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Penetration depth of a superconducting superlattice

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We have measured the magnetic-flux expulsion of a superconducting superlattice and related it to the Meissner penetration depth. The temperature dependence of the penetration depth is in quantitative agreement with theoretical expectation based on mean-field theory. The zero-temperature penetration depth is found in excellent, quantitative agreement without adjustable parameters with theoretical predictions for dirty superconductors.

The physical properties of superconducting superlattices have received considerable attention in recent years.[1] This was mainly motivated by the observation of the dimensional crossover phenomenon in the temperature-dependent upper critical field of Josephson[2] and proximity[3] coupled multilayers. The measurement of the Meissner penetration depth, however, has received very limited attention.[4,5] We present here a measurement of the magnetic flux expulsion and penetration depth in Nb/Cu superlattices. The temperature and magnetic field dependence of the flux expulsion and penetration depth agree with predictions based on the two-fluid model.[6] The functional relation of the zero-temperature penetration depth to the residual electrical resistivity and the critical temperature T_c follows quantitatively Gorkov's relation[7] for dirty superconductors.

Nb/Cu superlattices have been prepared and characterized as described earlier.[8] Briefly, the samples (~ 1 μm thick) were prepared on $\sim 200\,^{\circ}$C single-crystal sapphire substrate by alternately rotating above a Nb and Cu sputtered beam. The thickness of the multilayer was determined by four independent methods: (1) high-angle superlattice x-ray diffraction peaks, (2) low-angle multilayer x-ray diffraction peaks, (3) calculation based on sputtering rate and time spent above each source, and (4) by dividing the experimentally measured thickness by the total number of passages above each gun. All these measurements gave values which were within 5% of each other. The superconducting flux expulsion in a parallel field was measured directly in the temperature range 1–10 K and field range 1–10 G using a flux transformer coupled to a SQUID. The field was applied parallel to the sample and was supplied by a superconducting coil in the persistent mode. Care was taken to avoid spurious signals from the Cu sample holder. The temperature was measured with an accuracy of 1 mK using a calibrated germanium thermometer with a heater in a feedback loop. More details on the apparatus and measuring technique are given in Ref. 9. Checks were also run by performing measurements on pure In and amorphous ribbons[9] of Zr_xCu_{1-x}.

Figure 1 shows a typical flux-expulsion curve measured for a Nb(54 Å)/Cu(54 Å) sample. All measurements were done by cooling the sample in a constant applied magnetic field. In this case, the change in magnetic flux is proportional to the field and is reversible with temperature. If the sample is cooled in zero field below T_c before the magnetic field is applied, the change in flux measured for increasing temperature, at constant H (<10 Oe), is irreversible in temperature and the results are typical of multiply connected samples. The origin of this behavior is under investigation. In such low fields a complete Meissner state is expected with the expelled flux proportional to the field. This is beautifully illustrated in Fig. 1 where the field was applied above T_c and the flux expulsion for six different applied fields was found to fall on a universal curve, if normalized by the externally applied field.

The flux expelled from the sample is given by $\Delta\Phi(t) = H_0 D[d - 2\delta(t)]$, where $t = T/T_c$ is the reduced temperature, D and d are the width and thickness of the sample, respectively, and $\delta(t)$ is the experimental penetration depth defined by

$$\delta(t) = \frac{1}{H_0}\int_0^{d/2} H(x,t)\,dx \ , \qquad (1)$$

H_0 being the external applied field. The relation between

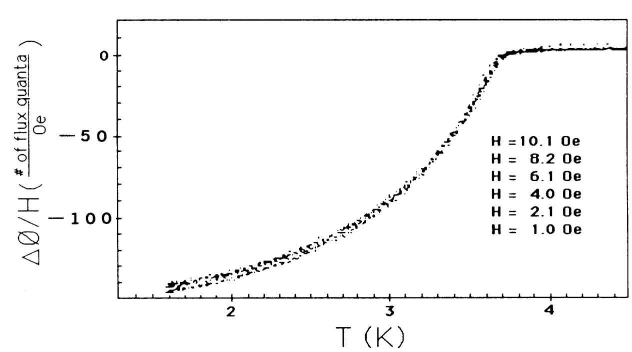

FIG. 1. Normalized expelled flux ($\Delta\phi/H$) vs temperature for a Nb(54 Å)/Cu(54 Å) sample in six different fields in the range 1–10 G. The width of the sample is ~ 0.6 cm and the thickness is ~ 1 μm. The low-temperature flux expulsion observed in this figure is of the order of 50% of the total expulsion it would have for a zero penetration depth.

