Destruction of localized electron pairs above the magnetic-field-driven superconductor–insulator transition in amorphous In–O films

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(Submitted 24 July 1998)
Pis'ma Zh. Éksp. Teor. Fiz. **68**, No. 4, 337–342 (25 August 1998)

The field-induced superconductivity-destroying quantum transition in amorphous indium oxide films are investigated at low temperatures down to 30 mK. It is found that, on the high-field side of the transition, the magnetoresistance reaches a maximum and the phase can be insulating as well as metallic. With further increase of the magnetic field the resistance of the film drops and in the high-field limit approaches the resistance value at the transition point, so that at high fields the metallic phase occurs for both cases. We give a qualitative account of this behavior in terms of field-induced destruction of localized electron pairs. © *1998 American Institute of Physics.*
[S0021-3640(98)01716-2]

PACS numbers: 74.25.Jb, 74.76.Db, 74.70.Ad

The theoretical description of the zero-field and field-induced quantum superconductor–insulator transitions (SIT) in a 2D superconductor is based on the concept of electron pairs which are delocalized on the superconducting side and localized on the insulating side of the transition.[1–3] According to Refs. 1–3, the temperature dependence of the film resistance near the field-induced SIT is controlled by the deviation $\delta = B - B_c$ from the critical field B_c, and the most specific among the perceptible features of the SIT is a fan-like set of resistance-versus-temperature curves $R_\delta(T)$. Such a set is expected to collapse onto a single curve as a function of the scaling variable $\delta/T^{1/y}$, where y is the critical exponent (see review[4]). Many of the SIT studies have been performed on amorphous In_2O_x ($x<3$) films, whose conductivity is caused by an oxygen deficiency compared to the fully stoichiometric insulating compound In_2O_3: by changing the oxygen content one can cover the range from a superconductor to an insulator and thus realize a zero-field SIT. On the insulating side of this SIT, activational behavior of the resistance, $R \propto \exp(T_0/T)^p$ with $p=1$ (Arrhenius law), was observed, with the activation energy T_0 tending to zero as the phase boundary is approached.[5] It was later found that applying a magnetic field results in a decrease in the resistance and a weakening of its temperature dependence from the Arrhenius law to the Mott law with exponent p

TABLE I. Parameters of two states of the sample. R_r is the resistance at room temperature; the values of R_c and B_c are determined by means of scaling analysis as described in Ref. 11.

State	R_r, kΩ	R_c, kΩ	B_c, T
1	3.4	7.5	2
2	3.0	9.2	7.2

$=1/4$ (Ref. 6). This was explained in Ref. 6 by magnetic-field-caused suppression of the binding energy Δ of localized electron pairs, which is manifested as a gap at the Fermi level.

A field-induced SIT is realized on the superconducting side of the zero-field SIT. It is indicated by the fan-like structure of the experimental curves $R_\delta(T)$, such that, in accordance with the scaling analysis, the expected collapse is indeed the case.[7] Above the field-induced SIT, the existence of two insulating phases was postulated on the basis of the results of Hall measurements;[8] however, the temperature dependence of the resistance of these phases was not studied. Reversal of a zero-bias peak in the differential resistance at the critical field B_c was observed and attributed to the granular structure of the films.[9]

Here we investigate the phase on the high-field side of the SIT, where the occurrence of localized electron pairs is predicted. We find that while this phase can be insulating or metallic, in the high-field limit the system always enters the metallic phase. This is interpreted as field-induced breaking of localized electron pairs.

The experiments were performed on a 200 Å thick amorphous In_2O_x ($x<3$) film without pronounced granularity, as was checked by the absence of a quasi-reentrant transition, i.e., the absence of a minimum on the $R_\delta(T)$ curves at low temperatures.[10] The oxygen content x could be reversibly altered by heat treatment; all experimental procedures are described in detail in Ref. 6. Assuming for the sake of simplicity that the film disorder remains unchanged during heat treatment, one finds that the quantity x controls the carrier density n, and then it is the variation of n that causes the zero-field SIT. Two states of the film were studied, having the parameters listed in Table I. Under the above assumption, the carrier density in a state should be inversely proportional to its room temperature resistance. Hence, state 2 is farther from the zero-field SIT and deeper in the superconducting phase as compared to state 1. The magnetoresistance of both states was measured in an 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 the magnetic field at fixed temperature.

