PHYSICAL REVIEW B VOLUME 50, NUMBER 17 1 NOVEMBER 1994-I

Thermal depinning of a single superconducting vortex in Nb

Junghyun Sok and D. K. Finnemore

Ames Laboratory, U.S. Department of Energy and Department of Physics, Iowa State University, Ames, Iowa 50011

(Received 6 June 1994)

Thermal depinning has been studied for a single vortex trapped in a superconducting Nb thin film in order to determine the value of the superconducting order parameter and the superfluid density when the vortex depins and starts to move around the film. The value depends on the pinning site, but typically the location of the vortex begins to change when the order parameter is about 24% of the $T = 0$ value and the superfluid density is about 5% of the $T = 0$ value. For all the pinning sites probed, the vortex would exit the film when the superfluid density was under 1%. This implies that there is a window between 9.1 and 9.2 K where vortices will spontaneously leave the film in a microtesla environment even though the film is still superconducting.

I. INTRODUCTION

With the development of methods to determine the location of a single vortex in a superconducting thin film and systematically move it from one pinning site to another, it has become possible to address many fundamental problems relevant to the motion of an isolated vortex.[1–4] As discussed previously,[2,3] there is a unique connection between the location of the vortex in the thin film and the shape of the Fraunhofer-like interference pattern of a cross-strip Josephson junction placed over the thin film. Hence the measurement of the interference pattern will determine the vortex location to an accuracy of about 0.5 μm for a 50×50 μm^2 junction.[2] Furthermore, the vortex can be pushed around the junction in any direction[4] using transport currents in either leg of the junction providing that the procedure is carried out in a temperature interval near the transition temperature, T_c, where the vortex depins at a current less than the current needed to nucleate a second vortex.

The purpose of this work is to use these Fraunhofer interference methods to study the thermal depinning of a single vortex from a wide variety of different pinning sites. The goal is to determine whether thermal depinning normally takes place whenever the reduced bulk order parameter is depressed below 0.2. To make these measurements, a single vortex is nucleated at the edge of the thin film and pushed to a specified pinning site in the junction under the influence of the Lorentz force of a transport current. One can then remove the Lorentz force and start warming the sample to determine the temperature where the vortex thermally depins and begins to move. As the temperature rises, the order parameter and the superfluid density gradually decrease and thermal activation will cause the vortex to hop across a saddle point into the next pinning potential valley. Because Nb obeys the BCS theory[7] rather well, the value of the order parameter and the superfluid density can be determined from the ratio of the temperature T to the transition temperature T_c. By studying a wide variety of pinning sites, an estimate can be made of the range of superfluid density needed to prevent thermally activated flux flow for an isolated vortex.

There are many applications where it is useful to know how far the order parameter can collapse without the onset of vortex hopping and thermally activated flux flow. In micro-electronic circuits, the hopping of a single vortex can introduce unwanted noise; in bulk materials, thermally activated flux flow can limit the usefulness of a conductor for magnets or other high current applications. For example, if a tape conductor has an extended region or weak link having a reduced order parameter, vortices will begin to hop around and freely flow any time the order parameter is below this depinning threshold. Hence, it is a measure of the point in the H-T plane where defect pinning vanishes for that region of the sample. For a dense array of vortices, of course, shear in the flux-line lattice would be another contributing factor to thermally activated flux flow.

In a preliminary study of thermal depinning in Pb thin films,[5] it was discovered that the trajectory of the vortex as it thermally depins is not random. As the temperature rises, the order parameter and the superfluid density gradually decrease and the surface of the flux pinning potential diminishes accordingly. When a particular site becomes unstable against vortex motion, the vortex always crosses the same saddle point into the next more stable pinning site nearby. Hence the vortex will move through the same sequence of locations as T increases. Eventually, the vortex exits the thin film. For the particular Pb film and choice of pinning site studied earlier, the vortex first depinned when the reduced order parameter, $\Delta/\Delta_0 = 0.2$ or when the superfluid density was about 4% of the $T = 0$ value. As the temperature increased, the vortex went through five different pinning sites before it exited the sample all together. We wondered whether these values would be essentially the same for a variety of different superconductors and have selected Nb as the next candidate for study because it is so widely used in circuitry and it is relatively easy to prepare in very reproducible form.

