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2011 J. Phys.: Conf. Ser. 266 012079

(http://iopscience.iop.org/1742-6596/266/1/012079)

Dependence of pinning on domain wall spin structure and notch geometry

S Goolaup, S C Low, M Chandra Sekhar and W S Lew
Physics and Applied Physics Division, School of Physics and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371

E-mail: wensiang@ntu.edu.sg

Abstract. In this work, we present a systematic investigation of the domain wall spin structure and notch geometries on the pinning field strength. We observed that for transverse domain wall, pinning is strongly dependent on the transversely varying energy profile of the wall. Domain walls are pinned at notches only when the notch provides a barrier to the higher energy component of the domain wall. For all notch shapes investigated, we observed that when the notch height/nanowire width > 0.3, the depinning field reaches a maximum and remains constant. We also note that the pinning of a domain wall at a notch is markedly sensitive to the angle of the notch with respect to the domain wall.

1. Introduction

Magnetic domain walls in ferromagnetic nanowires are the focus of intense interest both from a fundamental perspective and due to their potential applications. Magnetic logic [1] and memory devices [2] based on domain wall (DW) motion and manipulation have been recently proposed and experimentally demonstrated. A key issue in the application of DW devices is the ability to manipulate the DW configurations using magnetic field [3,4] or spin polarized current [5,6]. As such, a detailed knowledge of the DW nucleation and propagation is needed. The control and manipulation of magnetic domain walls are the focus of intense research. Deliberately fabricated defects in ferromagnetic nanowires allow for the control of the position of DW as they create changes in the energy landscape which increase the propagation field. Artificial nanowire (NW) defect of different geometries acting as trapping sites have been investigated using both numerical simulation and experimental observations [7-10]. The strength of the pinning is directly correlated with the wall spin structure so that only the determination of its nanoscale spin structure will enable an in-depth understanding of the energetics governing the pinning strength. However, a detailed description of the pinning effect at the notch is still lacking.

In this work we present a systematic study on the propagation and pinning of transverse domain wall on the wall spin structure and notch geometry in nanowires. We observed that domain wall pinning is strongly dependent on the transversely varying energy profile of the wall. The pinning effect is highly effective when the notch provides a potential well to the higher energy component of the domain wall. For notch height/wire width > 0.3, the depinning field for the domain wall remains constant irrespective of the notch shape. We also observed that the angle of the notch with respect to the domain wall greatly determines the pinning strength of the notch.

2. Micromagnetic Simulation

The magnetization configuration and depinning processes were simulated using the Object Oriented Micromagnetic Framework (OOMMF) simulation software [11]. Domain wall pinning was simulated for a planar nanowire with various notch geometries and configurations. The structure simulated comprised of a large nucleation pad followed by a nanowire with a pointed end as seen in the schematic shown in Fig 1. The nanowire was 2um in length and 200 nm wide. The structure also comprises of a wire along the y-direction. This wire acts as a chirality filter to set the orientation of the transverse component of the domain wall generated. The position of the notch was set at 1um from the filter. The film thickness was maintained at 10nm. For the simulation, the parameters for Permalloy were used; saturation magnetization, Ms = 860 x 10^3 A/m, exchange constant, A = 1.3 x 10^{-11} J/m, with a cell size of 5 nm. The magnetocrystalline anisotropy was set to zero.

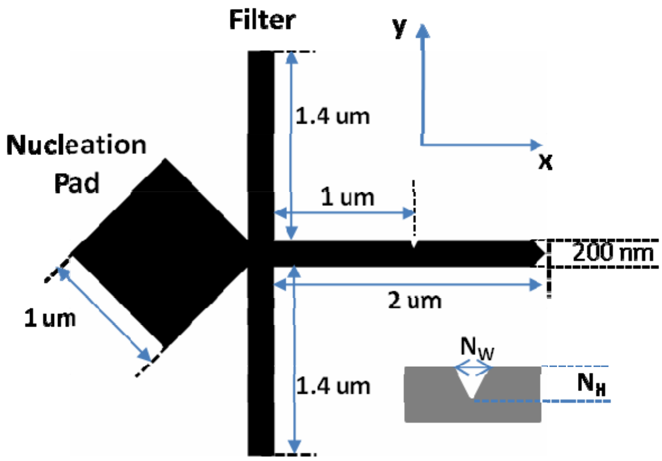


Figure 1: Simulated geometry consisting of a nucleation pad, a chirality filter and a nanowire of width 200nm. The notch is located at 1um from the filter. The notations used to define the notch geometry is also shown

For all the simulated geometries and domain wall type, a field of 1 kOe was applied along the positive(negative) x-direction to saturate the nanowire and then reduced to zero. This was followed by the application of small field of (-)200 Oe along the y-direction to set the orientation of the filter. The field was then increased incrementally in the x-direction to generate a domain wall in the wire. To obtain an accurate depinning field, the simulation parameters for the while were set, so that each step corresponds to a change of 0.5 Oe.

