Increase in the superconducting transition temperature of a thin film as a result of the deposition of a normal metal on its surface

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The superconducting transition temperature of a thin bismuth film has been observed to rise as a result of the deposition of silver on the surface of the film. The effect stems from a suppression of the localization of conduction electrons due to a decrease in the surface resistivity of the film.

The superconducting transition temperature of thin films decreases as their thickness is reduced. This behavior has been found in essentially all cases in which the films can be treated as 2D entities. Their description applies primarily to cold-deposited films of various metals and compounds of the MoGe type, which form homogeneous amorphous films at room temperature (Refs. 1–4, for example). It has now been established beyond question that the lowering of the superconducting transition temperature with decreasing film thickness is caused primarily by electron localization effects.

This situation was first taken up theoretically by Maekawa and Fukuyama[5] and by Takagi and Kuroda.[6] They showed that a weak localization of electrons in the BCS theory leads to an effective increase in the Coulomb repulsion and a corresponding decrease in the superconducting transition temperature T_c. For disordered films with a short mean free path the following result has been found:

$$\ln\frac{T_c}{T_{c0}}\simeq -\frac{1}{3}g_1\frac{e^2}{2\pi^2\hbar}R_{\square}\left(\ln\frac{\hbar}{T_c\tau}\right)^3,$$

where T_{c0} is the transition temperature in a bulk sample, the constant g_1 describes the Coulomb interaction, $R_{\square}$ is the surface resistivity of the film, and τ is the mean free time. Later, Finkel'shteĭn[7] showed that expression, which was derived with corrections of first order in $t=(e^2/2\pi^2\hbar)R_{\square}$, is valid only at $t\ll 1$. Nevertheless, the result that the transition temperature is determined primarily by $R_{\square}$ remains in force under any assumptions.

A point worth stressing is that the actual microscopic structure of the films is unimportant in a study of this effect; the only requirement is that the films be homogeneous over a fairly large length scale $L_D=(l_il_e)^{1/2}$, where l_i and l_e are respectively the inelastic and elastic mean free paths of electrons. at low temperatures, l_i is large, and even if l_e were on the order of the interatomic distance, we would have $L_D \simeq 10^3$–10^4 Å.

We have undertaken an experimental study of the situation in which the change in $R_{\square}$ results from the deposition of a normal metal on the thin superconducting film. In the normal state (at $T>T_c$), the deposition of another metal on the surface of the film leads to a decrease in the resistance and a corresponding decrease in the localization effects. At $T<T_c$ the situation is slightly more complicated, because the change in the film composition at the transition temperature must be taken into consideration along with the decrease in localization effects. The addition of atoms of a normal metal to a superconducting film should obviously lead to a decrease in T_c (except in the exotic case in which the two metals form a chemical compound which has a higher transition temperature).

When a film of a normal metal is deposited on a thin superconducting film, one should thus observe two effects: an increase in T_c due to a weakening of the localization and a decrease in T_c due to the atoms of the normal metal. In thin films, in which the superconductivity is substantially suppressed by electron localization, one might expect that the deposition of a normal metal would lead to a net increase in T_c.

Experiments were carried out on cold-deposited bismuth films, which form a stable amorphous structure with a transition temperature $T_{c0}\simeq 6.1$ K (Refs. 1 and 8). Silver was selected as the normal metal. Silver does not form superconducting compounds with amorphous bismuth (the transition temperature of the cold-deposited mixtures of bismuth with silver is lower than T_c of pure bismuth[9]).

The deposition was carried out on a glass substrate to which platinum electrodes had been soldered. The substrate was at liquid-helium temperature. Two different evaporators were used for the deposition. The apparatus was similar in design to that described in Ref. 10. The amount of metal deposited was determined from the frequency shift of a quartz resonator,. The results were converted into thicknesses with the help of the density values of bulk metal samples. The resistance of the films was measured by the four-probe method.

A total of two experiments were carried out with bismuth films of different thick-

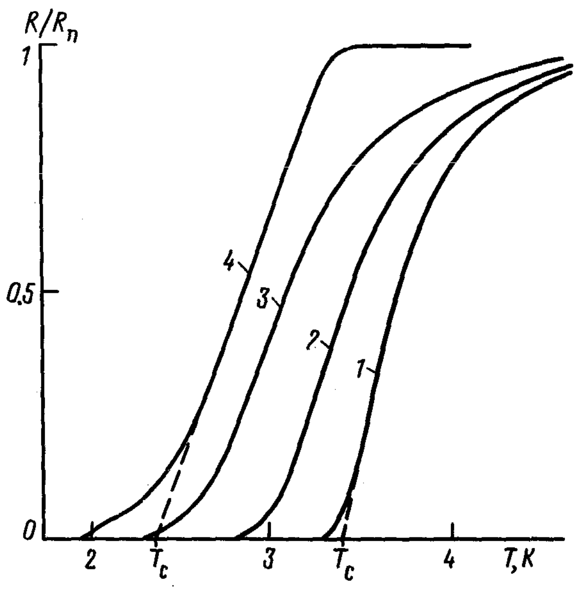

FIG. 1. Superconducting transitions for various thicknesses of the silver film. 1—$d_{\text{Ag}} = 18$ Å; 2—$d_{\text{Ag}} = 8$ Å; 3—$d_{\text{Ag}} = 0$ (the original bismuth film); 4—$d_{\text{Ag}} = 56$ Å. The dashed line illustrates the method to determine T_c.

