Domain Wall Motion Control for Racetrack Memory Applications

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Increasing demand for large capacity data storage can only be fulfilled by hard disk drives (HDDs) and to some extent by solid-state drives (SSDs). However, HDDs are favorable in many applications, as they are approximately 5–10 times cheaper than SSDs. Attempts are being made to increase the capacity of HDDs by technologies such as heat-assisted magnetic recording and microwave assisted magnetic recording. However, increasing the capacity has been a slow process and there are limitations in achieving areal density above 10 Tbpsi. Thus, the introduction of new technologies is important for attaining high capacity. In this scenario, domain wall (DW) memory is a potential candidate, but there are still many unsolved issues. One of these is ensuring controlled and reliable motion of DWs along the nanowire. In this paper, we provide an overview of existing technologies and our attempts to control DW motion. Many methods of fabricating pinning centers have been proposed and demonstrated. These methods can mainly be categorized as 1) geometrical and 2) non-geometrical methods. In the first part, we review the geometrical approach to pin DWs. Later, we provide an overview of our approaches to create pinning centers using non-geometrical means. Non-geometrical approach provides more advantages as it provides a variety of choices to tailor the properties. In particular, this approach suits scalability.

Index Terms— **Domain wall (DW) memory, DW pinning, geometrical pinning, non-geometrical pinning.**

I. Introduction

MAGNETIC hard disk drives (HDDs) fulfill a huge amount of continuously increasing data storage demands [1]. However, increasing areal density is a challenge for HDDs [2]–[8], despite the emergence of technologies such as heat-assisted magnetic recording (HAMR). Thus, it is very important to come up with a potential alternative [9]. One such technology is domain wall (DW) motion-based DW memory (or racetrack memory) technology [10], which has the potential for high storage capacities. For example, the existing technology, i.e., magnetic HDDs have areal density ~1 Tbpsi. With HAMR, it could go up to 4 Tbpsi. If one stacks 12 platters, a total capacity of about 40 TB can be achieved in HDDs. However, if one can fabricate nanowires at a pitch of 30 nm, and domain spacing of 15 nm, one can obtain an areal density of 2.8 Tbpsi. However, in racetrack memory, there is no spacing issue and we can stack layers. If 64 layers are stacked, we can achieve about 140 TB. Rather than a high density, a higher capacity is the advantage of racetrack memory.

Racetrack memory comprises a set of nanowires of ferromagnetic material, where information is stored in different domains. These devices can be fabricated horizontally, called horizontal racetrack, or perpendicularly, called perpendicular racetrack, with respect to the substrate plane. The magnetic domains in the nanowire are used to store the information. The domains with magnetization pointing in one direction (for example, pointing up in nanowire with anisotropy in a perpendicular direction) represent "1" and the regions with magnetization pointing opposite represent "0." The region between two magnetic domains is called the DW and acts as the boundary between two stored bits. The requirement of a DW memory can be divided into three parts: 1) writing, which means nucleating the domains in a particular direction at one end of the nanowire; 2) addressing the domains or equivalently DWs, i.e., moving the DWs along the racetrack; and 3) reading, which is the detection of bits [11].

Fig. 1 shows the schematic of writing, addressing, and reading process for DW memory devices. Writing can be performed using either a local magnetic field or spin-transfer torque effect from injected current [12]–[19]. Once the bit is written in a domain, they are shifted in the nanowire by means of an electric current or non-uniform magnetic field [20]–[25]. Reading of the bits in the nanowires is usually done using magnetic tunnel junction magneto-resistive sensing devices [10], [26].

Although this concept was proposed a decade ago, there are many challenges toward commercialization of DW memory. First, DW velocity, which determines the speed of the devices has to be improved. Second, the stability of the domains, which is an important parameter for deciding the lifetime of these devices, has to be considered [27], [28]. Third, the dimensions of the devices have to be scaled for high capacity, and finally, the motion of DWs and the DW positions have to be controlled. Although several studies have been carried out for observing DW dynamics and its motion under the magnetic field, electric field, and/or polarized current, controlling the position of DWs and their stability remains

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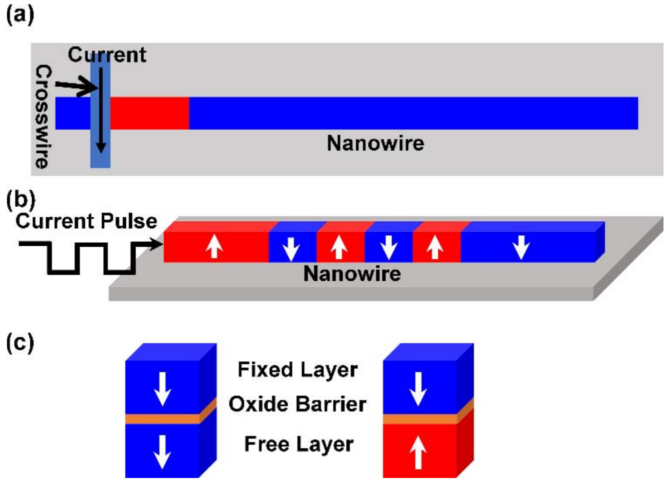

Fig. 1. Schematic of (a) writing using local Oersted field due to current flowing in the non-magnetic metallic crosswire, (b) moving the domains using current pulse via spin torque transfer for addressing, and (c) reading an information using magnetic tunnel junction magneto-resistive sensing devices.

