Anomalous behavior of the superconducting transition temperature of an Nb/SiO$_2$ superlattice

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Oscillations in T_c as a function of the SiO$_2$ thickness have been observed in Nb/SiO$_2$ superlattices. The oscillations show no tendency to decay at thicknesses up to 20 Å.

Superconducting superlattices have recently attracted increased research interest. Oscillations in the superconducting transition temperature T_c of superconducting films with a coating have been observed[1,2] as a function of the thickness of the coating. A similar effect can occur in superconducting superlattices, as was demonstrated in Ref. 1 in a five-layer vanadium-carbon structure. According to Kagan and Dubovskiĭ's theory,[3] the oscillations in T_c in a superconductor-semimetal system stem from oscillations of the state density in the superconductor, which are in turn caused by a periodic change in the boundary condition at the superconductor-semimetal interface. In superconductor-semiconductor systems there may be several oscillations in T_c because of a conversion of the semiconductor to a semimetal due to a band curvature. In the present study we observed oscillations in T_c in a system consisting of a superconductor and a wide-gap insulator (Nb–SiO$_2$), in which these oscillations should not occur, according to Ref. 3.

To fabricate the multilayer structures (Fig. 1), we used an rf sputtering apparatus. The sputtering was carried out in argon at a pressure $p = 1.3\times 10^{-3}$. The argon was admitted to a chamber which had been evacuated beforehand to 5×10^{-8} torr. As substrates we used KÉF-4.5 in the (100) orientation. To remove dirt and oxide from the surface, we annealed the substrates in vacuum for 10–15 min at 900 K, while exposing them to UV light. We then deposited a layer of Ni 500 Å thick, and then a layer of Ti 100 Å thick. According to neutron diffraction, this technique made it possible to reduce the degree of roughness. After the deposition of 100 Å of SiO$_2$, to suppress the proximity effect, we deposited the multilayer Nb/SiO$_2$ structure which was the subject of our study. The Nb layers were 100 Å thick, while the thickness of the SiO$_2$ layers, d_{SiO_2}, was varied. In all cases the number of periods was 15, so the total thickness of the Nb/SiO$_2$ superlattice was about 1500 Å. The thicknesses of the layers were determined from the deposition rate ($\sim$0.5 Å/s) and the deposition time. Previous detailed studies[4] of Si/SiO$_2$ superlattices have demonstrated that this method is reliable.

The resistance of the samples was measured by the ac four-probe method. As a rule, the contacts were deposited on the upper Nb layer, but as a control we fabricated several structures in which all of the Nb layers were short-circuited, and we also passed a current across the structure. The measurement current was 1 μA; the results

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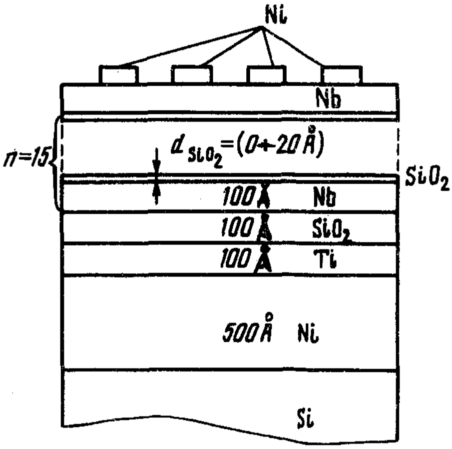

FIG. 1. The Nb/SiO$_2$ structure.

were unaffected as this current was increased by two orders of magnitude. The width of the superconducting transition did not exceed 0.1 K.

The dependence of T_c of the superlattice on d_{SiO_2} (Fig. 2) reveals some clearly expressed oscillations, with an amplitude ~1 K, which show no evidence of decaying up to $d_{\mathrm{SiO}_2} \approx 20$ Å. We carried out three series of measurements (as shown by the symbols of the different types in Fig. 2), with different deposition rates.

It follows from data on work function of Nb and the energy spectrum of SiO$_2$ (Ref. 5) that the Nb Fermi level lies near the center of the wide band gap of SiO$_2$

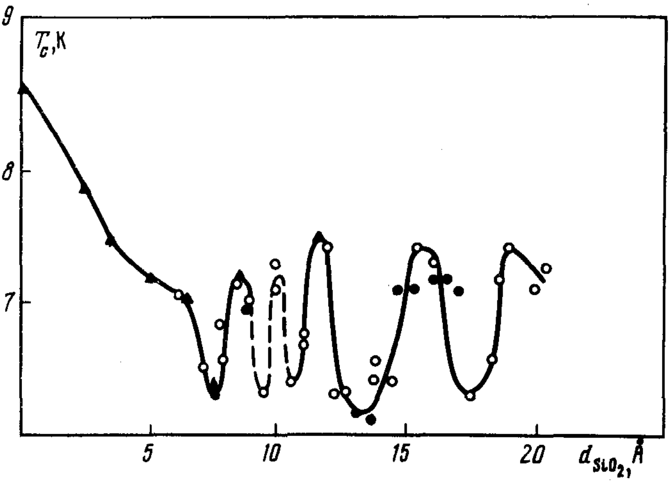

FIG. 2. The superconducting transition temperature of the Nb/SiO$_2$ superlattice versus the SiO$_2$ thickness at a constant Nb thickness, $d_{\mathrm{Nb}} = 100$ Å. The different symbols show the results for three series of samples, differing in deposition rate.

