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TRANSPORT PROPERTIES OF NORMAL AND QUASINORMAL STATES OF POOR SUPERCONDUCTORS

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There are some doubts whether materials near the superconductor–insulator transition (SIT), either on the insulating side, or with superconductivity suppressed by the magnetic field, behave like an ordinary metal. Two experiments in which this issue is addressed will be reviewed here, namely, transport measurements of two different materials: single crystals $YBa_2Cu_3O_{6+x}$ ($x \approx 0.37$) — a representative of the HTS family and amorphous InO_x where x is the oxygen content which could be changed through moderate-temperature annealing. The low-temperature normal resistivity $\rho(T)$ of YBaCuO crystals on both sides of SIT behaves as usual "bad" metal with conductivity below the Mott's minimum value. The amorphous In-O films behave differently. Those films with superconductivity do not display any characteristic magnetic field which can be interpreted as B_{c2}. Instead, they give out an example of a quantum phase transition and follow Fisher's model[1] for "the field-tuned SIT in disordered two-dimensional superconductors" though they are not precisely two-dimensional and their high-magnetic-field state may not be insulating at all. Apparently, the normal state of InO_x films comprises localized Cooper pairs.

1. Normal-State Resistivity of $YBa_2Cu_3O_{6+x}$[2]

Since the eighties, there have been repeated experimental indications that for disordered superconducting materials there is an intermediate region in the vicinity of the SIT in which the normal resistivity varies logarithmically with temperature:[3–6]

$$\rho(T) = \rho_0 + \Delta\rho = \rho_0 - \gamma_\rho \log T\,. \qquad (1)$$

Interest in this issue has been renewed after the publications by Ando, Boebinger *et al.*[7,8] They revealed the existence of the $\log T$-term in the resistivity of underdoped $La_{2-x}Sr_xCuO_4$ in the pulsed magnetic fields of 60 T.

We made corresponding experiments with YBaCuO system. Single crystals $YBa_2Cu_3O_{6+x}$ were grown by the flux method in aluminum crucibles.[9] Oxygenated at 500°C in the flowing oxygen, they had a T_c about 90–92 K and a fairly narrow resistive transition $\Delta T_c < 1$ K. To bring the samples to the boundary of the superconducting region, the oxygen content x was reduced by high-temperature (770–820°C) annealing in the air with subsequent quenching in liquid nitrogen.[9,10] To rearrange the chain-layer oxygen subsystem, the $YBa_2Cu_3O_{6+x}$ crystal was heated up to 120–140°C and quenched in liquid nitrogen. This procedure reduces the mean length of Cu–O chains; hence, the hole doping of CuO_2-planes decreases.[11] The equilibrium state with a larger hole density can be restored simply by exposing at room temperature. By interrupting the aging process, one can also obtain intermediate states. Thus the quenching and aging procedures allow us to vary gradually the carrier density and to tune the sample state through the boundary between the insulating and the superconducting regions.

The selected temperature of the x-affecting annealing had made the quenched and the intermediate states nonsuperconducting while the aged state became superconducting. Owing to that $T_c < 10$ K of the aged state was low, the available magnetic field $\mathbf{H} \| c$ of 8 T was almost enough to suppress its superconductivity. Fig. 1(a) presents the resistance measurements for all three states. Specific $\log T$ abscissa scale in Fig. 1(a) is chosen after Refs. 7, 8. The quenched and the intermediate states, both without superconductivity, demonstrate the resistivity which increases logarithmically with decreasing T over almost two decades in change of temperature. The magnetoresistance of the quenched state was below 1%; therefore, the perfect fit to straight line demonstrated in Fig. 1(a) is valid both with and without magnetic field, as well. It can be seen that $\rho_{ab}(T)$ curves for the aged state are approaching step by step the similar straight line with increasing of the magnetic field. Apparently, the representation of the data given in Fig. 1 agrees with that of Refs. 6–8 and 12.

However, this is not only possible interpretation. Assuming that our sample is a 3D-material, we can analyze the data with the help of the power functions,[2,13] in

