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Self-healing patterns in ferromagnetic-superconducting hybrids

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Abstract

We study magnetic flux dynamic effects in a superconducting (SC) bridge with thin soft magnetic stripes placed either on top or under the bridge. Voltage–current (VI) measurements reveal that the edges of magnetic stripes oriented transvers or along the bridge introduce channels or barriers for vortex motion, resulting in the decrease or increase of the critical current, respectively. We propose a self-healing mechanism for the hybrid with longitudinal stripes whereby the magnetic pinning strength increases with current. The self-field of the current polarizes the magnetic stripes across their length, which enhances the stray fields at their long edges and creates a dynamic vortex pinning landscape to impede vortex flow. We show a qualitative confirmation of the proposed mechanism which offers new strategies to engineer adaptive pinning topologies in SC–ferromagnetic hybrids.

Keywords: magnetic pinning, magnetic-superconducting hybrid, self-healing pattern

(Some figures may appear in colour only in the online journal)

1. Introduction

The efficient mitigation of highly dissipative vortex motion is a major scientific and technological challenge crucial for the wide application of superconducting (SC) materials for power transmission, energy generation and storage, transportation, electronics, medical diagnostic devices, and other cryogenic technologies [1–5]. A conventional approach for arresting vortex motion is the introduction of various structural defects, which would pin the normal core of the magnetic vortices and determine the maximum loss-free current in the superconductor. Although this method is highly effective at low temperatures (T), with increasing T , the core pinning of the vortices vanishes due to the divergence of the vortex core with temperature and reduction of the condensation energy responsible for the pinning potential. This problem is especially magnified in high temperature superconductors where the ubiquitous vortex liquid state occupies a large portion of the field-temperature phase diagram. Hence it is not a surprise that a large number of recent experimental and theoretical studies addressed the possibility of using magnetic pinning to directly couple the vortex flux quanta (Φ_0) to magnetic inhomogeneities (see reviews [6–10]). The

main idea is to make hybrid SC and ferromagnetic (FM) materials where SC vortices can interact directly with FM magnetization ($\mathbf{M}$) or with the stray fields of the FM elements. In both cases the interaction energy is proportional to $-\mathbf{M}\Phi_0$ [11–13] which is virtually temperature independent due to the very slow variation of $M(T)$ below the SC transition temperature (T_c). Several experiments using arrays of magnetic dots or magnetic layers with lattice of holes deposited on top or under a SC film confirmed that FM arrays substantially suppress vortex motion close to T_c (see references in [6–10]). Also, it was reported that vortex pinning by magnetic domain walls (DWs) can be a natural factor for increasing transport currents in continuous FM/SC multilayers [11, 14–23]. At the same time, it was shown that the stray fields of the domains and those created by the magnetic patterns can suppress superconductivity and form channels for vortex flow reducing critical currents ([6–10] and references therein). Manipulating such channels by external magnetic fields can be used to engineer asymmetric diode-like VI curves and SC switch behavior [24–32].

In this work we propose a magnetic pattern, which can enable new adaptive response of the FM/SC hybrid system to an applied current. The pattern leads to a remarkable

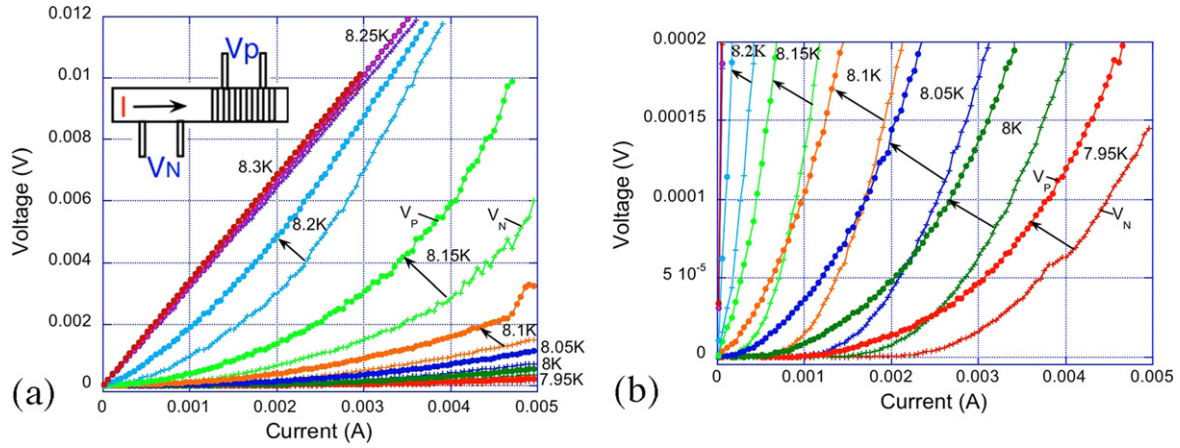


Figure 1. (a) VI curves in segments without (V_N , small crosses) and with (V_P , solid dots) Py stripes on top of the Nb bridge at various temperatures below $T_c = 8.31$ K. (b) Expanded region at low voltages (note the large difference in V -scales). VI s in the bare Nb segment are always lower as shown by arrows connecting curves measured at the same T .

