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MAGNETIC-FIELD-TUNED SUPERCONDUCTOR–INSULATOR TRANSITION IN AMORPHOUS InO$_x$ FILMS.

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The field-induced superconductivity-destroying quantum transition in amorphous indium oxide films was investigated at low temperatures down to 30 mK. The critical resistance at the transition R_c and the critical field B_c were identified from the crossing of isotherms $R(B)$. On the high-field side of the transition, the film resistance reaches a maximum, then drops and approaches in the high-field limit the resistance value at transition point. The pattern of the field dependence and the typical field values are the same with magnetic field along and normal to the film. We give a qualitative account of this behavior in terms of field-induced electrons localization with preserved pair correlations and destruction of localized electron pairs in higher field.

1 Introduction

The theoretical description of the zero-field and field-induced quantum superconductor-insulator transitions (SIT) in a 2D superconductor is based on a concept of electron pairs which are delocalized on the superconducting side and localized on the insulating side of transition.[1,2,3] According to the theory[1,2,3], the temperature dependence of the film resistance near the field-induced SIT is controlled by deviation $\delta_B = B - B_c$ from the critical field B_c and the most specific among perceptible features of SIT is fan-like set of resistance-vs-temperature curves $R(\delta_B, T)$. Such a set is expected to collapse onto a single curve as a function of scaling variable $\delta_B/T^{1/y}$, where y is the critical index, see review.[4] Many of the SIT studies were performed on amorphous In$_2$O$_x$ ($x < 3$) films whose conductivity was caused by oxygen deficiency compared to fully stoichiometric insulating compound In$_2$O$_3$: by changing the oxygen content one can cover the range from a superconductor to an insulator and thus realize the zero-field SIT at some critical electron concentration n_c. On the insulating side of this SIT, $n < n_c$, $\delta_n \equiv n - n_c < 0$ observation was reported of the activation behavior of the resistance $R \propto \exp(T_0/T)^p$ with $p = 1$ (Arrhenius law) and activation energy T_0 tending to zero as the phase boundary is approached.[5] It was found later that switching a magnetic field results in decreasing the resistance and weakening its temperature dependence from the Arrhenius law to the Mott law with exponent $p = 1/4$.[6] This was explained by magnetic-field-caused suppression of the binding energy Δ of localized electron pairs manifested as a gap at the Fermi level.[6]

Field-induced SIT is realized on the superconducting side of zero-field SIT, at $n > n_c$, $\delta_n > 0$. It was indicated by fan-like structure of experimental curves $R(\delta_B, T)$ such that, in accordance with the scaling analysis, the expected collapse was indeed the case.[7] The conclusion that the transition[2] indeed took place was based[7,8] on existence of the common crossing point of isotherms and on the scaling relations in the vicinity of the crossing point. Above the field-induced SIT, the existence of two insulating phases was postulated based on results of Hall measurements.[8] It was shown[9,10] that in the high-field limit the system with $n > n_c$ entered not the insulating, fermi-glass, but the metallic phase. This was interpreted as field-caused breaking of localized electron pairs.

Apart of the scaling relations, the theory[2] has two more aspects. Being based on the boson-vortex duality it can be applied only for the specific case of 2D superconductor in normal magnetic field. And it assumes that the magnetic field induces pair localization. Below we'll concentrate on these aspects.

One can rarely be sure that the film in such experiment can indeed be assumed as 2D. For