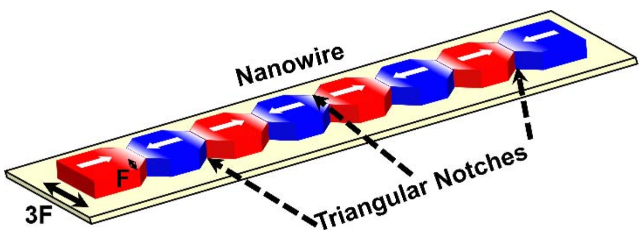

Fig. 2. Schematic of geometrically modulated pinning centers in the form of triangular notches introduced at desired positions along the ferromagnetic nanowire.

a big challenge [29]–[46]. The use of artificial pinning sites helps in designing the DW memory to the required size and density, which is very important from the high-density device point of view. In this paper, we provide an overview of some of these methods.

II. DW Pinning by Geometrical Methods

A. Controlled Pinning Using Notches

Controlling the DW motion along the nanowire has been demonstrated by fabricating notches at specific positions in the nanowire [44], [47], [48]. Fig. 2 shows a schematic of pinning sites in the form of the triangular notches. Kläui *et al.* [49] have studied DW pinning in ring-shaped permalloy nanowire with triangular notches using magnetoresistance (MR) measurements. Later on, Hayashi *et al.* [41] demonstrated controlled DW motion through a triangular notch in permalloy nanowire. They fabricated 10 nm thick permalloy nanowire with width ranging from 100 to 300 nm. Subsequently, they created a triangular notch at one edge of the nanowire. The depth of the notch was ~30% of the width of the nanowire. Since the magnetization direction in the soft magnetic material depends on the shape of the device, notches artificially change the magnetization structure locally and, hence, changes the energy required to move the DWs. They reported pinning and depinning of DWs at the notches upon the application of the magnetic field as well as electric current.

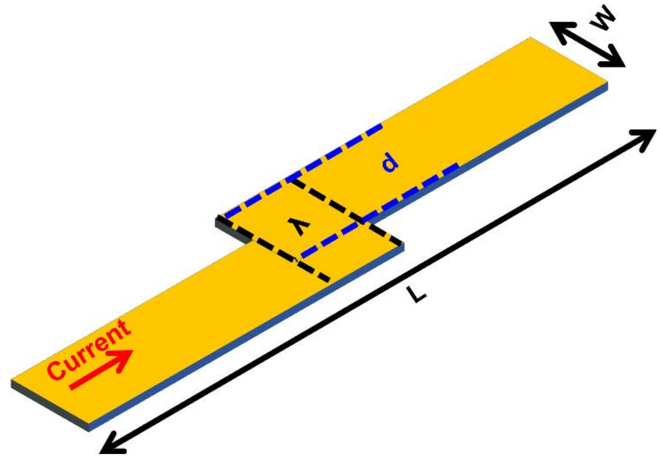

Fig. 3. Schematic of geometrically modulated pinning centers in the form of steps introduced at desired positions along the ferromagnetic nanowire.

Parkin *et al.* [10] demonstrated the motion of DWs along a nanowire with several triangular notches. When a series of the current pulse was applied to the nanowire, DW was pushed by spin transfer torque mechanism and stopped at the notches. The DWs were found to move in a direction opposite to that of the applied current.

Later, Huang and Lai [42] showed the dependence of depinning probability on the positions of the notches from one end of the nanowire in 2009. Endo *et al.* studied the pinning of the DWs in permalloy nanowires with double notches (at both sides) in the nanowire [50]. Moreover, Himeno *et al.* [51] studied the DW dynamics in antisymmetric notches in permalloy nanowire. A few researchers reported simulation results for different notch structures and dimensions. Bogart *et al.* [52] compared the DW dynamics for triangular and rectangular notches. They reported that the pinning field is different for triangular and rectangular notches. However, if notches are made with the smallest feature size F achievable with a particular lithography technique, the nanowire has to be bigger than F. This poses a limitation in the areal density of nanowires (as can be seen in Fig. 2).

