Magnetic-field dependence of the resistance of 2D type-II superconductors in weak magnetic fields

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Peaks have been observed in the resistance of amorphous thin films of NbO_x with a small number of pinning centers in weak magnetic fields, in which the current–voltage characteristics become nonohmic. The width of these peaks depends on the width of the film. The maximum peak height is more than an order of magnitude greater than the flux-flow resistance. It is suggested that the observed increase in the resistance results from a transition of the 2D type-II superconductor into a previously unknown phase. © *1995 American Institute of Physics.*

In this letter we report a study of the resistance of amorphous thin films of NbO_x with a small number of pinning centers in magnetic fields well below the second critical field H_{c2}.

Thin films (with a thickness less than or close to the correlation length, $d \leqslant \xi$) with a small number of pinning centers attracted our interest because of fluctuation-theory predictions[1–3] that fluctuations in 2D type-II superconductors may destroy the Abrokosov state not only near H_{c2}, as in 3D superconductors, but also over a wide part of the mixed state.

Previous studies[4] have shown that pinning arises in amorphous NbO_x films not near H_{c2}, as in bulk type-II superconductors,[5,6] but far below H_{c2}. As in Ref. 5, we detected the pinning from the onset of a nonohmic shape of the current–voltage characteristics in a perpendicular magnetic field. In certain films—ones which we believe have the fewest inhomogeneities—pinning does not arise until we reach fields weaker than H_{c2} by a factor of a thousand. The results of our study, primarily of these films, are reported in this letter.

The NbO_x films were grown by magnetron sputtering of Nb in a mixture of argon and oxygen. By varying the oxygen content in the mixture we could vary the content in the resulting film. The films used in the present study had the approximate chemical formula $Nb_{80}O_{20}$. Their composition was determined by Auger analysis. Transmission electron microscopy revealed that these films have an amorphous structure. The films had a transition temperature T_c of 1.8–2.8 K and a derivative $dH_{c2}/dT \simeq 22$ kOe/K. The second critical field was determined from measurements of the paraconductivity. The thickness of the films was 20 nm. The resistance in the normal state was 100 $\Omega/\Box$. The

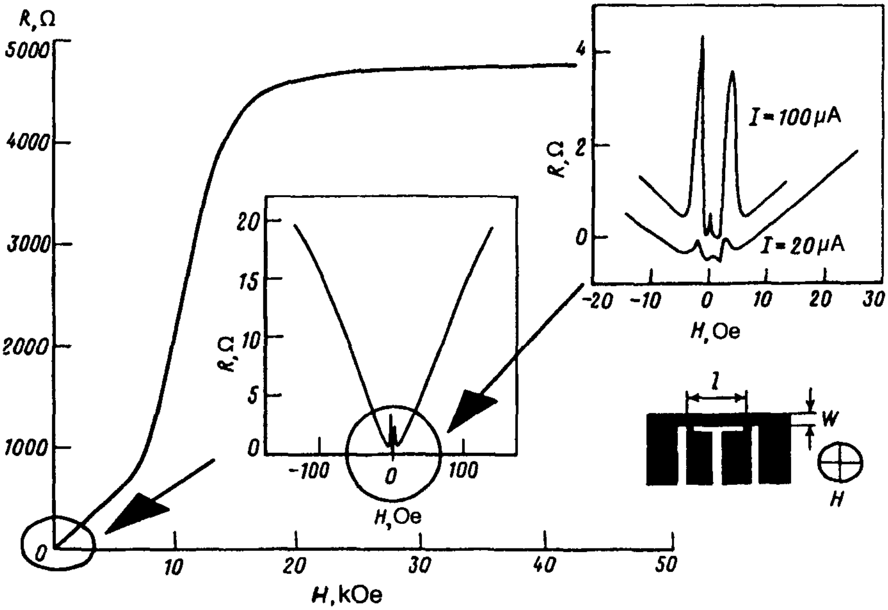

FIG. 1. The resistance $R = V/I$ versus the strength of the perpendicular magnetic field for an amorphous NbO_x film with a thickness $d = 20$ nm and a width $w = 50$ μm at the temperature $T = 1.68$ K ($T_c = 2.23$ K, $H_{c2} = 12\,700$ Oe). The distance between the potential contacts was $l = 2250$ μm. The curve for the current $I = 20$ μA in the second inset is shifted downward on the y axis by 0.6 Ω.

