Picovoltmeter for probing vortex dynamics in a single weak-pinning Corbino channel

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We have developed a picovoltmeter using a Nb dc superconducting quantum interference device for measuring the flux-flow voltage from a small number of vortices moving through a submicron weak-pinning superconducting channel. We have applied this picovoltmeter to measure the vortex response in a single channel arranged in a circle on a Corbino disk geometry. The circular channel allows the vortices to follow closed orbits without encountering any sample edges, thus eliminating the influence of entry barriers. © *2008 American Institute of Physics.* [DOI: 10.1063/1.3000683]

I. INTRODUCTION

The dynamics of vortices in confined superconductor geometries has generated much interest in recent years, with studies of both fundamental properties of vortex matter as well as devices based on the motion of vortices. Nanoscale channels for guiding vortices through superconducting films with a minimal influence from pinning have been developed for explorations of vortex melting,[1] commensurability,[2] mode locking,[3] and ratchets.[4] These channels are typically arranged across the width of a superconducting strip, so that the vortices enter the channel at one edge of the strip and exit at the other edge, resulting in edge barriers to the vortex motion through the channels.[5–7] The strip geometry also allows for the use of multiple channel copies in parallel to boost the flux-flow signal strength for measurement with a room-temperature amplifier.

It is possible to eliminate the edge barrier characteristic of a strip arrangement by using a Corbino geometry, consisting of a superconducting disk, with current injected radially between the center and the perimeter. Vortices in such a disk experience an azimuthal Lorentz force and can flow in closed circular orbits without crossing any edges. The Corbino geometry has been used for many studies of vortex matter in different superconductors, including bulk crystals of $YBa_2Cu_3O_{7-\delta}$ (Ref. 8) and $NbSe_2$.[9] We have patterned thin-film Corbino disks with submicron circular channels for probing vortex dynamics in a narrow region free from edge barriers. Because the current density decreases radially in a Corbino geometry, such that vortices at different radii experience a different Lorentz force,[10] we have designed our devices to have only a single channel. This poses a challenge for the amplifier used to detect the vortex motion. In this article, we present a scheme for driving a small number of vortices through a single, circular submicron channel and a picovoltmeter for resolving the ensuing flux-flow voltages.

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II. CHANNEL FABRICATION

We fabricate our channels from bilayers of 200-nm-thick films of amorphous-NbGe, an extremely weak-pinning superconductor ($T_c^{NbGe}=2.88$ K), and 50-nm-thick films of NbN, with relatively strong pinning ($T_c^{NbN}=9.6$ K), on a Si substrate. After patterning and etching a 1.5 mm diameter Corbino disk into such a bilayer, we define a 520 nm wide channel in a circle with a 500 μm diameter using electron beam lithography (Fig. 1). We etch this region down to a depth of 120 nm using a reactive ion etch with CF_4, thus completely removing the NbN in this region and etching partially into the NbGe layer. In addition to the circular channel, we etch two radial channels (portals) that extend from opposite sides of the circular channel out to the edge of the Corbino disk. These portals allow for the introduction of vortices into the channel by field cooling from temperatures $T_c^{NbGe}<T<T_c^{NbN}$, as they break up the circulating supercurrent in the outer NbN region.

We attach leads for driving the bias current I_b through the Corbino disk using 1.25 mil Al wire bonds, with 32 I_b^+ bonds around the perimeter of the disk. The I_b^- connection to the center consists of a superconducting Nb wire bond using annealed 2 mil Nb wire [Fig. 1(c)]. The azimuthal Lorentz force from I_b causes the vortices to flow around the channel when this force exceeds the residual pinning in the NbGe channel. The ensuing vortex dynamics in the channel can be characterized by measuring the radial voltage drop across the channel, V_x, which is proportional to the vortex velocity and density.