enhancement of the critical current, which we associate with a self-healing effect when vortex pinning increases upon increasing the current in the superconductor.

2. Samples

The samples were $100\ \mu\text{m}$ wide and $1\ \text{mm}$ long bridges of $100\ \text{nm}$ thick Nb film containing segments with lithographically deposited $9\ \mu\text{m}$ wide magnetic stripes of $75\ \text{nm}$ thick permalloy. Optical laser lithography followed by the lift-off process was used for manufacturing the Nb bridge with contact pads while e-beam lithography was used for defining the Py stripe pattern. The stripes were separated by $\sim 1\ \mu\text{m}$ gaps and oriented either parallel or perpendicular to the long axis of the bridge over a length of $300\ \mu\text{m}$. They were placed either underneath or on top of the Nb film and electrically insulated from the Nb with a $20\ \text{nm}$ SiO_2 film to avoid the proximity effect and to mitigate any current sharing that may result in voltage peaks near T_c [33]. A half section of each bridge was bare Nb film left as a reference. Dc and ac magnetron sputtering was used for deposition of the metal films and SiO_2 respectively. The bridges were fabricated with two pairs of voltage contacts, each spaced $200\ \mu\text{m}$ apart for simultaneous measurements of VI s in the bare Nb segment (V_N) and in the segments with Py stripes (V_P) (see inset to figure 1(a)). This allowed us to compare voltages in both the patterned and unpatterned segments under identical conditions to directly reveal the effect of the Py patterns. The resistivity curves of the samples showed sharp SC transitions ($\Delta T \sim 0.1\ \text{K}$) with slightly different values of T_c around $8.3\ \text{K}$. To elucidate variations of the magnetic pinning potential in the self-field of the current, we imaged the magnetic structure of the Py stripes in an applied in-plane field with magnetic force microscopy (MFM). The images prove that in soft magnetic stripe magnetic moments are easily tilted towards the in-plane field and increase the diverging stray fields at the stripe edges, which can effectively pin vortices. Using MFM scans in the presence of relatively small current in the SC

bridge at $T < T_c$ we obtained qualitative confirmation of the proposed magnetic pinning scenario.

3. Experimental results

3.1. Perpendicular Py stripes

We first discuss the results for samples with *Py stripes deposited on top* of the SC Nb film. Figure 1 shows VI curves obtained at different temperatures below T_c in the Nb bridge with perpendicular Py stripes. At lower temperatures, the VI data display a clear curvature due to nonlinear vortex motion. Upon increasing the temperature, the curvature decreases and in the close vicinity of T_c , VI s acquire a linear shape (normal resistance). For all temperatures below T_c , the VI curves of the segment containing Py stripes lie above those of the bare Nb film segment, indicating a lower critical current. The relative difference between VI curves in the segment with Py stripes and bare Nb segment is largest at lower T . In fact, the critical currents at $T < 8.05\ \text{K}$, obtained using a $1\ \mu\text{V}$ criterion, are a factor of two smaller in segments with perpendicular Py stripes (figure 1(b)). The effect disappears very close to T_c when in the nearly normal state the curves from the patterned and bare segments coincide.

A much stronger effect is revealed when *Nb is deposited on top* of the perpendicular Py stripes (see figure 2). The overall tendency remains the same, i.e. the VI curves in the segment with perpendicular Py stripes are shifted to lower currents. However, the increase of voltage V_P compared to V_N in the segment without Py for the same value of current and temperature is much larger. In addition, the VI curves in the bare Nb segment display a kink followed by a much slower rise at larger current. We attribute this reduction of the VI slope in the bare Nb segment to the inhomogeneous transition of the neighboring segment with Py stripes into highly resistive state. This results in a redistribution of currents and potentials across the bridge causing a local increase of potential on the electrode closest to the patterned segment so

