Nucleation and motion of an isolated Abrikosov vortex

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A new family of superconductor–normal-metal–insulator–superconductor ($S/I/N/S$) Josephson junctions have been developed in which a single Abrikosov vortex can be nucleated and systematically moved to selected positions. The location of the vortex within the junction is determined from the shape of the diffraction patterns. Methods have been developed to push the vortex to most any desired location within the junction by applying currents in either or both of the cross-strip legs of the junction. The elementary pinning force for a vortex in a pure Pb film was measured and found to be much smaller than for a Pb-Bi film. In addition, the vortex moves in much smaller steps for the Pb film than was found for the Pb-Bi films. For $S/I/N/S$ junctions, the voltages and currents are in the microvolt and milliamp range; so very conventional detection can be used if a device is to be built based on the motion of a single Abrikosov vortex.

I. INTRODUCTION

With the development of methods to trap a single vortex in a Josephson junction[1] and systematically move it around,[2] it has become possible to measure fundamental quantities such as the elementary pinning force on a single Abrikosov vortex f_p as a function of temperature.[2,3] The basic idea in these measurements was to trap a single vortex by cooling in a magnetic field perpendicular to the plane of the junction. The presence of a magnetic field from the vortex would then add to the parallel field used to determine a conventional Fraunhofer diffraction pattern. This causes the diffraction pattern to be distorted and it was shown that there is a unique connection between the location of the vortex and the shape of the diffraction pattern. This permits a kind of "microscopy" in which the vortex location can be determined or visualized by measuring junction critical currents. The vortex can be moved by applying a Lorentz force with a transport current in the superconducting strip containing the vortex; then the new location can be determined from the diffraction pattern. If the trajectory of the vortex can be constrained to move along specified paths, one simple Josephson critical current, I_c measurement will suffice to locate the vortex.

Superconductor–normal-metal–superconductor ($S/N/S$) junctions were used for all of the early work in this field. An 800-nm normal layer was used so that the barrier would be thick enough that the magnetic coupling between the two films is rather weak and the flux could leak out the edge. These vortices that leak out the edge are relatively easy to move and the analysis of vortex location is a bit less complicated. The difficulty with these $S/N/S$ junctions is that the impedances are very low so that voltages are in the pV range and require superconducting quantum interference device (SQUID) detection. This means that spurious noise often is a problem, the response of the device is slow, and the device is clumsy to use. If one wanted to use these devices in a memory array or a logic element, it would be much better to have the junction impedances in the mΩ to Ω range.

The purpose of these experiments is to develop a new family of superconductor–normal-metal–insulator–superconductor ($S/I/N/S$) junctions in which vortices can be nucleated and moved around a junction with the location of the vortex being detected by conventional μV-level electronics. Methods are developed to nucleate the vortex with a transport current and push the vortex in any direction. Although the shape of the current-voltage curves are a bit more rounded than the $S/N/S$ junction, essentially all the physics of the $S/I/N/S$ device is the same as for $S/N/S$ devices.

II. EXPERIMENT

The central experimental problem in constructing a Josephson junction to study the motion of a single Abrikosov vortex is to make the barrier uniform enough to give good Fraunhofer diffraction patterns and still have the desired thickness and impedance. The normal-metal layer, the N layer, must be thick enough to decouple the vortex in the bottom superconducting layer, the S_{Pb} layer, from the top superconducting layer, the $S_{\text{Pb-Bi}}$ layer. A calculation of the maximum coupling force[4] can be made using

$$F=\Phi_0^2/(8\pi^2 d_{\text{eff}}^2) , \tag{1}$$

where d_{eff} is the normal-metal thickness plus the penetration depth of the two superconducting films,

$$d_{\text{eff}}=d_N+\lambda_{\text{Pb}}+\lambda_{\text{Pb-Bi}} .$$

For $d_{\text{eff}}=500$ nm, the force is on the order of 10^{-12} N. Most of the junction impedance is in the insulating, or I, layer and this thickness should be controlled to a few monolayers.

