Deposition of cadmium films through a layer of liquid helium

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Dielectric films with a thickness of several tens of atomic layers were obtained by depositing cadmium through a layer of liquid helium.

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Cold-deposited metallic films are usually obtained by vacuum evaporation onto a dielectric substrate, whose opposite side is cooled with liquid helium. In so doing, metal atoms having the temperature of the evaporator arrive on the cold substrate. This process plays an important, role in the formation of the structure of films and it may be expected that if slow atoms reach the substrate, then the structure and the properties of such film will be completely different.

In our experiments, we performed the deposition onto a glass substrate situated beneath the surface of liquid helium and the atoms of the metal leaving the evaporator had to overcome a layer of superfluid liquid helium about 1 mm thick on their way to the substrate. Estimates show that such a layer of helium is sufficient for nearly total thermalization of the metallic atoms.

In this formulation of the experiment, the liquid He^4 has to be cooled to a point at which its vapor did not interfere with the motion of the metal atoms from the evaporator to the surface of the liquid. The He^4 bath was cooled to a temperature of about 0.6 K with the help of a cryostat, operating on evacuation of He^3 vapor. To decrease the

vapor pressure of He^4 built up as a result of evaporation of superfluid film, we used film suppressors, whose structure is analogous to suppressors used in dissolution cryostats.[1] As a result, the He^4 pressure in the device amounted to 3×10^{-4} Torr.

Since a single collision between a heavy metal atom and a light helium atom hardly changes the direction of the momentum of the heavy atom, most of the metal reached the liquid surface. Moreover, collisions between cadmium ions could be ignored (the mean-free path relative to this process greatly exceeded the length of the apparatus).

The deposition process was monitored and the thickness of the film was estimated by measuring the shift in the frequency of a quartz resonator, which was placed in the liquid helium at the same level as the substrate. Four platinum contacts were deposited on the glass substrate by cathodic atomization in such a way that the film had a thickness of 1 mm and a width of 2 mm. The resistance of the films was measured either by a two-contact or a four-contact method; in addition, the values of the resistances, measured by different methods for a single film coincided to within 10–20%. The maximum resistance that could be recorded was 10^9 Ω.

Control experiments were performed in the same apparatus, but without injected helium, which corresponds to the usual vacuum deposition onto a cold substrate (the pressure in the apparatus in this case was less than 10^6 Torr). The conductivity at the 10^{-8} Ω^{-1} level appeared at a thickness of ≈2 atomic layers[1)] and increased smoothly with increasing film thickness. Thus, with a thickness of five atomic layers, the resistance was ~100 Ω. The temperature of the superconducting transition for the film with a normal-state resistance $R_n = 60$ Ω was 1.1 K.

Completely different results were obtained with deposition through the liquid (approximately 20 films were deposited). The conductivity of such films appeared abruptly and only with a thickness of several tens of atomic layers (with a typical deposition time of about three hours, the conductivity appeared over a time of the order of seconds). The thickness at which the conductivity appeared was different in different experiments and varied in the range 20–50 atomic layers. After the appearance of the conductivity, the deposition was terminated and the films were annealed.

The films were annealed gradually–after heating to some temperature, the film was again cooled, the superconducting transition was recorded, and then a new annealing followed to a higher temperature. The results obtained in this manner are shown in Fig. 1. The irreversible decrease in the resistance of such films began near 2 K. We note that the jump in the resistance of one of the films at $T = 5$ K is not related to heating of the film and occurred during one of the cooling cycles; such jumps in the resistance were sometimes observed on the high resistance films.

When the films were heated to temperatures exceeding 100 K, their resistance began to increase irreversibly, in addition, the temperature of the onset of growth of the resistance was lower the thinner the films. For the thinnest films, shown in Fig. 1, this temperature was about 50 K.

