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Magnetic moment jumps in flat and nanopatterned Nb thin-walled cylinders

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ABSTRACT

Penetration of magnetic flux into hollow superconducting cylinders is investigated by magnetic moment measurements. The magnetization curves of a flat and a nanopatterned thin-walled superconducting Nb cylinders with a rectangular cross section are reported for the axial field geometry. In the nanopatterned sample, a row of micron-sized antidots (holes) was milled in the film along the cylinder axis. Magnetic moment jumps are observed for both samples at low temperatures for magnetic fields not only above H_{c1}, but also in fields lower than H_{c1}, i. e., in the vortex-free regime. The positions of the jumps are not reproducible and they change from one experiment to another, resembling vortex lattice instabilities usually observed for magnetic fields larger than H_{c1}. At temperatures above $0.66T_c$ and $0.78T_c$ the magnetization curves become smooth for the patterned and the as-prepared sample, respectively. The magnetization curve of a reference flat Nb film in the parallel field geometry does not exhibit jumps in the entire range of accessible temperatures.

1. Introduction

Penetration of magnetic flux into hollow superconducting cylinders is a long-standing field of interest. The Little-Parks effect and the quantization of trapped flux were intensively studied during the last fifty years [1–3]. Recent advances in nanotechnology have allowed for studying experimentally superconducting properties of thin films with different arrays of antidots, see e. g. [4] and references therein. In particular, for the observation of the aforementioned effects, cylinders or antidots of small diameter are required. At the same time, there has been much fewer work on the penetration of magnetic flux into hollow thin-walled cylinders with macroscopic sizes in magnetic fields parallel to its axis. It was expected that quantum phenomena cannot be observed in such samples because of the fact that one flux quanta for cylinders with a cross section area of 1 cm^2 corresponds to a magnetic field value of about 10^{-7} Oe. In this case the magnetization should be a smooth function of the magnetic field. However, experimental results obtained recently for thin-walled macroscopic cylinders do not meet this expectation. Namely, in such Nb cylinders we succeeded in monitoring the magnetic moment of the current circulating in the walls and observed dc magnetic moment jumps even in fields much lower than H_{c1} of the film itself [5].

So far it is not clear what mechanism is responsible for such flux jumps. Under an axial magnetic field the cylinder walls screen weak external fields, provided that $L \equiv Rd/\lambda^2 \gg 1$, where R is the cylinder radius, d is the wall thickness, and λ is the London penetration depth [2,6,7]. Therefore, it is expected, that a dc magnetic field, H, should penetrate into the cylinder as soon as the current in the wall exceeds the critical current and no field penetration should be observed at smaller fields. Only above H_{c1}, vortices created at the outer cylinder surface can move into the cylinder. For a magnetic field oriented perpendicular to the Nb film surface such vortex motion leads to flux jumps [8,9]. These flux jumps were interpreted as a thermomagnetic instability of the critical state. It was demonstrated that in a sample with an array of antidots, a flux jump propagates along the antidots row [10].

Here, we study how antidots affect the penetration of an axial dc magnetic field into thin-walled superconducting Nb cylinders of macroscopic sizes, with a rectangular cross section. A feature of the nanopatterned sample is that the critical current density in the isthmus between antidots is higher than in the film itself.

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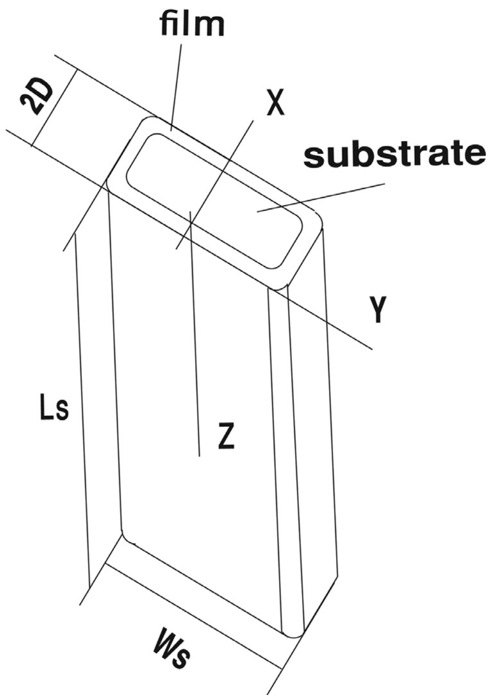

Fig. 1. Sample geometry. Here $L_s = 7.5z$ mm, $W_s = 3$ mm, and $2D = 1.4$ mm are the substrate length, width and thickness, respectively. The magnetic field is parallel to the *Z*-axis. Dimensions are not to scale.

We show that at low enough temperatures for both, a flat and a nanopatterned cylinder, even in the *vortex-free regime* at $H < H_{c1}$, the dc magnetic field penetrates through the cylinder walls in an "*avalanche*"-like fashion. Jumps of the dc magnetic moment also become apparent at fields above H_{c1} at low temperatures. For both samples, the field values at which jumps occur vary from one measurement to another, indicating that one deals with transitions between metastable states. At temperatures above $0.66T_c$ and $0.78T_c$ the magnetization curves become smooth for the patterned and the as-prepared sample, respectively.