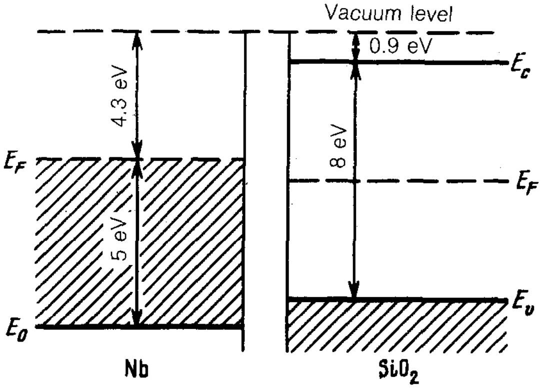

FIG. 3. Relative positions of the Nb and SiO_2 energy bands.

(Fig. 3). The electron wave functions decay with distance into the SiO_2, and there should be no oscillations in T_c according to Ref. 8. Consequently, the experimental results obtained here contradict the present theory.

One possible explanation for the oscillations can be found from a modification of the theory of Ref. 3 to allow for a nonparabolic SiO_2 spectrum. Let us assume for simplicity that the spectrum of the superconductor (Nb) is of the type $k_\parallel^2/2m_\parallel + k_z^2/2m$ and that the Fermi level lies near the edge of the conduction band of the insulator (SiO_2), which has a spectrum $k_\parallel^2/2m_\parallel + \epsilon(k_z)$. Here $k_\parallel^2 = k_x^2 + k_y^2$ and the z axis runs perpendicular to the interface. Let us examine the equation $\epsilon(k_z) = E$ for energies E corresponding to the band gap. Expanding the left side in powers of k_z^2, and retaining only a finite number of terms, we find an equation of integer degree in k_z^2. This equation can have (a) real roots, which correspond to solutions $k_z = \pm i\kappa$ and wave functions $e^{\pm \kappa z}$ and (b) pairs of complex-conjugate roots, which lead to groups of four solutions, $k_z = \pm k_1 \pm ik_2$ and to wave functions of the type $\cos(k_1 z + \alpha)e^{\pm k_2 z}$. In the latter case, by joining the wave functions we easily find that the oscillations of the boundary condition at the Nb–SiO_2 interface and thus the oscillations of T_c occur, but they decay exponentially over a length scale of $1/k$, which would be 1–2 Å for SiO_2. This distance may be increased by impurity states in the SiO_2.

The more likely explanation for the slowly decaying oscillations of T_c would be an interaction of the Nb layers through the SiO_2 valence band. According to Ref. 7, the distance from the Nb Fermi level to the bottom of the band, E_0, is 5 eV, so that after the chemical potentials equalize, E_0 turns out to be well below the top of the SiO_2 valence band, E_v (Fig. 3). As d_{SiO_2} is varied, oscillations occur in the local state density $N(E,z)$ for $E_0 < E < E_v$ and for values of z near the interface. These oscillations lead to oscillations in the charge distribution near the boundary and thus to oscillations in the boundary condition there. These oscillations in turn cause oscillations in the state density of the Fermi level and in the transition temperature T_c.

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Study of the $3d$ band of copper in $Y_1Ba_2Cu_3O_{7-x}$

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The results of an experimental study of the structure of a $3d$ band of copper in a superconducting film at two temperatures (300 K and 80 K) are presented. A smaller overlap of the orbitals of the Cu–O bonds and the effective repulsion potential of holes has been observed at a low temperature.

A characteristic feature of the new high-T_c superconductors is their proximity to the metal-insulator transition. Studies of complex oxides with a perovskite structure have made it possible to construct a generalized phase diagram which suggests that there are critical values of the metal-oxide overlap integral at which there is an abrupt transition from the insulating state to the antiferromagnetic state and then to a metallic state or a superconducting state. These transitions are the result of intensification of the spin-spin coupling, which is described by the constant $j = 4t^2/U$, and also the increase in the degree of delocalization of the d-shell electrons. These tendencies play a decisive role in the theory of resonance valence bonds[2] and spin-spin pairing.[3]

In the transition d-metals a resonance is known to occur in the Auger spectrum because of a strong hole-hole interaction. The state density in this case is taken into account in a complex way in the Auger spectrum and the Auger line profile is described by the expression[4]

$$A(E) = \frac{N(E)}{(1 - UI(E))^2 + (U\pi N(E))^2}, \qquad (1)$$

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