Dynamic Evolutions of Flux Distributions in a Superconductor by a Pulsed Current

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Abstract

We observed time–evolution of flux–density distribution in a superconductor by a pulsed current with the magneto–optical microscopy. The flux density distribution in a NbN film was measured up to 10000 frame per second by a high–speed camera. The voltage induced by the motion of vortices was simultaneously measured. Local reconfiguration of vortices occurred even below the critical current, which was qualitatively explained within the critical state model. However, some deviations between experiments and the theory were observed, indicating that the current flowing the sample was less than the critical current in the zero–field–cooled state.

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I. INTRODUCTION

Dynamics of vortices in a superconductor has long been investigated because it shows the complex flow patterns originating from nonlinearity and randomness of the pinning potential\cite{1,6}. The system is suitable for exploring non-equilibrium phase diagram since we can tune the density of vortices, the driving force in a systematic manner by changing magnetic fields and current. To study the dynamics of vortices, various experiments have been performed: $I-V$ characteristic\cite{1,7,8}, ac–response\cite{9–13}, voltage noise\cite{14–17}. Among them, some techniques can directly measure a spatial profile of flux density, $B$. The direct imaging of flux-density distributions must be powerful for the understandings of the dynamics of vortices\cite{18–21}, which enables us to compare experimental observations with theories more precisely. A Hall sensor array was used to reveal the geometrical barriers\cite{22} and revealed the spatial correlation of the noise\cite{23}. Scanning SQUID microscopy can visualize $B$ with the sub-\textmu m resolution\cite{24} with high sensitivity. Magneto–optical microscopy can measure $B$ with \textmu m scale and has better temporal resolution than the scanning probe microscopy\cite{25–27}. Flux penetration process has been observed with temporal resolution around 1 ms by magneto-optical imaging with using the high speed camera\cite{28}.

Theoretically, the penetration of vortices has been understood by the critical state model\cite{29}, which well explains the hysteresis in the magnetization, $M$ versus $B$ curve\cite{30}, and the spatial profile of the flux density\cite{26}. In this model, vortices are considered to enter a superconductor from edges, keeping the relation, $\frac{dB}{dx} = \mu_0 J_c$, where $\frac{dB}{dx}$ is the gradient of the magnetic field, $\mu_0$ is the vacuum permeability, and $J_c$ is the critical current density. Later, it was extended to thin films by Brandt et al.\cite{31} and Zeldov et al.\cite{32}. They calculated the current and the magnetic field distribution of a thin strip in various conditions with an applied magnetic field alone, with transport current alone, and with both of them. The experimentally observed flux distributions under the presence of magnetic fields and transport currents by the magneto-optical imaging were explained based on these models\cite{33,34}. However, almost all existing imaging experiments so far observed static flux distributions because of the limitation in the temporal resolution of the camera. A continuous time evolution of the critical state by the driving current has not been observed.

In this paper, we report the dynamic collapse of the critical state by real–time magneto–optical microscopy. The comparison of the experiment and the theory revealed that the
FIG. 1. (a) A schematic for the magneto-optical imaging apparatus. (b) An enlarged drawing around the sample. (c) An optical image of (b). (d) A typical image taken by the high speed camera and a schematic of the measurement of time dependence of flux densities. The intensity in the yellow square was averaged along the long axis and analyzed.

Current flowing the edge could be lower than the prediction of the critical state model. The deviation from the critical state model can affect the value of $J_c$ obtained by the magneto-optical microscopy and the magnetization measurements. As was shown by Pan et al. [35], the difference in $J_c$ among the different measurement techniques influences the interpretation of the pinning mechanisms. The further investigation of the validity of the critical state model is required.
II. METHODS

Fig.1(a) shows a schematic of the magneto-optical imaging. An NbN film was deposited on a magneto-optical indicator (Bi-substituted garnet film) by radio-frequency sputtering (Fig.1(c)). The thickness of the film was 1 µm, and the transition temperature was 15.1 K. The pattern was formed by putting a metal mask on the garnet film. A width of the current flowing area was 200 µm. The NbN film was fixed to a 1 mm thick sapphire substrate by indium, which also operated as electrodes (Fig.1(b)). The sapphire substrate was mounted onto a cold finger of a refrigerator by the silver paste. In order to monitor the temperature of the sample, a thermometer (CX-SD, LakeShore) was attached to the top of the sample. Magnetic fields were applied perpendicular to the film by a copper coil.

