Indication of an energy gap in the current-voltage characteristics of superconducting films

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(Submitted 4 October 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 10, 429–432 (25 November 1984)

Under certain conditions the current-voltage characteristics (IVC) of broad superconducting films have sharp features that coincide with the energy gap $2\Delta\ (T)$. This effect is linked with the mechanism for breaking of Cooper pairs on the phase-slip line (PSL).

1. The resistive state of thin, broad superconducting films with good heat transfer can occur as a result of the development of vortex instabilities that generate phase-slip lines[1-3]— the two-dimensional analog of the well-known phase-slip centers (PSC).[4] We studied the mechanism for formation of PSL by creating conditions that facilitate current-induced penetration of vortices into localized sites in the film. In so doing, we observed sharp peaks in the conductivity of Al, Sn, SnGe, and PbBi films at voltages $V = 2\Delta\ (T)/e$ (Figs. 1 and 2). Similar features have been observed previously only in the conductivity of tunnel junctions of the type *S–I–S*.

2. Flat samples with dimensions $W \times L = 1 \times 10$ mm and thickness $d = 30$–60 nm were obtained by sputtering a metal through clamped masks onto a glass substrate at a substrate temperature of 300 K in a vacuum of $\sim 2 \times 10^{-5}$ torr. The resistance of the films was $R_{\square} = 10$–$30\ \Omega$ (the mean-free path of quasiparticles $l \ll \xi$). Multicomponent Sn–Ge and Pb–$Pb_{40}Bi_{60}$ films were prepared by simultaneous evaporation of the components. The edge barrier against the entrance of fluxoids was lowered by depositing

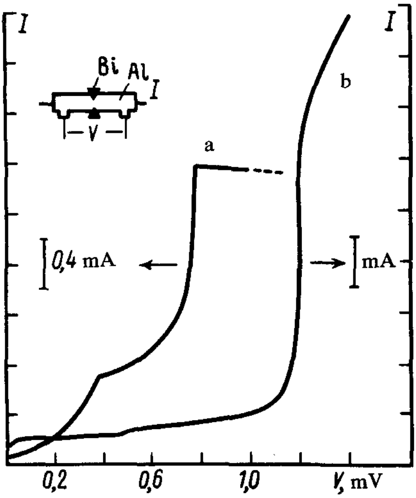

FIG. 1. The *I-V* characteristics of Al films at $T/T_c = 0.82$ (*a*) and of Sn films at $T/T_c = 0.416$ (*b*); T_c (Al) = 1.91 and T_c (Sn) = 3.72. The geometry of the "whiskers" is shown in the inset. $2\Delta_{Al} = 0.4$ mV; $2\Delta_{Sn} = 1.2$ mV.

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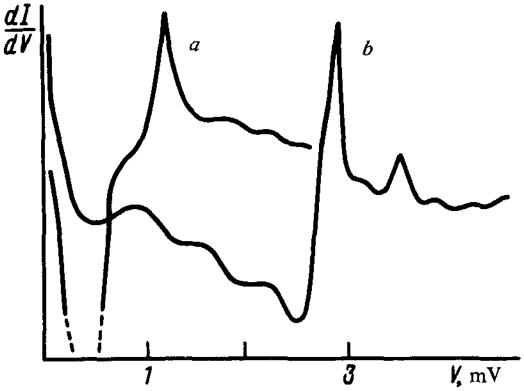

FIG. 2. Conductivity of Sn–Ge films at $T/T_c = 0.41$ (*a*) and of $Pb_{40}Bi_{60}$ films at $T/T_c = 0.2$ (*b*) $2\Delta_{Sn} = 1.2$ mV; $2\Delta_{Pb} = 2.8$ mV; $2\Delta_{Pb_{40}Bi_{60}} = 3.5$ mV.

whiskers of normal metal (Bi) under conditions that ensure the existence of the proximity effect. The radius of curvature of the whiskers (the inset in Fig. 1) is $\sim 10\,\mu$m and the spacing between them is 0.4 mm. The samples were shielded from external magnetic fields; the residual magnetic field did not exceed 1 mOe. For these samples the heat-transfer coefficient at the sample–helium (sample–substrate) boundary was of the order of 1 W/cm^2·deg, which for these operating currents allowed us to ignore the heating effects. The absence of appreciable thermal effects is also suggested by the hysteresis-free nature of the initial sections of the *I-V* characteristics.

3. Peaks were observed in the differential conductivity of the films at voltage V that were multiples of the energy-gap parameter of the superconductor studied here, $eV = N\Delta(T)$ $(N = 1, 2, 3 \ldots)$, while for multicomponent samples they were observed at values of eV that were multiples of the values of $\Delta(T)$ for each component in the mixture (Figs. 1–3). The most striking features generally corresponded to even numbers $N = 2, 4, \ldots$ (Fig. 1). The value of $\Delta(T)$ was monitored for several samples with the help of tunnel junctions formed from aluminum and the superconductor under study several millimeters from the location at which the edge barrier was delib-