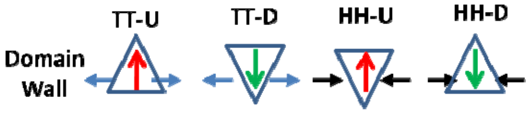
3. Results and Discussion

3.1. Domain Wall Chirality

In this section, we investigate the influence of domain wall spin structure on the pinning strength at notches along the nanowire. Four type of transverse domain walls (TDW) were generated during the simulation; Head-to-Head (HH) or Tail-to-Tail (TT) configuration with an “Up” or “Down” chirality as shown in Fig 2(a). The triangle encompassing the y-component of the wall, Fig 2(a), depicts how the transverse spin components are aligned within the TDW.

For this simulation, a triangular notch with notch width, N_W and height, N_H set at 66nm (~1/3 of nanowire width) was chosen. Three different types of notch configuration were investigated; with the notch positioned at the upper edge or/and lower edge of the nanowire as seen in Fig 2(b). The depinning fields, as extracted from the simulation, for the different types of TDW and notch configurations are shown in Fig 2(b). In our simulation, the field needed to inject a domain wall into the nanowire was (-)100 Oe. At this field, some DW simply passed through the notch without any evidence of pinning. For these DWs, we have set the depinning field to be equal to the nucleation field of (-)100 Oe.

(a)



(b)

Notch		Depinning Field (Oe)			
		TT-U	TT-D	HH-U	HH-D
1		-100	-257.5	257.5	100
2		-257.5	-100	100	257.5
3		-262.5	-262.5	262.5	262.5

Figure 2: (a) Four types of transverse domain walls (b) Depinning field strength for different notch configurations and domain walls. Domain walls that passed through the notch were assigned a value of (-)100 Oe which equals to the nucleation field of the domain wall.

When the notch is on the upper edge of the nanowire, Fig 2(b)-1, we note that the TDW with Tail-to-Tail with “Down” chirality (TT-D) and Head-to-Head with “Up” chirality (HH-U) are pinned. For both these wall, TT-D and HH-U, the field needed to depin from the notch has the same magnitude of 257.5 Oe. On the otherhand, the TT-U and HH-D simply passed through the notch.

For the notch on the lower edge of the nanowire, Fig 2(b)-2, we observed a reversal in the pinning in the TDW. In this case, the TT-U and HH-D are pinned at the notch, while requiring the same exact field of 257.5 Oe to depin from the notch. The HH-D and TT-U walls passed through the notch. For a double notch configuration, Fig 2(b)-3, we observed that all the TDWs are pinned and required a field of 262.5 Oe to depin. Interestingly, the field needed to depin the wall is marginally larger as compared to the field of single notch configuration by 5 Oe, an increase of less than 2%.

As the notch acts as a potential well, since all the TDWs have the same depinning field for a double notch geometry, this implies that all the TDWs configuration have the same total energy. The energy profile of the TDWs though may be different, as evidenced from the pinning of domain wall pairs at the notches on the lower and upper edge of the nanowire.

To better understand this result, we look into the energies of the domain wall. From the domain wall theory, the energy of the domain wall, E_{DW} is given by [13]:

$$E_{DW} \approx \frac{\pi^2 A}{\partial} + K\partial \qquad (1)$$

where A is the exchange stiffness constant, K is the anisotropy energy density and δ is the wall thickness. The domain wall thickness, δ, is a function of the number of planes (N) over which the magnetization rotates and the lattice constant (a). As such, for the transverse domain wall, δ vary as function of the width of the transverse component of magnetization, which has a triangular shape as seen in Fig 2(a). Thus, all the TDWs have the same energy but their transverse energy profile varies as a function on their specific spin structure. Due to the triangular shape of the transverse component of the TDW, the energy of the wall varies along the y-direction, with the base of the wall (triangle) having the highest energy. From Fig 2(b), we note that pinning is effective only when the notch provides a potential barier to the highest energy component of the domain wall.

3.2. Geometry Dependence

To gain a better understanding of the pinning mechanism in the nanowire structures, we have investigated of the notch geometry on the pinning field of the nanowires. For comparison, the notch depth was set to 66nm, while the notch width on the upper edge of the nanowire was kept at 133nm. Shown in Fig 3 is the depinning field for a Tail-to-Tail "Down" chirality (TT-D) transverse domain wall for all the different geometries. We observed that the depinning field is highly dependent on the geometry of the notch. The depinning field ranged from 212.5 Oe for a trapezoidal shaped notch to a maximum of 228 Oe for a triangular notch.

Geometry	Trapezium 	Rectangle 	Semicircle 	Triangle 
Depinning Field (Oe)	212.5	220	227.5	228

Figure 3: Depinning field strength for a Tail-to-Tail "Down" chirality for different notch geometries. The notch width was set to 133nm and notch height was 66nm.