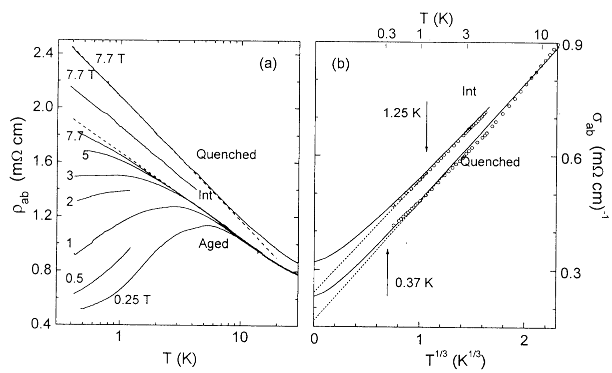

Fig. 1. (a) In-plane resistivity versus $\log T$ for a single crystal YBaCuO with a fixed content of oxygen but for different treatments (quenched, intermediate and aged states). Only the aged state is superconducting and the set of curves demonstrates how the magnetic field $\mathbf{H} \| c$ destroys the superconductivity. Dashed lines are extrapolation of the linear dependence $\rho_{ab}(\log T)$. (b) The same data replotted as σ_{ab} versus $T^{1/3}$. Solid lines — fits by Eq. (2) with T^* values indicated by arrows, dashed lines — asymptotes in the $t \gg 1$ region.

the line of the scaling theory:

$$s^{3/2} = s^{1/2} + t^{1/2}\,, \qquad s = \sigma(T)/\sigma(0)\,, \qquad t = T/T^*\,. \tag{2}$$

According to Fig. 1(b), the data for the quenched state of the sample replotted as σ versus $T^{1/3}$ are approaching the straight line at large T and satisfy the equation (2) with the values of the parameters $\sigma(0) = 0.23$ mOhm$^{-1}\cdot$cm^{-1} and $T^* = 0.37$ K. Those parameters for the intermediate state are equal to $\sigma(0) = 0.32$ mOhm$^{-1}\cdot$cm^{-1} and $T^* = 1.25$ K. We should expect that the aging of the sample increases the conductance $\sigma(0)$ due to the increasing the hole density.

Thus, the plots do not provide us with the choice between $\log T$- and T^m-representations. Since the later representation indicates the normal-metal state, we can claim that *there is no message from the magnetotransport of YBaCuO single crystals that it is a marginal metal with the strong interelectron correlations*.

It is different for amorphous In-O as it follows from data which are summarized in the next section.

2. Vicinity of the Superconductor–Insulator Transition in Amorphous In_2O_{3-x}[a]

The conductivity of the amorphous films of the indium oxide In_2O_{3-x} is examined for different oxygen deficiency and is compared to the fully stoichiometric insulating compound In_2O_3. By decreasing the oxygen content, one can cover the range from an insulating material with activating conductivity to a metallic, superconducting material.[14] Due to such flexibility, these films have proved to be very useful material for investigation of the transport properties near the SIT.[14–18]

The transport properties of the films In_2O_{3-x} reveal a number of specific features which lead to the assumption that localized Cooper pairs do exist in this material.

— Deep in the insulating region, the giant negative magnetoresistance is observed, with temperature-activated conductivity $\sigma \propto \exp(-\Delta/T)$ without magnetic field and with Mott's law $\sigma \propto \exp[(-T_0/T)^{1/4}]$ in the high magnetic fields.[16] This indicates the existence of the single-particle tunneling in the presence of a gap Δ in the spectrum of localized electrons, this gap being destroyed by the magnetic field.

— The negative magnetoresistance exists also in the superconducting region, in the external magnetic fields above those which destroy the superconducting response, i.e. above the positive magnetoresistance (see Fig. 1 in Ref. 17). The deeper in the region the smaller is the negative magnetoresistance.

[a] The experiments were performed together with V. Golubkov, those below 0.3 T — together with V. Dolgopolov, A. Shashkin and G. Tsydynzhapov; the films were kindly presented by A. Frydman and Z. Ovadyahu from Jerusalem University.

— Field-induced quantum phase transition[1] is observed inside the region of the positive magnetoresistance.[15,17] The model[1] assumes the existence of the localized pairs in magnetic fields above the transition.
— Field-induced change of the sign in zero-bias peak of I-V-characteristics (see Figs. 2 and 3 in Ref. 19). The sign of the peak in the high magnetic fields can be explained by assuming that the electric field destroys the localized pairs.

The crucial point in dealing with disordered superconducting systems is to determine the scale length of the disorder. Experiment gives an empirical criterion:[20] quasireentrant transition, when the resistance after decreasing starts to increase at the lowest temperatures, is typical for materials with long-scale disorder (granular, etc.) while in materials with atomic-scale disorder there is no extremum in the resistance curves $R(T)$ below T_c. In Fig. 2 we present two sets of the field-tuned SIT in the indium oxide: quasireentrant transition on the left and "ideal" on the right. The main results on SIT with indium oxide films[17,19] have been obtained with

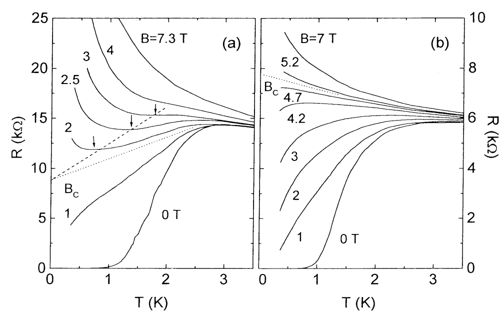

Fig. 2. Temperature dependence of the resistance of two different amorphous In–O films, both 200 Å thick, in various magnetic fields. Sets (a) and (b) represent two types of films behavior (see text).

