SUPERCONDUCTING PROPERTIES OF FRESHLY DEPOSITED MERCURY FILMS

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Mercury films obtained by the method of condensation in high vacuum on a backing at a temperature close to that of liquid helium have been studied. The experimental results are compared with the Abrikosov-Gor'kov theory of superconducting alloys.

THE study of freshly deposited metal films, condensed at liquid-helium temperature,[1-5] is of considerable interest in that it appears that a material is obtained which does not possess very sharply pronounced peculiarities, although it is very different from the initial material. From the very high resistivity and the absence of a dependence of conductivity on thickness [3,5] in freshly deposited films in the normal state, it can be assumed that in the condensation process a deposit is formed with isotropic structure, in which the electron mean free path is considerably less than the thickness of even the thinnest films.

Mercury is most convenient as a substance to study for establishing the process of low temperature condensation, since, with a relatively high vapour pressure, sufficiently thick specimens can be obtained easily while using a very small power in the evaporation. Appleyard et al [6] have previously studied the specific resistance and the superconducting properties of mercury films, condensed on a backing at a temperature from 4.2 to 90° K. However, films condensed at 4.2° K have not been studied systematically.

PREPARATION OF THE SPECIMENS AND THE MEASUREMENTS

The mercury films were prepared in the apparatus shown in Fig. 1. The backing for the condensation was the outer plane polished base of a glass beaker, through which platinum leads are inserted. Before being sealed into the apparatus, the beaker was thoroughly treated with a mixture of nitric and chromic acids and boiled in distilled water. A monel shield was fitted to the beaker, leaving open only the middle part of the base of the beaker for condensation. A thin walled glass capsule ~ 10 mm in length with an exit opening 1.0 – 1.5 mm in diameter served as the evaporator, and the platinum wire was wound on the outside and half sealed into the glass for better thermal contact. The power generated in the evaporator did not exceed 0.2 watt. A thin glass capillary was fixed into the capsule to avoid bubbles, which could form during the working of the evaporator. The distance between the orifice of the evaporator and the bottom of the beaker was varied from 30 to 50 mm in different apparatus. The assembled apparatus was pumped by a diffusion pump to 10^{-6} mm Hg, and its upper half was baked in an oven for 3—4 hours at a temperature of 300° C.

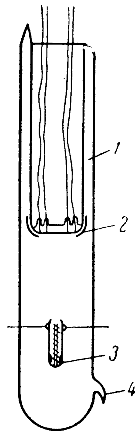

FIG. 1. Apparatus for obtaining the films: 1 – beaker with plane polished base, 2 – monel shield, 3 – capsule with mercury, 4 – side tube for filling the apparatus with liquid helium.

Condensation of the films took place at 4.2° K (the boiling point of helium) at a rate of $(1.1 - 1.3) \times 10^{-3}$ g/min. The thickness of the films obtained was calculated from the mass of mercury evaporated, on the assumption that the distribution of current density of the particles evaporating follows the cosine law. As a check on the calculated thickness, an experiment was made in which one of the thickest films was collected from the bottom of the beaker, after the heating, and weighed. The thickness, determined in this experiment, was 20% larger than calculated. This discrepancy can evidently be explained by the existence of a directed particle current, not taken into account by the cosine law.

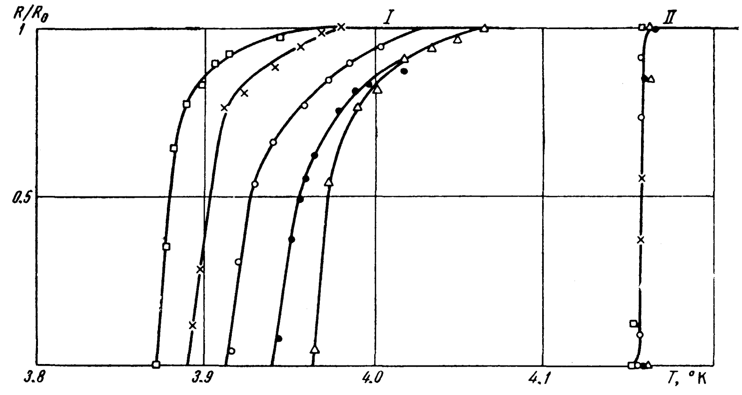

FIG. 2. The temperature dependence of the resistance of the films: I – freshly deposited films, II – annealed films. Film thicknesses in 10^{-5} cm: Δ – 0.46, • – 0.58, o – 0.89 × – 2.8, □ – 4.0.