3.3. Height and Width Variation

The depinning field has been predicted to increase with decreasing constriction width, implying that walls in narrower constriction are more strongly pinned [14,15]. In this section, we investigate the effect of different notch heights on the depinning field of DWs that are trapped at a notch. For this set of simulations, we have investigated the depinning field of a Tail-to-Tail TDW with "Down" chirality, TT-D at a notch on the upper edge of the nanowire. Four notch geometries as discussed in section 3.2 were investigated. In Fig 4(a), we present the plot of the depinning field as a function of the notch height,N_H to nanowire width, NW_W ratio, N_H/NW_W. For all the geometries investigated, we observed that the depinning field increases with the notch height, until a N_H/NW_W ratio of 0.3. Beyond this ratio, the depinning field remains constant, irrespective of the notch height and geometry. This is in contradiction of the assumption that as notch height increases, the depinning strength should increase. Our result, can be explained by looking at the energy profile of the TDW. As the transverse spin structure adopts the shape of an isoceles triangle, a height of 0.3 from the base of the wall, correspond to an area containing almost 50% of the wall energy. From section 3.1, in the double notch configuration, we have shown that once the higher energy component of the wall is impeded, the pinning of the lower energy component results in marginal increase in the depinning field.

We have further investigated the effect of the notch width on the depinning field of the domain wall. In Fig 4(b), we present the plot of the depinning field of a transverse down Tail-to-Tail (TT-D) DW for different notch geometries, as a function of the notch width to wire width, while the notch height is kept fixed. We observed a non-monotonic variation of the depinning field, with a maximum field 277Oe occurring at a N_W/NW_W ratio of 0.65. Further increase in the notch width leads to a gradual decrease of the depinning field until a N_W/NW_W of 1.5. Beyond this N_W/NW_W, the wall just passes through the notch with a depinning field of 100 Oe. This can be explained by the fact that the potential landscape as induced by the notch changes as the notch width increases. The notch can be seen as acting as an abrupt energy barrier to the domain wall. An increase in the notch width while maintaining fixed notch height, leads a gradual change in the width of the wire at the notch, as seen in the inset of Fig 4(b). Thus the angle of the notch with respect to the domain wall decreases, leading to a smoother change in the energy barrier. For the rectangular notch, an almost constant depinning field of 210 Oe is obtained for $N_W/NW_W > 0.5$. This can be explained by the fact that, for the rectangular geometry, the angle of the notch remains fixed irrespective of the notch width.

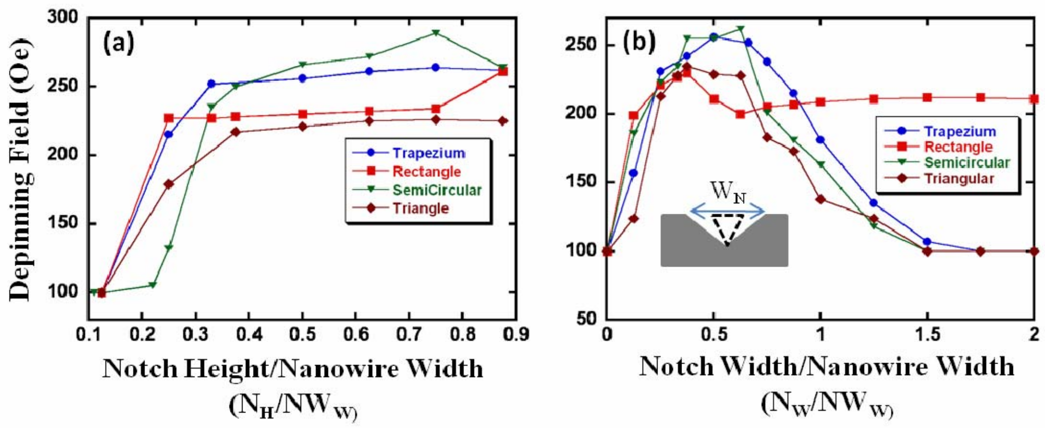


Figure 4: Depinning field strength for a Tail-to-Tail "Down" chirality for different notch geometries as a function of; (a) notch height, N_H while the notch width, N_W is kept fixed (b) notch width, N_W while the notch height, N_H is kept fixed

4. Conclusion

In summary, we have investigated the depinning of transverse domain wall at notches of different geometry and shapes. We note that the pinning of a domain wall at a notch is highly dependent on the energy profile of the domain wall. The pinning of a domain wall by a notch is most effective when the notch acts as a potential barrier to the higher energy component of the domain wall. We observed that depinning field strength does not scale with the notch height. Beyond a height to wire width ratio of 0.3, the depinning field remains constant. As regards to the width of the notch, we observed that the angle of the notch with respect to the domain wall determines the strength of the depinning field. The smaller the angle, the gradual is the change in the potential landscape, resulting in a decrease in the depinning field.

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