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Magnetoresistance Detection of Vortex Domain in a Notched FeNi Nanowire *

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Revealing the physical nature of vortex wall (VW) behavior in magnetic nanostructures has been of great importance for future device concepts. Here we introduce the superior properties of VW in a notched FeNi nanowire under the action of an electronic current. The pinning-dependent VW propagation is demonstrated by a successive in-field magnetic force microscopy, an anisotropic magnetoresistance measurement, as well as micromagnetics. Based on the developed method, the propagation of VW can be effectively captured by monitoring the change of magnetoresistance in the FeNi nanowire, which sheds light on the development of future spin-based devices.

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Discovering the kinetic mechanisms of magnetic domain walls (DWs), such as formation, movement, intrinsic pinning, and spin transfer torque, has been attracting considerable attention due to their extensive applications for advanced magnetic devices.[1−5] One of the most fascinating study topics concentrates on one-dimensional systems, such as a patterned nanowire, which has been considered as a model system to investigate the mechanisms of DWs controlled by magnetic field or electronic current.[6,7] Recently, some groups have studied the dynamical behavior of vortex walls (VWs) in magnetic nanowires with pinning barriers.[6−9] It is found that the pinning sites can interact with the vortex core so that the VW behavior appears as step-like or point-like features.[10,11] The result proposes a subject regarding whether or not the VW behavior could be helpful for investigating the intrinsic pinning sides of real materials such as defects, or the intrinsic magnetic properties such as hysteresis loops. As a result, the investigation into pinning-dependent VW behavior in a one-dimensional nanowire proves to be urgent for material design and device concept.

In this Letter, the behavior of VWs under a spin-polarized current in a notched FeNi nanowire is demonstrated by in-field magnetic force microscopy (MFM) and the anisotropic magnetoresistance (AMR) measurement. Based on the developed method combined with micromagnetics, the propagation of VWs can be effectively captured by monitoring the change of magnetoresistance in the FeNi nanowire.

Ta (3 nm)/$Ni_{80}Fe_{20}$ (30 nm)/Ta (3 nm) films are deposited on oxidized Si substrates by the magnetic sputtering deposition method with base pressure of 3×10^{-7} Torr. The thin films were etched into the rectangular nanowires with length of 9 μm and width of 300 nm using an electron beam lithography and Ar ion-beam etching system. The thin films with the Cr (3 nm)/Au (30 nm) structure are used as the electrical contacts, which can be prepared by electron beam lithography in the second step. The magnetic domain structure can be captured by a successive in-field MFM.[12] The spin-transfer-toque induced VW motions can be evidenced by the AMR measurement combined with micromagnetics.

Figure 1(a) shows the scanning electron microscopy (SEM) measurement of the notched FeNi nanowire, with the Au electrodes (BB′) as well as the contact lines for detecting the AMR effects. A notch was created between the two electrical contacts (BB′) to pin the VW. Figure 1(b) shows the MFM images of the nanowire captured with or without the VW at the notch, respectively. The MFM imaging was performed on the nanowire demagnetized with a magnetic field perpendicular or parallel to the wire axis, and the details of imaging the magnetic vortex via a successive in-field MFM can be found in our previous work.[12] Figure 1(c) shows the micromagnetic result of the nanowire demagnetized with a magnetic field perpendicular to the wire axis, indicating a head-to-head VW structure at the notch, and the micromagnetic model and simulation parameters can be seen in the following. Figures 1(d) and 1(e) show the variation of magnetoresistance versus the external magnetic field of the FeNi nanowire with or without the VW at the notch. The resistance can be measured by applying a dc current of 50 μA and a magnetic field H along the wire axis, and the resistance change of the wire can be defined as $\Delta R = R(H) - R(0)$. First, the wire has been demagnetized parallel to the wire axis.

