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Thickness and hole-shape dependence of flux penetration into square superconducting networks

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ABSTRACT

We have observed flux penetrations into square superconducting networks of Nb with various thicknesses and hole-shapes by using magneto-optical imaging method. The penetrated pattern does not depend on the thickness and extends along diagonal direction when the samples have smaller area in the intersection of networks. We have also observed similar superconducting networks with and without small holes at the intersection. The small holes at the intersection do not work as a promoter for the diagonal flux penetration though the parallel flux penetration becomes weak. We discuss possible origins of these anomalous anisotropic flux penetrations.

1. Introduction

With rapid development of nanofabrication in the last decades, many researchers enthusiastically have studied the way to control vortices in superconductors. The motion of vortices is governed by temperature, current, magnetic field, and especially sample geometry. Superconducting anti-dot arrays (SAA) have been extensively studied on flux penetration [1,2]. In SAA, vortices easily penetrate along a direction between nearest anti-dots, so called vortex channeling model [2]. However, our group has reported an anomalous flux penetration pattern which extends along the diagonal direction of the lattice in square superconducting networks (SNs) with a relatively large lattice constant *a* [3,4]. This phenomenon becomes dominant at lower temperatures, larger *a*, smaller line width *w* of networks, and the smaller ratio of *w*/*a*. In addition to these results, a time-dependent Ginzburg–Landau (TDGL) simulation has reproduced this phenomenon [5]. In this paper, we present the thickness and hole-shape dependence of the diagonal flux penetration pattern to discuss the origin of the anomalous diagonal penetration. In addition, we place small holes at the intersection of SNs to clarify whether the vortex channeling model supports the diagonal penetration.

2. Experiments

We have fabricated several finely shaped SNs of Nb on Si substrates by using sputtering, photo lithography and SF6 reactive-ion etching technique. As shown in Fig. 1a, the whole shape of a sample is $1 \times 1.8\ \mathrm{mm}^2$ rectangle with six narrow slits whose dimensions are $25 \times 300\ \mu\mathrm{m}^2$. The slits concentrate applied magnetic flux perpendicular to the paper and enforce vortices to penetrate from the ends of them. Square lattices of square holes are fabricated next to each other with various lattice constants *a* from 2 μm to 16 μm and the same ratio $w/a = 0.5$, where *w* (μm) is the line width of SNs as shown in Fig. 1b. We named each region of the samples as T*t*-*a*, where *t* is the thickness of sample in Angstrom with the value from 500 to 3000 Å. The shape of holes is defined with the parameter α which is the ratio of two characteristic lengths as shown in Fig. 1(c). For example, $\alpha = 1$ is for the square hole. We named these samples as Sα-*a* with a thickness of 500 Å. In addition to square holes, we have fabricated small holes with a diameter of 0.5 μm at the intersection as shown in Fig. 1d. We named these samples as H*t*-*a* with a thickness *t* of 500 Å.

We use magneto-optical (MO) imaging technique in which Faraday effect in the magnetic garnet film is used to detect spatial distribution of the flux density. We use a cooled-CCD with 12 bit resolution (ORCA II-ER, Hamamatsu) and He flow cryostat (MicrostatHighRes II, Oxford Instruments). The differential MO method is used to improve field resolution and remove unnecessary modulation coming from artificial magnetic domain and scratches on the garnet film [6,7].

3. Results and discussion

Fig. 2 shows MO images of flux penetrations into square SN samples with various thicknesses after zero-field cooling. The best MO images are chosen to show the clear flux penetration patterns. Fig. 2a and b show temperature dependence in T500-*a* samples.

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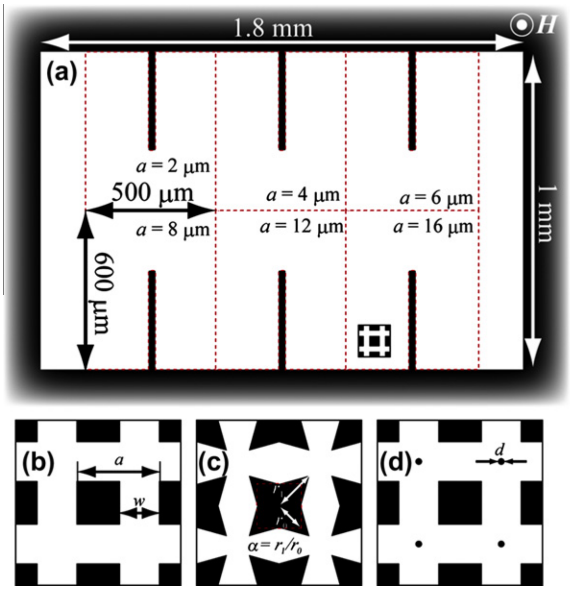

Fig. 1. Schematic drawings of square superconducting network samples. (a) Whole shape of the samples with six slits in order to concentrate magnetic flux. A part of the network with the (b) lattice constant a and the line width w. (c) Definition of the different shape of holes with a parameter of ratio α. (d) A superconducting network with small holes at intersection points.