II. EXPERIMENTAL DETAILS

To prepare the junctions, a Nb strip 50 μm wide and about 0.35 μm thick was sputtered onto an oxidized Si substrate. Typical Ar partial pressures were 4.6 mTorr and the sputtering rate was 1.5 nm/s. A large circular Al pad about 180 nm thick was sputtered over the film and oxidized in the glow discharge to give an Al_2O_3 barrier. A second Nb film 50 μm wide and 0.40 μm thick was then sputtered at right angles to the first Nb layer to form a superconductor/normal metal/insulator/superconductor (SNIS) cross-strip junction. For the top film, T_c was 9.16 K but the parts of the bottom film exposed to oxygen during the glow discharge had a reduced T_c of 8.70 K. The junction had a normal state resistance at 10 K of 14 mΩ and a Josephson critical current that dropped from 5 mA at 4.2 K to 10 μA at 8.1 K roughly obeying a relation where $I_c^{2/3}$ is linear in T as reported for SNIS junctions previously.[6] For convenience, a coordinate system is used in which the bottom film lies along the y axis, the top film lies along the x axis, and the Josephson currents flow through the junction along the z axis. All of the interference patterns to determine the location of the vortex are taken at 5.00 K where the critical currents are high and the temperatures are easy to control.

Many other details of the experiment were the same as in the previous work,[5] but several new procedures were introduced to see how they would work. First, some exposed regions of the bottom Nb film were degraded somewhat during the glow-discharge preparation of the Al_2O_3, and so the vortex always was nucleated in the top film rather than the bottom film as was done before. Second, to nucleate a vortex, a transport current was applied to the top film and the sample was slowly cooled through T_c with the current applied, whereas before the sample was cooled through T_c with zero current and the vortex was nucleated by applying a current at some temperature below T_c. Third, the vortex was moved by applying a pulse of current to the bottom leg. This induced currents across the top film and applied a Lorentz force in the x direction.[4]

III. RESULTS AND DISCUSSION

A. Sample quality

As a test of the junction quality, the Fraunhofer diffraction pattern was observed at 5.00 K and compared with theory as shown in Fig. 1(a). At $H_y = 0$, the critical current is 3.3 mA, and the position of the first minimum occurs at 1.0 Oe. For a 50 μm wide film this implies a combined thickness of the Al barrier and penetration depths $d_n + 2\lambda$ of 400 nm. If the $d_n = 180$ nm, this means that $\lambda = 110$ nm, a value about twice as large as expected for pure Nb at 5 K.

To test the uniformity of the top Nb layer, a vortex was nucleated by slowly cooling through T_c (9.20 K) with an applied current of -2.1 mA in the top Nb layer. The diffraction pattern taken at 5.00 K is shown by the open circles in Fig. 1(b) and compared with theory shown by

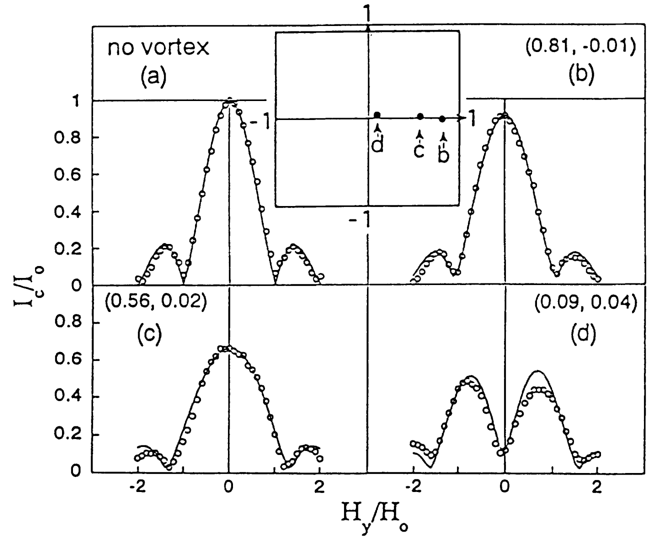

FIG. 1. Motion of a vortex along the negative x axis direction using various depinning currents at 8.95 K.

the solid line. The fit shown in Fig. 1(b) reveals that the vortex is at [0.81, -0.01] where distances are measured in units of half the junction width. Hence the vortex is essentially on the x axis as sketched on the inset. It is assumed that small deviations of the fit from the data arise because the barrier thickness and the films are not quite uniform.

B. Motion of the vortex

To test our ability to move the vortex around reproducibly, a vortex is nucleated and moved to position [0.81, -0.01] as above. Then, the sample is warmed to 8.95 K and a depinning current of -0.5 mA is applied in the lower Nb film and turned off. This current induced currents in the upper Nb film in the y direction and thus a Lorentz force on the vortex along the x axis. If the sample is then cooled to 5.00 K, the diffraction pattern of Fig. 1(c) is obtained. The fit shows that the vortex is now located at [0.56, 0.02] so that the vortex was moved in the direction of the Lorentz force in the negative direction along the x axis. Repeating the above procedure, the sample was warmed to 8.95 K and a current of -1.2 mA was applied to the bottom Nb strip and turned off. The diffraction pattern of Fig. 1(d) taken at 5.00 K shows that the vortex again moved further along the x axis in the negative x direction to a new location of [0.09, 0.04].

