Peak Effects in 2H-NbSe₂ Single Crystals Induced by Particle Irradiations

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Abstract. Effects of three kinds of columnar defects in NbSe₂ single crystals introduced by 320 MeV Au irradiation with a dose equivalent matching field \( B_\theta \) up to 4 T were studied. Through the magnetization measurement using a SQUID magnetometer, two pronounced peak effects in the external field dependence of critical current density \( J_c \) were observed in crystals introduced with splayed and tilted columnar defects. In crystals with splayed columnar defects, \( J_c \) at the peak field reaches the maximum for splay angle \( \theta_{CD} = \pm 10^\circ \), which is a little different from that found in YBa₂Cu₃O₇ and iron-based superconductors, where optimal \( \theta_{CD} \) is equal to \( \pm 5^\circ \).

1. Introduction

Strong enhancement of the critical current density \( J_c \) by the creation of columnar defects (CDs) has been confirmed by many experiments [1-3], and the \( J_c \) enhancement after introduction of CDs has been explained with several theoretical analyses [4-6]. \( J_c \) is enhanced in a different manner when CDs with different morphology were introduced in superconductors. Anomalous peak effects at around \( 1/3B_\theta \) have been reported when the external field is applied along the \( c \)-axis for (Ba,K)Fe₂As₂ with splayed CDs at splay angle \( \theta_{CD} = \pm 15^\circ \) [7]. A similar peak effect has been observed in YBa₂Cu₃O₇ introduced with tilted CDs when the external field is applied parallel to CDs [8]. Due to natural splay of discontinuous CDs introduced by 580 MeV Sn in YBa₂Cu₃O₇ [8] the peak effect at around \( 1/3B_\theta \) after introducing tilted CDs can be understood to have been originated from the same mechanism as that in (Ba,K)Fe₂As₂ with splayed CDs. Recently, a similar peak effect was also reported in a conventional superconductor NbSe₂ introduced with tilted CDs when the external field was applied parallel to the CDs [9]. In NbSe₂, the peak effect shows up at around \( 1/5B_\theta \) which is slightly different from the peak effect located at around \( 1/3B_\theta \) in (Ba,K)Fe₂As₂ and YBa₂Cu₃O₇. The authors of Ref. [9] interpret the peak effect in NbSe₂ with tilted CDs as being caused by the self-field related phenomenon. However, when we calculate the self-field in [9], the self-field \( B_{self} \sim J_c t \sim 850 \) G, which is far from the observed peak field \( H_p \sim 6 \) kOe [9].

On the pinning mechanism in YBa₂Cu₃O₇ and iron-based superconductors with CDs, there have been many studies. However, for conventional superconductors, there have been only a few studies on what will happen if CDs are introduced. NbSe₂ is a conventional layered superconductor with a \( T_c \sim 7.2 \) K,
with an anisotropy in the upper critical field \( \sim 3.2 \) [12]. The superconductivity in this system is competing with charge-density wave (CDW) around \( \sim 33 \) K, and competition between different ground state also attracts attention recently [13-14]. Since the origin of the peak effect in superconductors with tilted and splayed CDs in cuprate and iron-based superconductors are still unclear, it is important to study the effect of CDs in NbSe\(_2\) with similar morphology.

In this study, we introduced parallel, tilted, and splayed CDs in NbSe\(_2\) single crystals by 320 MeV Au irradiation. The factors which affect the behavior of the peak effect are discussed.

### 2. Experimental details

Single crystals of NbSe\(_2\) were prepared by iodine vapor transport method [15]. The starting materials of stoichiometric amounts of Nb and Se are sealed in an evacuated quartz tube with 2.5 mg/cc of iodine. The starting materials were kept at a temperature gradient of \( \sim 50 \) °C in a tube furnace (high temperature at 800 °C, low temperature at 750 °C). After vapor transport process for two weeks, we obtained NbSe\(_2\) single crystals with well-defined surface with dimensions up to \( \sim 5 \) mm (length) \( \times 5 \) mm (width) \( \times 30 \)μm (thickness). 320 MeV Au irradiations were performed at JAEA in Tokai. Before performing the irradiation, the single crystals were prepared in thin plates with a thickness of \( \sim 6 \) μm along the \( c \)-axis, which is much smaller than the projected range of 320 MeV Au for NbSe\(_2\) of \( \sim 17 \) μm, calculated by SRIM-2008 (the Stopping and Range of Ions in Matter-2008) [16]. By controlling the angle between the irradiation beam and the crystallographic \( c \)-axis of the sample, we introduced parallel, tilted, and splayed CDs in NbSe\(_2\). The magnetization measurements were performed using a commercial SQUID magnetometer (MPMS-XL5, Quantum Design). After measuring the magnetic hysteresis loops (MHLs), we use the extended Bean model [17] to estimate the \( J_c \). In this model, \( J_c [A/cm^2] \) is given by

