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Unique depinning fields at symmetric double notches in a ferromagnetic permalloy nanowire

Sug-Bong Choe*

Department of Physics, Seoul National University, Seoul, Korea 151-742, Republic of Korea

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Abstract

Ferromagnetic domain-wall pinning and depinning mechanisms were investigated at permalloy nanowire notches using a micromagnetic calculation. A unique depinning field originated from the symmetric double notches irrespective of the wall polarity or the propagation direction, whereas several distinct pinning mechanisms appeared from single or asymmetric notches. The depinning field was principally determined by the exiting notch slope due to the dynamic narrowing of the domain wall thickness.

Keywords: Ferromagnetic nanowire; Domain wall; Depinning

Ferromagnetic nanowires have attracted much technological attention primarily due to their possible applications in memory and logic devices. Domain-wall memory devices potentially couple the performance of non-volatile solid-state random access memory with the storage capacity of hard disk drives [1]. Domain-wall logic devices could enable logical operational architecture based on metallic nanowires as an alternative to conventional semiconductor-based electronics [2]. To define the memory bits in these applications precisely, it is common to introduce structural constraints, such as notches [3–7], where the domain wall is trapped by reducing the internal energy. In this paper, we report a unique depinning field using symmetric double notches that is insensitive to the wall polarity and propagation direction, as opposed to single or asymmetric notches, which have several distinct depinning fields.

We examined ferromagnetic nanowires, such as those illustrated in Fig. 1. Both ends of each wire were tapered to sharp points to reduce edge domain formation [7–9]. The wires were 10 times longer than their width. Stray fields from the wire ends had a negligible effect on the depinning field (less than 0.2 mT), as shown by comparing them with longer wires. The notch, located at the center of the wire, consisted of two right-angle triangles with a common height h and base length $b_{L,R}$, where the subscripts L and R refer to the left and right triangles. Permalloy nanowires that were 5 nm thick and 150 nm wide were examined at a saturation magnetization of 8.6×10^5 A/m and an exchange stiffness of 1.3×10^{-11} J/m. The magnetocrystalline anisotropy was ignored.

A micromagnetic simulation was performed using OOMMF [10]. First, a head-to-head (or tail-to-tail) transverse domain wall was located at the notch by setting the initial magnetization configuration to a bi-domain state. Note that the head-to-head and tail-to-tail domain walls showed mirrored but identical behavior, and thus we report only the head-to-head domain walls in this paper. Then, the equilibrium state was calculated for each applied magnetic field in 0.1-mT increments. An internal maximum torque of less than $2 \times 10^{-4}\ M_S^2$ was used as the criterion for determining that an equilibrium state had been reached. To speed the relaxation, a relatively large Gilbert damping parameter (0.5) was used. We defined the depinning field as the field where the domain wall escapes from the notch and is followed by wire saturation in the field direction. To evaluate the notch, a cell size of 2.5 nm was chosen, which is sufficiently smaller than the exchange length (~5.3 nm).

*Tel.: +82 2 880 9254; fax: +82 2 884 3002.
E-mail address: sugbong@snu.ac.kr

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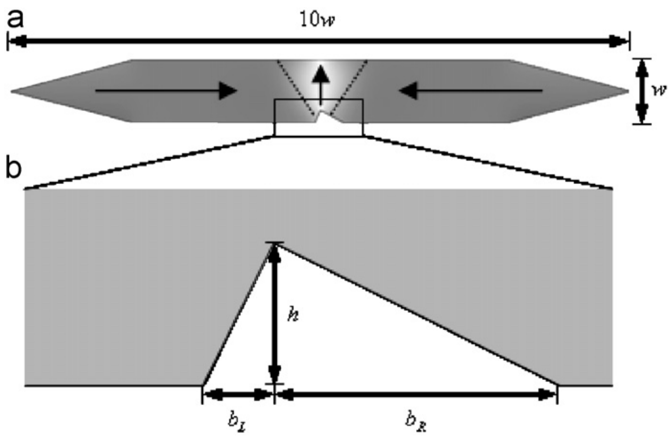

Fig. 1. The geometry of the (a) nanowire and (b) notch examined in the simulation. In (a), the arrows indicate the planar direction of the magnetization and the gray color corresponds to the $+y$ component of the magnetization. The dotted lines indicate the triangular shape of the transverse domain wall.