III. PICOVOLTMETER DESIGN AND CHARACTERIZATION

The flux-flow voltage for vortices moving in a single channel at a low velocity can be quite small. For example, vortices with a density corresponding to a magnetic induction of $B_{ch}=1$ G in the channel moving at a velocity of 1 m/s, less than 1% of the typical Larkin–Ovchinnikov instability velocity for NbGe,[11,12] produce a flux-flow voltage of

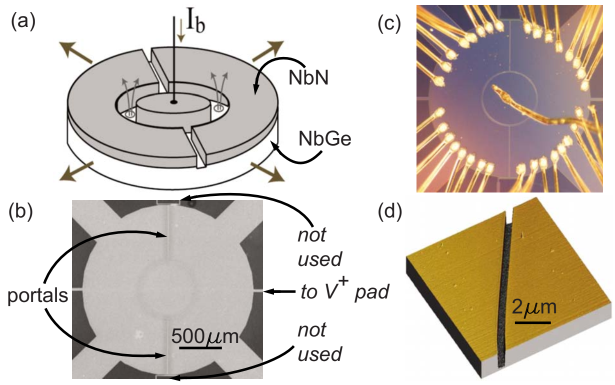

FIG. 1. (Color online) (a) Corbino channel schematic. (b) Scanning electron micrograph of Corbino disk; narrow lines at top and bottom not connected to disk. (c) Optical micrograph of disk showing wire bonds. (d) Atomic force microscope image of channel.

$\sim$50 pV. The measurement of such small signals would not be possible with a conventional low-noise room-temperature voltage amplifier with a noise floor of a few $nV/Hz^{1/2}$. In order to resolve these small flux-flow voltages, we have developed a voltmeter, based on a Nb dc superconducting quantum interference device (SQUID), which we obtained from ez SQUID. Sensitive voltmeters were one of the original applications of SQUIDs,[13] and SQUID voltmeters have been used previously to probe the nature of the vortex state in bulk crystals of $YBa_2Cu_3O_7$ (Ref. 14) and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Ref. 15). To the best of our knowledge, our scheme is the first application of a dc SQUID to form a picovoltmeter for resolving vortex dynamics in a patterned thin-film structure, as well as in a Corbino geometry.

We connect the voltage leads across the NbGe channel to the SQUID input coil with a resistor, R_{st}, consisting of a segment of brass foil ($3.7\times3.2\times0.025$ mm^3). This converts the flux-flow voltage to a current through the input coil, which has a self-inductance L_i and a mutual inductance M_i to the SQUID [Fig. 2(a)]. Except for R_{st}, all of the voltage connections are superconducting. We make the voltage contacts on the Corbino disk with Nb wire bonds, where the V_x^- connection shares the superconducting Nb wire to the center of the Corbino disk with the I_b^- connection, while the V_x^+ Nb wire bond is attached to a pad of the NbGe/NbN bilayer that extends from the perimeter of the Corbino disk [Fig. 1(b)].

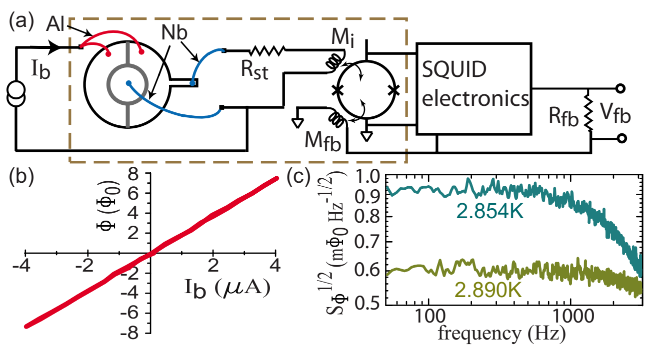

FIG. 2. (Color online) (a) Voltmeter circuit schematic; portions outside dashed box are at room temperature. (b) Flux coupled to SQUID vs I_b at 4.2 K. (c) Flux noise spectra above and below T_c^{NbGe}, both measured with $I_b=0$, $H_a=0$.

The other ends of these Nb wire bonds are attached to superconducting solder-tinned copper traces on our chip carrier using Pb washers. The V_x^+ connection is soldered to R_{st}, then the traces are attached to a twisted pair of 3 mil Nb wire with a second set of screw terminals using Pb washers. Finally, this Nb twisted pair is coupled to the input circuit on the SQUID holder with superconducting screw terminals.

