Nonlocal magnetoresistance of bismuth films in nonuniform field of Abrikosov vortices

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Certain aspects of the behavior of a weakly localized magnetoresistance stem from the circumstance that the phase relaxation length L_φ is greater than the size of the region into which the magnetic field penetrates.

By putting a sample in the immediate vicinity of the surface of a superconductor [Fig. 1(a)] one can experimentally realize a situation in which the distance over which the magnetic field varies in the sample is much smaller than one of the length scales of the properties of the sample. Certain effects which might occur in a microscopically nonuniform magnetic field were studied in Refs. 1–3. It was shown in Refs. 1 and 3 that at sufficiently low temperatures a magnetic field which varies periodically in space can give rise to minigaps in the energy spectrum of highly mobile 2D electrons (a "magnetic superlattice"). Rammer and Shelankov[2] calculated the weak-localization corrections to the conductivity in a nonuniform magnetic field.

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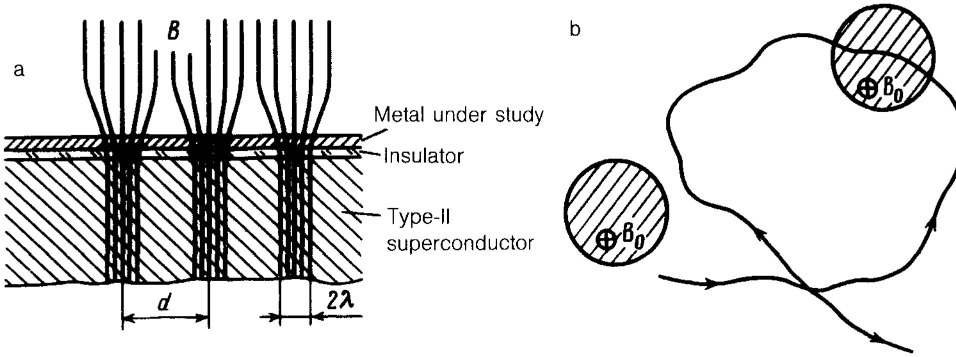

FIG. 1.

In this letter we are reporting a study of a weakly localized magnetoresistance of thin Bi films in a perpendicular magnetic field near the surface of a type-II superconductor. The magnetic flux penetrates into a superconductor of this sort in the form of flux quanta (fluxoids) (Abrikosov vortices) which have a characteristic dimension $\approx 2\lambda$ (λ is the depth to which the magnetic field penetrates) and which are separated from each other by distances $d \approx (\phi_0/B)^{1/2} \approx 5[B(\mathrm{G})]^{-1/2}$ μm. The nonuniformity of the magnetic field persists over a distance d from the surface of the superconductor.[2,3] In the experiments, single-crystal wafers of Nb-5% Mo with dimensions of $10\times10\times0.2$ mm were used. These wafers had the following properties: $\lambda \approx 850$ Å, $H_{c1} \approx 350$ Oe, $H_{c2} \approx 4.2$ Oe at $T = 4.2$ K, and $T_c \approx 7.6$ K. The superconductor was covered with an insulating anodic oxide 200-300 Å thick. A Bi film (≈ 200 Å thick, with a surface resistance $\rho \approx 400$ Ω/□) was deposited on the surface of this oxide.

The solid lines in Fig. 2 show the resistance in a uniform magnetic field of control films deposited on a quartz substrate. The observed behavior is associated with a weak localization of the electrons with strong spin-orbit scattering and is described by

$$\Delta R / R = (1/2)(e^2/\pi h)\rho f_2(B/B_\varphi), \qquad (1)$$

where $B_\varphi = \phi_0/4\pi L^2_\varphi$ (Ref. 2), and $L_\varphi \approx 0.12$ μm at 4.2 K and ≈ 0.3 μm at 1.3 K. These values are typical of Bi films of this thickness.