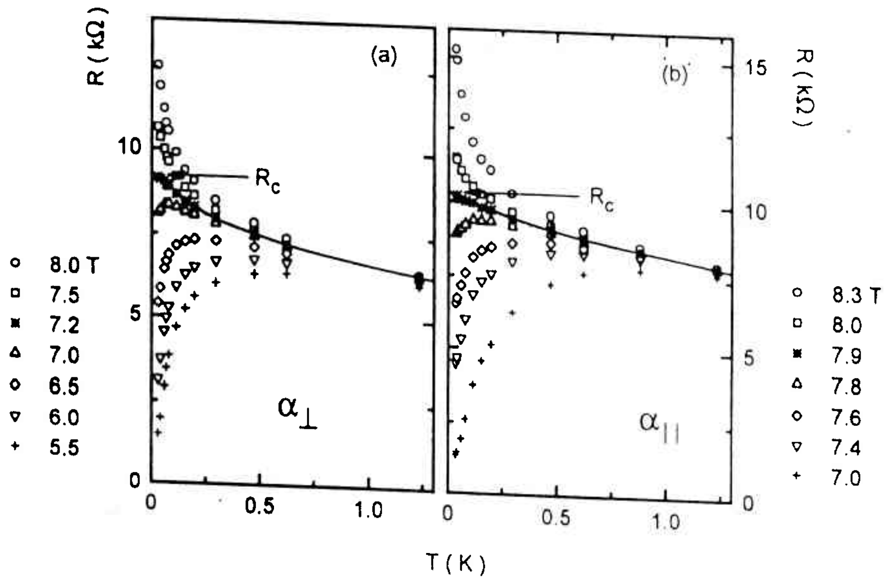

Figure 1: Amorphous In-O film demonstrates similar behavior at the field normal to the film (a) and parallel to it (b). The carrier densities in the two states of the film ($\alpha_\perp$ and $\alpha_\parallel$), as determined from the room temperature resistance, are very close. Both separatrices $R(T, B_c)$ (solid lines) have nonzero slopes near $T = 0$.

instance, the mean free path l in the normal state of the amorphous In-O films is of the order of 10 Å,[9,10] i.e. lower than the film thickness in [7,10]. We'll focus below on the magnetic field orientation and show that it does not affect the behavior of the resistance. Then we turn to the other aspect of the transition scenario [2,4]: to localized pairs. There is still no strict evidence for existence of such localization. The examination of experimental arguments in favor of such localization will be the second topic of this talk.

2 Results

The experiments were performed on 200 Å thick amorphous In_2O_x ($x < 3$) films without pronounced granularity as was checked by the absence of quasireentrant transition, i.e., the absence of minimum on dependences $R_\delta(T)$ at low temperatures.[11] The oxygen content x could be reversibly altered by heat treatment; all experimental procedures are described in detail elsewhere[5]. The magnetoresistance was measured in Oxford TLM-400 dilution refrigerator in the temperature range 1.2 K to 30 mK using a four-terminal lock-in technique at a frequency of 10 Hz. The current across the sample was equal to 5 nA and corresponded to the linear response regime. The measurement runs were made by sweeping magnetic field at fixed temperature.

2.1 Role of the Field Direction

Fig. 1 demonstrates that the change of the magnetic field direction practically does not affect the character of the family of $R(T, B)$ curves. The two states from Fig. 1 are denoted as $\alpha_\perp$ and $\alpha_\parallel$. Both families have an unstable fixed point $(T, R) = (0, R_c)$ that belongs to the separatrix $R(T, B_c)$. The only difference from the scheme proposed by Fisher is its nonzero slope near $T = 0$. Explanation of the temperature dependence of the critical resistance $R_c(T) \equiv R(T, B_c)$ is to be postponed until the conductivity mechanism of this boundary state is clarified. Here we emphasize that it is not affected by the magnetic field direction, i.e. is not determined by the movement of vortices.

The curves in Fig. 1 correspond to restricted range of the magnetic field values. The full available field range is used for the next couple sets of curves, for sets of low-temperature

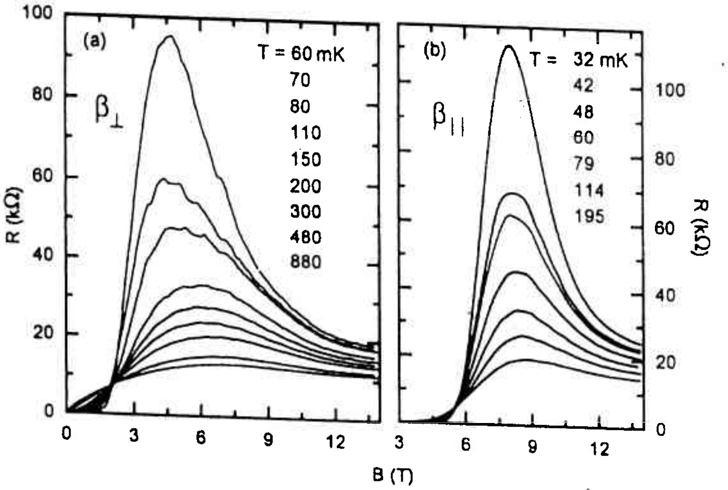

Figure 2: Low-temperature isotherms for an amorphous In-O film at the field normal to the film (a) and parallel to it (b). The carrier density in these two states of the film ($\beta_\perp$ and $\beta_\parallel$) correspond to smaller δ_n values as compared to states $\alpha_\perp$ and $\alpha_\parallel$ in Fig. 1.

