Unexpected fourfold symmetry in the resistivity of patterned superconductors

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We report the magneto-optical observation of a surprising fourfold symmetry of the flux penetration in a superconducting $YBa_2Cu_3O_{7-\delta}$ thin-film disk containing a square array of antidots, leading to an angular variation of the critical current by a factor of nearly 2. This behavior is explained using a vortex channeling model. Potential applications in superconducting devices are discussed

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If a thin disk of copper or of a superconductor is subjected to a changing perpendicular magnetic field, the screening currents have full rotational symmetry (see Fig. 1). Perforating the copper disk with a fine-meshed square array of holes does not destroy the symmetry of the response (on a scale where the individual holes are invisible). In contrast, we demonstrate in this paper that if a superconducting disk is perforated with the same square array of holes, the current density exhibits quite surprisingly a fourfold symmetry. We demonstrate that the observed behavior can be quantitatively explained by noting that the principle of superposition of current does not hold in a superconductor, which is a nonlinear conductor, and by using a model based on the anisotropic entry of magnetic flux (vortices) into the superconductor.

For the experiments, an antidot array with 2-μm-diam holes on a square 10-μm mesh grid is etched in a 100-nm-thick $YBa_2Cu_3O_{7-\delta}$ film epitaxially grown on a $SrTiO_3$ substrate by pulsed-laser deposition.[1] The antidots are holes, etched into the superconductor and like other artificial defects[2–6] commonly used to reduce dissipation and increase critical currents in superconductors by trapping vortices.

To study the critical current anisotropy, a disk of 2 mm diameter and two 2×2 mm^2 squares were patterned. The edge of one of the squares is parallel to the antidot lattice (denoted "0° square"), and the other is tilted by 45° (denoted "45° square"). All patterning is done by optical lithography and ion beam etching.[7]

For direct observation of resistivity versus polar angle we induce an electric field $\vec{E}$ in the superconductor through Maxwell's law $d\vec{B}/dt=-\vec{\nabla}\times\vec{E}$ by sweeping an external magnetic field at a rate $d\vec{B}/dt$. As a result, at low magnetic fields, a current starts to flow in a narrow band parallel to the edge of the sample. We visualize this current-carrying band through its associated magnetic field using our fast magneto-optical system.[8] This yields directly a 782×582 pixel map of the z component of the local magnetic field, μ_0H_z, at a maximum frame rate of 10 Hz, thus enabling dynamic measurements (the z axis is perpendicular to the plane of the film). Figure 2(a) shows the μ_0H_z map for the disk-shaped sample after cooling in zero field to 4.2 K and subsequent application of 10 mT. To enhance spatial resolution we measure only one-quarter of the disk, shown in color (even at this magnification, the individual antidots are invisible). The current carrying band close to the edge of the disk is shown in blue and green, while the current free inner region is shown in yellow and red. For increasing external field similar patterns are observed [Figs. 2(b)–2(e)]. Clearly, the width of the band varies as a function of polar angle α [as defined in Fig. 2(a)] and displays a fourfold anisotropy. Due to the continuity of *current* (there are no sources or drains in the disk), the *current density* $j(\alpha)$ is inversely proportional to the width $d(\alpha)$ of the band [indicated by the red arrows in Fig. 2(a)]:

$$j(\alpha)/j(0)=d(0)/d(\alpha). \tag{1}$$

Hence also the (normalized) current density displays a clear fourfold anisotropy, as shown in Fig. 3. The anisotropy ratio $R=j_{max}/j_{min}$ is close to 2.

