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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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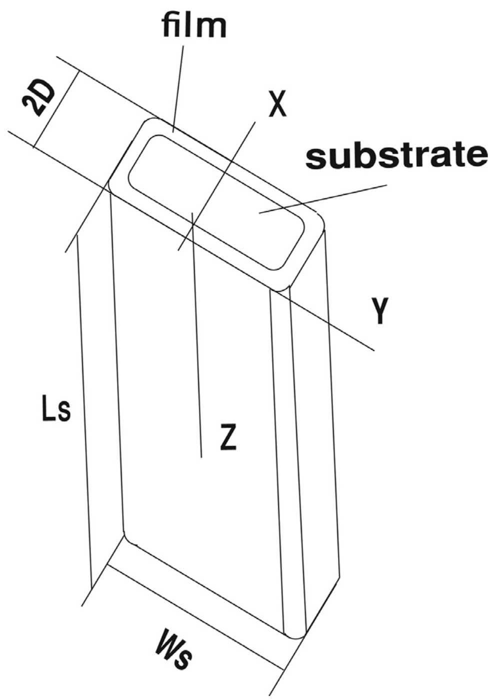

Fig. 1. Sample geometry. Here $L_s = 7.5z$ mm, $W_s = 3$ mm, and $2D = 1.4$ mm are the substrate length, width and thickness, respectively. The magnetic field is parallel to the *Z*-axis. Dimensions are not to scale.

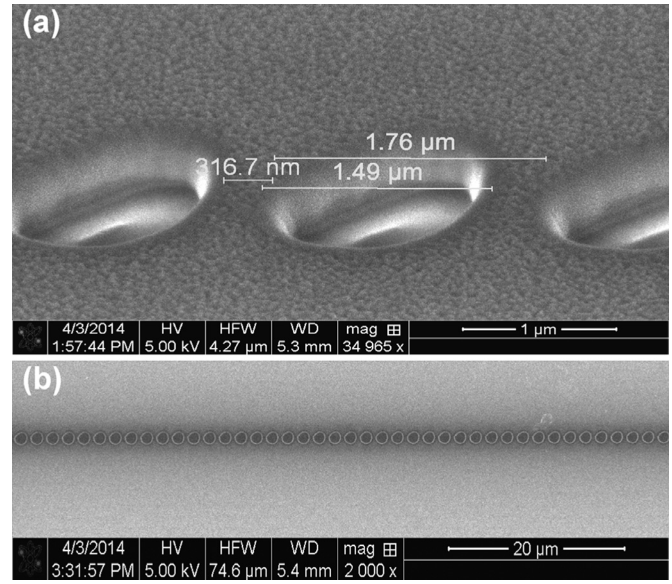

Fig. 2. SEM images of the surface of sample B. (a) The antidots have an average diameter of 1.5 μm and an average edge-to-edge distance of 300 nm. (b) Overview SEM image of the row of FIB-milled antidots.

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. 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.