An experimental study of the magnetoresistance in the field of Abrikosov vortices is seriously complicated by the spatially nonuniform penetration of vortices into the superconductor, associated with pinning at defects.[4] As the external magnetic field B_e is varied, a gradient appears in the vortex concentration: $\partial n/\partial x \approx \mu_0\phi_0^{-1}\,\Delta N J_c$, where J_c is the critical current, and ΔN is the deviation of the demagnetizing factor of the wafer from unity.[4] Despite the low critical current density in the Nb–Mo samples which we used ($J_c \approx 10^2$ A/cm^2 in moderate magnetic fields), the pinning was sufficient to completely screen the magnetic field from the central part of the sample, up to values $B_e \approx 200$ G. In order to achieve a uniform distribution of vortices over the entire Bi film, we cooled the samples at each selected value of the magnetic field, from $T > T_c$ to the measurement temperature: 1.3 K or 4.2 K. That this procedure for

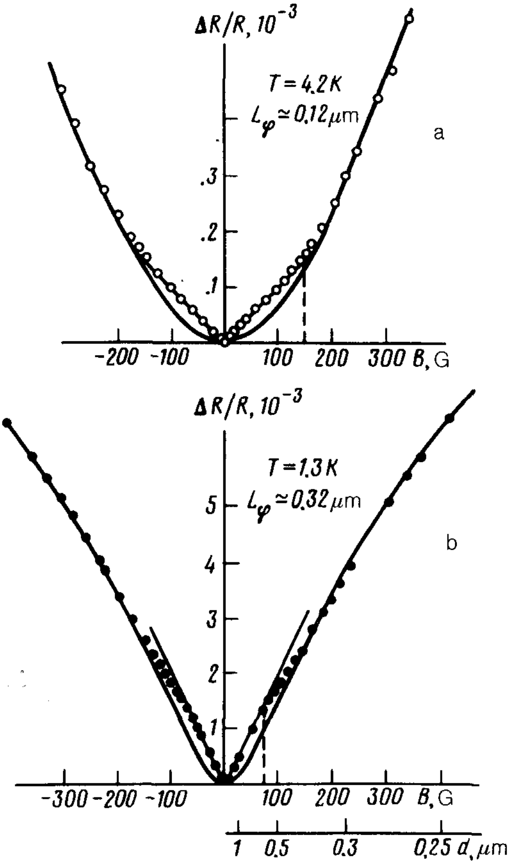

FIG. 2. Magnetoresistance of a bismuth film in (solid lines) a uniform magnetic field and (points) a microscopically nonuniform field produced by Abrikosov vortices.

introducing the magnetic field resulted in a uniform distribution of vortices was confirmed by numerous direct observations of the vortex structure through a decoration with ferromagnetic particles, in some cases on the Nb-Mo samples which we used[1)] (Ref. 5). Further evidence that the concentration of vortices which penetrate the Bi film corresponds to the external magnetic field ($B = B_e$) comes from the observed linear dependence of the Hall resistivity $\rho_{xy} = R_x B$ of the test film on B_e over the entire range of magnetic fields.

The values found for ΔR^*, the magnetoresistance of the Bi film in the field of the Abrikosov vortices, are shown in the points in Fig. 2. Aspects of the behavior of the magnetoresistance which are the same at $T = 1.3$ K and 4.2 K are the linear dependence of the resistance, $\Delta R^*(B)$, in weak fields (< 50 G) and the agreement of ΔR^* and the resistance in a uniform magnetic field, $\Delta R(B)$, at $B > 200$ G. The linear magnetoresistance evidently means that the individual vortices act independently on the conductivity of the Bi when they are far apart ($d \gg L_\varphi, \lambda$): ΔR^* increases in proportion to the concentration of vortices. A decrease in d leads to an overlap of the magnetic fields of the individual vortices and to a decrease in the nonuniformity of the magnetic field in the Bi film, with the result that the $\Delta R(B)$ dependence sets in.