B. Stepped Nanowires for Controlled Pinning

The idea of pinning DWs using a stepped nanowire was conceived in 2016 [53]. This paper reported the exact geometry of steps suitable for pinning and depinning of domain walls in in-plane magnetized nanowires. Fig. 3 shows the schematic of the concept. In this paper, we present micromagnetic simulation results for the DW pinning and depinning from a step notch in a magnetic nanowire with perpendicular magnetic anisotropy (PMA) under the influence of in-plane spin-transfer torque. To study the DW pinning and depinning behavior, non-thermal micromagnetic simulations were carried out with OOMMF (Object Oriented MicroMagnetic Framework) simulation software using a stepped nanowire for pinning DW in the desired position. The simulations illustrate that it is possible to control the DW by adjusting the nanowire step length and its width.

First, we present the results of DW motion when a current is applied to the conventional wire without any geometrical

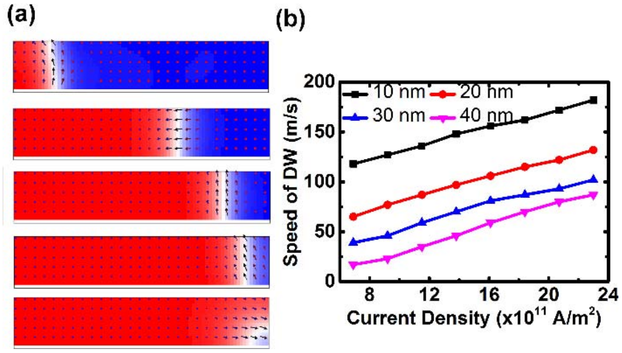

Fig. 4. (a) Movement of DW when current density $J = 6.9 \times 10^{11}$ A/m^2 is applied along the nanowire. (b) Plot of average DW velocity as a function of current density for w (width of the nanowire) = 10, 20, 30, and 40 nm.

modification [as shown in Fig. 4(a)]. Here in all cases, the DW is created and could be moved by spin-transfer torque effect from left to right. In Fig. 4(b), average DW velocity is plotted as a function of the current density "J" for different nanowire width values. We observe that an average DW velocity of approximately 150 m/s could be obtained for the case of narrow nanowires.

As a next step, we investigated DW dynamics in the stepped nanowire. The length ($L = 200$ nm), width ($w = 40$ nm) of the nanowire, and its thickness ($t = 3$ nm) were kept the same for all cases and magnetic properties (saturation magnetization $M_s = 802.5 \times 10^3$ A/m, anisotropy constant $K_u = 5.3 \times 10^5$ J/m^3, exchange constant $A = 2 \times 10^{11}$ J/m, damping parameter $\alpha = 0.02$, and non-adiabaticity factor $\beta = 0.02$) are the same as conventional wire. In this design, two parameters, namely, d (length of the step) and λ (width of the step) were studied. This is in order to investigate their influence on the pinning of DW. The DW is created as initial state in all simulation cases and the current is applied to move the DW. The λ parameter was fixed when the values of d were varied. We found that the DW was blocked in the stepped area for $d > 10$ nm and $\lambda < 15$ nm. Fig. 5(a) illustrates the pinning of the DWs at the step. Once the DW was pinned in the stepped area, we kept this state as the initial state to find minimum current J_{de} to depin the DW from the stepped position to reach the right edge of the nanowire. Fig. 5(b) and (c) is the summary of depinning current required for various values of λ and d.

From this study, we conclude that the step design provides control parameters such as the length and width of step to control the DW position. Also, the depinning current can be tailored by changing these two parameters.

III. DW Pinning by Non-Geometrical Methods

In this section, we describe some of the non-geometrical methods of DW pinning. One of the earlier approaches of non-geometrical methods of DW pinning was proposed by Polenciuc *et al.* [54]. They proposed that exchange bias field at regular intervals of a nanowire can help to pin the DWs in a controllable manner. The sample structure NiCr (6 nm)/IrMn (5 nm)/CoFe (20 nm) was used for achieving the exchange bias. They achieved exchange bias by fabricating antiferromagnetic wires over and below the

