Investigation of single Abrikosov vortex pinning in superconducting Josephson junctions using artificially induced pinning sites

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Investigation of single Abrikosov vortex pinning in superconducting Josephson junctions using artificially induced pinning sites

by

Matthew Joseph Breitwisch

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Major: Condensed Matter Physics
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ABSTRACT

Cross-strip superconductor-normal-insulator-superconductor Josephson junctions have been fabricated in order to study the pinning of a single Abrikosov vortex trapped within thin films of Nb. The vortex would be induced to move either by thermal depinning or by pushing on the vortex with a transport current in one of the films. Thermal depinning studies show that the temperature of the initial motion of the vortex is independent of applied fields up to ±20 mG but the temperature where the vortex exits the junction seems to be about 50 mK lower in ±20 mG than in zero field. Lorentz force depinning studies show that for a vortex pinned in the top Nb film, there is a large difference between the top and bottom film depinning currents. A transport current in the top film will depin a vortex in the top film with about one-tenth the current needed in the bottom film to depin this vortex. Attempts to create artificial pinning sites by depositing Fe balls on the junction were successful with the vortex being pinned to the site of the Fe ball. Attempts to create an artificial pinning site by depressing the order parameter with a thin strip of Au on the surface of the Nb was not successful. Pinning sites in the Nb were not correlated with the location of the Au lines.
1 INTRODUCTION

In 1911, just three years after helium was first liquefied, H. Kamerlingh Onnes [1] discovered superconductivity. He found that at a critical temperature, $T_c$, a superconductor undergoes a phase transition from a state of normal electrical resistivity to a state of zero electrical resistivity. In 1933 W. Meissner and R. Ochsenfeld [2] found experimentally that magnetic field is expelled from a superconductor, both upon cooling through $T_c$ with an applied field and applying a field when already in the superconducting state. Magnetic field is exponentially screened from the interior of a superconductor with a characteristic penetration depth $\lambda$ that is typically 100 nm. Superconductivity will be destroyed if the applied field becomes strong enough because it requires energy to expel flux. This critical magnetic field, $H_c$, is related to the free energy difference between the normal and superconducting states and is temperature dependent. The difference between the Helmholtz free energies per unit volume in the normal state in a field and the superconducting states in zero field is given by $H_c(T)^2/8\pi$.

There are two distinct characteristic lengths in a superconductor, one for magnetic field variations, $\lambda$, and one for variations in the superfluid density, $\xi$, which is called the coherence length. $\xi$ is the minimum spatial extent of a transition layer where the superfluid density rises from zero in the normal state to one in the superconductor. The coherence length and the penetration depth both depend on the mean free path of the conduction electrons in the normal state. As the mean free path increases the coherence length increases and the penetration depth decreases.

The ratio of $\lambda/\xi$, denoted by $\kappa$, also has importance because it controls the interfacial surface energy between a superconducting and normal region of the material. Consider an interface within a material between normal and superconducting regions. The sign of the
surface energy divides superconductors into two major classes depending on the size of this ratio. For type I superconductors the surface energy is positive and $\kappa < 1/\sqrt{2}$. This class obeys the Meissner effect where upon increasing an external field, the field is completely expelled up to a critical field $H_c$. For fields greater than $H_c$, superconductivity is destroyed, and the field penetrates completely in a first-order transition.

For type II superconductors the surface energy is negative and $\kappa > 1/\sqrt{2}$. Up to a field $H_{c1}$ a type II superconductor will expel the field from its interior completely. For fields between $H_{c1}$ and $H_{c2}$, however, it is energetically favorable for the superconductor to break up into normal and superconducting regions allowing the field to penetrate the material in quantized flux bundles [3]. In this so-called mixed state between $H_{c1}$ and $H_{c2}$ the magnetic flux penetrates in regular arrays of flux tubes each carrying a quantum of flux $\Phi_0 = hc/2e = 2.07 \times 10^{-7}$ Gcm$^2$. Around each flux tube is a vortex of circulating supercurrent concentrating the flux towards the center of the vortex. The circulating charge carriers each have one quantum of angular momentum [4, 5]. The vortex is basically made up of a cylindrical core region where the superconducting order parameter rises from zero to unity over a distance comparable to $\xi$ and another cylindrical region where the supercurrents circulate within a radius $\lambda$. These flux tubes are called Abrikosov vortices after the theoretical physicist who first predicted their existence [4].

Another important breakthrough of our understanding of superconductivity came with the realization of the existence of an energy gap $\Delta$, of order $kT_c$, between the ground state and the quasi-particle excitations of the system. Experimental evidence for this energy gap arose from precise specific heat measurements of a superconductor by Corak et al [6]. The electronic specific heat well below $T_c$ is dominated by an exponential dependence which implies a minimum excitation energy per particle of $\sim 1.5 kT_c$ [7]. Electromagnetic absorption experiments by Glover and Tinkham [8] could also be interpreted in terms of an energy gap of 3 to 4 times $kT_c$.

In 1957, Bardeen, Cooper and Schrieffer (BCS) [9] put forth their microscopic pairing theory of superconductivity. The BCS theory shows that even a weak attractive interaction between electrons causes an instability in the normal Fermi-sea ground state of the electron gas with respect to the formation of bound pairs. For most materials this attraction is caused by the
electron-phonon interaction and the resulting bound pairs, called Cooper pairs, occupy states of equal and opposite momentum and spin. The electron-lattice-electron interaction leads to an energy gap, separating the ground state from excited states, which agrees with measurements of the energy gap found in heat capacity, infrared absorption and tunneling experiments [9].

Keeping all of these properties of superconductivity in mind, there is an essential universal characteristic of the superconducting state, which is the existence of a many-particle condensate wavefunction $\Psi(\vec{r})$. This wavefunction has amplitude and phase and maintains phase coherence over macroscopic distances [10]. The existence of the phase factor in $\Psi(\vec{r}) = |\Psi(\vec{r})| e^{i\phi(\vec{r})}$ and the single-valuedness of $\Psi(\vec{r})$ requires that $\phi(\vec{r})$ returns to itself modulo $2\pi$ upon going around a superconducting ring. This condition requires that the fluxoid $\Phi' = \Phi + \frac{m e}{}\frac{c}{(2\pi)^2} \int_{\Gamma} \vec{A} \cdot d\vec{S}$ take on only integral multiples of $\Phi_0 = \frac{hc}{2e}$ where $\Phi = \oint \vec{A} \cdot d\vec{S}$ is the ordinary magnetic flux through the integration loop. If the fluxoid is within a material whose dimensions are large compared to $\lambda$, the integration loop can be taken where $\int_{\Gamma} = 0$ since the current sustaining the flux flows only in a layer of thickness $\lambda$ around the center of the fluxoid. Hence, within a superconductor the quantization condition implies that the flux itself has the quantized value $n\Phi_0$ where $n$ is an integer.

For type II and thin film superconductors energy considerations dictate that $n = 1$ so that each vortex contains one quantum of flux, $\Phi_0$. As the external field is increased from $H_{c1}$ to $H_{c2}$ more and more vortices enter the superconductor forming a vortex lattice. A vortex feels a repulsive force from other vortices. To minimize the interaction energy between vortices, the vortices arrange themselves in periodic arrays. Defects and irregularities that locally weaken or suppress the superconducting wave function will cause vortices to be located on the defects or pinning sites. Flux pinning is of practical importance because it determines the critical current of a type II superconductor. A transport current will provide a Lorentz force on the vortices. Once the force becomes large enough the vortex lattice will begin to move. By Faraday's law, when the magnetic flux of a vortex begins to move a voltage is induced and therefore a finite resistance develops. Hence for dissipationless supercurrent, the vortices must be pinned. Vortices tend to get trapped on defects such as impurities, dislocations, grain boundaries and voids.
The interaction between a single vortex flux line and a single defect is called the elementary pinning force. To analyze forces for an array of vortices, the elementary pinning forces then add together in some complicated manner to form a holding force on the elastic flux lattice.

Several methods have been developed to observe or image vortices in superconductors. Direct observation of the structure of the vortex lattice was first made with the aid of neutron diffraction [11] techniques in which the magnetic moment of a neutron scatters off the magnetic field gradient produced by a vortex. A rather different technique called magnetic decoration [12] has also been used to image the location of vortices by producing a smoke of small iron particles which tend to stick to the surface of the material preferentially where the field is strongest, i.e. at the location of a vortex. Other methods have been developed to image individual vortices and study the elementary pinning force. These include scanning electron microscopy [13], scanning tunneling microscopy [14], SQUID-based techniques [15, 16, 17] and electron holography [18].

The method used for this study depends on the control of the phase of the wave function in a Josephson junction to determine the location of the vortex. A Josephson junction consists of two superconducting films which are separated by a thin insulator or normal metal barrier. Each superconductor induces into the barrier a finite pair amplitude [19, 20, 21] which decays exponentially towards the middle of the barrier. Provided the barrier is not too thick, the overlap of the two pair wavefunctions will be large enough for the coupling energy [22, 23] of the two superconductors to exceed the thermal fluctuation energy [23, 24]. As a result, phase coherence will be established across the junction, and Josephson tunneling, which involves tunneling of the Cooper pairs, becomes possible.

A method to locate the vortex in the junction was worked out by Miller et al. [25] and Hyun et al. [27] using the dc Josephson equation [28] \( J = J_0 \sin(\gamma) \), where \( \gamma \) is the gauge invariant phase difference across the junction. This phase depends on the local magnetic field, so when a vortex is present in the junction, its magnetic field has a direct impact on the measured Josephson current density across the junction. S. Miller and D. Finnemore [29] were the first to locate a single vortex in a superconductor-normal metal-superconductor (SNS) junction as
part of a study of Fraunhofer oscillations close to $T_c$. O. B. Hyun et al. [27] measured the elementary pinning force of a single vortex trapped in a $PbBi(2.5 \text{ at } \%)$ thin film and O. B. Hyun [30] investigated the single vortex motion in a SNS Josephson junction made of $PbBi(2.5 \text{ at } \%)-AgAl(4 \text{ at } \%)-PbBi(2.5 \text{ at } \%)$.

The SNS junctions first used in this work had the disadvantage of having a small junction resistance ($\mu\Omega$ range) which required the use of a SQUID to measure the small voltage signals. Adding an insulating region to the normal region made the junction resistance high enough so that the voltage signals could be easily measured. Qiang Li [31] used a $Pb-Al-Al_2O_3-PbBi$ (SNIS) junction in order to further investigate the motion of a single vortex and measure the elementary pinning force. He showed that SNIS behavior for the one-vortex problem was the same as SNS response except that the $V-I$ characteristics were linear near $V = 0$ instead of following resistive shunted junction behavior of SNS junctions. Sanders [32] studied the thermal depinning process in a $Pb-Al-Al_2O_3-PbBi$ junction and found that vortices begin to thermally depin when the order parameter is reduced to about 20% of the $T = 0$ value. He found that raising the temperature would suppress the order parameter and thus enable the vortex to thermally depin. Typically the vortex would hop to three or four different locations before it exited the film. Then Junghyun Sok [33] studied thermal depinning for a $Nb-Al-Al_2O_3-Nb$ junction and found that the first depinning occurs when the order parameter of the bulk $Nb$ is about 24% of the $T = 0$ value.

There are several reasons to study $Nb$-based Josephson junctions: (1) It has the highest elemental transition temperature, $T_c \approx 9.2 \text{ K}$, which allows access to a large temperature range in the superconducting state. (2) Its oxide coating is a good insulator, very inert against acids, mechanically hard, stable, dense and well bonded to $Nb$ [34]. (3) $Nb$ has a melting point above 2000 K and low diffusivity below 400 K yielding good long-time stability of the junction including thermal cycling to 400 K [35]. (4) Finally, $Nb$ junctions are used in a wide range of electronic applications such as superconducting quantum interference devices (SQUIDs). Unwanted noise in these devices can be caused by thermally activated motion of trapped vortices generating fluctuating fields and currents. It should also be mentioned that bulk $Nb$
is a type II superconductor, in contrast to the majority of metallic superconductors which are type I when they are bulk and act as type II only when they are thin films [36, 37, 38, 39].

The goal of this research was to further study the interaction of single vortices with pinning sites and circulating currents in Nb-based Josephson junctions. To probe more into the nature of the pinning mechanism, the fabrication of artificial pinning sites has been attempted. First, \~10\mu m diameter balls of Fe placed on top of the junction region created pinning sites in the top Nb film that were not present without the Fe. Next, it was attempted to incorporate \~40 nm radius balls of Ag into the top Nb film so that the pinning force could be measured as a function of the size of the defect. The process of incorporating Ag balls into the film caused so many strong pinning sites that it was impossible to clear the junction region of vortices. As the number of Ag balls in the junction region was reduced their size also reduced, making it impossible to differentiate (using SEM) the Ag balls from other contaminants unavoidably introduced into the film.

As a final means of trying to induce artificial pinning sites, Josephson junctions were fabricated on top of a thin strip of Au. Sanders [32] had previously attempted this with a Pb-based junction, but the Pb-based junction experiments were hindered by the presence of Pb_{2}Au precipitates that may form [40] near the Au strip at room temperature.

A gold strip in contact with the Nb film may provide suitable pinning sites by the proximity effect in which normal electrons from the Au suppress the order parameter in that region of the Nb [5]. Upon thermally depinning, a vortex trapped above the Au strip may preferentially wander along the strip. Also, a vortex pinned above the Au strip may be more easily depinned from a Lorentz force parallel to the strip than perpendicular to it. The goal was to measure this anisotropy.

Two junctions were successfully fabricated on top of Au strips. The locations of the Au strips were not known until after all measurements were taken because there may be degradation of the junction during the SEM characterization. For each pinning site found, thermal depinning measurements and 4-directional current depinning measurements were made to see if any asymmetry in the pinning sites could be observed.
This chapter will review the method used to determine the position of an Abrikosov vortex in a thin film of superconducting material. A sandwich consisting of superconductor-normal-insulator-superconductor (SNIS) layers, arranged to minimize the geometrical complexity, is constructed to utilize the Josephson effect. The junction is a cross-strip, square junction with width \( W \), thickness \( t_1 + d_n + t_2 \), where \( t_1 \) and \( t_2 \) are the thicknesses of the superconducting layers and \( d_n \) is the thickness of the normal material.

