Precise control of domain wall injection and pinning using helium and gallium focused ion beams

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In experiments on current-driven domain wall (DW) motion in nanostrips with perpendicular magnetic anisotropy (PMA), the initial DW preparation is usually not well controlled. We demonstrate precise control of DW injection using Ga and novel He focused ion beam (FIB) irradiation to locally reduce the anisotropy in part of a Pt/Co/Pt strip. DWs experience pinning at the boundary of the irradiated area. This DW pinning is more pronounced at the He irradiation boundary compared to Ga. This is attributed to a better He beam resolution, causing an anisotropy gradient over a much smaller length scale and hence, a steeper energy barrier for the DW. The results indicate that He FIB is a useful tool for anisotropy engineering of magnetic devices in the nanometer range. © *2011 American Institute of Physics*. [doi:10.1063/1.3549589]

I. INTRODUCTION

The dynamics of domain walls (DWs) in magnetic nanostrips is of great scientific interest due to the prospect of new spintronics devices.[1,2] In addition to the well-known DW dynamics in permalloy strips,[2,3] there is a booming interest in current- and field-induced DW motion in materials with high perpendicular magnetic anisotropy (PMA).[4–7] These materials promise efficient current-induced DW motion, because they exhibit simple and narrow Bloch walls leading to large nonadiabatic spin torque contributions.[8,9]

In order to study DW physics, one needs to initially create the DWs in a reproducible way. For in-plane DW devices, a geometric approach is often chosen, where variations in the shape can be used to locally lower the switching field because of demagnetization effects. Such an approach is not viable for PMA materials, since the huge anisotropy dominates over shape-induced effects. Surprisingly, a geometric approach with a large "nucleation pad" attached to one end of the device is also widely employed in PMA systems.[5–7] This approach works to some extent, because a larger area means a larger statistical chance of having a defect where DW nucleation is favorable. However, this approach is not very elegant, as the magnetic field needed for DW creation is not controlled and nucleation may occur at unintended spots. Alternative approaches include thermomagnetic writing with a laser spot[10] or using the Oersted field generated by a nearby current pulse line, but these methods pose restrictions to the experimental environment and sample design.

In a previous letter,[11] we proposed to use a focused ion beam (FIB) of Ga ions to locally reduce the magnetic anisotropy, thereby controlling both the position and magnetic field needed for DW injection. The influence of high energy ion irradiation on magnetic properties has been widely studied in the past, first using Ga ions[12] and He ions[13,14] and more recently with highly focused Ga beams.[15,16] However, very recently also helium ion microscopy (HIM) systems have become commercially available, using a focused He beam that has several advantages for imaging and nanostructuring, the most notable advantage being the subnanometer resolution.[17,18] In this paper, we report for the first time the use of such a focused He beam to alter magnetic properties. Using He ions, we have achieved a significantly improved control of DW injection and pinning as compared to a conventional Ga FIB. The observed effects of an anisotropy gradient over a much smaller length scale (<10 nm) is very promising for precise and reproducible anisotropy engineering of magnetic nanodevices.

II. EXPERIMENT

Pt (4 nm)/Co (0.6 nm)/Pt (2 nm) strips exhibiting PMA were fabricated using electron beam lithography, sputtering, and lift-off on a Si/SiO_2 substrate. The structures are $1 \times 10\ \mu m^2$ in size. After fabrication, a part of each strip was irradiated with either Ga or He ions at varying dose, as indicated in Fig. 1. In case of Ga, a FEI Nova NanoLab DualBeam system was used and the energy of the incident ions was 30 keV at a beam current of 2 pA, which was the lower limit. For He, a Zeiss Orion Plus helium ion microscope was used, operating at 25 keV at a beam current of 1.5 pA, which is close to the upper limit of this machine. The Ga and He irradiation was performed on the same wafer in order to have a direct comparison between the two techniques. For each dose, 12 identical structures were prepared to obtain decent statistics. The magnetic switching behavior of the strips was studied using a wide-field Kerr microscope from Evico magnetics,[19,20] which gives a direct image of the domain structure while the magnetic field is swept from negative to positive saturation.

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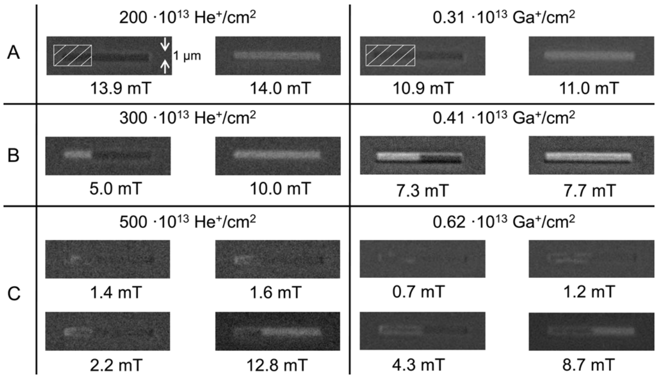

FIG. 1. Kerr images of magnetization switching of Pt/Co/Pt strips irradiated with various He (left) and Ga (right) doses. Zero-field background images were subtracted. The irradiated region is indicated by the hatched area. Three regimes (A, B, C) are identified as described in the text.

