Electron localization and superconductivity in cold-deposited mercury films

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The appearance of superconductivity as a result of increasing the thickness of mercury films with resistance $R \sim 1$ mΩ is investigated. It is shown that superconductivity is observed in films, whose activation energy ϵ is less than the superconducting gap $\Delta(T)$ and, in addition, $\Delta(0)$ is constant over a wide range of thicknesses.

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The anomalous properties of thin, cold-deposited, mercury films were first discovered and investigated in Ref. 1. The most interesting characteristic is the unusually large thickness, 60 A, at which conductivity appears. This indicates that a continuous mercury film, statistically uniform over its thickness, is an insulator for thicknesses less than

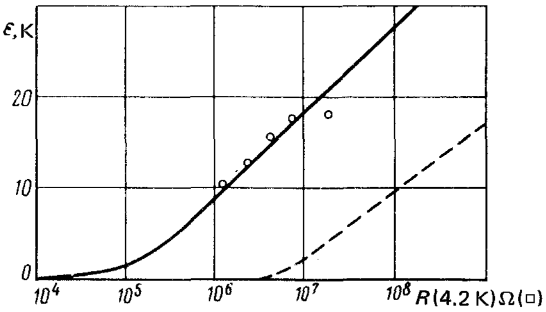

FIG. 1. The dependence of the activation energy on the resistance of a film at 4.2 K. The continuous line is for Cs and Rb, according to data in Ref. 2 and the dashed line is for mercury, according to data in Ref. 1. The points are for mercury with small measuring voltages.

twenty atomic layers. (The uniformity of the film is indicated, for example, by its behavior with annealing. See the discussion of this problem in Ref. 1.) For comparison, we point out that in Cs and Rb films, prepared by using a similar procedure,[2] conductivity already appears at an average film thickness ~0.7 atomic layers.

The other anomaly of mercury films consists of the fact that according to the data in Ref. 1 (the dashed line in Fig. 1), the transition to metallic conductivity occurs at a resistance ~1 MΩ/□, which agrees poorly with the predictions of localized theories.

Unfortunately, the measurements of the temperature dependences of the resistance in Ref. 1 were carried out with a voltage of 1.5 V on the film, i.e., on the strongly nonlinear part of the current-voltage characteristics. If in Cs and Rb films the temperature dependences of the resistance for all films with $R > 10^5$ Ω/□ follow with a good accuracy the law

$$R(T) = R_0 \exp(\epsilon / kT), \tag{1}$$

where ϵ is the activation energy, characterizing the given film, while $R_0 = 10^5$ Ω/□ and does not depend on thickness, then in Ref. 1 it was necessary to choose a separate value of $R_0(\epsilon)$ for each film.

In this work, we measured $R(T)$ for limiting small measuring voltages (1-10 mV). We also carried out a more detailed investigation of the current-voltage characteristics of films at different temperatures and voltages up to 1.5 V. The procedure for preparing the films is largely analogous to that developed in Ref. 1. The films were rectangular with length 1.9 mm and width 0.55 mm. All values of resistances, presented in what follows, are scaled to a square geometry.

The measurements in the range of resistances $R(4.2\text{ K}) = 1 - 10$ MΩ are presented in Fig. 1. In this region, the functions $R(T)$ for small voltages follow Eq. (1) with $R_0 = 10^5$ Ω, as in the case of Cs and Rb. Thus, the dependence $R(\epsilon)$ is explained well by the theory and is close to the results obtained for other metals. The dependence of the resistance on the intensity of the applied electric field E at temperatures $T \geqslant 4.2$ K is described well by the Frenkel-Pool law

$$R(E) = R_0 \exp[(\epsilon - eEL)/kT], \tag{2}$$

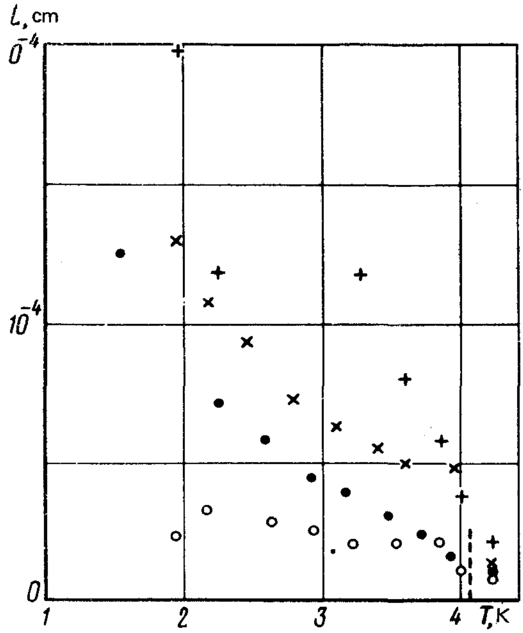

FIG. 2. The temperature dependence of the characteristic length L for films with different activation energies: $+ - \epsilon = 12.8$ K; $\times - \epsilon = 15.7$ K; $\bullet - \epsilon = 17.8$ K; $\circ - \epsilon = 18.2$ K. The resistances of these films are presented in Fig. 1.

where the characteristic length L is about 10^{-5} cm. When the temperature is decreased below 4.05 K, the dependence (2) is satisfied only for small values of E, and, in addition, the characteristic length L depends on temperature (Fig. 2).