To prepare a junction, a pyrex substrate is cleaned, rinsed, dried, and placed in a turbopump evaporator system and the entire junction is prepared in a vacuum of 10^{-8}–10^{-9} Torr without opening the chamber. A Pb strip about 55 μm wide and 380 nm thick is evaporated for the S_{Pb} layer. A large pad of Al about 3 mm by 7 mm by 300 nm thick was deposited for the N layer. This Al pad is oxidized in a glow discharge for about 3 min at 4 °C to create the Al_2O_3 I layer. It was found that it was much easier to control the growth of the oxide if the Al had a large area with the junction in the middle. The mask that was used for the S_{Pb} layer was then rotated through 90°, and a Pb 2.5 at. % Bi layer about 55 μm wide and 560 nm thick is deposited for the $S_{Pb\text{-}Bi}$ layer. The Pb-Bi layer goes superconducting at a higher temperature than the Pb layer so the Pb-Bi will act as a superconducting ground plane while a vortex is being nucleated in the Pb film. For the purposes of discussion, a coordinate system is adopted such that the x axis is along the $S_{Pb\text{-}Bi}$ layer, the y axis is along the S_{Pb} layer, and the z axis is perpendicular to the plane of the junction. The earth's magnetic field in the region of the cryostat is reduced to about 1 mOe using μ-metal shields and a Pb cylinder is used to shield against other ac fields.

A variety of different currents are needed for these experiments so a complicated series of filtered circuits are needed. For the Josephson critical current (I_c) studies, a symmetric[2] current feed is used with equal current coming in both ends of the S_{Pb} layer and exiting with equal current in each arm of the $S_{Pb\text{-}Bi}$ layer. Hence, the Josephson currents are along the z axis. To apply a force on a vortex in the junction in the x direction, F_x, a transport current in the y direction in the S_{Pb} layer is needed. To apply a force in the y direction, F_y, a transport current in the x direction in the $S_{Pb\text{-}Bi}$ layer is needed.[5] All the current supplies were battery-powered current sources with very quiet control circuits. Several aspects of the experiment were computer automated but the basic voltage-current, V-I, curves were still taken on an x-y recorder. Because the junction impedances were on the order of 0.1 Ω, conventional electronics could be used for the detection of all of the voltages.

III. RESULTS AND DISCUSSION

The quality of the junction is normally assessed by measuring the transition temperature T_c of each film, the junction resistance, the shape of the voltage-current, V-I, curves, and the Fraunhofer pattern with no vortex in the junction. For the data presented here, the Pb film has $T_c = 7.28$ K, the Pb-Bi film has $T_c = 7.37$ K, and the junction resistance is 0.2 Ω. The V-I curves differ from the resistively shunted junction (RSJ) behavior of the earlier $S/N/S$ (Ref. 2) junctions in that there is a small amount of rounding with the onset of voltage.[5] The V-I characteristics[5] are very similar to the $S/I/N/S$ results reported by Blackburn and co-workers.[6] The critical current is defined to be the intersection of steepest descent line and the $V=0$ axis. Using this definition, the junction maps out a diffraction pattern that follows the Fraunhofer relation to better than 1% of the zero-field critical current, I_0. In many early attempts to make junctions with a small Al pad for a barrier, it was difficult to control the junction resistance because the oxidation was too rapid. With a large area of Al to oxide, the oxidation was much slower and seemed to be more regular.

IV. NUCLEATION OF A VORTEX

The most convenient way to nucleate a single vortex in the Pb film is to warm above T_c of both films and cool in zero field to a temperature below the T_c of Pb, typically about 6.60 K. The current in the Pb film is then increased until the self-field at the edge of the film reaches the nucleation field. Bulk Pb is a type-I superconductor but, as shown by Tinkham,[7] a Pb film less than about 500 nm thick will behave as a type-II material and fluxoids will enter as a single quantum of flux. The procedure is to measure the zero-field critical current, I_0, as a reference point. Then the current in the Pb film, I_{Pb}, is increased to some value, I_n, and turned off. The critical current in zero applied field, I_{c0}, was then measured to see if it had changed from I_0 indicating the entry of a vortex. Often rather small increases in I_{Pb} above the nucleating current will also push the vortex quite a distance into the junction. This is illustrated in Fig. 1 where the value of I_{c0}/I_0 is plotted versus I_{Pb} for two different temperatures of 6.60 and 6.70 K. The magnetic field at the edge of the film corresponding to the nucleation current of 41 mA at 6.60 K is about 43 mT compared to the predicted value[8] of 42.2 mT.