\[
J_c = \frac{20\Delta M}{a(1-a/3b)} (b > a),
\]

where \( \Delta M [emu/cm^2] \) is the difference of magnetization when sweeping the external field down and up. \( a [cm] \) and \( b [cm] \) are sample width and length, respectively.

![Figure 1](Image)

**Figure 1.** External field dependence of the critical current density at \( T = 4 \) K for the 320 MeV Au irradiated NbSe\(_2\) single crystals along the \( c \)-axis with \( B_\Phi = 1, 2, \) and 4 T.
3. Results and discussion

As we know, according to the Debye model, the temperature dependence of the phonon contribution to the specific heat at low temperatures is proportional to \( T^3 \), which means that the superconductor at low temperatures is very sensitive to the temperature variation. In almost all the 320 MeV \( \text{Au}^2 \) irradiated NbSe\(_2\) single crystals we studied, we observed flux jumps at around zero field below 3 K due to very large \( J_c \). That is the reason why we present magnetization results only at \( T = 4 \) K.

Figure 1 shows the results for NbSe\(_2\) introduced with parallel CDs. \( J_c \) monotonically increases with increasing \( B_\phi \), and no clear peak effect has been observed. It should be noted that in some studies about the effect of tilted CDs in superconductors, a pronounced peak effect has been observed when the external magnetic field was applied parallel to the CDs [8, 9]. Next, we show the result of NbSe\(_2\) with tilted CDs. Figure 2 (a) shows magnetic field dependence of \( J_c \) in NbSe\(_2\) with tilted CDs introduced 30° from the c-axis (\( \theta_{CD} = 30^\circ \)) with different \( B_\phi \). When \( B_\phi \) is lower than 0.2 T, \( J_c \) decreases monotonically with magnetic field as in the case of parallel CDs. However, when \( B_\phi \) is larger than a critical value of 0.5 T, the peak effect starts to show up. The peak field shifts from low field to high field with increasing \( B_\phi \). This evolution seems reasonable if the origin of this peak effect comes from the self-field. Since the self-field is given by \( B \sim J_d \) (\( t \): thickness of the sample), and with increasing \( B_\phi \), \( J_c \) increases. Hence, the peak field should shift from lower field to higher field. However, the self-field for these crystals at low field is typically 100 G, which is much smaller than the peak field (>1 kOe). This indicates that the peak effect in NbSe\(_2\) with tilted CDs is caused by a different mechanism. When we compared the \( J_c \) enhancement of NbSe\(_2\) with tilted and parallel CDs with \( B_\phi = 1 \) T and 2 T, the sample introduced with tilted CDs shows a higher \( J_c \) enhancement. \( H_p \) as a function of \( B_\phi \) in NbSe\(_2\) with tilted CDs is shown in Fig. 2(b). Here, data from Ref. [9] is also included. It is clear that for \( B_\phi > 0.2 \) T, \( H_p \) increases almost linearly with \( B_\phi \). However, the slope is \(~1/5\), smaller than the case of anomalous peak effect observed in (Ba,K)Fe\(_2\)As\(_2\).

![Figure 2](image)

**Figure 2.** (a) The external field dependence of critical current density at \( T = 4 \) K for 320 MeV \( \text{Au} \) irradiated NbSe\(_2\) single crystals with tilted CDs. Fixed tilting angle is 30° and \( B_\phi \) varies from 0.1 T, 0.2 T, 0.5 T, 1 T, and 2 T. (b) Matching field dependence of the peak field at \( T = 4 \) K when the external magnetic field was applied parallel to the CDs.

