Enhancement of critical current density in a superconducting NbSe₂ step junction

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Abstract

We investigate the transport properties of a NbSe₂ nanodevice consisting of a thin region, a thick region and a step junction. The superconducting critical current density of each region of the nanodevice has been studied as a function of temperature and magnetic field. We find that the critical current density has similar values for both the thin and thick regions away from the junction, while the critical current density of the thin region of the junction increases to approximately 1.8 times as compared with the values obtained for the other regions. We attribute such an enhancement of critical current density to the vortex pinning at the surface step. Our study verifies the enhancement of the critical current density by the geometrical-type pinning and sheds light on the application of 2D superconductors.

Keywords: NbSe₂ step junction, critical current density, self-field, vortex pinning

When a perfect type-II superconductor is in an external magnetic field higher than its lower critical field, but lower than its upper critical field, Abrikosov vortices penetrate the superconductor,¹ and form a vortex lattice.^{2, 3} In a magnetic field stronger than the upper critical field, the superconductor is fully penetrated by the normal cores of the vortices and superconductivity is lost.¹ When an electric current flows through a superconductor, it generates a magnetic field, called the self-field, which plays a role similar to that of an external magnetic field.⁴ Therefore, even in zero external magnetic field, vortices can penetrate a superconductor and make it a normal conductor once the applied current is large enough.⁴ In a non-perfect superconductor with defects, vortices are pinned⁵⁻⁷ and resist forces exerted by the current, leading to a higher critical current density.⁸ To meet the requirements for different applications of superconductors, tremendous efforts have been made to increase the critical current.⁹⁻¹³ Most of them focus on introducing more defects (or pinning centers) into superconductors. This, however, comes at the cost of decreasing the critical temperature.^{10, 11, 13} A potential alternative to this approach may be the use of the geometrical-type pinning by introducing surface steps.¹⁴⁻²¹ Micro-methods, such as Bitter decoration,^{14, 15} magnetic force microscopy,²⁰ scanning superconducting quantum interference device microscopy¹⁶ and scanning tunneling microscopy²¹ have been employed to explore the spatial distribution of vortices in the vicinity of surface steps and proved that the surface steps indeed pinned the vortices and impeded their motion. However, unlike disorder induced pinning, which has been proved to increase critical current and applied in industrial production of superconductors,^{22, 23} the question whether a surface step enhances the critical current density has not been explored directly by the transport measurements.

In a bulk superconductor much thicker than the London penetration depth, the vortices can tilt to accommodate surface features such as surface steps,^{16, 24} thus the pinning effect of the steps may not be significant. In two-dimensional (2D) superconductors much thinner than the London penetration depth, the vortices are much more sensitive to the surface steps.¹⁵ Given that the critical current density is determined by the pinning strength,²⁵ transport measurements in 2D superconductors should provide more information about interactions of vortices with the surface steps. Recently, the 2D

superconductor of a transition metal dichalcogenide NbSe₂ has attracted particular interest due to its unique features, such as unconventional Ising pairing protected by the spin-momentum locking,²⁶ the existence of a so-called quantum metallic state²⁷ and the unusual continuous paramagnetic-limited superconductor-normal metal transition.²⁸ Moreover, the behavior of the vortex lattice close to the surface steps in bulk NbSe₂ has been studied by real-space imaging.¹⁵ For these reasons, 2D NbSe₂ seemed to be the right candidate for our study of the effect of surface steps on superconductivity. The standard method to create a surface step in NbSe₂ is etching, but it introduces defects that also contribute to the pinning and make the experiments ambiguous. An exfoliated NbSe₂ step junction with a naturally formed surface step provides an alternative solution that allows one to exclude such artificial effects.

In this work, we explore the transport properties of a single NbSe₂ step junction naturally formed by exfoliation. We find out the enhancement of the critical current density and discuss the pinning mechanism of the step junction.