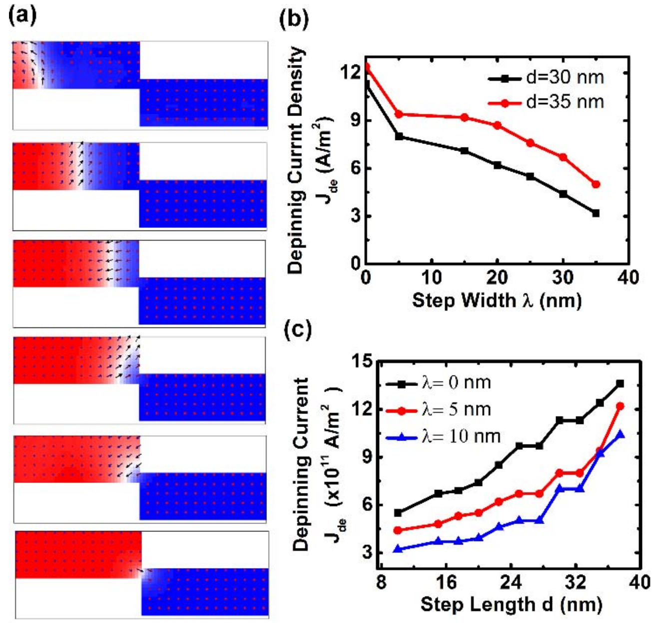

Fig. 5. (a) Movement of DW in stepped nanowire with step parameters $d = 30$ nm and $\lambda = 0$ upon the application of the current density $J = 4.6 \times 10^{11}$ A/m^2. Here, the DW is pinned in the step position and this state is used as the initial state for finding out the depinned current density J_{de}. (b) Graph of the depinning current density J_{de} versus the step width λ for different values of d. (c) Graph of depinning current density J_{de} versus the step length d for different values of λ.

ferromagnetic wire and subsequently by field cooling. The width of the cross wire was varied in the range of 1–2.5 μm. It is important to note that the antiferromagnetic wires were fabricated orthogonal to the ferromagnetic wire. Using this method, they reported the successful DW pinning at the pinning sites. The simplicity of design and fabrication makes this method considerable. We have carried out a detailed work on various other forms of non-geometrical methods of DW pinning, as described in the subsequent sub-sections A, B, and C.

A. Local Metal Diffusion

We have proposed a method of artificially creating pinning sites based on changing the magnetic properties of a ferromagnetic nanowire locally by controlled diffusion of non magnetic metal [55]. When crossbars of a different non-magnetic material are deposited on the top of a magnetic nanowire and are annealed, the heating conditions would cause a diffusion of elements (Fig. 6). This diffusion at selected locations would modify the magnetic and structural properties locally. Such a modification could be tailored to form pinning sites. By choosing the suitable material and annealing conditions, the pinning strength could be controlled. Preliminary results on the role of cross-bar materials in modifying the magnetic properties of NiFe have been reported earlier [55]. In that study, we optimized the favorable conditions at the thin film level, by depositing thin films of the type Si/(SiO_2)/$Ni_{80}Fe_{20}$ (10 nm)/X (5 nm) using dc magnetron sputtering, where X represents Ta, Cr, Cu, or Ru. We annealed these samples at temperatures ranging from 100 °C to 400 °C for 1 h. Upon a detailed study, we found

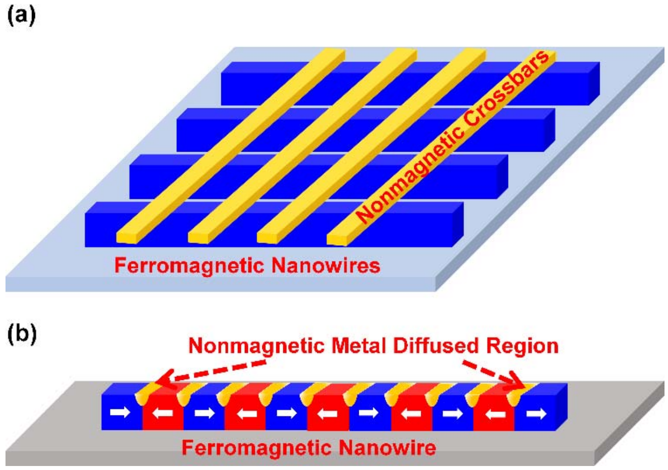

Fig. 6. (a) Schematic of creating pinning sites at the device level via fabricating ferromagnetic nanowire and non-magnetic cross bar. (b) Schematic illustration of the pinning sites along the permalloy nanowire.

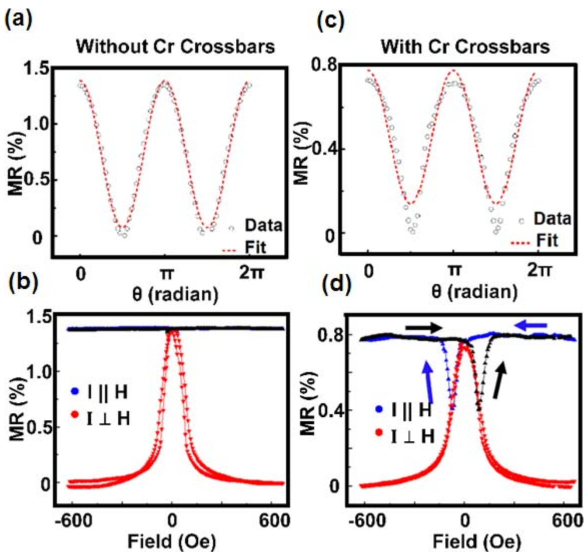

Fig. 7. (a) Resistance ratio MR versus θ (here, the angle θ is between current and magnetic field), the resistance ratio MR versus in-plane magnetic field applied along ($\theta = 0$) and perpendicular to NiFe wire direction ($\theta = \pi/2$) for (a and b) without Cr diffused and (c and d) Cr diffused NiFe nanowire.

