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OBSERVATION OF THE PARALLEL-MAGNETIC-FIELD-INDUCED SUPERCONDUCTOR-INSULATOR TRANSITION IN THIN AMORPHOUS InO FILMS

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We study the response of a thin superconducting amorphous InO film with variable oxygen content to a parallel magnetic field. A field-induced superconductor-insulator transition (SIT) is observed that is very similar to the one in normal magnetic fields. As the boson-vortex duality, which is the key-stone of the theory of the field-induced SIT, is obviously absent in the parallel configuration, we have to draw conclusion about the theory insufficiency.

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A good deal of work was performed on the investigation of the magnetic-field-induced superconductor-insulator transition (SIT) on superconducting amorphous films of InO [1–3], MoGe [4], and MoSi [5] with thickness comparable to the superconducting coherence length. It was found that with increasing field B the resistance R of all studied films rises abruptly at a magnetic field B_c and then passes through a maximum followed by a drop in high magnetic fields [2, 3]. The film state just above B_c was identified as insulating although at lowest temperatures about 30 mK the maximum resistance does not exceed 100 kΩ and the temperature dependences of $1/R$ correspond to the activation energies which do not exceed by far the lowest temperatures. Near B_c at sufficiently low temperatures, the resistance $R(T,B)$ was found to be a function of single scaling variable $u = (B - B_c)/T^y$ with exponent $y \approx 0.8$. The above experimental findings are regarded to confirm the theory of the quantum SIT [6] in two-dimensional (2D) superconducting films subjected to a normal magnetic field. This theory exploits the concept of the hypothetical system of charged bosons in a random potential and is based on the boson-vortex symmetry of the model Hamiltonian. In the vicinity of the SIT point $(T = 0, B = B_c)$ the film resistance $R(T,B)$ is expected to be a universal function of the single scaling variable which is defined as the ratio of the correlation length $\xi \propto (B - B_c)^{-\nu}$ and the dephasing length $L_\phi \propto T^{-1/z}$, where ν and z are the critical indices. The form of the scaling variable implies that the value $1/z\nu$ has to be identified with exponent y. The concept of the localization of electron pairs, or bosons [6], has been supported recently by the work of Ref. [7]. There, it is shown that for a 2D superconducting film with strong disorder the region of fluctuation superconductivity, where the electron pairs occur, should extend down to zero temperature. In this region the unpaired electrons are supposed to be localized whereas the bosons can be either localized or delocalized, dependent on the value of magnetic field.

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Other experimental results were interpreted within the model of electron pair localization: (i) a crossing of Hall isotherms $R_{xy}(B)$ was observed at a field $B_{c0} > B_c$ and attributed to a transition between the Bose-insulator and a Fermi-insulator that consists of localized single electrons, i.e., pairing was presumed to be destroyed at B_{c0} [1]; (ii) the resistance drop in high fields was explained in terms of the electron pair breaking which occurs gradually with increasing B owing to the different binding energies of bosons in a random potential [2, 3].

However, a very similar SIT has been observed recently on amorphous MoSi films with the thickness $d = 1700$ Å which is an order of magnitude larger compared to the superconducting coherence length ξ_{sc} [8]. This fact causes one to think that either the theory is inadequate or its restrictions are too severe.

Here, we investigate the influence of a parallel magnetic field on the superconducting properties of a thin amorphous InO film with variable oxygen content. For all film states we find a complete similarity in the behaviour of the resistance $R(T, B)$ for both parallel and perpendicular magnetic field.

The sample is an amorphous InO film with thickness 200 Å that was grown by electron-gun-evaporation of a high-purity In_2O_3 target onto a glass substrate [9]. Oxygen deficiency compared to fully stoichiometric insulating compound In_2O_3 causes the film conductivity. By changing the oxygen content one can cover the range from a superconducting material ($\xi_{sc} \approx 500$ Å) to an insulator with activated conductance [10]. The procedures to change reversibly the film state are described in detail in Ref. [2]. To reinforce the superconducting properties of the film we used heating in vacuum up to a temperature from the interval 70 – 110 °C until the sample resistance got saturated. To shift the film state in the opposite direction we made exposure to air at room temperature. As the film remains amorphous during these manipulations, it is natural to assume that the treatment used results mainly in a change of the carrier density n and that the value n is inversely proportional to the room temperature resistance R_r of the sample. Seven superconducting states of the film were studied.