nesses. First, a bismuth film was deposited on the substrate, and T_c was determined from the temperature dependence of its resistance. A small amount of silver was then deposited on this film, and the new value of T_c was determined. These procedure was repeated several times.

Figure 1 shows several superconducting transitions for various thicknesses of the silver, d_{Ag}: Figure 2 shows T_c as a function of d_{Ag}. At small silver thicknesses, there is a significant increase in the transition temperature; at large thicknesses this increase

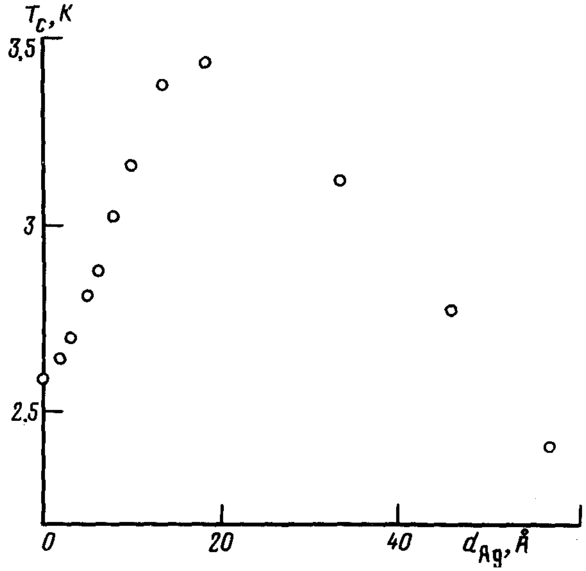

FIG. 2. T_c versus the thickness of the silver film; the thickness of the bismuth film is $d_{\text{Bi}} = 18$ Å.

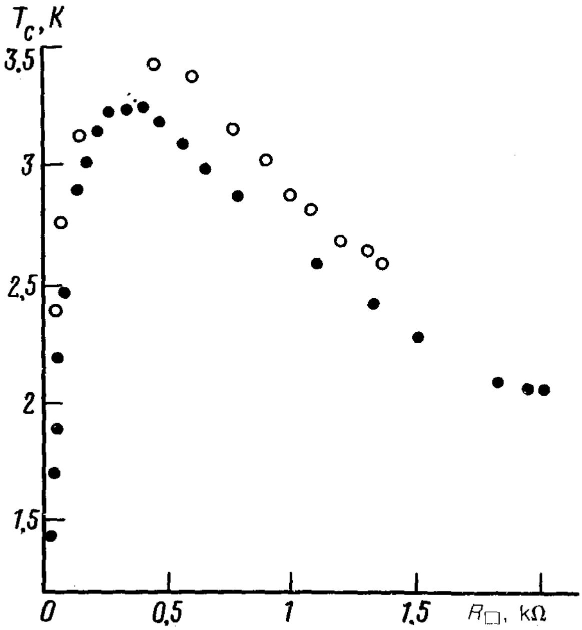

FIG. 3. T_c versus the surface resistivity of the films. ○—d_{Bi} = 16 Å; ●—d_{Bi} = 18 Å.

gives way to a decrease. The experimental results are plotted as values of T_c versus $R_{\square}$ in Fig. 3. Unfortunately, the exact geometric dimensions of the thinner film are not known, and it is not possible to convert its resistance into a value of $R_{\square}$. Consequently, the plot of T_c versus $R_{\square}$ for this film is only qualitative.

We believe that these results show convincingly that (1) the property which primarily determines the value of T_c in a thin superconducting film is the surface resistivity of the film and that (2) a decrease in this resistivity, even if caused by the addition of a normal metal, leads to a significant increase in the transition temperature.

Since the ratio T_c/T_{c0} plays a role in localization theories, the superconductivity in these films must be studied in more detail if we wish to carry out a quantitative analysis of these results. At large thicknesses the situation can be described in terms of a proximity effect, while at small thicknesses, where the total thickness is small in comparison with the size of the superconducting pairs, ξ_0, the specific distribution of the bismuth and silver atoms should not play an important role. If the amount of silver is small, the values of T_{c0} for this layered film should apparently be the same as that of a homogeneous solid solution of the same concentration.

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