Flux avalanches in Nb superconducting shifted strip arrays

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Abstract
Flux penetrations into three-dimensional Nb superconducting strip arrays, where two layers of strip arrays are stacked by shifting a half period, are studied using a magneto-optical imaging method. Flux avalanches are observed when the overlap between the top and bottom layers is large even if the width of each strip is well below the threshold value. In addition, anomalous linear avalanches perpendicular to the strip are observed in the shifted strip array when the overlap is very large and the thickness of the superconductor is greater than the penetration depth. We discuss possible origins for the flux avalanches, including linear ones, by considering flux penetration calculated by the Campbell method assuming the Bean model.

1. Introduction
Superconductors have been fabricated into three-dimensional structures, to realize their unique functionalities. They can be used as metamaterials with unusual electric permittivity or magnetic permeability [1, 2], which can realize magnetic cloaking without disturbing the external magnetic lines of force compared with conventional magnetic shielding by superconductors or mu-metals [3–5]. The rapid single-flux quantum device is also a major application which can replace the conventional CMOS semiconductor device due to its high operational speed with low power consumption [6]. Additionally, the superconducting Roebel cable with a three-dimensional structure can suppress AC losses by twisting superconducting tapes [7]. For these applications, bulk magnetization measurements, the evaluation of device operations, and transport measurements have been extensively undertaken, as well as theoretical calculations [8]. However, little is known about the local magnetic response of such three-dimensional superconductors. Therefore, it is of great importance to investigate the local magnetic properties to obtain scientific and technological information about these three-dimensional superconductors and to improve the performance of their applications.

Magnetic flux penetrates into superconductors as quantized vortices under magnetic fields above the lower critical field, and the vortices arrange themselves in a self-organized manner into the critical state, where the Lorentz force from the shielding current balances the pinning force from defects [9]. On the other hand, unique phenomena known as flux avalanches (flux jumps) due to thermo-magnetic instabilities are often observed when the heat generated by the vortex motion surmounts the heat diffusion [10, 11]. This instability becomes an obstacle for applications of superconductors due to quenching [12] or the generation of noise [13]. The conditions for flux avalanches depend on various kinds of parameters; temperature, applied field, thermal conductivity, the geometry of samples, and so on [14]. Flux avalanches can occur at very low magnetic fields in thin film samples due to a stronger demagnetization effect [15]. This effect can be enhanced even more in superconducting structures consisting of many thin films arranged close by [16]. Recently, electromagnetic responses in hexagonal arrays of superconducting strips have been reported...
Figure 1. Schematic drawing of a shifted strip array. Each strip has width \( w \) and thickness \( d_s \). In each layer, strips are arranged periodically along the \( x \) axis with a period of \( a_x \) and separated into two layers with an insulating gap \( d_i \). Schematic flux penetrations into the strips are shown as green regions in the middle unit cell, which propagate from the edges to the center (yellow arrows).

Table 1. List of shifted strip array samples. Each sample has thickness of superconducting film \( d_s \) and thickness of insulator gap \( d_i \).

| Name          | \( d_s \) (nm) | \( d_i \) (nm) |
|---------------|----------------|----------------|
| SSA50–50      | 50             | 50             |
| SSA100–100    | 100            | 100            |
| SSA200–200    | 200            | 200            |
| SSA300–300    | 300            | 300            |
| SSA300–50     | 300            | 50             |
| SSA500–50     | 500            | 50             |

Flux distributions in SSAs are observed under an external magnetic field \( H \) (0–40 mT) along the \( z \) axis after cooling down to a temperature \( T \) ranging from 4.5 to 8.5 K under zero field. To visualize flux penetrations in SSAs, we use a magneto-optical (MO) imaging technique in which the spatial variation of the out-of-plane flux density is detected using the Faraday effect in a ferromagnetic garnet film [20, 21]. The gap between the sample and the garnet film has been minimized by gently pushing down the garnet film with two small phosphor bronze plates. In MO measurements, we used a commercial optical microscope (Olympus BX30MF) with a ×20 objective lens (Nikon CF Plan 20X) and a cooled-CCD camera with 12-bit resolution (ORCA-ER, Hamamatsu). The samples are cooled down to temperatures ranging from 4.2 to 8.5 K under zero field using a He-flow cryostat (Microstat HighRes II, Oxford Instruments). A magnetic field was applied along the \( z \)-axis isothermally at each temperature. The obtained MO images are integrated over tens of images and subtracted by a zero-field background image to improve the magnetic resolution and to suppress artifacts originated from in-plane magnetic domains or scratches on the garnet film [22]. It should be noted that even single vortices can be observed by this technique [22–25].

