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Depinning field from notches on Co/Pd multilayer nanowires with perpendicular magnetic anisotropy

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Domain-wall pinning and depinning mechanisms of ferromagnetc nanowires with perpendicular magnetic anisotropy were investigated. Micromagnetic simulation results revealed that the depinning field from notches were determined solely by the gap distance between the notches, irrespective to the wire width and the notch size. The double-notch wires exhibited two-fold décalcomanie domain patterns and one half patterns were identical to those of single-notch wires. Therefore, the double-notch wires showed the same depinning field compared to single-notch wires with half width.

1 Introduction

Ferromagnetic nanowires have been extensively studied in recent years, motivated by the possible applications to the domain-wall memory [1] and magnetic logic devices [2]. The information bits in the memory and logic elements are stored in the form of magnetic domains. For higher elements density as well as better spin-torque operation efficiency, the nanowires with perpendicular magnetic anisotropy recently drew technological attention because of their smaller domain size and narrower domain-wall width [3]. To define the precise position of the domain wall in these ferromagnetic nanowires, it is common to introduce structural constraints such as notches. Understanding of the pinning and depinning mechanisms from notches are thus of importance for better performance of the application. In this study, we investigated the domain-wall evolution dynamics in nanowires composed of Co/Pd multilayers which exhibits strong perpendicular magnetic anisotropy [4]. A micromagnetic model was adopted to predict the depinning field from single or double notches for various notch sizes and the nanowire widths.

2 Micromagnetic model

For this study we designed nanowire structures with double notches and single notch as shown in Fig. 1. The wire length was 10 times longer than the wire width w to avoid the dipolar interaction effect from the wire ends. The notches were located at the centre of wire in the form of the right-angled equilateral triangle as shown in the figure. The notch height was denoted by h and the gap distance between the notches was denoted by l. The domain wall was initially located at the notch under zero field bias. The equilibrium state was attained for each applied magnetic field with increment of 0.1 mT. At a certain field, the domain wall escaped from the notch. We denote this critical field as the depinning field. The depinning field was calculated for various wire widths and notch heights. The film thickness was fixed to 5 nm. The micromagnetic calculation was performed by OOMMF [5]. The internal maximum torque less

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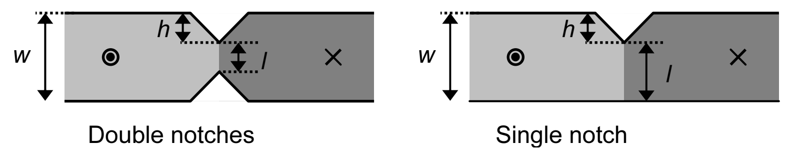

Fig. 1 Simulation geometries of the nanowires with double notches and single notch. The gray contrast corresponds to the magnetization direction.

than $2.0\times10^{-4}\ M_s^2$ was employed as the criterion of the equilibrium state. A relatively large Gilbert damping parameter (0.5) was used for fast relaxation. The cell size was chosen to be 2.5 nm, sufficiently smaller than the exchange length (~12.9 nm) in order to elaborate the notch. The saturation magnetization 2.1×10^5 A/m, the exchange stiffness 4.6×10^{-12} J/m, and the perpendicular magnetic anisotropy 1.0×10^5 J/m^3 were used in the simulation, which corresponds to the magnetic properties of the (0.2 nm-Co/1.1 nm-Pd) multilayers [4].

3 Results and discussion

Interestingly, the two types of the nanowires exhibited identical depinning fields. Figure 2 shows the depinning field from the (a) double notches and (b) single notch with respect to the notch height for several wire widths. It is interesting to see that both plots show almost identical dependences of the depinning field on the notch height. The correspondence existed between the two types of nanowires where the double-notch nanowires had exactly twice wider than the single-notch nanowires. To demonstrate the correspondence some values of the depinning field are listed in Table 1.

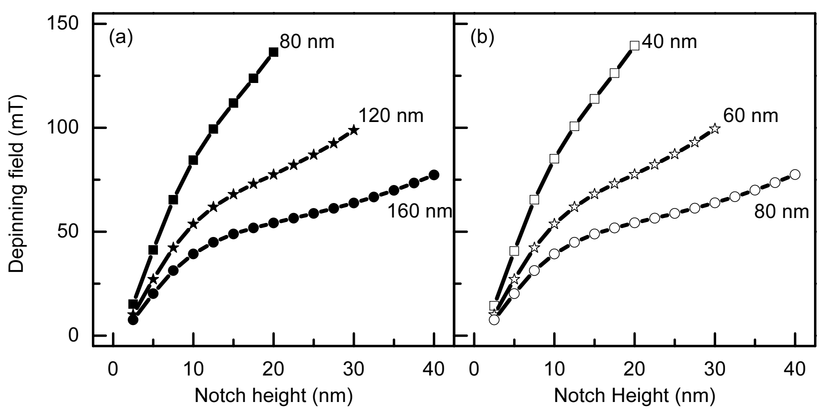

Fig. 2 Depinning field of the (a) double notches and (b) single notches with respect to the notch height for several wire widths.

