Insulator-to-superconductor transition driven by a dc current

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Abstract

We measured the resistance of quench-condensed amorphous ultrathin beryllium films near the thickness-tuned superconductor-insulator transition. We observed, quite unexpectedly, that films just on the insulating side of the transition can be driven into a superconducting state when a sufficiently large dc bias current is applied. We show that this current-induced superconducting state is very sensitive to applied perpendicular magnetic fields.

Key words: Thin films; Superconductivity; Quantum phase transition

1. Introduction

One normally expects the application of a dc bias current to degrade superconducting behavior since the current should induce the flow of vortices. Therefore, the observation of a current-driven insulator-to-superconductor transition, as we discuss below, is rather counter-intuitive. This current-induced superconducting behavior is interesting in its own right. It may also have important implications to a number of other subjects. For example, since it is observed in the vicinity of the thickness-tuned superconductor-insulator (SI) transition [1–3], its underlying mechanism could be the key for understanding the SI transition. Furthermore, similar phenomena may also be observable in other disordered low-dimensional systems.

2. Experiment and discussion

The ultrathin Be films used for this study, $\sim$ 10 Å in thickness, were quench-condensed onto glass substrates held near 20 K using a thermal source [4–6]. With increasing film thickness, such Be films undergo a sharp transition from the insulating state to the superconducting state as the film sheet resistance, $R_\Box$, at 20 K is reduced below a critical resistance, R_c, of $\sim$ 10 k$\Omega/\Box$. Thinner films on the insulating side of this superconductor-insulator (SI) transition demonstrate a sharply increasing $R_\Box$ as the temperature is lowered, while the transition temperature, T_c, of the films on the superconducting side increases with increasing film thickness. In the vicinity of the SI transition, films having sheet resistance values very close to 10 k$\Omega/\Box$ at 20 K demonstrate reentrant behavior [4] as shown by Curve (a) in Fig. 1 : film resistance shows a minima and eventually increases sharply with decreasing temperature. Below, we describe a current-driven insulator-to-superconductor transition in such reentrant films.

In Fig. 1, we plot the sheet resistance as a function of the temperature for a typical reentrant film. Such resistance data were measured in a four-terminal geometry using a PAR 124A lock-in amplifier operating at 27 Hz with an ac probe current of 1 nA. The film area between the voltage leads was 3×3 mm^2. Curve (a) measured in the absence of any dc bias current shows the typical reentrant behavior. However, when a sufficiently large dc bias current, $I_{bias} \geq 200$ nA, was applied, the film becomes superconducting, as shown by Curve (b) in Fig. 1 for $I_{bias} = 2.5$ μA. Film sheet resistance increased sharply when I_{bias} was increased above 15 μA, indicating a critical current of about 15 μA for this film. In Fig. 2, we plot the film sheet resistance as a function of the applied perpendicular mag-

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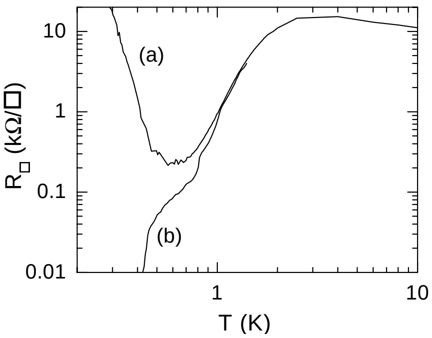

Fig. 1. The sheet resistance of a typical reentrant film in the vicinity of the superconductor-insulator transition is plotted as a function of the temperature. Curve (a) was measured in the zero-current limit, showing a resistance minima near 0.6 K and strongly insulating behavior at lower temperatures. Curve (b) was measured when a dc bias current of $I_{bias} = 2.5\ \mu$A was applied, indicating that this same film becomes superconducting in the presence of the dc bias current.

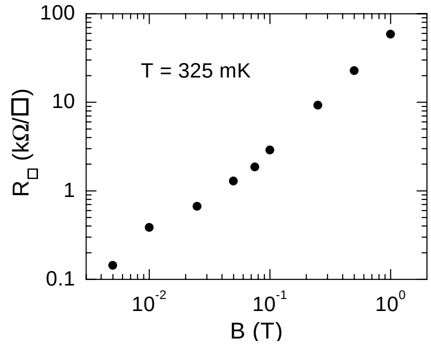

Fig. 2. The sheet resistance of the film in Fig. 1 in the presence of a dc bias current $I_{bias} = 2.5\ \mu$A is plotted at 325 mK as a function of the magnetic field applied perpendicular to the plane of the film, showing that the current-induced superconducting state is very sensitive to the applied magnetic field.

netic field at 325 mK with a bias current $I_{bias} = 2.5\ \mu$A applied to the film. This plot shows that the current-induced superconducting state is suppressed by a weak magnetic field. Therefore, we believe that the above data convincingly shows a current-driven insulator-to-superconductor transition.

In an earlier report [4], we have described the highly anisotropic magnetoconductance data measured in these Be films. Such data allowed us to calculate a finite superconducting phase coherence length, L_ϕ, for films near the SI transition, describing the length scale over which Cooper pairs remain coherent. For reentrant films in the temperature regime where the sheet resistance decreased with decreasing temperature, L_ϕ was found to increase with decreasing temperature. This observation was in agreement with a similar study using quench-condensed Pb films [7]. This increasing L_ϕ resulted from the suppression of thermal fluctuations with decreasing temperature. However, we also observed in the reentrant films [4] that L_ϕ *decreased* with *decreasing* temperature in the low-temperature regime where the film resistance increased with decreasing temperature. Although the exact dephasing mechanism is not understood, this observation shows the competition between superconductivity and localization. For the current-driven insulator-to-superconductor transition reported here, it is unlikely that the current plays a role in inducing pairing. Rather, we believe that the bias current suppresses the localization of the Cooper pairs and restores the superconducting phase coherence. Therefore, understanding the mechanism for this current-driven insulator-to-superconducting transition is crucial for understanding the SI transition.

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