The observed anisotropy in current density is, of course, a consequence of anisotropy of the sample "resistivity." However, this resistivity cannot be represented by the ordinary resistivity tensor $\vec{\vec{\rho}}$, since with suitable choice of the coordinate system, $\vec{\vec{\rho}}$ is diagonal:

$$\vec{\vec{\rho}}=\begin{pmatrix}\rho_{xx} & 0\\ 0 & \rho_{yy}\end{pmatrix}.$$

As a consequence, ordinary anisotropic resistivity can have at most a twofold symmetry, provided $\rho_{xx}\neq\rho_{yy}$. In our experiment, however, $\rho_{xx}=\rho_{yy}$ by symmetry of the square antidot lattice and consequently no anisotropy is expected. Hence the resistivity tensor as used in normal metals cannot describe our anisotropic observation. There is an analogous problem if one would like to describe the macroscopic anisotropy of our sample by the *anisotropic* Ginzburg-Landau (GL) theory, where anisotropy is introduced through a mass tensor with the same symmetry properties as the resistivity tensor (although a numerical approach, using the *isotropic* GL theory and the full geometry of the sample with antidots, should work). Indeed an important review paper[9] states that "the angular dependences of physical quantities in an anisotropic superconductor are given by $\varepsilon(\vartheta)=\varepsilon^2\cos^2\vartheta+\sin^2\vartheta$," thus implying at most twofold anisotropy. In principle, fourfold anisotropy might be induced by the d-wave

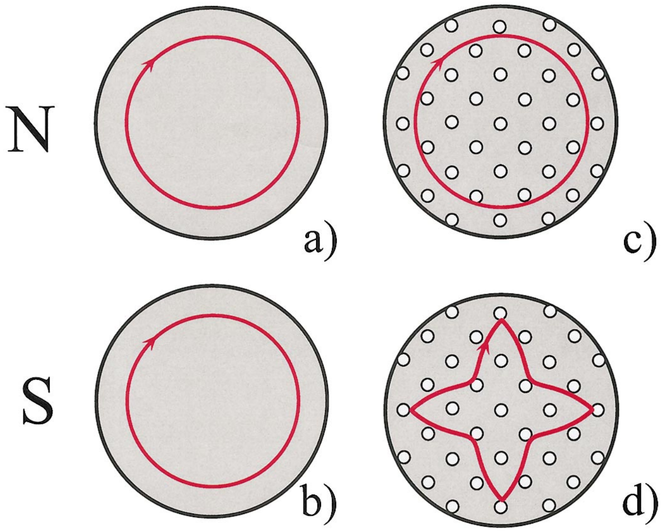

FIG. 1. (Color) Schematic representation of the current flow (red lines) induced by a changing perpendicular magnetic field in a normal conductor (N) and a superconductor (S) thin disk with and without a square array of microholes. In the unperforated normal metal (a) and superconductor (b) the screening currents have, of course, full rotational symmetry. Perforating the normal metal disk with a square array of holes (c) does not modify the symmetry of the response. However, if the superconducting disk is perforated with a square array of holes (d), we find experimentally (see Fig. 2) that the current density displays a surprising fourfold symmetry. Note that the holes are not shown to scale: we consider microholes that are invisible on the scale of macroscopic observation.