**Josephson effect**

Macroscopic quantum effects may occur when two superconductors are separated by a thin layer of non-superconductive material. In 1962, Josephson suggested the possibility of electron pairs tunneling through closely separated superconductors even with no potential difference [28]. Josephson predicted two main features of this type of junction. The first, known as the ac Josephson effect, relates the voltage difference across the junction, \( V \), with the time rate of change of the phase difference, \( \Delta \theta \), across the junction:

\[
\frac{d\Delta \theta}{dt} = \frac{2eV}{\hbar}.
\]  

(2.1)

Supercurrent electrons oscillate back and forth across the junction with frequency \( \omega = \frac{d\Delta \theta}{dt} \) such that the energy difference between the two levels, \( eV \), is equal to \( \hbar \omega \). The second, known as the dc Josephson effect, relates the local Cooper pair tunneling density with the phase difference of the order parameter across the junction at that point. This can be written as

\[
J_s(r) = J_o(r)\sin\Delta \gamma(r),
\]  

(2.2)
where $J_s$ is the supercurrent density, $J_o$ is the temperature-dependent amplitude and $\Delta \gamma$ is the gauge-invariant phase difference across the junction,

$$\Delta \gamma(r) = \theta_a - \theta_b - \frac{2\pi}{\Phi_0} \int_a^b dA \cdot A,$$

(2.3)

the integral being carried out along a straight contour across the junction from a to b.

The Ginzburg-Landau theory is used here to quantitatively describe the order parameter because this theory includes effects caused by spatial variations of fields and wave functions. The main result of this theory is the derivation of the local free energy of the superconductor. In this theory, the free energy is written as a function of a wave function like order parameter as a variational parameter. Minimizing this free energy with respect to the parameters of the theory leads to the Ginzburg-Landau differential equations:

$$\alpha \psi + \beta |\psi|^2 \psi + \frac{1}{2m^*} \left( \frac{\hbar}{i} \nabla - \frac{e^*}{c} A \right)^2 \psi = 0,$$

(2.4)

$$J = \frac{e^*}{2m^*} (\psi^* \nabla \psi - \psi \nabla \psi^*) - \frac{e^*}{m^*c} \psi^* \psi A,$$

(2.5)

where $\alpha$ and $\beta$ are parameters of the theory, $A$ is the vector potential, $\psi = |\psi|e^{i\theta}$ is the order parameter and $J$ is the supercurrent density.

**Spatial variation of the phase difference**

If no external magnetic fields are applied, the phase is constant along each side of the junction and the current of Eq. (2.2) is uniform across the junction. When an external field, $B$, is applied there will exist a vector potential $A$, where $B = \nabla \times A$, resulting in a position-dependent phase difference across the junction.

The total current can be found by integrating $J(x, y)$ over the entire cross section of the junction. In order to do so, one needs to calculate $\Delta \gamma$ as a function of $x$ and $y$. Substituting $\psi = |\psi|e^{i\theta}$ into Eq. (2.5), using $e^* = -2e$, $m^* = 2m$ and $\hbar e = \Phi_0$, and solving for $A$ gives

$$A = -\frac{\Phi_0}{2\pi} \nabla \theta - \frac{mc}{2e^2|\psi|^2} J.$$

(2.6)

To relate the gauge-invariant phase difference across the junction to the magnetic field within the junction, the vector potential $A$ is integrated around the contour shown in Fig. 2.1.
Figure 2.1 Integration path across a Josephson junction.
It is well known [41] that supercurrents flow only on the surface of a superconductor and so \( \mathbf{J} \) can be taken as zero deep inside the superconductor. Furthermore, \( \mathbf{J} \cdot d\mathbf{l} \) is zero along the contour shown even where \( \mathbf{J} \) is non-zero since the supercurrents flow parallel to the surface. Using this result combined with Stoke's theorem yields

\[
\oint_{\Gamma} d\mathbf{l} \cdot \mathbf{A} = \int_{a}^{d} d\mathbf{l} \cdot \left(-\frac{\Phi_0}{2\pi} \nabla \phi\right) + \int_{d}^{e} d\mathbf{l} \cdot \mathbf{A} + \int_{e}^{h} d\mathbf{l} \cdot \left(-\frac{\Phi_0}{2\pi} \nabla \phi\right) + \int_{h}^{a} d\mathbf{l} \cdot \mathbf{A} 
\]  

(2.7)

\[
= -\frac{\Phi_0}{2\pi} (\phi_d - \phi_a) + \int_{d}^{e} d\mathbf{l} \cdot \mathbf{A} - \frac{\Phi_0}{2\pi} (\phi_h - \phi_a) + \int_{h}^{a} d\mathbf{l} \cdot \mathbf{A} 
\]  

(2.8)

\[
= \frac{\Phi_0}{2\pi} (\Delta \gamma_{ah} - \Delta \gamma_{de}) 
\]  

(2.9)

\[
= B_x d_{\text{eff}} y, 
\]  

(2.10)

where \( d_{\text{eff}} = \lambda_1 + \lambda_2 \) and \( B_x \) is the component of the magnetic field along the \( x \)-axis. If we take point \( a \) to be \( y = 0 \) then

\[
B_x d_{\text{eff}} y = \frac{\Phi_0}{2\pi} (\Delta \gamma(0) - \Delta \gamma(y)). 
\]  

(2.11)

Differentiating with respect to \( y \) yields

\[
\frac{\partial \Delta \gamma}{\partial y} = -\frac{2\pi}{\Phi_0} B_x d_{\text{eff}}. 
\]  

(2.12)

A similar argument leads to

\[
\frac{\partial \Delta \gamma}{\partial x} = \frac{2\pi}{\Phi_0} B_y d_{\text{eff}}, 
\]  

(2.13)

which implies that in general [23]

\[
\nabla_2 \Delta \gamma(x, y) = \frac{2\pi d_{\text{eff}}}{\Phi_0} \mathbf{B} \times \mathbf{z}. 
\]  

(2.14)

This equation describes \( \Delta \gamma(x, y) \) in terms of the magnetic fields within the junction.

**Physical interpretation of Eq. (2.14)**

Now that we have \( \Delta \gamma(x, y) \) in terms of the magnetic field inside the junction, the next step is to insert it into Eq. (2.2) and integrate over the cross-section of the junction to determine the total current flowing through the junction. Before doing that let us physically interpret
Eq. (2.14) [42]. Upon doing so it will be more straightforward to derive $\Delta \gamma(x, y)$ for any given field, $\mathbf{B}$, within the junction.

Consider a square junction of width $W$ and thickness $d_{\text{eff}}$ as in Fig. 2.2. The integration of Eq. (2.14) along the path $PQ$ can be written as

$$\int_{PQ} \nabla^2 \Delta \gamma \cdot d\mathbf{l} = \frac{2\pi d_{\text{eff}}}{\Phi_0} \int_{PQ} (\mathbf{B} \times \mathbf{z}) \cdot d\mathbf{l}. \quad (2.15)$$

Rewriting $(\mathbf{B} \times \mathbf{z}) \cdot d\mathbf{l} = \mathbf{B} \cdot (\mathbf{z} \times d\mathbf{l})$ leads to

$$\Delta \gamma \bigg|_P^Q = \frac{2\pi d_{\text{eff}}}{\Phi_0} \int_{PQ} \mathbf{B}_t d\mathbf{l}, \quad (2.16)$$

where $\mathbf{t} = \hat{z} \times d\mathbf{l}/|d\mathbf{l}|$ is the unit vector which lies on the $x-y$ plane and is perpendicular to $d\mathbf{l}$ at every point on the $PQ$ curve. Note that the quantity $\Phi_{\text{strip}} = d_{\text{eff}} \int_{PQ} \mathbf{B}_t d\mathbf{l} = \int \int_{\text{strip}} \mathbf{B}_t d\mathbf{l} dz$ is just the magnetic flux through the strip $PQQ'P'$. Typically the point $P$ is chosen as a reference point and is taken as the origin $(0, 0)$, as in Fig. 2.3. If the coordinates of point $Q$ are $(x, y)$, then the above result can be written as

$$\Delta \gamma(x, y) = \gamma_0 + 2\pi \frac{\Phi(x, y)}{\Phi_0} = \gamma_0 + \Theta(x, y), \quad (2.17)$$

where $\Phi(x, y)$ is the flux through the strip $\Gamma$ in Fig. 2.3, $\gamma_0 = \Delta \gamma(0, 0)$ and $\Theta(x, y) = 2\pi \Phi(x, y)/\Phi_0$. If the path $\Gamma$ is chosen along a field line, the flux through the corresponding strip is zero. This means that $\Delta \gamma$ is constant and from Eq. (2.2) the current density is also constant. In other words, the magnetic field lines in the junction are also equicurrent density lines.

### Critical current

The total current $I$ through the junction can be calculated by integrating the Josephson current density $J$ over the junction's cross section. Inserting Eq. (2.17) into Eq. (2.2) gives

$$I = \iiint dxdy J_0 \sin (\gamma_0 + \Theta(x, y)) = \sin \gamma_0 I_1 + \cos \gamma_0 I_2, \quad (2.18)$$

where $I_1 = J_0 \int \int dxdy \cos \Theta(x, y)$ and $I_2 = J_0 \int \int dxdy \sin \Theta(x, y)$. The above expression can be written as

$$I = (I_1, I_2) \cdot (\sin \gamma_0, \cos \gamma_0) = (I_1^2 + I_2^2)^{1/2} \sin \gamma_0^2 + \cos \gamma_0^2)^{1/2} \cos \alpha, \quad (2.19)$$
Figure 2.2  Physical interpretation of Eq. (2.14) [42].
where \( \alpha \) is the angle between the vectors \((I_1, I_2)\) and \((\sin \gamma_0, \cos \gamma_0)\). The critical current, \( I_c \), which is the maximum current allowed before a potential is developed across the junction, is found by maximizing Eq. (2.19). This is done by setting \( \alpha \) equal to 0. Therefore
\[
I_c = (I_1^2 + I_2^2)^{1/2} = I_0 \left\{ \langle \sin \Theta(x, y) \rangle^2 + \langle \cos \Theta(x, y) \rangle^2 \right\}^{1/2},
\]
where the brackets \( \langle \ldots \rangle \) denote spatial averaging over the junction area, \( A = W^2 \) and \( I_0 = J_0 A \).

**External magnetic field parallel to the junction**

Now consider a magnetic field applied in the \( y \)-direction. It can be seen by examining Fig. 2.3 that the flux through \( \Gamma \times d_{eff} \) is given by \( B_y d_{eff} x \). Using the results of the previous two sections it follows that
\[
\Theta(x, y) = 2\pi \frac{B_y x d_{eff}}{\Phi_0} = \pi \frac{B_y x}{B_o}.
\]
where $B_o = \Phi_0/d_{\text{eff}}W$ and $x'$ is the normalized x-coordinate $x' = x/(W/2)$. When this result is inserted in Eq. (2.20), it leads [43] to

$$\frac{I_c}{I_0} = \left| \frac{\sin(\pi B_y/B_o)}{\pi B_y/B_o} \right|.$$  \hspace{1cm} (2.22)

This characteristic of a Josephson junction was first observed by Rowell [44] in 1963. This equation also describes the familiar Fraunhofer pattern in optics, which leads to calling an $I_c$ vs. $B_y$ curve a diffraction pattern.

For the rest of this work the symbols $x$ and $y$ will be used without primes to denote the corresponding normalized coordinates $x/(W/2)$ and $y/(W/2)$.

**Single vortex**

When a vortex is trapped in either the top or bottom superconducting layer, within the junction area, one pole of the vortex lies within the junction and the other lies outside the junction. An interior pole acts as a source or sink of magnetic field and can be treated as a magnetic monopole with total flux equal to $\Phi_0$. The outer pole is shielded from the interior of the junction so it has no influence on the current characteristics of the junction. Therefore, as long as we are only concerned with the Josephson current, a trapped vortex may be regarded as a magnetic monopole.

The situation can be more complicated if the flux lines created by the vortex find their way through the second superconducting layer as well. This is called a dipole vortex. There can also be more than one vortex trapped in both the bottom and top layers. The following will treat the case of a single vortex trapped either in the top or bottom superconducting layer. Since the size of a vortex is much smaller than the size of the junction, whether the vortex is in the top or bottom superconducting layer becomes indistinguishable in this treatment.

A vortex will be referred to as a positive vortex if the monopole acts as a source of magnetic field lines and referred to as a negative vortex if the monopole acts as a sink for the magnetic field lines. The top and bottom superconducting layers force the field within the junction to be in the plane of the junction resulting in a 2-dimensional problem.
Consider a positive vortex at position \((x_o, y_o)\) as in Fig. 2.4. If we assume the field lines in the barrier spread out isotropically, then only a fraction \(\gamma/2\pi\) of the quantum of flux \(\Phi_o\) produced by the monopole goes through \(\Gamma \times d\), where \(\gamma = \gamma(x, y, x_o, y_o)\) is the angle that the vortex at \((x_o, y_o)\) subtends the points \((0, 0)\) and \((x, y)\). Therefore

\[
\Phi_+(x, y, x_o, y_o) = \frac{\gamma(x, y, x_o, y_o)}{2\pi} \Phi_o \quad (2.23)
\]

and

\[
\Theta_+(x, y, x_o, y_o) = 2\pi \frac{\Phi_+(x, y, x_o, y_o)}{\Phi_0} = \gamma(x, y, x_o, y_o), \quad (2.24)
\]

where the + on \(\Theta_+\) refers to a positive vortex. In the case of a negative vortex the flux passing through the same stripe is opposite and so \(\Theta_-(x, y, x_o, y_o) = -\gamma(x, y, x_o, y_o)\).