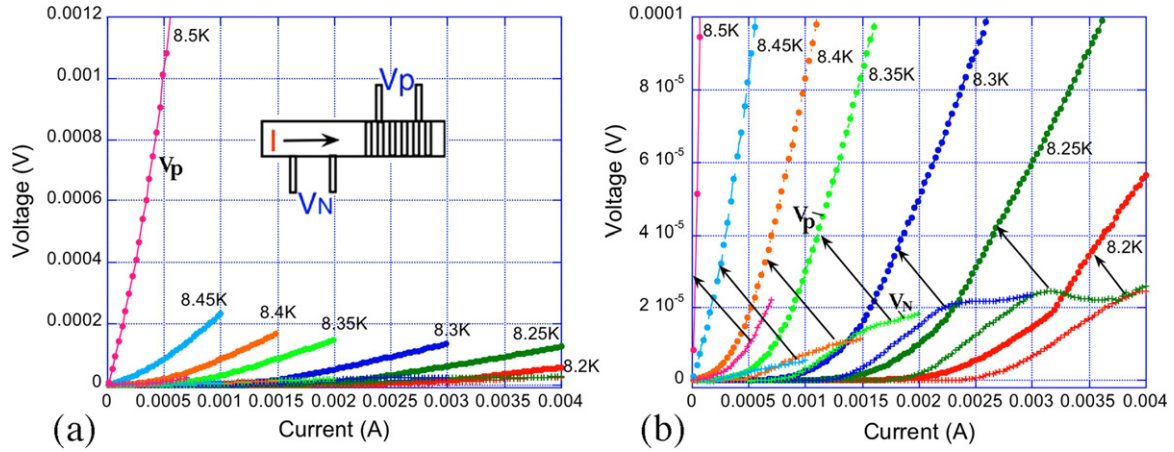


Figure 2. (a) Same as in figure 1(a) for Nb bridge placed on top of perpendicular Py stripes. Onset $T_c = 8.52$ K. (b) Expanded view of the low voltage region in (a). V_I s in the segment without Py are lower but the difference between V_P and V_N is much larger than in the sample with Py stripes placed on top of the Nb bridge.

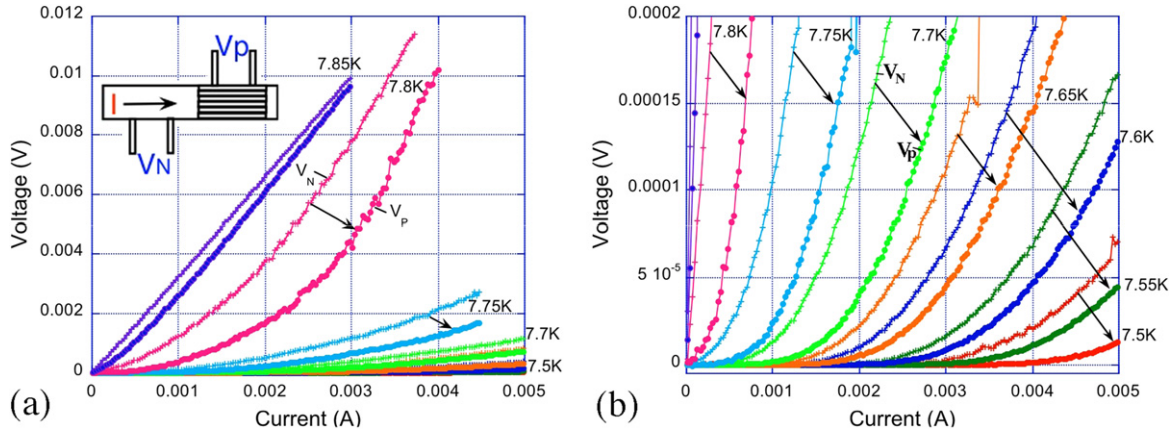


Figure 3. (a) VI curves in segments without Py and with longitudinal Py stripes on top of the Nb bridge (onset $T_c = 7.85$ K). (b) Expanded view of the low voltage section of (a)

that the voltage (potential difference) V_N measured across the bare Nb part decreases.

3.2. Parallel Py stripes

A different situation occurs when the Py stripes are oriented parallel with the Nb bridge. The VI curves for sample with parallel Py stripes deposited on top of the Nb bridge are presented in figure 3. Here, V_I s in the segment containing Py stripes are shifted to higher currents with respect to those of the bare Nb segment thus revealing a noticeable enhancement of the critical current. Again, the relative difference between the curves measured in the patterned Py stripe area and the bare Nb area is largest at low temperatures. However, the absolute voltage difference increases with temperature and drops only at $T \sim T_c$.

This effect is further amplified when the Nb film is placed on top of the parallel Py stripes. In this case VI curves in the segment with Py stripes drop to the very bottom of the plot shown in figure 4(a). They can be evaluated only at very small voltages (figure 4(b)), while voltages in the bare Nb segment are considerably larger.

