Response of a superconductor NbSe$_2$ flake to magnetic field detected with small tunnel junctions

Naoki Hoshi, Dai Inoue, Hiroki Sonoda, Daisuke Yabe, Hikari Tomori, Akinobu Kanda
Division of Physics, Faculty of Pure and Applied Sciences, University of Tsukuba, Tennodai, Tsukuba, Ibaraki 305-8571, Japan
E-mail: kanda.akinobu.gs@u.tsukuba.ac.jp

Abstract. We have experimentally studied response of a superconductor NbSe$_2$ flake to perpendicular magnetic fields using small tunnel junctions. The NbSe$_2$ film (lateral size $\sim$ several $\mu$m, thickness $\sim$ 50 nm) was obtained using the mechanical exfoliation of a bulk crystal and was transferred on top of predefined Au electrodes, forming an Au/NbSe$_2$/Au double SIN tunnel junction system. At 4.2 K, between the lower and upper critical fields ($H_{C1}$ and $H_{C2}$), the voltage of the Au/NbSe$_2$/Au structure under constant current of 1 $\mu$A exhibited random-telegraph-noise-like fluctuations as a function of the magnetic field which was applied perpendicular to the NbSe$_2$ flake. The origin of the voltage fluctuations is discussed.

1. Introduction
In a mesoscopic superconductor with sizes comparable to the superconducting coherence length and/or the magnetic penetration depth, the quantum confinement of Cooper pairs dramatically modifies the superconducting properties.[1] The resultant mesoscopic superconducting states are attractive not only from the viewpoint of fundamental physics but also from the viewpoint of application to classical and quantum devices.

Peculiar mesoscopic effects appear in vortex states: When a mesoscopic type-II superconductor contains several quantum vortices, the arrangement of the vortices depends not only on the vortex-vortex interaction but also on the interaction between a vortex and the sample edge, so that the triangular Abrikosov vortex lattice, which is characteristic of bulk superconductors, is deformed into a multivortex state (MVS) in which the vortex arrangement is strongly influenced by the sample shape, or a giant vortex state (GVS) in which the multiple vortices coalesce.[2, 3, 4, 5]

So far, we have experimentally investigated the vortex states in mesoscopic superconductors using our original small tunnel junction method,[6, 7] in which the arrangement of the vortices was estimated from the transport properties of the small tunnel junctions attached to edges of the superconductor. The superconductors were made from electron-beam evaporated aluminum. We successfully confirmed the existence of a giant vortex and transitions between different MVSs or between an MVS and a GVS in mesoscopic circular and square thin films. These transitions were induced by an applied magnetic field [8, 9] as well as by a locally injected supercurrent.[10, 11, 12, 13] Such controllability of the vortex states is important for the future realization of classical and quantum devices based on mesoscopic vortex states. During a
series of experiments, however, we noticed a serious problem that the vortex arrangement was strongly influenced by the existence of defects. For example, in the single vortex state (vorticity $L = 1$) in a circular sample, the vortex did not situate at the center of the circle.[8] Also, the magnitude of the magnetic field/injected current which induced a transition between different vortex states varied sample to sample even when the nominal sample shape and sizes were the same. We speculate that these incidents are due to defects caused by the surface roughness of the sample. The surface roughness is inevitable in the vacuum-evaporated aluminum films. We note that we have also investigated the effect of artificially introduced defects on vortex state transitions.[14, 15, 16]

Recently, the mechanical exfoliation technique, developed in the graphene research [17, 18], has been applied to layered superconductors, and thin superconductors with atomically flat surface can be easily obtained.[20, 21] Such atomically flat superconductor might resolve the above defect problem. Here, as the first step toward the precise control of the mesoscopic vortex states in thin layered superconductors, we investigate the response of a thin layered superconductor flake to magnetic field using small tunnel junctions.