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In this case, no VW can be observed at the notch as evidenced by the in-field MFM. The AMR plot of the wire is presented in Fig. 1(d). It is seen that the AMR of the wire presents nearly constant values in the absence of VWs. Secondly, the wire was demagnetized perpendicular to the wire axis, and a VW with a clockwise structure can be successfully captured at the notch by the in-field MFM. In this case, the AMR plot of the wire can be seen in Fig. 1(e). It is noted that the AMR remains nearly constant at the magnetic field below 10 mT. Further increasing the magnetic field drives the VW to pass through the notch and annihilate at the end of wire. Meanwhile, ΔR rises abruptly as the field strength is greater than 10 mT, as seen in Fig. 1(e). The measured resistance difference in the presence/absence of VWs shows about 0.2 Ω (in the presence/absence of VWs, the resistance shows about 110.4/110.6 Ω), which agrees well with the VW resistance of the FeNi strip.[13] The pinning of a VW at the notch leads to a reduction of resistance, which can be explained by the AMR effect. It is known that the AMR of the FeNi wire depends on the angle between current flow and magnetic orientation. For FeNi ferromagnetic materials, the AMR ratio is defined as $\mathrm{AMR} = (\rho_1 - \rho_2)/\rho_2$, where ρ_1 (ρ_2) is the resistivity as the magnetic moment is pointing parallel (perpendicular) to the current flow (in the case of FeNi, the AMR ratio is greater than 0). In the presence of clockwise or anti-clockwise VW at the notch, the VW contains a magnetic moment perpendicular to the current flow, therefore, causing the reduction of resistance. Based on the experimental results, the detection of VW can be realized by an electrical control, which sheds light on the development of spin logic devices.

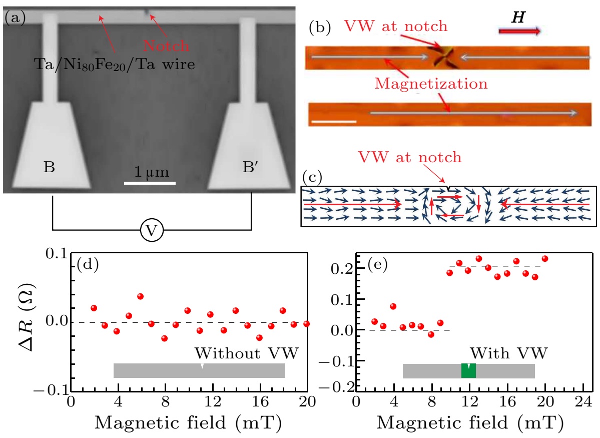

Fig. 1. (a) The SEM image of the nanowire incorporated with Au contacts for detecting the AMR effects. A notch was created between the two electrical contacts (BB′) to pin the VW. (b) The MFM images of the nanowire captured with the presence/absence of the VW at the notch, respectively. (c) The micromagnetic results of the DW structure, indicating a head-to-head VW structure of the wire. [(d), (e)] The AMR plots in the presence/absence of the VW at the notch.

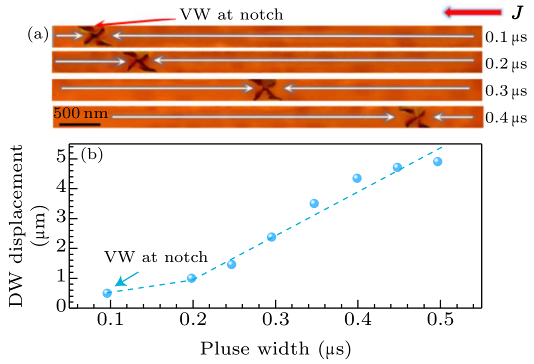

Fig. 2. (a) Observation of VW propagation under an electrical current pulse. The current pulse flows through the wire with a current density ($J = 1.2 \times 10^{12}$ A/m^2) and time duration ranging from 0.1 to 0.5 μs. (b) The DW displacement with respect to the time duration of a current pulse.

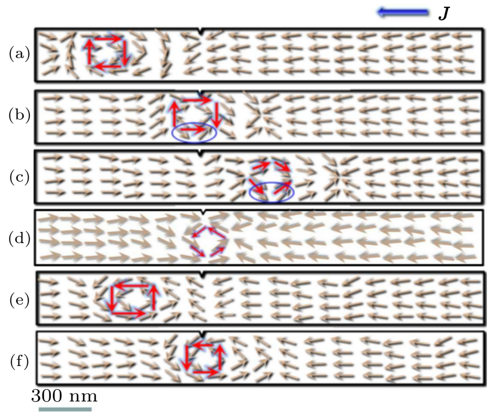

Fig. 3. (a)–(f) The time-evolution of the DW motion near the notch induced by a spin transfer toque.