Using the standard exfoliation method, a non-uniform NbSe₂ sample consisting of four regions of different thicknesses was found on a SiO₂/Si substrate, as shown in Fig. 1a. Two connected regions that mostly differ in thickness were chosen to form a junction whose thicknesses were measured to be 31 nm and 16 nm, respectively (Fig. 1a), with the surface step being 15 nm high. Eight electrodes were then fabricated using E-beam lithography and subsequent E-beam evaporation. As shown in Fig. 1b and 1c, every four electrodes located on either side of the step junction were used to measure the resistance of the thick and thin regions. The two middle electrodes, which define the step junction, were used to measure the transport properties across the surface step. To avoid confusion, the thick, thin, and junction regions were labeled S_{Thick} , S_{Thin} , and S_{Junction} , respectively. The thick and thin components of S_{Junction} were labeled $S_{\text{J-thick}}$ and $S_{\text{J-thin}}$, respectively, as shown in Fig. 1c. All measurements were performed in a four-point configuration.

The relationships between the normalized four-point resistance $R(T)/R(300)$ for S_{Thick} , S_{Thin} , and S_{Junction} , in zero magnetic field and for temperatures ranging from 1.8 K to 300 K are shown in Fig. 2a and 2b, respectively. The residual resistance ratios for S_{Thick} , S_{Junction} and S_{Thin} are calculated to be 24, 21, and 21, respectively, which means our sample is of high quality.²⁹ The temperature at which the resistance reduced to half of the resistance of the normal state right above the superconducting transition was defined as the critical temperature.³⁰ These critical temperatures were found to be ~ 6.76 K and ~ 6.57 K for S_{Thick} and S_{Thin} , respectively, a result consistent with those previously reported.³¹ The critical temperature for S_{Junction} (~ 6.73 K) was found to be in between the values obtained for S_{Thick} and S_{Thin} , due to the proximity effect.³² The zero temperature energy gap $2\Delta_{BCS} \sim 4.3K_B T_C$ was then calculated to be 2.50 meV (S_{Thick}), 2.43 meV (S_{Thin}) and 2.49 meV (S_{Junction}), respectively.²⁸

To understand the effect of the surface step on the critical current, we investigated the relationship between the critical current and the external magnetic field. The plots for the differential resistance versus current, for S_{Thick} , S_{Thin} , and S_{Junction} under various magnetic fields at 1.8 K, are shown in Fig. 3a-c, respectively. The critical currents can be found at the differential resistance peaks.³³ We found that, for all three regions, the differential resistance is bilaterally symmetrical while sweeping the current from negative to positive. When increasing the magnetic field, the height of all differential resistance peaks decreased monotonically to zero, and the peak position moved toward the zero current position, indicating a gradual weakening of the superconductivity. We noted that such a process was fast at the beginning, when the field was low, but became slower when the field surpassed 1T, indicating that the superconductivity was suppressed in a nonlinear manner. To see the different behaviors of those regions clearly, the differential resistance versus current graph under 0.1 T at 1.8 K was plotted in Fig. 3d. For S_{Thick} and S_{Thin} , we observed one peak on the positive or negative side of each curve, corresponding to one value of the critical current. In contrast, for S_{Junction} , there were two peaks superimposed on both sides, showing the two critical currents of the junction. The two peaks were identified by fitting; the peak with the smaller current belonged to $S_{\text{J-thin}}$, whereas the other

one belonged to $S_{J\text{-thick}}$, circled in Fig. 3d. The field dependence of the critical currents for all regions, at 1.8 K, was extracted from Fig. 3a-c, respectively, and subsequently plotted in Fig. 3e, in which the critical currents of $S_{J\text{-thick}}$ were slightly smaller than that of the corresponding values of S_{Thick} (which could be due to the proximity effect); on the other hand, the critical currents of $S_{J\text{-thin}}$ were found to be much larger than the corresponding values for S_{Thin} .

To make a more accurate comparison, the critical current densities of all four regions (S_{Thick} , S_{Thin} , $S_{J\text{-thick}}$, and $S_{J\text{-thin}}$) were calculated and plotted in Fig. 3f. The critical current densities of S_{Thick} , S_{Thin} , and $S_{J\text{-thick}}$ almost coincided with each other, reflecting the intrinsic property of NbSe₂. However, surprisingly, the critical current density of $S_{J\text{-thin}}$ was much larger than others (the ratio is ~ 1.8 when the external magnetic field is zero), especially when the external field was weak (Fig. 3f). If the proximity effect had induced this effect, the critical current density of $S_{J\text{-thin}}$ would have been lower than the higher critical densities of S_{Thin} and $S_{J\text{-thick}}$ that are in contact with $S_{J\text{-thin}}$. This, however, was found inconsistent with Fig. 3f, and therefore, this hypothesis was excluded. If the effect were due to the intrinsic pinning by defects, the corresponding critical current density would be the same all over the sample, as the defect density would have been uniform in such a small sample exfoliated from a bulk NbSe₂. This would also be in contrast with Fig. 3f, in which the critical current density of $S_{J\text{-thin}}$ is the highest one. Thus, the pinning effect due to defects should be ruled out as well. Therefore, we argue that the pinning induced by the surface step is the cause of the enhanced current density. It is due to the energy difference between the vortices on two sides of the step, determined by the difference in the vortex length.¹⁴