Cr to be more effective in changing the magnetic properties upon annealing.

For demonstrating this concept at a device level experimentally, we fabricated 10 nm thick permalloy nanowire and then we overlaid Cr crossbars [Fig. 6(a)]. After this step, we annealed the samples for achieving diffusion of Cr into the permalloy nanowire [Fig. 6(b)].

We carried out anisotropy MR measurement for understanding the magnetic properties of NiFe magnetic wire with and without Cr diffusion. Fig. 7(a) shows the dependence of the MR on the angle between the direction of magnetization and the current orientation for NiFe wire. The red line is a fit to the well-known cosine dependence [56]. For the current parallel to the magnetic field, the MR is small. For current perpendicular to the magnetic field, a change in resistance value of $\sim$1.5% is observed. Fig. 7(b) shows the MR change when the magnetic field was swept from -600 to 600 Oe and the field was applied along and perpendicular to the nanowire. When the field was applied parallel to the current direction, a high resistance was observed and for field perpendicular to the current direction, a drop in the resistance was observed at high fields. A high magnetic field perpendicular to the nanowire orients the magnetization in the perpendicular direction to the current, and hence, a drop is observed. In the case of the magnetic field along the nanowire direction, the change in resistance is not significant, as the domains are swept rapidly, and hence, the magnetization is always parallel or antiparallel to the current direction.

In the case of NiFe wires with Cr pinning bars, the MR ratio is lower ($\sim$0.8%), which indicates the effect of Cr diffusion. Fig. 7(c) shows the angle dependence of MR on the angle between the direction of magnetization and the current orientation for NiFe wire with Cr crossbars. The results for the case of the current perpendicular to the field are similar with NiFe wire without Cr crossbars. However, the observed results for the case of the current parallel to the magnetic field are different and interesting. Two obvious dips are observed in the R–H curves as shown as [Fig. 7(d)]. The dips are due to the formation of reversed domains. Fields as high as 100 Oe, which are much larger than the coercivity are required to completely reverse all the domains. These results indicate that the regions with Cr are acting as a DW pinning center. When the large magnetic field (600 Oe) along the nanowire applied, the magnetization is saturated and parallel to the current, and the resistance is larger. Sweeping the magnetic field to opposite direction, the DW is nucleated and pinned at the Cr crossbar position, which is formed by local diffusion of Cr inside the NiFe. Correspondingly, less resistance is observed in R–H loop.

Although NiFe nanowires were investigated at first, materials of such type with a low anisotropy are not suitable for achieving high densities. Therefore, we investigated nanowires based on Co/Pd multilayers for high-density DW memory. We studied the effect of Cr diffusion for the case of Co/Pd multilayers, which exhibits (PMA). For obtaining high PMA, we fabricated 15 layers of Co/Pd.

Fig. 8 shows the in-plane and out of plane hysteresis loop of $(Co/Pd)_{15}$ after annealing at a temperature 400 °C for 20 min. From hysteresis loops, we can see that the samples exhibit PMA even after annealing, indicating that the annealing process does not deteriorate the PMA of Co/Pd multilayers. As the next step, we deposited a Cr cap layer on this film stack and annealed at a temperature of 400 °C for 20 min. This process resulted in the change of anisotropy direction from out-of-plane to in-plane direction as shown in Fig. 8(b). This is expected to be due to the interlayer mixing of Cr, Co, and Pd. We also investigated domains configuration of these samples using magnetic force microscopy (MFM). Fig. 9 shows the MFM domain maps of these samples annealed at different temperatures. Note that the annealing time is the same for all the samples. Domain maps of the samples annealed at 400 °C confirm our attribution. The absence of clear stripe domains in Cr diffused samples confirms the change of anisotropy direction from out of the plane to in-plane direction.

From these results, we proposed a method of changing the magnetic properties locally of a nanowire. This can be done

