Experimental observation of stimulation of superconductivity in niobium thin films

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A stimulation of superconductivity has been observed experimentally in niobium thin films constituting the interlayer in double-barrier Nb/Nb′/Nb superconductor structures. An explanation is offered for the experimental data on the basis of a model in which the time scale for inelastic relaxation of quasiparticles depends on the energy at energies near the gap. © *1995 American Institute of Physics.*

Stimulation of superconductivity has been observed previously in superconducting thin films of aluminum, tin, and indium, either upon the application of external microwave radiation or as a result of quasiparticle injection. The stimulation has been explained on the basis that the quasiparticle distribution function, which arises when the material is subjected to an external agent, is not a Fermi distribution.[1,2] In thin films with a short mean free path, $l<10$ nm (e.g., in niobium), in contrast, no stimulation of superconductivity has been observed previously. The reason is that at liquid-helium temperatures the electron–electron interaction time τ_{e-e} becomes shorter than the electron–phonon interaction time τ_E. As a result, the quasiparticle distribution becomes thermalized when the external agent is applied. The quasiparticle distribution function remains a Fermi distribution; the only change is in the effective temperature of the electron gas.[3]

As was first pointed out by Parmenter,[4] superconductivity stimulation is intensified in a superconducting thin film S′ sandwiched between two tunnel junctions with superconducting banks S (an S/S′/S structure, where the / represents a tunnel barrier). The reason is that, when there is a nonzero voltage across the structure, the injection of quasiparticles is accompanied by an extraction of quasiparticles from superconductor S′. This extraction is equivalent to an effective cooling of the system. Zaĭtsev[5] has carried out a detailed theoretical analysis of this effect on the basis of a microscopic theory. Heslinga *et al.*[6] have carried out a calculation on the basis of a model for the balance of quasiparticles crossing the barriers. Experimentally, an anomalously strong stimulation of superconductivity has been observed[7,8] in double-barrier superconductor Nb/Al/Nb structures with a fairly large deviation of the quasiparticles from equilibrium. Specifically, the rate of the tunneling injection of quasiparticles from the Nb into the Al, $\Gamma=v_FD/d$ (d is the thickness of the interlayer, v_F is the electron velocity at the Fermi level, and D is the transmission of the barrier), was greater than the reciprocal time scale for inelastic relaxation of quasiparticles with an energy greater than the gap Δ' and the temperature T in the interlayer[2)] ($\Gamma\tau_{\text{in}}>1$). At T above the transition temperature of the interlayer, T_c', a gap size in Al equal to 60% of the gap size in Al at $T=0$ K has been observed experimentally.[7,8]

In this letter we are reporting an experimental observation of superconductivity stimulation in Nb thin films in Nb/Nb′/Nb double-barrier superconductor structures for the case in which the deviation of the quasiparticles from equilibrium is small ($\Gamma\tau_{\text{in}}<1$). We show that the increase in the gap size observed experimentally can be explained by an increase in the time scale for inelastic relaxation under the condition[3)] $E\equiv\Delta'$.

In the experiments we studied double-barrier superconductor structures of Nb with a barrier of aluminum oxide fabricated by a known procedure for fabricating single tunnel junctions.[9] We measured independent current–voltage characteristics and the dependence of the differential resistance on the voltage across the superconducting banks, $R_d(V)$, at $T=4.2-10$ K for interlayer thicknesses $d=10$ and 20 nm. The entire apparatus was enclosed in an electromagnetic shield, and the leads to the sample were filtered, in order to reduce stray pickup.

Figure 1a shows current–voltage characteristics of structure J6N5 ($d=20$ nm) at $T=4.2$ K. In general, the shape of the I–V characteristic corresponds to that of a superconducting S/S′ tunnel junction: At $V=0$ we observe a critical current due to the Josephson effect. As the current is raised, the hysteresis region on the current–voltage characteristic (shown by the dashed lines in Fig. 1a) gives way to a gap feature at $V\approx4.5$ mV and a region of a linear increase in the voltage with the current. The occurrence of the gap feature at such high voltages and the essentially vertical gap feature indicate that two series-connected SIS junctions of Nb are involved in a tunneling process (the gap feature of Nb/Nb′ junctions is usually observed at $V\approx2.5$ mV at $T=4.2$ K). Since the voltages of the two S/S′ junctions combine additively, features are observed on the current–voltage characteristic of the double-barrier superconductor structure at the following voltages:

$$V_{++}=\frac{\Delta_1+\Delta_2+2\Delta'}{e},\quad V_{--}=\frac{\Delta_1+\Delta_2-2\Delta'}{e}.$$

