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Cyclic resistance change in perpendicularly magnetized Co/Ni nanowire induced by alternating current pulse injection

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ABSTRACT

We report on cyclic anisotropic magnetoresistance change induced by current pulse injection in perpendicularly magnetized Co/Ni nanowire. By alternating the polarity of the injection pulse, domain walls (DWs) can be deterministically created and annihilated within the nanowire. The injection induces a combined effect of spin transfer torque and Oersted field that leads to simultaneous creation and driving of DWs in the nanowire. DW created by single pulse injection exhibits a fixed depinning field. For multi-pulse injection, the depinning field increases and this is ascribed to the formation of DWs with opposite chirality.

1. Introduction

Magnetic nanostructures with perpendicular magnetic anisotropy (PMA) have attracted strong interest for the development of domain wall (DW) based devices [1–3]. Controlled creation, pinning, and driving of DW is crucial for the realization of DW memory [4]. The creation of DW in PMA nanowire can be achieved via in-line or field-based injection method [5,6]. For the in-line injection method, electrical current is pulsed through a nanowire comprising of two distinct regions with in-plane and out-of-plane magnetic anisotropy [7]. The spin transfer torque effect at the boundary between the two regions results in the creation of a DW within the nanowire [8]. On the other hand, the field-based injection utilizes local Oersted fields generated from a current-carrying strip line to enable switching of localized magnetization, and has been widely reported in PMA DW study [9]. The preferred DW configuration in PMA nanowire is either Bloch or Néel wall configuration. For a PMA nanowire, the DW configuration can be influenced by the Dzyaloshinskii-Moriya interaction (DMI) or spin torques effect in asymmetric PMA structure [5,10–13]. The properties of the created DW in the nanowire depend on various parameters, such as the amplitude and duration of the current pulse [14].

There are several ways for carrying out electrical detection of DW in the nanowire. The created DW can be detected by the change in Hall voltage, as the DW passes through a Hall bar [15–18]. The DW properties can be inferred via the Hall resistance change that is induced by DW propagation or pinning in the vicinity of a Hall bar [19,20]. To date, direct electrical detection of DW in PMA nanowires has been limited. Franken et al. measured the DW resistance using a combination of Wheatstone bridge and AC lock-in technique [21]. Discrete unequal steps in nanowire resistance were observed when DWs were nucleated and annihilated in a Pt/Co/Pt PMA nanowire.

In this work, we report on the direct detection of DW via anisotropic magnetoresistance change. DWs are created by current pulse injection through the nanowire. The combined effects of spin transfer torque and Oersted field lead to local reversal of the magnetization at the injection line. By alternating the polarity of the injection pulse, DWs can be deterministically created and annihilated within the nanowire. We show that the injection technique allows for a maximum of two DWs to be present within the system. The increase in the depinning field is correlated with the number of current pulses applied to generate the DW.

Abbreviations: DW, domain wall; AMR, anisotropic magnetoresistance.

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2. Result and discussion

Multilayered Ta(3 nm)/Pt(3 nm)/[Co(0.25 nm)/Ni(0.5 nm)]$_{\times 4}$/Co(0.25 nm)/Ta(3 nm) structures were grown on Si/SiO_2 substrate using sputtering deposition techniques. The magnetic thin film stack was patterned into nanowires of 6 μm long and 500 nm wide, using a combination of electron beam lithography (EBL) and Ar^+ ion etching techniques. A Ta Hall bar structure was added transversely to the Co/Ni nanowire. Contact electrodes of Ta/Cu/Au structure were deposited for electrical measurement. Fig. 1(a) shows scanning electron microscopy (SEM) image of the fabricated Co/Ni nanowire device and the electrical setup for anomalous Hall effect (AHE) measurement. A constant dc current (I_{dc} = 100 μA), which translates into a current density of $J = 1.4 \times 10^{10}$ A/m^2, is applied to the nanowire for AHE measurement. The Hall voltage (V_{xy}) is recorded across the Ta Hall bar by sweeping an external out-of-plane field. The result of the AHE measurement is shown in Fig. 1(b). The magnetization switching (up and down states) is observed at a coercive field of ±1.5 kOe.

