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Scanning Hall probe microscopy of vortex patterns in superconducting micro-squares

K. De Keyser *, R.B.G. Kramer, T. Nishio, V.V. Moshchalkov

INPAC – Institute for Nanoscale Physics and Chemistry, Nanoscale Superconductivity and Magnetism Group, K.U.Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

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Abstract

Vortices confined to micro-sized thin superconducting Pb squares are visualized using scanning Hall probe microscopy (SHPM). High resolution images are obtained after field cooling to 4.2 K for different magnetic fields using a standard AC-method for the Hall voltage readout. Vortex configurations for vorticity 1, 2 and 3 are observed and compared with theoretical predictions for the vortex patterns.

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In the mixed state of type-II superconductors, the lowest energy state in bulk materials and films is a triangular configuration of the vortices, called the Abrikosov lattice [1]. When nanofabrication has started to be commonly used in research and technology, the question was addressed of what would happen with the Abrikosov lattice if the sizes of the superconductor become comparable with the penetration depth or the coherence length. Superconductors of this length scale are called mesoscopic superconductors. During the first experiments on mesoscopic superconductors, the H–T phase boundary was measured in squares and square rings [2]. The phase boundary was explained in terms of giant vortex states. Chibotaru et al. [3] calculated the H–T phase boundary for an infinitely thin mesoscopic square using the linearized Ginzburg–Landau equations and showed that antivortices are formed to preserve the symmetry of the mesoscopic sample. The creation of vortex–antivortex pairs was also predicted in vortex patterns close to the critical temperature T_c for a triangle [4] and for a disk, triangle and square of finite thickness [5]. The calculated symmetry-induced vortex configurations were evidenced by transport measurements on a mesoscopic triangle [6] and perforated disks [7] and by Hall magnetometry measurements [9,8]. Recently, vortex patterns have been observed in mesoscopic disks with the Bitter decoration technique [10].

In this paper, we will focus on the direct observation of vortex patterns in superconducting mesoscopic squares at low temperature using scanning Hall probe microscopy (SHPM). The technique, intensively used to visualize flux structures of high T_c superconductors in the past [11], allows to visualize the evolution of the flux patterns as function of temperature. Chibotaru et al. [12] predicted recently the complete phase diagram of a mesoscopic superconducting square by Monte Carlo calculations using the full Ginzburg–Landau equations. Close to the phase boundary of this phase diagram, all vortex configurations have four-fold symmetry, as a consequence of the symmetry of the sample. However, deeper in the superconducting state, the influence of the sample boundaries diminishes. This leads to a phase transition at a given temperature between the symmetry-induced and the broken-symmetry phase for certain vorticities, e.g., instead of a giant vortex

* Corresponding author.
E-mail address: katrien.dekeyser@fys.kuleuven.be (K. De Keyser).

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with vorticity $L = 2$ two individual vortices appear on one of the diagonals of the square upon temperature decrease.

For the experiments, a commercial microscope from Nanomagnetics Instruments is used. The setup is based on the microscope developed in Ref. [13] where a GaAs/AlGaAs Hall probe with an integrated STM tip is placed on a piezo scanner. Fig. 1a shows a typical Hall probe. The two dimensional electron gas of the Hall probe has a sensitivity of $S_I = 0.132\ \Omega/\mathrm{G}$ and the size of the Hall cross is 800 nm. The STM tip is situated approximately in a distance of 15 μm from the Hall cross. Due to the tip, it is possible to control the distance between the Hall probe and the sample by measuring the tunnel current between the tip and the conducting sample surface. The piezo scanner has a scan range of $150 \times 150\ \mu\mathrm{m}^2$ at 300 K and $18 \times 18\ \mu\mathrm{m}^2$ at 4.2 K. A coarse approach system based on a slip-stick piezo motor allows to approach the sample to the Hall probe. The typical distance between the two dimensional electron gas of the Hall probe and the surface of the sample is 850 nm.

To obtain high resolution images the noise in Hall voltage reading is reduced by replacing the DC readout of the commercial SHPM setup by a phase sensitive lock-in amplifier technique. An AC current of 15 μA amplitude and a frequency of 5877 Hz is applied to the Hall cross. The lock-in time constant is set to 10 ms for scanning.

The investigated sample consists of a periodic array of Pb squares of $4 \times 4\ \mu\mathrm{m}^2$ size. The thickness of the Pb film is 50 nm. T_c of the lead is 7.2 K. After cooling down to 4.2 K, a small magnetic field is applied perpendicular to the plane of the Pb squares. An array of dark square-shaped dots is observed in Fig. 2. In this conditions the squares are in the Meissner state and expel the magnetic field which leads to the dark contrast of the squares. The dots indicate therefore the positions where the Pb squares are situated.

To obtain the vortex state in the superconducting square, the sample is field cooled at different magnetic fields. After field cooling at $H_a = 5$ G a first vortex appears at a corner of the square (Fig. 3a). We would expect the appearance of the first vortex in the center of the micro-square [12]. However, we observe for different squares of

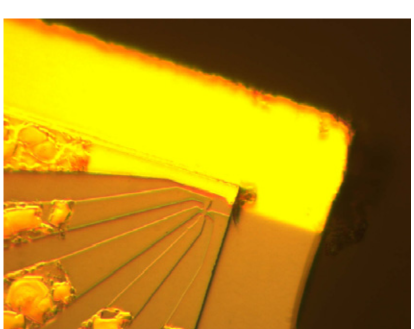

Fig. 1. Eight hundred nanometers sized Hall probe with gold STM electrode. The Hall cross and the STM tip are visible in the center of the image. The distance between the STM tip and the Hall cross is ~15 μm.

