A new approach for tracking the footsteps of quantum flux motion in superconductors

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Local polarization of a magnetic material has become a well-known and widely used method for storing information. Numerous applications in our daily life such as credit cards, computer hard drives, and the popular magnetic drawing board toy, rely on this principle. In this work, we present compelling experimental evidence that this principle can be applied for imprinting in a magnetic layer the trajectory of superconducting vortices, submicroscopic units of quantized magnetic flux. We were able to record the flux distributions into the permalloy layer at cryogenic temperatures and observe them *ex situ* at room temperature, well above the critical temperature of the superconducting state. The undeniable appeal of the proposed technique lies in its simplicity and the possibility to improve the spatial resolution, possibly down to the single vortex scale.

Introduction

Superconductors are materials exhibiting interesting properties when cooled down to low temperatures. Remarkably, their resistance is zero, meaning they can carry an electrical current without energy losses. Moreover, when immersed in a magnetic field, screening currents flow in the material to keep its bulk completely flux-free. These striking phenomena are exploited in multiple applications, namely in levitating trains, or in the powerful magnets used in medical imaging equipment or particle accelerators.

Unfortunately, the perfect conductivity and perfect diamagnetism regimes exist only under particular conditions, putting limits on the maximum current, magnetic field and temperature the material can sustain. In the so-called type-II superconductors, used in most applications, magnetic flux lines enter the material when the magnetic field is strong enough and form vortices, submicron bunches of flux lines where the magnetic flux is quantized. These vortices move under the action of an electrical current, which in turn causes dissipation in the non-superconducting vortex cores. It is thus easy to see why vortex motion strongly limits the development of applications based on current transport. The ultimate performance of superconducting systems with technological interest are ruled by the displacement of these tiny magnetic flux sources and hence, being able to track their trajectories is of high interest. In this article, we describe a new promising technique, that may be improved to potentially reach single vortex resolution, to image *ex-situ* the magnetic flux landscape in superconductors.

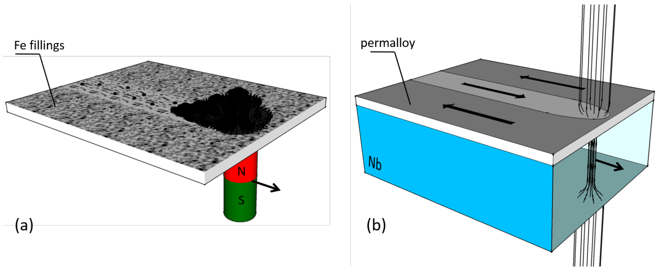

Figure 1: *(a) A magnet moving under a plate covered with iron fillings attracts the magnetic particles and leaves a trail marking its trajectory. (b) A similar principle is used in our experiments, where a vortex moving in a superconductor (Nb here) flips the polarization of a magnetic layer (permalloy) placed on top of it.*

Imprinting magnetic fields

A widespread method to store information, currently used in hard drives and credit cards, consists in polarizing locally a magnetic material. In practice, it relies on two basic ingredients: a localized source of magnetic field and a ferromagnetic material with finite remnant moment. In the magnetic drawing board toy, very popular with children, the magnetic tip of the pencil produces a magnetic field that attracts the magnetic particles in the board, leaving a black trail where the tip has passed. Another common example is represented in Fig. 1(a): a magnet moving in the vicinity of a plate covered with iron fillings attracts the magnetic particles and leaves a trail, clearly marking its trajectory. Our idea is to extend the principle presented in Fig. 1(a) to the microscopic scale, since vortices in type-II superconducting materials can be regarded as sources of magnetic field, confined at the submicron scale. By depositing a magnetic layer (NiFe, also called permalloy, Py) on top of a superconductor (Nb), we have exploited the possibility to use the quantum flux units as tiny magnetic scribers, leaving a trail of polarized magnetic material along their trajectories. This situation is represented in Fig. 1(b). The magnetic layer is polarized in-plane in a given direction, and the in-plane field of a vortex, moving in opposite direction, is able to flip the polarization of the permalloy, thus leaving a trail along its path.

Experimental results

The sample is represented in Fig. 2(a) and consists of a 2×2 mm^2 140 nm-thick Nb film with a critical temperature of 9 K, topped by a polygonal 50 nm-thick Py layer, having intrinsic in-plane magnetization. The two layers are electrically insulated from each other by a 5 nm-thick silicon oxide layer. The sample is mounted in a He closed-cycle cryostat. The magnetic field distribution is mapped using the magneto-optical (MO) imaging technique, based on the Faraday effect, providing us with images where the intensity is proportional to the out-of-plane local magnetic field.