To understand the pinning effect of the surface step more deeply, we studied the temperature dependence of the critical current due to the self-field. The relationships between the differential resistance and the current for S_{Thick} , S_{Thin} , and S_{Junction} , at various temperatures, are shown in Fig. 4a-c, respectively. The differential resistance versus current, for different regions at 2K, was extracted and plotted in Fig. 4d. Similar to Fig. 3d, the sole peak on the positive or negative side in Fig. 4d belonged to the unique critical

current for S_{Thick} or S_{Thin} , whereas the two peaks, also distinguished by fitting, could be assigned to the two critical currents for $S_{\text{J-thick}}$ and $S_{\text{J-thin}}$, respectively (circled in Fig. 4d). To better understand the pinning effect of the step, the critical current versus temperature was also extracted and plotted in Fig. 4e. The critical currents of $S_{\text{J-thick}}$ were found just slightly lower than those of S_{Thick} , whereas the critical currents of $S_{\text{J-thin}}$ were clearly higher than those of S_{Thin} , similar to that in Fig. 3e. The current density was also calculated and plotted in Fig. 4f. It is worth noting that the critical current densities of S_{Thick} , S_{Thin} , and $S_{\text{J-thick}}$ overlap with each other, showing the intrinsic temperature dependence of the critical current density of NbSe₂. In contrast, the critical current density of $S_{\text{J-thin}}$ was found to be approximately 1.8 times of those of S_{Thick} , S_{Thin} , and $S_{\text{J-thick}}$ when the temperature was low, indicating that the vortices created by the self-field were also pinned by the step.

Although the pinning of the self-field vortices has not been observed directly to this day, plenty of experiments have proved that the enhanced pinning leads to the remarkable increase in the self-field critical current density,³⁴⁻⁴² implying the pinning of the self-field vortices. When considering the configuration of the step junction (Fig. 5), we argue that the critical current density in our experiment must be affected by pinning as well. To further support our hypothesis, we derived the characteristic lengths of the sample, including the coherence length and the London penetration length. By sweeping the magnetic field perpendicular to the sample, the relationships between the four-point resistance and the magnetic field for S_{Thick} , S_{Thin} , and S_{Junction} were determined in Fig. S1 in the Supporting Information, from which the critical magnetic fields were extracted and plotted in Fig. 6. Since the temperature dependence of the critical field H_{C2} can be

described by the Tinkham's model, $H_{C2}(T) = \frac{\phi_0}{2\pi\xi(0)^2} \left[1 - \left(\frac{T}{T_c} \right)^2 \right]$, where ϕ_0 is the flux quantum,

$\xi(0)$ is the Ginzburg-landau coherence length at 0 K, and T_c is the critical temperature.²⁷

The coherence lengths $\xi(0)$ for S_{Thick} , S_{Thin} , and S_{Junction} were fitted to be 9.0 nm, 10.6 nm, and 9.3 nm, respectively. The corresponding critical temperatures for S_{Thick} , S_{Thin} , and S_{Junction} were obtained to be 6.78 K, 6.59 K, and 6.70 K, respectively, consistently with the results from the R-T measurements (above). Using the BCS-based model and the Matlab code provided by Talantsev and Tallon,^{4, 43} we can write