temperature dependence of the normal resistance was very weak. The relative change in this resistance over the temperature range 20–40 K, in which superconducting fluctuations are small, did not exceed 0.0002. The resistance increased with decreasing temperature, perhaps because of a weak localization. For the measurements we used film structures prepared by lithography (Fig. 1).We carried out the resistance measurements in strips with widths $w = 10$ and 50 μm. The distance between the potential contacts was $l = 2250$ μm. The perpendicular magnetic field was produced by a superconducting solenoid.

Previous studies[4] had shown that the behavior of the excess conductance as a function of the temperature and strength of a perpendicular magnetic field is described by the Ami–Maki paraconductivity theory[7] above H_{c2}, in the region in which the linear approximation is valid. That result confirms that the films are homogeneous 2D type-II superconductors. In the critical region, both above and below H_{c2}, the behavior of the excess conductivity as a function of the temperature and the magnetic field is described by the theoretical expression derived in the Hartree approximation for the paraconductivity for a case in which there is an interaction of fluctuations. Below H_{c2} the resistance falls off monotonically with decreasing magnetic field (Fig. 1). Far from H_{c2}, the resistance is close to the flux-flow resistance (Fig. 1).

In weak magnetic fields H_w the current–voltage characteristics become nonohmic. The resistance $R = V/I$ measured at a current density above 10^3 A/cm^2 does not decrease,

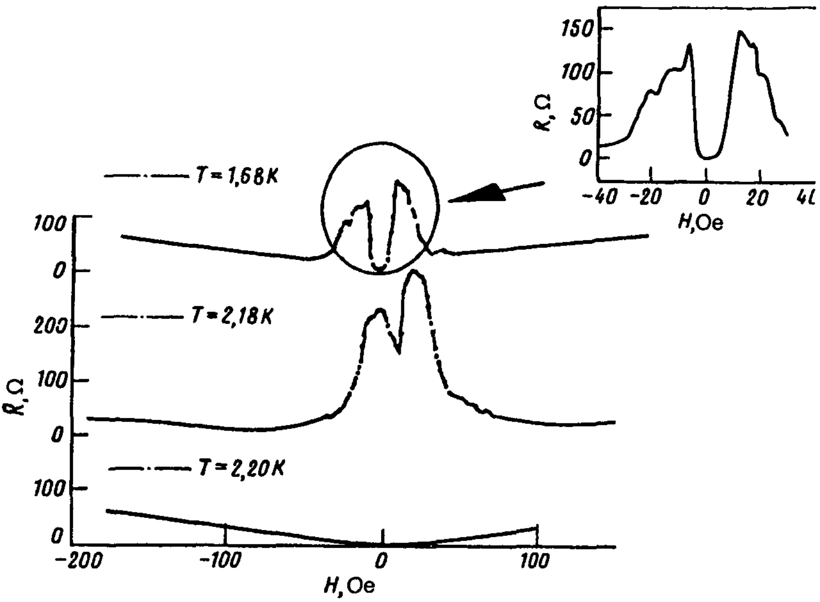

FIG. 2. The resistance $R=V/I$ versus the strength of the perpendicular magnetic field for an amorphous NbO_x film with a thickness $d=20$ nm and a width $w=10$ μm at various temperatures. $T_c=2.65$ K, $(dH_{c2}/dT)_{T=T_c}=-22$ kOe/K, $R_n=$ 23 000 Ω. The distance between the potential contacts is $l=2250$ μm. The current is $I=12$ μA.

as it has been observed to do in bulk superconductors,[5,8] but instead increases (Figs. 1 and 2). The value of H_w depends on the width of the strip used for the measurements (Figs. 1 and 2). For a strip with a width $w=50$ μm at $T=1.68$ K, we have $H_w=6$ Oe ($H_{c2}=12\,700$ Oe, $T_c=2.23$ K) (Fig. 1). In a strip of width $w=10$ μm at $T=1.73$ K, we have $H_w=40$ Oe ($H_{c2}=18\,000$ Oe, $T_c=2.65$ K) (Fig. 2). As the temperature is raised to $T=2.18$ K, this field increases (Fig. 2).