Fig. 2(b) shows an MO image of the sample at 10 K, thus above the critical temperature of the superconductor. The magnetization of the permalloy is defined along the vertical direction and the stray field of the magnetic layer is clearly visible as white/blue (positive field) and red (negative field) stripes.

We subsequently cool the sample to 4 K and we apply an out-of-plane magnetic field $H =$ 4.8 mT. In this regime, vortices enter the superconductor very abruptly and form flux avalanches, whose origin is similar to actual snow avalanches: flux accumulates at the border of the sample, until it abruptly enters the material, releasing a significant amount of heat in the process. Flux avalanches are visible in Fig. 2(c) as finger-like structures, starting at

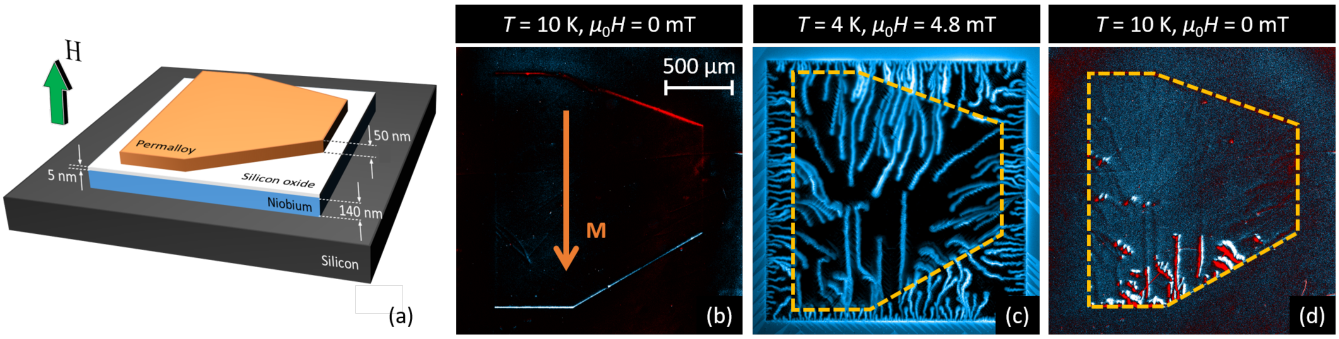

Figure 2: *: (a) Layout of the superconductor (Nb)-ferromagnet (Py) structure. (b) Magneto-optical image of the out-of-plane stray field of the magnetic layer, with in-plane magnetization indicated by the orange arrow. White/blue areas (red) correspond to positive (negative) out-of-plane magnetic field. (c) Magnetic flux distribution in the superconducting state, in the so-called flux avalanche regime. (d) Flux avalanches observed in (c) leave clear imprints in the magnetic layer,that are stable up to room temperature.*

the border of the Nb film. Fig. 2(d) shows an image of the sample obtained by starting from the state in Fig. 2(c), warming up to 10 K and setting $H = 0$ mT. It presents compelling experimental evidence that we were able to imprint the trajectories of flux avalanches in the magnetic layer, by flipping locally the orientation of the in-plane magnetization. Indeed, the printings show very good correspondence with the actual avalanches of Fig. 2(c). However, the printing mostly occurs on the side of the sample where the flux enters in the direction opposed to the magnetization of the permalloy layer. The reason is that flipping of the polarization takes place only if the in-plane component of the vortex field is in the opposite direction.

Interestingly, the flux distributions we recorded at cryogenic temperatures could still be observed *ex situ* at room temperature, well above the critical temperature of the superconducting state. Notice that other techniques having higher spatial resolution than magneto-optical imaging, such as magnetic force microscopy or scanning Hall probe microscopy, could be subsequently used to image the avalanche printings in the magnetic layer, something difficult to realise directly on the superconductor alone, since the signal is lost above the transition temperature. The undeniable appeal of the proposed technique lies in its simplicity and the possibility to explore superconductors with high critical temperatures. This work might therefore trigger further experimental and theoretical pursuit to discover new magnetic compounds optimizing the resolution of the technique down to single vortex imprints.

References

[Brisbois et al., 2016] Brisbois, J. et al. (2016). Imprinting superconducting vortex footsteps in a magnetic layer. *Scientific Reports*, 6:27159.