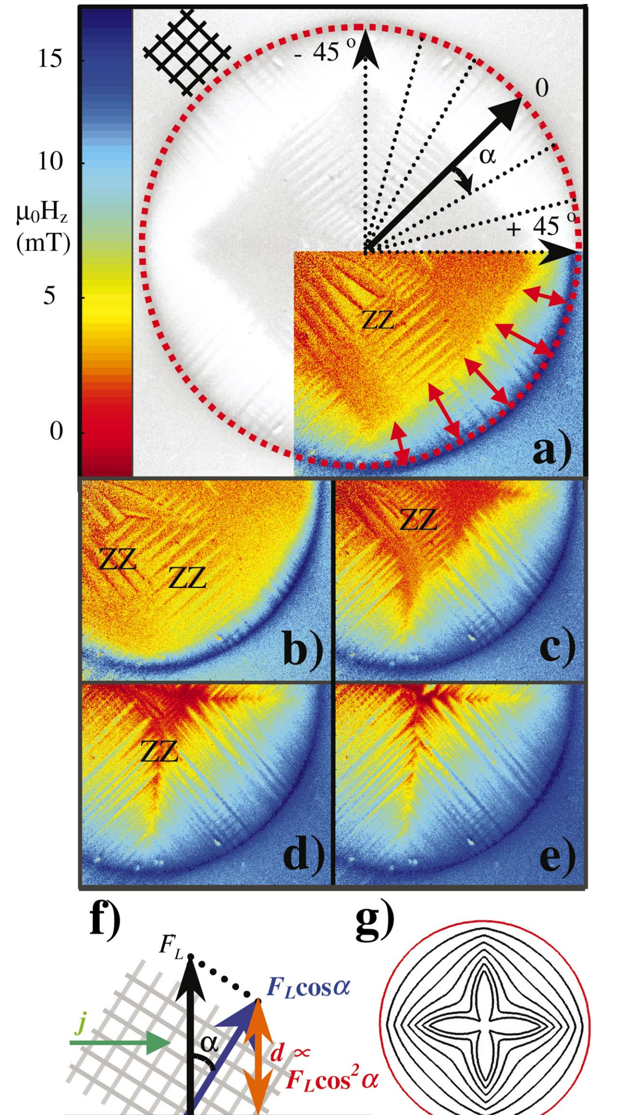

FIG. 2. (Color) Anisotropic penetration of magnetic flux in a thin-film superconductor with antidots. (a) Local magnetic field $\mu_0 H_z$ in a superconducting $YBa_2Cu_3O_{7-\delta}$ thin film patterned in a disk shape (red dotted line), containing a square array of antidots of 2 μm diameter on a 10-μm grid (orientation defined by the inset), as obtained from magneto-optical measurements. The experiment is performed at 4.2 K, after zero-field cooling and application of a field of 10 mT. The measurement corresponds to the colored region. The gray shadowed whole disk is indicated in (a) for clarity of the geometry. (b), (c), (d), and (e) Magneto-optical pictures obtained at 6, 16, 25, and 30 mT. (b)–(e) are scaled for maximum contrast and the color bar of (a) does not apply. In all pictures, zero-field areas are in red and high-field areas in blue. The anisotropy of the current density can be obtained by measuring for various angles the width of the flux penetration [red arrows in (a)]. The zigzag patterns ("ZZ") within the (red and yellow) Meissner area are an artifact due to domains in the garnet indicator and are not relevant. (f) Schematic explanation of the anisotropy in j_c (see text). (g) Flux fronts calculated using Eq. (2), for various $d(0)$ (corresponding to various applied fields). Note the nice agreement with the experimental results of (b)–(e).

nature of high-temperature superconductivity, possible twinning-induced doubling of a twofold anisotropy, Fermi surface anisotropy,[10] and so-called nonlocal effects. However, all these effects are obviously not operative in our epitaxial films as no anisotropy is observed in samples without antidots which are otherwise identical (see also Ref. 11). We conclude that the fourfold anisotropy induced by the square antidot pattern is indeed rather surprising. The reason for the nonapplicability of the resistivity tensor and mass tensor concepts is the highly nonlinear current-voltage characteristic of superconductors. This precludes simple vector addition of currents, which is a necessary condition for the use of such tensors.

A key to a more detailed understanding of the observed fourfold symmetry is the parallel streaks in the current carrying (blue-green) regions, seen clearly, e.g., in Fig. 2(d). These streaks occur because the magnetic field penetrates the superconducting disk as vortices that preferentially move along lines of nearest-neighbor antidots, i.e., along the antidot lattice vectors.[12] In fact, the vortices penetrate in channels parallel to the lattice vector that is closest to the normal to the edge of the sample [$-45° < \alpha < 45°$: see Fig. 2(a)]. This channeling causes the observed anisotropy. Upon increase of the external field, vortices are pushed inwards along the channels by the Lorentz force. Since the Lorentz force F_L is always perpendicular to the edge (the current is always parallel to the edge and the magnetic moment of a vortex is normal to the plane of the superconductor), its component along the channel direction is only $F_L \cos\alpha$ and the resulting penetration distance *along the channel* is proportional to $F_L \cos\alpha$. The *perpendicular* penetration distance d