III. RESULTS

Exemplary Kerr images acquired for various He and Ga irradiation doses are shown in Fig. 1. These images confirm the interpretation of our previous study on Ga irradiated strips,[11] where hysteresis loops were measured using the anomalous Hall effect. For He as well as Ga, three regimes can be distinguished in Fig. 1. In regime (A), the irradiated area switches at a reduced field compared to an as-grown structure due to a reduction of the anisotropy. As soon as the irradiated area switches, the nonirradiated area also switches due to movement of a DW originating from the irradiated area. Therefore, a sudden change from down (black) to up (white) magnetization over the entire structure is observed at a well-defined field. In regime (B), once the irradiated area is reversed, the DW does not propagate into the nonirradiated area but instead remains pinned at the boundary between the irradiated and nonirradiated areas. In Fig. 1 (part B, left image), this is seen as a black/white contrast between both sides of the strip. Only if the field is increased further, this DW is allowed to propagate into the nonirradiated area which then switches as well. In regime (C), the irradiated area is in-plane magnetized due to the high dose lowering the effective PMA, resulting in an in-plane easy axis dominated by shape anisotropy. This is seen in the images by the very small change of contrast in the irradiated area when the magnetic field is increased. Still, the nonirradiated area switches by DW movement originating from the irradiation boundary (the switching can be seen in the last images of Fig. 1, part C).

A systematic analysis is presented in Fig. 2(a), where the injection field is plotted as a function of Ga (bottom axis) and He dose (top axis). The injection field is simply defined as the switching field of the nonirradiated part of the wire, which in any case occurs due to a DW propagating from the irradiated into the nonirradiated area. The error bar represents the standard deviation of the injection field among the 12 identical structures. The data are similar to our previous results on Ga in Ref. 11, but with greater detail. The three aforementioned regimes are observed and qualitatively understood from micromagnetic modeling as shown in Fig. 2(b), where we have taken into account a reduction of the anisotropy with increasing dose.[11] To summarize, the injection field decreases in regime (A) because the anisotropy in the irradiated region is decreased. This is followed by recovery in regime (B), because DW pinning at the interface scales linearly with the difference in anisotropy between the two parts of the wire. This recovery flattens off in regime (C), because the DW resides at the interface between in-plane and out-of-plane areas.

To compare the data for He and Ga irradiation in Fig. 2(a), we have plotted the data on the same axes by scaling the doses in regime (A) to each other, because this regime scales linearly with the anisotropy. It is then clearly observed that the pinning field in regime (B) is significantly higher for the He irradiated structures. Indeed, when the anisotropy step at the boundary is much sharper due to the better resolution of the He beam, this should lead to a steeper energy barrier for the DW. In line with this observation, micromagnetic modeling revealed that the pinning field reduces when the anisotropy changes more gradually. Assuming that the effective perpendicular anisotropy constant increases linearly from K_{eff} to $K_{\mathrm{eff},0}$ over a gradient length δ, it was found that[11]

$$\mu_0 H_{\mathrm{pin}} = \frac{K_{\mathrm{eff},0} - K_{\mathrm{eff}}}{2M_s}\frac{2\Delta}{\delta}\tanh\left(\frac{\delta}{2\Delta}\right), \qquad (1)$$

where M_s is the saturation magnetization and Δ is the DW width. The pinning strength thus increases with the anisotropy difference and decreases with the ratio δ/Δ, as seen in the simulated data of Fig. 2(b). The much steeper pinning