After nucleation, slight additional increases in I_{Pb} cause a gradual decline in I_{c0}/I_0. A study of the full diffraction pattern for each point along this curve shows that the decrease arises from the motion of vortex into the junction and not from the nucleation of additional vortices at the edge. Site A, at $I_{Pb} = 42.5$ mA, and site B, at $I_{Pb} = 45.0$ mA, marked on Fig. 1 for the 6.60 K data, correspond to the diffraction patterns of Figs. 2(a) and 2(b), respectively. The solid lines are least-squares fits of the single vortex model[1,3] and the solid circles are data.

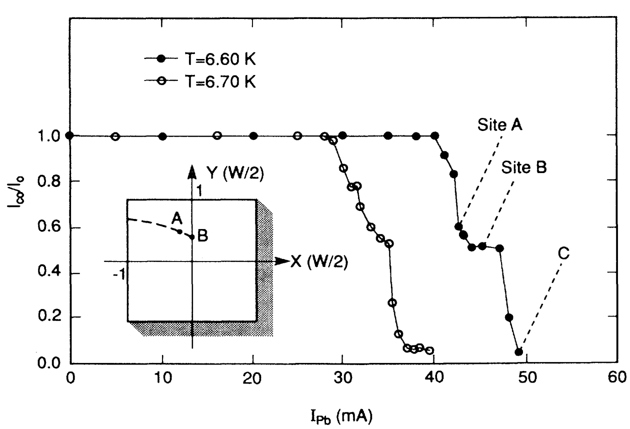

FIG. 1. Changes in the normalized critical current as a vortex is nucleated at the edge and propagates into the junction at 6.60 and 6.70 K. The inset shows the location of the vortex at two locations. For the ordinate, $I_0 = 0.195$ mA.

Vortex locations were determined to be site A $(-0.20,0.47)$ and site B $(-0.03,0.41)$ in units of the half-width of the junction, $W/2$. This is illustrated by the inset in Fig. 1 where the whole trajectory is plotted. Close to the edge of the junction, the diffraction patterns differ very little from a Fraunhofer pattern so it is difficult to specify just where it is along the junction edge. When the vortex is more than about 15% of $W/2$ away from the edge, the distortions of the diffraction are large enough to specify the location to about 2% of $W/2$.

If I_{Pb} is increased to 49 mA or site C on Fig. 1, it is not possible to model the diffraction pattern with one vortex in the junction. As shown in Fig. 2(c), if the data are fit at zero field, the peaks at higher field are too far apart. The only locations where the I_c is close to zero at zero field, H_x, are close to the origin. The fit shown by the solid line is the best fit for the one vortex situation. Presumably there are two or more vortices in the junction. For this case it is difficult to find a unique fit.