Films with thicknesses from 0.46×10^{-5} to 12.2×10^{-5} cm (these thicknesses are calculated on the assumption that the cosine law applies) were produced and studied. Measurements were carried out both immediately after condensation of the films and after they had been heated to liquid-nitrogen temperature. The resistance of the films was measured with a standard potentiometer circuit, using a measuring current not exceeding 100 μa. Temperature was determined from the helium saturated-vapor pressure. The temperature dependence of resistivity in zero magnetic field was measured both immediately after condensation and on cooling the films down a second time. These curves for films of different thicknesses are shown in Fig. 2.

The transition temperatures of the freshly deposited films lie somewhat lower than that for bulk mercury (we took the temperature in the middle of the transition as the transition temperature of a film; $R = 0.5\ R_0$, where R_0 is the resistance in the normal state). The observed dependence of transition temperature on thickness agrees well with Prozorova's results.[5] The transition temperature for the annealed films practically coincides with the value of the transition temperature for bulk mercury (4.15° K) and is independent of film thickness (see Fig. 3); the superconducting transitions are sharper than for freshly deposited films.

Other physical properties of the films naturally change after annealing also. For example, the resistivity in the normal state decreases more than 10 times. The form of the variation of resistivity with film thickness also changes. It remains constant in freshly deposited films up to the smallest of the thicknesses studied. The conductivity of the annealed films, however, increases proportionally with their thickness. The absolute

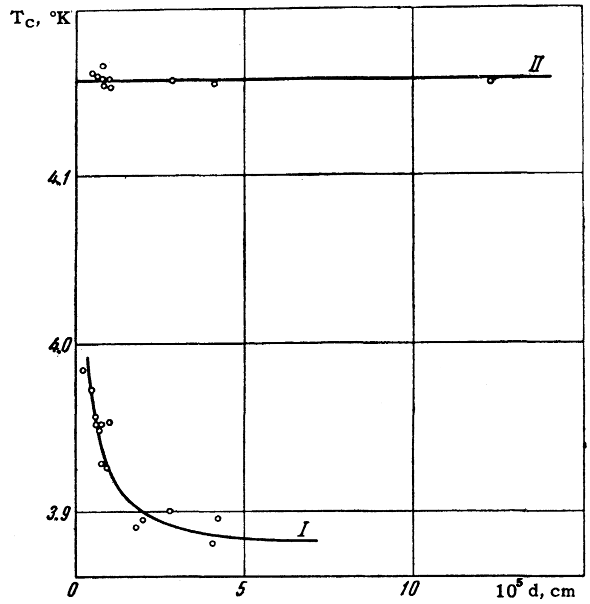

FIG. 3. The dependence of the transition temperature of a film on its thickness: I – freshly deposited films, II – annealed films.

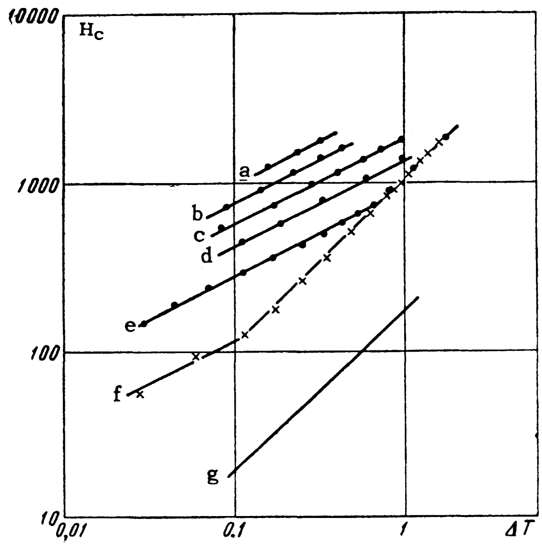

FIG. 4. The dependence of H_c on ΔT ($\Delta T = T_c - T$) for films of different thickness (in 10^{-5} cm): a – 0.47, b – 0.58, c – 0.76, d – 0.90, e – 2.8, f – 4.2, g – bulk specimen.