The total phase difference across the junction calculated by linear superposition of phases
contributed by all the individual sources is

\[ \Theta(x, y, x_0, y_0) = \pi \frac{B_y}{B_0} x + \gamma(x, y, x_0, y_0). \] (2.25)

The last effect that will be considered in this approximation is boundary effects due to the finite size of the junction. Screening currents circulating parallel to the edge of the junction force the magnetic field lines of Fig. 2.4 to be perpendicular to the edge. By treating the vortex as a magnetic monopole, the problem becomes that of the 2-D electrostatic problem of a charge in a grounded rectangular box. The vortex generates an infinite number of image vortices arranged in a periodic lattice surrounding the junction as shown in Fig. 2.5. Including these boundary effects, Eq. (2.25) must be modified to become

\[ \Theta(x, y, x_0, y_0) = \pi \frac{B_y}{B_0} x + \gamma(\text{real vortex}) + \gamma(\text{all images}) \] (2.26)

An exact analytical solution for \( \Theta(x, y, x_0, y_0) \) from Clem can be found in Hyun's dissertation [30]. In practice it is good enough to include a finite number of image vortices when calculating \( \Theta \). The critical current can then be calculated numerically by substituting the result of Eq. (2.26) into Eq. (2.20).

Finally, to add the effects of including more than one vortex in the junction, simply add to Eq. (2.26) \( \gamma(\text{real vortex 2}) + \gamma(\text{all images from vortex 2}) \). Equation (2.26) can then be inserted into Eq. (2.20) yielding the desired result for the critical current.

**Symmetry and symmetry breaking**

The previous result of the critical current as a function of applied field and vortex location is not unique. Due to geometrical symmetries of the junction, different vortex configurations can lead to identical diffraction patterns. If it is assumed that only one vortex is within the junction, a measurement of \( I_c \) as a function of an applied field \( B_y \) determines the vortex position/sign to four possibilities. A positive vortex at \( (x_0, y_0) \), a positive vortex at \( (-x_0, y_0) \), a negative vortex at \( (x_0, -y_0) \) and a negative vortex at \( (-x_0, -y_0) \) give identical results. Likewise, a negative vortex at \( (x_0, y_0) \), a negative vortex at \( (-x_0, y_0) \), a positive vortex at \( (x_0, -y_0) \) and a positive vortex at \( (-x_0, -y_0) \) also give an identical diffraction pattern. The four vortex positions of
Figure 2.5 Image vortex lattice.
Fig. 2.6b result in the diffraction pattern shown in Fig. 2.6a. If the diffraction pattern is inverted about the $y$-axis the polarity of the possible vortex positions of Fig. 2.6b is reversed.

It is possible in theory to break this symmetry. By applying a current in the $y$-direction and measuring again to see which direction the vortex moved, the symmetry is decreased by a factor of two. Then, applying $B_z$ and measuring which way the vortex moved allows only one solution. Assuming the vortex moved in the direction of the force acting on it from the current through the film and the applied $B_z$, the position and sign of the vortex can be determined.

The magnitude and direction of the force per unit length on a vortex from a transport current in the film is given by $J \times \phi_0/c$. Here, $J$ is the current density at the position of the vortex. See Appendix for sample calculations involving this force. A more detailed description is given in Hyun’s dissertation [30].

No direct measurement exists that can determine which film the vortex is in. Instead, care must be taken in nucleation of the vortex so as to increase the likelihood of the vortex being in one or the other film. If the two films have differing $T_c$s there is a possible method for increasing the probability of nucleating a vortex in the film with the lower $T_c$. Warm the junction above both $T_c$s in zero field, lower the temperature so as to reside between the $T_c$s of each film, apply a current through the film with the lower $T_c$ and finally lower the temperature with the current still applied. While the temperature is between the $T_c$s of each film, magnetic flux will be expelled from the film with the higher $T_c$ and allowed to penetrate the other. As the temperature is lowered further, magnetic flux can be trapped only in the film with the lower $T_c$.

In the film containing current, the vortices that might be nucleated on the edge of the film feel a Lorentz force towards the opposite edge. The screening currents induced in the other film provide a Lorentz force acting on a vortex that could be nucleated on the edge of that film along the length of the film. Therefore, there is only a small chance of nucleating a vortex in the upper film if current is flowing through the bottom film.

Furthermore, cooling with an applied perpendicular magnetic field results in a vortex with the same polarity of the applied field. Using this method requires only one further measurement of pushing on it to determine the location of the vortex.
Figure 2.6 Measuring a diffraction pattern shown in a) implies the vortex positions shown in b) where +/- refers to a positive/negative vortex. The units of b) are W/2 where W is the width of the junction.
Effects of a second vortex on the edge of the junction

A second vortex added to the junction will change the shape of the diffraction pattern produced by a single vortex. However, the effect will be small if the second vortex is near the edge. As the second vortex moves in from the edge there will be a decrease in $I_{oo}$, an increase in $B_o$ and other possible asymmetric shifts in the pattern. Figure 2.7 shows the effects of a second vortex, of the same polarity, in the junction. The first vortex is held at (0.0, 0.0) and a second vortex is moved along the diagonal towards the center of the junction. The one-vortex diffraction pattern is nearly identical to the diffraction pattern obtained when the second vortex is at (0.95, 0.95). Not until the second vortex reaches (0.80, 0.80) is there an appreciable difference in the diffraction pattern.

As a second example, Fig. 2.8 shows the effect of one vortex held at (0.05, 0.55) and a second vortex of the same polarity moved along the z-axis. Again, not until (0.80, 0.00) does the diffraction pattern vary much from the one-vortex diffraction pattern.
Figure 2.7  Effect of a second vortex on the single vortex diffraction pattern of position (0.0, 0.0). A second vortex moves along the junction diagonal with position shown in label.
Figure 2.8  Effect of a second vortex on the single vortex diffraction pattern of position $(0.05, 0.55)$. A second vortex moves along the $x$-axis with position shown in label.
3 EXPERIMENTAL TECHNIQUES AND CONDITIONS

Sample preparation

The Josephson junctions used in this work were fabricated using the sputtering method of deposition in a high vacuum chamber. The junctions are of the cross type with composition $Nb$-$Ag$-$Al$-$Al_2O_y$-$Nb$. A schematic of a junction is shown in Fig. 3.1.

Figure 3.2 shows a schematic of the sputtering process [42]. The $Si$ substrate rests on a mask which exposes part of the substrate to a DC magnetron sputtering source. A constant $Ar$ gas pressure of 5 - 20 mTorr is maintained within the chamber. Electrons are forced out of the sputtering source due to a negative potential, in the range of 200 - 500 volts, with respect to the substrate. A magnetic field from the source's magnets cause the electrons to travel in a spiral lengthening their path and increasing the chance of collision with $Ar$ atoms. The $Ar$ atoms that are ionized accelerate in the presence of the electric field towards the source, ejecting atoms at the surface. Atoms from the source come flying off in all directions, including that of the exposed substrate. Using this process the source material is deposited onto the substrate in a shape defined by the mask.

In order to speed the oxidation of the $Al$ layer, a process known as glow discharge was used. During this process an aluminum ring 10 cm in diameter is biased at a negative voltage, $-512$ volts, with respect to the chamber ground. The glow discharge ring is located in the center of the upper half of the sputtering chamber. During oxidation the substrate is raised above the rotating disk to a position about 22 cm to the side of the $Al$ ring. A constant pressure of oxygen, about 80 mTorr, is maintained within the chamber. This causes glow discharge which ionizes the oxygen gas allowing the $Al$ layer, and everything else, to be oxidized more readily.

A schematic of the sputtering chamber is shown in Fig. 3.3. Its main features are a sample
Figure 3.1 Cross type Josephson junction.
Figure 3.2 The sputtering process [42].
Figure 3.3 The high vacuum sputtering chamber.
exchange port which allows the insertion and removal of the sample without breaking the high vacuum, and a load-lock mechanism which can transfer the sample between any four of the receptacles holding different masks. A Sycon Instruments thickness monitor is located near the Al and Nb sputtering guns allowing a direct in-situ measurement of the Al and Nb thickness. A shutter is used to cover the sputtering source while presputtering, a process which cleans the surface from any possible surface absorbents.

Table 3.1 shows the parameters used when fabricating samples Mb4-82, Mb6-63 and Mb6-72. The main difference in the sample preparations was that sample Mb4-82 was oxidized using glow discharge while the other two samples were oxidized in air. Sample Mb4-82 was deposited on an oxidized Si wafer. Samples Mb6-63 and Mb6-72 were deposited on a Si substrate that had an array of Au lines on it. An oxidized Si wafer was coated with 10 nm of Ti followed by 20 nm of Au in a parallel array 2 μm wide spaced 60 μm apart using standard photolithography techniques. The function of the Ti is to provide a better sticking coefficient for the Au. An array of Au lines was needed because the placement of the Nb films relative to a single Au line is not sufficiently precise. Also, collimators were added to the masks to reduce shadowing effects for samples Mb6-63 and Mb6-72. The widths of the Nb films of sample Mb4-82 were approximately 100 μm while those of samples Mb6-63 and Mb6-72 were approximately 55 μm.

The method used to fabricate sample Mb4-82 follows. First, a piece of Si wafer, one by one half cm, was cleaned by rigorously rinsing it with deionized water. Next, a small smear of high-vacuum Apiezon N grease was spread on the bottom of the sample holder and the substrate was lightly pressed to it. A small amount of grease held the substrate in place firmly while allowing easy removal when the fabrication process was completed.

A turbo pump was used to evacuate the sputtering chamber. Baking the system at 100 °C for about ten hours was needed to eliminate most of the water vapor. Once the pressure was below $2 \times 10^{-5}$ Pa the sample could be loaded into the chamber using the sample exchange port without breaking the high vacuum. The sample may be loaded before the baking process but this is not necessary.

After closing the main valve the exchange port was vented with nitrogen gas. While
Table 3.1 Deposition and oxidation parameters.

<table>
<thead>
<tr>
<th>sample</th>
<th>layer</th>
<th>time</th>
<th>P(mTorr)</th>
<th>I(A)</th>
<th>V(V)</th>
<th>rate(Å/s)</th>
<th>t(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB4-82</td>
<td>Nb</td>
<td>58 min</td>
<td>20 Ar</td>
<td>0.65</td>
<td>295</td>
<td>1.1</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>Ag</td>
<td>1 min</td>
<td>5 Ar</td>
<td>0.4</td>
<td>427</td>
<td>~ 1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>6 min</td>
<td>10 Ar</td>
<td>0.6</td>
<td>504</td>
<td>9.7</td>
<td>3500</td>
</tr>
<tr>
<td></td>
<td>AlxOy</td>
<td>70 min</td>
<td>80 O</td>
<td></td>
<td>-500</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nb</td>
<td>59 min</td>
<td>20 Ar</td>
<td>0.65</td>
<td>292</td>
<td>1.1</td>
<td>4000</td>
</tr>
<tr>
<td>MB6-63</td>
<td>Nb</td>
<td>55 min</td>
<td>20 Ar</td>
<td>0.65</td>
<td>334</td>
<td>1.2</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>Ag</td>
<td>1 min</td>
<td>5 Ar</td>
<td>0.4</td>
<td>425</td>
<td>~ 1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>10 min</td>
<td>10 Ar</td>
<td>0.6</td>
<td>504</td>
<td>8.3</td>
<td>3500</td>
</tr>
<tr>
<td></td>
<td>AlxOy</td>
<td>1 min in air</td>
<td></td>
<td></td>
<td>430</td>
<td>~ 1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nb</td>
<td>60 min</td>
<td>20 Ar</td>
<td>0.65</td>
<td>325</td>
<td>1.2</td>
<td>4000</td>
</tr>
<tr>
<td>MB6-72</td>
<td>Nb</td>
<td>55 min</td>
<td>20 Ar</td>
<td>0.65</td>
<td>315</td>
<td>1.2</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>Ag</td>
<td>1 min</td>
<td>5 Ar</td>
<td>0.4</td>
<td>430</td>
<td>~ 1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>10 min</td>
<td>10 Ar</td>
<td>0.6</td>
<td>410</td>
<td>8.3</td>
<td>3500</td>
</tr>
<tr>
<td></td>
<td>AlxOy</td>
<td>1 min in air</td>
<td></td>
<td></td>
<td>305</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

continuing to allow the gas to flow, the exchange door was opened and the sample holder was moved onto the load-lock mechanism. After the door had been closed, the exchange port was evacuated using a Barodyne oil-less pump. The port was then flushed with nitrogen gas and evacuated three times. When the pressure in the exchange port was below 500 mTorr the main valve was opened.

The sample holder was lowered down to the receptacle containing the mask for the bottom layer of Nb. The substrate rests on top of the mask, making contact, which minimizes shadow effects during sputtering. The load-lock mechanism was then raised so that the disk was free to rotate. The disk was then rotated so that the substrate was directly above the Nb sputtering gun. The shutter was aligned between the gun and substrate.

The cold trap was filled with liquid nitrogen once the pressure again reached 2 x 10⁻⁵ Pa. The cold trap freezes any remaining water vapor to the sides of it lowering the pressure by another order of magnitude. Once the pressure was below 2 x 10⁻⁶ Pa the sputtering process
was begun. The cold cathode vacuum gauge was turned off and the turbo was restricted. The
gas-flow valve was opened and the pressure controller was set so that a constant flow of $Ar$
gas could be maintained at 20 mTorr.

$Nb$ of 99.99% purity was used as the sputtering target. A constant current of 0.65 Amp
was maintained by the MDX-1.5K Advanced Energy DC sputtering power supply yielding a
voltage of about 290 volts. After presputtering for 60 minutes the shutter was opened and
the deposition began. It was found that $Nb$ films displayed better superconducting properties
when this long presputter time was used. Presputtering this long ensures that the $Nb$ target
is clean when sputtering begins and has a gettering effect which reduces the amount of water
and other contaminants in the chamber.

The sputtering rate, monitored by the thickness monitor, was about 1.1 Å/sec. The power
supply was kept at this moderately low level to avoid heating up the target beyond the cooling
capabilities of the gun. After about 62 minutes of sputtering the thickness monitor displayed
4000 Å. At this point the power to the sputtering gun was turned off, the $Ar$ gas flow was
turned off, the gas flow valve was closed and the turbo was unrestricted. The same procedures
were used when sputtering $Al$ and $Ag$.

With the sample holder on the same mask as was used for the bottom $Nb$ strip, about 1500
Å of $Ag$ was deposited. The current was set at 0.41 Amp and and the $Ar$ pressure held at
5 mTorr. After presputtering five minutes, the shutter was opened and sputtering took place
for one minute. The purpose of this layer is to protect the $Nb$ layer from oxidizing during the
oxidation of the $Al$.

