Magnetic switching of phase-slip dissipation in NbSe$_2$ nanoribbons

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The stability of the superconducting dissipationless and resistive states in single-crystalline NbSe$_2$ nanoribbons is characterized by transport measurements in an external magnetic field ($\mathbf{H}$). Current-driven electrical measurements show voltage steps, indicating the nucleation of phase-slip structures. Well below the critical temperature, the position of the voltage steps exhibits a sharp, periodic dependence as a function of $\mathbf{H}$. This phenomenon is discussed in the context of two possible mechanisms: the interference of the order parameter and the periodic rearrangement of the vortex lattice within the nanoribbon.

DOI: 10.1103/PhysRevB.75.020501

PACS number(s): 74.78.Na, 74.40.+k, 74.25.Sv

One-dimensional (1D) superconductors refer to wirelike superconducting materials whose thickness and width are smaller than the Ginsburg-Landau coherence length ($\xi$) and magnetic penetration depth ($\lambda$). These materials have a uniform current distribution over their cross sections, and the onset of resistance in the current ($I$)-biasing condition is characterized by a sequence of regular voltage ($V$) steps, corresponding to the nucleation of phase-slip centers (PSCs). Recent advances in the synthesis of nanostructured materials have yielded a variety of 1D superconductors, including electrodeposited Pb and Sn nanowires, nanotube-templated amorphous MoGe films, laser-ablated YBa$_2$Cu$_3$O$_{7-\delta}$ nanowires, and MgB$_2$ nanowires.

Mesoscopic wires and strips, with one or more dimensions wider than $\xi$, can also exhibit PSC-like $V$ steps, attributable to Josephson weak-links and spatially extended PSCs. Mesoscopic superconducting wires are also thick enough to support vortices, and thus they provide an interesting model system for investigating the coexistence and the interplay between the PSC-like structures (PSSs) and the Abrikosov vortex lattice. Although mesoscopic NbSe$_2$ films have been used to study single-vortex physics in absence of an applied $I$, $I$-driven few-vortex physics has never been investigated in superconducting nanowires.

Here we report transport studies of individual NbSe$_2$ nanoribbons that explore the effect of an external magnetic field on the stability of PSSs. The $I$-$V$ characteristic of the nanoribbons displays a series of $V$ steps attributable to nucleating PSSs. At low temperatures, the $I$-$V$ curves become hysteretic. When an external magnetic field ($\mathbf{H}$) is applied, the hysteresis sharply decreases for small windows at periodic values of $\mathbf{H}$, indicating the switching on and off of phase-slip dissipation caused by thermal activation. We discuss this phenomenon in the context of two possible mechanisms, the interference of the order parameter and the periodic rearrangement of the vortex lattice within the nanoribbon.

Single-crystalline NbSe$_2$ nanoribbons were synthesized by annealing NbSe$_2$ nanoribbons in an inert gas and converting them into NbSe$_2$ nanoribbons. Transmission electron microscopy and x-ray diffraction studies show that the NbSe$_2$ nanoribbons are single crystalline and have a ribbon-like geometry with the $c$-axis perpendicular to the axis of the nanoribbon (Fig. 1). The thickness ($d$) and width ($w$) of typical NbSe$_2$ nanoribbons are $\sim 100$ nm.

Devices incorporating individual NbSe$_2$ nanoribbons were fabricated by suspending the nanoribbons in isopropanol, depositing them on a SiO$_x$ or AlN substrate, and contacting

FIG. 1. (a) Transmission electron micrograph of NbSe$_2$ nanoribbons. Inset (left): a high-resolution transmission electron micrograph of a nanoribbon. Inset (upper right): an electron diffraction pattern of the circled nanoribbon. (b) A scanning electron micrograph of a typical four-probe device.
them to bonding pads using conventional electron-beam lithography followed by the sputtering of 60-nm Cr and 200-nm Au layers. Immediately before sputtering, the nanoribbons were cleaned with an Ar plasma in the sputtering chamber. This procedure allows the formation of metal-nanoribbon junctions with low contact resistance (20–100 Ω).