Here $\Delta_1\approx\Delta_2=\Delta$ and Δ' are the sizes of the energy gap in the banks and the interlayer, respectively. Furthermore, as the critical current is decreased because of an external electric field, we observe features[4)] $V_+=(\Delta+\Delta')/e$ and $V_-=(\Delta-\Delta')/e$, which can be attributed to the presence of features at $V=V_+/2$ and $V_-/2$, which arise at the S/S′ junctions because of multiparticle tunneling. These features are strengthened because of multiple Andreev reflection at the superconductor tunnel junctions with a high-transmission tunneling layer.[10]

The temperature dependence of the gap features at higher temperatures is determined from the curves of $R_d(V)$ (Fig. 1b). Here again we see that both tunnel barriers of the double-barrier structure are in a resistive state at $V>V_-$: There is no region of a sharp increase in R_d on the $R_d(V)$ curve. Such a region does arise when one of the barriers goes into a resistive state. The curves of $R_d(V)$ are used to determine the bank transition temperature T_c and the interlayer transition temperature T_c'. We find $T_c=9.2$ K from the deviation of the $R_d(V)$ curve from $R_d(V)=\text{const}$. We find $T_c'=7.4$ K from the

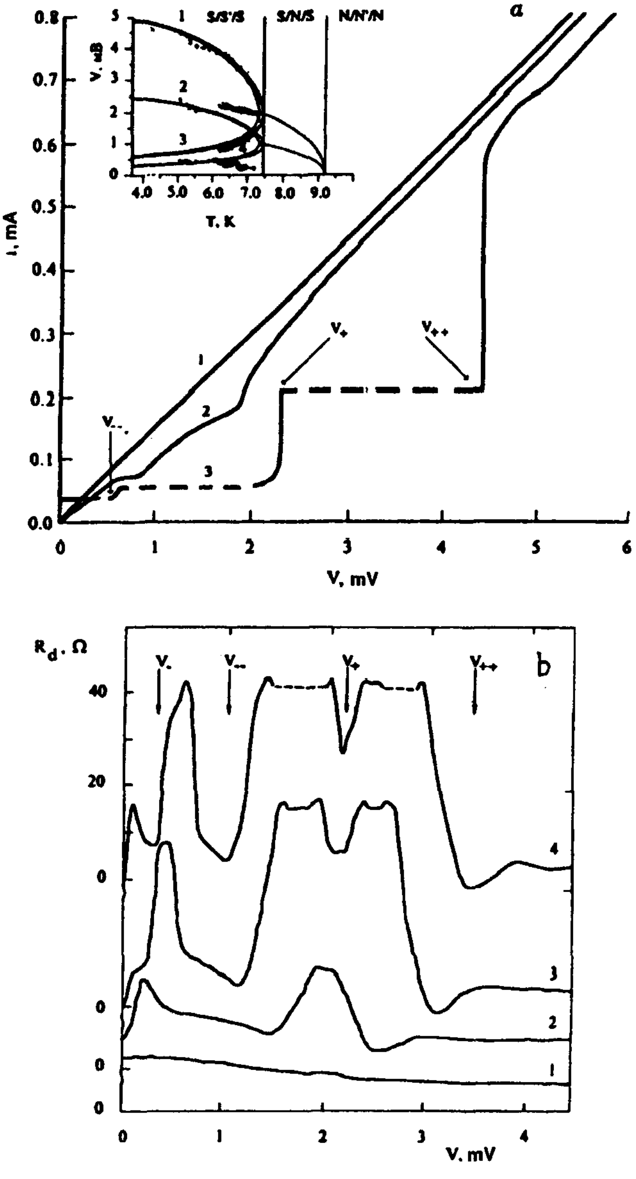

FIG. 1. a: Current–voltage characteristic of double-barrier superconductor structure J6N5, with an interlayer thickness of 20 nm, at $T=4.2$ K. The dashed lines show the hysteresis regions of the current–voltage characteristic. The inset shows the temperature dependence of the features, observed at the following voltages. Curve 1—$V=V_{++}$; 2—V_{+} ; 3—V_{--} ; 4—V_{-} . b: Family of curves of the differential resistance versus the voltage at various temperatures. 1—$T=7.46$ K; 2—7.28 K; 3—6.97 K; 4—6.72 K.