166 $J_c^{\text{II}}(\text{sf}) = \frac{H_{c1}}{\lambda} = \frac{\phi_0}{4\pi\mu_0\lambda^3(T)}(\ln k + 0.5)$, where $J_c^{\text{II}}(\text{sf})$ is the critical current of type II
167 superconductor in self-field, H_{c1} the lower critical magnetic field, λ the London penetration
168 depth, ϕ_0 the flux quantum, μ_0 the permeability of the free
169 space, and $\kappa = \frac{\lambda}{\xi}$ is the Ginsburg–Landau parameter. The London penetration depths at
170 0 K ($\lambda(0)$), for S_{Thick} , S_{Thin} , $S_{\text{J-thick}}$ and $S_{\text{J-thin}}$ were acquired to be 471.6 nm, 468.8 nm,
171 474.4 nm, and 385.2 nm, respectively, with $\lambda(0)$ for $S_{\text{J-thin}}$ being smaller, due to the
172 pinning effect, but others remaining consistent with the value reported previously.⁴⁴
173 These results showed that the length of $S_{\text{J-thin}}$ ($\sim 1 \mu\text{m}$) was comparable with the London
174 penetration depth, suggesting that the critical current density due to the self-field depends
175 on the pinning. Moreover, the diameter of the vortex core ($2\xi(0)$) was found comparable
176 with the step height (15 nm), meaning that almost the entire vortex core can be pinned
177 by the step.

178 The phenomena observed in Fig. 3 and Fig. 4 can be explained as follows: the intrinsic
179 critical current density for NbSe₂ is $J_l = J_c^{\text{II}}(\text{sf}) = \frac{H_{c1}}{\lambda}$, which is determined by the
180 coherence length and London penetration depth.⁴ In the absence of the step pinning, the
181 self-field vortices generated by a current with density J are under the self-imposed Lorentz
182 force $J \times B_s$ and prevented from self-annihilating by surface and bulk pinning.⁴ Once
183 $J > J_l$, the self-field vortices begin to annihilate, leading to a non-superconducting state;
184 ⁴ J_l equals the critical current densities of S_{Thick} , S_{Thin} , and $S_{\text{J-thick}}$. While when the step
185 pinning with pinning force F_p is considered, J must be increased to a larger value J_p
186 ($J_p \times B_s > F_p$) to collapse the vortices such that the whole junction can enter a non-
187 superconducting state.⁴ This results in a higher critical current density, which is equal to
188 that of $S_{\text{J-thin}}$. When an external magnetic field ($\mathbf{B}$) is applied, the same scenario takes
189 place, except that the Lorentz force becomes $J \times (B_s + B)$, and the vortices that are
190 induced by both the self-field and the external field are pinned by the surface step. It is
191 worth noting that the pinning of the surface step is not strong enough. Thus the critical

current of $S_{J\text{-thin}}$ is increased but still lower than the intrinsic critical current of $S_{J\text{-thick}}$ (Fig. 3e and 4e). Therefore, the critical current of $S_{J\text{-thick}}$ is not enhanced. This reminds us that stronger pinning is needed to increase the critical currents of both $S_{J\text{-thin}}$ and $S_{J\text{-thick}}$.

Moreover, to further verify the pinning effect of the surface step, we also compare the critical current densities of S_{Thick} , S_{Thin} , $S_{J\text{-thick}}$, and $S_{J\text{-thin}}$ with their theoretical limit, the depairing current density $J_d(0)$ ($J_d(0) = \frac{\phi_0}{3\sqrt{3}\pi\mu_0\lambda(0)^2\xi(0)}$).^{45, 46} Using $\lambda(0)$ and $\xi(0)$ obtained above, the depairing current density is calculated to be $4.7 \times 10^6 \text{ A/cm}^2$, about one order of magnitude higher than the critical current density of S_{Thick} , S_{Thin} and $S_{J\text{-thick}}$, and about five times as high as the critical current density of $S_{J\text{-thin}}$ (Fig. 4f). This is because the width of our sample (around $13 \mu\text{m}$) is much larger than both the coherence length and the penetration depth, leading to the piling up of the current at the edges, as well as the nucleation and then movement of the vortex.^{47, 48}

In conclusion, we have fabricated a NbSe_2 step junction consisting of thick and thin regions and studied its electronic transport properties. We found the critical current density of the thin component of the junction to be much higher than the intrinsic critical current density of NbSe_2 in both a self-field and external magnetic field, which can be attributed to the pinning induced by the surface step. This study represents a major step forward in verifying the enhancement of the critical current density by geometrical-type pinning and provides a new method for increasing the critical current of 2D superconductors.

