Flux-flow instability in 2H-NbSe$_2$ superconducting thin crystals stamped on SiO$_2$/Si substrates

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Abstract. We have investigated the nonlinear flux flow in the mixed state of 2H-NbSe$_2$ superconducting thin crystals stamped on SiO$_2$/Si substrates. The nonlinearity in the flux flow behavior is marked with upward bending and subsequent voltage jump in the current-voltage characteristics. The results were analyzed within the framework of a modified Larkin-Ovchinnikov model, including the estimation of inelastic relaxation time of quasiparticles in the crystal and heat transfer coefficient between the crystal and SiO$_2$/Si substrate. The analysis provides an insight into the quality of acoustic match at the crystal-substrate interface.

1. Introduction
Nonlinear current-voltage ($I-V$) characteristics in the mixed state of type-II superconductors provides an unique opportunity to investigate the inelastic relaxation of quasiparticles in the flux-flow state. In an earlier theoretical model proposed by Larkin and Ovchinnikov (LO) [1], the nonlinearity is triggered by the shrinkage of a vortex core which leads to the reduction of a viscous damping coefficient for driven vortices and an increase in the vortex velocity (flux-flow voltage). The nonlinear flux flow has been investigated for decades in a variety of superconducting films like Sn [2], TiN [3], Nb [4], and shown discrepancies in critical parameters (like the critical vortex velocity) for the flux-flow instability. It turns out that the Joule heating of quasiparticles inherent in experiments becomes not negligible as vortex density increases. Bezuglyj and Shklovskij (BS) extended the LO model by taking into account the finite removal rate of the power dissipation through a substrate, and proposed two qualitatively different mechanisms of the instability depending on applied magnetic field $B$ [5]. One is the nonthermal mechanism of the instability proposed by LO ($B < B_T$) and another is dominated by the Joule heating ($B > B_T$). These are separated by a crossover field $B_T$, of which analytical result is given for the dirty limit as

$$B_T = 0.375 \frac{e \rho_n h \tau_{qp}}{k_B d}$$

with the electronic charge $e$, (low-temperature) normal resistivity $\rho_n$, the Boltzmann constant $k_B$, the sample thickness $d$, the inelastic relaxation time of quasiparticles $\tau_{qp}$, and heat-transfer coefficient $h$ characterizing the heat flow from the sample to the substrate. Later, Peroz and Villard have made comparative studies on clean and dirty Nb superconducting films [6]. Although the dissipation process behind the flux-flow instability is different between in the two limits, they made qualitative determination of $\tau_{qp}$ for both films according to the BS model.
In this study, we report nonlinear flux flow in thin crystal films of a clean 2H-NbSe$_2$ superconductor. By employing techniques of mechanical exfoliation and optical identification developed by the success of the substrate-supported graphene research \[7\], we fabricated microbridges of NbSe$_2$ thin crystals stamped on SiO$_2$/Si substrates. We observed the nonlinear $I-V$ characteristics indicative of the flux-flow instability and analyzed them within the framework of the BS model. We estimated the inelastic relaxation time of quasiparticles and heat transfer coefficient and discussed the quality of acoustic transparency at the crystal-substrate interface.

### Table 1. Properties of NbSe$_2$ thin crystal microbridges on SiO$_2$/Si substrates.

| Sample | $RRR$ | $\rho_n(2K)$ ($\mu\Omega$m) | $d$ (nm) | $w$ (nm) | $T_c$ (0K) extrapolated linearly to zero temperature | $\tau_{qp}$ (ns) | $h$ (Wcm$^{-2}$K$^{-1}$) |
|--------|-------|--------------------------|---------|----------|---------------------------------|----------------|-----------------|
| A      | 32    | 0.037$^a$                | 91$^b$  | 7.6      | $\approx$ 0.75 T/K             | 0.63           | 5.8             |
| B      | 31    | 0.039$^a$                | 43$^b$  | 7.0      | 64                              | 0.33           | 3.4             |

$^a$ $\rho_n(2K)$ was determined from the magnetic field dependence of resistance at 2 K.