We operate the SQUID in a conventional flux-locked loop, using a 4 MHz electronics system from ez SQUID, with the feedback signal V_{fb} supplied through a feedback resistor R_{fb} to a wire-wound coil with a mutual inductance M_{fb} to the SQUID. The SQUID holder is mounted in a Nb cylindrical shield that is closed on one end. The entire bottom end of the experimental insert is enclosed in a Pb cylindrical shield, and the Dewar is surrounded by a μ-metal shield that is closed on the bottom.

A simple circuit analysis leads to the following expression relating V_{fb} to the voltage across the channel V_x:

$$V_{fb}=\left(\frac{R_{fb}}{R_{st}}\right)\left(\frac{M_i}{M_{fb}}\right)V_x. \qquad (1)$$

The ratio R_{fb}/M_{fb} can be obtained in the usual way by measuring the difference in V_{fb} with the SQUID locked in adjacent wells (590 mV), and M_i was measured to be 6.6 nH through a separate calibration. We estimate R_{st} to be 2 mΩ based on the size of the brass foil, but we can obtain a more careful calibration of the voltmeter gain through a series of low-temperature measurements. We first measure the current-voltage characteristic of the Corbino channel at 4.2 K, where the NbGe channel is in the normal state, while the NbN banks are superconducting. Figure 2(b) shows the flux coupled to the SQUID plotted against the bias current I_b, which was monitored by tracking the voltage drop across a room-temperature current-sensing resistor. Because the channel is in the normal state, I_b divides between the channel, with resistance R_n, and the SQUID input coil with series resistance R_{st}. Based on 4.2 K measurements of similar NbGe channels of various geometries, we estimate R_n for this Corbino disk to be 3 mΩ.

The flux noise at $I_b=0$ and zero field is essentially white with a high-frequency roll-off determined by L_i and the relevant resistance in the voltmeter circuit. By comparing the flux noise below this roll-off for temperatures above and below T_c^{NbGe}, we can obtain measurements of both R_{st} and R_n. Above T_c^{NbGe}, the flux noise is determined by the Nyquist noise current generated by $R_{st}+R_n$ flowing through M_i, while for $T<T_c^{NbGe}$, the only resistance is R_{st} [Fig. 2(c)]. In both cases the flux noise is more than an order of magnitude larger than the intrinsic flux noise for the SQUID, 10 $\mu\Phi_0/Hz^{1/2}$ at 100 Hz and 4.2 K from a separate measurement with the voltmeter circuit disconnected from the input coil. This analysis leads to $R_{st}=1.9$ mΩ and $R_n=2.6$ mΩ, consistent with our rough estimates. In addition, the location of the flux noise roll-off corresponds to $L_i=110$ nH, consistent with the design of the input coil on this particular SQUID.

Applying our measured circuit and SQUID parameters with Eq. (1) yields a gain of 9.8×10^8. The measured flux noise at $T=2.854$ K can be referred back as a voltage noise

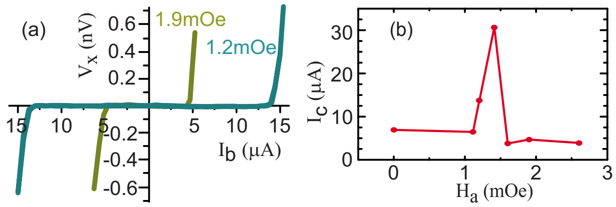

FIG. 3. (Color online) (a) IVCs for two different cooling fields at $T=2.874$ K. (b) I_c for different H_a, extracted from IVCs.

across the Corbino channel of 0.55 $\mathrm{pV/Hz^{1/2}}$, more than three orders of magnitude lower than would be possible with the best conventional room-temperature voltage amplifier. Integrating over the 2.7 kHz bandwidth of the voltmeter yields an rms noise level of 25 pV. Of course, this noise could be reduced further, simply by using a smaller value of R_{st}, with a concomitant reduction in the measurement bandwidth. While a smaller R_{st} couples a larger flux noise to the SQUID by $R_{st}^{-1/2}$, the gain increases by R_{st}^{-1}, according to Eq. (1), thus, the voltage noise referred to the sample decreases like $R_{st}^{1/2}$.