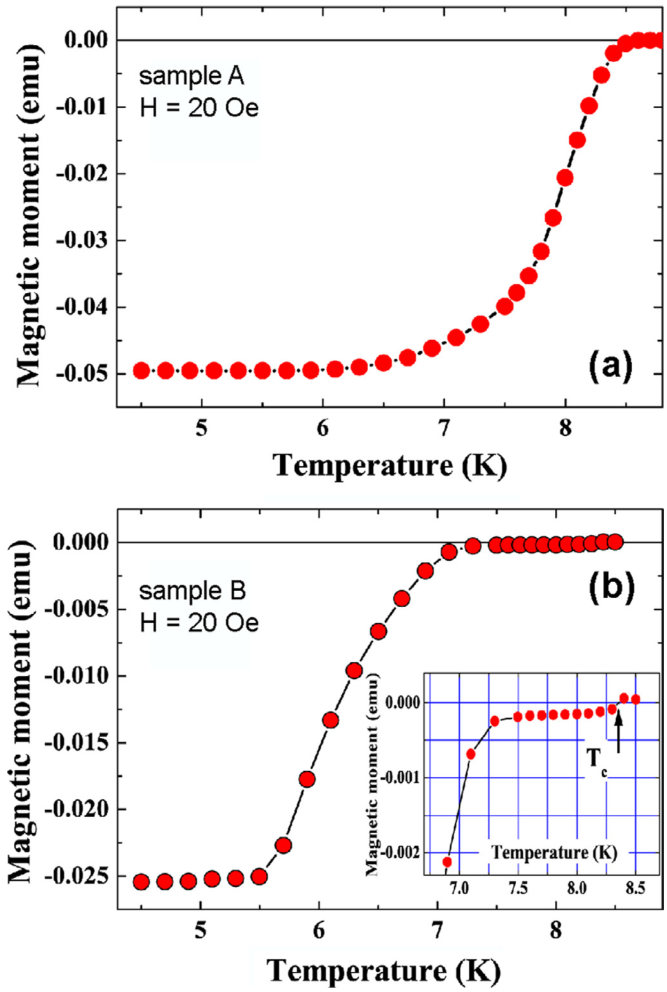

Fig. 3. Temperature dependences of the magnetic moment of samples A (a) and B (b). Inset to the lower panel shows the temperature dependence of M_0 of sample B near T_c.

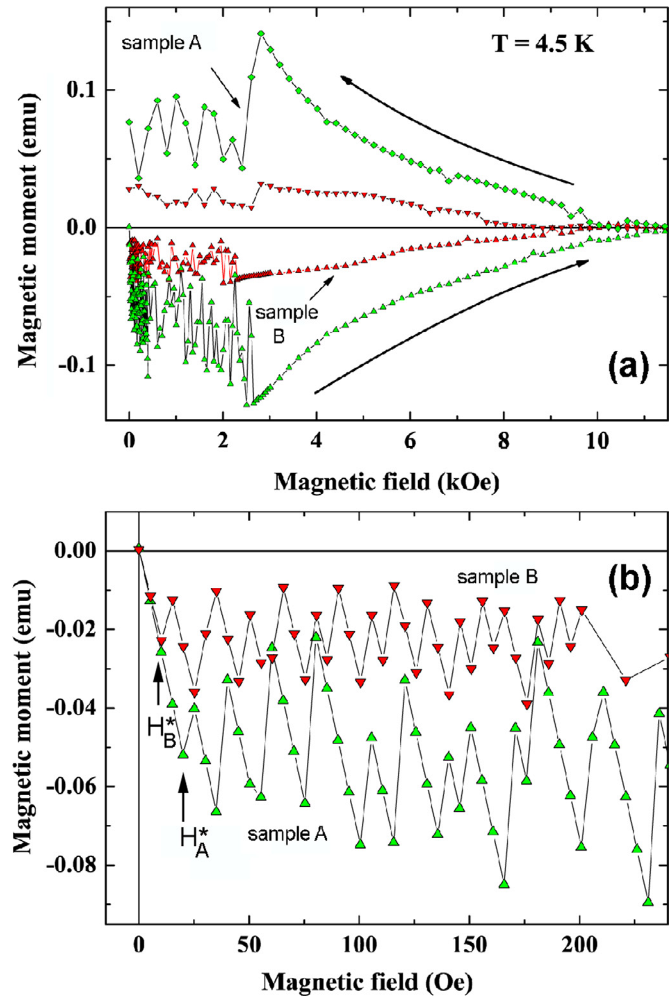

Fig. 4. (a) The dependences $M(H)$ of samples A and B after ZFC. (b) Expanded view of the magnetization curves in the low-field range for samples A and B.

4. Discussion

The physical reasons for the observed flux jumps at small magnetic fields are not clear. One can suggest that the alignment of the magnetic field with respect to the sample surface is not perfect. Indeed, the latter cannot be ruled out completely, and a small field component perpendicular to the surface, $H_\perp$, should create vortices which might be responsible for the flux jumps at small magnetic fields. Hence, one may expect that flux jumps could be present at small magnetic fields in a reference planar film as well. This assumption has been examined in an additional control experiment with a reference planar film. Fig. 5 displays ascending branches of the magnetization curves of the planar Nb film of 240 nm thickness sputtered onto a silicon substrate, for the magnetic field inclination angles $\varphi = 0^\circ,\ 10^\circ$, and 45°. For $\varphi = 10^\circ$ and 45° the component $H_\perp \approx 0.17H$ and $H_\perp \approx 0.71H$, respectively. Vortices created by this field component exist at small magnetic fields. This experiment demonstrates that in small fields the magnetic moment is a linear function of the magnetic field value and vortices created by $H_\perp$ *do not induce any flux jumps* at small fields. The magnetic moment at small fields remains a linear function of the magnetic field for planar films of different thicknesses. Magnetic moment jumps first appear in the magnetization curve at inclination angles larger than 10°. Such a field inclination angle is at least a factor of 3 larger than the orientational misalignment of the sample orientation with respect to the field direction in our experiment. Therefore, the results obtained for planar films suggest that the vortices created by the small field component perpendicular to the surface are not the cause for magnetic moment jumps at small magnetic fields in the cylindrical samples.