To check whether the vortex could be pushed along the x axis in the positive x direction with equal ease, a vortex was nucleated by cooling through T_c with a current of -2.1 mA in the upper Nb film. This nucleates a vortex and moves it to position [0.06, -0.19] which is rather close to the center of the junction. The diffraction pattern used to determine the location and the fit are shown in Fig. 2(a). By applying a current of $+14.4$ mA through the lower Nb strip at 8.85 K, the vortex is moved to [0.17, -0.28] as shown by the diffraction pattern of Fig. 2(b).

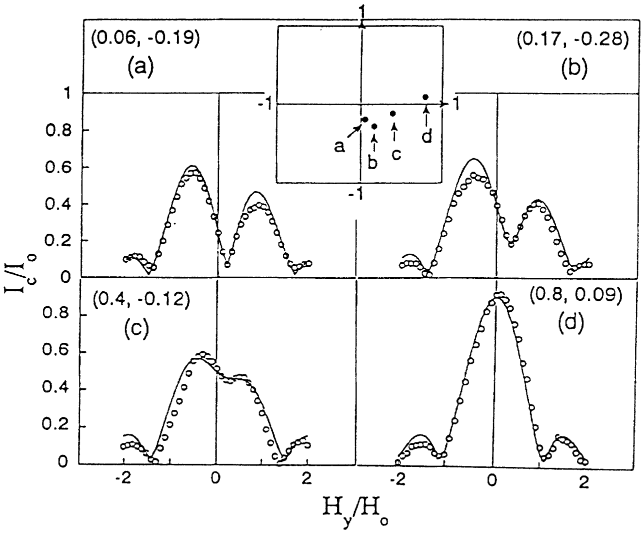

FIG. 2. Motion of a vortex along the positive x axis direction using various depinning currents at 8.85 K.

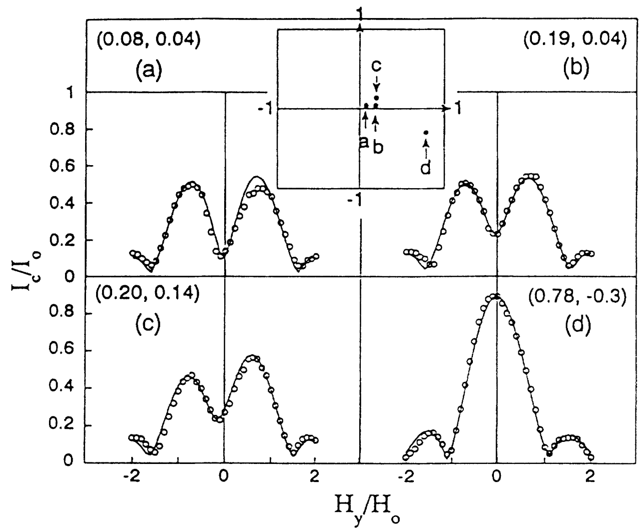

FIG. 3. Thermal depinning starting from a location near the center of the junction.

A further application of 15.0 mA pushes the vortex to [0.40, −0.12] as shown in Fig. 2(c). Finally, it can be pushed to [0.80, 0.09] of Fig. 2(d) by the application of 15.5 mA through the bottom Nb strip at 8.85 K. Hence the vortex can be moved back and forth along the x axis with relative ease. The trajectory is not in a straight line but the motion is predominantly along the direction of the force. This behavior of moving in the same direction as the applied force is to be contrasted with the Pb film reported previously where the vortex often went off in a diagonal direction to the force. This is taken to mean that the Nb film is more uniform.

C. Thermal depinning

To study thermal depinning in the sample, a vortex was first prepared at a location fairly close the center of the junction. This was done by cooling through T_c with a current of −2.35 mA in the upper Nb layer. After pushing the vortex around with several pulses of current, the vortex was located at [0.08, 0.04] as determined from the diffraction pattern in Fig. 3(a). This site is illustrated in the inset as position a.

Successive warming to ever higher temperature with no external force on the vortex showed that the vortex first thermally depinned at 8.99 K. The diffraction pattern taken at 5.00 K, shown in Fig. 3(b), showed that the vortex moved mostly along the x axis to [0.19, 0.04]. The locations of the starting position and first stop are shown in the inset sketch as positions a and b. The value of Δ/Δ_0 derived from BCS theory is 0.24 at this temperature and ρ_s/ρ_{s0} is 6.0%.

