Elementary Pinning Force for a Superconducting Vortex

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The elementary pinning force f_p has been measured for a single vortex trapped in one of the superconducting layers of a cross-strip Josephson junction. At temperatures close to the transition temperature the vortex can be pushed across the junction by a transport current. The vortex is found to move in a small number of discrete steps before it exits from the junction. The pinning force for each site is found to be asymmetric and to have a value of about 10^{-6} N/m at the reduced temperature $t=T/T_c=0.95$. As a function of temperature, f_p is found to vary approximately as $(1-t)^{3/2}$.

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The elementary pinning force f_p for a single quantized vortex is a fundamental quantity that previously has not been directly measured, because it is difficult to locate a single vortex and follow its motion under the influence of a known applied force. With the discovery that diffraction patterns in the Josephson critical supercurrent versus applied magnetic field, I_c vs B, can be used to locate a vortex in a junction,[1-3] the essential ingredients became available to measure f_p directly.

In the past few years there has been considerable progress in the theoretical understanding of both the elementary pinning force[4,5] and the depinning critical current for a flux-line lattice.[5,6] Extensive experiments involving a lattice of vortices show rather good agreement with many aspects of the theory, especially in the regime where the collective pinning models apply. Kes recently has written[6] an excellent review of the situation. So far, however, all the experimental work has centered on depinning of a flux-line lattice. In this paper an experimental study of depinning of a single vortex is reported.

The basic idea of the experiment is to trap a single vortex in a cross-strip Josephson junction by cooling the junction through the transition temperature T_c in a small magnetic field applied perpendicular to the plane of the junction, $B_{\perp \mathrm{cool}}$. The perpendicular field is then turned off and the location of the vortex is determined from a diffraction pattern similar to a Fraunhofer pattern for I_c vs $B_\parallel$, where I_c is the Josephson critical current and $B_\parallel$ is a field applied parallel to the plane of the junction. As shown previously,[1,2] there is a unique diffraction pattern for each location of the vortex in the junction. For this work, a superconductor–normal-metal–superconductor (S-N-S) junction with a thick N layer ($\sim$800 nm) is used so that the vortex in the primary S layer (bottom strip) is nearly decoupled from the vortex in the secondary S layer (top strip). This decoupling permits a large misalignment of the vortex in the primary from the one in the secondary and a substantial component of B field in the N layer parallel to the junction. It is this parallel field from the vortex misalignment that contributes to distortions in the diffraction patterns. With this decoupling, the vortex in the primary can be pushed around by a control current I_p flowing in the primary strip of the junction. The force per unit length on the vortex is then $\mathbf{J}_p \times \boldsymbol{\phi}_0/c$, where J_p is the current density, ϕ_0 is the flux quantum of 2.07×10^{-7} G cm^2, and c is the speed of light. Although a full diffraction pattern is needed to specify the location of the vortex, the parameter usually used to detect motion of the vortex is the Josephson critical current at zero field, I_{c0}.

To conduct an f_p measurement, a vortex is trapped by field cooling; $B_{\perp \mathrm{cool}}$ is turned off; I_{c0} is measured; I_p is raised to some value and turned off; I_{c0} is measured again to see if the vortex has moved; if not, the procedure is repeated for increasing I_p until I_{c0} changes; the depinning current I_p^d is defined as the lowest value of I_p needed to move the vortex. Once the vortex has moved, a full diffraction pattern is taken to find the new location. Generally speaking, the vortex will have moved a substantial distance and the motion always is found to be irreversible.

In addition to the flux motion and vortex depinning effects, one can have a vortex nucleate at the edge of the junction as a result of the self-field of I_p. For example, if I_p is increased, the self-field from I_p will also increase, and if the vortex pinning is strong enough a new vortex will nucleate at the edge of the junction[2] for some value, I_p^n, which can be less than I_p^d. These nucleation processes greatly complicate the measurement of I_p^d and the value of I_p^d easily can be measured only for the temperature range where $I_p^d < I_p^n$.

