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Origin of pinning enhancement in a ferromagnet-superconductor bilayer

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Vortex pinning has been studied for the superconducting Nb film covering ferromagnetic Co/Pt multilayer with perpendicular magnetic anisotropy, in which the magnetization reversal proceeds via domain-wall motion. Large enhancement of pinning in the Nb film has been observed in the final stages of the reversal process, and we demonstrate that it is caused by residual uninverted dendrite-shaped magnetic domains. © *2005 American Institute of Physics*.
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The pinning of vortices in structures consisting of a superconducting (SC) layer on the top of magnetic dots or holes,[1–3] or in ferromagnet-superconductor bilayers (FSBs)[4–8] attracts much attention. The interest is generated by the technological promise of devices in which magnetic field can tune the magnitude of the critical current by adjusting the flux pinning. There are theoretical predictions that the magnetic flux of the vortex in the SC layer may be pinned by the stripe domains of the ferromagnetic (FM) layer.[4] Recent magnetic[5–7] and transport[8] studies of the FSB's confirm that the enhancement of pinning occurs. However, the origins of the enhancement are not evaluated in detail in most of these studies, except for the case of 50 nm Pb film [weak type II superconductor with the Ginzburg–Landau parameter $\kappa \approx 1$], deposited on the top of Co/Pt multilayer with perpendicular magnetic anisotropy.[7] In this case, the enhancement is found to be caused not by the stripe domains but by the isolated bubble domains nucleated in the FM layer during the reversal of magnetization. The question arises if similar origins are behind the pinning enhancement in the FSBs consisting of typical type II superconductors with κ well above 1, which are the materials for applications.

We study the FSB consisting of Nb film grown on a top of Co/Pt multilayer. We use the magnetic force microscopy (MFM) to image the domain structure of the FM layer, and the superconducting quantum interference device magnetometer to measure the magnetization in the superconducting state. Our results indicate a large, 2.5 times, enhancement of pinning which occurs exclusively in the final stage of the magnetic reversal process of the FM layer, and we show that it is caused by residual uninverted dendrite-shaped magnetic domains. While the details of this behavior differ from the effect reported for Pb film,[7] the origins are similar, in both cases related to pinning on isolated domains, suggesting that this type of pinning may be generally the most effective pinning in the FSB structures.

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The FSBs were made by sputtering in a high-vacuum chamber on a Si substrate covered with amorphous Si [Fig. 1(a)]. A 10 nm Pt layer was grown first, followed by five repeats of Co(0.4 nm)/Pt(1 nm) multilayer structure, and topped by a 3 nm Si buffer layer to avoid proximity effect between the SC and the FM layers. Some of the samples were reserved for the MFM measurements, and on others a 78 nm Nb film was grown next, topped again by about 3 nm of Si for protection. The Nb film has a superconducting transition temperature T_c of 8.8 K. From the measurements of the upper and lower critical fields versus temperature (all measurements described in this article are for sample oriented perpendicular to the magnetic field, H), we estimate the penetration depth $\lambda(0) \approx 95$ nm, and the coherence length

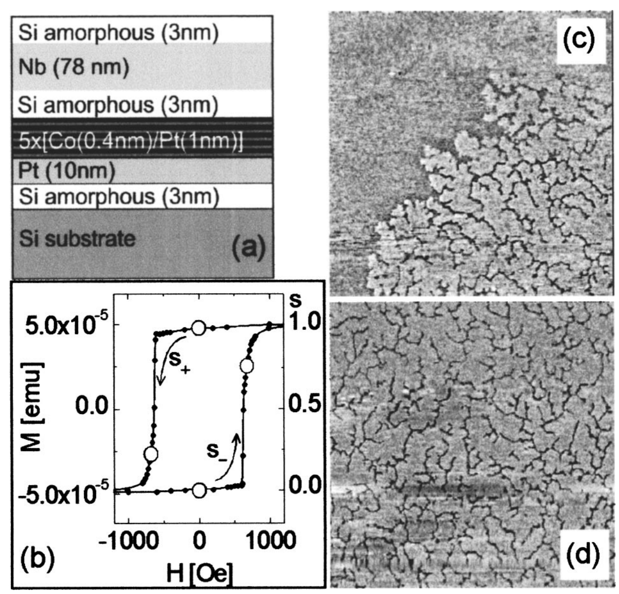

FIG. 1. (a) Schematic cross section of the FSB structure. (b) Hysteresis loop of the Co/Pt multilayer at $T=10$ K. The right scale defines the parameter s. Open points show four magnetization states at which data in Fig. 2 are taken. (c) and (d) MFM images taken for s equal to 0.43 and 0.2, respectively. The image size is 100×100 μm.

$\xi(0) \approx 35$ nm, which indicate $\kappa \approx 2.7$ and good quality of the Nb film.

