High-field side of Superconductor-Insulator Transition

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Abstract

We report the experimental observation of a magnetic-field-tuned superconductor-insulator transition (SIT) in ultrathin TiN films. The low temperature transport properties of these films show scaling behavior consistent with a transition driven by quantum phase fluctuations in two-dimensional superconductor. The magnetoresistance reveals peak and a subsequent decrease in fields higher than the critical field. The temperature dependences of the isomagnetic resistance data on the high-field side of the SIT have been analyzed and the transition from insulating to metallic phase is found, with at high fields the zero-temperature asymptotic value of the resistance being equal to h/e^2.

Key words: Quantum transitions; Scaling relations; Superconducting films

The zero-temperature superconductor-insulator transition (SIT) is a phase transition of the second order and is driven by fluctuations of a quantum nature. The superconducting phase is considered to be a condensate of Cooper pairs with localized vortices, and the insulating phase is a condensate of vortices with localized Cooper pairs. The theoretical description based on this assumption was suggested in Ref. [1]. According to the theory: (i) the film resistance R near the field-induced SIT at low temperature T in the vicinity of the critical field B_c is a function of one scaling variable $\delta = (B - B_c)/T^{1/\nu z}$, with νz being a parameter; (ii) at the transition point the film resistance has the universal value $h/4e^2$ (the quantum resistance for Cooper pairs). Although much work has been done, and in many systems the scaling relations hold, the SIT in disordered films remains a controversial subject, especially concerning the insulating phase and the bosonic conduction on the high-field side of the SIT at $B > B_c$. In some works the behavior of the resistance in this region can be explained by weak-localization theory. In Ref. [2] it has been 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 at high fields the zero-temperature asymptotic value of the resistance is approximately equal to R_c (the value of the resistance at $B = B_c$). Here we present a careful examination of the presence of the insulating phase and its evolution on the high-field side of the SIT.

A TiN film with a thickness of 5 nm was formed on 100 nm of SiO_2 grown on top of <100> Si substrate by atomic layer chemical vapour deposition at 400°C [4]. Analysis by atomic force spectroscopy shows that the film exhibits low surface roughness and consists of a dense packing of grains, with a rather narrow distribution of grain size and the average size is roughly ~ 30 nm.

The samples for the transport measurements were fabricated into standard Hall bridges using conventional UV lithography and subsequent plasma etching. The channel length and width were 250 and 50 μm, respectively. The magnetoresistance measurements were performed in a temperature-stabilized dilution refrigerator. The magnetic field was applied perpendicular to the film. Four terminal transport measurements were performed using standard low frequency techniques.

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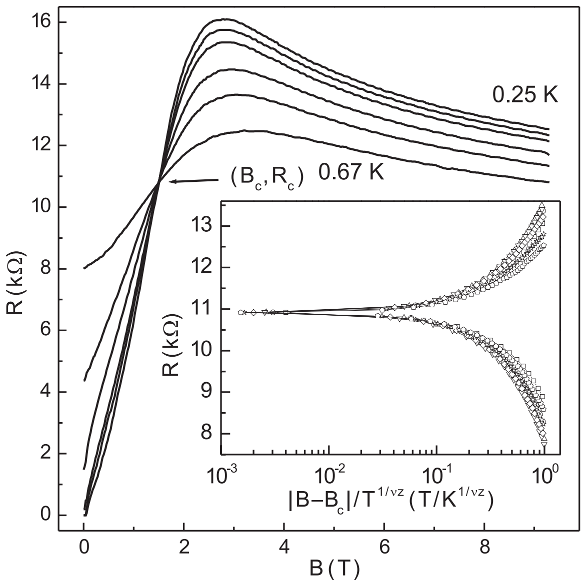

Fig. 1. Low-temperature isotherms in the (B, R) plane. Different curves represent different temperatures: 0.25, 0.38, 0.42, 0.51, 0.61, and 0.67 K. The point of intersection: $B_c = 1.52$ T is the critical magnetic field, and $R_c = 10.9$ kΩ is the critical resistance. The inset shows a scaled plot of the same data with $\nu z = 1$.

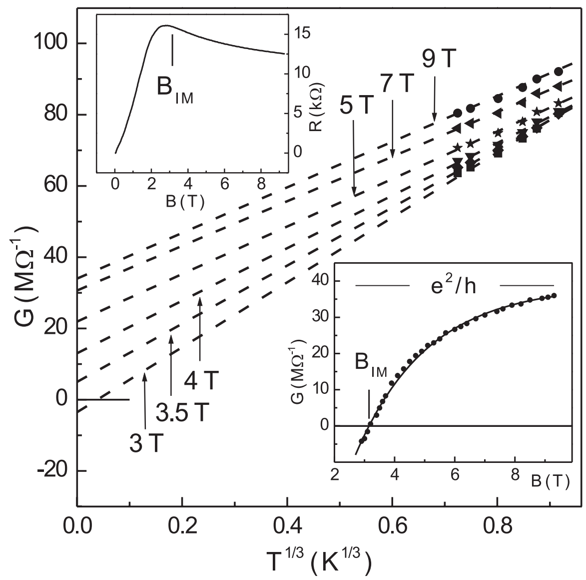

Fig. 2. Conductance $G = 1/R$ vs $T^{1/3}$ at different magnetic fields on the high-field side of the SIT. The lower inset shows the magnetic field dependence of the zero temperature conductance determined from extrapolations in accordance with Eq. (1) (symbols). The upper inset: B_{IM} marks the value of the field of the insulator-metal transition.

The resistance data were taken at a measurement frequency of 10 Hz with an ac current 1 nA.

A typical set of resistance per square vs magnetic field data is given in Fig. 1. The main features of these results are the presence of the point of intersection (B_c, R_c) and the negative magnetoresistance in high fields. Using the B_c, we plot the same data against the scaling variable $|B - B_c|/T^{1/\nu z}$, and adjust the power νz to obtain the best visual collapse of the data. Such behavior, previously regarded as the main evidence of the existence of SIT, is actually not incontestable proof of the presence of the insulating phase at $B > B_c$. Following the approach of the authors in [2], we analyze the temperature dependence of the film resistance on the high-field side of the SIT in terms of 3D "bad" metals in the vicinity of the metal-insulator transition [3]:

$$G(T) = a + bT^{1/3}. \qquad (1)$$

The sign of the parameter a discriminates between a metal and an insulator at $T \to 0$. If $a > 0$, it yields the zero temperature conductance $G(0) \equiv a$, whereas negative a points to activated conductance at lower temperatures. The temperature dependence of the high-field conductance at different magnetic fields is shown in Fig. 2. It is well described by Eq. (1). As $G(0)$ is negative in fields higher than the critical field we can conclude that this phase is insulating. With further increase of B the resistance decreases. This behavior is in agreement with the concept of localized Cooper pairs in the insulating phase, and that of field-induced Cooper-pair breaking. Extrapolation to $T = 0$ allows us not only to determine the field of the insulator-metal transition (B_{IM}), but also the magnetic field dependence of the zero temperature conductance. The result of this procedure is presented in the lower inset to Fig. 2. The zero temperature conductance at $B > B_{IM}$ is well described by an empirical expression $G(B) = e^2/h(1 - \exp[(B_{IM} - B)/B^*])$ shown by the solid line in the lower inset to Fig. 2. In contrast to the statement of the authors in [2], the resistance at $T \to 0$ on the high-field side of the SIT approaches the value of h/e^2 rather than R_c. The exponential dependence of $G(T = 0, B)$ may result from a broad dispersion of the binding energies of localized Cooper pairs.

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