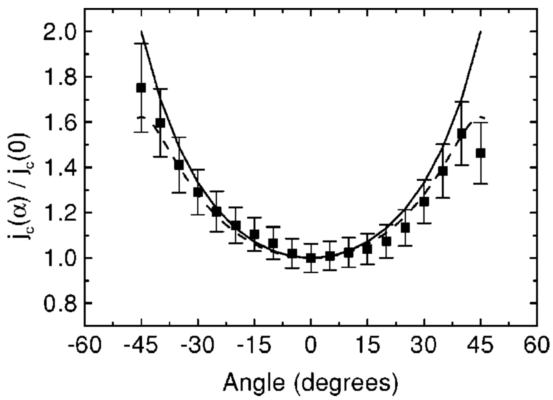

FIG. 3. Angular dependence of the critical current density, normalized at one for $\alpha=0°$. The period of this behavior is 90°. The critical current density ratio is obtained by measuring for various angles the width of the flux penetration. The maximum anisotropy occurs when the driving force makes an angle of 45° with the antidot array. The angular variation can be fitted by $\cos^2\alpha$ (plain line), although the experimental values are somewhat lower for $\alpha=45°$. A fit (see Ref. 13) that takes into account the mutual influence of meeting channels (dashed line) is closer to the experimental data.

is only a fraction $\cos\alpha$ of the penetration distance along the channel [see Fig. 2(f)] and hence

$$d(\alpha)=d(0)\cos^2\alpha. \tag{2}$$

With Eq. (1) we thus find for the current density $j_c(\alpha)=j_c(0)\cos^{-2}(\alpha)$ for $-45°<\alpha<45°$ in good agreement with the observed behavior (solid line in Fig. 3). In Fig. 2(g) flux fronts for various values of the external field, as calculated from Eq. (2), are shown in nice agreement with the flux front shapes in Figs. 2(b)–2(e).

The experimentally obtained values for the anisotropy at large angles ($\alpha\approx 40°-45°$) are found to be slightly smaller than theoretically expected. This may be caused by switching of vortices from one channel to an adjacent parallel one[12] or by the meeting of vortices that penetrate through perpendicularly oriented channels thus influencing each other. A more elaborate model,[13] taking the interaction between perpendicular channels into account, gives the dashed curve in Fig. 3, in agreement with experiment. The effect of meeting channels is expected to be more prominent at higher fields, and indeed we observe a small reduction of anisotropy with increasing field.

Figures 4(a) and 4(b) show the flux penetration in the two square films after cooling in zero field to 4.2 K and subsequent application of 10 mT. In the 0° square the flux penetrates along channels normal to the sample edges. In the 45° square the critical current density is in agreement with the arguments given above, but no channels are observed [see Fig. 3(b)]. Indeed, for $\alpha=45°$ the two inward bound directions at each antidot are equivalent and it is expected that vortices penetrate in a random zigzagging motion. In the circle we see similar behavior for angles $\alpha=45°\pm\Delta\alpha$ with $\Delta\alpha\leqslant 5°$. This *range* of angles arises, because at each antidot, the choice between the, say, $+45°+\Delta\alpha$ and $-45°+\Delta\alpha$ directions is given by the effect of Lorentz force plus random static (due to crystallographic defects in the superconductor) or dynamic (due to thermal fluctuations) noise. For small $\Delta\alpha$ the difference in Lorentz force between the two directions is so small that the choice is dominated by random noise; for large $\Delta\alpha$ the difference in Lorentz force between the two directions is so large that the process becomes deterministic and channeling occurs.