Incident light from the halogen lamp passed the first polarizer. The linearly polarized light was reflected at the surface of the NbN film. The reflected light was focused by the objective lens (5x), and passed the second polarizer. The angle between the first polarizer and the second polarizer, \( \phi \), was set to be 10° from the crossed Nicole configuration. The intensity of the light was detected by a high speed camera (Q1V, NAC Image Technology). The frame rate was 10000 frame per second. If there is a magnetic flux parallel to the incident light at the magneto-optical indicator, the light experiences a rotation of its polarization vector due to the Faraday effect. The rotation of the polarization vector changes the intensity of the light at the detector. Thus, the flux density at the magneto-optical indicator was measured by observing the intensity of the reflected light (see Supplemental Material in detail).

A triangular current pulse was applied to the NbN film by a function generator (3390, Keithley) and an I–V converter (BWS18-15, Takasago), which was operated at the constant current mode. The applied current was monitored by measuring a voltage drop of a 100 mΩ resistor in series with the sample using an oscilloscope (DL750, YOKOGAWA). The width of the pulse was changed from 1 ms to 20 ms in order to evaluate the effect of Joule heating. Similar current dependence was observed in these pulse widths so that we will discuss the result of 5 ms pulse as the representative. Simultaneously, the voltage due to the flux motion in the sample was measured, and was monitored by the oscilloscope.

It should be noted that the magneto-optical response of the indicator also depends on the in-plane component of the flux density, \( B_x \). In our measurements, the applied current induced the magnetic flux around the film, which has \( B_x \). However, it is difficult to estimate
FIG. 2. (a) The flux profile, $B_{\text{eff}}(x, t)$, (b) $\Delta B_{\text{eff}} \equiv B_{\text{eff}}(x, t) - B_{\text{eff}}(x, t = 0)$, (c) the applied current as a function of time in the remanent state, which was prepared by decreasing a flux density to 0 mT from a field cooled state, at 10.5 mT. (d) $B_{\text{eff}}(x, t)$, (e) $\Delta B_{\text{eff}}$, (f) the applied current and the voltage as a function of time in a field-cooled (FC) state at 10.5 mT. (g) $B_{\text{eff}}(x, t)$, (h) $\Delta B_{\text{eff}}$, (i) the applied current and the voltage as a function of time in a zero-field-cooled (ZFC) state at 10.5 mT.

$B_x$ without the knowledge of the flux density across the area with and without the sample[26], which could not be obtained in this measurement. Therefore, we denote the measured flux density as $B_{\text{eff}}$ indicating that it contains some contributions of $B_x$. According to Johansen et al.[26], although $B_x$ decreases the intensity of the reflected light, it had little influence on the qualitative spatial profile of the flux density. Thus, we believe that $B_x$ does not change an interpretation of our results in which we discuss only the changes in a spatial profile of $B_{\text{eff}}$, not the absolute value of $B_{\text{eff}}$.

### III. RESULTS AND DISCUSSIONS

In Fig. [2] we show the flux profile, $B_{\text{eff}}(x, t)$, and $\Delta B_{\text{eff}} \equiv B_{\text{eff}}(x, t) - B_{\text{eff}}(x, t = 0)$ together with the applied current and the voltage for the following three cases: (i) a remanent state,
which was produced by decreasing the flux density to 0 mT after the field cooling, (ii) a field-cooled (FC) state, (iii) a zero-field-cooled (ZFC) state, where \( x \) is the position and \( t \) is the elapsed time. In these three cases, the applied flux density was 10.5 mT, and the temperature of the cold head was 9 K. The plotted area was limited inside the film (-66 \( \mu\)m < \( x \) < 84 \( \mu\)m), where the response of the magneto-optical indicator was confirmed to be linear.

In the remanent state, vortices were trapped at the center of the film: the red area of Fig. 2(a). The applied current was shown in Fig. 2(c), and the voltage drop was not observed. The red area gradually shrank with increasing the applied current. The flux density started to decrease from the one edge(Fig. 2(b)), corresponding to the direction of the driving force.