2. Experimental

As a layered superconductor, we used NbSe$_2$. The device structure is shown in Fig. 1. An NbSe$_2$ flake (lateral area $\sim 21$ ($\mu$m)$^2$, thickness $\sim 50$ nm) was placed on top of four predefined Au electrodes (thickness: 60 nm, width: 1 $\mu$m) with an adhesive layer of Al (5 nm). No intentional tunnel barrier was inserted between Au and NbSe$_2$. The junction areas for electrodes A and B (see the inset of Fig. 2(a)) are $\sim 2.1$ and $2.4$($\mu$m)$^2$, respectively.

In the sample fabrication, first NbSe$_2$ flakes were obtained using the mechanical exfoliation of a bulk crystal on a SiO$_2$/Si substrate.[17] One of the flakes was then transferred to a substrate with Au electrodes by a microscope and a micro-manipulator using a transparent elastomer stamp (a poly dimethyl siloxane (PDMS) film) covered with poly-propylene carbonate (PPC) layer.[19] Finally the PPC layer, which was left on the NbSe$_2$ flake, was dissolved with acetone.

Electron transport between two electrodes were measured at 4.2 K in vacuum in a cryostat with appropriate cryogenic lowpass filters. The differential conductance was obtained by numerically differentiating the current-voltage characteristics. Magnetic field was applied
Figure 2. (a) Differential conductance ($dI/dV$) as a function of the bias voltage ($V$) for electrode pairs, A-B, A-D and B-D. The electrode C did not work in the measurement. The inset indicates the label of each electrode. (b) $dI/dV - V$ curves of electrode pair A-B for several magnetic field values.

perpendicular to the substrate.

The superconducting transition temperature of NbSe$_2$ flakes was $\sim 7.0$ K and the upper critical field at 4.2 K was $\sim 2.0$ T from the resistance measurement of other flakes (not shown in this paper). The literature value of the lower critical field is $\sim 0.02$ T.\cite{22} The superconducting energy gap $\Delta$ was 1.1 meV calculated from the BCS theory.

3. Results and discussion

Figure 2(a) shows the differential conductance ($dI/dV$) as a function of the bias voltage ($V$) for electrode pairs, A-B, A-D and B-D. The label of each electrode is indicated in the inset of Fig. 3(a), in which the electrode C did not work in the measurement. The current-voltage characteristics were almost linear. However, there appears a distinct structure only in the $dI/dV - V$ curve of electrode pair A-B. Because the separation of the $dI/dV$ peaks agrees with $4\Delta$ and the structure fades away as the magnetic field approached $H_{C2}$, as shown in Fig. 2(b), we can conclude that tunnel barriers were formed for electrodes A and B and the structure in the $dI/dV - V$ curve reflects the superconducting energy gap of the NbSe$_2$ flake. The tunnel barrier might be due to the naturally formed oxides on the surface of the NbSe$_2$ flake. The reason for the absence of the structure for the other electrode pairs is not clear at this moment.

To elucidate the magnetic field dependence of the transport of the junctions, we fixed the current from electrode A to B to 1 $\mu$A, and measured the voltage between electrodes A and B as a function of the magnetic field. The result is shown in Fig. 3 for sweeping-up (Figs. 3(a)(c)(e)) and sweeping-down (Figs. 3(b)(d)(f)) the magnetic field. As shown in Figs. 3(a) and (b), a lot of random-telegraph-noise-like voltage fluctuations are seen below the upper critical field $H_{C2} \approx 2.0$ T both for sweeping-up and sweeping-down the magnetic field. Also, as shown in Figs. 3(c) and 3(d), the steep voltage change is less pronounced around $B = 0$ T. For increasing the magnitude of the magnetic field, $|B|$, the first steep voltage change appears at $\approx 0.05$ T.
Figure 3. Magnetic field dependence of the voltage between electrodes A and B under a constant current of 1 \( \mu \)A in sweeping-up (a,c,e) and sweeping-down (b,d,f) the magnetic field \((B)\). In (c)-(f), the data for three successive \( B \)-sweeps are shown but the data for each sweep are offset vertically for clarity. The noise level of the voltage measurement was \( \approx 2 \mu \text{V} \).
Taking into account that generally the penetration field of the first vortex is larger than the lower critical field \( (H_{C1}) \) due to the surface barrier\[23\], we speculate that the random-telegraph-noise-like voltage fluctuations occur in the vortex state (under a magnetic field between \( H_{C1} \) and \( H_{C2} \)).

