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Effect of Transverse Magnetic Fields on dc Josephson Current*

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We have observed diffraction patterns in critical dc Josephson tunnel current versus magnetic field applied perpendicular to the junction plane. The patterns can be explained by assuming that the perpendicular field penetrates the edge of each film and channels through the junction parallel to the films. An "edge penetration depth," $\lambda_\perp$, gives a quantitative description of the patterns and their dependence on the angle of field direction. We have found $\lambda_\perp(T)\propto(1-T/T_c)^{-1/2}$.

If a magnetic field is applied parallel to the plane of a Josephson tunnel junction, the zero-voltage critical current (I_c) as a function of magnetic field (H) will exhibit a diffractionlike pattern.[1,2] Existing theory[2-4] shows that I_c is given by

$$I_c=I_J\left|\frac{\sin(\pi HLd/\Phi_0)}{\pi HLd/\Phi_0}\right|, \qquad (1)$$

where I_J is the Josephson zero-voltage critical current in zero magnetic field, L is the dimension of the junction perpendicular to H, $d=2\lambda_\parallel+l\approx 2\lambda_\parallel$ with $\lambda_\parallel$ the surface penetration depth and l the oxide thickness, and Φ_0 is the magnetic flux quantum equal to 2×10^{-7} G cm^2. The critical current goes to zero whenever the junction contains an integral number of flux quanta, i.e., for the nth zero the magnetic field satisfies

$$H_n=n\Phi_0/Ld, \quad n=1,2,\ldots . \qquad (2)$$

According to this theory, if the magnetic field is applied at an angle θ with respect to the plane of the junction (see inset of Fig. 1) the magnetic field necessary to produce the nth minimum of

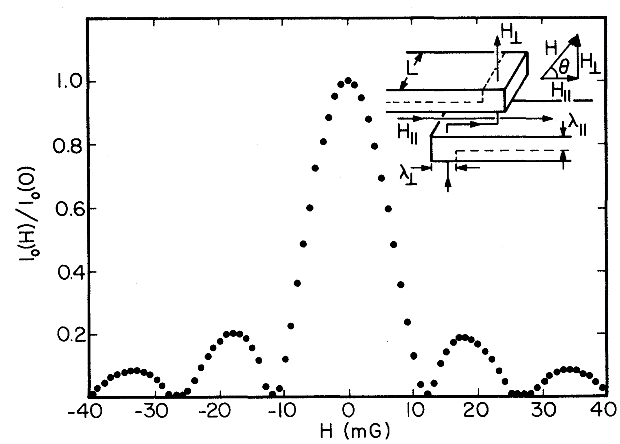

FIG. 1. Typical diffraction pattern for $\theta=90°$ at $T=2.50$ K. Junction dimensions are 0.74 mm×0.35 mm. The inset shows the magnetic-field orientation relative to the junction.

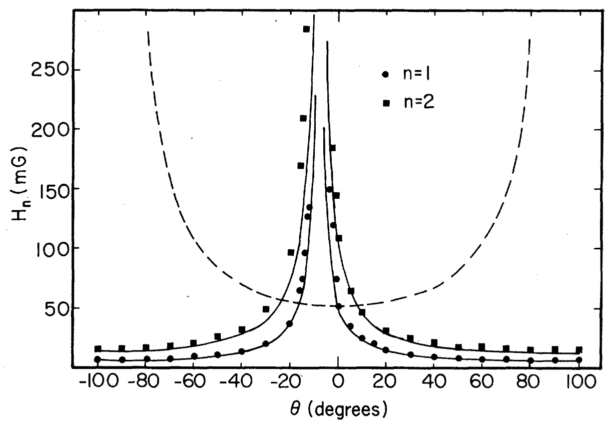

FIG. 2. Comparison of angular-dependence data with theory. Dashed line is proportional to $(\cos\theta)^{-1}$; solid lines are from Eq. (4).

the diffraction pattern will increase as $(\cos\theta)^{-1}$. This is because only the parallel component of H will determine the diffraction pattern. Therefore, if the magnetic field is applied in the perpendicular direction, the diffraction pattern should not be observed. Contrary to this conclusion, as shown in Fig. 1, we have observed diffraction patterns in perpendicular magnetic fields. We have also studied the angular dependence of H_1 and H_2 (which are the magnetic fields required to produce the first and second minima respectively). The result is entirely different from the expected behavior as shown in Fig. 2.

