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Critical states and thermomagnetic instabilities in three-dimensional nanostructured superconductors

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ABSTRACT

Critical state field profiles and thermomagnetic instabilities are studied in two kinds of three-dimensional nanostructured superconductors. We find that the critical state field profiles in some simple bi-layer systems are not simple superpositions of critical states in the two layers. Competition between the divergence of the local field at the edges of the film and the shielding by the neighboring layer makes novel critical state field profiles. We also studied flux avalanches in shifted strip arrays (SSAs) with layer numbers up to six. Various forms of avalanches either perpendicular or parallel to the strip are observed when the overlap between strips in neighboring layers is large. We also find that introduction of asymmetry in various forms to SSA affects the shape of flux avalanches sensitively.

1. Introduction

By stacking nanofabricated superconducting layers on top of others, three-dimensional nanostructured superconductors can be fabricated, and various kinds of new functionalities can be achieved. One of such examples is superconducting metamaterials with unusual magnetic permeability [1,2] and they can realize magnetic cloaking without any disturbance to the external field distribution in contrast to the conventional magnetic shielding by superconductors [3–5]. Logic devices made of superconductors such as rapid single-flux quantum (SFQ) devices are other major applications of three-dimensional nanostructured superconductors may defeat the conventional CMOS technology with their high operation speed and low power consumption [6]. For the characterization and development of these applications, magnetization and transport measurements as well as theoretical calculations have been performed. However, knowledge is limited on the local magnetic properties of such three-dimensional nanostructured superconductors. In particular, thin-film geometry imposes a strong demagnetization effect which can produce divergence of the local field and facilitate thermomagnetic instabilities. We chose two simple three-dimensional systems and studied their local electromagnetic responses. The first is bi-layer systems where simple but different shapes of superconductors are stacked. We studied critical state field profiles in such simple bi-layer superconducting systems. The second is multi-layer stacks of arrays of superconducting strips, where neighboring layers are shifted by a half period so that the maximum shielding effect is realized, which is called shifted strip array (SSA). We have investigated SSA with 2-layers and found that novel avalanches can be induced due to enhanced demagnetization effects [7] in contrast to conventional flux avalanches in large plane films [8]. In this initial investigation, we have also studied how the overlap of neighboring layers, thicknesses of superconducting and insulating layers, and temperature affect the flux avalanches. We also studied the layer-number dependence up to four [9–11], and observed the variation of the form of avalanches in SSAs. Here we report layer-number and temperature dependences of the flux penetrations and avalanches in SSAs with a layer number up to six by magneto-optical imaging (MOI). We also study the effect of asymmetry in various forms on flux avalanches.

2. Experiments

Two kinds of three-dimensional Nb nanostructured superconductors are fabricated on Si substrates by using magnetron sputtering, photolithography, and SF6 reactive ion etching technique. In particular, caldera planarization [12] is applied to make reliable

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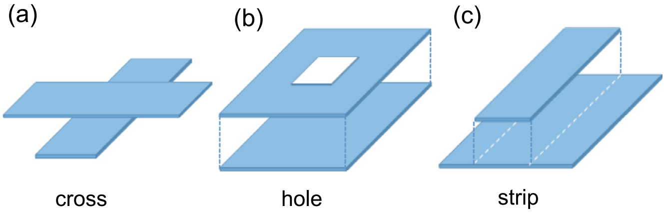

Fig. 1. Schematic drawings of bi-layer Nb structures of (a) “cross”, (b) “hole”, and (c) “strip”. In all cases, 300 nm SiO_2 layer is sandwiched by two 300 nm Nb layers.

structures on top of the lower layers. The first sets of samples are bi-layer systems, which are named as “cross”, “hole”, and “strip”. In all cases, 300 nm SiO_2 layer is sandwiched by two 300 nm Nb layers. In the case of “cross”, two 60 × 200 μm^2 rectangles are crossed as shown in Fig. 1(a). In the case of “hole”, one 200 × 200 μm^2 square is covered by another square with the same dimensions and with a 100 × 100 μm^2 hole at the center as shown in Fig. 1(b). In the case of “strip”, one 100 × 200 μm^2 rectangular strip is placed at the center of 200 × 200 μm^2 square as shown in Fig. 1(c). We also fabricated samples with the top and bottom layers interchanged. However, obtained results are essentially the same. So, we only discuss the case shown in Fig. 1.