The second hop to position c took place at 9.02 K and the vortex moved mostly along the y axis to [0.20, 0.14] of Fig. 3(c). The corresponding values are $\Delta/\Delta_0 = 0.22$ and $\rho_s/\rho_{s0} = 4.8\%$. The third hop to position d took place at 9.03 K to location [0.78, −0.30] of Fig. 3(d). The corresponding values are $\Delta/\Delta_0 = 0.21$ and $\rho_s/\rho_{s0} = 4.4\%$. Positions c and d are sketched in the inset. Finally, when the sample was warmed to 9.04 K, the vortex left the junction and the undistorted Fraunhofer pattern is recovered. The corresponding values of $\Delta/\Delta_0 = 0.20$ and $\rho_s/\rho_{s0} = 4.0\%$ were obtained for the final exit of the vortex.

Thermal depinning from a different site followed a similar pattern. A vortex was nucleated and pushed to site a at [0.34, 0.31] as determined from the diffraction patterns of Fig. 4(a). The thermal depinning events took place at 8.94, 8.97, and 9.06 K for the successive locations illustrated in Figs. 4(b)–4(d). The vortex left the junction at 9.07 K.

To illustrate the reproducibility of the results, a vortex was nucleated and moved to [0.81, −0.01]. It was then moved to [0.47, 0.21] with a pulse of current. On warming, it depinned at 9.02 K and hopped back to [0.81,

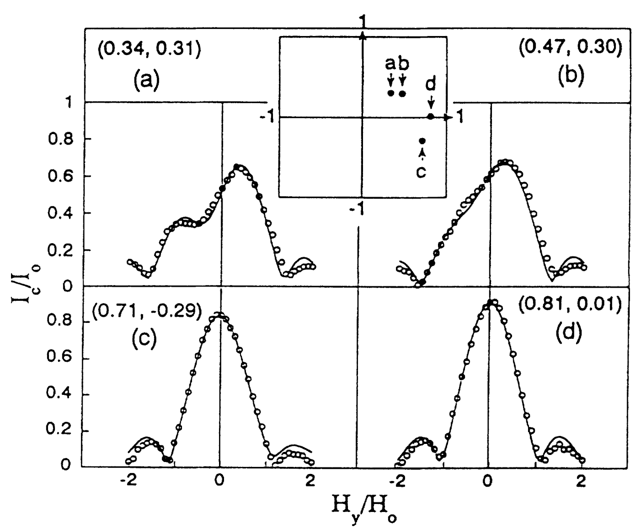

FIG. 4. Thermal depinning starting from a site along the junction diagonal.

-0.01]. This experiment was repeated 3 times with the same result.

There is an implication from the above results that there is a temperature interval close to T_c where the sample is superconducting but it excludes all the vortices. To test this, the sample was cooled in 3 Oe and cooled through T_c to trap hundreds of vortices. It was warmed to 9.07 K in a field of a few mOe and then cooled to 5.00 K. An undistorted Fraunhofer pattern was obtained indicating that there were no more vortices trapped. Hence, the vortices can be swept out by cycling to 9.07 K and back.

IV. CONCLUSIONS

Thermal depinning of a single vortex trapped in a Nb film consistently occurs when the reduced superconducting order parameter Δ/Δ_0, is approximately 0.22 and the superfluid density is approximately 5% of the total density. These values are about 20% larger than those reported earlier for a Pb sample having a Au line decorating the junction, but the values are really very close. For the Nb sample, pinning is probably dominated by grain boundaries whereas, for the Pb sample with Au decoration, pinning may have been dominated by an array Pb_3Au precipitates. Because roughly the same answer was obtained for these rather different kinds of pinning site, there is a reasonable chance that this is a general value within factors of 2 for a wide range of materials. In addition to this central conclusion, it is clear that these Nb films are very uniform and the vortex moves under a Lorentz force in approximately the direction of the force. With a suitable sequence of pulses, the vortex can be moved to most any location in the junction. Finally, there appears to be a small interval near T_c between 9.1 and 9.2 K where the film is superconducting and the pinned vortices are expelled.

ACKNOWLEDGMENTS

Ames Laboratory is operated for the U.S. DOE by Iowa State University under Contract No. W-7405-ENG-82 and supported by the DOE, the Office of Basic Energy Sciences.

[1] S. L. Miller, K. R. Biagi, J. R. Clem, and D. K. Finnemore, Phys. Rev. B **31**, 2684 (1985).
[2] O. B. Hyun, D. K. Finnemore, L. A. Schwartzkopf, and J. R. Clem, Phys. Rev. Lett. **58**, 599 (1987).
[3] O. B. Hyun, J. R. Clem, and D. K. Finnemore, Phys. Rev. B **40**, 175 (1989).
[4] Qiang Li, J. R. Clem, and D. K. Finnemore, Phys. Rev. B **43**, 12834 (1991).
[5] S. C. Sanders, J. Sok, D. K. Finnemore, and Qiang Li, Phys. Rev. B **47**, 8996 (1993).
[6] H. C. Yang and H. E. Horng, J. Low Temp. Phys. **70**, 493 (1988).
[7] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).