IV. MEASUREMENTS OF FLUX FLOW IN CORBINO CHANNEL WITH PICOVOLTMETER

We have applied our voltmeter to measure the current-voltage characteristics (IVCs) of our single Corbino channel at $T=2.874$ K for several different cooling fields H_a. During our measurements, the Corbino disk and SQUID circuitry are immersed in a pumped helium bath. For each value of H_a, the insert was raised just above the bath and heated to 6 K, above T_c^{NbGe}, and was then cooled in H_a, generated with a superconducting coil. We recorded V_{fb} and I_b with a digital oscilloscope, taking 1024 averages per point, for convenience on our particular oscilloscope. Fewer averages could be used, thus speeding up the acquisition, while increasing the noise level on the acquired signal by $N^{-1/2}$, where N is the number of averages. The IVCs [Fig. 3(a)] exhibit a zero-voltage region at small I_b followed by an increasing flux-flow voltage for I_b beyond a depinning critical current I_c. Using a voltage criterion of 50 pV, we extract $I_c(H_a)$, which has a peak around 1.4 mOe. This peak points to zero absolute field, or the limit of no vortices trapped in the channel. In contrast to a superconducting strip, which has a moderate critical current even in zero applied field corresponding to the entry of vortices and antivortices at the strip edges from the self-field of the strip,[5,7] the Corbino disk should have a large critical current when no vortices are present, as I_c in this case would correspond to the breakdown of superconductivity in the entire disk.

While the values of H_a in our measurements are rather small, the intermediate field-cooling scheme generates substantial flux-focusing effects into the NbGe channel due to the superconducting NbN. A rough estimate, considering screening currents around the central disk of NbN inside the channel, and along the outer NbN banks,[5,16] indicates the enhancement of B_{ch} may be of the order of $10\times H_a$. Thus, cooling in an absolute applied field of 1 mOe should nucleate at least approximately ten vortices in the channel, where the effective area includes not only the channel but also the penetration of the vortex circulating currents into the NbN banks as well. A more detailed treatment of this flux focusing in the channels is beyond the scope of this paper.

Our measurements presented here have been performed close to T_c^{NbGe}, where the residual pinning in the channels was especially weak. This was necessary because of our wiring configuration, where the I_b^- lead was shared with the V_x^- connection to the center of the Corbino disk along a superconducting Nb wire bond. This Nb wire bond had a somewhat small critical current, thus requiring us to operate at temperatures where I_c was below the Nb wire bond critical current. In future Corbino measurements, it should be possible to separate these leads attached to the center of the disk, with the Nb wire bond used only for the SQUID input connection, which does not need to sustain large currents because of the presence of R_{st}, with separate Al wire bonds for the I_b^- connection, which does not need to be superconducting.

In summary, we have demonstrated a SQUID picovoltmeter circuit for resolving vortex dynamics in a single, weak-pinning superconducting channel in a Corbino geometry. If one is measuring a configuration with multiple flux-flow channels, perhaps in the more typical strip geometry, the flux-flow signal might be detectable with a conventional room-temperature amplifier. In this case, the moderate overhead required for the SQUID picovoltmeter would be unnecessary. However, probing flux flow in a single channel and at low velocities would not be possible with a room-temperature amplifier, while the SQUID picovoltmeter is ideally suited to this task. The minimum detectable product of vortex density and flux-flow velocity scales with the voltage noise floor of the particular amplifier used, thus, this quantity can be over three orders of magnitude smaller with our picovoltmeter. This technique will be useful for investigations of small numbers of vortices moving at low velocities in nanofabricated structures, such as vortex ratchets.[4] For example, measurements of vortex dynamics in a single Corbino channel with a ratchet configuration could reveal details of the ratchet dynamics that would otherwise be masked by the more conventional arrangement involving multiple channels in a strip geometry using a room-temperature amplifier.

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