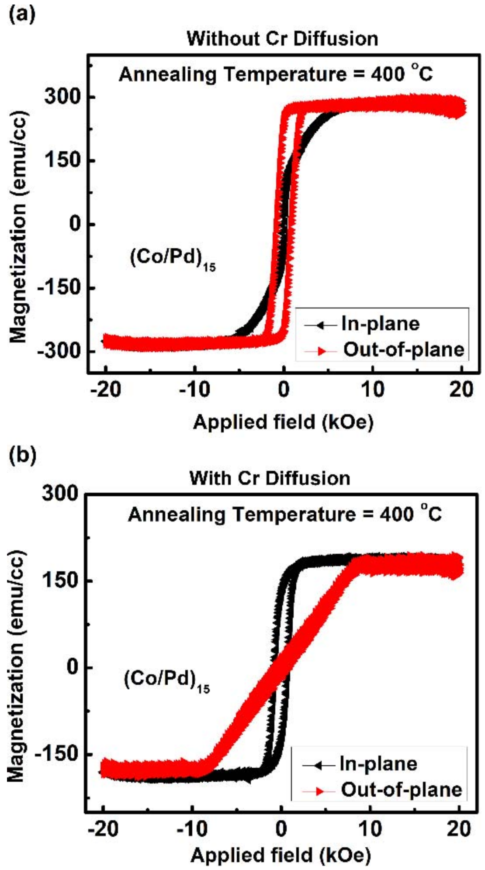

Fig. 8. Magnetic hysteresis loops of (a) $(Co/Pd)_{15}$ multilayer samples without and (b) with Cr cap layer annealed at 400 °C for 20 min.

by fabricating a Cr crossbar perpendicular to the ferromagnetic nanowire and then annealing. The magnetically modified region is supposed to act as pinning site for the ferromagnetic nanowire.

B. Ion Implantation

Ion implantation is a powerful technique for local modification of structural and magnetic properties of a ferromagnetic material through the movement of atoms in the lateral direction and across the interface [57]. Recently, we observed that the ion implantation of $^{14}N^+$ and $^{40}Ar^+$ decreases the anisotropy constant locally for masked $Co_{80}Pt_{20}$ and $Fe_{50}Pt_{50}$ magnetic thin films [58]–[60]. Thus, this is a potential technique for creating the pinning sites for the DW memory devices. Burn and Atkinson [61] reported Ga^+ ion irradiation on permalloy nanowires as a technique for creating the pinning sites. They reported a decrease in the magnetization upon the Ga^+ ion irradiation. A similar study was also carried out by Benitez *et al.* [62]. We have made an attempt to study the DW dynamics for Co/Pd multilayers, where pinning sites were formed using B^+ ion implantations (as illustrated in Fig. 10) [63].

At first, we performed micromagnetic simulations for testing our hypothesis. When an electric current with a density of 5×10^{10} A/m^2 was applied along a nanowire without pinning sites, the DWs propagated rapidly without stopping. When

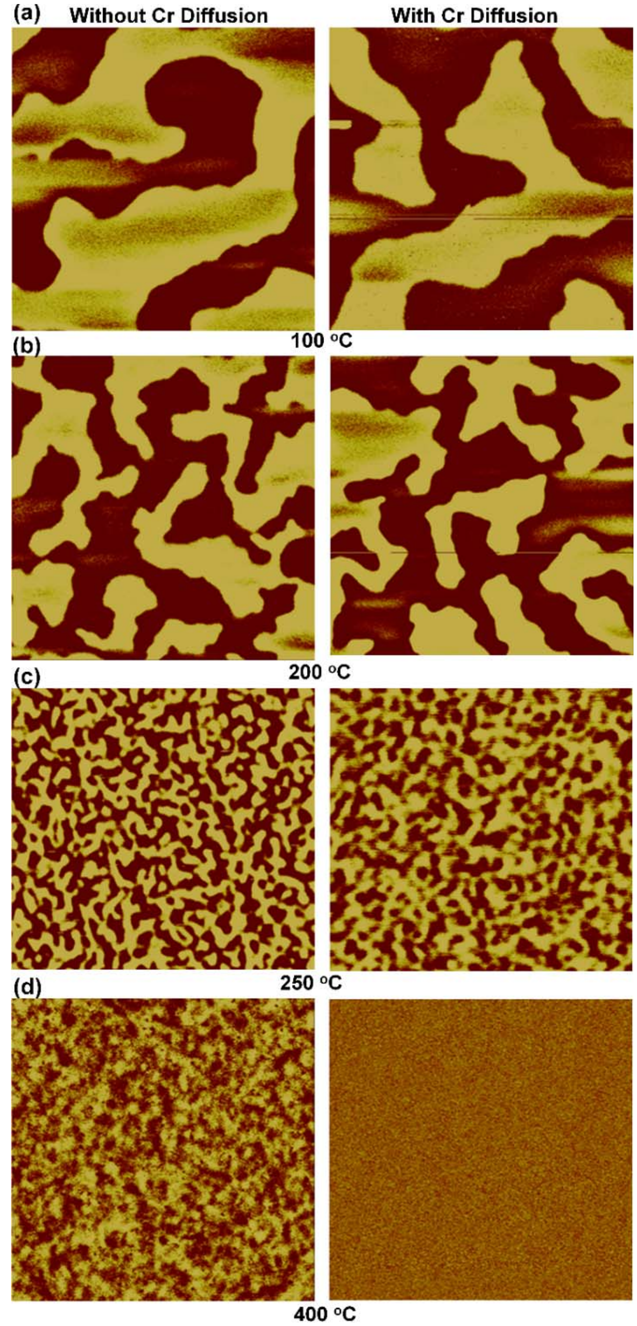

Fig. 9. MFM domain maps of $(Co/Pd)_{15}$ multilayer samples without/with Cr cap layer annealed at (a) 100 °C, (b) 200 °C, (c) 250 °C, and (d) 400 °C for 20 min.