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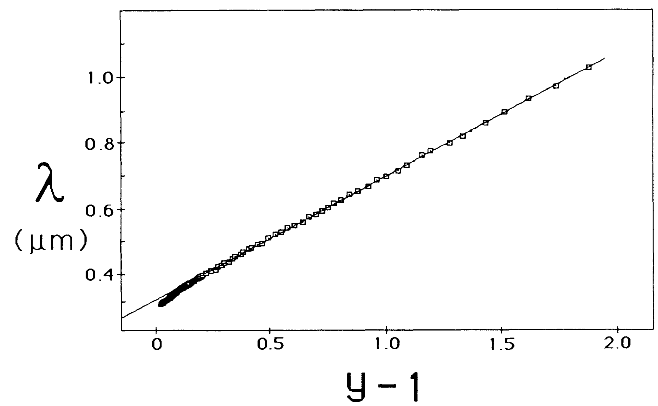

FIG. 2. Penetration depth, λ vs $(y-1)$, $y=(1-t^4)^{-1/2}$ (open squares). The theoretical prediction based on the two-fluid model is given by the solid line.

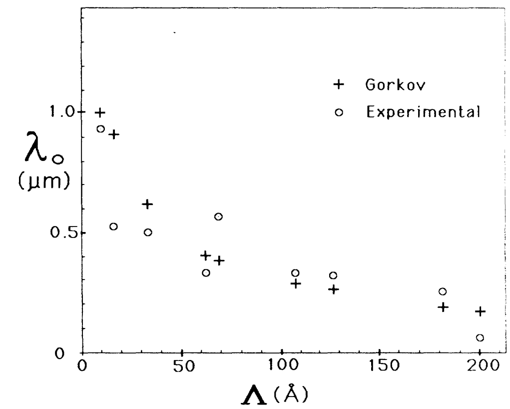

FIG. 3. Slope of the temperature-dependent penetration depth λ_0 as a function of superlattice periodicity Λ extracted from the slopes in Fig. 2 and from Gorkov's theory using Eq. (3).

$\phi(t)$ and $\lambda(t)$ is given by[6] $\delta(t)=\lambda(t)\tanh[d/2\lambda(t)]$. The temperature dependence of the penetration depth from the two-fluid model together with theoretical predictions for dirty superconductors[7] gives

$$\lambda=\lambda_0 y \ , \qquad (2)$$

where

$$\lambda_0=1.29\times10^{-2}(\rho/T_c)^{1/2},\ y=(1-t^4)^{-1/2} \ , \qquad (3)$$

and ρ is the normal state resistance of the sample. Agreement with this temperature dependence is illustrated in Fig. 2, where the penetration depth is plotted as a function of $y-1$. The deviation from the straight-line prediction given by this simple model is expected and is due to the temperature dependence of the superconducting energy gap. We should point out the samples measured in this study are strongly coupled[3] so dimensional effects are not expected to show up.

The slopes[10] of curves similar to the one in Fig. 2 for a number of samples are plotted in Fig. 3. These values can be compared directly (Fig. 3) to the ones obtained from a calculation based on Gorkov's theory and the independently measured transition temperatures[11] and resistivities[12] [Eq. (3)]. The intrinsic assumption in this comparison is that only the parallel resistivities contribute to the flux expulsion. This assumption is expected to hold since most of the shielding currents flow parallel to the sample surface. It is important to note that *no adjustable parameters* are used in this comparison. Within the scatter in the data the agreement is excellent. The general trends in the data are also consistent with the unpublished conclusions of Refs. 4 and 5.

In summary, we have measured directly the flux expulsion as a function of magnetic field and temperature in Nb/Cu superlattices. The penetration depth extracted from these measurements is in excellent quantitative agreement with theoretical predictions without adjustable paramaters.

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