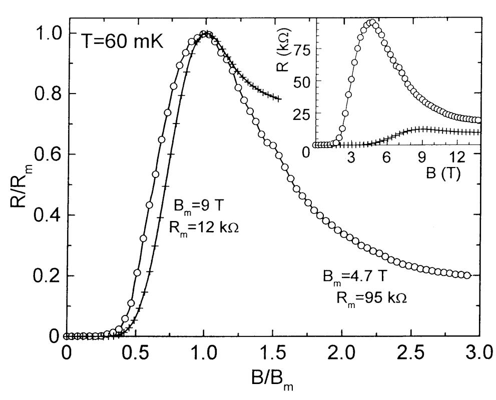

Fig. 3. Normalized magnetoresistance of two different states of amorphous In–O film at one and the same temperature $T = 60\,\mathrm{mK}$. Inset – the same but not normalized curves.

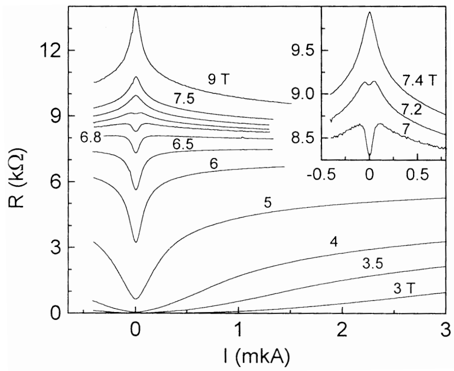

Fig. 4. Differential resistance of the state with the critical field value of $B_c = 7.2$ T at the temperature $T = 60$ mK. Inset — enlarged central parts of three curves near the crossover.

the quasireentrant materials. Below we demonstrate similar results with "ideal" samples.

In this study, to reinforce the superconducting properties and to increase T_c, we used samples annealed in oxygen-free vacuum at fixed temperature from the interval 70°C–110°C; we carried out annealing under control of the sample resistance and it was continued at least until the resistance was saturated. Several additional hours of the sample annealing in the oxygen-free vacuum after its resistance has already saturated favored in obtaining the sample with the "ideal" behavior. To shift the sample properties into the opposite direction, the sample was exposed at room temperature on air.

Figure 2 illustrates that the increasing of the magnetic field induces the change in the sign of the second derivative $\partial^2 R/\partial T^2$ in the low-temperature limit. Following Fisher,[1] we interpret the behavior of the function $R(T, B)$ as a quantum phase transition and demonstrate that near the critical field B_c the scaling variable can be introduced.

Our experiment allowed to compare different states of a single sample. Fig. 3 presents an example of such comparison. The distances of these states from the SIT are characterized by the critical magnetic field B_c (see Fig. 2(b)). Inset demonstrates curves $R(H)$ obtained at 60 mK. The main plot contains the same curves with coordinates normalized to their maxima, so these maxima positions coincide. The normalized curves illustrate reduction of the negative magnetoresistance which accompanies the shift of the state of the sample away from the SIT.

One more thing happens near the critical magnetic field B_c: the sign inversion of zero-bias peak in the I-V-characteristic. A zero-bias dip at low fields had natural explanation: decreased resistance in the zero-current limit is determined by random Josephson junctions. Bounding of localized electrons into pairs creates a gap at the Fermi-level and makes the resistance exponentially large. The exponent is eliminated by the finite electric field.

3. Conclusion

Both materials, single crystals $YBa_2Cu_3O_{6+x}$ and amorphous InO_x, were led to SIT by reducing the carrier density. In InO this happened on the background of the utmost disorder while in YBaCuO the disorder was spatially separated from planes where the carriers were located. We conclude that the strong disorder is the main factor which affects the scenario of SIT in InO_x. This influence may be due to granular structure of the material, either initially coming from the background, or induced by the phase separation.[21,22] But relying upon existence of the negative magnetoresistance deep in the insulating region[16] and upon the "ideal" behavior of our films (Fig. 2(b)) we assume that the transport properties of both, metallic and insulating, states are affected by localization of pairs.

Acknowledgments

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