The behavior of ΔR^* at 4.2 K agrees qualitatively with the magnetoresistance expected in a nonuniform magnetic field is the local limit[2]: $L_\varphi \ll \lambda$. In this case the magnetic field varies fairly slowly over space, and the magnetoresistance is described by expression (1), with the magnetic field being a function of the coordinates. If we simplify the situation and treat the vortices as regions in which the magnetic field has a constant induction B_0, we can write[2]

$$\Delta R^*(B) = (B/B_0)\Delta R(B_0). \tag{2}$$

In the local limit at $B \ll B_0$ the magnetoresistance should therefore be a linear function of B, while at $B \gg B_0$ the behavior described by (1) should set in. Incorporating the actual spatial distribution of the magnetic field in a vortex,[4] $\approx K_0(r/\lambda)$ leads to (2) with $B_0 \approx 0.5H_{c1}$ at low value of B. As B is increased, the overlap of the fields of the individual vortices leads to an increase in the resultant magnetic field in the vicinity of each vortex, and at distances $d^* \lesssim 2\lambda_{eff}$ ($\phi_0 = B_0\pi\lambda^2_{eff}$) between vortices there should be a significant deviation of the magnetoresistance from a linear behavior, in the direction of an increase (!) in ΔR^*. This behavior of the magnetoresistance has been seen experimentally at 4.2 K ($L_\varphi \approx \lambda$); the values $B_0 \approx 0.5H_{c1} \approx 150$ G and $\lambda_{\rm eff} \approx 0.2$ μm found from Fig. 2 agree well with H_{c1} and λ of Nb-5% Mo.

Cooling the samples from 4.2 K to 1.3 K results in a pronounced (threefold) increase in L_φ, while leaving the other properties of both the Bi and Nb–Mo films essentially constant (in particular, λ decreases by only 5%; i.e., essentially no structural changes occur in the magnetic field in the film). The behavior of the magnetoresistance observed here [Fig. 2(b)] differs in a qualitative way from that which we would expect in the local case at 1.3 K. In the first place, in low magnetic fields the slope of the $\Delta R^*(B)$ line exceeds that in the local limit [expression (2)]. Furthermore, an extrapolation of the linear dependence to strong fields does not intersect the $\Delta R(B)$ curve. Second, the deviation from a linear magnetoresistance is in the direction of a decrease in ΔR^*, again in contradiction of a local behavior. Third, the external magnetic field which corresponds to a significant deviation of ΔR^* from a linear behavior for $L_\varphi \approx 0.3$ μm is roughly half that for $L_\varphi \approx 0.1$ μm [cf. Fig. 2(a)].

We link these features of the magnetoresistance with a transition to a nonlocal case: $L_\varphi \gg \lambda$ (Ref. 2; the actual value in the experiments was $L_\varphi \approx 4\lambda$), so that the weak-localization corrections to the conductivity are formed in a very nonuniform magnetic field. A corresponding calculation was carried out in Ref. 2 for $d \gg L_\varphi$; it was shown there that the linear magnetoresistance increases greatly in comparison with the local limit:

$$\Delta R^*_{NL} / \Delta R^*_L \approx \frac{(B_0/B_\varphi)}{\ln^2(B_0/B_\varphi)} . \tag{3}$$

The subscripts NL and L specify the nonlocal and local limits, respectively. The increase in the magnetoresistance is explained on the basis that the magnetic field of the vortices results in a phase relaxation on paths with self-intersections, which pass not only inside the regions with a magnetic field but also outside them [Fig. 1(b)]. The effect of the magnetic field is intensified in accordance with the ratio of areas: $L^2_\varphi/\lambda^2 \approx B_0/B_\varphi$. This estimate agrees with logarithmic accuracy with (3). The nonlocal effect of the magnetic field has the further consequence that regions of the Bi film which are affected simultaneously by two or more vortices appear in magnetic fields B_e which are weaker than those at which the magnetic fields of the individual vortices overlap (and at larger values of d) [Fig. 1(b)]. The corresponding distance d^*) over which the behavior of ΔR^*_{NL} should deviate from linearity can be estimated from $d^* \approx 2\lambda_{\text{eff}} + L_\varphi$. The experimental values found from Figs. 2(a) and 2(b), d(4.2 K) $\approx$0.4 μm and d(1.3 k) $\approx$0.6 μm, agree numerically with this formula.

In summary, these experiments have revealed a nonlocal effect of a magnetic field on the conductivity which is evidence of the formation of weak-localization corrections at distances on the order of L_φ.

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