Our preceding study has confirmed the existence of a magnetic-field-tuned quantum SIT in such films and revealed that this phenomenon is more general than the one considered in Ref. 2. In particular, to attain collapse of the $R_\delta(T)$ data in the vicinity of the transition in a plot versus the scaling variable $\delta/T^{1/y}$, one must take into account, e.g., the temperature dependence of the critical resistance R_c, which gives rise to a term linear in T in the dependence $R_\delta(T)$.[11]

Figure 1 displays the magnetoresistance traces for the two states of the film at a temperature of 60 mK. The critical field B_c and resistance R_c at $T=0$ (Table I) are

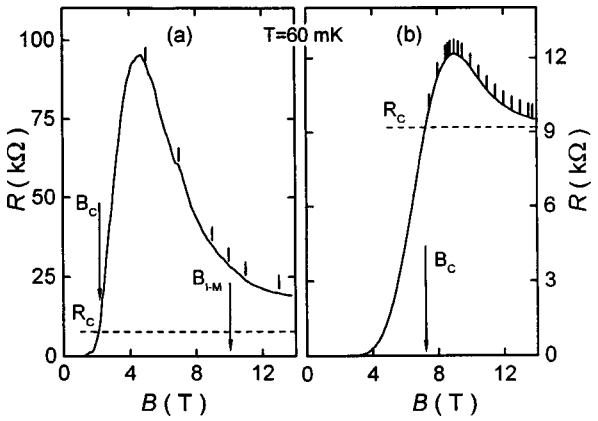

FIG. 1. Magnetoresistance of the film in state 1 (a) and in state 2 (b). The critical values R_c and B_c at $T=0$ are indicated. Also shown is the position of the metal–insulator transition, B_{I-M}, determined from Fig. 2. The temperature dependences of the resistance are analyzed at fields marked by vertical bars.

determined with the help of a scaling analysis, as described in detail in Ref. 11. One can see from the figure that with increasing field the magnetoresistance for both of the states reaches a maximum $R_{\max}$ above B_c and then drops, so that in the high-field limit it approaches the value of R_c. The relative value of the maximum $R_{\max}/R_c$ is considerably larger for state 1, which is closer to the zero-field SIT; moreover, the phase right above B_c is insulating in state 1 and metallic in state 2, as will be shown below.

The vertical bars in Fig. 1 mark the magnetic field values at which the temperature dependence of resistance is analyzed. The results of such an analysis for state 1 are represented in Fig. 2. At fields near the resistance maximum the $R(T)$ curves exhibit the

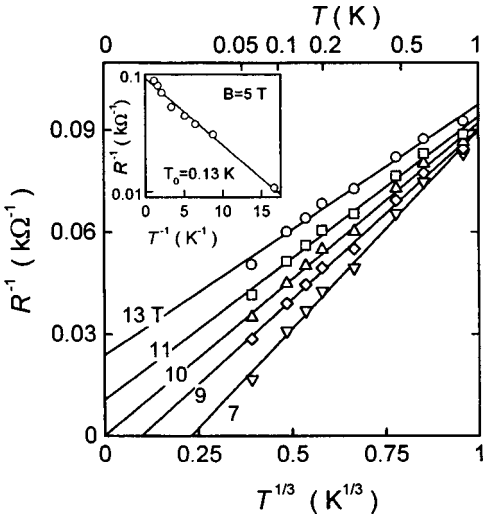

FIG. 2. Temperature dependence of the high-field conductance of state 1 at various magnetic fields. An Arrhenius plot of the conductance at $B=5$ T is displayed in the inset.

