Current Applied Physics 17 (2017) 98–102

Contents lists available at ScienceDirect

Current Applied Physics

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

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ARTICLE INFO

Article history:
Received 14 July 2016
Received in revised form
21 September 2016
Accepted 3 November 2016
Available online 9 November 2016

Keywords:
Nanowire
Perpendicular magnetic anisotropy
DW creation
AMR
Anomalous Hall effect

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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http://dx.doi.org/10.1016/j.cap.2016.11.005
1567-1739/

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

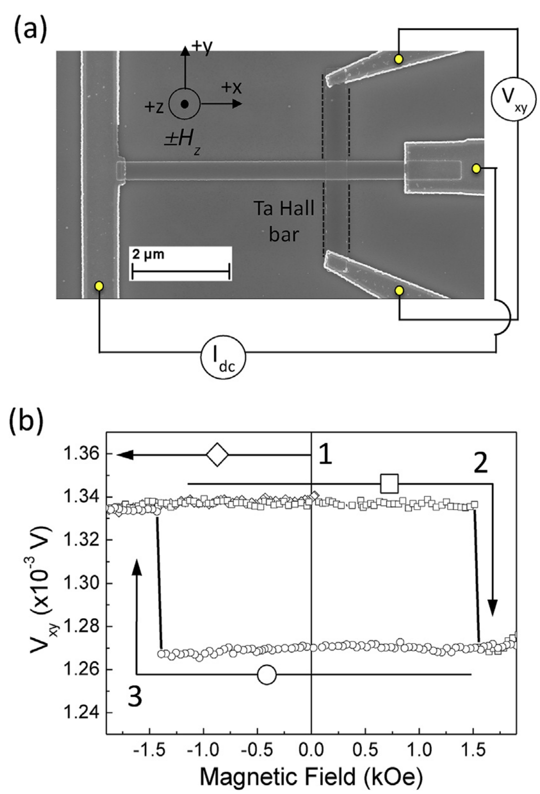

Fig. 1. (a) Scanning electron microscopy (SEM) image of the fabricated Co/Ni nanowire with Ta Hall bar. The Hall measurement setup and the sweeping field direction are shown in the figure. (b) The measured anomalous Hall effect hysteresis loop, along with the direction of the field being swept.

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 $\Delta R_{up} \approx 0.5$ Ω and $\Delta R_{down} \approx -0.4$ Ω 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