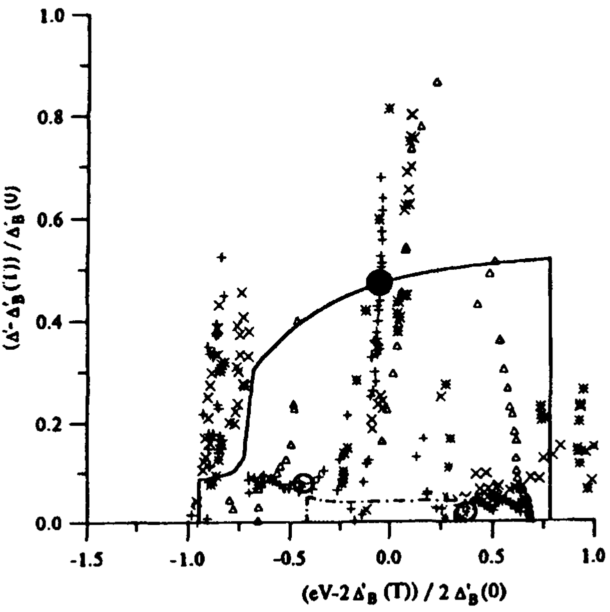

FIG. 2. Experimental values of the deviation of the energy gap in the layer from the prediction of the BCS theory as a function of the voltage across the double-barrier superconductor structure. *—Sample J6N1, layer thickness of 20 nm; ×—J6N3, same thickness; +—J6N5, same thickness; Δ—H3N1, thickness of 10 nm. Experimental values for double-barrier superconductor structure J6N5 at $T=7$ K: ●) $V=V_+$; O) $V=V_{++}$ and $V=V_{--}$. The curves are theoretical results for two functions $\tau_{\min}(E)$ under the condition $\Gamma\tau_{\text{in}}\cong 10^{-2}$. Dot-dashed curve—$\tau_{\text{in}}(E)=\text{const}$; solid curve— $\tau_{\text{in}}(E)\cong\tau_{\text{in0}}[1+(\Delta'/(|E|-\Delta'))^{3.5}]$.

onset of a critical current [from a decrease in $R_d(0)$]. In the region $T_c'<T<T_c$ (curve 1 in Fig. 1b) the banks are in the superconducting state, while the interlayer is in the normal state. In this case we observe an $R_d(V)$ curve corresponding to two series-connected SIN junctions with a maximum $R_d(0)$. At $T<T_c'$ the interlayer is in the superconducting state, and gap features appear on the $R_d(V)$ curve (curves 2–4 in Fig. 1b).

Curves of the features V_{--}, V_{++}, V_+, and V_- versus the temperature are shown in the inset in Fig. 1a. The solid curves show corresponding results found from the values of Δ_B and Δ_B' on the basis of the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity. We see that in the temperature interval 6 K$<T<$7.4 K the experimental values of $(\Delta+\Delta')(T)/e$ are considerably larger than the values predicted by the BCS theory. This difference is evidence of a stimulation of a superconducting gap in the interlayer.

Figure 2 shows experimental results on the change in Δ' for all the test samples, as found from the values of V_{--}, V_-, V_+, and V_{++}. Results corresponding to a suppression of the superconducting gap are not shown in Fig. 2. We see that the stimulation of Δ' occurs at values of V in the interval $2\Delta-2\Delta'\leqslant eV\leqslant 2\Delta+2\Delta'$. This result is in qualitative agreement with the calculations of Refs. 5 and 6. The extent of the increase in the gap, $\Delta'-\Delta_B'$, is lower than the theoretical value[5,6] under the condition $\Gamma\tau_{\text{in}}>1$. This difference can be explained entirely on the basis that there is no pronounced deviation from equilibrium in our double-barrier structures (experimentally, we have $\Gamma\tau_{\text{in}}\sim 10^{-2}$ s at $\tau_{\text{in}}=5\times 10^{-10}$ s for niobium at $T=7$ K; Ref. 11). Substitution of the experimental value of $\Gamma\tau_{\text{in}}$ into the calculations of Ref. 5 yields a value of $(\Delta'-\Delta'_B)(V)$ (the dot-dashed curve in Fig. 2) which is much smaller than the experimental value for $V=V_+$.