Table 1 Some selected values of the depinning fields for double notches and single notches.

(a) double notches

h \ w	120 nm	160 nm
5 nm	27.1 Oe	20.2 Oe
10 nm	53.7 Oe	39.3 Oe
15 nm	68.0 Oe	48.9 Oe
20 nm	77.5 Oe	54.2 Oe

(b) single notch

h \ w	60 nm	80 nm
5 nm	27.1 Oe	20.2 Oe
10 nm	53.7 Oe	39.3 Oe
15 nm	68.1 Oe	48.9 Oe
20 nm	77.6 Oe	54.3 Oe

A close look on the domain configuration revealed that the correspondence was ascribed to the geometrical symmetry. Figure 3 shows the simulated domain-wall configuration for (a) double-notch wire and (b) single-notch wire. The former was 160-nm wide and the latter was 80-nm wide. All notches were 25-nm in height. Both the snapshot images were taken at equilibrium state under an external magnetic field (=58.7 Oe), which was 0.1 Oe smaller than the depinning field.

For double-notch nanowire as shown in Fig. 3(a), the magnetic field pushed the domain wall to a side and the domain wall was bended into a circular arc with two end points trapped at the notch slopes. The domain wall crossed the notch slopes at nearly right angles. With increasing the external field up to the depinning field, the domain wall moved further along the notch slopes and consequently, escaped from the notches. On the other hand, the single-notch nanowire was geometrically one half piece of the double-notch nanowire as seen in Fig. 3(b). Interestingly enough, the single-notch nanowire exhibited the identical domain pattern, which exactly matched to the half piece of the double-notch nanowire. Both the single and double-notch nanowires showed identical domain evolution patterns with respect to the strength of the external magnetic field and consequently, had the same depinning field.

Another interesting finding was that there existed a universal law of the depinning field. Figure 4 shows the depinning field with respect to the gap distance l between the notches. Surprisingly, all the values gathered into a single straight line. The straight line was best fitted by

$$H_{dp} = a \cdot l^{-0.84}, \tag{1}$$

for double-notch wires, where $a = 3.0$ [T·nm$^{0.84}$]. The fit for the single-notch wire was given simply by replacing l in Eq. (1) by $2l$, in accordance with the symmetry argument discussed above. This fit held only when both the gap distance l and the notch size h were larger than the domain-wall thickness. The domain-wall thickness was measured to be about 15 nm from the simulated domain images.

It is interesting to note that the depinning field was independent to the nanowire width or the notch size but given by a function of the gap distance. It provides an insight on the depinning mechanisms: the depinning field was mainly determined by the process to tear off the domain wall from the apexes of the notches. Once the domain wall starts to move from the apexes, it spontaneously passes the notch slopes under the same external field and finally escapes from the whole notch.

Fig. 3 Simulation results of domain wall configuration at the instant of depinning from (a) double notches and (b) single notch. The grey contrast corresponds to the y-component of the magnetization.

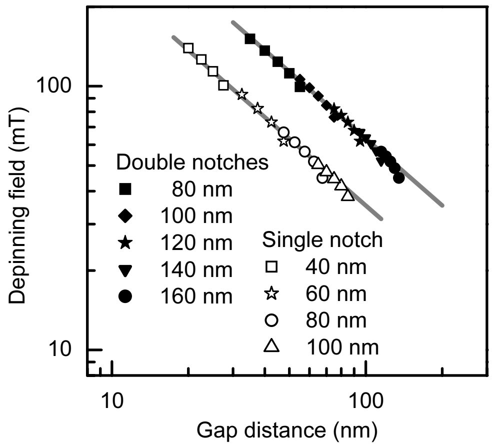

Fig. 4 Depinning field with respect to the gap distance for double and single

4 Conclusions

We investigated the depinning field from notces of ferromagnetic Co/Pd multilayers with perpendicular magnetic anisotropy. The single-notch nanowires and the double-notch nanowires exhibited identical and two-fold symmetric behaviour in domain-wall evolution mechanisms and showed the identical depinning field. The depinning field was determined solely by the gap distance, irrespectively to the wire width and the notch size.

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