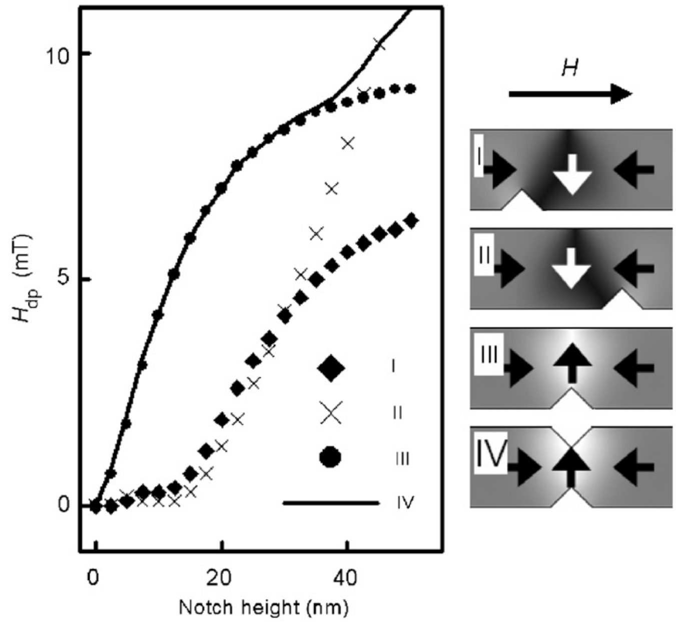

Fig. 2. The depinning field plotted against notch height for symmetric notches with a slope of unity for the cases described in the text. The images show the zero-bias equilibrium states for 40-nm-high notches. The arrows indicate the polarity in the wall.

The simulation results revealed three distinct pinned states for a single notch, as shown in cases I–III in Fig. 2. All three cases had a symmetric notch with a slope of unity, i.e., $h/b_{\mathrm{L,R}} = 1$. The images in the figure show the equilibrium states of the domain walls under zero field bias. Essentially, the wall was trapped at each vertex of the triangular transverse wall where the exchange energy was minimized by removing the non-collinear spin alignment. Note that geometrically cases I and II are identical, except for their mirrored configuration about the notch. In case I, with a field applied in the $+x$ direction, the domain wall needed only to escape from the notch, whereas in case II it had to get through the notch. Therefore, the latter experienced two critical mechanisms: overcoming an energy barrier of the right vertex to move into the notch and then depinning of the left vertex to escape from the notch. We denote the former as H_{R} and the latter as H_{L}. Both H_{R} and H_{L} were calculated as a function of notch depth. The simulation results showed that H_{R} (for case II) was initially negligible, but increased more rapidly than H_{L} (for case I) and the crossover took place at $h{\sim}30\,\mathrm{nm}$. Conversely, case III had polarity (or chirality in Ref. [11]) opposite that of the domain wall, which was pinned at the central vertex. Here, the polarity was defined as the sign of M_y in the wall. The depinning field, H_{C}, of the central vertex behaved completely differently from the others. A consistent experimental result was seen with a big notch [11].