$^b$ We estimated the thickness from room-temperature resistance $R(295K)$ and resistivity $\rho_n(295K)=1.2 \mu\Omega$m \[10\].

## 2. Experimental

We used 2H-NbSe$_2$ crystals grown by iodide transport method \[8\]. Cleaved thin platelet flakes were gently rubbed onto a SiO$_2$ (290 nm) /Si substrate with an adhesive polydimethylsiloxane stamp \[9\]. Combining conventional lithographic and reactive dry etching techniques, we patterned thin flakes into microbridges with the dimension of 7-8 μm in length $l$ and ~100 μm in width $w$ and ~100 μm in length. Good electronic contacts (much less than 0.1 Ω) were achieved by a subsequent deposition of Ag/NiCr films ($d_{Ag}/d_{NiCr} \approx 50 nm/3 nm$) on top of the microbridges with lift-off technique, as shown in the inset to Fig. 1. The distance $L$ between electrical voltage contacts was 31 μm. The flake thickness was calculated from the resistance at room temperature \[10\]. The values of the thickness are consistent with ones estimated from our optical identification color code for NbSe$_2$ flakes on SiO$_2$(290 nm)/Si substrates \[11, 12\].

The superconducting transition temperature $T_c$ was 7.1 K, the slope of the second critical field perpendicular to the planes $S(= -dB_{c2}(T)/dT|_{T=T_c})$ was 0.75 T/K, and the residual resistance rate $RRR$ was $\approx$ 30 \[13\]. The Ginzburg-Landau coherence length parallel to the planes was determined from the second critical field $B_{c2}(0)$ extrapolated linearly to zero temperature as $\xi(0) \approx \sqrt{\Phi_0/2\pi B_{c2}(0)} \approx \sqrt{\Phi_0/2\pi T_c S} \approx 8 nm$, where $\Phi_0 = \pi\hbar/e$ is the magnetic flux quantum and $\hbar$ is the plank constant divided by $2\pi$. The mean free path $l$ was calculated as $l = (3\pi^2 n^2/\hbar c^2 n^{2/3}(S/F)) \rho_n \approx 70 nm$ where we used the product of $n^{2/3}(S/F)$ with carrier density $n$ and a weighting factor $S/F$ for the Fermi surface with respect to the free-electron model reported in Ref. \[8\]. Some characteristic parameters of two samples (A and B) we focus in this study are summarized in Table 1.

We employed pulsed $I-V$ measurements to minimize the sample heating in the flux-flow state. We used an arbitrary wave function generator to generate stepwise current ramps with 40 μs width. The transient voltage signal from the sample was amplified with a low noise preamplifier (NF corporation LI 5307 and/or LI 75A) and traced, together with one from the standard resistor (500 Ω), in a 2-channel digital oscilloscope (Yokogawa DL-5700). To eliminate an inductive response from the sample, we averaged the voltage signal over the middle of the steady state for each ramp, and obtained $I-V$ curves. To check any possible errors in the
pulsed measurement, we also made conventional dc $I-V$ measurements for comparison. Good accordance between the two measurements were observed, except for high current regime where dc measurement was limited by the heating effect. For the good temperature stabilization, the sample space was immersed in superfluid of $^4$He.

![Figure 1](image_url)  

**Figure 1.** (Color online) Current($I$)-voltage($V$) characteristics of sample A taken in different magnetic fields at $T = 2$ K. Micrograph of the sample is given in the inset.

3. Results and discussions

Typical $I-V$ curves observed in the sample A at $T = 2.0$ K($\approx 0.3\ T_c$) in different magnetic fields are given in Fig. 1. At low currents (above the depinning current $I_c$), the $I-V$ curve, e.g. at 0.3 T, is almost linear, indicative of the conventional flux-flow state, while at high currents, an upward bending becomes remarkable and the nonlinearity ends with an abrupt voltage jump, indicative of the flux-flow instability. This behavior is a common feature observed in our samples studied.