As the magnetic field is weakened further, the resistance $R=V/I$ increases, goes through a maximum at $H=H_p$, and then falls off sharply (see the figures). In a film 50 μm wide we observe a single large peak, at a field approximately equal to $H_p=2$ Oe at $T=1.68$ K (Fig. 1). The position of this peak does not depend on the value of the current I at which the resistance is measured (Fig. 1). In a film 10 μm wide at $T=1.7$ K with $I=12$ μA, we observe three peaks, at fields of 20, 15, and 10 Oe. The height of the largest of these peaks reaches 150 Ω at $H=H_p=10$ Oe (Fig. 2; the resistance in the normal state is $R_n=23\,000$ Ω; before the peaks, at $H=40$ Oe, we have $R=13$ Ω). As the magnetic field is reduced below H_p, the resistance decreases sharply and vanishes. Measurements carried out on a strip 10 μm wide showed that the critical field can exceed 10 mA (5×10^6 A/cm^2) in a zero magnetic field (without screening).

As the temperature is raised, the resistance peaks increases in height, but then they quickly disappear (Fig. 2). In a film with $T_c=2.65$ K the resistance peaks are observed below 2.2 K; in a film with $T_c=1.95$ K they are observed below 1.45 K.

These resistance peaks were not observed in all the samples, and they varied in height. High peaks were observed only in samples with ohmic current–voltage characteristics at $H > H_w$.

The measurement current density did not exceed 10^4 A/cm^2. This is three orders of magnitude below the depairing current and far below the measured critical current 5×10^6 A/cm^2 in a zero magnetic field. The magnetic field generated by this current at the edge of this film is 0.03 Oe, much smaller in scale than the fields at which the effect described above is observed. Accordingly, this effect cannot be caused by known dissipation mechanisms involving the induction of normal regions of various types (thermal normal domains, edge injection of vortices and antivortices, a phase-slippage line, or a dissociation of Kosterlitz–Thouless vortex–antivortex pairs[9]) by the transport current.

Above H_w the magnetic-field dependence of the resistance can be described by a generalized Bardeen–Stefan formula $R/R_n = k \cdot 2\pi\xi^2 B/\Phi_0 = kn$, where n is the volume fraction of the film occupied by the normal phase, B is the magnetic induction, Φ_0 is the flux quantum, and the coefficient k, which is determined by various dissipation mechanisms,[10] has a value of 0.25 at $T = 1.7$ K. This value is close to that which has been measured in amorphous superconductors.[11]

The increase in the resistance below H_w may thus be due to an increase in the coefficient k caused by a change in dissipation mechanism or due to an increase in the volume fraction of the film occupied by the normal phase. We regard the latter possibility as unlikely, since the value of n should decrease with decreasing magnetic field according to thermodynamic considerations. We accordingly suggest that the increase in the resistance below H_w is due to a change in dissipation mechanism, which may be caused by a change in the spatial distribution of the normal phase. It has been shown[3] that the spatial distribution of the order parameter is a less stable characteristic than the average density of this parameter.

The increase in resistance is accompanied by a qualitative change: The current–voltage characteristics become nonohmic. This effect and also the circumstance that the effect is observed in certain limited ranges of the temperature and the magnetic field suggest that the effect stems from a transition of the superconductor into a new state.

The value of H_p is inversely proportional to w. This dependence of the position of the resistance peak on the width is characteristic of a Josephson junction. If we assume that H_p corresponds to the flux quantum Φ_0, we can estimate an effective "magnetic" length: $d_m = \Phi_0 / wH_p = 20\ \text{Oe} \cdot \mu\text{m}^2 / 100\ \text{Oe} \cdot \mu\text{m} = 0.2\ \mu\text{m}$.

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