In the FC state, the current was applied in the same manner as for the remanent state, and the voltage drop due to the flux motion was observed(Fig. 2(f)). \( I_c \) was estimated to be 1.27 A with the criteria of 10 \( \mu\)V, and the corresponding critical current density, \( J_c \), was \( 6.35 \times 10^5 \) A/cm\(^2\). Vortices penetrated inside the film uniformly as shown in Fig. 2(d). \( B_{\text{eff}} \) decreased in the lower half of the film with increasing the applied current, while it increased in the upper half of the film(Fig. 2(e)). The magnitude of the change was 1–4 mT, depending on the position in the film. The self field by 1 A current was estimated to be 1–6 mT from the equation, \( B(x) = \pm \mu_0 d J_c \ln \left( \frac{\sqrt{W^2 - x^2}}{\sqrt{W^2 - b^2}} \right) \), where \( d \) is the thickness of the film, \( W \) is half of the width of the film, and \( b \) is half of the width of the field-invariant region. The calculated \( B \) was comparable to the experimentally observed change. Therefore, we concluded that the change in \( B_{\text{eff}} \) was originated from the self field generated by the applied current. Once the flux density was changed by the self field effect, it remained almost unchanged after the applied current became zero. This hysteretic behavior of the flux density as for the application current history was probably caused by the pinning of vortices as was observed by Bobyl \textit{et al.} [34].

In the ZFC state, the voltage drop was observed as well for the FC state(Fig. 2(i)). Penetrated vortices are considered to form the critical state in which the current equal to \( J_c \) flows over the edges of the film. The field-free region at the center of the film gradually shrank with increasing the current(Fig. 2(g)). In addition, the decrease of \( B_{\text{eff}} \) was observed in the lower half of the film(Fig. 2(h)). The decrease of \( B_{\text{eff}} \) was similar to the FC state, indicating that the self field caused the decrease. From the spatial profile of \( B_{\text{eff}} \), \( J_c \) was estimated to be \( 1.1 \times 10^6 \) A/cm\(^2\) using the relation, \( J_c = \pi \frac{B_c}{\mu_0 d \ln \left( \frac{\pi}{2} \right)} \), where \( a \) is half of the length of
FIG. 3. (a) A Change of the magnetization per unit volume as a function of current in the remanent state. The applied current was normalized by $I_c$ determined from the $I$–$V$ curve. The magnetization and the applied current was normalized by the initial magnetization and the critical current, respectively. The magnetization was calculated by integrating $B_{\text{eff}}(x)$ with respect to $x$. The plotted circle was an average of the magnetization of three trials obtained by changing the integral interval. The error bars correspond to the maximum deviation of each trial from the average. (b) Current dependence of one edge of the field-free region($\Delta a^L$) in the zero-field-cooled state. $\Delta a^L$ was normalized by $W$. $a^L_{\text{exp}}$ (the red circle) and $a^L_{\text{theory}}$ (the blue square) correspond to the experimentally obtained $a^L$ and the numerically calculated $a^L$, respectively. The red dashed line, $0.31(I/I_c)^{1.9}$, is the curve which represents $a^L_{\text{exp}}$ well.

the field-free area[32]. It was higher than $J_c$ obtained from the $I$–$V$ characteristics(Fig[2](i)). The Joule heating is considered to be responsible for the difference in $J_c$.

The intensity of the reflected light depended on the magnetic–domain structure. The absolute value of $B_{\text{eff}}$ changed by ±5 mT in each experiment, possibly due to the changes
of the magnetic-domain structure of the magneto-optical indicator caused by changing flux
densities in various procedures. $B_{\text{eff}}$ was easily influenced even by a small change in the
intensity of the incident light, since the typical signal to noise ratio was 0.025. On the other
hand, $\Delta B_{\text{eff}}$ showed the similar current dependence in measurements for three different films.
In order to compare them with the theoretical prediction \[32\] quantitatively, we focused on
$\Delta B_{\text{eff}}$, and calculated the magnetization per unit volume, $M$, and the one edge of the field–
free region, $a^L$, for the remanent state and the ZFC state, respectively.

For the remanent state, we discuss the change of the magnetization, $\Delta M \equiv M(I) - M(I = 0)$, and denote experimentally observed $M$ as $M_{\text{exp}}$ and theoretically predicted $M$ as $M_{\text{theory}}$.