There are three essential ingredients for the success of the experiment. First, the N layer must be thick enough that the magnetic coupling force between the primary vortex and the secondary vortex is small compared to the pinning force. Second, the leads for I_p must be well shielded so that noise in this circuit does not unlock the SQUID detector for the Josephson junction. Finally, I_p^d must be less than I_p^n. For these high-pinning Pb-Bi films, this means that it is necessary to operate close to the transition temperature, T_c, that is, between 6.7 and

7.25 K.

The SNS junctions reported here are square with a width $w=46$ μm, an N-layer thickness of 800 nm, and S-layer thicknesses of 500 nm. The parallel-field maximum Josephson currents follow the Fraunhofer diffraction-pattern formula $I_c = I_0/\sin(\pi\Phi/\phi_0)/(\pi\Phi/\phi_0)$ to very good accuracy if there are no vortices in the junction. Here, I_0 is a temperature-dependent constant and Φ is the flux enclosed in the junction. When the junction was cooled through T_c in a small magnetic field perpendicular to the plane of the junction, $B_{\perp\mathrm{cool}}$, a well defined step structure was observed in the I_{c0} vs $B_{\perp\mathrm{cool}}$ curve, as will be reported elsewhere.[3] Each step in this curve represents a different configuration of vortices trapped in the junction. It is these sharp steps, in fact, which confirm that quantized flux entry is being observed.

Vortex trapping begins in the junction for $B_{\perp\mathrm{cool}}=21$ mG, a value which is slightly larger than that needed for one quantum, which is estimated to be $\phi_0/w^2=9.45$ mG for this junction. If the field is reversed, it is found that the first vortex nucleates very reproducibly at $B_{\perp\mathrm{cool}} = -14$ mG with the opposite polarization. For both of these steps a full diffraction pattern shows the vortex to be located in the primary film at $(x,y)=(0.10,0.04)$ and in the secondary at (0.10, 0.22), where x and y are coordinates measured from the center of the junction in units of $w/2$. We refer to this vortex as the primary-secondary vortex.

Preliminary attempts to move the primary-secondary vortex by applying a transport current in the primary, I_p, were not successful because the pinning is too strong. In every case the self-field generated by I_p led to the nucleation of a new vortex at the edge of the film[2] before the primary-secondary vortex in the center could be moved. If, however, the sample is warmed above T_c and field cooled in $B_{\perp\mathrm{cool}} = -16$ mG, a primary-secondary vortex is trapped near the center as above, but an additional vortex is trapped in the primary S layer at $(-0.59, 0.10)$. This latter vortex then leaks field out the edge of the junction but, as shown in Fig. 1, does not penetrate the secondary. We refer to this vortex as the primary-only vortex.

The primary-only vortex is not trapped so strongly as the primary-secondary vortex trapped near the center.

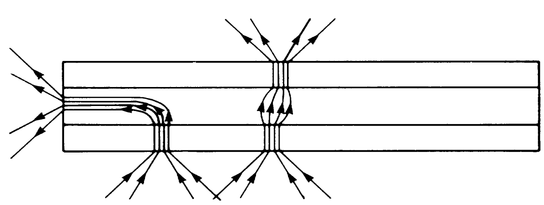

FIG. 1. Illustration of the vortex configuration trapped in the junction for $B_{\perp\mathrm{cool}}=0.016$ G. The misaligned primary-secondary vortex is shown near the center, and the primary-only vortex is sketched at the left.

For temperatures above 6.7 K the depinning current is less than the nucleation current, so that f_p can be measured for this vortex. In the rest of this paper we shall concentrate on the motion of the primary-only vortex; in the course of these measurements, the primary-secondary vortex does not move.

After the primary-only vortex has been trapped in the junction by field cooling, it can be moved back and forth across the junction by applying a force in the x direction via the Lorentz force caused by I_p. Both I_p and $B_\parallel$ are along the y direction and $B_{\perp\mathrm{cool}}$ is along the z direction. If, at 6.9 K, the vortex is pushed in the minus **x** direction it first moves a rather small distance from $(-0.59, 0.10)$ to $(-0.63, 0.10)$, which corresponds to a jump of 2.0 μm at $I_p^d=12$ mA. This corresponds to a pinning force per unit length of $f_p=1.1\times10^{-6}$ N/m or a total force for this film of 5.5×10^{-13} N. It is not possible to compare this with theory, because details of the pinning site are not known.[4-6] A very crude estimate can be made, however, by multiplying the core volume $(\pi\xi^2 d_s)$ by the free energy per unit volume $(H_c^2/8\pi)$ and dividing by the coherence distance ξ. Inserting values for this film gives approximately 3×10^{-6} N/m which is the right order of magnitude. Because the coherence distance has a temperature dependence near T_c of $(1-T/T_c)^{-1/2}$ and the critical field goes as $[1-(T/T_c)^2]\sim2[1-T/T_c]$ near T_c, a temperature dependence close to $(1-T/T_c)^{3/2}$ might be expected. It should be emphasized that these are very rough estimates. More complete theoretical estimates vary greatly depending on details of the model.[4-6]