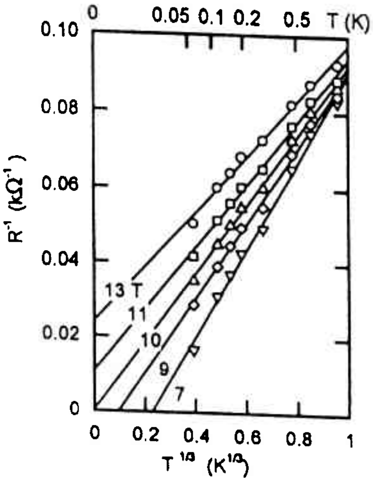

Figure 3: Extrapolation of the conductance of the state $\beta_\perp$ at various magnetic fields to zero temperature.

isotherms in Fig. 2, once more, the first (a) with B normal to the film, the second (b) with B along the film. The corresponding states of the film, $\beta_\perp$ and $\beta_\parallel$, are much closer to the zero field transition then states $\alpha_\perp$ and $\alpha_\parallel$ in Fig. 1, i.e. with smaller value of δ_n. All the isotherms of each set cross in the same point; this means that the separatrices $R(T, B_c)$ are horizontal, without linear in T term, exactly as in the model.[2] The qualitative difference between the sets is clearly seen only in the region below B_c where it is due to the movement of vortices. Above B_c the sets are qualitatively identical: the curves reach a maximum $R_{\max}$ at $B_{\max} > B_c$ and then drop so that in the high-field limit they return to the level of R_c.

The ratio $R_{\max}/R_c$ in Fig. 2 exceeds ten. It is far less in the states with larger δ_n.[9,10] On the contrary, the reduced high-field limiting values R_∞/R_c are comparable.[10] In the next section, we focus our attention on the range $B > B_{\max}$ where the negative magnetoresistance takes place.

2.2 Negative Magnetoresistance

There is a general rule: to decide whether the state should be count as insulating or metallic one has to extrapolate the values of its conductance function $\sigma(T)$ to $T = 0$. This procedure is applied to the conductance function of the state $\beta_\perp$ at various fields. In Fig. 3 we succeeded in fitting the film resistance over the field range of 7 to 13 T by

$$\sigma(T) = a + bT^{1/3}, \qquad b > 0, \tag{1}$$

where the sign of the parameter a discriminates between a metal and an insulator at $T \to 0$.[6] If $a > 0$, it yields zero temperature conductivity $\sigma(0) = a$, whereas the negative a points to activated conductance at lower temperatures.

We are assessing the transport properties at $T = 0$ as obtained by extrapolation from above 30 mK. Bearing this in mind, we determine from Fig. 3 the field $B_{I-M} \approx 10$ T of insulator-metal transition for state $\beta_\perp$. Thus a conclusion of the previous work[8] that two phases exist above the SIT is confirmed. Yet, in contrast to it[8], we find that their phase boundary is not near $B_{\max}$ but at appreciably higher field and also that the high-field phase is metallic.

It is natural to attribute the transition into the metallic state to increase of delocalized electrons density $n_d(B)$. In this case, all the changes in the resistance R with the field turn to be in agreement with theoretical ideas about localized electron pairs. The rise of the resistance

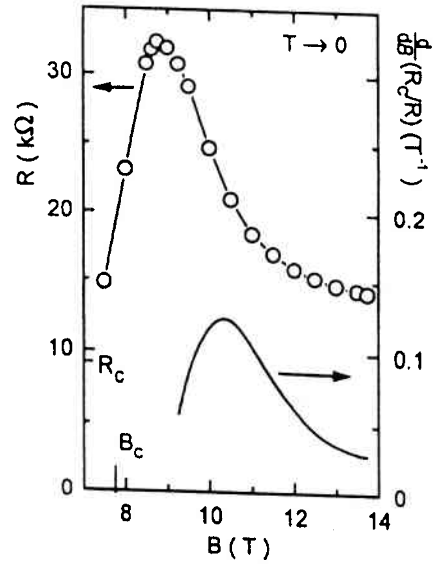

Figure 4: Extrapolated to $T = 0$ by (1) field dependence $R(B)$ and its derivative; state $\alpha_\perp$.