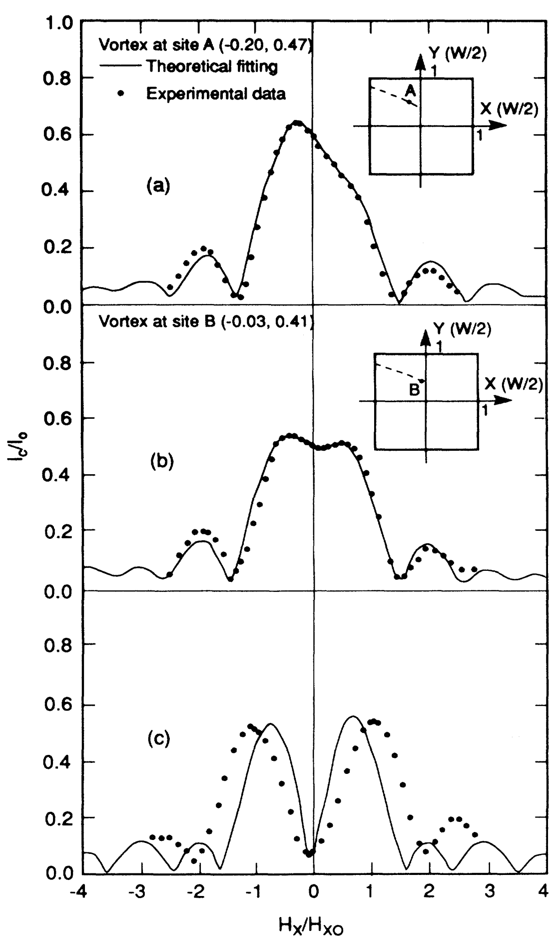

FIG. 2. Comparison of the model calculations (solid lines) with the data (solid circles) for two locations, site A $(-0.20,0.47)$ and site B $(-0.03,0.41)$. For the curve marked C, no single vortex model would describe the data. For the ordinate and abscissa, $I_0=0.195$ mA and $H_{x0}=0.81$ Oe.

V. MOTION ALONG THE y DIRECTION

The obvious direction to push a vortex in the Pb film is along the x axis using I_{Pb} to create the Lorentz force. To produce a Lorentz force along the y axis, one can pass a current through the Pb-Bi film, $I_{\mathrm{Pb\text{-}Bi}}$. This creates a magnetic field in the y direction in the Al barrier and the screening currents in the superconducting Pb film will flow in the x direction. Hence, a Lorentz force in the y direction is created.[5]

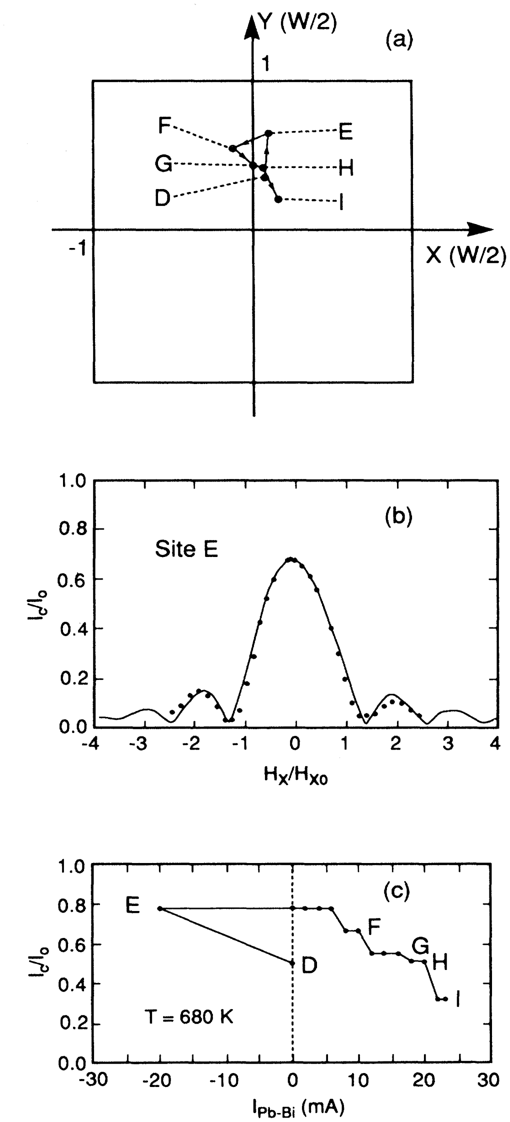

FIG. 3. (a) Trajectory of a vortex around the junction. The vortex is nucleated at the junction edge and pushed parallel to the x axis to point D, and then pushed parallel to the y axis to E, F, G, H, and I. (b) Diffraction pattern for location E. (c) Plot of I_{c0}/I_0 vs the push current $I_{\mathrm{Pb\text{-}Bi}}$. For the ordinate and abscissa, $I_0=0.195$ mA and $H_{x0}=0.81$ Oe.

To illustrate the y-axis motion, a vortex is nucleated in the Pb film and moved in the x direction to site D as shown in Fig. 3(a). These data are taken at 6.80 K so the depinning currents of Fig. 3(c) are lower than the vortex nucleation current in the Pb-Bi film at 6.80 K. By increasing $I_{\text{Pb-Bi}}$ in the negative direction, the vortex in the Pb film can be moved along the y axis to point E. Figure 3(b) shows the diffraction pattern used to determine the location. By reversing the current $I_{\text{Pb-Bi}}$, the vortex can be moved in the negative-y direction. A simple reversal of $I_{\text{Pb-Bi}}$ did not push the vortex back to site D but instead a rather smaller current of 5 mA moved the vortex to site F. In this Pb film, the direction of the motion of the vortex is different from the direction of the Lorentz force because the vortex is moving through an array of pinning potentials created by defects in the Pb film. The I_{c0}/I_0 plot of Fig. 3(c) shows the same plateau-like structure as Fig. 1. The picture that emerges from these data is that slight increases in the Lorentz force often cause further motion of the vortex but at certain locations, there are plateaus of strong pinning where substantial increases in $I_{\text{Pb-Bi}}$ or I_{Pb} are needed to move the vortex.

