Field- and current controlled switching between vortex states in a mesoscopic superconductor

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Abstract. We study the controllable manipulation of vortices in a mesoscopic, superconducting “island” of Nb, using an integrated Josephson junction as a field-sensitive vortex detector. The island, divided by a single Josephson junction and suspended by Nb microbridges, was fabricated from a Nb/Pt_{1-x}Ni_x/Nb tri-layer using a focused ion beam. We find that the system at select magnetic fields behaves as a vortex memory cell, where current pulses can be used to switch the vortex configuration between metastable states of distinctly different junction critical currents. Non-destructive read-out of a state is then easily done with an intermediate current. Furthermore, we show that the Josephson junction displays a strong magnetoresistive effect at current bias well above the junction critical current but below the onset of flux flow. This enables the junction to be used as a quantitative probe of magnetic field with better than single flux quantum resolution.

1. Introduction
Mesoscopic superconductors are the subject of intense studies with promising potential in devices [1, 2]. Advanced applications typically involve quantum interference through the interplay of several Josephson junctions, but even rather simple systems are rich in physics when vortices are involved. Vortex states in mesoscopic superconductors are determined not only by the applied magnetic field but also by sample boundaries and geometry. This leads to pronounced metastability that could be used in applications such as vortex memory cells. Several methods exist to study vortices in mesoscopic superconductors, including transport, ballistic Hall magnetometry [3], small superconducting-insulator-normal metal tunnel junctions [4, 5] and scanning tunneling microscopy (STM) [6]. Here we use a single Josephson junction embedded into a mesoscopic, superconducting island both as a vortex state detector and as a quantitative, field-sensitive device.

2. Experimental method
Layers of Nb/Pt_{1-x}Ni_x/Nb were deposited onto an oxidized Si wafer. The Nb layers were 225 nm and 350 nm thick and the junction layer 20 – 30 nm. Using a focused ion beam (FIB), islands with a central superconductor-ferromagnet-superconductor (SFS) junction and suspended by micro-bridge connectors were cut-out. Details of the sample fabrication can be found in [7]. The results are presented for a sample with 50 at.% Ni, which is sketched in figure 1.

Measurements were carried out in a cryogen-free magnet system with a flowing gas insert reaching 1.6 K base temperature. The magnetic field was applied perpendicular to the island.
Figure 1. Sketch of the sample. A mesoscopic island of Nb with a center SFS junction was sculptured from a Nb/PtNi/Nb tri-layer. The island width was 1140 nm, total height 495 nm, the lead-to-lead distance 2 \( \mu \)m and the island thickness 230 nm. The magnetic field was applied in parallel with the 20 nm thick junction, driving vortices into the island as illustrated schematically.

surface, yielding maximum geometry-stabilizing effect for vortex trapping, see figure 1. An arbitrary waveform generator was used as a current source. The sample voltage was measured using a 24-bit analog-to-digital converter. For measurements of differential resistance, a set of synchronized lock-in amplifiers built around a field-programmable gate array was used. To avoid hysteresis arising from the magnet inductance while sweeping the magnet, the signal of a Hall sensor was measured simultaneously with the sample and used to determine the magnetic field. Critical currents were determined by finding the highest current with a voltage below the zero-current voltage noise level.

3. Results and discussion

In figure 2, some basic sample characteristics are shown. The bridge critical temperature is \( T_c = 8.6 \) K, corresponding to the lowest \( T_c \) of the two Nb layers. The junction critical current \( I_c \) at \( T = 2 \) K is 1.6 mA, which is slightly lower than the current \( I_{ff} \approx 2.5 \) mA needed to drive the system into the flux-flow state, see the top right inset of figure 2. This difference between \( I_c \) and \( I_{ff} \) increases in magnetic field and with increasing temperature, since \( I_c \) is more sensitive to magnetic field and temperature than \( I_{ff} \).

The Fraunhofer pattern of figure 2 indicates good junction uniformity with a periodicity \( \Delta H \approx 9 \) mT. The regular periodicity of the Fraunhofer pattern is, however, limited to measurements at low currents and for moderate changes in magnetic field. Figure 3 illustrates that the Fraunhofer pattern changes depending on how the measurement is performed. At low currents, field sweeps give rise to pronounced hysteresis, as seen in panel (a). When varying the applied magnetic field, the driving force for adding or removing vortices is tuned. In mesoscopic samples, the Meissner screening currents interact with interior vortices, causing metastability. Vortices thus enter at a higher field than they exit so that each state change becomes irreversible.