Generally, the shape of the current-voltage curve of a superconductor/insulator/normal metal tunnel junction is sensitive to the superconducting energy gap at the interface, which is a function of the local supercurrent and the magnetic field.\[24, 25\] In the present case, under a magnetic field larger than \( H_{C1} \), not only a shielding supercurrent is flowing near the periphery of the sample (NbSe\(_2\)), but circular current around each vortex exists inside the sample. Since the junction size (\( \sim \mu m \)) is larger than the penetration depth, \( \lambda_{\perp} = \lambda_L^2 \xi_0/d^2 \approx 140 \text{ nm} \), where \( \lambda_L \) is the London penetration depth, \( \xi_0 \) is the coherence length and \( d \) is the thickness,\[24\] both the shielding supercurrent and vortices exist at the junction interface, as illustrated in Fig. 4(a). Thus, the local superconducting energy gap at the interface exhibits spatial variation. The junction voltage would reflect the averaged value of the local superconducting energy gap, which is affected both by the shielding supercurrent and by the vortex arrangement. In particular, for the electrode pair A-B, the junction size is much larger than \( \lambda_{\perp} \), so that the gradual change in the shielding supercurrent due to the magnetic field sweep would not result in a noticeable change in the junction voltage.

Here, we consider the origin of the random-telegraph-noise-like voltage fluctuations. The magnetic field for one flux quantum per the sample area and per the junction area are 0.08 mT and \( \sim 1 \text{ mT} \), respectively, both of which are much smaller than the typical separation of the steep voltage changes, as seen in Fig. 3(e) and 3(f). Thus, the voltage jumps are not caused by individual vortex entrance/expulsion in the sample or in the junction interfaces.

On the other hand, magneto-optical imaging of vortices in NbSe\(_2\)[26] revealed that under magnetic field sweep, the vortex motion is non-uniform and occurs in isolated jumps as well as collective motion involving many vortices. While the collective motion of vortices would lead to continuous change in the junction voltage, isolated jumps of vortices would correspond to steep voltage jumps. Here, we note that nominally tens or hundreds of vortices are situated in the junction area, depending on the magnetic field. For example, an applied magnetic field of 0.05 T corresponds to 50 vortices in the junction interface with area of \( \sim 2 (\mu m)^2 \). Thus, we can conclude that the random-telegraph-noise-like steep voltage change is caused by vortex jumps in and near the junction interface.

Finally, we would like to comment on the difference of the present result to our previous observations of the vortex states in aluminum mesoscopic superconductors. In our previous works,\[8, 9, 10, 11, 12, 13, 14, 15, 16\] we were able to detect the individual vortex entrance/expulsion. This is because the junction size (\( \sim 0.2 \mu m \)) was smaller than the magnetic penetration depth of the aluminum thin films (\( \lambda_L \approx 420 \text{ nm} \)), so that there existed no vortices at the junction interface and the junction voltage mainly reflected the change in the shielding supercurrent, as illustrated in Fig. 4(b).

There would be two methods for the detection of individual vortex penetration/expulsion in mesoscopic NbSe\(_2\) samples. The first is to make the junction smaller. However, this might be challenging because of the spatial resolution of the transfer process of a NbSe\(_2\) flake. The other is to make the flake thinner. Since even a monolayer film can be obtained in the mechanical exfoliation, the penetration depth can be largely enhanced.

4. Conclusions

We have experimentally investigated the response of a superconductor NbSe\(_2\) flake to magnetic field using small tunnel junctions. At 4.2 K, we observed random-telegraph-noise-like voltage fluctuations under a magnetic field sweep, which was attributed to vortex jumps around the junction interface. The difference of the present results from our previous results on
Figure 4. The junction area is compared with the magnetic penetration depth for the present NbSe$_2$ sample (a), and for the previous aluminum samples (b).

aluminum mesoscopic superconductors comes from the junction size compared with the magnetic penetration depth.