The next layer to be sputtered was $Al$. The same mask used for the previous two steps
was used but with the substrate raised approximately 1 mm above the mask. This ensured
full coverage of the bottom $Nb$ and $Ag$ layers. The power supply was set at 0.6 Amp and the
$Ar$ pressure at 10 mTorr. After presputtering for 20 minutes the shutter was opened. The
thickness monitor displayed a rate of about 11.8 Å/sec. 3540 Å of $Al$ was deposited in about
seven minutes.

The $Ag$ contact pads, used later to attach wires, were deposited at this time before the
oxidation step so as to minimize any oxide barrier between the Al and Ag. The Ag was sputtered for 4.5 minutes with a current of 0.4 Amp and Ar pressure of 5 mTorr.

The oxidation step was performed next. Biasing the Al ring -512 volts with respect to the chamber ground in the presence of 78.6 mTorr oxygen gas produced a strong glow discharge in the chamber. This was continued for 70 minutes. This pressure and time was chosen after trying several different times and pressures. Smaller pressures and times lead to insufficiently thin oxide barriers. After turning off the voltage and shutting off the gas flow the gas line was pumped on for several hours before filling it with Ar gas to minimize oxygen contamination.

Finally, the top Nb layer was deposited with similar parameters to the deposition of the bottom Nb strip, again with an extended presputtering time of 60 minutes. The extended time ensured the elimination of the top layer of the Nb target that may have been oxidized during the glow discharge process.

Before removing the sample from the system it was allowed to equalize with the room temperature. After removing the sample from the sputtering chamber via the sample exchange port, it was immediately put into the measuring cryostat shown in Fig. 3.4. Cu wires were attached to the contact pads by pressing pieces of In onto the wires as illustrated in Fig. 3.1. A fresh surface of In was needed to stick to the Ag. Once the contact was made there was never a problem with the wires coming off the contact pads. Transferring the sample from the sputtering chamber into the measuring cryostat took approximately 45 minutes.

**Cryostat**

A schematic of the cryostat used in this experiment is shown in Fig. 3.4. After the Cu wires were attached to the Ag contact pads the sample was attached to the end of the Cu block with a small amount of Dow Corning High-Vacuum grease. The Cu wires are soldered to the posts further up on the Cu block. Cu wires soldered to the non-sample side of the Cu block wrap around the block 11.4 cm from the sample then run up through a stainless steel tube. At the top of the sample insertion rod are two hermetic seal feed-throughs to which the wires are attached. The Cu block can be raised vertically out of the cryostat to mount a sample.
Figure 3.4 The cryostat.
Located 0.64 cm away from the sample is a LakeShore carbon-glass thermometer embedded within the center of the Cu block which is used to measure the temperature of the sample. The closest Cu posts are located 4.1 cm from the sample. The 26 ohm heater, in the form of 45.7 cm of Manganin wire is located 7.6 cm from the sample. The Manganin wire was doubled, then twisted before wrapping it around the Cu block so as to cancel any magnetic field from current going through it. A Si-diode thermometer is 1.9 cm further up the Cu block from the heater wire. A LakeShore 330 temperature controller is connected to the heater wire and the Si-diode thermometer. The temperature controller can maintain a constant temperature in the range of 5 - 10 K with a stability of ±2 mK and a set point resolution of 3 mK. A Cu shield is placed over top the Cu block to increase temperature stability and uniformity.

The sample space is evacuated to 5.8 - 7.0 mTorr. If the pressure goes below this range the Cu block becomes so isolated from the He bath that heat coming down the sample insertion rod can warm the sample to above 100 K. If the pressure goes above this range a large amount of power is needed in the heater to maintain the desired temperature. The more power supplied to the heater the faster the He boils away.

Between the sample space and the He bath is an isolation space that is kept at 6 mTorr. This extra space is to help keep the Cu block at a uniform, constant temperature. Both the sample and isolation spaces are filled with He gas. In both spaces the desired pressure can be achieved using mechanical pumps.

Surrounding the isolation can are two Helmholtz coils, one oriented so as to generate a magnetic field perpendicular to the sample, z-direction, and the other to generate a magnetic field parallel to the sample, y-direction. The Cu block can be rotated about the z-axis to allow the magnetic field to point in any direction in the z-x plane. The coils are made by wrapping Nb-Ti wire several hundred times around spools made of g-10 cloth impregnated plastic. The wire is superconductive when in liquid He so no heat is generated when running current through it. The coils are in the standard Helmholtz arrangement so as to maximize the uniformity of the magnetic field over the Josephson junction. The coils were calibrated removed from the isolation can. Calibration constants of 81.6015 G/A and 52.5437 G/A for the
central region of the \( B_y \) and \( B_z \) coils respectively were measured using a Hall probe attached to a Hewlett Packard DC milliammeter.

Several layers of Co-netic shielding were placed both within the \( He \) bath region surrounding the Helmholtz coils and surrounding the entire cryostat so as to minimize the external field caused by the Earth and other sources.

**Data acquisition**

Voltage and current leads were connected to each \( Ag \) pad as shown in Fig. 3.1. The pads are numbered 1 to 4 beginning with the top pad and counting clockwise as shown in the figure. The resistance of either film can be measured separately by connecting the current and voltage leads to pads 1 and 3 or 2 and 4.

Current is fed through the junction symmetrically when measuring \( V - I \) curves for diffraction patterns. This is done by putting current in through pads 1 and 3 and taking it out through pads 2 and 4. Voltage leads were connected to pads 1 and 2. The symmetric current feed is used for two reasons. First, the current through the junction is more uniform. Second, the magnetic fields produced by the currents approaching the junction cancel each other out. Likewise, the fields produced by the currents flowing away from the junction in opposite directions cancel each other out.

In order to eliminate thermal emfs both positive and negative currents are used during \( V - I \) curves. Alternatively, the thermal emf can be measured at zero current and subtracted from the measured voltages.

**Measurements and procedures**

This section describes the measurements and procedures used to extract data from the Josephson junctions. First, in order to determine the critical current of the junction, \( I_c \), at a given temperature, one needs to have a consistent method for extracting \( I_c \) from a \( V - I \) curve. \( I_c \) is determined as follows: 1) measure a \( V - I \) curve; 2) find the best line that goes through
the first five data points above 10% of the highest voltage point; 3) extrapolate to the $I$-axis to determine $I_c$ as shown in Fig. 3.5.

Next, the method used to nucleate vortices in this study are described. A vortex can be nucleated in the junction several different ways including cooling through $T_c$ with an applied magnetic field and cooling through $T_c$ with current through one of the $Nb$ strips. Vortices were nucleated in sample Mb4-82 by applying current through the bottom $Nb$ strip while cooling through $T_c$ at a rate of 1 K/min. Vortices were nucleated in sample Mb6-63 by cooling through $T_c$ either with a current in the bottom $Nb$ film or with an applied, perpendicular magnetic field. Vortices in sample Mb6-72 were nucleated by cooling through $T_c$ with a current in the bottom $Nb$ film.

To characterize the pinning sites, thermal depinning as a function of applied, perpendicular
magnetic field experiments were carried out using the following procedures: 1) trap a vortex in the central region of the junction; 2) determine the location of the vortex by measuring $I_c$ vs. $B_y$ at a temperature $T_{\text{measure}}$; 3) apply $B_z$, increase the temperature to $T_{\text{push}}$ and back down to $T_{\text{measure}}$ again to avoid overshooting and then remove $B_z$; 4) check to see if the vortex moved; 5) repeat with $T_{\text{push}}$ increments of 3 mK until the vortex leaves the junction. Using this method, the temperature at which the vortex first depins and the temperature at which the vortex leaves the junction can be determined as a function of applied magnetic field.

In order to determine the elementary pinning force at a given temperature, $T_{\text{push}}$, the following method was used: 1) trap a vortex in the central region of the junction and determine its position; 2) slowly ramp the temperature from $T_{\text{measure}}$ to $T_{\text{push}}$ and then apply a current through one of the Nb films for 2 seconds; 3) return to $T_{\text{measure}}$ and check to see if the vortex moved; 4) repeat until the vortex leaves the junction.
4 EXPERIMENTAL RESULTS WITH SAMPLE Mb4-82

The first attempt to fabricate artificial pinning sites within a Josephson junction consisted of placing Fe balls on top of an already characterized junction. The magnetic moment of the Fe balls may be large enough to nucleate a vortex and may be strong enough to pin the vortex under it. By using an already working junction, the intrinsic pinning sites in the top film could be mapped out before the artificial pinning sites are even added, so one is not mistaken for the other. Strengths of the intrinsic pinning sites with respect to thermal activation and a Lorentz force are first measured for comparison with the strength of artificial pinning sites.

Sample characterization

The Josephson junction can be characterized by values of the resistance vs. temperature of the Nb films and critical current of the junction vs. temperature. These were measured as part of the basic characterization of the Josephson junction. Figures 4.1a and 4.1b show the resistivity measurements performed on the top and bottom Nb film respectively. These films seem to be of much higher quality than the films described in the following two chapters. The graphs display resistance measured while both raising and lowering the temperature. The value of $T_c$ shown in the figures represents a lower bound on the $T_c$ of each film in the region of the junction. Since the transition is spread out over temperature, different parts of the films may go superconducting at slightly different temperatures. The $T_c$s shown were determined by the point at which the resistance became larger than zero by an amount equal to the error in measuring the resistance. The oxidation of the Al always seems to degrade the $T_c$ of the bottom film, presumably because some oxygen gets into the bottom layer Nb even though it is coated with both Ag and Al. Also, since the entire bottom strip is covered with Ag, $T_c$ could
Figure 4.1 Resistance vs. temperature for Mb4-82. a) Top Nb and b) bottom Nb.
be lowered from the proximity effect.

The critical current of the junction as a function of temperature is shown in Fig. 4.2. The critical current of the junction goes to zero at approximately 9.0 K.

For these experiments where the goal is to locate the position of a vortex, the most crucial feature of a Josephson junction is its magnetic field dependence of the critical current. To ensure current flows uniformly through the junction, current is fed symmetrically into the junction. Also, the temperature is chosen so that the critical current is small enough to be in the small-junction limit (see Appendix), and large enough so that the signal-to-noise ratio is large. A temperature of 8.466 K was chosen to measure the diffraction patterns for this sample. A typical no-vortex pattern for this junction is shown in Fig. 4.3. The symmetry of the pattern with respect to positive and negative $B_y$ and the fact that the minima of the pattern nearly reach zero indicate the junction is suitable for locating vortices.

Intrinsic pinning sites in bottom film

Figure 4.4 shows the interference patterns and locations of all the sites on which single vortices were trapped in the bottom film. (Note that it is only known that the location is one of four possibilities discussed in Chapter 2). The close agreement between the data (circles) and the theory (lines) lends confidence to the applicability of the theoretical model used for this physical system. The main assumptions for this model are current is uniformly flowing through this nearly square Josephson junction and a single vortex is penetrating the junction. No trapped vortices could be obtained in the top film by cooling through $T_c$ with a transport current flowing through the top film up to 0.35 mA.

Thermal depinning in the presence of an applied perpendicular magnetic field

At temperatures well below $T_c$ vortices tend to get trapped on pinning sites in the thin film. As the temperature increases, thermal activation and lowering of the pair potential result in vortex hopping. Once the thermal energy becomes comparable to the energy difference between
Figure 4.2 Critical current as a function of temperature of the junction.
Figure 4.3 No-vortex pattern for sample Mb4-82 with $I_{oo} = 0.72$ mA, $B_o = 380$ mG and $B_{offset} = -64$ mG.
Figure 4.4  Initial vortex positions in bottom film used in thermal depinning experiments.
the vortex residing on the pinning site and off the site, it becomes probable that the vortex will hop off the site.

In these experiments the temperature at which the vortex first depins is measured. As the temperature is raised above this initial threshold the vortex may get stuck on another, perhaps deeper, pinning site. Upon raising the temperature high enough the vortex will leave the junction region either by traveling along the film out of the junction area or leaving the film altogether.

Three vortices were trapped at (0.05, 0.55) and thermally depinned in the absence of an external magnetic field. The first vortex depinned at 8.856 K and moved to (0.75, −0.75) and then left the junction altogether at 8.924 K. The second vortex depinned at 8.901 K and moved to (0.75, −0.75) and then left the junction all-together at 8.952 K. The third vortex depinned at 8.964 K and left the junction region in one motion.

In addition to these zero-field results, the effects of a perpendicular magnetic field on thermal depinning were studied. A sketch of the field lines inside the junction and induced currents in the bottom film as a result of a positive, perpendicular magnetic field [25] are shown in Fig. 4.5. Upon reversing the applied field, all fields and currents within the junction are reversed. The induced screening currents apply a Lorentz force on the vortex in the same direction of the magnetic field lines shown in Fig. 4.5. The total force on a vortex is the sum of this Lorentz force, the image force (described in chapter 2) and the force from the pinning site.

The ideal situation would be to have a series of thermal depinning experiments with varying applied perpendicular fields each with the same initial position of the vortex. This way, the variations between the pinning sites would not mask any observable effect of the magnetic field on the temperature at which the vortex depins. It was found that a vortex could be pinned at (0.05, 0.55), the diffraction pattern shown in Fig. 4.4a, by stabilizing the temperature at 9.25 K, applying 0.25 mA through the bottom film and cooling through \( T_c \) by turning the power to the heater off.

Thermal depinning experiments with vortices initially pinned at (0.05, 0.55) were performed
Figure 4.5  Field lines inside the junction and induced current in the bottom superconductor.
with $B_z$ of $-20, -15, -10, -5, 0, 5, 10, 15$ and $20$ mG. Each experiment was repeated two or three times for reproducibility. Figure 4.6 shows the temperature at which the vortex first depinned versus applied field. For these data, the temperature interval between successive depin points is $3$ mK. Sixteen experiments were performed with the starting point of the vortex at $(0.05, 0.55)$. During these sixteen experiments, the vortex first hopped to position $(0.75, -0.75)$ twelve times, as shown by the triangles in Fig. 4.6. The other four times the vortex pinned at no intermediate sites before exiting the junction, as shown by the solid squares in Fig. 4.6. The reason for the scatter in the data is not understood, but the most likely explanation is that, even though the starting location of the vortex is nominally $(0.05, 0.55)$, there are several pinning sites close to this point so that the starting configuration is slightly different each time. There is no obvious $B_z$ dependence on the temperature at which the vortex first depins. Also, applying $B_z$ does not change the trajectory of the vortex upon thermal depinning. Either the vortex leaves the junction on the first jump or it moves to the location $(0.75, -0.75)$ when it starts from $(0.05, 0.55)$. Data were not taken at higher $B_z$ because even at $15$ and $20$ mG, multiple vortices were nucleated in the junction. The implication of this "First Move" experiment is that at the temperature slightly below where the vortex begins to thermally depin, the holding force of the pinning site on the vortex is much larger than the Lorentz force from the screening currents induced by fields up to $20$ mG.