VI. ELEMENTARY PINNING FORCE

In measurements of the elementary pinning force, it is important to know the spatial variation of the current density, J, so that the Lorentz force per unit length of vortex, $\mathbf{J}\times\boldsymbol{\phi}_0/c$, can be related to total current, I_{Pb}. For this experiment, twice the penetration depth is less than the film thickness, which, in turn, is less than the film width, $2\lambda < d_s < W$. Hence, to a good approximation,[9] the current per unit width of the junction is given by

$$I'=(I_{\text{Pb}}/\pi)[(W/2)^2-x^2]^{-1/2}, \tag{2}$$

where x is measured from the film center. The elementary pinning force is

$$f_p=(I'\phi_0)/c, \tag{3}$$

using Gaussian units where c is the speed of light. Near the center of the film, I' can be approximated by $I'=(2I_p)/(\pi W)$. Calling the depinning current I_d and using $W=55$ μm and converting to practical units gives

$$f_p=2.4\times10^{-11}I_d, \tag{4}$$

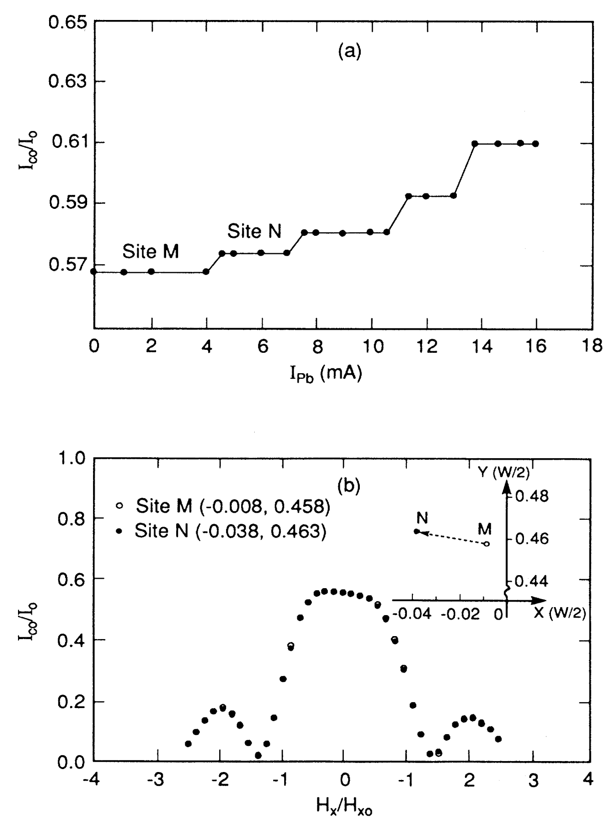

FIG. 4. Plot to show the precision in locating the vortex. (a) Expanded plot of I_{c0}/I_0 vs I_{Pb} as the vortex moves near the y axis. Each step corresponds to a vortex motion of about 500 nm. (b) Diffraction pattern for sites M and N located about 0.8 μm apart as shown by the inset. For the ordinate and abscissa, $I_0=0.195$ mA and $H_{x0}=0.81$ Oe.