Since the applied magnetic field was zero, $M(x) = B(x)/\mu_0$ in the film. We assumed
$M(x) \simeq B_{\text{eff}}(x)/\mu_0$ because normal component of $B$ is continuous at the boundary between
the film and the magneto-optical indicator. Then, $M$, is $\frac{1}{2WLd}\int_{-W}^{W} B_{\text{eff}}(x)/\mu_0 dx$, where $L$ is
the length of the measured region. Fig.3(a) shows $\Delta M_{\text{exp}}(I)/M_0 \simeq \int \Delta B_{\text{eff}}(x,I) dx / \int B_{\text{eff}}(x, I = 0) dx$ together with $\Delta M_{\text{theory}}/M_0$, where $M_0$ is the initial magnetization. According to the
theory \[32\], the magnetization changes following the relation, $M_{\text{theory}} = M_0(1 - I/I_c)$; $\Delta M_{\text{theory}}$ is linear in $I/I_c$. However, $\Delta M_{\text{exp}}$ was rather almost quadratic to $I/I_c$. The fitting
provides that $\Delta M_{\text{exp}} = k(I/I_c)^n$ with $k = 1.0–1.1$, and $n = 1.9–2.2$.

Next, for the ZFC state, we discuss the current dependence of one side of a flux-front
position, $\Delta a^L(I) \equiv a^L(I) - a^L(0)$, as shown in Fig.3(b). The experimentally observed $a^L$,$a^L_{\text{exp}}$, corresponds to the dashed line in Fig.2(g). On the other hand, the numerically
computed $a^L$, $a^L_{\text{theory}}$, showed the different current dependence from $a^L_{\text{exp}}$, as was also the
case for $\Delta M$ of the remanent state (see Supplemental Material for the calculation detail).
While $\Delta a^L_{\text{theory}}$ was almost linear in $I/I_c$, $\Delta a^L_{\text{exp}}$ was expressed by the almost quadratic
function, $\Delta a^L_{\text{fit}}/W = 0.31(I/I_c)^{1.9}$.

We considered the modified flux distribution from the critical state as a possible explana-
tion for the deviation between the experiment and the theory. As was discussed by Gaevski
et al. \[33\], the flux creep can change the flux distribution from the theoretically predicted one.
In their experiment, under the transport current, the flux creep caused the deeper penetra-
tion of flux than expected by the critical state model. In addition, since we applied the
magnetic field instantaneously, the flux could enter inside the film due to the local heating,
which decreases $J_c$ \[29\]. The deeper flux penetration can result in a gentle gradient of $B$;
$\mu_0 J = dB/dx < \mu_0 J_c$, where $J$ is the current density. If $J$ is below $J_c$, the edge of the
strip can afford more current until it reaches $J_c$. It can explain that $\Delta M_{\text{exp}}$ and $\Delta a^L_{\text{exp}}$ were almost unchanged at the lower current regime, $I/I_c < 0.4$.

A Joule heating effect cannot explain the observed difference between the experiment and the theory. A heating lowers $J_c$, and should induces the flux motion. Thus, under the effect of a heating, $\Delta M_{\text{exp}}$ and $\Delta a^L_{\text{exp}}$ are considered to change faster than $\Delta M_{\text{theory}}$ and $\Delta a^L_{\text{theory}}$, respectively. However, $\Delta M_{\text{exp}}$ and $\Delta a^L_{\text{exp}}$ were fitted by the quadratic function of the current. The observed changes of them were smaller than the theoretical prediction at the lower current regime, indicating that vortices did not move. Thus, a heating effect should not be responsible for the deviation between the experiment and the theory.

IV. CONCLUSION

In conclusion, we observed the dynamic evolution of the flux distribution under the transport current with the magneto-optical microscopy incorporating the high-speed camera. The initial flux distributions was prepared by decreasing a magnetic field to zero from the FC state (a remanent state), field-cooling, and zero-field-cooling. The observed changes by the current could be explained qualitatively by the critical state model for the film and the self field. However, $\Delta M_{\text{exp}}$ and $\Delta a^L_{\text{exp}}$ showed the deviation from the theoretical prediction. These differences indicate that the current flowing at both edges may be below $j_c$ due to a flux creep. Our results show that important modification is necessary in theories to reproduce the experiment. In order to test the hypothesis, spatial current distribution under a transport current has to be measured together with $I_c$, which is in progress.

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