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Flux Penetration in a Ferromagnetic/Superconducting Bilayer

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An array of miniature Hall sensors is used to study the magnetic flux penetration in a ferromagnetic/superconducting bilayer consisting of Nb as a superconducting layer and Co/Pt multilayer with perpendicular magnetic anisotropy as a ferromagnetic layer, separated by an amorphous Si layer to avoid the proximity effect. It is found that the magnetic domains in the ferromagnetic layer create a large edge barrier in the superconducting layer which delays flux penetration. The smooth flux profiles observed in the absence of magnetic pinning change into terraced profiles in the presence of domains.

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1. Introduction

The flux penetration into superconductors is usually described by critical state models, the simplest of which, the Bean model, predicts that the magnetic induction decreases linearly with the distance from the sample edge, $B(x) \sim -x$. In thin superconducting (S) films B(x) is nonlinear but the flux profiles remain smooth. The profiles may change dramatically in the presence of artificial pinning. It has been predicted theoretically that in the presence of ordered array of pins the profile will be "terraced", with large regions in which the vortex lattice

Z. Adamus et al.

is commensurate with the pins and therefore strongly pinned, separated by the regions in which a rapid flow of vortices occurs [1]. Numerical simulations of the flux dynamics in the presence of ordered array of pins suggest an even more complex picture, with flux pinned initially close to the sample edge, and subsequent propagation of these pinned, domain-like regions towards the sample center [2].

So far there has been no experimental confirmation of these predictions, mainly because of the thermomagnetic instabilities in flux penetration. These instabilities cause flux avalanches which dominate at low temperatures and mask the role of artificial pinning [3]. In the present work we study the flux profiles in the presence of magnetic pinning (MP) induced by the domain pattern predefined in the ferromagnetic (F) layer. The MP dominates at high temperatures (close to the superconducting transition temperature, T_c) when the thermomagnetic instabilities are absent [4, 5]. This allows us to observe the terraced flux profile.

2. Experimental details, results, and discussion

The F/S bilayer is grown by the magnetron sputtering on the Si substrate. An F layer is the $[Co(0.4 \text{ nm})/Pt(1 \text{ nm})] \times 8$ multilayer, covered by an amorphous, 10 nm thick Si film to avoid the proximity effect, and Nb film, 78 nm thick, as an S layer. The parameters of the S film are as follows: $T_{\rm c} = 8.8$ K, penetration depth $\lambda(0) = 95$ nm, coherence length $\xi(0) = 35$ nm [5]. The hysteresis loop for the F layer, measured at T = 10 K is typical of the F film with perpendicular magnetic anisotropy, with a sudden drop of magnetization when the inverted domains nucleate and with the long "tails" caused by the residual uninverted (RU) domains. The coercive field, $H_{\rm c}$, is about 700 Oe. The magnetic force microscope images taken at 300 K show that the process of magnetic moment reversal starts from several nucleation centers and spreads to cover the whole sample with a maze of RU domains. The density of the RU domains is the largest when the magnetic reversal process is in the final stage. These RU domains provide MP in the sample, as described previously [4, 5]. To study the flux entry the sample is cut into 200 μ m wide strip, and the set of 10 collinear miniature Hall sensors, of the area $5 \times 5 \ \mu m^2$ each, is placed across the strip 20 μm apart. The additional sensor residing a few millimeters away from the line measures the background signal.

The experiment proceeds as follows. First the RU domain pattern is predefined at $T > T_c$. This is done by applying a high magnetic field H to saturate the F layer, followed by the reversing and the increase in H to the vicinity of H_c . Finally, H is switched off. The RU domains defined in this way remain stable. To describe the stage of the magnetic reversal we define a parameter s which is equal to 1 (0) when all the magnetic moments are up (down), and the magnetization at saturation is M_s $(-M_s)$. At any other state with magnetization M, $s_{\pm} = \frac{1}{2}(M/M_s + 1)$, where the subscript + (-) indicates the reversal process starting from s = 1 (s = 0). The RU domains are positive (negative) in the s_+ (s_-) process, respectively.



Fig. 1. Flux profiles measured at T = 7.5 K during increasing H for $s_{+} = 0.99$ (a) and for $s_{+} = 0.18$ (b). Vertical lines indicate the edge of the sample at $x = 0 \ \mu m$ and the middle of the sample at $x = 120 \ \mu m$, respectively. (c) H_{loc} versus H measured at the sample edge for various s at T = 7.5 K.

Next, the sample is cooled just below T_c , and the measurements of the local magnetic induction are performed simultaneously by all sensors while H is increased from zero up to +90 Oe. Figure 1a shows the flux profiles measured at T = 7.5 K when $s_+ = 0.99$, i.e. when the MP is negligible. It is seen that the profiles are smooth and the dependence B(x) is close to linear indicating that the Bean state with critical current independent of B is established. The flux penetrates to the middle of the sample at $H \approx 6$ Oe. Similar patterns are observed when the negative RU domains are present in the F layer. The reason is that the interaction between the negative domains and positive field created by vortices is repulsive and so it does not lead to MP.

The flux profiles change dramatically when $s_{+} = 0.18$, so that the positive RU domains are present (Fig. 1b). Two effects are evident. First, there is a large accumulation of flux near the sample edge. Apparently, flux is pinned by the domains which reside near the edge, creating the "edge barrier". As a result, the flux penetration is delayed — the flux appears in the sample center when $H \approx 12$ Oe. Moreover, the flux penetration towards the center is not smooth. We see flat regions separated by a region with a large slope of B(x). The flat regions correspond to the pinned flux, and the large slope appears when the flux propagates inside the sample. These terraced flux profiles are very close to the profiles predicted by theories [1, 2].

We define the local magnetic field (equivalent to the global magnetization) $H_{\rm loc} = B - H$, and examine its value at the sample edge. It is a direct measure of the "edge barrier", or extra flux trapped near the sample edge. Figure 1c shows the dependence of $H_{\rm loc}$ on H for various s_+ parameters. $H_{\rm loc}$ increases for a small H, has a maximum and starts to decrease when the flux trapped under the edge

Z. Adamus et al.

sensor starts to leak away towards the sample center. The maximum is strongly enhanced when the positive RU domains are present, and the largest enhancement occurs for $s_+ = 0.22$. Taking into account the area under the sensor we estimate that the amount of extra flux lines trapped at the edge is equal to 3 and 12 when $s_+ = 0.99$ and $s_+ = 0.18$, respectively. A further work is needed to understand how the domain shape and density affect the amount of trapped flux.

3. Conclusion

Local measurements of the flux penetration into the F/S bilayer with the MP centers reveal the enhanced edge barrier and the terraced flux profile inside the S film. Our results are the first observations of the magnetic-pinning created barrier, and the first observation of terraced flux profile, predicted theoretically in Ref. [2].

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