Figure 2 shows curves of the superconducting transition for two films after different stages of annealing. We also note the strong dependence of the resistance of the films on the current at a temperature below the critical temperature (Fig. 3). In the

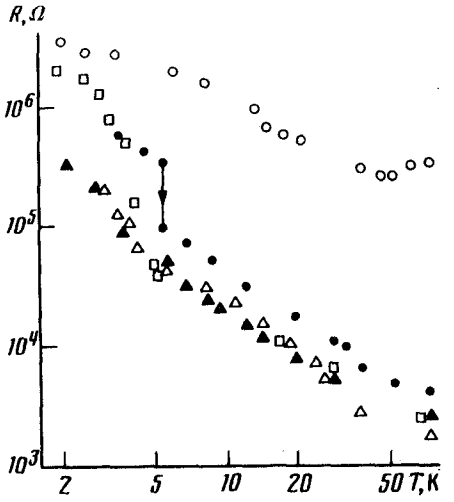

FIG. 1. Dependence of the resistance of films on the annealing temperature. —Thickness of 20–25 atomic layers; ●, □, △, ▲ — thickness of 40–50 atomic layers.

normal state, the resistance of the high-resistance films also increased irreversibly with increasing current, but much more weakly: R_n of the film shown in Fig. 3 increased from 2 MΩ (with a current of 5×10^{-8} A) to 3 MΩ (with a current of 2×10^{-6} A).

The results presented in this paper indicate that deposition through a liquid helium layer is accompanied by the appearance of a new modification of cadmium, which is not conducting. This modification probably corresponds to larger interatomic distances than in usual conducting cadmium.

The abrupt appearance of conductivity is related to changes in the structure of the film. As a result, conduction channels appear between the electrodes. It is possible that electromagnetic adjustments through the measuring circuits can stimulate the transi-

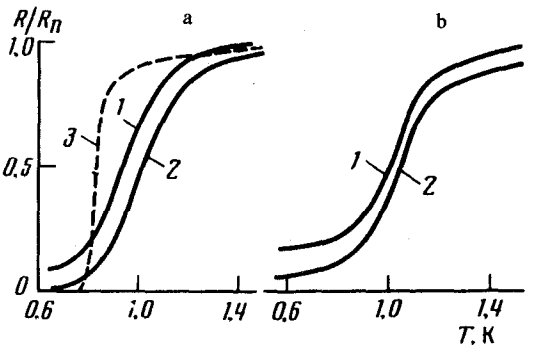

FIG. 2. Dependence of the resistance on the superconducting transition temperature. a) After annealing to 4.2 K, $R_n = 440$ kΩ (1); after annealing to 10 K, $R_n = 43$ kΩ (2); after annealing to 70 K, $R_n = 1.5$ kΩ (3); (b) before annealing, $R_n = 4$ MΩ (1), after annealing to 3.5 K, $R_n = 2.7$ MΩ (2).

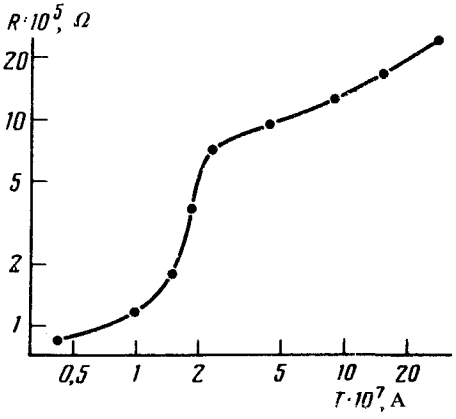

FIG. 3. Dependence of the resistance on the current $T = 0.58$ K.

tion to the conducting state, this could explain the appearance of conductivity with different film thicknesses and the fact that the resistance of the films after the transition can differ greatly even for films with the same thickness.

We emphasize that the starting film, deposited through the layer of liquid helium, can contain only inhomogeneities related to the statistical spread in the thickness. However, depending on the annealing, the structure of the films can change in such a manner that the inhomogeneity of the films increases; this explains the fact that the resistance of the films remains very high after annealing.

In conclusion, we would like to thank A. I. Shal'nikov for many useful remarks and E. G. Astrakharchik for discussing the problems touched upon in this paper.

[1)]The density of bulk cadmium was used in rescaling.

[1]W. P. Kirk and E. D. Adams, Cryogenics **14**, 147 (1974).

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