The experimental data demonstrate the existence of magnetic instabilities in fields below H_{c1}. At 4.5 K, the flux starts to penetrate into the cylinders A and B at $H = 20$ Oe and 10 Oe, respectively, Fig. 4(b). The field of the first jump, H^*, is defined by some critical current (not to be confused with a depairing current). If we assume that the critical current density in the isthmus between two antidots is the same as in the film, then the ratio H^*_B/H^*_A should be ≈ 0.16. However, the experiment shows that this ratio is about 0.5, see Fig. 4. This means that the critical current density in the isthmuses is higher than in the as-grown film. We note that the ratio of the magnetic moments in ZFC in field 20 Oe for samples B and A amounts to 0.5, see Fig. 3. In accordance with the thermodynamic criterion [5] $H^* \propto \sqrt{d}$. Comparison H^* for sample A and samples from [5] shows that thermodynamics cannot describe these magnetization jumps in samples without antidots.

In Ref. [4] it was demonstrated that at low temperatures and at magnetic fields higher than some critical value, H_{th}, the magnetization curve becomes smooth and H_{th} is sufficiently larger in the sample with an array of antidots. The latter experiments were done with the field perpendicular to the film surface. In our case we deal with one row of antidots and the magnetic field is paral-

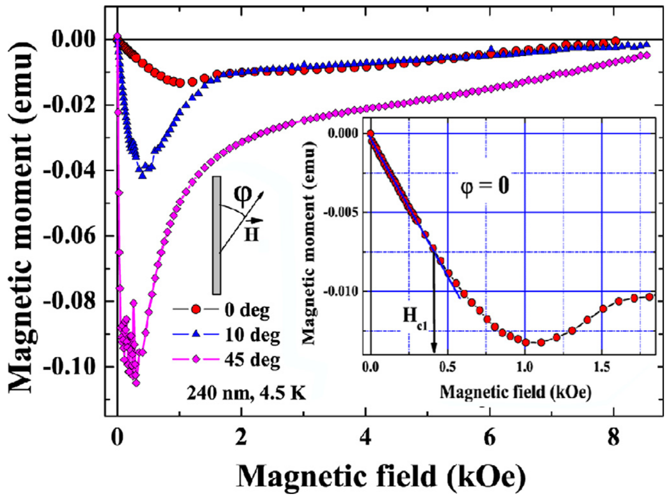

Fig. 5. Ascending branches of the magnetization curves of a planar Nb film in parallel and inclined magnetic fields. Inset: determination of H_{c1} of the planar film.

lel to the film surface. The difference between the perpendicular and parallel geometries is crucial. It, in particular, reflects in that the vortex velocity in the perpendicular geometry is a few orders magnitude larger than that for the parallel one, see Ref. [12]. We therefore believe that this is the main reason why H_{th} is lower for the sample with antidots, see upper panel of Fig. 4.

The theoretical model developed in Ref. [13] predicts that superconducting nanowires with a long mean free pass could exhibit cascades of magnetic moment jumps in the fields parallel to the wire axis. One could expect the proposed model could explain the experimental findings presented in this paper because the film thickness of the walls is rather small. However a mean free pass of electrons in our samples is much shorter than film thickness. The estimation of a mean free pass can be done using following procedure. Correlation lengths of a single crystal Nb [14] and sample A are about 50 nm and 20 nm, respectively. It means that a mean free pass in sample A is $\leq$ 30 nm. And in addition cascades of the magnetic moment jumps were predicted in [13] for magnetic fields well above H_{c1}. So the model proposed in Ref. [13] cannot explain our experimental results.

The effect of the end faces, consisting in that the magnetic force lines are bending near the sample ends could be another reason for the observed flux jumps. The influence of the sample end faces on the flux jumps in such samples remains to be elaborated using a local probe technique.

5. Conclusion

By magnetic moment measurements we have investigated how magnetic flux penetrates into thin-walled cylinders of superconducting Nb with and without a row of antidots. The dc magnetization curves demonstrate an “avalanche”-like penetration of the magnetic flux into both cylinders. The effect is observed at a temperature of 4.5 K and completely disappears at 6.5 and 5.5 K ($0.66T_c$ and $0.78T_c$) for the patterned and the as-prepared sample, respectively. Such a behavior resembles a thermomagnetic instability of vortices, but it is observed in fields below H_{c1} of the Nb films, i. e., in the vortex-free state. The physical reasons for the observed flux jumps at small magnetic fields remain unclear.

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