Transport measurements were performed using either a vapor-cooled variable-temperature insert or a 300 mK helium-3 insert in an Oxford Instruments cryostat. The resistance of NbSe$_2$ nanoribbons were measured by $I$-biasing the nanoribbons with a home-built current source and then measuring the four-probe $V$. Differential resistance ($dV/dI$) of the device was also recorded simultaneously, using a lock-in amplifier set at frequency $f=1$ kHz. Measurements on multiple NbSe$_2$ nanoribbon samples showed that the superconducting transition temperature ($T_c$) of NbSe$_2$ nanoribbons typically ranged between 2 to 2.3 K, lower than bulk values ($T_{c,\text{bulk}}=7$ K).$^{14}$ The $T_c$ suppression is most likely caused by disorder, in particular Se impurities resulting from the incomplete conversion of NbSe$_3$ to NbSe$_2$. Previous studies have shown that $T_c$ is very sensitive to stoichiometry [a 5% deviation suppresses $T_c$ from 7 K to 2.2 K (Ref. 14)].

Figure 2(a) shows the basic $I$-$V$ characteristic of device A at $T=1.7$ K ($T_C=2.1$ K for this nanoribbon). At low $I$, the $V$ drop across the nanoribbon is small but nonzero and increases with $I$. As $I$ increases above a switching current ($I_{sw}$), the first $V$ step appears followed by several more. The $I$-$V$ curves are reproducible and, at this temperature, non-hysteretic. The linear regions between the $V$ steps roughly extrapolate to a single point, $I_s=4.2±0.5$ µA. At high $I$ ($I>40$ µA), the $I$-$V$ characteristic curves toward the asymptote $V=R_N I$, where $R_N$ is the normal-state resistance of the nanoribbon, indicating that the nanoribbon becomes normal.

The steps in $V$ appear as peaks in $dV/dI$. Figure 2(b) shows the evolution of these peaks as a function of $T$. As $T$ increases, the positions of the $V$ steps gradually move inward toward zero current, their width and magnitude soften, and a single $I$-$V$ step occasionally branches into two distinct steps. These features are symmetric across $I=0$, again confirming the absence of $I$-$V$ hysteresis at $T=1.7$ K.

The inset to Fig. 2(a) shows the $I$-$V$ characteristic of device A at $T=300$ mK, and shows that hysteresis emerges at lower temperatures. Specifically, the positions of the innermost $V$ step for the $I$ sweep-up (switching current $I_{sw}$) and sweep-down directions (retrapping current $I_s$) differ significantly from each other ($I_{sw}>I_s$). Additional $V$ steps also appear in the range $I_{sw}<I<I_s$ during the $I$ down sweep. The device behavior before the first $V$ step is characterized by a dissipationless regime ($0<I<I_s$) and a low-resistance regime ($I_s<1<I_{sw}$). The low-resistance regime is too small to be visible in the Fig. 2(a) inset, but it shows up clearly in Fig. 3.

The investigation of the device $I$-$V$ characteristics at $T=300$ mK and nonzero $H$ reveals an intriguing feature that is periodic in $H$. Specifically, Fig. 3 shows the evolution of $dV/dI$ from device B as a function of $H$, where $H||b$ (see Fig. 1 for the definition of the crystalline axes). As $H$ is increased, $I_s(H)$ is periodically enhanced with period $ΔH=270±30$ mT. These enhancements have a finite width, $ΔH=35±5$ mT and a binary on-off character, at least within the resolution of our scan (5 mT). The boost to $I_s$ at these values of $H$ is accompanied by a diminishment to $I_{sw}$, although the effect of $H$ on $I_{sw}$ is generally smaller and more varied than its effect on $I_s$. The other steps do not display the periodic variations, although they do gradually move inward as an increasing $H$ suppresses the order parameter.

The periodic features illustrated in Fig. 3 were observed in five out of the seven devices that have been measured in detail. Moreover, Fig. 4 shows that these periodic features appear regardless of the $H$ orientation with respect to the nanoribbon axis, although not every device showed the periodic feature for every orientation of $H$. Furthermore, the feature only appeared at low temperatures (below 1 K). Comparison of the field scale in Figs. 4(a) and 4(b) indicates that...
the misalignment of \( \mathbf{H} \) with respect to the nanoribbon axis cannot account for the \( H \)-periodic features for three different \( \mathbf{H} \) orientations. As Fig. 4(b) shows, the evolution of the \( I-V \) curves is symmetric about \( H=0 \) for a given orientation of \( \mathbf{H} \).