Figure 3(a) shows magnetic field dependence of \( J_c \) in NbSe\(_2\) with splayed CDs with different \( \theta_{CD} \) from 0° to \( \pm 15^\circ \) at 4 K. All five NbSe\(_2\) with different \( \theta_{CD} \), except for \( \theta_{CD} = 0^\circ \), show pronounced peak effects which are not located at zero field. For \( \theta_{CD} = \pm 5^\circ \), \( \pm 10^\circ \), and \( \pm 15^\circ \), peak effects are quite broad and the peak field shifts from high field to low field. By contrast, for samples with \( \theta_{CD} = \pm 20^\circ \) and \( \pm 30^\circ \), the peak with maximum \( J_c \) value is narrow and could be explained by the self-field effect [11]. In these two irradiated samples, the self-field is \( \sim 450 \) G, which is close to the peak field. It should be noted that in these two samples there are other weak broad peaks at around \( \sim 5 \) kOe. Here, we can
interpret that the peak effect observed in samples with $\theta_{\text{CD}} = \pm 5^\circ, \pm 10^\circ$, and $\pm 15^\circ$ may follow one mechanism, and the peak field is not related to the self-field peak effect. Actually, using the relation $B \sim J_c$, we can calculate the self-field for sample with $\theta_{\text{CD}} = \pm 5^\circ$ is $\sim 300$ G. On the other hand, the peak field which gives the maximum $J_c$ is located at $\sim 3$ kOe. It is also clear that weak peaks at around 5 kOe observed in samples with $\theta_{\text{CD}} = \pm 20^\circ$ and $\pm 30^\circ$ are also not related to the self-field peak effect. In a previous study on the effects of splayed CDs in iron-based superconductors [8], similar broad peak effects at around $1/3B_0$ have also been reported, and called anomalous peak effect. The possible origin of this broad peak effect may be related to the presence of crossing point between the two splayed CDs. If a similar mechanism is operative in NbSe$_2$ with splayed CDs, rather than the solid line in Fig. 3(b), the peak field should be followed as in broken line. It should be noted that the anomalous peak effect in (Ba,K)Fe$_2$As$_2$ is most pronounced at $\theta_{\text{CD}} = \pm 15^\circ - \pm 20^\circ$, while the peak in NbSe$_2$ with splayed CDs is most pronounced at $\theta_{\text{CD}} = \pm 5^\circ - \pm 10^\circ$. In addition, although peak effects in NbSe$_2$ with splayed CDs share some features in common with the anomalous peak effect observed in (Ba,K)Fe$_2$As$_2$ with splayed CDs, there are several discrepancies. Further studies are necessary to clarify the mechanism of the peak effect in NbSe$_2$ with CDs. In Fig. 3 (a), we also compared $J_c$ enhancement between the cases of parallel and splayed CDs. It is clear that all samples with splayed CDs show higher $J_c$ enhancement at high external fields compared with that with parallel CDs.

![Figure 3](image_url) (a) External field dependence of the $J_c$ at $T = 4$ K for the 320 MeV Au irradiated NbSe$_2$ single crystals with total $B_0 = 4$ T. The angle between $c$-axis and irradiated direction varies from 0° (parallel CDs), $\pm 5^\circ$, $\pm 10^\circ$, $\pm 15^\circ$, $\pm 20^\circ$, and $\pm 30^\circ$. (b) $\theta_{\text{CD}}$ dependence of the peak field in NbSe$_2$ with splayed CDs at 4 K.

4. Summary

We introduced three kinds of columnar defects in NbSe$_2$ single crystals by 320 MeV Au irradiation. The sample with tilted and splayed CDs both show a higher $J_c$ enhancement compared to those with parallel CDs. A pronounced peak effect was observed in NbSe$_2$ with tilted and splayed CDs. In the case of tilted CDs, 30° from the $c$-axis, peak effects appear only above $B_0 = 0.5$ T at $H_p/B_0 \sim 1/5$. On the other hand, in the case of NbSe$_2$ with splayed CDs with total $B_0 = 4$ T, broad peak effects appear from $|\theta_{\text{CD}}| = 5^\circ$ at $H_p/B_0 \sim 1/8-1/12$. In addition, the peak becomes very weak above $|\theta_{\text{CD}}| = 20^\circ$. Although peak effects in NbSe$_2$ with splayed CDs share some features in common with the anomalous peak effect observed in (Ba,K)Fe$_2$As$_2$ with splayed CDs, there are several discrepancies. Further studies are necessary to clarify the mechanism of the peak effect in NbSe$_2$ with CDs.

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