Figure 1(b) shows the hysteresis loop measured for the Co/Pt multilayer at $T=10$ K. The loop is characteristic for the FM film with perpendicular magnetic anisotropy, with the coercive and saturation fields equal to $H_c=630$ Oe and $H_s=1500$ Oe, respectively. We describe the magnetic reversal process by the parameter s, which is equal to 1 (0) when all the magnetic moments of the FM layer are "up" ("down") and the magnetization at saturation is equal M_s $(-M_s)$. At any other state with the magnetization M, $s=1/2(M/M_s+1)$. We introduce also subscripts to s to distinguish processes of reversal, that is s_+ (s_-) process is the one starting from $s=1$ $(s=0)$.

The magnetic reversal process has a sharp onset, it is very rapid at the beginning, and more gradual as H_s is approached. Such a process has been shown to proceed via the domain-wall motion, leaving behind some uninverted domains which contribute to the gradual approach to saturation.[9] The domain wall may be directly observed in MFM images taken for various s in samples without Nb topping, as shown by the examples in Figs. 1(c) and 1(d). Prior to imagining the sample is magnetized in a magnetometer at room temperature, first to saturation, and then to a specific value of s, while the magnetization is monitored. The image of Fig. 1(c) is for the magnetization close to zero $(s_+=0.43)$, when about one-half of the magnetic moments are reversed from the original up direction. We see that a domain wall runs diagonally across the image. The top-left part of the image is the sample with the original saturated up magnetization. At bottom right is the reversed part. It contains a maze of uninverted dendrite-shaped domains, randomly distributed and narrow, with the width of about 0.5 μm. The image of Fig. 1(d) is for $s_+=0.2$. A domain wall is absent and there is only the reversed part of the sample, with the maze of uninverted domains. This domain structure remains stable after removing H. From the MFM images, we estimate the average surface area with inverted magnetic moments, and it agrees very well with the magnetization measured with the magnetometer.

To measure the hysteresis loop in the superconducting state, we first magnetize the FM layer to some value of s at temperature slightly above T_c. Next, H is brought to zero, the magnet is quenched to remove any residual magnetic flux, the temperature is lowered below T_c, and the hysteresis loop is measured between −100 and +100 Oe. Finally, the temperature is increased above T_c, and the magnetization is measured again to check if the cycling below T_c has any effect on the magnetic state of the FM layer. The results indicate that there is no effect. Figure 2 shows hysteresis loops measured at $T=8$ K for four s values marked in Fig. 1(b) by open points. The black symbols are for a uniformly magnetized FM layer with $s_+=1$ and $s_-=0$. Two anomalies are seen, a sudden jump when H crosses the zero value [shown by the grey arrow in Fig. 2(a)], and a small shift of the central magnetization peak (CMP) away from $H=0$ (black arrow). The measurements of the local magnetic induction using an array of Hall sensors placed on the top of the sample, which will be described in detail elsewhere, show that both effects

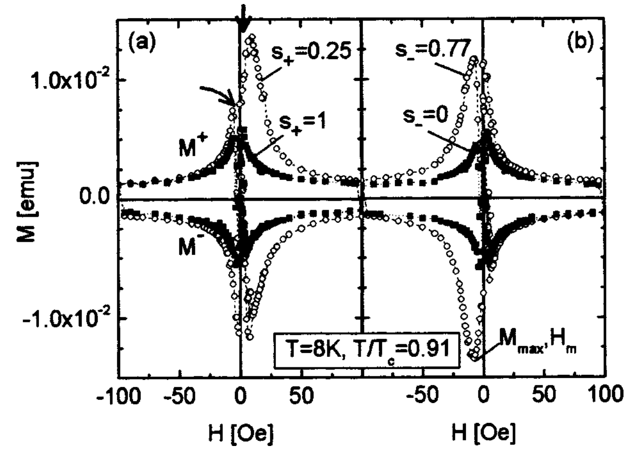

FIG. 2. Hysteresis loops of Nb at $T=8$ K measured for four stages of the reversal process: (a) $s_+=1$ and $s_+=0.25$ and (b) $s_-=0$ and $s_-=0.77$.

are absent in the sample center. The jump in the magnetization is most likely caused by the thermomagnetic flux instability, possibly triggered by the electronics of the commercial magnetometer, and we ignore this effect in the following discussion. On the other hand, Hall results show that the CMP shift is a real effect. It is absent in the sample center but has substantial values at other positions, reflecting complicated spacial distribution of the flux. The magnetometer measures the CMP shift averaged over the sample area.

The open symbols in Fig. 2 show hysteresis loops measured for $s_+=0.25$, and $s_-=0.77$, when the FM layer contains a maze of dendrite-shaped domains as in Fig. 1(d). We see that the magnitude of magnetization for both the positive (M^+), and the negative (M^-) branches of the hysteresis loop is about 2.5 times larger than for uniformly magnetized FM layer. The enhancement of magnetization is strongly asymmetric with respect to the relative orientation between the residual domains and the external magnetic field. That is, for the s_+ (s_-) reversal process, the enhancement is the largest for the positive (negative) magnetic field. This may be explained by the vortex pinning on the residual uninverted domains. The domain dipole moment m interacts with the vortex magnetic field B, introducing a contribution to the vortex energy, $E=-mB$. Therefore, the positive domains $(m>0)$ which appear in the s_+ reversal process, induce the pinning for positive external field and negative domains $(m<0)$ in the s_- process produce pinning for negative magnetic field. This asymmetric pinning resembles the behaviors observed both in the FSB with the Pb film,[7] and in the niobium film with the embedded array of magnetic dipoles.[3]