we changed the magnetic properties locally, to represent the pinning sites, DWs stopped in those regions. Fig. 11(a) shows the pinning of the DWs at the magnetically modified region. In order to see the depinning of the DWs, we changed the applied current density and again determined the DW position at different simulation times. At around 2×10^{11} A/m^2, we noticed the depinning of DW.

In the second step, we fabricated the device for observing the DW pinning and depinning experimentally. For this purpose, we fabricated the nanowire and modified certain regions along the nanowire using B^+ implantation. Fig. 12(a) is an image of our device, which consists of the nanowire with

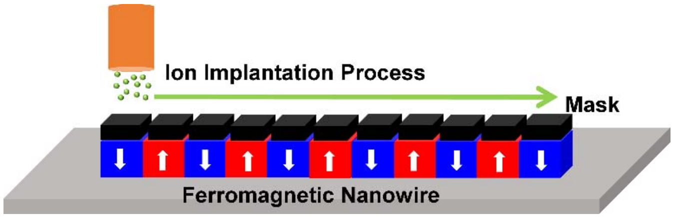

Fig. 10. Schematic of ion implantation process through mask for creating local modifications in magnetic properties along a ferromagnetic nanowire.

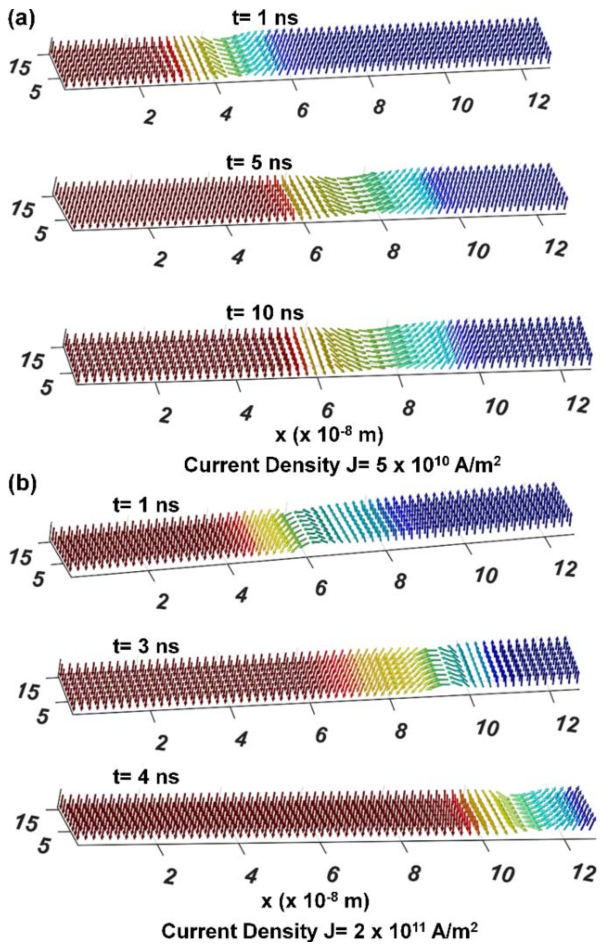

Fig. 11. Micromagnetic simulations for observing (a) DW pinning for applied current density $J = 5 \times 10^{10}$ A/m^2 and (b) DW depinning for applied current density $J = 2 \times 10^{11}$ A/m^2 in the (Co/Pd)$_{10}$ nanowire with ion implantation induced magnetically altered regions.

modified regions. After the injection of a DW through the injection line, a magnetic field of 900 Oe was applied in the $+z$ direction. Due to this field, the DW moved and stopped at the magnetically modified region [Fig. 12(b)]. When we increased the magnetic field to 920 Oe, the DW depinned and moved toward the end of the nanowire [Fig. 12(c)]. Thus, the modified region through the ion implantation helps to stop the DW and make the domain motion precise.