4. Discussion

The appearance of voltage at $T < T_c$, is caused by the current induced generation and motion of vortices. Comparison of the VI curves in segments of bare Nb and Nb/Py stripes shows an enhancement of the vortex motion for perpendicular stripe patterns and suppression of flux mobility for parallel stripe patterns. The former can be explained by the easy channeling of vortices assisted by the long edges of Py stripes oriented perpendicular to the bridge (see figure 5(a)). In turn, the latter can be explained by the formation of continuous barriers for transverse vortex motion at the edges of longitudinal Py stripes (figure 5(b)). The larger differences in voltage–current characteristic when the Py stripes are placed underneath the Nb film can be associated with additional vortex pinning and changes of the effective magnetic fields acting on vortices due to the corrugations of the Nb overlayer near the edges of the Py stripes (see figure 5(c)). Both self-fields of the SC current and stray fields of the FM pattern are modified due to folds of the Nb film formed around the stripe edges. Also, the length of vortices is increased and their shape becomes distorted at the folds. Although accurate reconstruction of the vortex

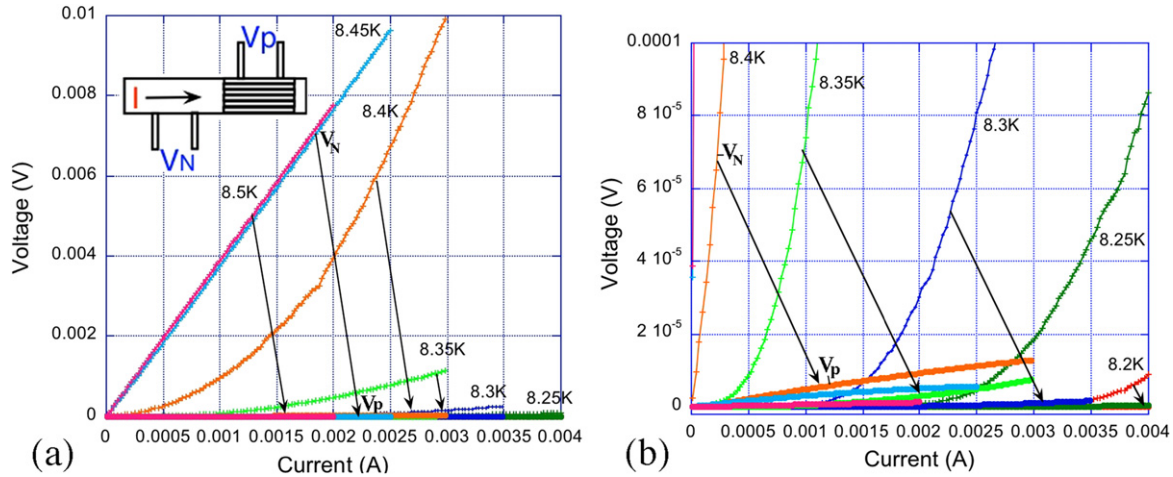


Figure 4. (a)–(b) Same as in figure 3 for the bridge with Nb placed on top of the Py stripes (onset $T_c = 8.47$ K).