We denote the magnitude of the magnetization at the maximum by $M_{\max}$, and the magnetic field at which magnetization reaches a maximum by H_m. In Fig. 3, we plot the dependence of $M_{\max}$ and H_m on $s_\pm$ for two branches $(M^\pm)$ of the hysteresis. The largest increase of $M_{\max}$ is seen when the reversal process is 3/4 advanced, i.e. when $s_+ \approx 0.25$, or $s_- \approx 0.75$. This may be explained if we assume that the enhancement of pinning is directly related to the amount of isolated uninverted domains, which becomes the largest in the second half of the reversal process just after the domain wall sweeps across the whole sample. This is correlated with

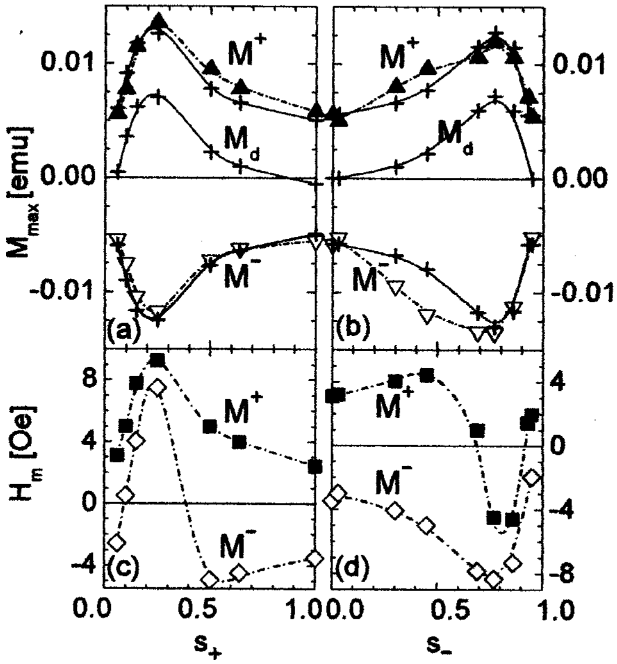

FIG. 3. (a) $M_{max}(s_+)$, (b) $M_{max}(s_-)$, (c) $H_m(s_+)$, and (d) $H_m(s_-)$ for $M^{\pm}$ branches of the hysteresis. In (a) and (b) triangles are experimental data and crosses show the calculated quantities; grey crosses: the dendrite-induced magnetization M_d; and black crosses: the total magnetization $M^{\pm}_{max}=\pm(M_d+M_0)$, where M_0 is a the contribution from intrinsic pinning. All lines are guides for the eyes.

the behavior of H_m. H_m is symmetrically shifted away from zero for both branches of the hysteresis when the FM layer is uniformly magnetized to saturation (this is the CMP shift). However, at $s_+ \approx 0.25$ ($s_- \approx 0.75$), the H_m shifts to positive (negative) values for both branches as a result of the asymmetric enhancement of pinning.

This result differs from the one described for the FSB with Pb film,[7] mainly because the magnetic reversal proceeded in that case by nucleation so that the isolated bubble domains appeared both at the beginning, and at the end of the reversal process. The pinning enhancement is also larger in the present experiment when the SC layer is a type II superconductor with κ substantially larger than 1. In addition, the observation of both branches of the hysteresis loop allows us to extract the magnetization induced by the pinning on dendrite-shaped domains, M_d, from the total magnetization, $M=M_d+M_0$. Here, M_0 is the contribution from intrinsic pinning, which exists in the absence of isolated domains. When $M=M_0$, the two branches of the hysteresis are coupled by antisymmetric relation: $M_0^+(H)=-M_0^-(-H)$. A different relation is expected for the dendrite-induced magnetization: $M_d^+(H)=-M_d^-(H)$. Therefore, we can extract M_d by computing the sum $M^+(H)+M^-(-H)$, in which the contribution from intrinsic pinning is subtracted away. Figure 3 shows M_d at its maximum value as a function of $s_{\pm}$ (grey crosses). Next, assuming that M_0 is constant, we calculate the total magnetization at maximum for two branches of the hysteresis, $M^{\pm}_{max}=\pm(M_d+M_0)$ (black crosses). While this assumption is probably not exact, our estimate describes the experimental data quite well and clearly demonstrates that the dendrite-induced pinning is responsible for most of the pinning enhancement.

In conclusion, our study shows that the magnetic domain reversal induces strong enhancement of vortex pinning in the FSB structures which contain typical type II superconductor. The effect may be attributed almost entirely to the pinning by the isolated uninverted dendrite-shaped domains which are created during the reversal process. It would be interesting to investigate if the enhancement of pinning by isolated domains is a universal feature present in different FSB structures.

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