3. Results and discussion

Figure 2(a) shows an optical image of SSA300–50 with \( a_x = 9 \) \( \mu \)m. The number of strips in the \( x \) direction is chosen to limit the samples within a range of 200 \( \mu \)m. In this sample, 23 and 24 strips are fabricated on the top and bottom layers, respectively. The length of strips in the \( y \) direction is also 200 \( \mu \)m, which is long enough to consider the system as a collection of infinite strips. MO images of flux penetration into the sample are shown in figures 2(b)–(d) under the same conditions at 4.2 K and under \( H = 10 \) mT repeatedly. These images are colored in three kinds of channel (red, green, and blue) and are added into an image as shown in figure 2(e). In this combined image, the gray scale regions show the reproduced flux penetrations, known as the usual critical state. On the other hand, the colored areas indicate that the flux front is not reproducible. This phenomenon is known as the flux avalanche caused by thermo-magnetic instability, which rapidly appears with increasing field and has non-reproducible shapes [26]. Some avalanches, however, repeatedly occur at similar locations, possibly due to defects in the superconductor or the stray field generated by the magnetic domains in the indicator film. Flux avalanches usually occur when their positions are far from each other due to the nonlocal repulsive force between flux in thin films, and the observed flux avalanches similarly do not overlap but align. There are two noteworthy differences in flux avalanches in SSA compared with those in plain films. One is about their morphology. The observed flux avalanches have linear shapes traversing many strips. Flux avalanches in plain films are known to have various kinds of shapes [27]: uniform [28], finger-like [29], and dendritic [30]. On the contrary, flux avalanches in SSAs likely jump from one strip to another and tend to form anomalous linear shapes perpendicular to...
Figure 2. (a) Optical micrograph of SSA300–50 with \(a_x = 9 \, \mu \text{m}\). (b)–(d) Three MO images of flux penetration after cooling down to 4.2 K and applying \(H = 10 \, \text{mT}\). (e) Image obtained by adding the three MO images. The black bar shows 100 \(\mu \text{m}\) length scale.

Figure 3. Temperature and \(a_x\) dependences of flux penetrations in SSA300–50. (a) An optical micrograph and MO images of flux penetration with \(a_x = 9 \, \mu \text{m}\) at (b) 4.2 K and 10 mT, (c) 6 K and 9 mT, (d) 7 K and 6 mT, (e) 8 K and 4 mT, and (f) 8.5 K and 2.2 mT. The size of flux avalanches along the \(x\) and \(y\) directions is defined as \(l_x\) and \(l_y\), respectively. Optical micrographs and MO images at 4.2 K with \(a_x = (g), (h) 11 \, \mu \text{m}\) at 11 mT, (i), (j) 13 \(\mu \text{m}\) at 8 mT, and (k), (l) 16 \(\mu \text{m}\) at 8 mT.

The second difference concerns the starting point of flux avalanches. They do not start at the outermost edges of SSAs as they would in plain films. In addition, we should not overlook that linear flux avalanches have knots around the middle of the lines and they may have initiated there. Thus time-resolved measurements of flux propagation are needed to discuss where flux avalanches start from [31].

Figure 3 shows the \(T\) and \(a_x\) dependences of flux penetrations in SSA300–50. The MO images show the flux
distribution after applying magnetic fields isothermally at each temperature. With \( \alpha_s = 9 \, \mu m \), flux avalanches occur at high temperatures up to 8.5 K (0.92T_c) as shown in figure 3(f). Generally, a flux avalanche occurs in strips or films below a characteristic field-dependent temperature, the so-called threshold temperature, and in a range of magnetic fields above a threshold field and below a certain upper field in isothermal conditions [14, 32, 33]. A typical value for the threshold temperature in Nb film is about 5 K [30, 33–35]. According to equation (1) of [30], flux avalanches occur only below a threshold temperature \( \sim 1 \) K in an isolated superconducting single strip with a thickness of 300 nm and a width of 8 \( \mu m \) assuming typical physical parameters for Nb [30]. Therefore, it seems reasonable to suppose that the three-dimensional structures of SSAs enhance flux avalanches. We will discuss how the structures induce flux avalanches in the latter part of this paper.