Note that the wall polarity can hardly be controlled without an additional sizable magnetic field in the y direction, which might disturb the overall domain configuration and dynamics. Therefore, it is technologically wise to have symmetric double notches, as illustrated by case IV. A unique depinning field, irrespective of the wall polarity, is clearly expected from the symmetry. The depinning field, H_{D}, of the double notches was determined as the largest of the depinning fields of the three configurations. For notches smaller than 40 nm, the depinning field was uniquely determined independent of the field direction, or the domain wall polarity. Note that in this case there was no additional gain in the depinning field H_{D} for double notches compared with H_{C} for a single notch. In contrast to the unique depinning field of the triangular transverse domain walls in this study, the vortex domain walls, which generally appear on thicker and wider nanowires, are essentially pinned at one side due to their rectangular geometry, and thus they exhibit two distinct depinning processes depending on the magnetic field direction even for the symmetric double notches [11].

A closer look reveals that only the right slope of the notch plays a role in the pinning mechanism. Fig. 3 plots the depinning field of asymmetric notches against the notch height. Case I was an asymmetric notch with $h/b_{\mathrm{L}} = 1/2$ and $h/b_{\mathrm{R}} = 2$, whereas case II was the opposite. The images illustrate snapshots at the instant of depinning. For comparison, symmetric notches were examined: case III had $h/b_{\mathrm{L,R}} = 2$ and case IV had $h/b_{\mathrm{L,R}} = 1/2$. It is clear from the plot that case I matched case III and case II matched case IV. Note that the former two cases and the latter two cases had the same right slopes, respectively. Therefore, it is clear that the depinning field is determined only by the slope of the right (or exit) notch. This asymmetric behavior suggests technologically important opportunities for one-way diodes and two-way bipolar domain-wall channel devices. Further, micrometer-sized notches behave similarly [12–14].

We ascribe the asymmetric behavior of our nanometer-sized notches to the dynamic narrowing of the domain wall thickness. Under zero field bias, the domain wall was

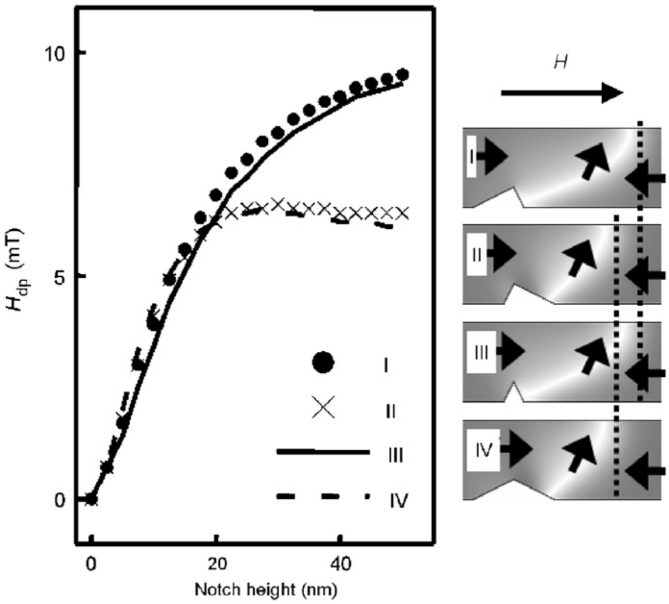

Fig. 3. The depinning field plotted against the height of asymmetric notches for the cases described in the text. The snapshots were taken at the moment of depinning for the 40-nm-high notches.

triangular, with a base length comparable to the wire width (refer to the images in Fig. 2). However, on application of a magnetic field, the domain wall was pushed to the side and became curved with a finite thickness, as seen in Fig. 3. At this moment, the wall had an almost uniform thickness of about 70 nm, irrespective of the wire width. Therefore, the finite-sized wall could interact only with the exiting side of the notch (when the notch was larger than the wall width). Clear asymmetric behavior appeared only for notches larger than the domain wall width; otherwise, the wall was insensitive to the small details of the notches and was affected only by the averaged vacancy of the notch. In the same sense, tiny imperfections resulted in a symmetric depinning field.

The finite wall thickness also caused the convergent behavior of the depinning field with increasing notch size; the domain wall was sensitive only to the local area around the exiting vertex. The dipolar interaction from the other side of the notch also diminished with increasing notch size.

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