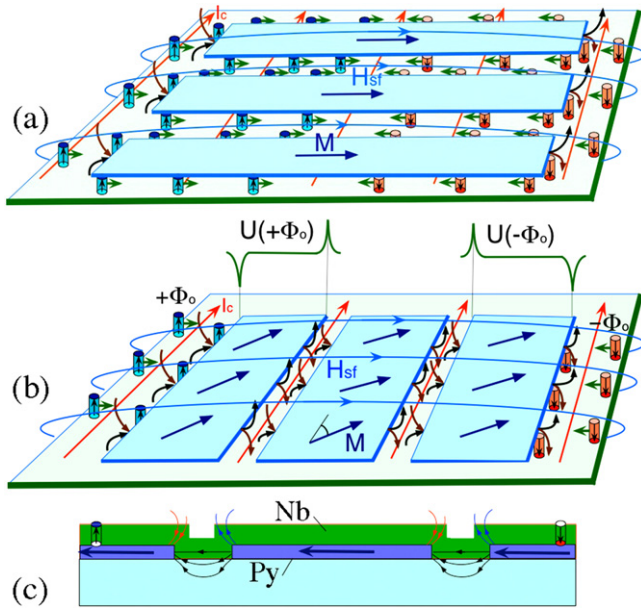


Figure 5. (a) Schematic of transverse FM stripes polarized by the self-field H_{sf} of the current I_c in a flat SC film. Vortices generated at the sides of the SC bridge are attracted to the edges of the FM stripes and channel along them. Short arrows show the direction of vortex motion. (b) Longitudinal FM stripes acquire a component of magnetization proportional to H_{sf} across their width yielding stray fields (shown by curved lines), which increase as $\sim 1/R$ at approaching by distance R to the FM stripe edge and forming the magnetic pinning potential U with sharp minimum and maximum at the opposite long edges of the FM stripe. For negative vortices ($-\Phi_0$) the sign of the pinning potential inverts but the pinning strength stays the same. The strength of U should increase with current in the bridge generating H_{sf} . (c) Corrugation of the Nb film at the edges of the Py stripes should deform transversely moving vortices and enhance magnetic pinning.

potential generated around folds requires rigorous computer modeling, our experiments show that it strongly enhances channeling of vortices along perpendicular stripes possibly due to additional anisotropy of the vortex mobility along the folds. In turn, it boosts pinning due to increased length of vortices moving across the folds in the case of longitudinal stripes.

Note, that in the majority of experimental studies of magnetic pinning, where the FM patterns (nanodots or bars of different geometries [34–39]) are overlaid by a SC film, the effect of the resulting corrugations of the SC layer is ignored. Our data indicate that these corrugated surfaces can magnify the effect of the underlying magnetic structures on vortex dynamics, compared to flat SC films.

The larger absolute shift of IVs at higher T in segments with perpendicular Py stripes can also be explained by the peculiarities of the vortex dynamics induced by the FM pattern. Channeling of vortices along the edges of Py stripes perpendicular to the current remains the main cause of the voltage increase. However, at temperatures close to T_c , vortices move faster and heat the superconductor more efficiently, resulting in enhanced vortex channeling and generation of a larger voltage. The situation changes in the close vicinity of T_c when the channels revert to the normal state along with the major section of the bridge. In the normal state the effect naturally disappears as illustrated in figures 1 and 2. Note, that even in samples with Nb placed on top of the Py stripes (figure 2), the VI curves obtained very close to T_c in segments with and without Py are practically identical, indicating that corrugations of the Nb film contribute only a small change to the total cross-section of the bridge.

Our data suggest that the long edges of the Py stripes play a dominant role in the flux dynamics, which we associate with the enhanced attraction of vortices to the FM stripe edges. In thin Py stripes with in-plane magnetization and relatively large spatial dimensions, one should expect extended closure domain structures, negating the edge stray fields. In this case, the stray fields appear only at the DWs. Vortices generated by the current in the Nb film carry normal flux and should not interact with the in-plane magnetization $\mathbf{M}$ of the Py domains and can couple only to the DWs. However, due to the very small magnetic anisotropy of Py, the magnetic field of the vortices can tilt $\mathbf{M}$ from the Py film plane and thus promote vortex-FM coupling. The highest attractive potential will be formed at the edges of the Py stripes. Here, the vortex aggregation and channeling should occur when Py stripes are perpendicular to the bridge while the strongest barrier for the

vortex motion will form in the case of the longitudinal stripes. For the stripes perpendicular to the bridge, the self-field of the current is parallel to their long sides. This is different from the situation studied in [24] when a wide FM stripe perpendicular to the SC bridge was polarized by the external magnetic field parallel to the bridge and the resulting strong stray fields at the stripe edges caused the suppression of superconductivity and increase of resistance. In our samples with perpendicular Py stripes, the stray fields are generated by the self-field of the applied current, appearing at the short ends of the stripes near the edges of the SC bridge. They play only a minor role compared to the larger channeling effect of the long stripe edges. In contrast, in the case of continuous FM coverage over the entire superconductor, the stray fields at the edge of the bridge can be the major factor modifying the vortex entry barrier and introducing asymmetric V I's [26, 40, 41]. We did not observe any asymmetry of the V I curves for + and – currents. This can be explained by the reversal of magnetization direction in the Py stripes by the self-field (H_{sf}) of the applied current in accordance with the current sign. Such a reversal of thin magnetically soft Py film can be expected even at relatively weak H_{sf} . Apart from the very edge of the Nb film, H_{sf} is parallel to the surface and is directed transverse to the Nb bridge. For the perpendicular Py stripes, H_{sf} is parallel to their long sides (figure 5(a)) and does not change the conditions for vortex channeling. However, longitudinal stripes should be polarized in proportion to H_{sf} transverse to their length and strong normal stray fields will be generated at their long edges, forming a continuous obstacle for any vortex motion across the Nb bridge (figure 5(b)). A potential well will appear on one side of the stripe and a potential barrier will form on the other side of the stripe, both hampering the vortex motion. This magnetic pinning should increase with the strength of H_{sf} and thus with the applied current in the bridge. Such an enhancement of vortex pinning with increasing current contributes to a *self-healing* pinning potential.

