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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 (SQUID) 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.

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, 6, 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 barriers 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 YBCO [8] and NbSe2 [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.

II. CHANNEL FABRICATION

We fabricate our channels from bilayers of 200 nm-thick films of amorphous-NbGe, an extremely weak-pinning superconductor ($T_{c\text{NbGe}}^{\text{c}} = 2.88$ K), and 50 nm-thick films of NbN, with relatively strong pinning ($T_{c\text{NbN}}^{\text{c}} = 9.6$ K), on a Si substrate. After patterning and etching a 1.5 mm-diameter Corbino disk into such a bilayer, we define a $520 \mu$m-wide channel in a circle with a $500 \mu$m diameter using electron beam lithography (Fig. 1). We etch this region down to a depth of 120 nm using a reactive ion etch with CF4, 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 $T_{c\text{NbGe}}^{\text{c}} < T < T_{c\text{NbN}}^{\text{c}}$, as they break up the circulating supercurrent in the outer NbN region.

![Corbino schematic](image1)

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 wirebonds. (d) Atomic Force Microscope (AFM) image of channel.

We attach leads for driving the bias current $I_b$ through the Corbino disk using 1.25 mil Al wirebonds, with 32 $I_b$ bonds around the perimeter of the disk. The $I_b$ connec-
tion to the center consists of a superconducting Nb wirebond 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, \( V_r \), which is proportional to the vortex velocity and density.

III. PICOVOLTAMETER 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 one percent of the typical Larkin-Ovchinnikov instability velocity for NbGe \([11,12]\), produce a flux-flow voltage of \( \sim 50 \) pV. In order to resolve such signals, we have developed a voltmeter, based on a Nb dc 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 YBCO \([14]\) and BSCCO \([15]\). To the best of our knowledge, our scheme is the first application of a NbGe channel at a low velocity can be quite small. For example, \( I_b \) divided by \( M_b \), both measured with \( I_b = 0, R_a = 0 \).

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 \((3.7 \times 3.2 \times 0.025 \text{ mm}^3)\). This converts the flux-flow voltage to a current through the input coil, which has a self inductance \( I_s \) 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 wirebonds, where the \( V_{fb} \) connection shares the superconducting Nb wire to the center of the Corbino disk with the \( I_s \) connection, while the \( V_{st} \) Nb wirebond is attached to a pad of the NbGe/NbN bilayer that extends from the perimeter of the Corbino disk [Fig. 1(b)]. The other ends of these Nb wirebonds are attached to superconducting solder-tinned copper traces on our chip carrier using Pb washers. The \( V_{fb} \) 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 \( \mu \)-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 \( V_c \):

\[
V_{fb} = \left( \frac{R_{fb}}{R_{st}} \right) \left( \frac{M_b}{M_{fb}} \right) V_c. \tag{1}\]

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 \((590 \text{ mV})\), and \( M_b \) was measured to be 6.6 nH through a separate calibration. We estimate \( R_{st} \) to be 2 m\( \Omega \) 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 m\( \Omega \).

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 \( R_n + R_{st} \) 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 \( \mu \)V/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 $9.8 \times 10^8$. The measured flux
noise at $T = 2.854$ K can be referred back as a voltage
noise across the Corbino channel of $0.55$ pV/Hz$^{1/2}$. In-
tegrating 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.

IV. MEASUREMENTS OF FLUX-FLOW IN
CORBINO CHANNEL WITH PICOO Voltmeter

We have applied our voltmeter to measure the current-
voltage characteristics (IVCs) of our single Corbino chan-
nel 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 $T^*_{NbGe}$, 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. 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 cur-
rent $I_c$. 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
anti-vortices 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, con-
sidering screening currents around the central disk of
NbN inside the channel, and along the outer NbN banks
[8, 10], indicates the enhancement of $B_{c1}$ may be of the
order of $10 \times H_a$. Thus, cooling in an absolute applied
field of $1$ mOe should nucleate at least $\sim 10$ vortices in
the channel, where the effective area includes not only
the channel, but 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 per-
formed close to $T^*_{NbGe}$, where the residual pinning in
the channels was especially weak. This was necessary
because of our wiring configuration, where the $I_c$ lead
was shared with the $V_{fb}$ connection to the center of the
Corbino disk along a superconducting Nb wirebond. This
Nb wirebond had a somewhat small critical current, thus
requiring us to operate at temperatures where $I_c$ was be-
low the Nb wirebond 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 wirebonds for the $I_c$
connection, which does not need to be superconducting.

In summary, we have demonstrated a SQUID picovolt-
meter circuit for resolving vortex dynamics in a single,
weak-pinning superconducting channel in a Corbino ge-
ometry. This technique will be useful for investigations
of small numbers of vortices moving at low velocities in
nanofabricated structures, such as vortex ratchets.

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