2. Experimental

The cylindrical samples were prepared by dc magnetron sputtering of Nb on a rotated sapphire substrate at room temperature. The sizes of the substrate with rounded corners (radius 0.2 mm) are $1.4 \times 3 \times 7.5$ mm^3. We thereby fabricated a thin-walled hollow superconducting cylinder with a rectangular cross section. The nominal film thickness of both samples was $d = 100$ nm. The sample geometry is presented in Fig. 1.

The reference sample A was kept as-grown, while the second one, sample B, was patterned with a row of antidots at the mid of the larger surface over the entire length of the sample. The row of antidots was milled by focused ion beam (FIB) in a scanning electron microscope (FEI, Nova Nanolab 600). The beam parameters were 30 kV/0.5 nA, while the defocus and blur were 560 μm and 3 μm, respectively. The pitch was equal to the antidot center-to-center distance of 1.8 μm and the number of beam passes needed to mill 150 nm-deep antidots was 2000. The antidots row with a length of 7.5 mm was milled by iteratively stitching the processing window with a long size of 400 μm. SEM images of the nanopatterned surface of sample B are shown in Fig. 2. The antidots have an average diameter of 1.5 μm and an average edge-to-edge distance of 300 nm.

The dc magnetic moment was measured using a commercial MPMS5 magnetometer. Temperature and field dependences of the magnetic moment were measured after cooling the sample down to the desired temperatures in zero field (ZFC).

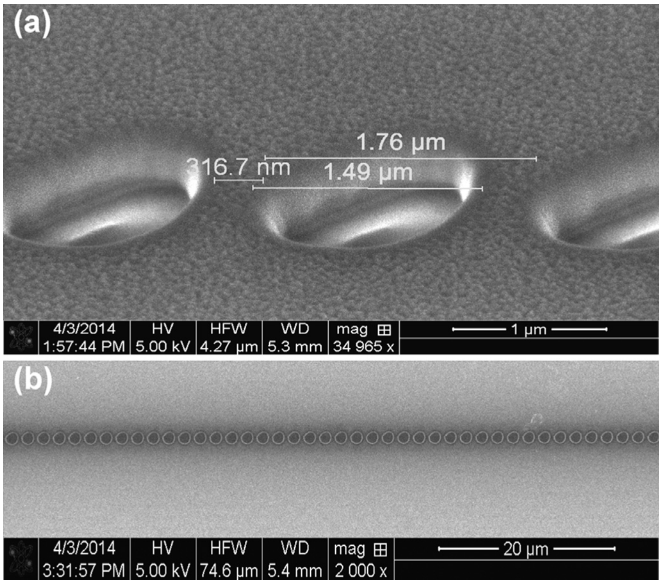

Fig. 2. SEM images of the surface of sample B. (a) The antidots have an average diameter of 1.5 μm and an average edge-to-edge distance of 300 nm. (b) Overview SEM image of the row of FIB-milled antidots.

Fig. 3 displays the temperature dependences of the magnetic moment, *M*, of samples A and B, respectively, in the magnetic field $H = 20 \pm 2$ Oe. The critical temperatures of both samples are nearly the same, $T_c \approx 8.3$ K, the transition width for sample A is 1.3 K and it is 2.7 K for sample B. Sample B demonstrates a two-stage transition, see the inset to the lower panel of Fig. 3. At low temperatures, the magnetic moment of sample A is a factor of two larger than that of sample B.

3. Results

The magnetization curves $M(H)$ for samples A and B at 4.5 K are shown in Fig. 4(a). The magnetization curves in the ascending branch were measured in the hysteresis mode with the 5 Oe step at low fields. The $M(H)$ curves in Fig. 4(a) indicate that the H_{c2} values of samples A and B are different. Determination of H_{c2} for sample B is less accurate than that of sample A, due to the magnetic moment relaxation, which at high fields is larger for sample B [11]. An expanded low-field range of both magnetization curves is shown in Fig. 4(b). The curves demonstrate *saw-tooth-like jumps*. The field values of the first jump, H^*, are about 20 Oe and 10 Oe, while the numbers of jumps in magnetic fields up to 100 Oe are 5 and 7 for samples A and B, respectively. Such jumps of the magnetic moment were observed in a wide range of magnetic fields, *including fields below* H_{c1} for both samples. This behavior is reminiscent of magnetic flux jumps in Nb thin films in magnetic fields directed perpendicular to the film surface [8,9]. Those jumps were interpreted as a thermomagnetic instability of the Abrikosov vortex lattice [8,9]. However, the presence of jumps in fields below H_{c1} for the field-parallel-to-film-surface geometry has been reported in our previous work only recently [5]. A direct determination of H_{c1} for the thin-walled cylindrical samples investigated here is impossible due to magnetic moment jumps at low fields. Though, H_{c1} can be estimated using the magnetization curves of an additional reference flat Nb film, refer to Fig. 5. Accordingly, for the investigated cylinders $H_{c1} \approx 350$ Oe at 4.5 K.

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