Figure 2. Bottom: Fraunhofer pattern of the junction critical current as a function of magnetic field at \( T = 2.0 \) K. The periodicity of 9 mT corresponds to one flux quantum in an area of \( 1.14 \times 0.20 \) \( \mu \)m\(^2\). Top left: Temperature dependence of the normal state resistance. Top right: Current-Voltage (I-V) characteristics in near zero field. The junction resistance is seen to be about 0.15 \( \Omega \), while the flux-flow resistance is several ohms.
Figure 3. Critical current as a function of magnetic field. (a) Sweeping up (gray) and down (black) without pulsing the current at $T = 3$ K. Before sweeping the field down, the system was driven into the flux flow state at $H = 0.4$ T. After equilibration at high current, the obtained vortex state initially remains metastable. However, after the field has been swept down 50 mT to 100 mT, jumps start to occur with an average distance about the same as the Fraunhofer pattern periodicity. (b) Increasing magnetic field at $T = 2.3$ K. Before each measurement of $I_c$, the current was pulsed to 2.4 mA for a few ms, driving the system to the flux flow state. Black curves correspond to a positive pulse while gray corresponds to a negative. (c) As in (b) but for decreasing magnetic field. (d) $I_c(H)$ at $T = 3$ K (black) compared to the curves of (c) (gray). $I_c$ of the 3 K curve is scaled by $1/1.85$.

The system may also be brought between different states by pulsing current through the island. In fact, comparing panels (b) and (c) of figure 3, it is seen that current pulses bring the system back into a pseudo-equilibrium, where information about the field sweep direction is lost. When pulsing the current, the magnetic flux in the junction may take several different values for the same applied magnetic field. Interestingly, positive and negative pulses sometimes favor different, unique states, as is seen by comparing the gray and black curves in the panels at for instance 74 mT. The system at these conditions works as a vortex memory cell.

The observations are consistent with vortices being driven in and out of the mesoscopic island by means of magnetic field and current. When the system is in the Meissner state and the field is increased, the screening currents increase until the Lorentz force for flux entry is exceeded. At this point, the screening currents suddenly decrease and with them the local field in the junction.

It is clear from figure 3 that the vortex configuration can be controlled both by current and magnetic field. However, it is hard to determine the number of flux quanta each jump corresponds to from $I_c(H)$. Fortunately, it appears that the SFS junction displays a fairly strong magnetoresistive effect. By measuring the junction differential resistance $dV/dI$ at a current level well above $I_c$ but below $I_H$, it is possible to obtain a quantitative measure of the magnetic field in the junction. Figure 4 shows $dV/dI$ for increasing and decreasing fields. The Meissner state is clearly discernible and displays a quadratic field dependence. When vortices start to enter the island the screening decreases and the differential resistance drops. In decreasing fields, instead, each expulsion of flux is accompanied by an increase in resistance. The smallest branch spacing is found to be about 3 mT, in good agreement with the value $\Delta H = 3.6$ mT that corresponds to a single flux quantum $\phi_0$ in the $1.14 \times 0.495 \mu m^2$ island area. Most jumps, however, involve several vortices.

In figure 5, measurements of $dV/dI$ over a wider field range are shown. In these measurements no current offset was used, to minimize the influence of the Lorentz force. It is seen that the hysteresis disappears at about 1.2 T at 1.6 K, at which point additional flux flow resistance starts to add to the signal. At 6 K the corresponding field is 0.4 T (not shown). Close to $T_c$, irreversible behavior is no longer found, as seen in the inset of figure 5. Rotation of magnetic
domains in the Pt$_{1-x}$Ni$_x$ junction layer could, in principle, cause hysteresis and jumps in the junction local field. The observed temperature dependence, current dependence and behavior of sub-loops, however, all indicate that the current observations are dominated by vortex physics.

4. Conclusion
In conclusion, we have studied the behavior of vortices in a mesoscopic island by using an integrated SFS Josephson junction as a field sensitive detector. We have found that the vortices can be probed both through junction critical current and junction magnetoresistance. The vortices enter and leave the island via a barrier potential, which is overcome either by magnetic field pressure or current drive. At selected magnetic fields, current-programming between persistent vortex states is possible, with non-destructive read-out of distinctly different critical currents.

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