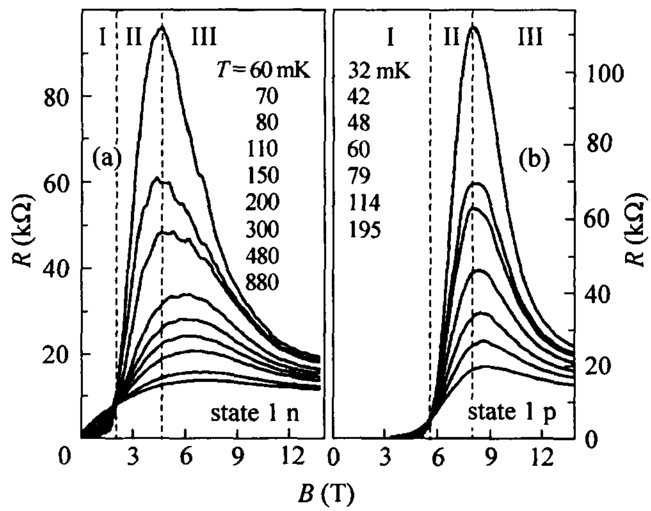

Fig.1. Isotherms $R(B)$ for a normal (a) and parallel (b) magnetic field. The dashed lines separate regions I, II, and III and correspond to the critical field B_c and the resistance maximum at the lowest temperatures

The film was mounted into the top loading system of a dilution refrigerator; it was set either parallel or normal to the magnetic field within 1° accuracy. A four-terminal lock-in technique at a frequency of 10 Hz was used to measure the resistance of the sample. The ac current through the sample was equal to 1 nA.

The experimental dependences $R(B)$ for two close states of the film in the normal and parallel field orientation are presented in Fig.1. As seen from the figure, for both field orientations the isotherms cross at the critical field B_c which separates the superconducting region I and the insulating region II. The resistance drop with B in region III down to values about h/e^2 indicates that at high magnetic fields the film state is metallic. The critical field B_c is found to vary with field direction by about a factor of two. Nevertheless, near B_c, the experimental data collapse onto a single curve equally well for both perpendicular and parallel magnetic field with the close values of exponent y, see Fig.2.

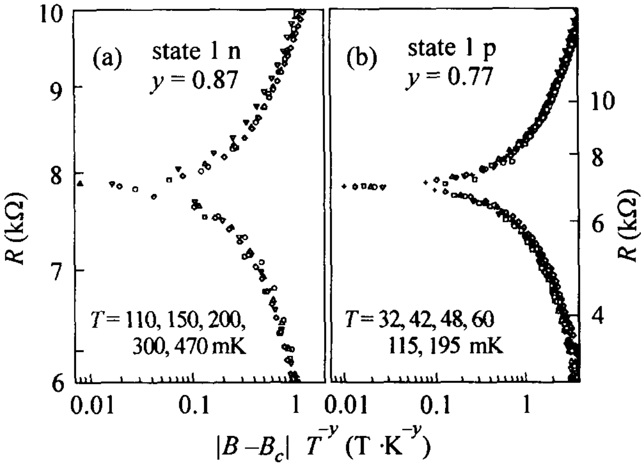

Fig.2. Scaling plot for both normal (a) and parallel (b) magnetic field

Fig.3 displays the behaviour of the relative resistance maximum R_{max}/R_{14T} at the lowest temperature and of the critical field B_c with changing film state. As seen from the figure, the resistance ratio decreases and approaches unity as one goes deeper into the superconducting phase. The value B_c for both field directions increases when departing from the zero-field SIT, being higher in the parallel configuration.