Next, the kinetic mechanisms of VW along the wire are investigated by an electrical monitoring system combined with micromagnetics. The current pulse flows through the wire with a current density $J = 1.2 \times 10^{12}$ A/m^2 and time duration ranging from 0.1 to 0.5 μs, as shown in Fig. 2(a). The 'pinwheel' MFM contrast is related to the VW structure, in which the magnetization rotates within the film plane, leading to the gathering of magnetic charges at the VW. In the presence of an electrical current pulse, the motion of the VW is effectively motivated, and the spin-transfer torque plays a major role in determining the VW creep. Figure 2(b) presents the VW displacement with respect to the time duration of a current pulse. It shows a nearly linear relation between the VW displacement and the time duration, and the slope of the curve represents the averaged VW velocity (about 13 m/s) along the wire axis. It is also found that the velocity of VW reduces when passing through the notch, due to the pinning barriers for hindering the VW motion. To obtain a physical insight into the VW creep near the notch, the spin-transfer torque induced VW motion has been simulated by micromagnetics. The studied model was set to be a 2.5 μm-long, 0.3 μm-wide, and 0.03 μm-thick rectangular shaped wire. The following parameters were used: the Gilbert damping constant 0.01, a saturation magnetization 850 emu/cm^3, the magnetocrystalline anisotropy constant 1.55×10^4 ergs/cm^3, the driven current density $J = 1.2 \times 10^{12}$ A/m^2, and the electrical current pulse of 0.1 μs, respectively. The calculated magnetization patterns are indicated in Figs. 3(a)–3(f). When the VW arrives at the notch, the VW structure deteriorates due to the pinning effect, leading to the formation of an anti-vortex core (Fig. 3(b)); the mechanism of the formation of an anti-vortex can be seen in the Supplementary Materials, section 1. As the DW firstly goes through the notch, the anti-vortex core grows up and propagates along the wire (Fig. 3(c)). Further propagation of the anti-vortex core would lead to a regression of DW motion passing through the notch (Figs. 3(d)–3(e)), finally the motion of VW stops and the wall pins at the notch (Fig. 3(f)), and the mechanism of VW motions around the notch can be seen in the Supplementary Materials, section 2. Similar behavior can also be found in the field-induced VW propagations in the presence of a magnetic pulse field. The micromagnetic simulation shows the physical insight of the pinning-dependent VW features driven by a magnetic field or electronic current, illustrating that the strength of pinning points should significantly influence the VW behavior, such as formation, movement, and propagation, which is crucial for material designs and device concepts.

In summary, Ta (3 nm)/$Ni_{80}Fe_{20}$ (30 nm)/Ta (3 nm) films have been prepared and etched into nanowires with length of 9 μm and width of 300 nm using an electron beam lithography and Ar ion-beam etching system. The behavior of VWs under a spin-polarized current in a notched FeNi nanowire has been demonstrated by an in-field MFM and the AMR measurement. In the presence of an electrical current pulse, the fluctuations of pinning strength greatly modulate the spin-transfer torque induced VW creep. As the VW propagates, the presence/absence of the VW leads to an abrupt change of magnetoresistance due to the positive AMR ratio of NiFe nanowires. Our results show the physical insight of the VW behavior, and will shed light on the development of future spin-based materials and devices.

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Supplementary Materials: Magnetoresistance detection of vortex domain in a notched FeNi nanowire*

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(A) The mechanism of the formation of anti-vortex core

A common understanding of the interaction between the domain wall and notch is based on the pinning potential of the notch. For a triangular shaped notch, as shown in Fig. S1, when the vortex wall (VW) arrives at the notch, the magnetic charges appear at the triangular edges of the notch, for example, the positive magnetic charge concentrates at the left side edge while the negative charge forms on the right side. Therefore, VW structure deteriorates due to the pinning field arising from the notch, leading to the formation of an anti-vortex core inside the VW structure.

(B) The mechanism of forward and backward motions of VW around the notch

To better understand the mechanism of forward and backward motions of VW around the notch, the time variations of the VW displacement, total energy (E_{tot}), exchange energy (E_{ex}) terms have been studied, as shown in Fig. S2. Once an anti-vortex core is formed at the notch, it continuously moves along the nanowire owing to its gyrotropic motion. In the process of its gyromotion, E_{ex} nearly remains unchanged, E_{tot} first decreases according to the variation of VW structure, and then increases due to its gyrotropic motion, therefore the VW moves first forward and then backward, respectively, as evidenced by the trajectories shown in Fig. S2.

Figure S1

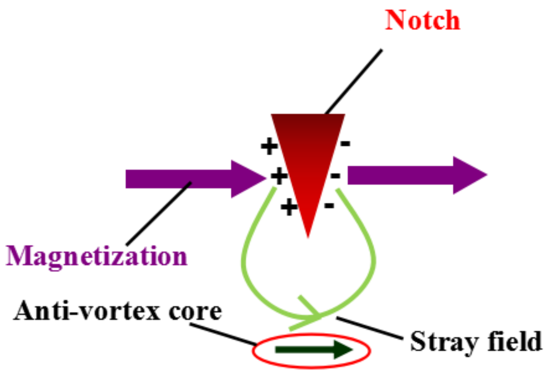

Figure S2