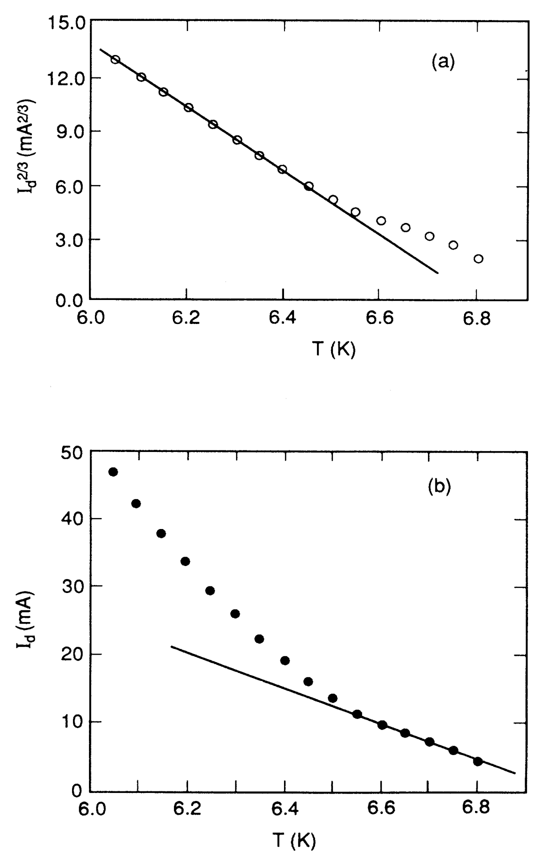

FIG. 5. Temperature dependence of f_p or equivalently, I_d. (a) Below 6.5 K, $I_p^{2/3}$ is approximately linear in T. (b) Above 6.5 K, I_d is approximately linear in T.

in units of N/A.

The precision of measuring the position of the vortex and the depinning current is rather high as illustrated in Fig. 4(a). Note the expanded scale. Steps in the ratio I_{c0}/I_0 are plotted as a function of I_{Pb}. A depinning current of 4.3 mA, for example, corresponds to $f_p = 1.03 \times 10^{-13}$ N or $f_p/d_s = 2.7 \times 10^{-7}$ N/m. Each step corresponds to a distance of about 1.0 μm so the precision is rather good. In addition, the pinning sites are about 0.5–1.0 μm apart in this region of the Pb film. These pinning forces are about a factor of 10 less than found by Hyun *et al.*[2] for Pb-Bi. The full diffraction pattern changes are small as shown on Fig. 4(b). The coordinates are shown by the inset of Fig. 4(b).

For these Pb films, there seems to be two distinct regimes for the temperature dependence for f_p as shown by Fig. 5 where the depinning current for site A is plotted two different ways. Above 6.85 K, the vortices are not stable and seem to move around spontaneously in response to noise in the system. No values of f_p are reported for this region.

No simple relation seems to describe the temperature dependence of f_p. Below 6.5 K, the data show $I_d^{2/3}$ approximately linear in T as was found[2,3] for Pb-Bi. A very simple core-pinning model[2] with smooth surfaces gives this $(1-T/T_c)^{2/3}$ behavior. Above 6.5 K, the data show I_d approximately linear in T. One possible interpretation of these results is that, close to T_c, surface roughness controls the pinning length. If surface roughness determines Δx in the relation

$$f_p = \Delta E/\Delta x = [(H_c^2/8\pi)(\pi\xi^2)]\Delta d_s/\Delta x \ , \qquad (5)$$

$$f_p \sim (1-T/T_c)^2/(1-T/T_c) = (1-T/T_c) \ , \qquad (6)$$

The difference between the two regimes is the replacement of a coherence distance for Δx at low temperature with a temperature-independent term related to surface roughness at high temperature. Direct measurements of the surface roughness optically and with the scanning electron microscope indicate a 0.5-μm scale for the surface roughness.

VII. CONCLUSIONS

Cross-strip $S/I/N/S$ Josephson junctions are well suited for the development of an Abrikosov vortex memory device. Vortices can be nucleated and moved to essentially any location in the junction. After a vortex has been nucleated in the Pb strip, it can be pushed across the strip by currents along the Pb strip in the x direction. Alternatively, a current in the counter electrode can be used to induced currents across the Pb strip which will move the vortex along the y direction. Voltages in the $S/I/N/S$ junction are in the μV to mV range so conventional electronics will suffice. This is a vast improvement over the $S/N/S$ devices that require a SQUID detector. The value of f_p in Pb is found to be much smaller than that found for Pb-Bi as expected. The precision in reading the location of a vortex is about ± 0.3 μm in a junction 55 μm wide.

ACKNOWLEDGMENTS

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