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Controlled domain-wall injection in perpendicularly magnetized strips

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For applications of domain wall (DW) motion in magnetic devices, it is vital to control the creation and position of the DW. We use Ga⁺ irradiation of Pt/Co/Pt strips to locally change the perpendicular magnetic anisotropy. This allows us to controllably inject DWs into a device at a tunable field. The observed initial linear decrease and subsequent increase in the DW injection field upon increasing irradiation dose are explained by micromagnetic simulations and an analytical one-dimensional model. © 2010 American Institute of Physics. [doi:10.1063/1.3432703]

Traditionally, the most studied system for domain wall (DW) motion is based on in-plane (IP) magnetized permalloy wires, which, due to a negligible magnetic anisotropy, exhibit wide and complex DWs.1–3 More reports have recently appeared on perpendicularly magnetized systems where the magnetization is oriented out-of-plane (OOP) due to a high perpendicular magnetic anisotropy (PMA).4–6 These seminal studies are mainly inspired by the prospect of low critical currents for current induced DW motion when dealing with narrow and simple Bloch type DWs.7,8

For applications and research of DW motion in nanostuctures, it is vital to precisely control the position where a DW is initially created/injected. For IP DW devices, this problem is easily overcome by demagnetization effects. Hence, a change of the local geometry can be used to locally lower the switching field, creating a reliable and reproducible way to create/inject DWs. This is, however, not viable for OOP systems since the PMA dominates over demagnetization effects. Surprisingly, this geometric approach is still widely used for PMA systems.9,10 By attaching a large nucleation pad to the device, the statistical chance to find an imperfection where a DW will nucleate at low field is increased. This naturally depends on the quality of the fabrication process and obviously does not lead to reliable and reproducible devices. Alternatively, it has been shown that low-dose irradiation by Ga⁺ ions leads to a reduction of the OOP anisotropy.10,11 Therefore, if only part of a structure is irradiated, this nucleation area switches first as demonstrated before.12,13 However, in these studies the magnetic field needed to depin a DW from such an irradiated area has not been further investigated.

In this paper, we study the effect of local irradiation of a Pt/Co/Pt strip for DW injection. We will present a systematic analysis of the injection field \(H_{in}\) needed to inject a DW into a device as function of Ga⁺ dose. Interestingly, we observe that \(H_{in}\) sharply decreases under low Ga⁺ dose, but then increases again with increasing dose due to DW pinning. This counterintuitive behavior is shown to match well with micromagnetic simulations and is additionally supported by a simple analytical one-dimensional (1D) DW model, allowing to tune and predict \(H_{in}\). We anticipate that the proposed way to introduce DW injection points and engineered DW pinning sites will accelerate the research and device implementation of PMA materials.

The devices under investigation are shown in the sketch of Fig. 1(a). The strips consist of Pt(4 nm)/Co(0.6 nm)/Pt(2 nm) patterned by electron beam lithography, lift-off, and grown by dc-sputtering on a Si/SiO₂ substrate. Prior to electrical contacting, the Hall cross is partly irradiated [see sketch Fig. 1(a)] with a varying dose of Ga⁺ ions (0.1–5.0 \(\mu\)C/cm² with beam settings: 30 keV, 2 pA) with a focused ion beam (FIB).

To verify that the magnetization reversal is initiated in the Ga⁺ irradiated area we use polar Kerr microscopy.14 In Fig. 1(a) a sequence of Kerr images is shown for increasing applied field. One can clearly see that with increasing field (4.4–6.8 mT) the irradiated area starts to reverse its magnetization by progressive nucleation and expansion of domains, indicating that the Ga⁺ irradiation generates local nucleation sites where domains are easily nucleated at low field due to the lowered anisotropy. At 6.9 (7.7) mT the left (right) DW depins followed by the reversal of the left (right) part of the structure by DW motion. This process is reproducible but the depinning field varies slightly due to the stochasticity induced by thermal activation. We define \(H_{in}\) as the average of the depinning field of the right and left DW.