The penetrated patterns are very similar to earlier studies [3,4], e.g. flux penetration patterns extending along the diagonal direction of the networks appear at lower temperature with the larger a. In Fig. 2b and c, T500-2 and T1000-2 samples show finger like flux penetrations. These are flux avalanches caused by magneto-thermal instabilities [8]. Each column in Fig. 2 shows the thickness dependence of flux penetration patterns at $0.5T_c$ and $0.9T_c$, respectively. Obviously, the pattern does not depend on the thickness. This result contradicts the earlier discussion that the magnetic concentration near vertices of square holes by the demagnetization effect is the possible origin of the diagonal flux penetration patterns [3].

Fig. 3a–f shows MO images of flux penetrations into samples with various hole-shapes. Each column of Fig. 3 shows the α dependence of the flux penetration patterns at $0.5T_c$ and $0.9T_c$, respectively. The diagonal flux penetration pattern becomes dominant with the larger α as seen in MO images of $S\alpha$-6 at $0.5T_c$. Even at temperature close to T_c, only the diagonal flux penetration appears as shown in Fig. 3f with large $\alpha = 1.4$ though only the parallel patterns appear with α less than unity. To discuss the effect of α, two effects have to be considered. First, the sharper edges of square holes with the larger α enlarge the demagnetization effect, which does not affect the penetrated patterns as was discussed in the thickness dependences. Second, the larger α leads to the narrower intersection area of the networks as shown in Fig. 3g and h. Considering the gap between next nearest holes, the gap becomes 40% smaller for $\alpha = 1.41$ than for $\alpha = 1$, which enhances the current density J_d in that area. These results indicate that the current driven flux penetration might have an important role to the diagonal penetrations. Similar result is also reported in the TDGL simulation of flux penetration into superconducting networks [5]. However, we

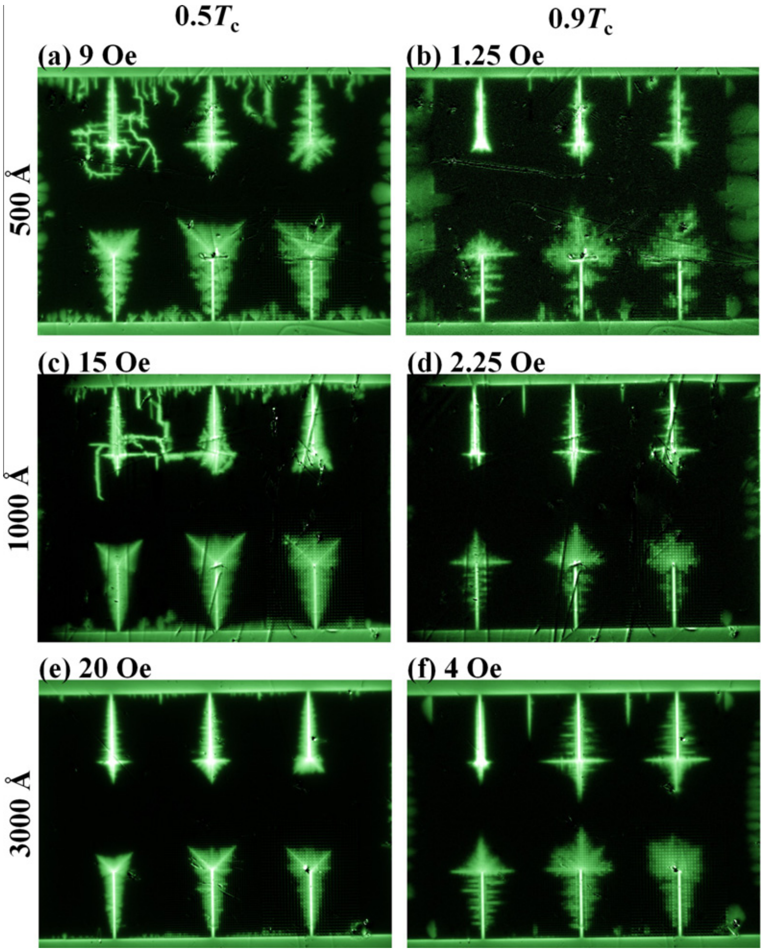

Fig. 2. MO images of flux penetration patterns into the samples with different thickness of (a, b) 500 Å, (c, d) 1000 Å, and (e, f) 3000 Å at $0.5T_c$ and $0.9T_c$, respectively.