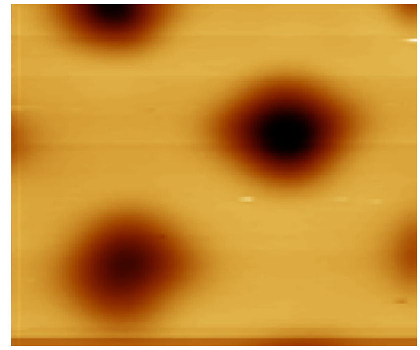

Fig. 2. Scanning Hall probe image showing the superconducting squares (dark) in the Meissner state at 4.2 K. The orientation of the squares is clearly visible. The image size is $18 \times 18\ \mu\mathrm{m}^2$.

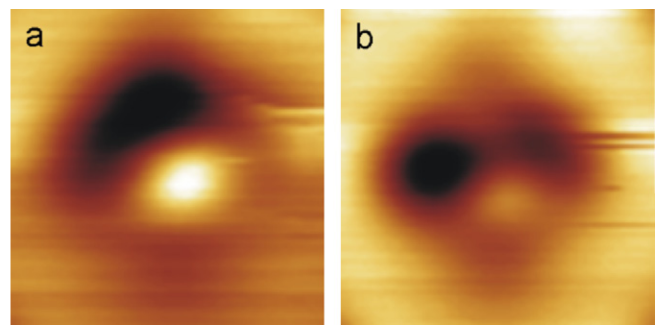

Fig. 3. (a) Image after field cooling at 5 G. One vortex appears in the square. (b) Image after field cooling at 7 G. Two vortices are situated on opposite corners of the square. Both images are obtained at 4.2 K and their size is $9 \times 9\ \mu\mathrm{m}^2$.

this sample that the first vortex appears in a corner. Vortex pinning effects can be an explanation for this observation. During the cool down to 4.2 K pinning centers localize the vortices that were moving in the superconductor. The pinning potential of lead is, however, small in comparison to other superconducting materials. Pinning can be caused also by surface roughness or impurities in the lead.

After field cooling at $H_a = 7$ G a second vortex has entered the micro-square (Fig. 3b). The vortices appear at opposite corners of the square which coincides with the predicted vortex pattern. At 4.2 K the sample is deep in the superconducting state and the influence of the boundaries of the sample is small. In consequence, two individual vortices are expected in the sample instead of one giant vortex.

We tried to reproduce these measurements on a second sample. Here, strong gating influenced the scan image. Gating is the effect of electrical fields on the two dimensional electron gas leading to Hall voltage changes due to, e.g. surface charges. We see a square-shaped spot at the position of the Pb square even when field cooling at zero field. However, an evolution of the images is observed after field cooling at $H_a = 6$ G and switching off the field. A bright spot appears at the corner of the square-shaped structure which indicates a vortex. The magnetic field can be switched off after field cooling as the vortices remain

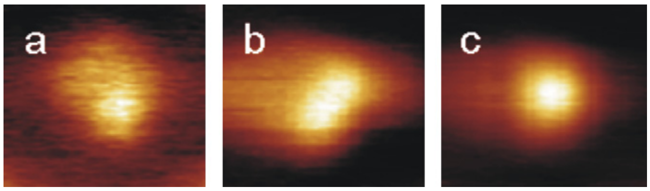

Fig. 4. (a) Image at 6 G. One vortex is trapped in the square. (b) Image at 12 G. Two vortices are situated on neighboring corners of the square. (c) Image at 20 G. All images are obtained after field cooling to 4.2 K and switching off the applied field. Image size is $9 \times 9\ \mu m^2$.

trapped due to natural pinning centers in the Pb square. A remanent vortex state with nonzero magnetization is created. After increasing the field cooling to $H_a = 10$ G the circular spot becomes rectangular which might indicate a second vortex (Fig. 4b). Here, both vortices are found in neighboring corners.

Increasing the field cooling increases the contrast of Fig. 4b but the rectangular spot remains unchanged. However, at $H_a = 20$ G the image evolves again to a circular spot centered in the middle of the square (Fig. 4c). This might indicate the vortex pattern of four vortices with one antivortex in the middle [12]. Vortices are attracted to the antivortex and the distance between them becomes small. However, deep in the superconducting phase, at 4.2 K, the influence of the symmetry is small and tree vortices with $L = 1$ should appear in the micro-square.

The observed vortex patterns differ in both samples. This is probably due to different distribution of pinning sides in the squares. In principle, the actual T_c could vary between both samples which could affect the vortex configuration. However, we never measured changes of T_c of more than 0.2 K in our samples. Since the images are taken well below T_c at 4.2 K, the influence of a slight T_c variation on the vortex pattern is negligible.

The vortices in Fig. 4b and c could not be resolved independently. The spatial resolution of the setup is not high enough. To gain higher spatial resolution the distance between the sample and the Hall probe needs to be further reduced and smaller Hall probes must be used.

In conclusion, the flux at the surface of mesoscopic Pb squares was measured locally using a scanning Hall probe microscope. Individual vortices have been observed in a $4 \times 4\ \mu m^2$ square. The first vortex appeared in a corner of the square instead of in the center like theoretical predicted. The second vortex is found in the opposite corner in agreement with theory. In another sample slightly different behavior is found with two vortices in neighboring corners. Natural pinning effects may explain this observations.

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