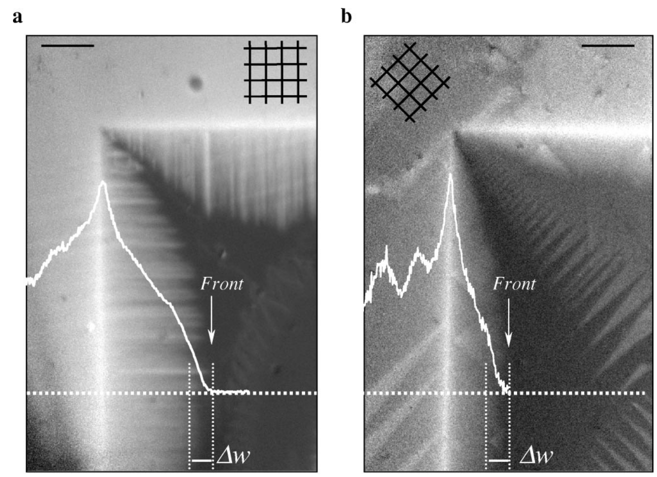

FIG. 4. Magneto-optical images of the flux penetration in two square samples patterned on the same substrate, and containing an array of antidots parallel to its edge (a) or at 45° (b). The direction of the antidot array is given by the black schematic (not on scale) at the top right (a) and left (b) corner. The scale bar corresponds to 200 μm. Pictures are taken at 4.2 K, for an applied field of +10 mT, after zero-field cooling of the sample. Field profiles at the position of the dashed line are indicated by plain white lines. The penetration along channels is clearly visible on the square in (a), while in (b), no channels are visible. The penetration distance is larger in (a) than in (b), which confirms the results of the disk (Fig. 2). Note that over a certain width of the front (indicated by Δw), the slopes in the profiles are almost equal. In this region, the antidots are not yet filled, and the anisotropy is reduced. The zigzags in the dark area (Meissner zone) are an artifact due to in-plane magnetization domains in the magneto-optical indicator.

Note in Figs. 4(a) and 4(b) that in the region close to the flux front (indicated by Δw), the antidots are only partially filled and the effect of the antidots on the flux density profile (the slope in the overlay graph) and hence the critical current is strongly reduced. This also contributes to a lowerering of the maximum anisotropy ratio.

Antidots were previously used[14,15] to reduce the noise in high-T_c superconducting quantum interference devices (SQUID's). We propose to exploit the anisotropy found in the present work to further decrease the noise by guiding vortices away from the sensitive area in a more effective manner. Another potential application is current modulation in a superconducting transistor, which is simply a square array of antidots with a modulating current running perpendicular to the main current.

In conclusion, we have shown that superconducting disks containing a square array of antidots exhibit a large anisotropy of the critical current density with fourfold symmetry. This occurs because linear superposition of current does not apply in superconductors. The observed anisotropy can be explained, however, using a simple vortex channeling model.

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[1] B. Dam *et al.*, Appl. Phys. Lett. **65**, 1581 (1994).
[2] D. Bourgault *et al.*, Phys. Rev. B **39**, 6549 (1989).
[3] L. Civale *et al.*, Phys. Rev. Lett. **67**, 648 (1991).
[4] M. J. Van Bael *et al.*, Phys. Rev. Lett. **86**, 155 (2001).
[5] A. F. Hebard *et al.*, IEEE Trans. Magn. **MAG-13**, 589 (1977).
[6] P. Selders *et al.*, Appl. Supercond. **5**, 269 (1997).
[7] J. Schneider *et al.*, Appl. Phys. Lett. **63**, 2426 (1993).
[8] R. J. Wijngaarden *et al.*, Rev. Sci. Instrum. **72**, 2661 (2001).
[9] G. Blatter *et al.*, Rev. Mod. Phys. **66**, 1125 (1994).
[10] P. C. Hohenberg and N. R. Werthamer, Phys. Rev. **153**, 493 (1967).
[11] Ch. Jooss *et al.*, Physica C **299**, 215 (1998).
[12] R. Surdeanu *et al.*, Europhys. Lett. **54**, 682 (2001).
[13] The fourfold symmetry of j_c can be mathematically modeled, in analogy with electronic bands for an electron in a weak periodic potential, by $j=j_m\cos^{-2}\phi$ and $j=j_m\cos^{-2}(\pi/2-\phi)$, assuming an interaction V between the 90°-shifted currents. The lowest "current band" of the interacting channel system is given by $j=[(\cos^{-2}\alpha+\sin^{-2}\alpha)-\sqrt{(\cos^{-2}\alpha-\sin^{-2}\alpha)^2+4V^2}]/2$. The parameter V is only important near 45°, when there is competition between the two "bands."
[14] P. Selders *et al.*, IEEE Trans. Appl. Supercond. **9**, 2967 (1999).
[15] R. Wördenweber *et al.*, Physica C **332**, 27 (2000).