Three-dimensional nanostructures consisting of superconducting Nb strips are named as “shifted strip array (SSA)”. Fig. 2(a) is an optical image of six-layer SSA. Strips along y-axis with a width $w = 20$ μm and thickness of 300 nm are arranged with a period of $a = 23$ μm along x-axis. Strips in different layers are shifted by a half period $a/2$ with insulating layers of 300 nm as shown in Fig. 2(b) for the case of six-layer SSA. In some of 2-layer SSAs, we introduced asymmetries. In “SSA-shift”, we shifted the top layer with respect to the bottom strips by s. s/w is changed from 0 to 20%. In “SSA-$w3$” (“SSA-$w4$”), the width of the strip in the bottom (top) layer is made narrower. $w3/w$ ($w4/w$) is changed from 100% to 70%. We also fabricated 2-layer SSA with a large number of strips or arranged strips in a circular fashion in order to check the extent of thermomagnetic instability.

Flux penetrations and critical state field profiles into three-dimensional nanostructured superconductors are imaged by 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 [13]. In order to maximize the spatial resolution, the gap between the sample and the garnet films is minimized by mechanically pressing the garnet film. We used a commercial optical microscope (Olympus BX30MF) and a cooled-CCD camera with 12-bit resolution (ORCA-ER, Hamamatsu) to capture MO images. Samples are cooled using a He-flow cryostat (Microstat HighRes II, Oxford Instruments). A magnetic field was applied perpendicular to the film plane. Usually, obtained MO images are integrated over tens of images and subtracted by a background image at zero field to improve the magnetic field resolution and to suppress artifacts originated from the in-plane magnetic domain or scratches on the garnet film [14,15]. It is noted that by applying such an integration and differential method, even single vortices can be visualized [16–18].

3. Results and discussion

3.1. Critical state field profiles in “cross”, “hole”, and “strip”

MO images of “cross”, “hole”, and “strip” in the critical state at 5 K is shown in Fig. 3(a), (b), and (c), respectively. Generally speaking, in a bi-layer superconducting system, there is a competition between the divergence of the local field at the edges of the sample and shielding of magnetic field by the overlapping superconducting layer. Let us discuss the characteristic features one by one. In the case of “cross”, the competition between the divergence of the local field and its shielding by the neighboring layer is most dramatically observed. Namely, the negative divergence of the local

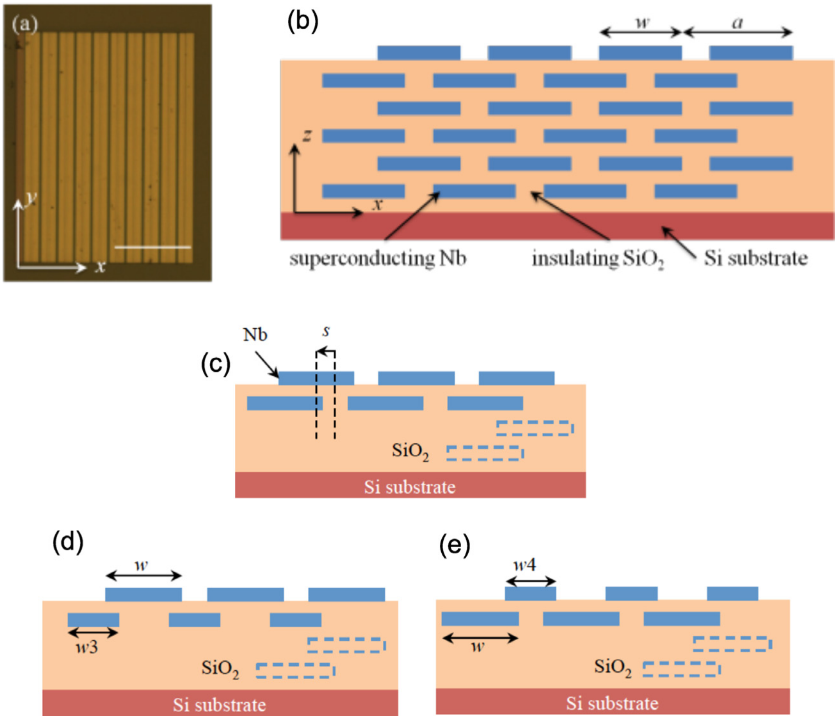

Fig. 2. (a) An example of optical micrograph of SSA with $w = 20$ μm and $a = 23$ μm. (b) Cross section of 6-layer SSA, each 300 nm thick strips with a width w and period a are separated by 300 nm thick SiO_2 layers. (c) Cross section of “SSA-shift”, in which top layer is shifted by s with respect to the standard 2-layer SSA. Cross sections of (d) “SSA-$w3$” and (e) “SSA- $w4$”, in which the width of bottom (“SSA-$w3$”) or top (“SSA-$w4$”) layer is made narrower.

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