C. Tilted Magnetization by Exchange Interaction

In continuation to these studies, we have also proposed and demonstrated another method for pinning the DWs at the pinning sites based on exchange coupling between two layers

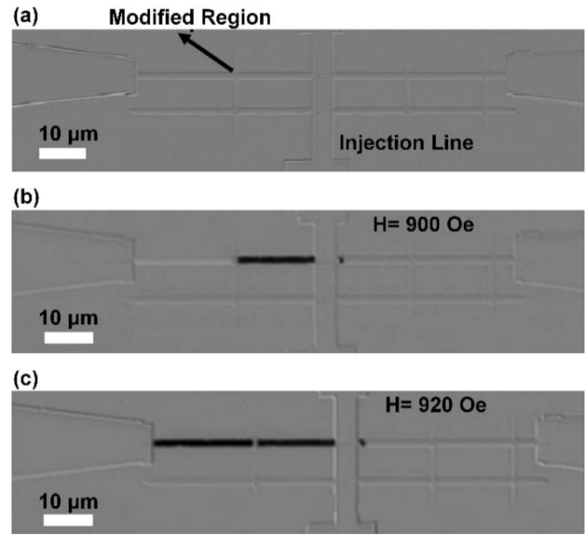

Fig. 12. (a) Schematic of the (Co/Pd) nanowire with magnetically modified (through B$^+$ ion implantations) regions, (b) pinning of the DW on the application of the magnetic field 900 Oe in the $+z$ direction, and (c) depinning of the DW after increasing the field to 920 Oe in the same direction.

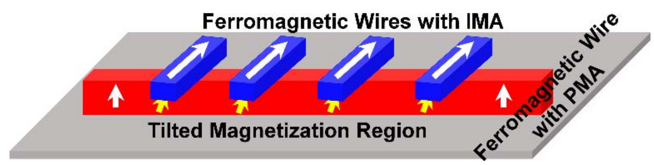

Fig. 13. Schematic illustration of creating pinning sites using exchange coupling between IMA and PMA ferromagnetic layers.

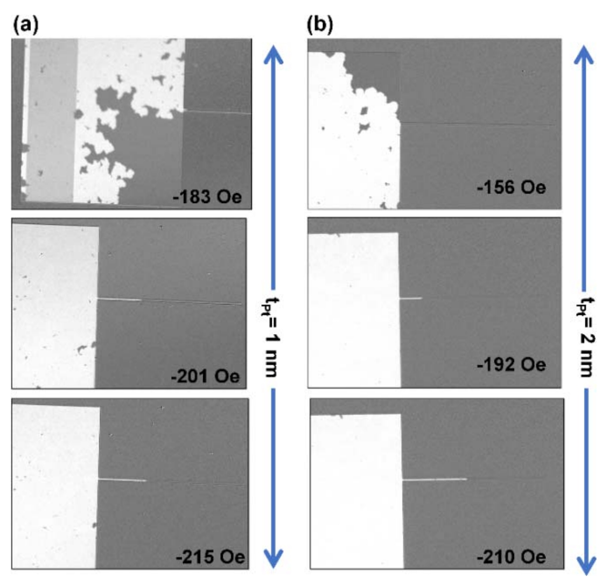

Fig. 14. Kerr microscopy images of (Co/Ni)$_2$/Pt (t nm)/Co samples showing (a) pinning for $t = 1$ nm and (b) no pinning for $t = 2$ nm upon the application of the reverse magnetic field.

with PMA and in-plane magnetization (IMA), respectively (as shown in Fig. 13). As (Co/Ni)$_2$ multilayers exhibit PMA and Co exhibit IMA, depositing these layers with a thin Pt spacer can alter the magnetization of (Co/Ni)$_2$ multilayers due to the exchange coupling. It is important to note that the thickness of Pt spacer decides the exchange coupling and, hence, the extent of tilting of magnetization in the $(Co/Ni)_2$ layer. In the thin film level, we optimized the thickness of the Pt layer and observed that the magnetization of $(Co/Ni)_2$ multilayer can be tilted for a Pt thickness of 1 nm. However, when Pt layer is 2 nm thick, $(Co/Ni)_2$ multilayers and Co layer are decoupled and cannot pin DW effectively.

To test the pinning at the device level, we first fabricated $(Co/Ni)_2$ nanowires with Pt as capping layer. Then, Co crossbars were fabricated to locally change the magnetization. As can be seen in Fig. 14(a), DW can be pinned at the field of −201 Oe and then depinned at the higher applied field, i.e., −215 Oe, for Pt thickness of 1 nm. On contrary, when Pt spacer layer thickness is 2 nm [Fig. 14(b)] DW shows continuous motion, i.e., DW does not get pinned. Thus, this method shows the potential to pin the DWs, but further studies are needed to understand this concept in detail.

IV. Conclusion

In this paper, we presented an overview of the methods used for the fabrication of pinning sites in the DW memory devices, which is very important for the controlled and reliable operation of these devices. The pinning sites can mainly be created in two ways: 1) locally modulating the shape of the nanowire and 2) locally changing the magnetic properties of the nanowire. The former requires complex lithography, which becomes more challenging when the size of the device shrinks. The latter is relatively easy, cheap, and provides a better control for researchers during the optimization process.

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