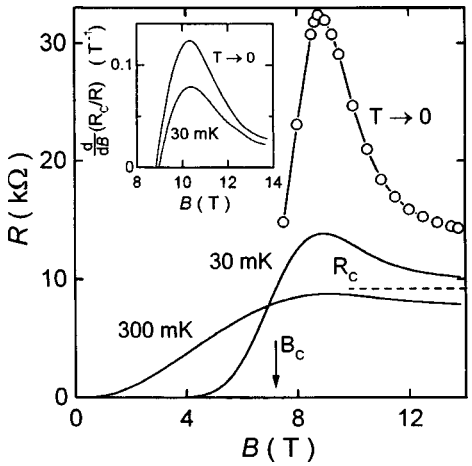

FIG. 3. Magnetoresistance of the film in state 2 at $T=30$ and 300 mK, and for $T\to 0$ as obtained from extrapolations (circles) in accordance with Eq. (1). The critical field and resistance are indicated. The field derivatives of R_c/R for $T\to 0$ and $T=30$ mK are compared in the inset.

activational behavior expected for an insulator (inset to Fig. 2). However, at higher fields the activation law does not hold, nor do the logarithmic corrections normally observed in 2D metals.[12] We therefore examine the film resistance over the field range 7 to 13 T in terms of 3D material behavior in the vicinity of metal–insulator transition:[13,14]

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

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

Let us emphasize that 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. 2 the value $B_{I-M}\approx 10$ T for the field of the metal–insulator transition for state 1. Thus the conclusion of Ref. 8 that two phases exist above the SIT is confirmed. Yet, in contrast to Ref. 8, we find that their phase boundary is not near the resistance maximum but at an appreciably higher field, and also that the high-field phase is metallic (Fig. 1).

For state 2 the parameter a 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 $R_0\equiv R_\delta(0)=1/a$ is presented in Fig. 3 along with the experimental curves $R(B)$ at 30 and 300 mK. 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 valid for the extrapolated dependence as well.

The rise of the resistance near the field-driven quantum SIT is in agreement with theoretical ideas about localized electron pairs: above B_c it reflects the decrease of the pair localization length $\xi_{\rm loc}$ with increasing B.[1–3] That the resistance reaches a maximum with further increase in B has so far not been discussed theoretically. Nevertheless, a qualitative account of the observed resistance drop with field can be given in terms of pair breaking caused by the magnetic field.[6] In this case the behavior of the system of

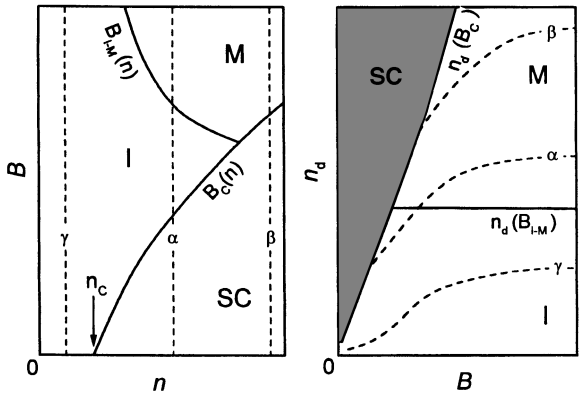

FIG. 4. Schematic phase diagram of the observed transitions in the (n,B) and (B,n_d) planes. The evolution of states α, β, γ with magnetic field is shown by dashed lines. In shaded area the value n_d is not defined.

depaired electrons is naturally determined by their density $n_d(B)$: at low n_d depaired electrons are certainly localized, whereas at sufficiently high n_d a metal–insulator transition may be expected. It is the second conduction channel that allows interpretation of the observed nonmonotonic dependences of the magnetoresistance.