Let us focus on the critical behavior at the voltage jump in nonlinear $I-V$ curves. As indicated, we define the critical current $I^*$ and the critical voltage $V^*$, and thus determined the critical power $P^* (= I^* \times V^*)$ at the anomaly. Shown in Fig. 2 is the results of the critical power density $p^*$ of the sample B plotted as function of magnetic field. In low fields, $p^*$ exhibits a monotonic increase with field, while in higher fields $p^*$ seems to be insensitive with field. The latter feature implies naively that the instability is set by the heat balance between the Joule heating by flux flow in the crystal and the heat removal through the substrate, as expected in the BS model, rather than the nonthermal instability dominated by the LO mechanism. This tempts us to analyze our results within the framework of the BS model. One can see a reasonable accordance between the experimental results and a theoretical curve (represented by a solid line) of the BS model, where we use the analytical result on the power density given as

$$p^*(B) = p_0\left(1 - \frac{1 + b + \sqrt{b^2 + 8b + 4}}{3(1 + 2b)}\right)$$  \hspace{1cm} (2)
with reduced magnetic field \( b = B / B_T \). Two adjustable parameters of \( B_T = 43 \) mT and \( p_0 = 4.0 \mu W/\mu m^3 \) are obtained from the accordance.

Figure 2. Critical power density vs magnetic field observed in sample B at \( T = 2 \) K.

The inelastic relaxation time of quasiparticles can be estimated from a relation given as

\[
\tau_{qp} = 2.67 \frac{B_T k_B (T_c - T)}{ep_0 \rho_n}.
\]

This assumes that the quasiparticles dissipate within vortex cores because the mean free path \( l \) is assumed to be shorter than the size of a vortex core (the coherence length \( \xi \)). Meanwhile, in a clean case \( (l > \xi) \), which corresponds to our case, quasiparticles escape from the vortex cores and diffuse around, resulting in nonequilibrium distribution of quasiparticles over a superconductor. Thus, \( \tau_{qp} \) becomes the nonequilibrium lifetime of quasiparticles [6]. Since a reasonable determination of \( \tau_{qp} \) is given in the clean Nb film [6], let us use Eq. (3) for the estimation of \( \tau_{qp} \) in our NbSe\(_2\) thin crystals. Substituting \( B_T \) and \( p_0 \) in Eq. (3), we obtain \( \tau_{qp} = 0.63 \) ns and 0.33 ns for samples A and B, respectively. These values are the same order of magnitude as \( \tau_{qp} = 3 \Lambda^2 / v_F l \sim 0.9 \) ns determined from the diffusion length \( \Lambda \sim 4 \mu m \) of quasiparticles of NbSe\(_2\) nanoribbons [14, 15] and Fermi velocity \( v_F = (\hbar / m)(3 \pi^2 n \sqrt{S / S_F})^{1/3} \approx 8 \times 10^5 \) m/s with electron rest mass \( m \). Thus, at least for the order estimate of \( \tau_{qp} \) in NbSe\(_2\) crystals, the BS model is useful.

Finally, we comment on the heat flow from the crystals to SiO\(_2\)/Si substrates due to their mutual phonon exchange. Substituting the values of \( \tau_{qp} \) and \( B_T \) in Eq. (1), we obtain the heat transfer coefficient \( h = 5.8 \) and 3.4 W/cm\(^2\)K for samples A and B, respectively. These values are decades larger than ones reported on NbSe\(_2\) crystals adhered on sapphire substrates with GE varnish [16], but remain the same order of magnitude as ones found in many combinations of superconducting films on standard substrates which do not show good acoustic match [5]. As pointed out by BS, for low phonon transparency of the crystal-substrate interface the nonequilibrium phonons are reabsorbed in the film by quasiparticles and the temperature of the film (both electronic and phonon temperatures) becomes higher than the substrate temperature.
This is consistent with our observation that the flux-flow instability in higher fields is dominated by Joule heating.

In summary, we have presented the nonlinear flux flow of 2H-NbSe$_2$ superconducting thin crystals stamped on SiO$_2$/Si substrates. Employing the modified LO model, we extracted the inelastic relaxation time of quasiparticles and the heat transfer coefficient from the critical parameters in the nonlinear $I-V$ characteristics. The results reveal the low phonon transparency of the crystal-substrate interface, which is likely responsible for the Joule heating mechanism governing the flux-flow instability in higher fields.

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