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Superconductor–insulator transition in amorphous In–O films

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Abstract

From experiments with amorphous InO_x films, three conclusions are made: (i) The pattern of the superconductor–insulator transition (SIT) seen before for 2D electron gas in normal magnetic field can be reproduced under different experimental conditions, with field parallel to the film; (ii) The negative magnetoresistance (NMr) observed in high fields is due to breaking of localized pairs and transformation of bosons into fermions, the latter having higher mobility; hence, NMr is a confirmation of the conception of localized pairs.; (iii) Assumption of existence near the SIN of two complementary groups of electrons, paired, i.e. bosons with density n_b, and unpaired fermions with density n_f ($2n_b + n_f = n$, the total density), can explain the nonuniversality of the critical resistance R_{c0} seen before and its temperature dependence which we found in films with comparatively high n. © 2000 Elsevier Science B.V. All rights reserved.

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In Ref. [1], Fisher proposed a scenario of the field-induced SIT with three main components.

(a) It formulated some "boundary conditions" for an experiment: the theory was elaborated for 2D electron gas and, as it was based on the vortex-boson duality, the magnetic field was assumed to be normal to the plane with electrons.
(b) It predicted that the insulating state was arranged from localized pairs.
(c) It predicted that at low temperature T in the vicinity of the critical field B_c the resistance R was a function of one scaling variable $u = (B - B_c)/T^{1/y}$ with y being a parameter:

$$R(T,B) = R_c r(u), \quad R_c = R_{c0}(1 + O(T^2)) \tag{1}$$

with $r(0) = 1$ and a universal constant R_{c0}. This meant a horizontal separatrix $R_c \equiv R(T, B_c)$ in the (T, R) plane and a common crossing point for all isotherms in the (B, R) plane.

Experiments done on amorphous InO_x [2] and MoGe [3] films matched the conditions (a). They confirmed prediction (c) – existence of the scaling relations in the vicinity of SIT (except of universality of R_{c0}). They did not deal with (b).

In this work, we try to analyze our experiments regarding all three aspects and to clarify the points listed in the Abstract. The experiments were made with 200 Å thick amorphous InO_x films. The oxygen content could be reversibly altered by heat treatment; all experimental procedures are described elsewhere [4,5].

Fig. 1 demonstrates that the change of the magnetic field direction practically does not affect the character of the function $R(T, B)$ preserving the crossing of the isotherms $R(B)$ in one point. This crossing was previously regarded as the main evidence of the existence of SIT [1–3]. We conclude that the scenario [1] realizes not only when the boson-vortex duality holds and that it is more universal.

The striking feature seen from Fig. 1 is the high-field NMr, strongly temperature-dependent but not sensitive to the field direction, which returns the resistance $R(B \to \infty)$ to the level of R_c where the isotherms cross.

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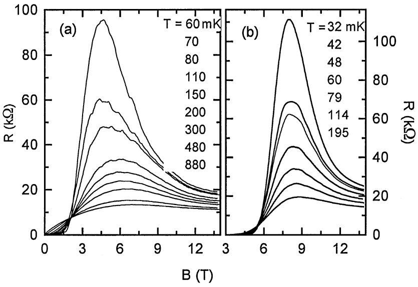

Fig. 1. Low-temperature isotherms $R(B)$ for an amorphous In–O film at the fieild normal to the film (a) and parallel to it (b). The difference in behavior exists only below the crossing point (B_c, R_c) where the resistance in the normal field configuration is determined by the vortex dynamics.

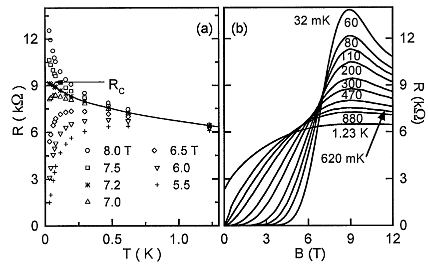

Fig. 2. Isomagnetic $R(T)$ curves (a) and isotherms $R(B)$ (b) of the function $R(T, B)$ for the film from Fig. 1 with increased through heat treatment carrier density n. Comparing with Fig. 1, note lower resistance values and decreased relative maximum magnitude on the isotherms.

This feeds the idea of the localized pairs and permits to propose a self-consistent description.

The binding depletes the density n_f and leads to a gap (or a soft gap, or a pseudogap) at the Fermi-level in the one-particle density of states. As the bosons are localized in random positions they have different binding energies δ. The larger is δ, the higher field is needed to break the pair. Hence, in each field the bosons and the fermions coexist. The density n_b goes down with increase of the field and n_f goes up and the gap shrinks. Bosons are localized above B_c and their hopping conductivity is very small. The fermions are localized at low n_f too but endure a Mott transition as n_f increases. Such field-induced insulator–metal transition was seen in Ref. [4]. Increase of n_f leads to NMr. NMr exists even when both groups are localized, because fermions do not need activation energy δ in the hopping processes while a bound electron needs.

Existence of two complementary groups may complicate scaling relations (1). There are no special reasons why the conductance of both groups should not depend on temperature in the region where the scaling relations hold. Then the function $R_c(T)$ gets a finite slope and the isotherms do not have a common crossing point. We see this on samples with higher total density n, which are deeper in the superconducting region (Fig. 2).

However, the scaling relations may be saved by introducing compensation of the slope. Expanding $R_c(T)$ and $r(u)$, we get instead of (1)

$$R(T, B) = R_c(1 + \alpha T + \cdots)(1 + \beta u + \cdots) \tag{2}$$

and not R but $\tilde{R} = R - \alpha T$ remains a one-parametric function until the product of the linear terms is small, $\alpha T \beta u \ll 1$ [5].

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