Stimulation of superconductivity in multilayer niobium structures

V. I. Dedyu and A. N. Lykov
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR

(Submitted 13 July 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 5, 184–186 (10 September 1987)

The critical temperature is found to increase with increasing number of layers in a multilayer niobium-based superconducting structure. The temperature dependence of a parallel critical magnetic field reveals a deviation from the square-root law. The results can be explained by an increase in the amplitude of the order parameter in the layers due to a weak Josephson coupling between them.

Several studies of artificially produced superconducting structures have recently been published.[1] In these studies attention has been focused principally on the structures with a strong binding between layers, i.e., those with a weak modulation of the order parameter. Superconducting structures with a strong modulation have essentially not been studied.

We studied structures with a strong modulation of the order parameter, comprised of niobium layers separated by thin oxide layers. Niobium was deposited on polished sapphire substrates at room temperature, with use of a magnetron. The thickness of the layers (d) varied over the range 100–400 Å and their number (N) varied between 1 and 20. The coupling between layers was varied by changing the oxidation regime. The product of the resistivity of the oxide layer, ρ_i, and its thickness, d_i, is a parameter of the coupling. We determined this parameter from the measurements of the tunnel junctions Nb-NbO_x-Nb which were fabricated in the specified oxidation regime. Auger analysis revealed the presence of a periodic structure. The procedure for fabricating these junctions is described in more detail in Ref. 2.

We measured the temperature dependence of the critical magnetic field H_{c2} and the critical temperature T_c as a function of the number (N) of layers. Figure 1 is a plot of the $T_c(N)$ curve for the samples with $N = 1–10$. The critical temperature is found to change by $\Delta T_c \approx 0.7$ K as the number of layers is increased. We attribute this change to the coupling between layers. Also shown in Fig. 1 is the $\gamma(N)$ curve, where $\gamma = \rho_{300}/\rho_{10}$ is the ratio of the resistivity at $T = 300$ K to that at $T = 10$ K. The fact that γ is constant shows that an increase in the critical temperature cannot be attributed to a change in the quality of the layers as they increase in number.

A stimulation of the critical temperature in the layered structure in a parallel field is also evident in the $H_{c2}(T)$ curves. The measurements were carried out with samples of various layer thicknesses and for three different values of $\rho_i d_i$. In two oxidation regimes the values of $\rho_i d_i$ were 10^{-5} $\Omega \cdot cm^2$ and 2×10^{-6} $\Omega \cdot cm^{-2}$. These are typical values for Josephson tunnel junctions. The third oxidation regime was prescribed in such a way that $\rho_i d_i < 10^{-6}$ $\Omega \cdot cm^2$. The $H''_{c2}(T)$ for a single-layer film of thickness $d < \xi(T)$ is given by a square-root dependence $H''_{c2} \sim (T_c - T)^{0.5}$. Figure 2 is a plot of

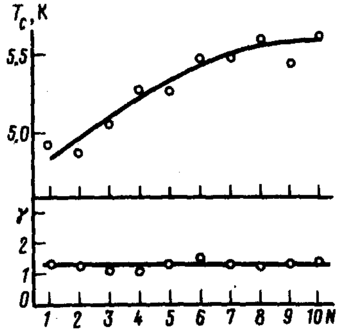

FIG. 1. Plots of $T_c(N)$ and $\gamma(N)$.

the $H''_{c2}(T)$ curve for the film with $d = 300$ Å and for three multilayer structures with $d = 300$ Å and $N = 10$, but with different values of $\rho_i d_i$. The experimental points for a single-layer film fit well on the square-root dependence (the solid curve). Multilayer structures reveal a divergence from the square-root law in weak magnetic fields up the temperature scale. This functional dependence can also be explained in terms of the increment ΔT_c due to the coupling, which is suppressed in strong magnetic fields. The magnetic field H^* at which the divergence begins increases with decreasing $\rho_i d_i$, i.e., with the intensification of the coupling between the layers. In the case of all the

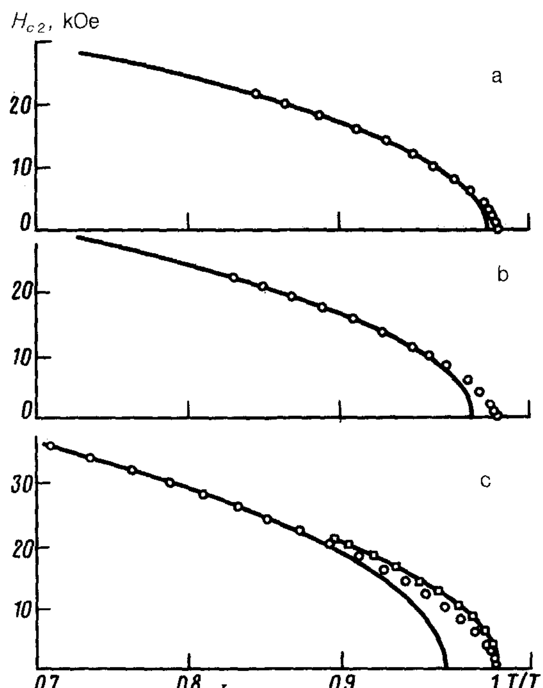

FIG. 2. Plots of $H''_{c2}(T)$ for samples with various binding strengths between the layers. (a) $\rho_i d_i = 10^{-5}\ \Omega\cdot\text{cm}^2$; (b) $\rho_i d_i = 2\times10^{-6}\ \Omega\cdot\text{cm}^2$; (c) circles—$\rho_i d_i = 10^{-6}\ \Omega\cdot\text{cm}^2$, squares—$\rho_i d_i = \infty$ (film).

samples studied here, the dependence of the perpendicular critical field is described by the usual linear dependence $H^{\perp}_{c2} \sim (T_c - T)$.

The stimulation of superconductivity in thin layers due to the coupling between them can be explained on the basis of the following qualitative model. The critical temperature of the film of thickness d, calculated from the Ginzburg-Landau equations is given by[3]

$$T_c = T_{c0}\left(1 - \frac{d_m}{d}\right),$$

where T_{c0} is the critical temperature of the bulk superconductor, and d_m is the effective thickness at which the order parameter near the film boundary is suppressed. For niobium films[3] $d_m \approx 40$ Å. The boundary conditions can change in layered crystals since a nonvanishing current flows through them in the direction perpendicular to the layers. The value of d_m decreases to a greater extent in the inner layers. With an increase in N, the contribution from the two boundary layers decreases, causing T_c to rise. In a parallel magnetic field the pairing correlation in a layered structure decreases along the layer in a power-law manner and across it in an exponential manner.[4] A strong magnetic field suppresses ΔT—the increment in T_c, due to the coupling at $H = 0$. The stronger the binding between the layers (the smaller the $\rho_i d_i$), the stronger must the field be in order to suppress this increment.

In summary, we have shown that a weak Josephson coupling between layers has a strong effect not only on the phase but also on the amplitude of the order parameter.

We wish to thank L. N. Bulaevskiĭ and K. B. Efetov for a useful discussion of this study.

[1]I. Banerjee *et al.*, Phys. Rev. B **28**, 5037 (1983).
[2]V. I. Dedyu and A. I. Lykov, Kratk. Soobshch. Fiz., No. 2, 11 (1987).
[3]J. Simonin, Phys. Rev. B **33**, 7830 (1986).
[4]K. B. Efetov, Zh. Eksp. Teor. Fiz. **76**, 1781 (1979) [Sov. Phys. JETP **49**, 905 (1979)].

Translated by S. J. Amoretty