Methods

Thin NbSe₂ flakes were mechanically exfoliated from a NbSe₂ bulk (purchased from HQ Graphene Company), onto SiO₂/Si (280 nm, 500 μm) substrates. The films that were produced exhibited different thicknesses in areas were located by optical microscope (Carl Zeiss Imager.A2 Vario with AxioCam HRc). Subsequently, eight electrodes were fabricated by E-beam lithography, followed by metal deposition by E-beam evaporator (Ti/Au = 10 nm/ 70 nm) on a selection of samples. All measurements of electronic properties were performed using a Quantum Design Physical Property Measurement System (PPMS-Dynacool). To avoid the degradation of superconductivity, the thickness of the samples was measured by AFM (Asylum Research MFP-3D) after the electronic transport measurements. To obtain an accurate value of the thickness, the samples were immersed in chloroform (60 °C, 4 hours) to remove the residual (poly(methyl methacrylate)) PMMA before AFM characterization.

227 **Supporting information**

228 Electronic supplementary information (ESI) available. See DOI: xxxxxxxx

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233 **Conflicts of interest**

234 There are no conflicts of interest to declare.

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Fig. 1. (a) Optical image of the exfoliated NbSe₂ flake composed of regions of different thicknesses. AFM topography of the step junction circled is shown in the inset. (b) Optical image of the NbSe₂ step junction with electrodes deposited on the sample in (a). The current is applied across the junction from electrode 1 to 8; the electrodes (2,3), (4,5) and (6,7) are used to measure the resistances of S_{Thin} , S_{Junction} , and S_{Thick} , respectively. The scale bar in both (a) and (b) is 10 μm . (c) Schematic diagram of the NbSe₂ step junction. The numbers on the electrodes correspond to the numbers in (b).

Fig. 2. (a) Temperature dependence of four-point resistance for the sample in Fig. 1b from 1.8 to 300 K. (b) Zoom-in view of the normal-superconducting phase transition interval of the step junction circled in (a).

Fig. 3. Differential resistance as a function of current for (a) S_{Thick} , (b) S_{Thin} and (c) $S_{Junction}$ under various magnetic fields at 1.8 K. (d) Differential resistance as a function of current for S_{Thick} , S_{Thin} and $S_{Junction}$ under 0.1 T at 1.8 K. (e) Extracted critical current as a function of the magnetic field for different regions at 1.8 K. (f) Magnetic field dependence of the critical current density of different regions (left-hand scale) and the ratio of the current density of S_{J-thin} to the average current density of S_{Thick} , S_{Thin} and $S_{J-thick}$ (right-hand scale) at 1.8 K. Note that the two peaks corresponding to S_{J-thin} and $S_{J-thick}$ respectively can only be clearly distinguished at low field in (c), thus the peak values are not given when the magnetic field is higher than 1.5 T in (e) and (f).

Fig. 4. Differential resistance as a function of current for (a) S_{Thick} , (b) S_{Thin} and (c) $S_{Junction}$ at various temperatures. (d) Differential resistance as a function of current for S_{Thick} , S_{Thin} and $S_{Junction}$ at 2 K. (e) Extracted critical current as a function of temperature for different regions. (f) Temperature dependence of the critical current density of different regions (left-hand scale) and the ratio of the current density of S_{J-thin} to the average current density of S_{Thick} , S_{Thin} , and $S_{J-thick}$ (right-hand scale).

Fig. 5. Schematic of the NbSe₂ surface step with the applied current and magnetic field. I and B indicate the applied current and magnetic field, respectively, while B_s indicates the self-field induced by the current. J_p indicates the critical current density of $S_{J\text{-thin}}$ with vortex pinning, whereas J_I indicates the critical current density of $S_{J\text{-thick}}$, which equals the intrinsic critical current density of NbSe₂. The width of $S_{J\text{-thin}}$ is approximately 1 μm ; the thicknesses of $S_{J\text{-thin}}$ and $S_{J\text{-thick}}$ are 16 nm and 31 nm, respectively.

Fig. 6. Upper critical magnetic field evolving with temperature. Critical magnetic fields (filled symbols) of different regions are extracted from Fig. S1, and subsequently fitted using Tinkham's

model (dash lines), $H_{c2}(T) = \frac{\phi_0}{2\pi\xi(0)^2} \left[1 - \left(\frac{T}{T_c} \right) \right]^{.27}$