Asymmetric ground state spin configuration of transverse domain wall on symmetrically notched ferromagnetic nanowires

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We report that a ground state spin configuration around a notch of ferromagnetic nanowires can have either symmetric or asymmetric transverse domain wall structure depending on the notch geometry by means of micromagnetic simulation with a systematic variation in the notch aspect ratio. An asymmetric off-centered domain wall configuration becomes stable for a certain range of the notch aspect ratio. © 2010 American Institute of Physics. [doi:10.1063/1.3459965]

Understanding and controlling domain wall (DW) behavior in ferromagnetic nanowires have been extensively explored in recent few years for realization of spin devices based on DWs such as magnetic logic devices. It has been found that an inner structure of DW plays an essential role in governing the DW dynamics in ferromagnetic nanowires. The DW inner structure is determined mostly by the wire geometry. Introducing a structural constraint such as a notch onto ferromagnetic nanowires, thereby controlling DW propagation behavior in nanowires has been intensively examined. Numerous studies have been reported on the DW dynamics driven by an external magnetic field or by a spin torque in notched ferromagnetic nanowires. The spin configuration around the notched wire or the nanocostriction is reported to show another kind of magnetic wall, besides the Bloch and Néel walls, since the inner spin structure of DW is determined mostly by the geometry of the constriction rather than the material parameters due to the much smaller constriction cross section than the cross section of the wide wire region far from the constriction.

Several experimental observations have been reported to investigate a spin configuration of DW around notches or antinotches by means of an electron holography, a magneto-optical Kerr effect, a Lorentz microscopy, and a magnetic force microscopy. An idea has been proposed to utilize the DW pinning behavior around the notch as a multibit memory cell. The detailed dynamic behavior of the DW propagating under an applied field or a spin torque through the notch has been investigated whereas relatively few studies have been addressed to identifying the DW ground configuration around the notch. In most cases, the DW configuration has been considered to be symmetric around a symmetric notch or antinotch. Interestingly, it has been reported recently that the DW configuration could be asymmetric even around a symmetric notch. Asymmetric DW has been experimentally evidenced by an electron holography and a Lorentz microscopy, where the asymmetric DW configuration is considered to be originated from irregularities such as the edge roughness or from the effect of nonuniform magnetization to the spin curling structure at the antinotch. However, no systematic investigation has been devoted to the symmetric or antisymmetric ground spin configuration of the DW around notches, which could be very essential in designing spin devices utilizing the DW behavior.

We have investigated detailed spin configurations of the DW in the notched ferromagnetic nanowires by means of public micromagnetic simulation software, OOMMF based on the Landau–Lifshitz–Gilbert equation. The length of ferromagnetic nanowires in the present study is 2000 nm, the width is 200 nm, and the thickness is 5 nm. The simulation has been carried out with a systematic variation in triangular notch aspect ratio between the bottom and the height of the triangular notch. The height of notch d is fixed to be 50 nm for comparison and the length of bottom s has been varied from 30 nm to 400 nm to have a corresponding change in the aspect ratio d/s from 1.67 to 0.125. Transverse DW with a head-to-head spin structure is initially prepared to be positioned at the center of the notch and the system is relaxed spontaneously to reach a minimum energy without an applied external magnetic field. Considering the width and the thickness of the wires, the transverse DW structure is energetically preferred in all configuration of s and d/s of the present study. The cell size of the simulation is 2.5 × 2.5 × 5 nm³ and the damping constant α is set to be 0.01. The material parameters of permalloy are used with the saturation magnetization Ms of 8.6 × 10⁴ A/m, the exchange stiffness coefficient A of 13 × 10⁻¹² J/m, and zero magnetocrystalline anisotropy.

Without a notch, the straight wire of 200 and 100 nm width with the same material parameters as the notched wires in the present study exhibits a symmetric transverse DW, as expected. With an introduction of the notch, the notch plays as a strong pinning site and the DW is stabilized by being positioned around the notch. The representative ground spin configurations of the DW around the notch with variation in s from 50 to 400 nm are listed in Fig. 1. Since we consider fully symmetric notched wires keeping the left-right and up-down symmetries, it is expected to have the symmetric DW configuration as demonstrated in the figure for the case of s=50 nm, which holds as well for the cases of s less than 50 (s=40 and 30 nm). Interestingly, it is observed in the figure that the DW spin configuration becomes...
off-centered from the notch center, for example, in case of $s=75$ nm, where the tilted DW spin configuration appears obviously with the broken left-right and up-down symmetries. The trend of spontaneous broken symmetry is observed for the cases of $s=75$, 100, and 160 nm in Fig. 1, while the DW spin configuration then becomes symmetric again for the larger $s$ (400 nm).