In thicker films, with resistances $R(4.2\text{ K}) = 0.5\text{-}1$ MΩ, the temperature dependence of the resistance deviated appreciably from the activation form of Eq. (1) at temperatures below 4.05 K. The degree of deviation, which is apparently related to the appearance of superconductivity in some part of the film, differs considerably with different voltages on the film. Figure 3 shows the characteristics $R(T)$ for films with $R(4.2\text{ K}) = 0.53$ MΩ for measuring voltages varying from 10 mV to 2.5 V. It is evident that these characteristics have an activation nature only for low voltages and look more like a superconducting transition with residual resistance for high voltages. The magnitude of this residual resistance, which depends both on the applied voltage and on the film thickness, constitutes only several percent.

With a further increase in thickness, the nature of the behavior of the films for small measuring voltages and temperature $T \leqslant 4.05$ K changes sharply. Films with $R(4.2\text{ K}) \leqslant 0.5$ MΩ are good superconductors with a sharp transition and without any residual resistance over the entire range of measuring voltages investigated. Thus, the resistance of a film with $R(4.2\text{ K}) = 0.49$ MΩ and a voltage of 1 mV applied to it decreased by a factor of 10^6 when the film was cooled to 2.2 K. The critical superconducting temperature depends weakly on thickness and when the resistance of the film $R(4.2\text{ K})$ decreases from 0.4 MΩ to 10Ω, it changes from 4.05 K to 4.07 K.

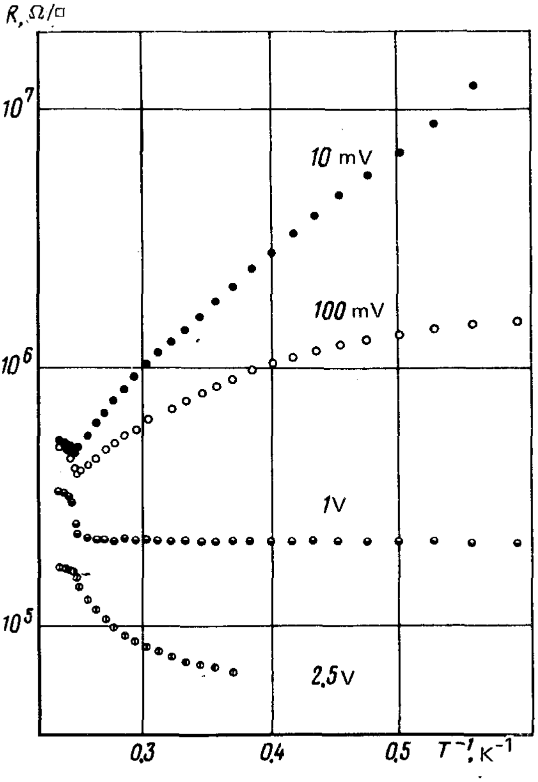

FIG. 3. The temperature dependences of resistances of films with $R(4.2\ \mathrm{K}) = 0.53\ \mathrm{M\Omega}$ for different measuring voltages.

In this range of thicknesses, the most interesting behavior occurs for films with $R(4.2\ \mathrm{K}) = 0.1\text{-}0.5\ \mathrm{M\Omega}$. These films have nonlinear current-voltage characteristics, obeying the Frenkel-Pool law (2) and an activation characteristic $R(T)$ for $T \geqslant 4.2$ K; in addition, they have zero resistance for small temperatures. Thus, superconductivity can exist in a system in which electrons with $T > T_c$ are localized to such an extent that the temperature dependence of the resistance obeys an activation law.

At present, both the reasons for the anomalously high thickness for the onset of conductivity in mercury films and the specific mechanisms for conductivity in the localized region of resistances are not understood. The origin of the large magnitude of $L \sim 1000$ Å in the Frenkel-Pool law is also unclear. On the other hand, the characteristics of films in the "semiconducting" range of thicknesses 0.5-10 MΩ, illustrated in Figs. 2 and 3, can be explained, if it is assumed that superconductivity can exist in a localized film with an activation energy ϵ less than some critical value, whose order of magnitude is comparable to the superconducting gap Δ.

From the behavior of $R(T)$ for small voltages (10 mV in Fig. 3), it is evident that the composition of the film is somewhat nonuniform. Part of the film undergoes a superconducting transition with a decrease in temperature below the critical value, while at the same time, the rest of the film remains in the resistive state. If a voltage is applied to such a film, then the resistance of the film will decrease due to the nonlinearity of the current-voltage characteristics and, in addition, the decrease for $T > T_c$ will differ considerably from the decrease for $T < T_c$. Indeed, if for $T > T_c$, the applied voltage is uniformly distributed over the film, then in a film, a large part of which has transformed into the superconducting state, all of the voltage will occur on the normal part. Since according to Eq. (2) the resistance depends exponentially on the applied voltage, the drop in the resistance in the latter case will be much greater.

The temperature dependence of the effective length L can be qualitatively explained in the same way. The increase in L with a decrease in temperature (Fig. 2), apparently, stems from the fact that as the temperature decreases and the superconducting gap $\Delta(T)$ increase, increasingly larger regions of the film are "short-circuited" by superconductivity.

The inhomogeneities observed in the film are related to the anomalously sharp dependence of the resistance and other parameters of mercury on thickness. Although the films investigated in this work were uniform over the entire specimen to within 0.01%, fine random inhomogeneities of the film over the thickness cannot be eliminated. It is also possible that inhomogeneities are a property of the model proposed for the description, rather than of the film itself.

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