The two diffraction patterns for these two locations are shown in Fig. 2. Even for this small jump the shift in pattern is clearly discernible. If the vortex is pushed in the $+\mathbf{x}$ direction, the vortex moves from $(-0.59, 0.10)$ to $(-0.43, 0.10)$ at $I_p^d=22$ mA, which corresponds to

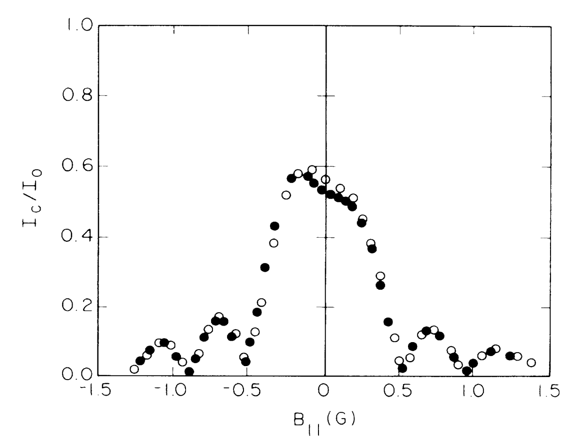

FIG. 2. Diffraction-pattern change for a small jump of the primary-only vortex in the **x** direction. Solid circles are for the vortex position $(-0.59, 0.10)$ and open circles are for $(-0.63, 0.10)$.

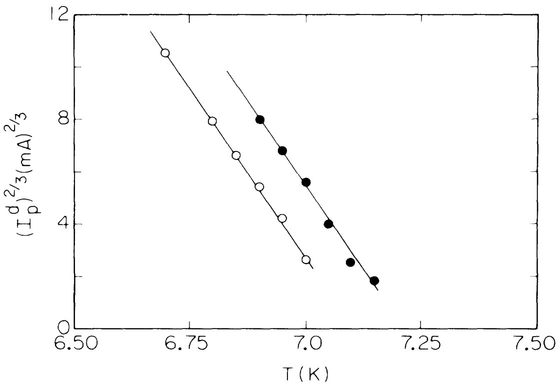

FIG. 3. Temperature dependence of the depinning current I_p^d.

$f_p = 1.8 \times 10^{-6}$ N/m. The pinning potential is clearly asymmetric in that the force required to depin the vortex in these two directions differs by about 80%.

For detailed study of the temperature dependence of f_p we have focused on the two steps on either side of the position of field-cooled trapping $(-0.59, 0.10)$. There is a fairly wide temperature range where the initial and final location of the vortex is the same for both of these steps. Data for the step toward the center of the junction from $(-0.59, 0.10)$ to $(-0.43, 0.10)$ are shown by the solid circles in Fig. 3. It is found that $(I_p^d)^{2/3}$ varies approximately linearly with T; so the data are plotted that way. At temperatures below 6.9 K and above 7.15 K the final position of the vortex was not $(-0.43, 0.10)$.

The data for the jump from $(-0.59, 0.10)$ to $(-0.63, 0.10)$ are shown by the open circles of Fig. 3. Again it is found that $(I_p^d)^{2/3}$ varies linearly with T and indeed has approximately the same slope as the motion in the other direction. At temperatures below 6.7 K data were not taken because new vortices nucleate at the edge of the junction before this vortex moves. At temperatures above 7.0 K, the final location of the vortex was not $(-0.63, 0.10)$.

A clear feature of the pinning of this vortex is that there are only a few stable pinning sites as I_p increases to push it across the junction. At 6.9 K, for example, there are 7 steps in the I_{c0} vs I_p curve. As the temperature is lowered, however, new intermediate stable pinning sites become important. This means that a vortex might jump between two locations in a single jump at 6.9 K but at 6.8 K it might have one or more intermediate stops as it moves between the same two locations.

The elementary pinning force f_p has been measured for a single vortex moving across a thin Pb-Bi superconducting strip. The magnitude of the force varies considerably from one pinning site to another, but it is found to be on the order of 10^{-6} N/m at $t = 0.95$. As the temperature is lowered, f_p increases approximately as $(1-t)^{3/2}$. Measurements of the difference in depinning current needed to push the vortex in the $+\mathbf{x}$ and $-\mathbf{x}$ directions revealed that the pinning potential is asymmetric.

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