In the following, a detailed account of linear flux avalanches is given. As shown in figure 3(b), the linear avalanches at 4.2 K expand over the entire width of the sample (200 \( \mu m \)). At higher temperatures (figures 3(c)–(f)), the length of the flux avalanche along the \( x \) axis, \( l_x \), becomes smaller and the avalanches form small fragments. It is obvious that the average length \( l_x \) monotonically decreases with increasing \( T \). In contrast, the behavior of the width of the linear flux avalanche along the \( y \) axis, \( l_y \), is different; it is smallest at 4.2 K (figure 3(b)), and increases with increasing \( T \) as shown in figures 3(c)–(f), followed by a decrease near \( T_c \) (figure 3(f)).

According to earlier theory and experiments [14, 36], the size of flux avalanches both along the \( x \) and \( y \) directions increases monotonically with increasing \( T \). This is the opposite to our result that the length \( l_x \) decreases as temperature increases. There is no satisfactory explanation for this anomalous temperature dependence at this stage. On the other hand, the positive temperature dependence of \( l_x \) in SSAs below 8 K agrees with the theory for the single strip. In addition, the anomaly of \( l_x \) at 8.5 K (figure 3(f)) can be explained by the large penetration depth near \( T_c \) which is even larger than the thickness \( d_i \) when we assume a two-fluid model for its \( T \) dependence [37]. The \( \alpha_s \) dependence of the flux avalanches at 4.2 K is shown in figures 3(g)–(i). With increasing \( \alpha_s \), the linear avalanches disappear at 11 \( \mu m \) as shown in figure 3(h). Instead of linear flux avalanches, spot-like avalanches appear in each strip. With larger \( \alpha_s \), the size of the spots shrinks (figure 3(j)). No flux avalanches occur in SSAs with \( \alpha_s = 16 \, \mu m \) (figure 3(l)), confirming that the threshold temperature in single strips with \( w = 8 \, \mu m \) is below 4.2 K as estimated above, because a SSA without an overlap can be treated as a quasi-two-dimensional array of single strips. This indicates that the three-dimensional structure in SSAs promotes flux avalanches. In the following section, we discuss possible origins for linear flux avalanches.

There are two scenarios to explain the origin of linear avalanches; thermal and magnetic coupling. Interlayer thermal coupling promotes linear flux avalanches. The heat generated by an avalanche diffuses into the surroundings which are usually considered as a heat bath at a fixed temperature. The heat transfer coefficient is an important parameter in determining the conditions for flux avalanches [14]. However, special care needs to be taken in SSAs because the strips are thermally coupled to each other via thin insulating layers. Therefore the heat produced by the first flux motion in one layer triggers the motion of another flux in the neighboring layer due to interlayer thermal coupling. Besides, linear flux avalanches can occur due to magnetic coupling between vortices in two overlapping layers. The motion of vortices in bilayer superconductors has been extensively studied for applications in DC superconducting transformers [38]. The stray field generated by a vortex in one superconducting layer attracts another vortex in the neighboring layer. Even when the Lorentz force is applied on only one of the vortices, the other vortex is dragged by the magnetic coupling force. Of course, the two couplings are not mutually exclusive, rather they can cooperate to promote the linear flux avalanche.

Figure 4 shows MO images of SSAs with different \( d_i \) and \( d_s \) for \( \alpha_s = 9 \, \mu m \) at 4.2 K. Considering the \( d_i \) dependence at a fixed \( d_s \) (see figures 4(b) and (f)), the length \( l_x \) increases with decreasing \( d_i \). This result is consistent with thermal/magnetic coupling scenarios. Next, the \( d_s \) dependence at a fixed \( d_i \) is non-monotonic as shown in figures 4(c)–(g), indicating that it is difficult to explain the \( d_s \) dependence only by the above scenario because the thermal/magnetic coupling should hold constant for the same \( d_i \). It is especially anomalous that no linear avalanche is observable for small \( d_s \) as shown in figure 4(e). To explain this behavior, a dashed line for the condition \( d_s \sim \lambda = 102 \, \mu m \) at 4.2 K is plotted in figure 4(a), where \( \lambda \) is the penetration length [37]. As noted for the temperature dependence, we confirm the anomaly occurs when \( \lambda \) becomes comparable to or larger than \( d_i \) (figure 3(f)). Finally, flux avalanches with equal \( d_i \) and \( d_s \) are shown in figures 4(b)–(e). This dependence is complicated because it has both \( d_i \) and \( d_s \) dependences. Similar to the \( d_i \) dependence at fixed \( d_s \), the length \( l_x \) decreases with increasing \( d_i \) when \( d_s \) is larger than 200 nm (figures 4(b) and (c)). However, even for thinner \( d_s \), the linear avalanches disappear when \( d_i \) is less than \( \lambda = 102 \, \mu m \) (figures 4(d) and (e)). From the results for \( \alpha_s \), \( d_i \), \( d_s \), and \( T \) dependences, the conditions for a linear avalanche can be summarized as follows: (1) large overlap between top and bottom layers; (2) thinner \( d_i \) for stronger interlayer thermal/magnetic coupling; (3) thinner \( d_s \) for longer length \( l_x \); and (4) the thickness \( d_s \) should be larger than \( \lambda \). In the following section, we discuss the origin of the flux avalanches in SSAs by considering the flux distribution.