The samples studied were Pb-PbO_x-Pb Josephson tunnel junctions of film thickness greater than 3000 Å prepared by conventional techniques of evaporation and oxidation. The I-V characteristics were typical of ideal junctions showing no evidence of leakage current or metallic shorts in the oxide. This is supported by the fact that the minima of I_c versus H do go to zero. The applied magnetic fields (in the range of milligauss) are much smaller than the perpendicular critical field H_{c1}.[5] So it is not expected that $H_\perp$ will penetrate the film into the junction. Also, $H_\perp$ is so small as not to affect I_J.[6]

To account for the above experimental observations, we assume that $H_\perp$ near the film edge can channel through the junction in the parallel direction.[7] For simplicity, we call this distance an edge penetration depth $\lambda_\perp$, in contrast to the surface penetration depth $\lambda_\parallel$. Therefore $H_\perp$ within a distance of $\lambda_\perp$ from the film edge will contribute to the magnetic field enclosed by the junction by an amount equal to $\lambda_\perp H\sin\theta/2\lambda_\parallel$ in the parallel direction. Using the existing theory with the above added contribution gives

$$I_c = I_J\left|\frac{\sin[\pi(\lambda_\perp LH\sin\theta + 2\lambda_\parallel LH\cos\theta)/\Phi_0]}{\pi(\lambda_\perp LH\sin\theta + 2\lambda_\parallel LH\cos\theta)/\Phi_0}\right|. \quad (3)$$

According to Eq. (3), I_c will be zero whenever the magnetic field satisfies the condition

$$n\Phi_0 = \lambda_\perp LH_n\sin\theta + 2\lambda_\parallel LH_n\cos\theta, \quad n = 1, 2, \ldots . \quad (4)$$

The parameters $\lambda_\parallel$ and $\lambda_\perp$ were obtained from the experimental values of H_1 at $\theta = 0°$ and $\theta = 90°$, respectively. For the sample shown in Fig. 2, $\lambda_\parallel$ is 2600 Å and $\lambda_\perp$ is 37 000 Å at 4.75 K. The comparison between experimental data and the theoretical curves ($n = 1$ and 2) using Eq. (4) is shown in Fig. 2. Agreement is quite good. The salient feature of Eq. (4) is that it predicts that $H_n(\theta)$ has an asymmetrical singularity at an angle $\theta = \tan^{-1}(-2\lambda_\parallel/\lambda_\perp) = -8°$. As can be seen, this is indeed the case within the experimental error of approximately $\pm 1°$.

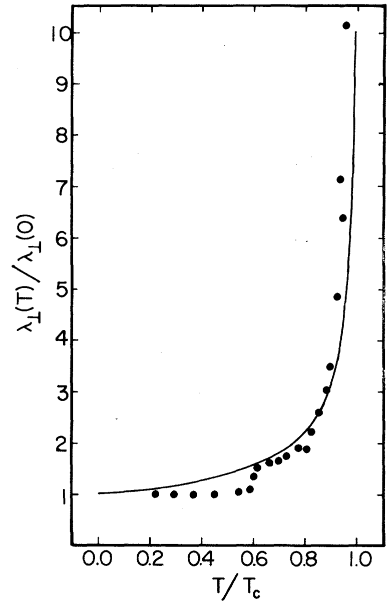

FIG. 3. Temperature dependence of $\lambda_\perp$ compared with theoretical temperature dependence of $\lambda_\parallel$.

To gain insight into the meaning of $\lambda_\perp$ we have studied its temperature dependence. In Fig. 3 the solid line shows $(1 - T/T_c)^{-1/2}$ which is the temperature dependence of $\lambda_\parallel$, valid for T near T_c. The experimental points for T/T_c greater than about 0.6 show a similar temperature dependence, suggesting that $\lambda_\perp$ can be interpreted as an edge penetration depth. If this is indeed the case, then a study of perpendicular diffraction patterns in Josephson tunnel junctions provides a means of investigating the temperature dependence of the edge penetration depth in superconductors, in a similar manner as has been done with the surface penetration depth.[8]

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Limiting Flux-Passage Time in Narrow Superconductors

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A limiting value for the supercurrent response of narrow superconductors upon flux passage has been deduced from measurements of the 9.2-GHz impedance of thin cylindrical films. The observed times are in good agreement with the predicted relation $\tau_1 \simeq \hbar/2\Delta(T)$, where $2\Delta(T)$ is the BCS energy gap for the material.

In the last several years much work has been devoted to the understanding of the dynamic behavior of superconductors under nonequilibrium conditions. Times characteristic of the coupled responses of the Cooper pairs, the quasiparticles, and the phonons have been extensively studied. In a recent paper[1] Langenberg has surveyed many of these characteristic times and concluded that there still remains considerable uncertainty in both theory and experiment. Several years ago Mercereau introduced a "finite relaxation time for the flux change" in a model for the operation of rf-biased thin-film superconducting quantum interference devices (SQUID's).[2] The flux movement in these devices is localized at a weak-link section of the film. In the limit of small weak links, where the weak-link dimensions are less than a coherence length, Mercereau deduced that the flux-passage time would have a minimum limiting value, $\tau_1 \sim \hbar/2\Delta(T)$, where $2\Delta(T)$ is the temperature-dependent BCS energy gap. The minimum response time of a SQUID, therefore, is found to be limited by the lifetime of the Cooper pairs in the weak link. This limiting response time may simply reflect the charateristic delayed response of a supercurrent to an electric field.[3] For SQUID's operating in the frequency range from 1 to 30 MHz, τ_1 can be ignored since the time between flux passages never approaches the flux-passage time. In studying SQUID's at microwave frequencies, however, we find that τ_1 can no longer be ignored, but can in fact be directly inferred from the data. We find that the magnitude and temperature variation of our experimental values for the flux-passage time, τ_1, agree quite well with Mercereau's