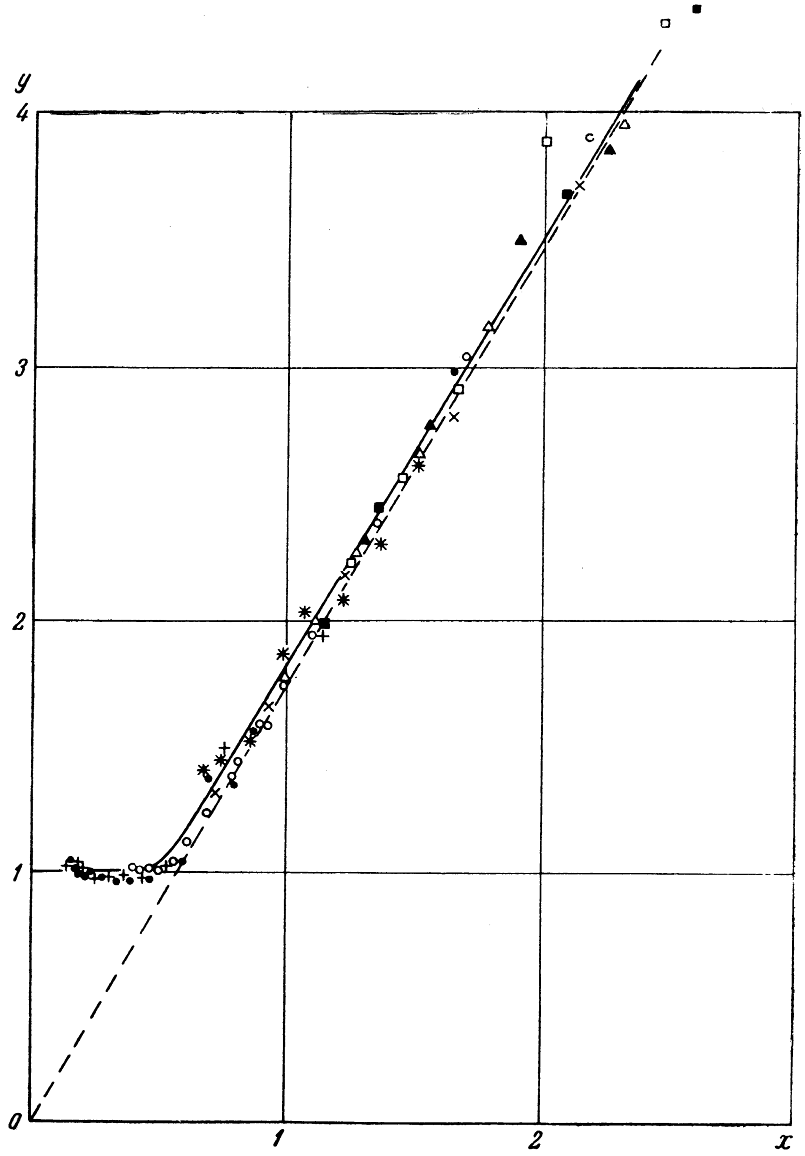

FIG. 5. The dependence of $y = H_c/2\theta^2$ on $x = 2.57 \times 10^{-4}/\theta d$ for films of thickness (in 10^{-5} cm): + – 4.2, ● – 4.0, ○ – 2.8, * – 1.0, × – 0.9, ■ – 0.83, □ – 0.81, △ – 0.76, ▲ – 0.72. Full line is the theoretical curve.

value of the conductivity of a freshly deposited film, measured in a separate experiment, was $\sigma = 0.15 \times 10^{18}$ cgs esu.

Curves of the destruction of superconductivity by a magnetic field, parallel to the plane of the films, were also measured for all the films obtained. Accuracy in setting the film parallel to the field was achieved by rotating the field, and did not exceed 0.1°. Figure 4 shows curves of $H_c(\Delta T)$ ($\Delta T = T_c - T$) for freshly deposited films of different thickness. The field at which the film resistance reached $0.5R_0$ was taken as H_c. As is seen from Fig. 4, $H_c \sim T^{1/2}$ for thin specimens, while a break is observed in the curves of the dependence of H_c on ΔT for thick films.

DISCUSSION OF THE RESULTS

The macroscopic theory of Ginzburg and Landau [7] was developed by Abrikosov [8] in a way applicable to the case of films obtained by low temperature condensation, on the assumption that the condition $\kappa \geq 1/\sqrt{2}$ (κ is the parameter of the Ginzburg-Landau theory) is valid for them. Such an assumption seems quite justifiable, since films condensed on a cooled backing show properties characteristic of alloys. Abrikosov obtained a universal relation, for all superconductors, between the critical magnetic field H_c for a film and its thickness d. Taking into account that $\kappa = (\sqrt{2}e_{eff}/\hbar c)H_{cb}\delta_0^2$ where $e_{eff} = 2e$, this relation can be written

$$H_c / 2\theta^2 = f(2.57 \cdot 10^{-4} / \theta d),$$

where $\theta = \sqrt{2e/\hbar c H_{cb}}\delta_0$ and H_{cb} is the critical field of bulk metal.