5. MFM imaging of the magnetic structure of Py stripes

To check the relevance of the above scenario, we first imaged the magnetic structure of Py stripes in the presence of an in-plane magnetic field (H_p) perpendicular to their length using room temperature MFM. Figure 6(a) shows the initial state of the stripes carrying rectangles and triangles of 90° closure domains and typical for thin Py films cross-tie 180° DWs [42]. There are practically no stray fields (except at DWs) at the edges of the Py stripes. However, there is a bright contrast in the one-micron gaps between the stripes, which appears due to the *attraction of the magnetized MFM tip to the stripe edges*. It is the same attraction, which couples vortices to the edges of perpendicular Py stripes at $T < T_c$ and forms channels for the vortex motion. The magnetic pattern changes with increasing H_p . First, the stripes evolve into a mono-domain state with only a few closure domains remaining at the ends of the stripes and a weak dark and bright contrast appears

around the gaps (figure 6(b)). At larger H_p , the stripes polarize along the field direction, yielding strong dark and bright contrast corresponding to alternating perpendicular stray fields at the long edges of the stripe pattern (figure 6(c)). Such an enhancement of the normal fields at the edges can explain the increased *relative* differences of the low-temperature V I's in figure 3(b) measured at high currents and hence larger H_{sf} . The images of figures 6(b)–(c) confirm that the pinning potential at the edges of the longitudinal stripes should be enhanced by the current in the bridge leading to self-healing behavior of our hybrid structure at $T < T_c$. When the field is switched off, the Py stripes return to the stray-field-free configuration (figure 6(d)) although the closure domain structure is different from the initial demagnetized state.

Similar behavior of the magnetic structure in the field was observed at low temperatures. Although at low T the coercivity for the domain wall motion slightly increases and at $T \sim 7$ K the stripes are monodomain only in transverse fields greater than 50 Oe. Current induced in-plane fields $H_{||}$ in our transport experiments are much smaller. $H_{||} = \mu_0 I/2l$ for a stripe of width l carrying current I which yields $H_{||} < 1$ Oe for ~ 5 mA current in our 100 μ m wide bridge. Expecting only slight variations in the domain structure, we attempted to directly image changes in the stripe edge field induced by the application of a dc current. As expected, MFM images taken at 7.2 K without a current were very similar to those obtained at + and –8 mA (figure 7(a)). However, differences between zero current and 8 mA images showed changes in the contrast. To check that the difference in images is not due to possible inconsistency of successive scans, MFM imaging was repeated under the same conditions several times. Differences of similar images did show some contrast, but it was mostly at the positions of the domain boundaries and was much weaker than that shown in figure 7. This confirms the validity of the differential procedure. The strongest variations, as illustrated in figure 7(b), are revealed in the difference between scans taken with opposite current polarities (brighter contrast at lower horizontal edges and darker at higher edges). It shows that the edge field of the Py layer is affected even with the small self-field of the applied current and gives a qualitative confirmation of the proposed magnetic pinning mechanism. At much larger currents in SC tapes, the effect of longitudinal soft magnetic stripes due to the self field H_{sf} of the current should be much stronger (e.g. $H_{sf} > 100$ Oe at $J_c \sim 10^6$ A cm^{–2} for 2 μ m thick YBCO).

6. Possible other flux damping mechanisms

In our geometry with thin FM stripes covering most of the SC film segment, one could expect the effect of magnetic screening, which should reduce the value of H_{sf} on the SC surface and enhance the dissipation-less transport current [43–45]. The magnetic screening could be responsible in part for the reduction of voltage at high temperatures in segments with longitudinal stripes. However, this factor is smaller than the pinning effect of the long stripe edges. In segments with perpendicular stripes, which have the same Py coverage, the