The electromagnetic responses of SSAs are calculated using the Campbell method, assuming the Bean model [39]. Figure 5 shows the flux distribution in SSA300–50 with \( \alpha_s = (a) \, 9 \, \mu m \) and (b) \, 13 \, \mu m \) under an applied field \( H = 0.1J_c d_i \), where \( J_c \) is the critical current density. The magnitude of the flux density, \( B \), is plotted in a color scale. It is noted that \( B \) becomes 10 times larger than \( \mu_0 H \) within the overlaps, and the maximum values are almost the same for different \( \alpha_s \). We speculate that this enhancement of the local flux density and its temporal evolution generate the large electric field and heat dissipation when the flux penetrates into the
Figure 4. (a) Schematic diagram of $d_s$ and $d_i$ for the SSA samples. MO images of flux avalanches in SSAs for different $d_s$ and $d_i$ with $a_x = 9 \mu m$ at 4.2 K under $H = (b) 11$ mT, (c) 9 mT, (d) 5.5 mT, (e) 5 mT, (f) 10 mT, (g) 40 mT.

Figure 5. Magnetic lines of force and distribution of magnitude of local flux density in SSA300–50 with $a_x = (a) 9 \mu m$ and (b) 13 $\mu m$ assuming the Bean model.

SSA, which finally promotes the flux avalanches at such high temperatures close to $T_c$. In addition to the $B$ distribution, the magnetic lines of force are shown as black solid lines in figure 5. The lines lie in-plane, indicating that magnetic coupling is weak in this system compared with a conventional superconducting DC transformer, where flux lines penetrate two films perpendicularly. Therefore, we can conclude that the most possible origin for linear flux avalanches is the thermal
4. Summary

Flux penetrations into three-dimensional double-layered superconducting strips, shifted strip arrays, are studied using a magneto-optical imaging method. Flux avalanches are observed when the period of a shifted strip array is small, or the overlap between the top and bottom layers is large. Anomalous linear flux avalanches are observed in the shifted strip array when the overlap is very large, when the thickness of the superconductor is larger than the penetration depth, and when the interlayer gap is small. We conclude that linear flux avalanches are caused by interlayer thermal coupling. We believe that our work opens up a new direction for the study of three-dimensional nanostructured superconductors.

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Figure 6. Schematic drawing of the process of a linear flux avalanche. (a) A flux avalanche occurs at A in one layer. Flux penetration proceeds towards B as shown by a yellow arrow. (b) Heat dissipation generated by the first avalanche diffuses into the surroundings which triggers new avalanches at C and D in another layer. Heat transfer is shown as black arrows. (c), (d) Linear flux avalanches are formed by repeating the same processes.

Finally, we explain how interlayer thermal couplings promote linear flux avalanches. Figure 6 shows a schematic model of how a linear avalanche evolves over time. We assume that the flux front of an avalanche can reach only the middle of the strip and that thermal diffusion is slower than magnetic diffusion. (a) An avalanche occurs at A due to thermal or magnetic fluctuations in one layer and it proceeds towards B in the strip as shown by a yellow arrow. (b) The heat generated by the avalanche diffuses out into the surroundings as shown by a red shadow. New avalanches are then triggered at C and D due to thermal fluctuations which are enhanced by heat transfer from the original strip via an insulating layer as shown by black arrows. (c) Linear flux avalanches proceed in the bottom layer via the same process and the generated heat is transferred to the top layer as shown by black arrows. (d) New linear avalanches are formed in the top layer as shown by yellow arrows. However, the process will stop when the following condition is satisfied: the heat transfer from one layer to the other is not sufficient for large $\alpha_s$ or $d_i$, which is shown by black arrows in figure 6(b). This consideration is consistent with experimental results that linear avalanches occur with small $\alpha_s$ or small $d_i$ as shown in figures 3 and 4.

Coupling between overlapping strips. It should be noticed that these numerical calculations correspond to flux distributions at low $T$ or large $d_s$ since $\lambda$ is considered to be much smaller than $d_s$. Therefore, further discussions on the condition where $\lambda$ becomes comparable to $d_i$ will be required to explain the experimental anomaly at high temperatures.

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