In addition to the thermal depinning experiments performed on vortices starting at position $(0.05, 0.55)$, the trajectory of vortices initially pinned at other locations, shown in Figs. 4.4b - 4.4e, were followed as they thermally depinned. Upon thermal depinning, vortices trapped at these initial positions stopped at as many as four or five intermediate locations before leaving the junction region. The motion of the vortex in two typical experiments are now discussed in detail. In the following figures the measured diffraction patterns are shown by the circles and the theoretical fits are shown with solid lines. The fits were obtained by varying the $x$ and $y$ coordinates of the vortex as well as $I_{oo}$, $B_o$ and $B_{offset}$ of the junction. A trapped vortex very close to the edge of the junction may depress $I_{oo}$ and alter $B_o$ as discussed in Chapter 2. Magnetic field external to the cryostat may leak in making $B_{offset}$ nonzero.
First Move  Starting Position = (.05, .55)

Figure 4.6  First thermal depin as a function of applied perpendicular magnetic field.
In the first experiment a perpendicular field of $B_z = 5 \text{ mG}$ is applied while the temperature is raised to thermally activate the vortex. Figure 4.7 shows the trajectory of the vortex as it thermally depins, corresponding to the diffraction patterns shown in Figs. 4.8a - 4.8f. Figure 4.8a shows the initial diffraction pattern. At $T_{\text{push}} = 8.904 \text{ K}$ a small shift in the diffraction pattern occurs. This could be from the vortex moving very slightly or from vortices trapped on the edge of the film moving. At $T_{\text{push}} = 8.998 \text{ K}$ the vortex moves from $(0.00, -0.20)$ to $(0.65, 0.10)$. Small changes in the diffraction pattern again occur at $T_{\text{push}} = 9.064 \text{ K}$ and $T_{\text{push}} = 9.106 \text{ K}$. The junction mainly clears at $T_{\text{push}} = 9.124 \text{ K}$. Mainly clears just means there are no vortices in the central region of the junction. There still may be vortices trapped on the edge of the film. The arrow showing the vortex leaving the junction region in Fig. 4.7 is not meant to imply the path taken by the vortex.

In the second experiment a perpendicular field of $-10 \text{ mG}$ is applied while the temperature is raised to thermally activate the vortex. Figure 4.9 shows the trajectory of the vortex upon thermally depinning, corresponding to the diffraction patterns shown in Figs. 4.10a - 4.10j.

Figure 4.10a shows the original diffraction pattern which matches the theoretical fit to position $(0.00, -0.15)$. Figures 4.10b and 4.10c show the diffraction patterns obtained after raising the temperature to $8.997 \text{ K}$ and $9.003 \text{ K}$ respectively. These patterns are very similar to the original one. The differences are either due to very small movements of the central vortex or movements of vortices trapped on the edge. At $T_{\text{push}} = 9.012 \text{ K}$ the central vortex makes a big jump as shown in Fig. 4.10d. As the temperature is raised further the vortex hops around as shown in Figs. 4.10e - 4.10g. At $T_{\text{push}} = 9.040 \text{ K}$ something new happens. The diffraction pattern becomes one which a single vortex diffraction pattern is unable to match. The interpretation is that a second vortex has entered the central region of the junction. It is unclear whether a new vortex was nucleated by the applied magnetic field or if a second vortex that was originally outside the junction region wandered in. Upon raising the temperature 3 mK higher the diffraction pattern, shown in Fig. 4.10i, goes back to the one of Fig. 4.10g. It appears that while one vortex was at $(0.10, 0.35)$ a second vortex was able to come into the junction region and leave again without disturbing the original vortex. Finally, at $T_{\text{push}} =$
Figure 4.7 Trajectory of vortex as it thermally depins with $B_z = 5$ mG.
Figure 4.8 Thermal depinning with $B_z = 5$ mG.
Figure 4.9  Trajectory of vortex as it thermally depins with $B_z = -10$ mG.
Figure 4.10 Thermal depinning with $B_z = -10$ mG.
Figure 4.10 (Continued)
9.049 K the vortex leaves the junction region all-together as shown in Fig. 4.10. The arrow showing the vortex leaving the junction in Fig. 4.9 only indicates that the vortex leaves the junction, it is not meant to imply that the path the vortex took upon leaving is known.

Figure 4.11 shows the temperature at which the junction is mainly cleared vs. applied field for all of the thermal depinning experiments. At both +20 mG and -20 mG the vortex exits the junction at about a 50 mK lower temperature than for the zero field case. There is a lot of scatter in the data, but a decrease in the upper bound of the temperature at which the vortex exits the junction as the magnitude of $B_z$ is increased is visible. If the Lorentz force from the Meissner screening currents of the applied $B_z$ were comparable to the pinning forces, we would expect a lower depinning temperature for fields of both the same and opposite sign as the field of the vortex. The fact that the temperature at which the vortex exits the junction is the same, within error bars, as the magnitude of the applied magnetic field increases tells us that the strength of the pinning forces is much larger than the Lorentz force of the screening currents induced from the applied magnetic field up to 20 mG. As the temperature is increased towards the temperature at which the vortex would have thermally depinned with no applied magnetic field, the vortex is helped off the pinning site by the Lorentz force.

Depinning via transport current of vortex at (0.05, 0.55)

Current depinning experiments were attempted on a vortex in the bottom Nb film at position (0.05, 0.55). Here, the goal is to measure the minimum Lorentz force supplied by the transport current needed to depin the vortex from the pinning site at a given temperature, $T_{push}$. In this manner, the elementary pinning force can be directly measured. The temperature is slowly ramped up from 8.466 K, where the diffraction patterns are measured, to $T_{push}$, at which point a current is passed through the bottom Nb film for two seconds. The temperature is then lowered to 8.466 K again and the diffraction pattern is measured to see if the vortex moved. It was found that for $T_{push} = 8.700$ K, vortices would be nucleated along the edge of the film before the central vortex would depin. Figure 4.12a shows the difference in the sequential diffraction patterns as a function of $I_{push}$, the current applied through the bottom
Figure 4.11  Temperature at which the junction is mainly cleared as a function of applied perpendicular magnetic field.
Figure 4.12  Current depinning experiment with $T_{\text{push}} = 8.700$ K. a) The change in diffraction pattern as higher $I_{\text{push}}$ is applied. b) Diffraction patterns at points 1, 2, 3, 4 and initial pattern.
The difference in diffraction patterns is determined by measuring $I_c$ at $B_y = -0.25$, 0.07 and 0.25 G and comparing these values with the $I_c$s of the initial diffraction pattern. The full patterns of points 1, 2, 3 and 4 as well as the initial pattern are shown in Fig. 4.12b. As $I_{push}$ is increased, the diffraction pattern is suppressed and widened along the $B_y$-axis. The interpretation is that the vortex at $(0.05, 0.55)$ remains fixed while vortices are nucleated along the edge of the film and pushed inward. Evidence for this lies in the fact that the general shape of the diffraction pattern remains the same (see Chapter 2).

At a higher $T_{push}$ of 8.950 K it was found that the central vortex could be depinned with only a small chance of further nucleation. Two current depin experiments are now described in which $T_{push} = 8.950$ K. Using larger intervals of $I_{push}$ decreases the amount of nucleation. Essentially, this is because the fewer times you apply a current, the fewer times vortices can get nucleated or pushed into the junction region. Figure 4.13 shows the results of applying $I_{push} = 5$ and 10 mA with no intermediate steps. Figure 4.13a shows the initial diffraction pattern. Applying 5 mA nucleated a second vortex and pushed it inward, as shown in Fig. 4.13b. Whether there is actually only a second vortex in the junction region or there are more vortices along the edge is impossible to determine. What is clear is that the diffraction pattern has become so distorted that no single vortex pattern comes close to matching it. Applying 10 mA pushed all vortices out of the junction as shown in Fig. 4.13c.

Since 5 mA nucleated multiple vortices in the previously mentioned experiment, the next experiment began with $I_{push} = 6$ mA. At this current the vortex was depinned and moved to $(0.10, -0.10)$ as shown in Fig. 4.14b. Upon applying 7 mA the vortex is pushed out of the junction as shown in Fig. 4.14c.

It appears that a vortex at position $(0.05, 0.55)$ can be depinned with a current of 6 mA at 8.95 K and the junction can be cleared at 7 mA at 8.95 K. Multiple vortices in the junction influence the current and temperature at which the central vortex will depin. Hence, the nucleation of other vortices increases the uncertainty and reproducibility of this result. There exists only a small region in which the temperature is low enough so as not to thermally activate the vortex and high enough so as not to nucleate more vortices with a transport current.
Figure 4.13 Current depinning experiment I with $T_{\text{push}} = 8.95$ K. a) Initial pattern, b) pattern after 5 mA is applied, and c) pattern after 10 mA is applied.
Figure 4.14  Current depinning experiment II with $T_{push} = 8.95\ K$. a) Initial pattern, b) pattern after 6 mA is applied, and c) pattern after 7 mA is applied.
Fe balls as artificial pinning sites

At this point sample Mb4-82 was taken out of the cryostat so that Fe balls could be placed on top of the junction. One drop of a hexane solution with Fe particles was placed on top of the junction region. The hexane quickly evaporated and the sample was placed back into the cryostat. No measurement was made to determine if any Fe balls had successfully been placed on top of the junction before returning the sample to the cryostat. It would not be until after all data were taken that the sample was taken to the SEM to determine if indeed there were Fe balls on top of the junction. In order to better understand the data, the results of the SEM analysis will be described first.

Figure 4.15 shows the SEM picture of the junction. The bottom film is along the y-axis. The bottom film is wider than the top film because the bottom Nb film has on top of it a layer of Al that is wider than the Nb film itself. The edges of the films appear rather fuzzy and not well defined. This can be explained as a result of two effects. Firstly, shadowing effects occurred during sample preparation, where the sputtered material is deposited beyond the bounds of the mask. Even though the substrate was in direct contact with the mask for the Nb deposition, the material was still able to extend slightly under the mask. Secondly, the effect is brought out more by the contrast setting. The contrast was maximized to illuminate the particles on top of the junction. As a result, the edges of the films appear to be more diffuse than they do at other contrast settings.

Energy Dispersive Spectroscopy (EDS) was used to check the composition of all the particles on top of the junction region. The two largest balls with coordinates (−0.05, −0.05) and (−0.80, −0.75) were determined to be Fe. These are only approximate coordinates as the junction region shown in Fig. 4.15 does not appear to be well defined. The other particles were determined to be dust. This dust came from the sample being exposed to air during the transfer of the sample from the sputtering chamber to the cryostat, taking the sample out to put Fe balls on, and from transporting the sample from the cryostat to the SEM.

As stated earlier, before the addition of the Fe balls there were no easily accessible intrinsic pinning sites in the top Nb film. Once the Fe balls were in place, this changed. Upon
Figure 4.15  SEM picture of sample Mb4-82 with Fe balls on top of the junction region.
cooling through $T_c$ with no applied magnetic field and no currents through either film, vortices could be nucleated and pinned, resulting in the diffraction patterns shown in Figs. 4.16a and 4.16b. The diffraction pattern in Fig. 4.16a matches very well with the theoretical curve for a positive vortex at $(-0.05, -0.05)$. Likewise, the diffraction pattern shown in Fig. 4.16b matches well with the theoretical curve for a positive vortex at $(-0.80, -0.75)$. It is difficult to say conclusively whether the vortex is pinned under the outer Fe ball. When a vortex is that close to the edge of the junction the diffraction pattern can be confused with many different locations near the edge. Since there were no pinning sites found before the Fe balls were put on the junction, however, this serves as strong evidence for the vortex actually being pinned under the outer Fe ball. One might ask whether any of the other dust particles could serve as pinning sites. Since the dust particles have no magnetic moment and are not metallic there is no reason for a vortex to be pinned under a dust particle. No other diffraction patterns were obtained upon cooling through $T_c$ in the absence of fields and currents, not even the no-vortex diffraction pattern. It appears that the magnetic moments of the Fe balls were strong enough to nucleate vortices and act as artificial pinning sites.

Once these two pinning sites were discovered, the next step was to characterize them with thermal and current depinning experiments. Figure 4.17 shows the results of thermal depinning of a vortex at the initial position of $(-0.05, -0.05)$. The difference in diffraction patterns is determined by measuring $I_c$ at $B_y = -0.25$, 0.07 and 0.25 G and comparing these values with the $I_c$'s of the initial diffraction pattern. The initial diffraction pattern is the same as that shown in Fig. 4.16a, indicating the vortex was pinned on the central Fe ball. As the temperature was increased, the initial diffraction pattern changed slightly without changing shape, indicating movement of vortices along the edge of the film. At a temperature of 9.145 K the diffraction pattern changed shape drastically, indicating the vortex depinned and moved to a position near the edge of the junction, most likely at the location of the second Fe ball. The diffraction pattern obtained is the same as the one shown in Fig. 4.16b. Upon raising the temperature higher, something rather unexpected occurred. The pattern changed back and forth between the original pattern and the second position. The interpretation is that the
Figure 4.16  Diffraction patterns obtained upon cooling through \( T_c \).
Figure 4.17  Thermal depinning experiment on central Fe ball pinning site.
magnetic moment of the central Fe ball is strong enough to nucleate a vortex and pin it well below $T_c$. It was not, however, strong enough to guarantee nucleation and pinning. Above $T_{push} = 9.145$ K sometimes the vortex was not found on the central Fe ball.

Next, three current depinning experiments in which positive current through the top film was used to push a vortex initially located on the central Fe ball. The first two experiments used $T_{push} = 8.420$ K and the third used $T_{push} = 9.000$ K. The first experiment began pushing with 1.0 mA and used increments of 0.5 mA. At a current of 6.5 mA the vortex depinned and moved to the location of the second Fe ball. Once the current was increased to 7.5 mA the diffraction pattern began to deviate from a one-vortex pattern indicating the nucleation of more vortices on the edge of the film.