We can sensitively measure the OOP magnetization in the Hall cross when we electrically contact the sample (lock-in detection, \(I_{dc}=10\) \(\mu\)A) by the extraordinary Hall effect (EHE). This is shown in Fig. 1(b) where partial hysteresis loops are shown of Hall crosses irradiated with different doses. Three regimes can be distinguished: (i) at the lowest dose \((0.1\ \mu\text{C/cm}^2)\) the hysteresis loop shape is similar to a non-irradiated sample (not shown). The square hysteresis loop indicates that the reversal mechanism is dominated by thermally activated domain nucleation at a certain imperfection and consecutive fast DW motion through the device. (ii) When we increase the dose to 0.6 \(\mu\)C/cm², a sharp reduction is seen in the start of the reversal, and \(H_{in}\) is greatly reduced. Furthermore, small steps are seen directly above \(\mu_0H=0\). This corresponds to the reversal taking place by a few small domains nucleating in the irradiated area of which the reversal is completed at around \(\approx 8.6\) mT. The large steps at \(\approx 9.3\) mT indicates the depinning of the right and left DW from the boundaries into the device, similar to what we have seen in Fig. 1(a). (iii) At a dose of 1.5 \(\mu\text{C/cm}^2\) we do not observe the small steps corresponding to the reversal

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of the irradiated area. Instead of the steps we observe a reduction of the remanence and a gradual slope around zero field, indicating that the magnetization is IP and the field is pulling the moments OOP. But more surprisingly, \( H_{in} \) has increased to 11.9 mT where the plateau around \( H_{in} \)'s indicates the field at which the magnetization is IP and the field is pulling the moments OOP.

To explain this peculiar behavior of \( H_{in} \), micromagnetic simulations are performed. A small strip \([400 \times 60 \times 1 \text{ nm}^3]\), shown in the inset of Fig. 2(b) discretized in \( 4 \times 4 \times 1 \text{ nm}^3 \) cells is split into two parts. The left part has a fixed effective OOP anisotropy of \( K_{eff,0} = K_0 - 1/2 \mu_0 N_z M_s^2 \), taking \( K_0 = 1.5 \text{ MJ/m}^3 \), \( M_s = 1400 \text{ kA/m} \), a demagnetizing factor of \( N_z = 0.96 \), and an exchange stiffness \( A = 16 \text{ pJ/m} \). The right part of the strip, which mimics the irradiated area of our experiments, has a reduced anisotropy \( K_{eff} < K_{eff,0} \). For now we assume a sharp boundary described by the boundary width \( \delta = 0 \).

In Fig. 2(a) simulated quasistatic OOP hysteresis loops taken over the whole structure are shown for different \( K_{eff} \), a positive (negative) \( K_{eff} \) indicates an OOP (IP) easy axis. A trend can be observed with decreasing \( K_{eff} \), viz. from a square hysteresis loop for \( K_{eff} > +110 \text{ kJ/m}^3 \), to a loop with a double step for \( +60 > K_{eff} > +10 \text{ kJ/m}^3 \) and finally a slanted loop with a single step when \( K_{eff} < 0 \).

Starting with a high \( K_{eff} \) (top) we find, as expected, a square hysteresis loop with a sharp switch at the anisotropy field \( H_{K_{eff}} = 2K_{eff}/(\mu_0 M_s) \). The \( \times \)'s indicate the field at which the \( K_{eff} \) area reverses its magnetization and thus corresponds to \( H_{in} \). The reversal always proceeds by a domain that is nucleated in the \( K_{eff} < K_{eff,0} \) region. When the DW arrives at the boundary the field is high enough to push the DW into the \( K_{eff,0} \) region and this region will also reverse by fast DW
motion. For $+60<K_{\text{eff}}<-10$ kJ/m$^3$ we observe an extra step in the hysteresis loop which corresponds to the DW getting pinned at the boundary, i.e., a higher field is needed to push the DW into the $K_{\text{eff,0}}$ region indicated by the extra step. When $K_{\text{eff}}<0$ we lose the well-defined perpendicular magnetization in the area with reduced $K_{\text{eff}}$. This is seen by the slope around zero field and the loss of 100% remanence. In Fig. 2(b), $H_{\text{in}}$ obtained from the simulations ($\delta=0$) is plotted as a function of $K_{\text{eff}}$. For $K_{\text{eff}}>-60$ kJ/m$^3$, $H_{\text{in}}$ is linear with anisotropy and exactly corresponds to the anisotropy field $\mu_0 H_{\text{eff}}$ (dashed line). When $K_{\text{eff}}<-60$ kJ/m$^3$, DW pinning at the boundary dominates the injection field and $H_{\text{in}}$ increases again.