Fig. 2(a) schematically shows the electrical current pulse injection. The nanowire was first saturated along the $+z$ axis with a 3 kOe field. A current density of $J = \pm 1.1 \times 10^{11}$ A/m^2 with pulse duration of 50 ns (±1.2 V) was applied via the injection line through the magnetic nanowire. A dc current ($J = 1 \times 10^{10}$ A/m^2) was applied across the nanowire to monitor the resistance change [22]. The creation of DW within the nanowire was detected by the change of the measured anisotropic magnetoresistance (AMR) value. The resistance of the nanowire under a series of positive and negative pulse injections, with a negative or positive initial pulse, is shown in Fig. 2(b) and (c), respectively. Cyclic step changes in the resistance can be clearly observed. The sequence of bipolar current pulse injection induces the periodic change in the resistance. Each current pulse injection is repeated for 20 times with a time interval of 2 s between pulses. This time interval is long enough to ensure heat relaxation, thus rendering the *Joule* heating effect negligible [23]. The measured baseline resistance gradually increases with more applied pulses due to the presence of locally created domains in the nanowire. The step decrease in resistance denoted by (I) and (II) in Fig. 2(d), originates from the annihilation of DWs within the nanowire. We note that multiple domains are created by multiple current pulse injection. The final step resistance change is too large to be induced by a single DW. Fig. 2(e) illustrates the effect of the initial three pulse injections on the magnetic configuration of the nanowire. The polarity (direction) of the current pulse determines the winding direction of local Oersted field around the injection line as illustrated in Fig. 2(e) (green and purple circle arrows). As seen in Fig. 2(e)-i, the injection of a single positive pulse results in the generation of local Oersted field at the intersection of the injection line and nanowire. This leads to the local reversal of magnetization along the $-z$-axis (downward) at the junction between the injection line and the nanowire. This results in the creation of DW in the magnetic nanowire. For positive pulse, spin polarized electrons flow from B to A, hence the angular momentum from the spin transfer torque pushes the DW towards the injection line [24]. Subsequent pulsing of the positive pulse does not influence the magnetization orientation at the intersection, as the Oersted field orientation will be in the same direction of the magnetization. A negative polarity pulse following the positive pulse leads to a twofold effect, as shown in Fig. 2(e)-ii, iii. The current flowing through the nanowire drives the DW via the spin transfer torque effect. At the same time, the Oersted field from the injection line switches the local magnetization towards the $+z$ orientation. In this case, the pulse polarity contributes to the propagation direction of the created DW. This results in the presence of two domain walls (DWs) inside the nanowire. Fig. 2(f) shows the MFM image of pinned DW, which was obtained after applying two pulses of opposite polarity. The MFM image indicates three distinct domains, with a reversed magnetic domain (dark contrast) underneath the Ta Hall bar. The domain comprises two DWs with chirality of up-DW-down and down-DW-up configurations. The length of the domain (dark contrast) is around 1 μm. To prevent the shading effect from Ta Hall bar, the MFM tip was scanned transversely to the long axis of the nanowire.

The cyclic step changes in resistance exhibit a $\Delta R_{up} \approx 0.5\ \Omega$ and $\Delta R_{down} \approx -0.4\ \Omega$ for 40 cyclic steps, as seen in Fig. 2(b) and (c). The discrepancy between the resistance values may be attributed to the creation of random domains in the nanowire as a function of the current pulse. For the 500 nm wide wire, Bloch wall is more stable than Néel wall. The anisotropic magnetoresistance (AMR) contribution to the resistance is independent of the number of Bloch walls, as the magnetic orientation of Bloch DWs is always perpendicular to the current flow. A stable current-driven DW motion without deformation does not change the AMR [25]. The abrupt creation of DW near the injection line may contribute to the AMR. One of the measurement artifacts is the resistance change caused by the anomalous Hall effect (AHE). To investigate the difference between the properties of the DWs created using single and multiple pulses, the Hall voltage (V_{xy}) measurement is carried out by sweeping the external perpendicular field. The characteristics of the created DW can be inferred from the pinning fields at the Hall bar [26]. The nanowire is first saturated along the $+z$ direction by applying a 3 kOe field. A single or bipolar current pulse for the DW or domain (two DWs) creation is injected through magnetic nanowire. This is followed by field sweeping along the $\pm z$ direction, to move a single DW or expand the domain by the motion of the two DWs. The measured Hall voltage indicates the presence of the

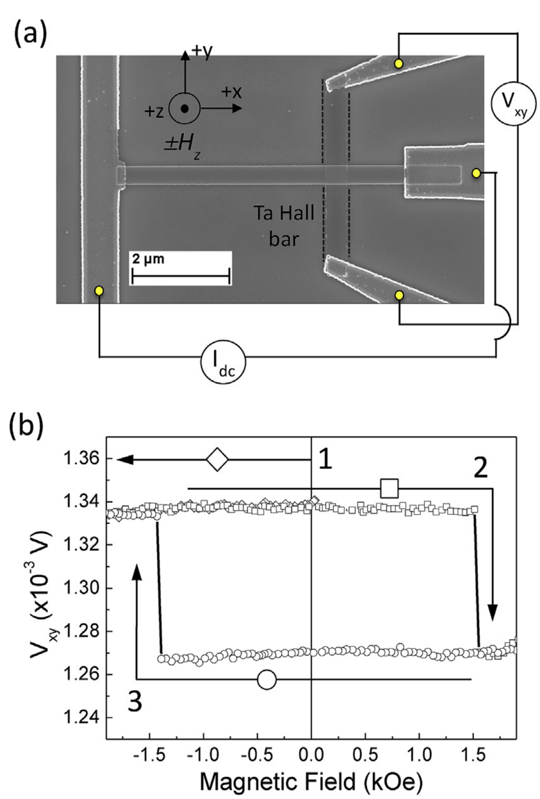

Fig. 1. (a) Scanning electron microscopy (SEM) image of the fabricated Co/Ni nanowire with Ta Hall bar. The Hall measurement setup and the sweeping field direction are shown in the figure. (b) The measured anomalous Hall effect hysteresis loop, along with the direction of the field being swept.