In order to find the depinning current more precisely, the experiment was repeated beginning with $I_{push} = 6.0$ mA using increments of 0.1 mA. The results are shown in Fig. 4.18. Figure 4.18a shows the initial diffraction pattern and the best theoretical fit of $(0.10, -0.05)$. As stated earlier, the fitting routine searches the upper and lower right quadrants for the best fit with a positive vortex. Since there is a symmetry with respect to the x-axis, the x-coordinate of 0.10 could come from a vortex at $x = +0.10$ or $-0.10$. Hence, this is roughly the same position as described in Fig. 4.16a. Figures 4.18b - 4.18f show the two peaks of the diffraction pattern slightly changing relative heights in response to 6.2 - 7.1 mA of current through the top Nb film. This implies the vortex was moving around slightly under the Fe ball. Figures 4.18g - 4.18j show the diffraction pattern changing more dramatically in response to $I_{push} = 7.3, 7.4, 7.5$ and 7.9 mA. At $I_{push} = 8.0$ mA the vortex moves to the location of the second Fe ball, as shown in Fig. 4.18k. Even though the best fit to the data is a vortex at $(0.00, 0.90)$, the diffraction pattern is just like the one shown in Fig. 4.16b. This is a result of the ambiguity of fitting a vortex near the edge of the junction as described earlier.

In order to be in a temperature region where fewer vortices would be nucleated, a current depinning experiment was performed with $T_{push} = 9.000$ K. It was found, however, that at this temperature the central Fe ball could nucleate a vortex making it difficult to make a meaningful measurement of the depinning current. Figure 4.19 shows the difference in the
Figure 4.18  Current depinning experiment with $T_{\text{push}} = 8.420 \text{ K}$. 
Figure 4.18 (Continued)
Figure 4.19 Current depinning experiment with $T_{push} = 9.000$ K.
diffraction patterns as a function of $I_{\text{push}}$. The numbers above each data point refer to the locations shown in Fig. 4.20. The vortex begins at the position of the central Fe ball. At the first $I_{\text{push}}$ of 0.5 mA the vortex moves to the position of the second Fe ball. Hence, the depinning current required to depin a vortex located at (0.10, -0.05) at $T_{\text{push}} = 9.000$ K is less than or equal to 0.5 mA. Upon applying higher currents the vortex moves between the locations shown in Figs. 4.20b - 4.20e until a new vortex is nucleated by the central Fe ball. Between $I_{\text{push}} = 3.0$ and 3.2 mA it appears the vortex stays at the location of the central Fe ball because the diffraction pattern doesn't change. What probably happened was that the current pushed the vortex off the site and another one was nucleated before the next diffraction pattern was taken.

Since there is no way to determine what the magnetization of the Fe balls is by measurement or otherwise, a prediction of the anticipated pinning force can not be made. However, an estimate of the total magnetic moment of the central Fe ball can be made by examination of the thermal depinning and current depinning results. The thermal energy required to depin a vortex pinned on the central Fe ball, $kT$, can be compared with the magnetic energy gained from the vortex aligning with the magnetic moment of the Fe ball, $\mu_{\text{Fe}} \cdot \mathbf{H}_{\text{vortex}}$. This comparison yields a result of $\mu_{\text{Fe}} \sim 1.7 \times 10^{-22}$ J/T. Also, the force between a magnetic particle and a vortex [26], $\frac{\mu_{\text{Fe}} \Phi_0}{2\pi \lambda_{\text{Fe}}}$, can be compared to the measured depinning force, $10^{-13}$ N. This comparison yields the result $\mu_{\text{Fe}} \sim 8.2 \times 10^{-21}$ J/T. These two different methods of determining $\mu_{\text{Fe}}$ are within a factor of two of each other. If the central Fe ball would have been one single domain, its net magnetic moment would have been $7.2 \times 10^{-11}$ J/T. This implies that the central Fe ball is divided into many domains with random orientations yielding a very small net magnetic moment. Furthermore, the directions of the magnetization of the Fe balls can not be determined although they appear to have some component along the positive $z$-axis since positive vortices were nucleated.
Figure 4.20 Diffraction patterns for current depinning experiment with $T_{push} = 9.000 \, \text{K}$.
Summary of results with sample Mb4-82

Artificial pinning sites have been successfully incorporated into the top layer of a Nb based Josephson junction in the form of Fe balls. These artificial pinning sites have been characterized in terms of thermal depinning and Lorentz force depinning. The magnetic moments of the Fe balls were so large that nucleation of a vortex would occur upon zero field cooling through $T_c$. The intrinsic pinning sites in the bottom Nb film have been characterized with thermal depinning in the presence of an external magnetic field and current depinning. No intrinsic pinning sites in the top Nb film were discovered before the addition of the Fe balls.

For the first time the locations of pinning sites determined by the diffraction-pattern method were verified by SEM measurements due to the large size of defects causing the pinning sites.
5 EXPERIMENTAL RESULTS WITH SAMPLE Mb6-63

Two Josephson junctions have been fabricated on top of thin strips of Au. The goal is to determine whether the proximity effect from the Au lines is strong enough to reduce the superconducting order parameter at the point of contact between the Au line and the superconductor, enough to act as a pinning channel for vortices. This chapter deals with the first junction fabricated on top of a Au line, Mb6-63.

The proximity effect from the Au line may be strong enough to pin vortices directly. In this case the pair potential would be reduced so much that it would become more energetically favorable for a vortex to reside on the line than on other intrinsic pinning sites off the Au line. The Au line may strengthen the intrinsic pinning sites that lay above the Au line. It would thus be more favorable for vortices to reside on the intrinsic pinning sites within the bounds of the line. If this were the case, upon thermal activation, a vortex should preferentially wander along the Au line rather than hopping to a region not effected by the Au.

There are several criteria which were used to determine if the Au line had an effect on the pinning of vortices. First of all, the pinning site must be at a location that coincides with the Au line. This was checked by use of the diffraction patterns which identified the locations of the vortices in conjunction with an SEM picture which gives the location of the Au lines. It may be that by chance an intrinsic pinning site within the bounds of the line would have pinned vortices even without the Au line. Hence, this condition is necessary but is not sufficient to correlate the pinning with the Au line. A second criterion that could be used to determine the correlation between pinning and the Au line is the symmetry of each pinning site. If pinning is caused by the Au line, it may be easier to push a vortex along the line rather than to push the vortex off the line, in a direction perpendicular to the line. As a final criterion, the trajectories
of the vortices were followed as thermal activation allowed them to depin from their initial pinning site and fall into the wells of other pinning sites.

Sample characterization

Figures 5.1a and 5.1b show resistance vs. temperature for the top and bottom Nb films of sample Mb6-63 respectively. The top Nb film has a fairly continuous transition beginning at 9.301 K and continuing until 8.120 K. On the other hand, the bottom Nb film has three transition regions. The oxidation of the Al layer seems to degrade the bottom Nb film even though it is covered with layers of Ag and Al. It appears that different sections of the film have different properties resulting in the multiple transitions. Resistance vs. temperature of the upper and lower portions of the bottom Nb film are shown in Figs. 5.2a and 5.2b respectively. The upper and lower halves of the bottom film can be isolated by running a current through the entire bottom film and measuring the voltage drop across contacts 1-2 and 3-4, referring to Fig. 3.1. The upper section goes completely superconducting at 8.144 K while the resistance of the lower section is still non-zero at 7.60 K. This implies that in the junction region, the bottom Nb film is completely superconducting at 8.144 K.

The superconducting transition temperature of each Nb film for sample Mb6-63 is much lower than those for the Nb films of sample Mb4-82 despite similar preparation methods. The only difference in sample fabrication between the two Josephson junctions was in the oxidation process. However, this difference in procedure should have no effect on the top Nb films which are deposited after oxidation. Since the transition temperature of the top Nb film of sample Mb6-63 is also lowered, it appears the method of oxidation was not crucial to obtaining a high Tc. Another possibility is that the Nb sputtering target could have been contaminated.

The critical current of the junction as a function of temperature is shown in Fig. 5.3. The critical current of the junction becomes vanishingly small at approximately 8.00 K. Then, at 8.244 K, the critical current rises sharply indicating that the bottom Nb film goes normal. This gives a good measure of Tc of the bottom Nb film in the junction region. The temperature at which no further pair tunneling occurs across the junction is not as relevant as the critical
Figure 5.1  Resistance versus temperature for a) the top Nb film and b) the bottom Nb film of sample Mb6-63.
Figure 5.2 Resistance vs. temperature for the bottom Nb film’s a) upper and b) lower half for sample Mb6-63.

Upper section of bottom Nb film

Lower section of bottom Nb film

$T_c = 8.144 \text{K}$
Figure 5.3 Critical current of the junction as a function of temperature for Mb6-63.

$T_c$ (bottom Nb) = 8.244 K
temperature of each Nb film in the junction region. As long as the Josephson junction gives good diffraction patterns, it serves its purpose of being a vortex microscope. Figure 5.4 shows a typical no-vortex diffraction pattern for this junction. A temperature of 4.992 K was chosen to measure the diffraction patterns for this sample. The symmetry of the pattern with respect to positive and negative $B_y$ and the fact that the minima of the pattern nearly reach zero indicate the junction is suitable for locating vortices. The side peaks of the experimental diffraction pattern do not reach as high as the theory. This may be due to vortices trapped right outside the junction region. Even so, the single-vortex diffraction patterns obtained from this sample show close agreement to theoretical single-vortex patterns.

**Nucleating vortices in the top and bottom Nb films**

Vortices were nucleated within the films of this junction using two methods. The first method involved cooling through $T_c$ of the bottom film with an applied current through the bottom film. In order to nucleate vortices in the bottom film, the temperature is stabilized below $T_c$ of the top film and above $T_c$ of the bottom film. Next, a current is applied through the bottom film. At this temperature the top film is superconducting so it acts as a ground plane and excludes the magnetic flux generated by the applied current. The temperature is then slowly cooled through $T_c$ of the bottom film, trapping vortices in the bottom film. It was found that stabilizing the temperature at 8.292 K, then cooling with ±10 mA in the bottom film would nucleate multiple vortices. To clear all but one vortex from the junction region the temperature was slowly ramped up until only one vortex remained. Using this method, one of two major pinning sites was obtained in the bottom Nb film.

The second method used to nucleate vortices was the field-cooling method. It was found that cooling from 8.440 K in the presence of 405 mG reproducibly nucleated single vortices. Normally, for junctions this size, single vortices can be nucleated by cooling through $T_c$ with fields as small as 10 mG. The reason such high fields are required to nucleate vortices cooling from 8.440 K is that the transition temperature of the top film is higher than this value. Vortices trapped with the field-cooling method do not clear the junction by thermal activation
Figure 5.4 No-vortex pattern for sample Mb6-63 with $I_{oo} = 1.00$ mA, $B_o = 795$ mG and $B_{offset} = 60$ mG.
until 8.503 K. Since $T_c$ of the bottom $Nb$ film in the junction region is 8.244 K, as determined by the temperature dependence of the junction critical current, vortices trapped by the field-cooling method must be located in the top $Nb$ film. A vortex can’t stay in the film if the temperature rises above $T_c$, driving the film normal. The temperature at which the junction is cleared gives a lower bound on the $T_c$ of the film containing the vortices. Hence, $T_c$ of the top $Nb$ film is at least 8.503 K.

Using the above-mentioned nucleation methods, vortices have been nucleated in both $Nb$ films. The next step was to determine the current at which vortices will begin to nucleate as a function of temperature. This information is needed to find a range of currents and temperatures in which current-depinning experiments can be performed without nucleating new vortices. This measurement was carried out by beginning with a vortex-free junction and increasing the current at a given temperature until the diffraction pattern changes, indicating that one or more vortices are within the junction. This was the same method used to determine the current at which a vortex depinned. In order to clear the films of all vortices the temperature was ramped to 9.5 K and then stablized at $T_{\text{nucleate}}$, at which point a current was passed through either the top or bottom $Nb$ film for 2.0 second. The temperature was then lowered and stablized at 4.992 K. Finally, the critical current of the junction, at zero applied field, was checked to see if vortices had been nucleated.

The minimum current required to nucleate a vortex, $I_N$, as a function of temperature for currents in the top and bottom $Nb$ films are shown in Fig. 5.5. At 7.30 K, nucleation begins at about 8.4 mA for both of the films. For increasing temperatures the current required to nucleate a vortex with current in the top $Nb$ film decreases more slowly than the bottom film nucleation current. Also shown in Fig. 5.5 are $T_c$ of the bottom film determined by critical-current measurements of the junction, 8.244 K, and a lower limit of $T_c$ of the top $Nb$ film as determined by thermal depinning measurements, 8.503 K. Figure 5.6 shows a typical current nucleation experiment. The critical current of the junction with no applied field, $I_o$, is plotted as a function of nucleation current through the bottom $Nb$ film at 7.40 K. Above 7.8 mA vortices are nucleated. As the nucleation current is increased, $I_o$ is suppressed more and more,
Figure 5.5 Nucleation current vs. temperature for sample Mb6-63.
Figure 5.6 $I_o$ vs. nucleation current in the bottom film at 7.40 K.
indicating multiple vortices within the junction. Figure 5.7 shows a nucleation experiment at 8.10 K with the nucleation current in the top Nb film. At 5.7 mA vortices begin to nucleate. Above 6.1 mA, no further nucleation occurs. This can be explained as follows. At 8.10 K the critical current of the top film is 6.1 mA. Hence, for currents higher than this in the top film, the top film is driven normal and no vortices can be nucleated in that film. No vortex nucleation was observed above 8.45 K. As the temperature approaches $T_c$ of the top Nb film the current region between the nucleation current and the critical current of the top Nb film becomes increasingly small.

**Thermal depinning of vortex in the bottom Nb film**

It was very difficult to obtain a single vortex within the bottom film using the current nucleation method. Figure 5.8a shows an initial vortex position in the region where vortices were most frequently obtained. At a temperature of 8.264 K a vortex on this initial position thermally depinned and left the junction region as shown in Fig. 5.8b. Since the vortex left the junction region in one move, no information about whether this pinning site was on the Au line was obtained.