The \( V \) steps in Figs. 2 and 3 are consistent with the nucleation of PSSs observed in low-dimensional superconductors. Specifically, the observation that the linear regions between the voltage steps extrapolate to the point \( I_s \) indicates that the \( V \) steps observed in NbSe\( _2 \) nanoribbon devices behave according to the RCSJ model proposed by Skocpol, Beasley, and Tinkham (SBT).\(^1\) According to the SBT model, the height of the PSC \( V \) step is given by

\[
V_{\text{step}} = \frac{2\Delta R_\phi (I-I_s)}{L},
\]

where \( \Delta \) is the quasiparticle diffusion length that signifies the length scale over which the electrostatic potential and the supercurrent density vary. The fit of the data in Fig. 2 to the SBT model yields \( \Delta \sim 4 \) \( \mu \)m. Since our NbSe\( _2 \) nanoribbons are too thick to be truly 1D superconductors, the observed PSSs may have internal structures, such as channels of flowing Abrikosov or kinetic vortices,\(^1\) which arise from the variation of the order parameter over the cross section of the superconductor. We estimate the coherence length of our nanoribbons to be \( (\xi_a, \xi_b) = (8\) \( \mathrm{nm}, 16\) \( \mathrm{nm} \) at reduced temperature \( T/T_c = 0.6 \). These values agree with bulk NbSe\( _2 \) parameters within our experimental error (the details of this calculation are available online in the EPAPS archive).\(^1\)\(^4\)\(^7\)\(^8\)

The \( I-V \) hysteresis observed in Fig. 3 can be best understood by the theory of underdamped resistively and capacitively shunted Josephson junctions (RCSJ) in the presence of thermal noise.\(^1\) A PSS is a temporal oscillation of the order parameter and thus can be considered as a dynamically generated Josephson junction.\(^1\) While Joule heating likely plays a role in our measurements and contributes to the hysteresis, the fact that \( I_s \) enhancements coincided with \( I_{sw} \) depressions in our data confirms the importance of the Josephson component to the PSSs. The importance of thermal fluctuations in Josephson junctions is measured by the parameter \( \Gamma = k_B T/E_J \), where the Josephson energy \( E_J \) is given by \( E_J = \Phi_0 I_s/2e \), and \( I_{sw} \) is the switching current at \( T=0 \). In the RCSJ model, thermal fluctuations both excite the junction out of the dissipationless state into its resistive state, reducing \( I_{sw} \) and prematurely trap the junction into its dissipationless state, increasing \( I_s \). The periodic feature in our data, which appears as a boost to \( I_s \) accompanied by a decrease in \( I_{sw} \), is thus explained by a periodic increase in \( \Gamma \) with \( H \).

Unfortunately, the experimental data in Figs. 2 and 3 by themselves do not provide a microscopic insight into the underlying cause of the periodic variation in \( \Gamma \). One possible
mechanism is the interference of the order parameter caused by the magnetic field threading through the PSS, leading to an oscillatory $E_r(H)$ behavior.\textsuperscript{20} The matching of vortex rows to the Bean-Livingston surface barrier\textsuperscript{21} can also explain such a periodic $E_r$ dip. In this scenario, vortices fill up the thin film row-by-row as $H$ is increased from zero. At certain special values of $H$ called matching fields, a complete chain of in-plane vortices will be filled, and the vortex lattice rearranges to form a new row. If we identify the current at which the vortex lattice becomes unstable with $I_{\text{m0}}$, then the instability of the vortex lattice corresponds to a minimum in $E_r$. In principle, Little-Parks oscillation,\textsuperscript{22} which causes a periodic dip in the $I_r$ enhancement may only be strong enough to induce switching near a maximum of $I_r$, thereby explaining the digital character of the $I_r(H)$ effect observed here.

Because the microscopic mechanism for the periodic $I_r$ enhancement remains poorly understood, so does the physical meaning of $\delta H$ and $\Delta H$. When $H$ is parallel to the nanoribbon axis, however, it is natural to normalize these quantities to $w$, $d$, and the flux quantum $\Phi_0$, effectively counting the number of vortices that penetrate the nanoribbon. For device B (C) shown in Fig. 4(b) (Fig. 4(d)), the period of the $I_r$ enhancement is $\Delta H = 500 \pm 20$ mT (700 $\pm$ 200 mT), corresponding to the addition of $\sim 11$ vortices, and the width of a single feature is $\delta H = 50 \pm 10$ mT (60 $\pm$ 20 mT), corresponding to the addition of 1.0 $\pm$ 0.3 vortices. The fact that the normalized $\delta H$ approximately corresponds to one vortex suggests that single or few vortex processes may play a role in the magnetic switching phenomenon.

The transport study of NbSe$_2$ nanoribbons presented here reveals that the values of $I_{\text{m0}}$ and $I_r$, which measure the stability of the superconducting dissipationless and resistive states, respectively, switch sharply and periodically as functions of $H$. Our results suggest that superconducting nanoribbons can be an interesting model system for illuminating the interplay between phase-slip dissipation and $I_r$-driven vortex physics.