In the experiment the sharpness of the boundary is limited by the Ga$^+$ beam profile specified to be 7 nm at FWHM. The width of the DW pinning potential at the boundary is governed by the DW width $\Delta=\sqrt{(A/K_{\text{eff,0}})}=7.2$ nm, i.e., they are of the same order. To investigate the effect of the beam profile in the simulations we implemented a linear change (stepwise in the cells) of the anisotropy at the boundary, with a boundary width of $\delta=20$ and 100 nm. The results are shown in Fig. 2(b). Again, a similar behavior is found, although with an overall reduced $H_{\text{in}}$ and a more gradual increase in $H_{\text{in}}$ for DW pinning at the boundary.

Comparing to the experimental data of Fig. 1(c), a very good qualitative correspondence of $H_{\text{in}}$ is seen where a higher Ga$^+$ dose corresponds to a lower $K_{\text{eff}}$. The magnitude of $H_{\text{in}}$ is, however, much lower in the experiment due to thermal activation processes playing a crucial role as is well known for these materials.\textsuperscript{16,17}

We now concentrate on the anisotropy regime where $H_{\text{in}}$ starts to increase due to DW pinning at the boundary i.e., $K_{\text{eff}}<-60$ kJ/m$^3$. Let us assume the 1D Bloch DW obeys the well-known profile,\textsuperscript{18} i.e., the OOP angle $\theta$ along the wire axis $x$ is given by: $\theta(x) = \pm 2 \arctan[\exp(x/\Delta)]$. The DW energy per unit area is then given by $E_{\text{DW}} = 4A K_{\text{eff}}$. Hence, the DW has to overcome a certain energy barrier to propagate into the $K_{\text{eff,0}}$ region. The energy landscape felt by the DW can be tilted by the Zeeman energy of an applied field pushing the DW into the $K_{\text{eff,0}}$ region as soon as the tilt slope cancels the maximum slope of the DW energy landscape. Assuming that the magnetization is OOP in both regions and the DW retains a Bloch profile, we find analytically that $H_{\text{in}} = (K_{\text{eff,0}} - K_{\text{eff}})/(2\mu_0 M_s)$, as is shown in Fig. 2(b) by the solid line. It corresponds exactly to the simulated data for $+60<K_{\text{eff}}<-140$ kJ/m$^3$, confirming that the assumed Bloch profile is reasonable. When we implement $\delta>0$ into the 1D model to mimic the finite Ga$^+$ beam width, we analytically find (assuming a linear change in the anisotropy) that the pinning at the boundary (solid line) is reduced by a factor $(2\Delta_{\text{eff}}/\delta)\tan(\delta/2\Delta_{\text{eff}})$. This factor corresponds with the observed reduction in $H_{\text{in}}$ found from micromagnetic simulations [Fig. 2(b), crosses symbols]. In that case, an effective DW width $\Delta_{\text{eff}}$ is used, obtained from a fit to the pinned DW profile.

When $K_{\text{eff}}<-140$ kJ/m$^3$ the pinning model starts to deviate from the simulated data due to an increasing IP character of the magnetization in the low $K_{\text{eff,0}}$ region, indicating that the assumed Bloch profile is no longer valid. For $K_{\text{eff}} < 0$ we can make a crude assumption by rescaling the Bloch profile from $\theta \in [0, \pi]$ to $\theta \in [0, \pi/2]$ giving $\theta(x) = \pm \arctan[\exp(x/\Delta)]$. Using a similar analysis as above with an OOP (IP) easy axis in the $K_{\text{eff,0}}$ ($K_{\text{eff}}$) region, we find $H_{\text{in}} = K_{\text{eff,0}}/\mu_0 M_s$. This relation is shown as the dotted line in Fig. 2(b) and matches the asymptotic behavior of the micromagnetic simulations. The small offset between the simulation and the model is due to the field already present at $H_{\text{in}}$ tilting the moments OOP in the $K_{\text{eff}}$ region which is not taken into account in the profile. Finally, from the above analysis a minimal injection field can be found from the intersection of $H_{\text{in}}$ and $H_{\text{in}}$ found around $K_{\text{eff}}=60$ kJ/m$^3$. This is given by $H_{\text{in,min}} = 2/5 \times K_{\text{eff,0}}/\mu_0 M_s$, giving at least a qualitative handle to tune $H_{\text{in,min}}$.

In this paper, it is demonstrated that Ga$^+$ irradiation can be used to controllably depin a DW in a perpendicularly magnetized Pt/Co/Pt strip which we substantiated by micromagnetic simulations and a simple analytical 1D DW model. The ease and tunability of the technique makes us believe that it will greatly stimulate the field of DW physics and devices.

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