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Magnetic field induced superconductor–insulator transition in InO$_x$ films — a 3D scenario?

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Abstract. Magnetic field driven superconductor – insulator transition in amorphous InO$_x$ film was studied down to 32 mK at different carrier concentrations. It was found that transitions exist both in the field normal to the film and parallel to it. Apparent difference between them is only in the values of critical magnetic fields. This finding contradicts to widely adopted two-dimensional theory of transition and requires to 3D approach.

Keywords: superconductor-insulator transitions, InO film
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The magnetic field induced superconductor–insulator transition (SIT), the transformation of the superconducting thin film under magnetic field into insulating state, was observed in a few systems including amorphous InO$_x$ films [1], MoGe films [2] and MoSi films [3, 4]. The theory of the phenomenon introduced by M.Fisher [5] is based on the boson (electron pair) – vortex duality in dirty two-dimensional superconductors. At low magnetic field and temperature below Berezinsky–Kostelitz–Thauless transition bosons are delocalized, vortices localized and the film is superconducting. Because of duality picture flips at a critical field B_c — bosons become localized and vortices delocalized which results in infinitely high resistance, i.e. insulating state of the film. The transition from superconducting phase into insulating is essentially quantum in nature, i.e. it is not governed by the temperature but by another parameter, in this case by the magnetic field. (For review on quantum phase transitions see [6].) According to the scaling theory of the phase transitions, the properties of the system are controlled by correlation length ξ, diverging at transition point

$$\xi = |B - B_c|^{-\nu} = \delta_B^{-\nu}, \qquad (1)$$

where ν is the critical index. The temperature dependences of the film resistance are predicted to be a function of the scaling variable $u = \delta_B / T^{1/z\nu}$

$$R = R_c f\left(\frac{B - B_c}{T^{1/z\nu}}\right), \qquad (2)$$

where z is dynamic critical index. The $f(u)$ is diverging as $u \to +\infty$, goes to zero as $u \to -\infty$ and $f(0) = 1$ [5]. As a result set of resistance–vs–temperature $R_B(T)$ curves at different magnetic fields around B_c obtains characteristic fan-like structure and isotherms $R_T(B)$ has common intersection point (B_C, R_C). This feature along

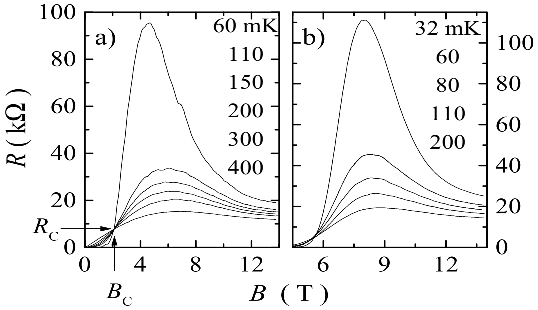

Fig. 1 States near the zero field SIT. a) Magnetic field normal to the film, $R_{room} = 3.4$ kΩ. b) Field parallel to the film, $R_{room} = 3.47$ kΩ.

with collapse of resistance on a single curve when plotted against scaling variable u is considered to be the main evidence of a SIT.

The purpose of this work was further investigation of field induced SIT and its evolution with variation of carrier density.

The experiments were performed on 200 Å thick amorphous InO_x films. We have studied several films which exhibited very similar properties, but all results presented here are obtained on one and the same film.

InO_x is very convenient material for the studying of SIT. By changing the oxygen content one can cover the range from a metallic superconducting material to an insulator with activated conductance [7]. To increase carriers density and enhance the superconducting properties of our film we used heating in vacuum at a temperature from the interval 70 – 110°C. To shift the sample properties in the opposite direction we made exposure to air at room temperature. (Details can be found in Ref. [8].) State of the film can be conveniently characterized by resistance at the room temperature R_R. Zero field SIT occurs in our films approximately at $R_R = 3.6$ kΩ.

The low-temperature measurements were carried out by a four-terminal lock-in technique at a frequency of 10 Hz in a Oxford TLM-400 dilution refrigerator in the temperature interval 1.2 K – 30 mK. The sample resistance $R(T, B)$ was studied as function of B at fixed T. The ac current was equal to 1 nA and corresponded to the linear regime of response. The aspect ratio of the samples was close to one.

First, we made sure we are able to reproduce results of previous studies. In the state with $R_R = 3.4$ kΩ we applied magnetic field normal to the film and obtained classical picture of field induced SIT (Fig. 1a) with distinct critical point at $B_c = 2\ T$ and with $R_c = 7\ k\Omega$. Above this point resistance increased rapidly on decreasing of the temperature indicating insulating state. Around maximum it follows activating law. Decrease of the resistance at high magnetic fields should be apparently connected to dissociating of electronic pairs. We were able to scale data around critical point according to (2) and get critical index $z\nu = 1.18$ in good agreement with previous results [1, 2].