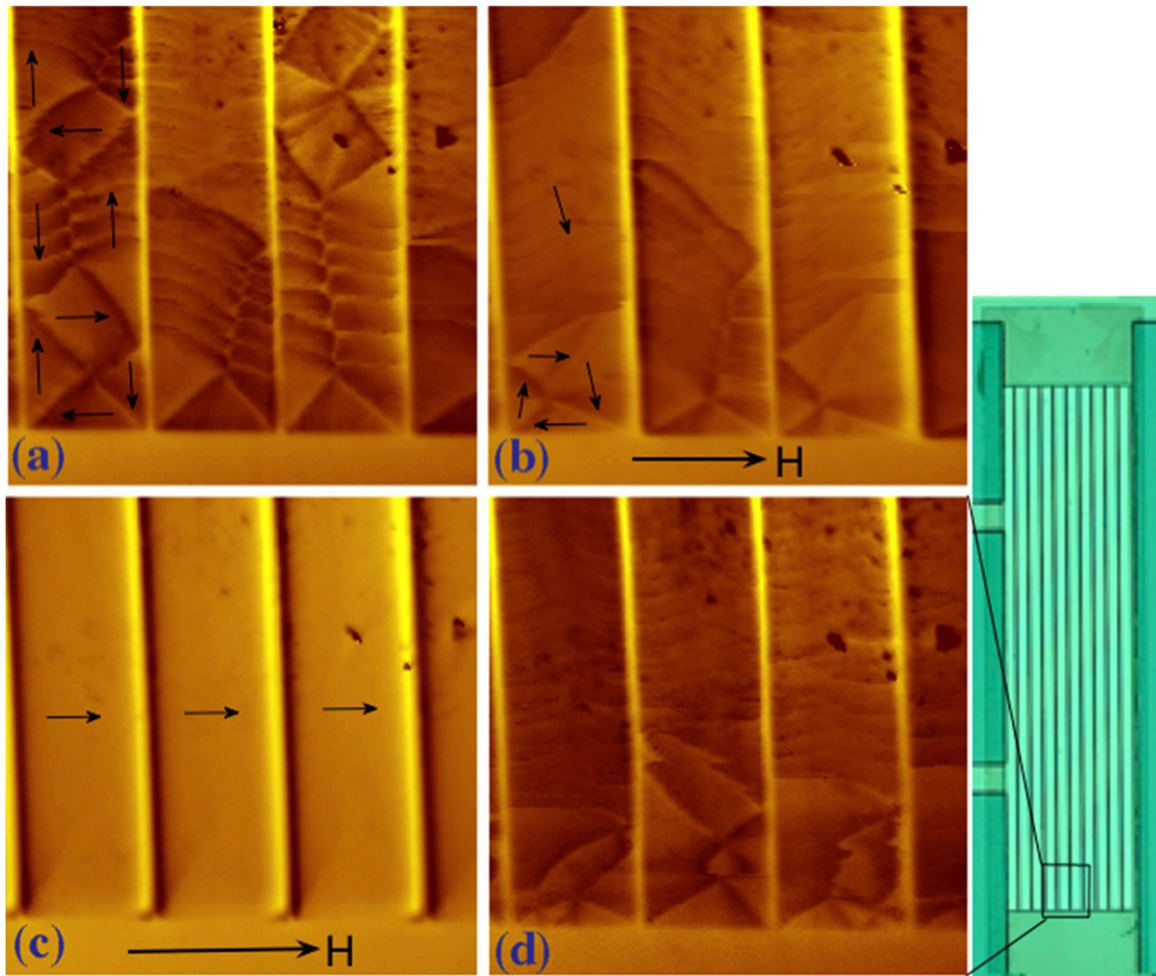


Figure 6. Room temperature MFM pictures of the magnetic structure near the ends of $9\ \mu\text{m}$ wide and $75\ \text{nm}$ thick Py stripes with $1\ \mu\text{m}$ gaps under the action of an in-plane magnetic field H perpendicular to their length. Short black arrows show the direction of the magnetic moments in the domains. (a)–(d) $H=0, 13.6, 36.2$, and $0\ \text{Oe}$. (b) Bright and dark contrast on two sides of each gap indicates the appearance of up and down stray fields. These stray fields are strongly enhanced in (c) but disappear in (d) when the field is switched off and new closure domains form. Insert on the right shows optical picture of a portion of the Nb bridge with Py stripes.

voltage is much larger than in the bare segments. This confirms that the effect of long stripe edges, causing the enhanced vortex channeling along perpendicular stripes, is also dominant over a possible screening effect.

Another contribution to the attenuation of flux dynamics could come from the Foucault currents induced in Py film by mobile vortices. In Py this contribution will be enhanced due to local dynamic out-of-plane tilts of magnetization induced by the normal field of moving vortices. This effect should be stronger in the case of longitudinal Py stripes where moving vortices cross the total width of the stripes. In the case of perpendicular stripes the channeling of vortices occurs primarily at the edges of the stripes and the Foucault and magnetic damping should be smaller. This could explain the slightly larger difference between the IV curves at higher currents and $T \sim T_c$ in the bare Nb and Nb/Py segments with longitudinal stripes (figure 3(a)) compared to that in samples with perpendicular stripes (figure 1(a)).