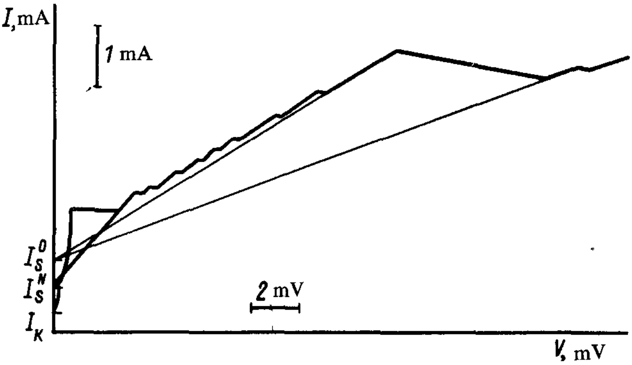

FIG. 3. Stepped structure of the *I-V* characteristic of an aluminum film at $T/T_c = 0.82$, showing a change in the excess current I_s^N as a function of the number N.

erately lowered. The presence of a tunnel junction had no effect on the shape of the I-V characteristic of the films. The reduction of the order parameter at the film edges decreased the critical current I_c responsible for the development of the vortex instability by an order of magnitude (Fig. 3). This made it possible to identify the discrete nature of the transition of the films to the resistive state for a wide range of temperatures $0.2 < T/T_c < 0.95$. For high bias voltages, $eV \gg \Delta$, the I–V characteristic of the samples consists of fragments with constant and multiple differential resistance $R_N = NR_0$ (Fig. 3) and a linear dependence of the current I on the voltage, $V = (I - I_s^N)R_N$. Here I_s^N is the value of the current obtained by extrpolating the slope of the I-V characteristic of the N-th fragment to $V = 0$ (the "excess" current). At low temperatures the "excess" current I_s^N increases with the number N and approaches a limit I_s^0 (Fig. 3); as $T \rightarrow T_c$, we have $I_s^0 \sim \Delta^2(T)$. The shape of the initial sections of the I-V characteristic of Al and Sn films differs markedly from the voltage jumps characteristic for the vortex instability[1,2] and from the shape of the I-V curves caused by the phase-slip centers in long superconducting channels.[4] First of all, the I-V curve (Fig. 1) is characterized by a wide, smooth plateau with a high differential resistance dV/dI and a sharp increase in current at $eV = 2\Delta$. As the temperature is raised, the jump in the current becomes more pronounced and the resistance of the plateau, dV/dI, increases. If the second feature does not follow immediately after the first one on the I-V curve, then the differential resistance of the curve asymptotically approaches the resistance $R_N = NR_0$ of the fragment in the normal state.

4. We see from the shape of the I-V curve (Fig. 3) that the observed localized objects have a differential resistance R_0 and can stabilize the average transmitted supercurrent, i.e., the excess current I_s^N, even if the value of I_s^N, is much lower than the limiting value I_s^0, for a given sample. This property of the objects, called below the phase-slip line, shows that the total current flowing through the region of the PSL, where the electric field is nonvanishing, can increase due to the normal component of the current. For this reason, the features on the I-V curve can be caused by various processes that increase the density of nonequilibrium quasiparticles, such as the threshold absorption by the film of the experimentally observed electromagnetic field that is self-generated by the PSL. The experiment involved a mixing of the signal from an external heterodyne at a frequency $f = 9.8$ GHz with the free-generation signal from the PSL and separation of the intermediate frequency $\Delta f = 100$ MHz in the region of the plateau on the I-V curve. From the relation $\hbar\omega_J = 2eV$, which holds for any resistive system,[4] it follows that the features on the I-V curve (peaks in the conductivity) occurring at $eV = \Delta(T)/n$ (where n is the number of the harmonic of the alternating field of the PSL, and ω_J is the oscillation frequency) must correspond to the threshold mechanism for the production of nonequilibrium quasiparticles. The same features arise as a result of the decay of Cooper pairs into quasiparticles as they pass an accelerating potential V, when $2eV + n\hbar\omega = 2\Delta(T)$. The fact that such channels for formation of nonequilibrium quasiparticles can occur is confirmed by the observed subharmonic structure of the I-V characteristics studied by us: peaks in the conductivity of films at eV, which are multiples of $\Delta(T)/n$ (Fig. 2). But why are the observed features identical to the equilibrium values of the energy-gap parameter $\Delta(T)$, in spite of the obviously nonequilibrium nature of the object being studied here (in the region $eV \sim \Delta, \hbar\omega_J$ and $\omega_J\tau_\epsilon \gg 1$, where τ_ϵ is the energy-relaxation time of the quasiparticles)?

The discrepancy is eliminated if the region where the nonequilibrium processes that stabilize the "hot" core of the PSL are localized is much smaller than the resistive region which is determined by the penetration depth of the electric field, $\delta_E = R_0 W / 2R_\square \sim 10^{-3}$–$10^{-4}$ cm; and $\delta_E \gg \xi$. At $eV < \Delta$ at low temperatures $T \ll \Delta$, the exponentially small quasiparticle density in this case is approximately equal to the equilibrium density almost in the entire resistive region. The threshold production of nonequilibrium quasiparticles in the region where the electric field penetrates into superconductors could therefore be responsible for the sharp increase in the quasiparticle current on the phase-slip line at $eV = \Delta (T)$.

We thank N. V. Zavaritskiĭ and A. F. Andreev for a discussion and valuable remarks.

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Translated by M. E. Alferieff
Edited by S. J. Amoretty