**Current depinning of vortices in the bottom Nb film**

Current depinning was attempted on vortices trapped within the bottom Nb film. The goal of these current-depinning experiments was to determine if the Au line induces artificial pinning sites by observing the symmetry of the pinning sites. As mentioned earlier, if the vortex is pinned on the Au line, it may depin more easily when pushed along the line. In these current-depinning experiments, multiple vortices were nucleated complicating the measurement of the elementary pinning force in different directions. Interactions with multiple vortices may affect the current at which the initial vortex depins. The locations of the pinning sites are mapped out and compared with the location of the Au line from the SEM picture to see if pinning is at least favored above the Au line.

No temperature was found at which the vortex would consistently depin without nucleating
Figure 5.7 $I_o$ vs. nucleation current in the top film at 8.10 K.
more vortices. The following six current-depinning experiments were performed with a \( T_{\text{push}} \) of 7.892 K. At this temperature the vortices could sometimes be moved without nucleation of more vortices. Care must be taken in the interpretation of the diffraction patterns to account for the possibility of additional vortices.

Figure 5.9 shows the trajectory followed by a vortex initially located at (0.45, 0.40) upon depinning from a positive current applied in the bottom film. The corresponding diffraction patterns are shown in Figs. 5.10a - 5.10l. At 4.6 mA it appears that a vortex trapped on the edge of the junction leaves the junction region resulting in a much better fit as shown in Fig. 5.10b. At 4.8 mA the central vortex depins and moves to position (0.30, 0.35). Another small movement occurs at 5.0 mA even though the best fit still gives (0.30, 0.35). At 5.2 mA the vortex moves to (0.30, 0.20) as shown in Fig. 5.10e. The vortex continues to move around until a current of 5.8 mA is applied, at which point a second vortex enters the junction near the edge. The reason it is believed a second vortex is present is because no single-vortex diffraction pattern matches the data as shown in Fig. 5.10g. This continues on, as shown in Figs. 5.10i - 5.10k, with the central vortex moving in small steps and edge vortices coming and going up to 7.0 mA above which a single vortex diffraction pattern is not recovered.
Figure 5.9  Trajectory of vortex during current-depinning experiment on vortex at (0.45, 0.40) with applied current in the bottom film.
Figure 5.10 Current-depinning experiment on vortex at (0.45, 0.40) with applied current in the bottom film.
Figure 5.10 (Continued)
Figure 5.11 shows the trajectory of a vortex initially at (0.45, 0.45) upon depinning from a negative current in the bottom film. The corresponding diffraction patterns are shown in Figs. 5.12a - 5.12e. During this experiment, the vortex hops to (0.50, 0.50), (0.50, 0.45) and then back to the original position before it leaves the junction region at −5.0 mA. The arrow showing the vortex leaving the junction is not meant to imply a specific path taken.

After pushing vortices starting at (0.45, 0.45) with both positive and negative currents through the bottom film, vortices at the same initial position were then pushed with currents applied in the top film. Figure 5.13 shows the trajectory of a vortex initially at (0.45, 0.45) upon depinning from a positive current in the top film. The corresponding diffraction patterns are shown in Figs. 5.14a - 5.14c. At 6.5 mA a second vortex comes in the junction region as shown in Fig. 5.14b. Then, at 7.3 mA the original vortex moves to (0.60, −0.60) and the second vortex leaves the junction region or moves to a position right on the edge as shown in Fig. 5.14c. At higher currents multiple vortices are nucleated.

Figures 5.15a and 5.15b show the results of a negative current in the top film. A current of −4.4 mA depins the vortex originally at (0.45, 0.45) and pushes it out of the junction region with no intermediate steps.

In the previous four experiments vortices were nucleated at (0.45, 0.45) by cooling from 8.292 K with 10 mA in the bottom film and pushed in different directions by applying positive and negative currents in the top and bottom films. Next, the sample was cooled from 8.292 K with −10 mA in the bottom film. This resulted in the pattern shown in Fig. 5.16a. This could be interpreted as a vortex with the opposite polarity located in the same vicinity of the previously obtained vortices, (0.40, 0.35). If there is a favorable vortex nucleation/entry point at the edge of the film, positive and negative currents will nucleate vortices of opposite polarities at this point. An alternative interpretation is that this vortex has the same polarity and is located at (0.40, −0.35). The vortex was pushed out of the junction region with 4.6 mA through the bottom film at 7.892 K with no intermediate stopping points. Hence, no further information about the pinning site was obtained that could validate either interpretation.

The only other vortex location obtained by current nucleation was at (0.40, 0.60) as shown
Figure 5.11  Trajectory of vortex during current-depinning experiment on vortex at (0.45, 0.45) with applied negative current in the bottom film.
Figure 5.12 Current-depinning experiment on vortex at (0.45, 0.45) with applied negative current in the bottom film.
Figure 5.13 Trajectory of vortex during current-depinning experiment on vortex at (0.45, 0.45) with applied current in the top film.
Figure 5.14  Current-depinning experiment on vortex at (0.45, 0.45) with applied current in the top film.
Figure 5.15  Current-depinning experiment on vortex at (0.45, 0.45) with negative applied current in the top film.

Figure 5.16  Current-depinning experiment on vortex at (0.40, -0.35) with applied current in the bottom film.
Figure 5.17 Current-depinning experiment on vortex at (0.40, 0.60) with applied current in the top film.

in Fig. 5.17a. This vortex was nucleated with $I_B=10$ mA cooling from 8.292 K. When a current of 6.0 mA was reached, the vortex was pushed out of the junction region with no intermediate steps as shown in Fig. 5.17b.

Figure 5.18 shows an SEM picture of Mb6-63. The dashed lines outline the Nb films. The contrast needed to display the Au lines obscured the outline of the bottom Nb film. The Nb films are much better defined than those of sample Mb4-82. There was much less shadowing during the deposition of the films due to the added collimators attached to the Nb film masks. The location of each vortex obtained in the bottom film is plotted in Fig. 5.19 along with the location of the Au line. Since the polarities of the vortices were not known, the locations could have been those shown in the figure or those generated by reflections about the $x$- and $y$-axes. The pinning sites seem to be clustered around the line $y = x$. Since the Au line runs in the $x$-direction, the pinning is probably not due to the proximity effect from the Au. Although a few of the pinning sites may lie on top of the Au line, the pinning sites span a large region of the junction.
Figure 5.18 SEM picture of sample Mb6-63 showing the location of the Au line within the junction region.
Figure 5.19 Positions of Au line and vortices trapped in the bottom Nb film within junction Mb6-63.
Investigation of pinning sites in top Nb film

Four pinning sites in the top Nb film are examined here. As stated previously, it is known that they are in the top film because vortices pinned at these sites thermally depin above $T_c$ of the bottom Nb film. The number of data points for each pinning site was determined by the frequency with which a vortex appeared on that site. The same nucleation procedure was used each time and favored some of the four sites over the others.

The first pinning site examined is (0.55, -0.40). In order to determine the temperature at which a vortex at this site is thermally depinned, the temperature was incremented by 3 mK until the vortex moves. At 8.443 K the vortex hopped to a site very close to the edge of the junction, roughly eight-tenths of the way from the middle to the edge.

Next, the symmetry of the pinning site, in terms of depinning currents applied in the upper and lower films, was examined. For this pinning site and the other three obtained by the field-cooling nucleation method, multiple vortices would be nucleated by applied current in the bottom film at temperatures below $T_c$ of the bottom Nb film, before the central vortex depinned. At 8.292 K and higher temperatures, however, the vortex could be depinned with a transport current through either Nb film before any further nucleation would occur.

Figure 5.20 shows the six initial diffraction patterns of vortices pinned at (0.55, -0.40) used in these depinning experiments. The solid line represents the theoretical pattern for a vortex at this position. There is only a small amount of scatter about this theoretical pattern. Hence, the initial position of the vortex for these current-depinning experiments is well established.

Figure 5.21 shows the depinning current as a function of temperature for currents in the top and bottom Nb films. At 8.292 K the vortex depins with 2.0 mA and -1.2 mA through the top Nb film. In contrast, the vortex does not depin until currents of 24.0 mA and -21.0 mA are applied through the top Nb film. Hence, it takes roughly a factor of ten times less current through the top film than the bottom film to depin the vortex. Each time the vortex at (0.55, -0.40) depinned it moved to a position at the edge of the film, roughly eight-tenths of the way from the middle to the edge of the junction. At this temperature, pinning sites that may have been available at lower temperatures are no longer able to pin vortices. This
Figure 5.20  Initial position (0.55, -0.40).
Figure 5.21 Depinning current with vortex at position (0.55, -0.40).
explains why there were no intermediate pinning sites visited before the vortex moved to the edge, in contrast with the current depinning experiments performed at a $T_{\text{push}}$ of 7.892 K where intermediate steps were often present.

The next pinning site studied has a location of $(0.15, -0.30)$. Fig. 5.22 shows the six initial diffraction patterns used in thermal and current-depinning experiments. A vortex on this site thermally depinned at 8.316 K and hopped to $(0.65, -0.10)$. Figure 5.23 shows the current at which the vortices located at $(0.15, -0.30)$ first depinned for currents in the top and bottom Nb films. Each time a vortex at position $(0.15, -0.30)$ depinned, it hopped to $(0.65, -0.10)$. The two diamonds on the $I_T$-axis represent the results of two separate current-depinning experiments performed at the same $T_{\text{push}}$ of 8.281 K. The solid line meets the $I_T$-axis at 1.4 mA, the average of the two trials. With this pinning site, as in the previous one, the same large asymmetry in the top and bottom depinning currents is observed.

The next pinning site studied has a location of $(0.00, -0.20)$. Figure 5.24 shows the twenty-one initial diffraction patterns used in thermal and current-depinning experiments. A vortex on this site thermally depinned at 8.431 K and hopped to $(0.65, -0.10)$. Figure 5.25 shows the current at which the vortices located at $(0.00, -0.20)$ first depinned for currents in the top and bottom Nb films. This initial position for the vortex occurred much more frequently than the two previous pinning sites discussed. The only function of the connecting lines in Fig. 5.25 is to group together the data from current-depinning experiments performed at the same $T_{\text{push}}$. There were only two times that the vortex, upon depinning, didn't hop to the position $(0.65, -0.10)$. These both occurred when a negative current in the bottom Nb film was being applied. During one experiment using a $T_{\text{push}}$ of 8.371 K, the vortex moved to a nearby position of $(0.00, -0.40)$ when $-5.0$ mA was applied. Then, at $-26.5$ mA the vortex depinned again and went to a position further out than $(0.65, -0.10)$, approximately eight-tenths of the way from the center to the edge of the junction. This data is not included in Fig. 5.25 because upon repeating this experiment at the same $T_{\text{push}}$ and direction of current in the bottom film, the vortex remained fixed at the initial position until $-28.5$ mA. The second time the vortex didn't move to $(0.65, -0.10)$ it moved to a position further out.
Figure 5.22 Initial position (0.15, -0.30).

The coordinates are $(0.15, -0.30)$.

- $I_0 = 0.951$ mAmp
- $B_0 = 0.945$ gauss
- Offset = $-0.110$ gauss
Figure 5.23 Depinning current with vortex at position (0.15, -0.30).
Figure 5.24  Initial position (0.00, -0.20).
Figure 5.25  Depinning current with vortex at position (0.00, -0.20).
The last pinning site studied in detail is located at (0.65, -0.10). Vortices pinned here were obtained both by field cooling nucleation and as products of current depinning from other pinning sites. Figure 5.26 shows twenty-nine initial diffraction patterns used for thermal and current-depinning experiments. A vortex at this position didn’t thermally depin until 8.503 K, at which point the vortex left the junction all-together. Figure 5.27 shows the results of fifteen current-depinning experiments performed on vortices with the initial position of (0.65, -0.10).

The temperature range in which comparative current depinning between top and bottom films was performed was limited by two factors. The temperature had to be above $T_c$ of the bottom Nb film or multiple vortices would be nucleated with current in the bottom film, before the original vortex depinned. Secondly, the temperature had to be below the temperature at which the vortex would thermally depin. Furthermore, currents above 40 mA produced appreciable heating of the Cu block which the sample was mounted on.

Temperature dependence of elementary pinning force

The pinning site located at (0.65, -0.10) was also used to determine the temperature dependence of the elementary pinning force using negative current through the top film. It was found that the nucleation current was larger than the depinning current for current in the top film down to 8.043 K. This allowed the top film depinning current to be measured in a wider range of temperatures than the bottom film depinning current.

Figure 5.28 shows the minimum negative current through the top film required to depin a vortex in the top film located at (0.65, -0.10) as a function of temperature. Also shown in Fig. 5.28 is the minimum current in the top film required to nucleate a vortex.

To convert the depinning current to a depinning force we use (see Appendix),

$$F[N] = \frac{6.59 \times 10^{-14}}{\sqrt{0.25 - (z')^2}} \frac{I[Amp]}{W[cm]},$$

(5.1)

where $W$ is the width of the film, $I$ is the applied current and $z'$ is the reduced coordinate of the vortex measured from the center of the film towards the edge of the film. The Lorentz force resulting from a current in the top film acting on a vortex in the top film located at
Figure 5.26 Initial position (0.65, -0.10).
Figure 5.27 Depinning current with vortex at position (0.65, −0.10).
Figure 5.28 Temperature dependence of negative depinning current for vortex in the top Nb film located at (0.65, -0.10).
(0.65,0.10), using 55 μm for the width of the film, is given by \( F[N] = (2.45 \times 10^{-11})I[\text{Amp}] \).

The elementary pinning force per unit length of the vortex flux line is the force in Eq. (5.1) divided by the thickness of the film, 4000 Å.

Figure 5.29a shows the elementary pinning force, \( F_p \), on a vortex located at (0.65, -0.10) as a function of temperature. At a reduced temperature of 0.95 the pinning force is \( 1.1 \times 10^{-13} \) N or \( 2.75 \times 10^{-7} \) N/m. This is an order of magnitude smaller than Lorentz force depinning measurements on Nb thin films by Allen and Claassen [17]. Above and below \( T_c \) of the bottom Nb film, \( F_p \) goes roughly like \( (1 - T/T_c)^n \) where \( n = 3/2 \) as shown in Fig. 5.29b. Similar values of \( n \) were also obtained from Lorentz-force depinning measurements on single vortices in Nb thin films ranging from \( n = 1.9 \) [15] to \( n = 3.5 \) [17]. The discontinuity is near \( T_c \) of the bottom Nb film, 8.244 K. Above this temperature the vortex is no longer bent into the normal region of the junction by the superconductivity of the bottom Nb film and extends outward in a continuous manner.