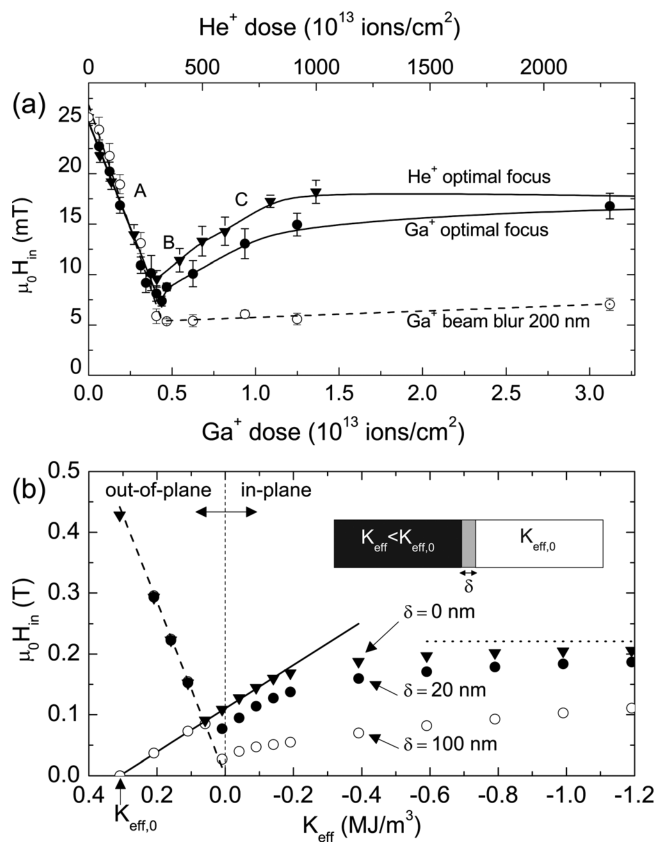

FIG. 2. (a) Injection field as a function of dose for He (triangles), Ga (closed circles), and blurred Ga (open circles) irradiation. The line is a guide to the eye. (b) Micromagnetic simulations of DW injection from an anisotropy boundary for various values of the gradient length δ (from Ref. 11).

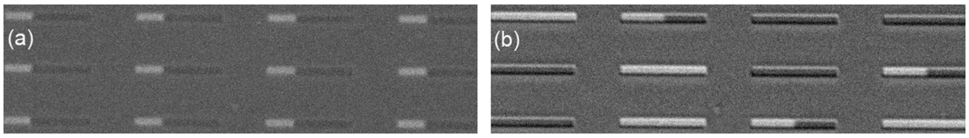

FIG. 3. (a) Twelve identical He irradiated structures (300×10^{13}ions/cm^2) at 7.5 mT, consistently having a pinned DW. (b) Ga irradiated structures (0.41×10^{13}ions/cm^2) at 7.5 mT.

field observed at the He irradiation boundary is thus evidence for a much smaller gradient length δ. We verified this trend by repeating the experiment with an intentionally blurred Ga beam by moving the sample out of focus during irradiation. The injection fields obtained for a beam blurred to a FWHM of ~200 nm are also shown in Fig. 2(a) (open circles). Indeed, pinning in regime (B) is strongly reduced due to the much larger gradient length δ. It is interesting to note that for applications where the injection field should be as low as possible, it is actually beneficial to work with a defocused beam.

We can obtain a crude estimate for the length of the anisotropy gradient at the boundary. The slope of the pinning regime (B) should decrease with the gradient length δ according to Eq. (1). We estimate this slope by a straight line through the origin and the onset of the pinning regime. By assuming a DW width of 10 nm (estimated from the micromagnetic simulations) and assuming that the gradient length at the He-irradiated boundary $\delta_{He} < 5$ nm (which is realistic given the <1 nm imaging resolution), it follows that $\delta_{Ga} = 22$ nm. The damage radius of the He beam causing the anisotropy reduction might thus be an order of magnitude smaller, allowing engineering of magnetic properties at the <10 nm scale.

Looking at the magnitude of the Ga and He doses in Fig. 2(a), one can see that a factor of 700 more He ions is required in order to have the same reduction in perpendicular anisotropy. This is an inherent advantage when very subtle control of the anisotropy is required. The dose is controlled by the product of the beam current and pixel dwell time and both are at the lower limit for the Ga doses used here, so that more subtle modifications are not viable.

We end by illustrating the reproducible DW pinning that can be achieved using He FIB in Fig. 3. In Fig. 3(a), a Kerr microscopy image of 12 identical He irradiated structures is shown, each displaying a DW pinned at the boundary (regime 2) and each having full perpendicular remanence. Because of the weaker DW pinning in the case of Ga irradiation, we could not obtain this fully reproducible behavior without loss of well-defined perpendicular anisotropy, even when fine-tuning the Ga irradiation dose in small steps. Some structures switch in one field step (pinning too weak), whereas in others the state with a pinned DW is stable, as shown in Fig. 3(b). With He irradiation, fine-tuning the irradiation dose was not even necessary.

IV. CONCLUSION

In conclusion, we have reported on the use of a He FIB for controlled injection of DWs in a Pt/Co/Pt strip. DWs experience pinning at the irradiation boundary, due to a different anisotropy at both sides of the boundary. At the He irradiation boundary, the pinning is much more pronounced compared to Ga irradiation for the same magnitude of the magnetic anisotropy. This is linked to a better resolution of the He beam, implying an anisotropy gradient over a significantly smaller length scale causing a steeper DW energy barrier. The HIM also offers more precise dose control due to the 700 times lower dose sensitivity for He ions as compared to Ga ions. Therefore, He FIB could be a useful new tool for nanoscale engineering of magnetic devices.

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