To understand the transitional behavior of the DW configuration around the notch, we have analyzed the magnetic energies of the system with variation of $s$ from 30 to 400 nm, as depicted in Fig. 2(a). Since we adopted the material parameters of Permalloy, the magnetocrystalline anisotropy is set to be zero. The Zeeman energy is also zero because there is no external field. Thus, the total magnetic energy is the sum of the magnetostatic energy and the exchange energy. It is immediately noted in the figure that the magnetic energy densities are mostly dominated by the magnetostatic energy rather than the exchange energy.

On the other hand, the magnetostatic energy density exhibits a significant variation with respect to the $s$ value. For a comparison, we plotted total, magnetostatic, and exchange energy densities for a case of 200 nm width straight wire, as in Fig. 2(a). The energy density for notched wires are all less than the energy density of the straight wire, which is originated from the energy gain of the DW positioned around the notch. By being positioned around the notch, the gradually varying transverse components of the DW can be more stabilized by being more parallel to the notch edge. This reduces the generation of magnetic free poles on the wire edge, which reduces the magnetostatic energy significantly. The trend of the magnetostatic energy density is directly reflected in the trend of the total energy density, which implies that the magnetostatic energy gain is the main reason of the existence of the spontaneous off-centered asymmetric DW.

We divided the Fig. 2(a) into three regions depending on the symmetric/antisymmetric ground DW configuration. Region I represents a region where the symmetric DW configuration is the ground state for smaller $s$ (30–50 nm). Region II represents a region where the asymmetric DW becomes the ground state for $s$ from 60 to 150 nm. Region III represents a region where the symmetric DW becomes the ground state again for larger $s$ (>160 nm). At each region boundary, an abrupt change of the energy density is observed. For example in the boundary of the region I and II, the magnetostatic energy density and thus, the total magnetic energy density abruptly decreases as $s$ changes from 50 to 60 nm.

To understand further, we have analyzed the DW inner structure by characterizing the DW width. The horizontal line profiles of $M_y$ component normalized by the saturation magnetization $M_s$ are plotted for $s=50$ nm [Fig. 2(b)] and $s=150$ nm [Fig. 2(c)], where the horizontal line is selected to be parallel to the wire axis and the $M_y$ is the magnetization component transverse to the wire axis. In case of $s=50$ nm (region I), the line profile of the DW transverse component has a distribution with a peak almost centered at the notch as in the figure, where the zero DW position is select to be the
horizontal center of the wire. In case of \( s = 150 \) nm (region II), the line profile has a distribution with an obviously off-centered peak. The position of the DW is determined by averaging the peak positions while the width (\( \delta \)) of the DW is determined by taking the full-width half-maximum of the averaged line profiles of the transverse component. The position and the width of the DW with respect to \( s \) are plotted in Fig. 2(d).

It should be noted that there exist distinctive three regions both in the DW width and the DW position. The DW position is around zero in region I, shifted about few tens of nanometers in region II, and then converges to zero again in region III, which is exactly corresponding to the DW inner structure changes from the symmetric to the asymmetric and finally to the symmetric spin configuration around the notch. We like to stress that the DW width, \( \delta \), exhibits also three distinctive phases. In region I, \( \delta \) is about 150 nm, which is comparable to the value of 200 nm straight wire without notch. In region III, \( \delta \) is about 100 nm and seems to converge to the value of 100 nm straight wire without notch, which is expected because the larger \( s \) means the wire with a narrower width. In region II, \( \delta \) is in the middle of the values of region I and III. \( \delta \) suddenly decreases to about 130 nm and stays almost constant throughout the region, which means the inner structure of the DW is stabilized in this region with the off-centered asymmetric DW spin configuration.

We have further carried out the micromagnetic simulation for determination of potential wells and depinning fields in the notched ferromagnetic nanowires using the method described in Ref. 11. By slowly varying the external field then subtracting the Zeeman energy, it has been found that the energy landscape around the notch exhibits a symmetric shape of potential well overall as demonstrated in Figs. 3(a) and 3(b) for two representative cases of \( s = 50 \) nm (symmetric DW) and \( s = 150 \) nm (asymmetric DW). Interestingly, there exists a small energy barrier in the center of the potential well in case of the asymmetric DW ground state. This tiny center hill potential barrier provides a double well shape of which two minimum ground states are displaced off from the wire center, as shown in the inset of Fig. 2(b). The double well structure clearly explains the origin of asymmetric DW configuration.

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