In the calculations of Refs. 5 and 6, τ_{in} was taken to be a constant, independent of the energy and of the extent of the deviation from equilibrium. We know, however, that at energies $E\sim\Delta'$ the quasiparticle relaxation in superconductors slows down dramatically because of coherence factors and features in the density of states. As a result, quasiparticles with an energy $E\sim\Delta'$ are not at equilibrium. We take this point into account in the present letter by introducing an energy dependence of τ_{in} in the following way:[12]

$$\tau_{\text{in}}(E)\cong\tau_{\text{in}0}\left(1+\left(\frac{\Delta'}{|E|-\Delta'}\right)^{3.5}\right). \tag{1}$$

This expression was derived under the assumption of a linear dispersion for phonons and under the assumption that the square of the matrix element for the electron–phonon interaction is proportional to the phonon wave vector. Under the condition $E-\Delta'\gg\Delta'$, the time $\tau_{\text{in}}(E)$ in (1) is the same as the time scale for electron energy relaxation in a normal metal. For Nb, we took this time to be[11] $\tau_{\text{in}0}=5\times 10^{-10}$ s at $T=7$ K. An inelastic relaxation of nonequilibrium carriers injected into the interlayer can occur as a result of electron–phonon and electron–electron interactions $(\tau_{\text{in}}^{-1}=\tau_{e-e}^{-1}+\tau_E^{-1})$. The stimulation of an energy gap in the interlayer of the double-barrier structure, which has been observed experimentally, and also the calculations of Refs. 12 and 13 indicate that electron–electron interaction processes are of minor importance in the quasiparticle tunneling[5)] (Ref. 13; $\tau_{\text{in}}\approx\tau_E$).

A numerical calculation of the energy gap in the interlayer has been carried out on the basis of a balance equation[6] incorporating the following processes: injection of carriers from the superconducting bank 1 into the interlayer, inelastic relaxation of the carriers in this interlayer, and subsequent extraction into superconducting bank 2. As a result, the expression for the distribution function in the interlayer, $f'(E)$, is[6]

$$f'(E)=\frac{N_1(E-eV/2)f_0(E-eV/2)+N_2(E+eV/2)f_0(E+eV/2)+\dfrac{f_0(E)}{\Gamma\tau_B(E)}}{N_1(E-eV/2)+N_2(E+eV/2)+\dfrac{1}{\Gamma\tau_B(E)}}. \tag{2}$$

Here N_i $(i=1,2)$ is the BCS density of states of the superconducting banks, $f_0(E)=1/[\exp(E/T)+1]$ is the Fermi distribution function, and the relaxation of the quasiparticles is assumed to be a linear function of τ_E. In the double-barrier structures which we studied, the proximity effect can be ignored, because of the condition[9,14] $d\gg\hbar v_F D/4\Delta(0)$. From the self-consistency equation we find the following equation for Δ' (Ref. 5):

$$\int_0^\infty dE\left[\frac{f'(E)\theta(|E|-\Delta')}{\sqrt{E^2-(\Delta')^2}}-\frac{1}{E}\tanh\left(\frac{E}{2T}\right)\right]=\ln\left(\frac{T}{T'_c}\right). \tag{3}$$

Here $\theta(x)$ is the unit step function. The results of the numerical solution of Eqs. (2) and (3) for a layer with $d=20$ nm at $T=7$ K are shown in Fig. 2 (solid curve). From the set of experimental points, we show in Fig. 2 those points for which the values of T and V are the same as those used in the numerical solution. We see that there is a good correspondence between the theoretical and experimental results in terms of the voltage V_+ (the large point in Fig. 2), at which the value of $\Delta'(7\text{ K})$ reaches 93% of $\Delta'(0)$. For the temperature dependence $(\Delta'-\Delta'_B)(T)$, determined at $V=V_+$, we observe a good agreement between the calculations and the experimental data. With increasing T, the relative stimulation Δ' increases. The probable reason is the fact that even small deviations of $f'(E)$ from equilibrium cause an increase in Δ' near T'_c. The apparent reason for the deviation of the experimental results from the theoretical results for the voltages $V=V_{++}$, V_{--}, and V_- is the model adopted for the collision integral.[5,6]

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[2)] Because of the small thickness of the interlayer, $d<\xi$, where ξ is the coherence length, in double-barrier superconductor structures, the condition $d<l_{in}=\sqrt{v_F l \tau_{in}/3}$ holds simultaneously. Because of this condition, there is a simultaneous distribution of nonequilibrium quasiparticles over the thickness of the interlayer.

[3)] Nonlinear effects which stem from the difference between the populations of the electron and hole branches of the spectrum are being ignored in this letter, since they do not lead to changes in the order parameter in the interlayer.

[4)] At $T=4.2$ K, the V_- feature is poorly expressed on the current–voltage characteristic; it is close to V_{--} in magnitude.

[5)] The experimental results show that for Nb thin films at $T\cong 10$ K we have $\tau_{e-e}\cong\tau_E$ (Ref. 11).

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