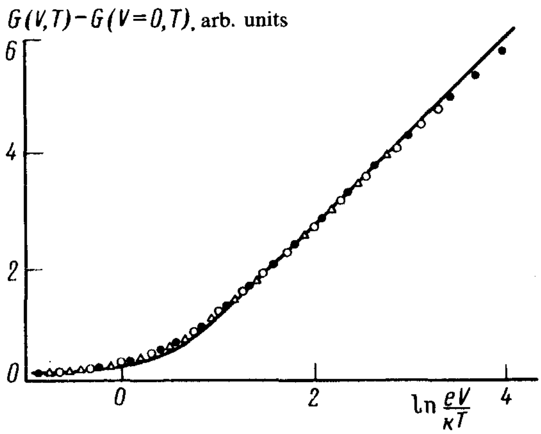


FIG. 2. The tunneling anomaly at various temperatures (●—9 K; ○—20 K; Δ—30 K). Solid line—theoretical curve $A\,[G(V, T) - G(V=0, T)]$ ($A$ is an adjustable parameter). The film thickness is $a = 1200$ Å and $R_{\square} = 35\,\Omega$.

$eV/kT$ coordinates. In these coordinates the curves $G(V, T) - G(V=0, T)$ lie on a single universal curve which corresponds within a factor to the theoretical dependence (3).

Figure 3 shows the curves $G(V=0, T)$ $T = 1.8$–$60$ K) ($V$, $T = 4.2$ K). These curves have the same logarithmic shape when plotted in the coordinates $\Delta G(z)$, $z = \max(eV, kT)$, consistent with theory. At finite temperatures, the behavior of the zero anomaly is thus in good agreement with the theoretical predictions of the electron-electron interaction.

Al'tshuler and Aronov[8] have shown that an application of a magnetic field causes, in addition to the $G$ anomaly, the appearance of characteristic features in the absence of a voltage bias, which are separated from the zero anomaly by $eV = \pm g\mu_B H$ ($g$ is the $g$-factor of an electron, and $\mu_B$ is the Bohr magneton). Despite the large Zeeman splitting in Bi (in a bulk material we have $g\mu_B H \sim 4$ meV at $H = 50$ kOe, $H \| C_3$), at $T = 4.2$ K in a field $H \leqslant 60$ kOe we saw no symmetric features in the curves $\partial I/\partial V(V)$ and $\partial^2 I/\partial V^2(V)$ which shift when the magnetic field is changed. We saw no such features apparently because these features, in contrast with the zero

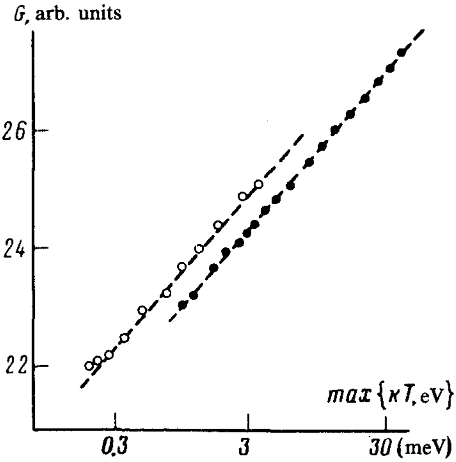


FIG. 3. Tunneling conductivity versus the temperature at $V = 0$ (○) and versus the resistivity at $T = 4.2$ K(●). The film thickness is $a = 630$ Å and $R_{\square} = 130\,\Omega$.

anomaly, become diffuse not only at a finite temperature but also by virtue of conduction-electron spin scattering.[8] This diffuseness becomes important if the condition $\hbar/\tau_{so} \sim g\mu_B H$ holds ($\tau_{so}$ is the spin-orbit-relaxation time). This condition is satisfied in the Bi films that we have tested [$\hbar/\tau_{so} \sim 2$ meV (Ref. 1)].

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