It was shown in [46] that magnetic stripes with perpendicular anisotropy deposited along or across the current in a SC layer yield a pronounced critical current anisotropy imposed by the stray fields emanating from the stripes.

Similarly, strong stray fields at the ends of longitudinally magnetized short magnetic bar arrays [47] result in a strong effect on the transport in the underlying SC layer. In both cases the existing stray fields and thus the magnetic pinning could be regulated by the applied perpendicular field. In our structures, soft magnetic stripes do not carry stray fields in the absence of the current (except at the domain boundaries). However, the stray fields appear at the edges of the longitudinal stripes due to the polarization of magnetic moments in Py by self-fields of the current. We believe that such current induced magnetic pinning could be a useful tool for arresting vortex dynamics in hybrid structures.

7. Conclusions

In summary, we have fabricated and studied SC bridges containing segments with thin stripes of soft FM material aligned perpendicular and parallel to the current flow. By comparing VI characteristics of segments with and without Py stripes in the same bridge, we investigated the effect of

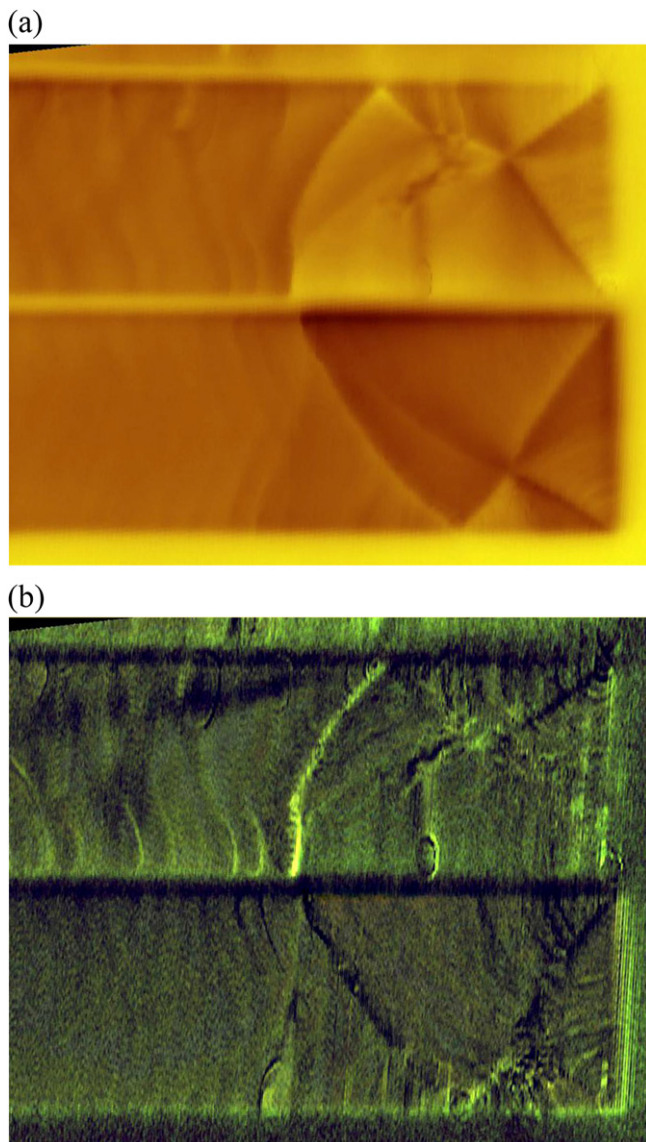


Figure 7. (a) MFM image of a part of the bridge with longitudinal Py stripes carrying dc current of 8 mA at 7.2 K. (b) Difference of scans taken at +8 mA and -8 mA currents. Brighter contrast at lower horizontal edges of the stripes and darker at higher edges reveals changes of the edge fields induced by the self-field of an applied dc current in the Nb layer.

magnetic interactions between vortices and FM patterns on vortex dynamics. The edges of in-plane magnetized FM stripes perpendicular to the bridge attract vortices and enhance their channeling under applied currents, which reduces the critical current value. In contrast, the edges of stripes parallel to the bridge form barriers for transverse vortex motion and enhance J_c . We assume that the alignment of magnetic moments in the soft FM stripes by the induced self-fields of the transport current enhances the strength of these magnetic barriers. Such an increase of vortex pinning with increasing current constitutes the realization of a self-healing pinning configuration, which demonstrates a new route for engineering efficient SC hybrids for high-current applications.

Acknowledgments

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