**Lorentz forces on a vortex from applied vs. induced currents**

Table 5.1 summarizes the results of all the current-depinning experiments. The most important feature is the large difference between the depinning current in the top and bottom films. To understand the cause of this asymmetry, the applied currents and induced currents in the films must be examined. Figure 5.30 shows the current that flows through the top and bottom films when an applied current is in the bottom film. The current flows within the penetration depth of the surface and is distributed across the film as \( I' = \frac{I}{\sqrt{(W/2)^2 - x^2}} \) where \( I \) is the total current through the film, \( W \) is the width of the film and \( x \) is measured from the center of the film. Within the junction region currents are induced in the bottom of the top film to screen the superconductor from the magnetic field generated by the current flowing in the top of the bottom film. The induced currents in the bottom of the top film are equal in magnitude and opposite in direction as the current in the top of the bottom film. The induced currents then wrap around the top film keeping the net current flow zero. Figures 5.31a and 5.31b show current flow through the cross-section of the top and bottom films when an applied
Figure 5.29 Temperature dependence of the elementary pinning force on a vortex in the top Nb film located at (0.65, -0.10). a) $F_p$ and b) $F_p^{2/3}$ vs. temperature.
Table 5.1 Minimum current at which vortex is depinned.

<table>
<thead>
<tr>
<th>position</th>
<th>$T_{push}$(K)</th>
<th>$+I_B$(mA)</th>
<th>$-I_B$(mA)</th>
<th>$+I_T$(mA)</th>
<th>$-I_T$(mA)</th>
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<td>(0.00, -0.20)</td>
<td>8.392</td>
<td>24.0</td>
<td>-24.0</td>
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<td>-1.5</td>
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<td></td>
<td>8.371</td>
<td>24.0</td>
<td>-28.5</td>
<td>2.7</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td>8.331</td>
<td>37.0</td>
<td>-27.8</td>
<td>3.0</td>
<td>-2.4</td>
</tr>
<tr>
<td></td>
<td>8.292</td>
<td>42.0</td>
<td>-40.0</td>
<td>4.0</td>
<td>-3.0</td>
</tr>
<tr>
<td>(0.55, -0.40)</td>
<td>8.382</td>
<td>24.0</td>
<td>-21.5</td>
<td>2.0</td>
<td>-1.2</td>
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<td>8.292</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.15, -0.30)</td>
<td>8.281</td>
<td>31.0</td>
<td>-27.0</td>
<td>1.0, 1.8</td>
<td>-1.6</td>
</tr>
<tr>
<td>(0.65, -0.10)</td>
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<td></td>
<td></td>
<td>-1.4</td>
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<tr>
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<td>8.423</td>
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<td>-2.1</td>
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<tr>
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<td></td>
<td>-2.4</td>
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<td>-36.0</td>
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<td>8.043</td>
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Figure 5.30 An applied current in the bottom film leads to induced currents in the top film which wrap around the top film.
Figure 5.31 Forces on a vortex from a) induced currents and b) applied currents.
current is in the bottom film [45]. Figure 5.31a shows the Lorentz forces acting on a negative vortex in the top film. The current flowing in the top of the top film pushes the vortex one way while the currents flowing in the bottom of the top film exert a force on the vortex in the opposite direction. Figure 5.31b shows the Lorentz forces acting on a negative vortex in the bottom film. Here, the vortex is in the same film as the applied current. In this case the direction of the current flow in the top and bottom of the bottom film is the same, resulting in forces acting on the vortex in the same direction. This difference in the forces acting on a vortex, a shear force from induced currents vs. forces that add in the same direction from applied currents, may explain the asymmetry in the top and bottom depinning currents. For the vortices, obtained from the field-cooling method, in the top film, a shear force on the vortex would result from an applied current in the bottom film. This shear force may be less effective for depinning a vortex than forces which add in the same direction on the vortex. For the current-depinning experiments of the vortices in the top Nb film, the current was applied while the bottom Nb film was normal. The current distribution in the bottom film is different than when it is superconducting, but the magnetic field generated within the junction region will be the same. Hence, the induced currents in the top Nb film will be the same.

For vortices pinned in the bottom Nb film, the top and bottom film depinning currents were rather similar. Those depinning measurements were carried out in a temperature region where multiple vortices sometimes nucleate from the transport current, interfering with the current depinning of the original vortex. For a vortex at (0.45, 0.45) with \(T_{push} = 7.892 \, \text{K}\), \(-5.9 \, \text{mA}\) through the bottom film cleared the vortex from the junction region without any intermediate steps or signs of vortex nucleation. Likewise, at the same starting position and \(T_{push}\), another vortex was pushed out of the junction region at \(-4.4 \, \text{mA}\) through the top film with no intermediate steps or signs of vortex nucleation. Up to 8.2 K vortices were nucleated when trying to depin a vortex in the bottom film with a current through the bottom film. No temperature region was found in which vortices in the bottom film could be depinned with a current without sometimes nucleating more vortices.
Summary of results with sample Mb6-63

A Josephson junction has been fabricated on top of a Au line. Pinning sites have been investigated in both the top and bottom Nb films. In the bottom film the pinning sites seem to congregate in a region off the Au line. In the top film the symmetries of four pinning sites have been investigated in terms of the top and bottom film depinning currents. Vortices in the top film depin with a current approximately ten times smaller with applied current in the same film as the vortex than in the other film. This asymmetry is possibly explained by the different Lorentz forces felt by the vortex from induced vs. applied currents. For a vortex pinned in the top Nb film, the temperature dependence of the elementary pinning force has been measured and ranges from $10^{-14}$ - $10^{-13}$ N in the reduced temperature range of 0.99 - 0.95.
This chapter describes the second attempt to induce artificial pinning sites within a Josephson junction by fabricating the junction on top of an Au line. With this junction, only a few pinning sites were found within the bottom Nb film. These locations are compared with the location of the Au line determined with an SEM picture of the junction.

The properties of this junction are similar to sample Mb6-63. Figures 6.1a and 6.1b show resistance vs. temperature for the top and bottom Nb films of sample Mb6-72 respectively. The top Nb film has a fairly continuous transition beginning at 9.214 K and continuing until 8.462 K. On the other hand, the bottom Nb film has multiple transition regions beginning at 9.591 K. The bottom Nb film doesn’t appear to go completely superconducting until 7.2 K. This means that somewhere along the length of the film there is a normal region up to this temperature. From thermal depinning measurements of vortices pinned in the bottom Nb film, $T_c$ of the bottom film in the junction region is at least 8.45 K.

It was very difficult to get the no-vortex diffraction pattern for this junction shown in Fig. 6.2a. Usually, cooling through $T_c$ with no applied currents or external fields led to the pattern shown in Fig. 6.2b. Vortices were nucleated in the bottom Nb film by stabilizing the temperature at 9.0 K and then cooling with 2.0 mA though the bottom Nb film. Only a few different diffraction patterns were obtained using this nucleation method as shown in Figs. 6.2c - 6.2f. All of the diffraction patterns shown in Figs. 6.2a - 6.2f were taken at 6.300 K except the pattern shown in Fig. 6.2b which was taken at 6.000 K.

Figure 6.3 shows an SEM picture of sample Mb6-72 displaying the location of the Au line within the junction region. The top Nb film is in the $x$-direction. The black, dashed square represents the junction region. Notice the defective region in the bottom right corner of the
Figure 6.1  Resistance versus temperature for a) the top Nb film and b) the bottom Nb film for sample Mb6-72.
Figure 6.2 Diffraction patterns obtained with sample Mb6-72.
Figure 6.3  SEM picture of sample Mb6-72 showing the location of the Au line within the junction region.
junction. It appears part of the top Nb film is missing in this region. This defective region may be a strong pinning site for vortices and may explain why a no-vortex pattern was difficult to obtain. The darkened rectangles in the center of the picture are due to the SEM beam being focused there at earlier times, they are not features of the Nb film.

Figure 6.4 shows a schematic of the junction region showing the position of the Au line and the location of the vortices. The actual locations of the vortices could be those shown in the figure or those generated by reflections about the x- and y-axes. It appears that the vortices do not lay over the Au line. Therefore, the Au line did not induce artificial pinning in this junction.
Figure 6.4  Au line and vortex positions within M6-72.
7 CONCLUSIONS

Thermal depinning of Abrikosov vortices pinned in the bottom Nb film of a SNIS Nb-Ag-Al-Al\textsubscript{x}O\textsubscript{y}-Nb cross-strip Josephson junction has been studied as a function of an external magnetic field perpendicular to the plane of the junction. The temperature at which the vortices began to thermally depin, 8.804 - 8.964 K, was not affected by fields up to ±20 mG but the temperature where the vortices cleared the junction region, 8.865 - 8.991 K, was approximately 50 mK lower than the zero field case. Higher fields could not be used because additional vortices would nucleate.

Lorentz-force depinning of vortices trapped in the top Nb film of a SNIS Nb-Ag-Al-Al\textsubscript{x}O\textsubscript{y}-Nb cross-strip Josephson junction was studied. A large difference was found between the current in the bottom film needed to move the vortex and current in the top film needed to move this same vortex. For these vortices the depinning current was approximately ten times smaller for applied currents in the top film than in the bottom film. The explanation may lie in the fact that the induced currents produce a couple-like force on the vortex whereas the direct currents push in the same direction all along the vortex. At a reduced temperature of 0.95 the elementary pinning force on a vortex pinned in the top Nb film was 1.1 \times 10^{-13} N or 2.75 \times 10^{-7} N/m. The temperature dependence of this pinning force was approximately $(1 - T/T_c)^{3/2}$ near $T_c$ of the top Nb film.

Artificial defects have been intentionally fabricated in three cross-strip SNIS Nb-Ag-Al-Al\textsubscript{x}O\textsubscript{y}-Nb Josephson junctions in order to produce pinning sites. Pinning centers were induced in the top Nb film of one junction by placing two Fe balls on top of an already characterized Josephson junction. Vortices tended to locate at the site of these Fe balls. The magnetic moments of the Fe balls were strong enough to nucleate and pin vortices beneath them even,
in zero applied field. The location of the induced pinning sites determined by the diffraction-pattern method were in agreement with SEM measurements of the locations of the Fe balls.

Two Josephson junctions were fabricated on substrates having 2 μm wide Au lines adjacent to the Nb layer in an attempt to depress the order parameter in the bottom Nb films and create pinning sites. For one junction, vortices trapped in the bottom Nb film adjacent to the Au were studied with Lorentz force and thermal depinning measurements. These results were not consistent with pinning that would have been induced by the Au line. For both junctions the locations of the pinning sites observed in the bottom Nb films were mapped out and compared to the locations of the Au lines determined by SEM measurements. The pinning sites were not preferentially located above the Au lines. The proximity effect from the Au line making contact with the bottom Nb film was not strong enough to pin vortices.
APPENDIX SAMPLE CALCULATIONS

Small-junction limit

In order to ensure uniform current distribution through a Josephson junction, the conditions of the small-junction limit must be met [46]. When this condition is met the applied magnetic field can penetrate the entire junction region without being screened by the Josephson supercurrents. The small junction limit is satisfied when

$$\frac{\lambda_J}{W} = \sqrt{\frac{c \Phi_0}{8\pi^2 d_{eff} I_c}} \gg 1,$$

(A.1)

where $\lambda_J$ is the Josephson penetration depth and $I_c = Jc/W^2$. Using $d_{eff} = \text{thickness of junction barrier plus 2 times the London penetration length of Nb (3.9 \times 10^{-6} \text{ cm})}$, in cgs units

$$\frac{\lambda_J}{W} = \sqrt{\frac{(3 \times 10^{10}\text{cm/s})(2.07 \times 10^{-7}\text{Gcm}^2)}{8\pi^2(5.78 \times 10^{-5}\text{cm})I_c}},$$

(A.2)

where $[I_c] = \text{StatAmp}$. Using the fact that 1 StatAmp = 1 StatCoulomb/Second which corresponds to $(3 \times 10^9)^{-1} \text{ Amp}$, the small-junction condition can be written as

$$\frac{\lambda_J}{W} = \frac{2.13 \times 10^{-2}}{\sqrt{I_c[\text{Amp}]}} \gg 1.$$

(A.3)

For $I_c = 1 \text{ mA}$, $\lambda_J/W = 0.67$. This value being less than 1 and the vortex-free diffraction patterns not matching the theory well on the side peaks, indicate that the applied magnetic field may not have been penetrating the junction region uniformly.

It can be seen that Eq. (A.2) is unit-less by noticing Gauss = $[B] = [E] = [q/r^2] = \text{StatCoulomb}$ in cgs units.
Lorentz force on vortex from current

The Lorentz force per unit length on a vortex from current density $J$ is given by $J \times \Phi_0/c$. When the penetration length < film thickness < width, in a thin film, the current per unit width can be written as

$$I' = \frac{I/\pi}{\sqrt{(\frac{W}{2})^2 - x^2}},$$

where $x$ is the measured from the center of the film. The Lorentz force can then be written as

$$F = \frac{\Phi_0 I}{c\pi W} \frac{1}{\sqrt{0.25 - (x')^2}},$$

where $x'$ is $x/W$. Plugging in numbers one can find the force in terms of $I$, $W$ and $x'$.

$$F[N] = \frac{(2.07 \times 10^{-7} Gcm^2) I[Amp](3 \times 10^9 StatAmp/Amp)}{(3 \times 10^{10} cm/s)\pi W} \frac{1}{\sqrt{0.25 - (x')^2}} (10^{-5} N/dyne),$$

or

$$F[N] = \frac{6.59 \times 10^{-14} I[Amp]}{\sqrt{0.25 - (x')^2} W[cm]].$$

Hence, the Lorentz force[N] on a vortex in a thin film at reduced coordinate $x'$, for a film of width $W$, from an applied current $I[Amp]$ is given by Eq. (A.7).
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