In agreement with experiment, Fig. 4 shows schematically the field behavior for three states of the sample. Two of these, α and β, that are selected in the superconducting phase above the zero-field SIT at $n>n_c$ correspond to the investigated states 1 and 2, respectively. State γ selected in the insulating phase at $n<n_c$ corresponds to samples from Ref. 6. With increasing B state α undergoes a field-induced SIT at $B=B_c$, so that the depaired electrons available are localized at that small density n_d (Fig. 4). With further increase of field the value of n_d increases on account of localized pair breaking, giving rise to a metal–insulator transition in the system of depaired electrons. At $B\rightarrow\infty$, all electron pairs are expected to be broken, and so the value of n_d should be equal to the carrier density n. The different behavior of state β is due to the higher density n_d at the field-induced SIT because of higher n and B_c. As a result, the depaired electrons are already delocalized at $B=B_c$, and thus the field range of the insulating phase shrinks as one moves away from the zero-field SIT; see Fig. 4. Finally, state γ approaches the metal–insulator phase boundary with increasing B but remains insulating for all fields.[6]

Thus the concept of field-induced pair breaking requires the additional assumption that a metal–insulator transition occurs in the system of depaired electrons. Also, the theory[1–3] should be extended to include the possibility of a direct superconductor–metal quantum transition.

Although the origin of localized electron pairs is still an open question, a likely candidate for their breaking might be the paramagnetic effect. In this case the pair-breaking field should be proportional to the binding energy of a pair $B^*=2\Delta/g\mu_B$, where g is the Landé factor. It is clear that the broad field interval of the negative differential magnetoresistance points to a wide distribution of pair binding energies. To estimate the distribution function $\nu(\Delta)$ for state 2 we presume for the sake of simplicity

that, at fields above the resistance maximum, $R_0(B)$ at $T\to 0$ is inversely proportional to the density of depaired electrons (the Drude limit)

$$R_c/R_0 = n_d/n, \tag{2}$$

where n is the carrier density in the metallic state at $B\to\infty$, and n_d is given by the formula

$$n_d = n - 2\int_{g\mu_B B/2}^{\infty} \nu(\Delta)\,\mathrm{d}\Delta. \tag{3}$$

Then it is easy to obtain the distribution function

$$\nu(\Delta) = \frac{2n}{g\mu_B}\frac{\mathrm{d}}{\mathrm{d}\,B}(R_c/R_0)\big|_{B=2\Delta/g\mu_B}. \tag{4}$$

The field derivative of the ratio R_c/R_0, which is proportional to $\nu(B)$, is depicted in the inset of Fig. 3. Its behavior is similar to that of the field derivative of $R_c/R(T = 30\ \mathrm{mK})$ in spite of the long extrapolation to get $R_0(B)$; see Fig. 3.

The fact that the distribution $\nu(\Delta)$ is broad allows us to distinguish between two scenarios for localization of the electron pairs: (i) the localization radius ξ_{loc} is larger than the pair size ξ_0; and (ii) $\xi_{\mathrm{loc}} < \xi_0$. In the first case the binding energy Δ is determined mainly by intrinsic factors and is expected to be approximately the same for all pairs. In the opposite case two electrons forming a pair are localized at separate sites, and so the binding energy of the pair depends crucially on the local random potential.[6] This implies that a wide variance in Δ values. Hence, the data obtained are likely to point to the second localization scenario. We note that the limit $\xi_{\mathrm{loc}} < \xi_0$ was assumed in a model of localized bipolarons.[15]

In summary, our study of the field-driven quantum SIT in amorphous In_2O_x films shows that, on the high-field side of the transition, with increasing B the film magnetoresistance reaches a maximum and then drops, approaching in the high-field limit the resistance R_c at the transition point. We find that the high-field phase is always metallic, while the phase right above B_c can be insulating or metallic, depending on the distance to the zero-field SIT. The experimental data obtained can be understood within a model of localized electron pairs if one includes (i) a concept of field-induced pair breaking that presumes a metal–insulator transition in the system of depaired electrons; and (ii) the concept of a superconductor–metal quantum transition. That the negative differential magnetoresistance is observed in a wide field region is likely to point to a large variance of the binding energies of the localized electron pairs.

This work was supported by Grants RFBR 96-02-17497, RFBR 97-02-16829, and INTAS-RFBR 95-302 and by the ''Statistical Physics'' program of the Russian Ministry of Sciences.

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Published in English in the original Russian journal. Edited by Steve Torstveit.