Acknowledgments
This work was supported by JSPS KAKENHI Grant Number JP15H05867 [Hybrid Quantum Systems]. The authors gratefully acknowledge fruitful discussions with M. Hayashi.

References
[1] Kanda A, Ootuka Y, Kadowaki K, Peeters F M 2010 Novel superconducting states in nanoscale superconductors The Oxford Handbook of Nanoscience and Technology vol 1, ed. A Narlikar and Y Y Fu (Oxford: Oxford University Press) chapter 19 pp 639-676
[2] Deo P S, Schweigert V A and Peeters F M 1997 Phys. Rev. Lett. 79 4653
[3] Moshchalkov V V, Qiu X G and Bruyndoncx V 1997 Phys. Rev. B 55 11793
[4] Schweigert V A and Peeters F M 1998 Phys. Rev. B 57 13817
[5] Bruyndoncx V, Rodrigo J G, Puig T, Van Look L, Moshchalkov V V and Jonckheere R 1998 Phys. Rev. B 60 4285
[6] Kanda A, Geisler M C, Ishibashi K, Aoyagi Y and Sugano T 2000 Physica B 284-288 1870
[7] Kanda A and Ootuka Y 2003 Physica B 329-333 1421
[8] Kanda A, Baelus B J, Peeters F M, Kadowaki K, Ootuka Y 2004 Phys. Rev. Lett. 93 257002
[9] Baelus B J, Kanda A, Peeters F M, Ootuka Y and Kadowaki K 2005 Phys. Rev. B 71 140502(R)
[10] Milosevic M V, Kanda A, Hatsumi S, Peeters F M, Ootuka Y 2009 Phys. Rev. Lett. 103 217003
[11] Hatsumi S, Ootuka Y and Kanda A 2009 Physica C 469 1080
[12] Hatsumi S, Kuroda Y, Ootuka Y and Kanda A 2010 J. Phys.: Conf. Series 232 012003
[13] Hatsumi S, Kuroda Y, Ootuka Y and Kanda A 2010 Physica C 470 1141
[14] Furugen R, Hatsumi S, Ootuka Y and Kanda A 2008 Physica C 468 1301
[15] Hatsumi S, Kanda A, Furugen R, Ootuka Y and Hayashi M 2009 J. Phys.: Conf. Series 150 022024
[16] Kuroda Y, Hatsumi S, Ootuka Y and Kanda A 2008 Physica C 470 1145
[17] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Science 306 666
[18] Kanda A 2013 Experimental approaches to graphene electron transport for device applications Physics and Chemistry of Graphene: Graphene to Nanographene ed T Enoki and T Ando (Singapore: Pan Stanford) chapter 3 pp 89-205
[19] Wang L, Meric I, Huang P Y, Gao Q, Gao Y, Tran H, Taniguchi T, Watanabe K, Campos L M, Muller D A, Guo J, Kim P, Hone J, Shepard K L, Dean C R 2013 Science 342 614
[20] Xi X, Wang Z, Zhao W, Park J-H, Law K T, Berger H, Forro L, Shan J and Mak K F 2015 Nat. Phys. 12 139
[21] Cao Y, Mishchenko A, Yu G L, Khestanova E, Rooney A P, Prestat E, Kretinin A V, Blake P, Shalom M B, Woods C, Chapman J, Balakrishnan G, Grigorieva I V, Novoselov K S, Piot B A, Potemski M, Watanabe K, Taniguchi T, Haigh S J, Geim A K and Gorbachev R V 2015 Nano Lett. 15 4914
[22] Boaknin E, Tanatar M A, Paglione J, Hawthorn D, Ronning F, Hill R W, Sutherland M, Taillefer L, Sonier J, Hayden S M and Brill J W 2003 Phys. Rev. Lett. 90 117003
[23] Bean C P and Livingston J D 1964 Phys. Rev. Lett. 12 14
[24] Tinkham M 2004 Introduction to Superconductivity (New York: Dover)
[25] Bardeen J 1962 Rev. Mod. Phys. 34 667
[26] Goa P E, Hauglin H, Baziljevich M, Il`yashenko E, Gammel P L and Johansen T H 2001 Supercond. Sci. Technol. 14 729