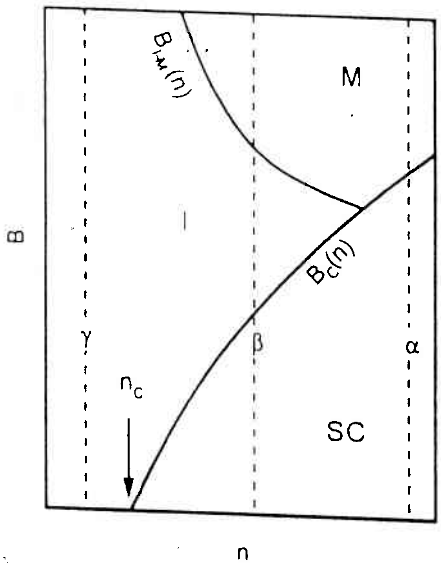

Figure 5: Schematic phase diagram of field induced transitions in (n, B) plane.

above B_c should be attributed to the decrease of the pair localization length ξ_{loc} with increasing B.[1,2,3] A qualitative account of the observed resistance drop with the field can be given in terms of pair breaking caused by magnetic field.[6] The density of pairs $n_p(B)$ decreases with rise of the field while $n_d(B)$ goes up: $n_d = n - 2n_p$. The behavior of the system of depaired electrons is naturally determined by their density $n_d(B)$: at low B and low n_d depaired electrons are also localized whereas at sufficiently high n_d the transition into the metallic state may be expected.

For states α with larger values of n the parameter a determined through approximation of data by Eq. (1) is positive over the entire field range 7.5 to 14 T above B_c so that there is no insulating phase. The corresponding field dependence of $R_0(B) \equiv R(0, B) = 1/a$ for the state $\alpha_\perp$ is presented in Fig. 4. Although the extrapolation is over a large distance, the tendency for the lowest temperature data to approach R_c in the high-field limit seems to be valid for the extrapolated dependence as well.

Fig. 5 schematically shows the obtained phase diagram in (n, B) plane with dashed lines denoting the studied samples (line γ corresponds to the sample studied elsewhere[6]).

Although the origin of localized electron pairs is still an open question, it is natural to assume the pair breaking field B to be proportional to the binding energy of a pair $B = \Delta/\mu$, with μ as a coefficient. With such interpretation, the broad field interval of the negative differential magnetoresistance points to a wide distribution of the pair binding energies $\nu(\Delta)$. Under several simplifying assumptions the relation between $R(B)$ and $\nu(\Delta)$ can be obtained[10]:

$$\nu(\Delta) = \frac{n}{\mu}\frac{\mathrm{d}}{\mathrm{d}B}(R_c/R)\Big|_{B=\Delta/\mu}. \tag{2}$$

The field derivative of the ratio R_c/R, which is proportional to $\nu(B)$, is also depicted in Fig. 4. The distribution $\nu(\Delta)$ is broad because the coupling takes place against the background of the random potential.

3 Summary

We conclude by summarizing the main experimental results obtained with amorphous In-O films and assumptions used in fitting them with the theory.

1. There exists a specific magnetic field B_c where isotherms $R(B)$ cross and the set of isomagnetic curves $R(T)$ has an unstable fixed point $(T,R) = (0,R_c)$. Scaling relations in the vicinity of this field are viewed as the main evidence that the quantum SIT[2,4] indeed takes place in In-O films,[7,8] as well as in other materials.[12,13]

2. This evidence is not questioned by the fact that the separatrix $R(T,B_c)$ may have nonzero slope near $T = 0$.[9] This can be incorporated into the scheme[2] and the oblique pattern of the isomagnetic curves (Fig. 1) can be easily taken into account.[9]

3. The Fisher scenario of the transition holds also in the parallel field configuration, i.e. under more general conditions as were formulated initially.[2] This implies that the problem of magnetic-field-induced pair localization should be treated regardless of sample dimensionality.

4. The fact that the transition scenario has been confirmed[7,8,9,10,12,13] does not mean that the idea of localized electron pairs has been proved experimentally. In-O seems to be the most appropriate material for studying this problem because it is the only still known material where the resistance $R(B)$ exceeds the value of R_c significantly in the close vicinity above B_c (see[7,8,9,10] and Fig. 2 of this paper where more then tenfold increase of R is demonstrated).

5. All the data on the negative magnetoresitance in In-O assembled together can be interpreted in the frame of the idea that the magnetic field may localize the pairs at B_c [2] and then decouple them in higher fields.[8] Deep in the insulating region this decoupling results in the crossover from Arrhenius to Mott activation.[6] In the superconducting region it may lead, at some critical concentration of decoupled electrons, to delocalization; hence, a split superconductor–insulator–metal transition takes place. Deeper in the superconducting region, where the total carrier concentration n is larger and the ranges of pair localization and decoupling overlap, the intermediate insulating state vanishes and we have the superconductor–metal transition.

6. Analysis of the function $R(B)$ in the negative magnetoresistance range can give information about the distribution function $\nu(\Delta)$ for the binding energies of the localized pairs.

Acknowledgment

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