We assume that near T_c

$$H_{cb} = (dH_{cb}/dT)_{T_c}\Delta T; \qquad \delta_0 = \delta_{00}\sqrt{T_c}(\Delta T)^{-1/2}/2.$$

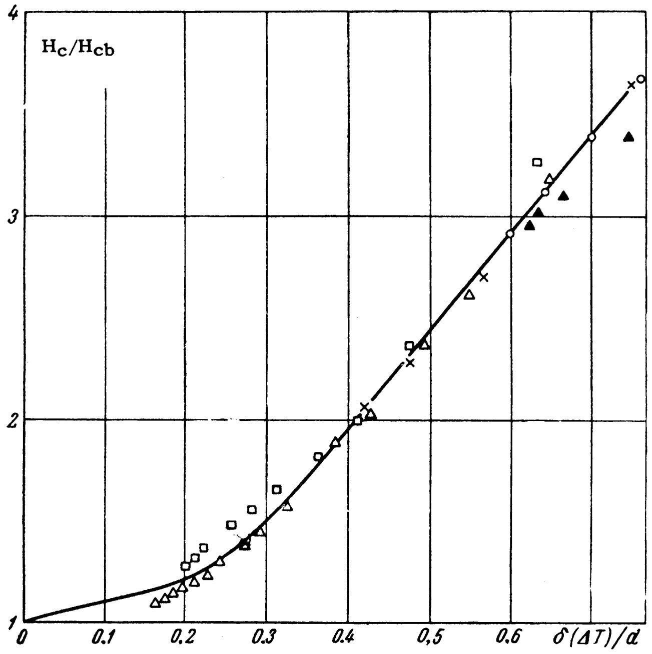

FIG. 6. The ratio H_c/H_{cb} as a function of δ (ΔT)/d. Film thickness in 10^{-5} cm: Δ – 4.9, □ – 4.1, × – 2.8, ○ – 1.0, ▲ – 0.9. The continuous curve shows the theoretical relation.

Then

$$\theta = A\Delta T^{1/2}, \qquad A = \sqrt{e/2\hbar c}\,(dH_{cb}/dT)_{T_c}\sqrt{T_c}\,\delta_{00}.$$

It can be seen from Fig. 5 that the experimental results are in good agreement with the above theory.

The constant, A, can be determined from the part of the curve corresponding to the limiting case $d/\delta_0 \gg 1$, and the constant coefficient δ_{00} in the temperature dependence of the penetration depth near T_c can be calculated. From our data $\delta_{00} = (22.6 \pm 2.3) \times 10^{-6}$ cm.

In the other limiting case, when $d/\delta_0 \ll 1$, we have

$$H_c/2\theta^2 = \sqrt{3}\cdot 2.57\cdot 10^{-4}/\theta d.$$

From this, the film thickness d can be determined. The calculation made for the thickest film of all agrees, within the limits of accuracy, with the value of the thickness obtained as a result of weighing the film itself directly.

From the new Abrikosov-Gor'kov theory of superconducting alloys [9] the parameter δ_{00} can be calculated from the value of the normal conductivity. It follows from this theory that for $1 \ll \delta_0$ (where l is the mean free path and δ_0 the penetration depth)

$$\delta_0(\Delta T) = \frac{c}{3.06\pi}\sqrt{\frac{\hbar}{2k\sigma}}\,\Delta T^{-1/2}, \qquad \delta_{00} = \frac{c}{3.06\pi}\sqrt{\frac{2\hbar}{kT_c\sigma}},$$

where σ is the conductivity in the normal state. We obtained for freshly deposited films the values

$$\sigma = 0.15\cdot 10^{18} \text{ cgs esu}, \quad \delta_{00} = 16\cdot 10^{-6} \text{ cm}.$$

This value of δ_{00} is somewhat lower than that obtained from data on critical fields. However, this discrepancy can be explained if we take into account that the calculation of σ was made for a film which was close to the evaporator when being produced, and in which, therefore, there might have been partial recrystallization and, consequently, an increase in the value of σ.

The experimental data on the critical fields of the annealed films agree well with deductions from the Ginzburg-Landau macroscopic theory.[7] The dependence of the critical fields of the films on thickness follows the following two equations in the limiting cases $d/\delta_0 \gg 1$ and $d/\delta_0 \ll 1$ respectively

$$H_c/H_{cb} = 1 + \delta_0/d, \qquad H_c/H_{cb} = 2\sqrt{6}\,\delta_0/d.$$

The results of the confirmation of these relations are shown in Fig. 6.

Considering the region $T \to T_c$, where we can write

$$H_{cb} = (dH_{cb}/dT)_{T_c}\Delta T, \qquad \delta_0 = \sqrt{T_c}\,\delta_{00}\Delta T^{-1/2}/2,$$

we calculated the value of the parameter from the experimental values of H_c for thin films ($d \ll \sqrt{5}\,\delta_0$),

$$\delta_{00} = (6.2 \pm 0.6)\cdot 10^{-6} \text{ cm}.$$

In conclusion I thank A. I. Shal'nikov, under whose direction this work was carried out, very sincerely, and A. A. Abrikosov for discussion of the results obtained.

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