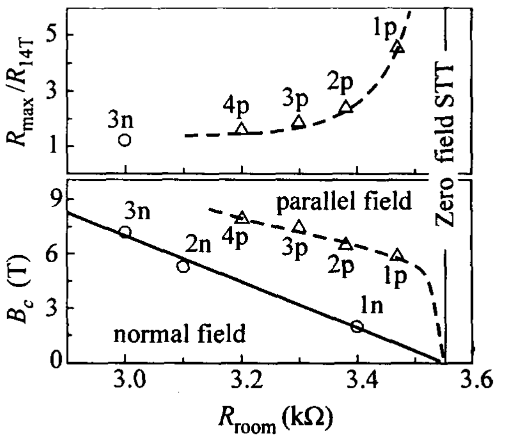

Fig.3. Change of the relative resistance maximum at $T \approx 30$ mK and of the critical magnetic field with changing film state as determined by the room temperature resistance of the film. The dashed lines are guides to the eye

The mean free path of the normal electrons in our film is small compared to the film thickness [3] and, hence, the metal-insulator transition expected in region III should be three-dimensional. In this case the conductance $1/R$ in the vicinity of metal-insulator transition is expected to change linearly with $T^{1/3}$ and extrapolation of the linear dependence to $T = 0$ should reveal whether the phase is metallic or insulating as judged by offset sign [11, 12]. Such a data analysis is shown in Fig.4. For both field configurations the experimental data behave similarly: the offset of the linear dependence increases with B passing through zero at the transition point.

The crucial point of the theory of the magnetic-field-driven SIT [6] is the boson-vortex duality for induced by external magnetic field vortices penetrating the film, which is not the case for a parallel magnetic field. The experimentally observed complete similarity of the SIT properties in the perpendicular and parallel magnetic field forces one to conclude that the theory is not directly applicable for actual superconducting systems with disorder.

Nonetheless, assuming that the parallel magnetic field is capable of localizing the fluctuation-induced Cooper pairs in the paraconductivity region, one can translate all experimental findings into the language of localized bosons. We emphasize that the speculations below are very attractive but do not have a sound experimental basis so far.

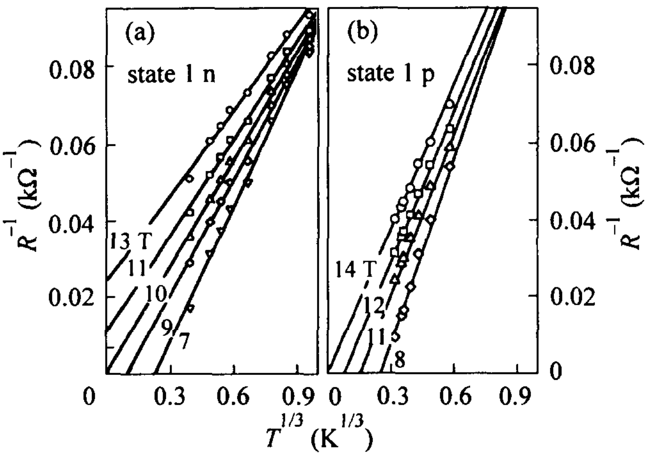

Fig.4. The temperature dependence of $1/R$ near the three-dimensional metal-insulator transition in a normal (a) and parallel (b) magnetic field

One can reckon that the resistance rise with B in region II is caused by decreasing boson localization length. Assuming additionally that the magnetic field not only localizes but also breaks electron pairs, it is easy to interpret the resistance drop in region III: breaking the correlations in localized electron pairs results in an increase of the electron hopping probability [2] and eventually electron delocalization at high fields [3]. For sufficiently deep film states in the superconducting phase, i.e., sufficiently high B_c, at $B > B_c$ the localized bosons coexist with delocalized normal electrons so that the state never becomes insulating. In other words, as one advances into the superconducting phase, a fraction of the localized bosons reduces. As a result, the relative amplitude of the resistance maximum R_{max}/R_{14T} tends to unity (Fig.3), and the SIT should transform into an ordinary superconductor to normal metal transition.

In summary, we have investigated the response of a thin superconducting amorphous InO film to a parallel magnetic field. At a critical field B_c a SIT has been observed that is very similar to the one in normal magnetic fields. That the boson-vortex duality is absent in the parallel configuration points to the insufficiency of the theory of the field-induced

SIT [6]. We find that the behaviours of the film resistance at fields above the transition are also similar for the parallel and normal magnetic field.

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