For the film shifted further into superconducting region, with resistance R_R reduced to 3.0 kΩ overall picture seemed to be preserved (Fig. 2a), but all particular features were lost. There were no more common intersection point — every pair of isotherms,

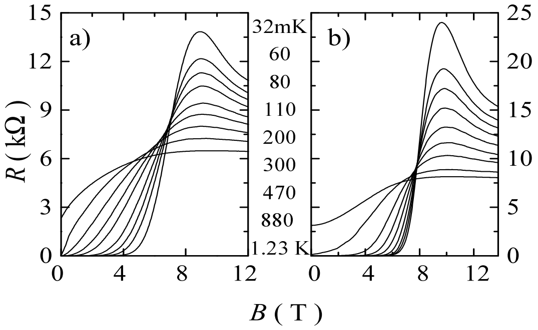

Fig. 2 States far from zero field SIT. a) Magnetic field normal to the film, $R_R = 3.0$ kΩ. b) Field parallel to the film, $R_R = 3.2$ kΩ.

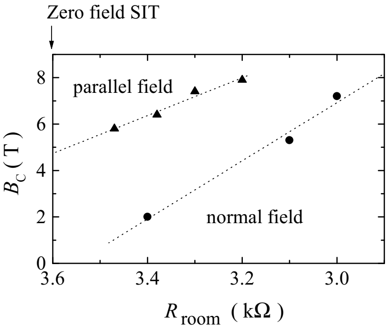

Fig. 3 Critical fields as function of resistance at the room temperature.

even at the lowest temperatures has its own one. The resistance around maximum became much less and increased slowly casting doubt on identifying it as a insulator. Evidently data did not satisfy (2).

The phenomena can be in principle incorporated into framework of Fisher model by supposing, as first suggested in [2], a second conduction channel, which depends slowly on temperature. It would reduce maximum resistance of the system and provide a temperature dependence to the critical resistance R_c in (2). This mechanism should be more effective in more superconducting state. A likely candidate seems to be electrons depaired by magnetic field, because (i) they certainly exist at high enough field and (ii) the deeper is film in superconducting region, the higher is the critical magnetic field.

Because of supposed temperature dependence of R_c and absence of an evident critical point one should have independent way to determine B_c. As an insulator should has infinite resistance at zero temperature and superconductor — zero resistance, we suggest the sign of second derivative at low temperatures as a criterium. At B_c resistance vs. temperature curve would be straight line in low temperature limit. We did observe such behavior and were able, after accounting for $R_c(T)$, obtain scaling of data with practically the same critical index $z\nu = 1.2$.

Our films are thick; their thickness is comparable and even greater then superconducting coherence length, estimated to be 80–150Å. But we still observe good SIT picture. More over, SIT observation were reported for the films as thick as 1000Å[4], and for theory [5] dimensionality is of crucial importance. So it was interesting to probe significance of two-dimensional nature of the sample. In order to do this we apply magnetic field parallel (with accuracy $\approx 1^o$) to the film. Surprisingly, we found that we were able to obtain the same phenomena in parallel field too. It is illustrated by right (b) parts of Figs. 1,2, where isotherms for the parallel field are presented. The states were picked to be close in resistance values and behavior to the left side of the picture. (Unfortunately, it was technically impossible to study the same state both in normal and parallel field.) It can be easily seen that left and right sides of the figures are very close to each other in all, but values of critical field. It is possible to make a scaling analysis for data from the Fig. 1b which gives the critical index $z\nu = 1.3$, close to that in the normal field. Temperature dependence of the resistance at maximum is activating, i.e. film is an insulator at this point. More over, comparison of Fig. 1 and Fig. 2 shows that evolution of the resistance with changing film state are also very similar in the parallel field. It diminishes maximum resistance value and eliminate common intersection point right in the same way as in case of normal field. Once again, the only difference is B_c values. The dependence of B_c on room temperature resistance is shown on Fig. 3. Evidently, there could not be any field induced SIT in non-superconducting film and according to this B_c for the normal field turns to zero near zero field SIT. The very intriguing is that B_c for parallel field don't, i.e. discontinuity must be expected.

In conclusion, we report observation of transition from the superconducting to the insulating state under the magnetic field parallel to the film. The Fisher's model is not applicable to the case because no boson–vortex duality exists. But its perceptible features — common crossing point, scaling according (2) — are not due to this particular model but are typical to a continuous quantum phase transition. So, we have observed quantum phase transition from superconductor into insulator tuned by magnetic field which required three-dimensional scenario.

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