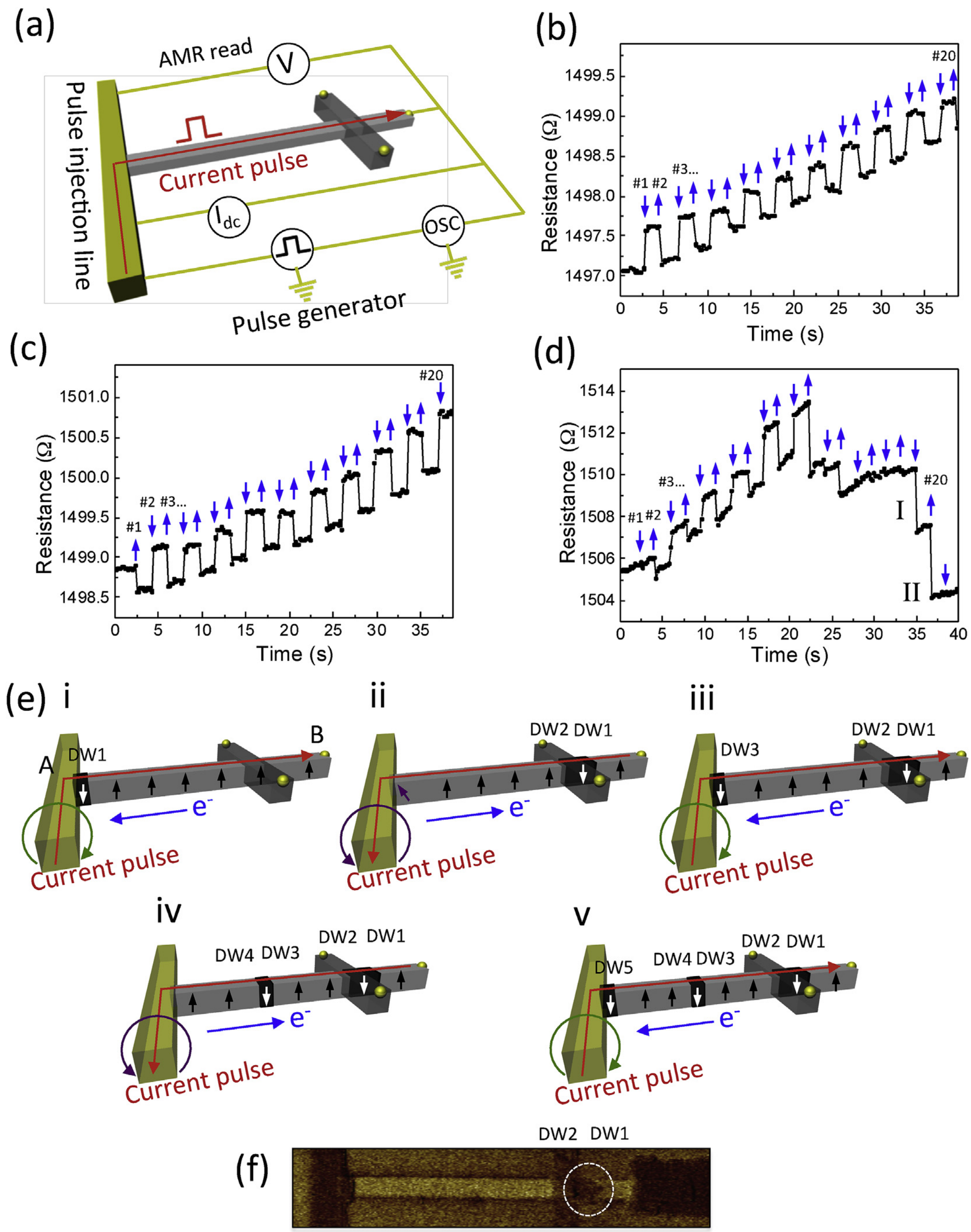

Fig. 2. (a) Schematic illustration of the current pulse injection and anisotropic magnetoresistance (AMR) measurement. The creation or annihilation of DW can be inferred from the changes of the measured AMR values. (b), (c) Cyclic resistance changes, $+\Delta R_{up} \approx 0.5\ \Omega$ and $-\Delta R_{down} \approx -0.4\ \Omega$. Up and down arrows indicate the voltage polarities during the current pulse injections. (d) The step decrease in resistance denoted I and II from the annihilation of DWs within the nanowire. The labeled numbers #1, #2 … and #20 correspond to the number of current pulse injections, with each successive pulse having alternating polarity. (e) Illustration of the DW creation with alternating current pulse injection direction (red arrow). The injected current pulse induces local Oested field, as depicted by the clockwise or anticlockwise arrows. (f) MFM image shows the pinned domain at the Ta Hall bar following the current pulse injection. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

propagating DW.

Fig. 3(a) shows an abrupt resistance drop after the injection of a single positive current pulse. Multiple resistance changes of the nanowire are observed as a series of positive and negative pulses are passed through the nanowire, as shown in Fig. 3(b) and (c). In both Fig. 3(b) and (c), consistent change in resistance is observed as the pulse is applied. Following the application of a bipolar (positive-negative or negative-positive) pulse, the resistance of the nanowire returns to its nominal value. The abrupt resistance change is $\mp\Delta R \approx 0.12\ \Omega$ for current pulse injection with amplitude of about ± 1 V. A decrement of current pulse amplitude can reduce the ΔR value, as shown in Fig. 2(b) and (c). Fig. 3 shows the change in Hall voltage (V_{xy}) due to the DW and domain propagation as a function of the external field. Following the injection of a domain or DW, the externally applied field along the $-z$ direction is increased. The change in the Hall voltage via the AHE, implies the presence of the

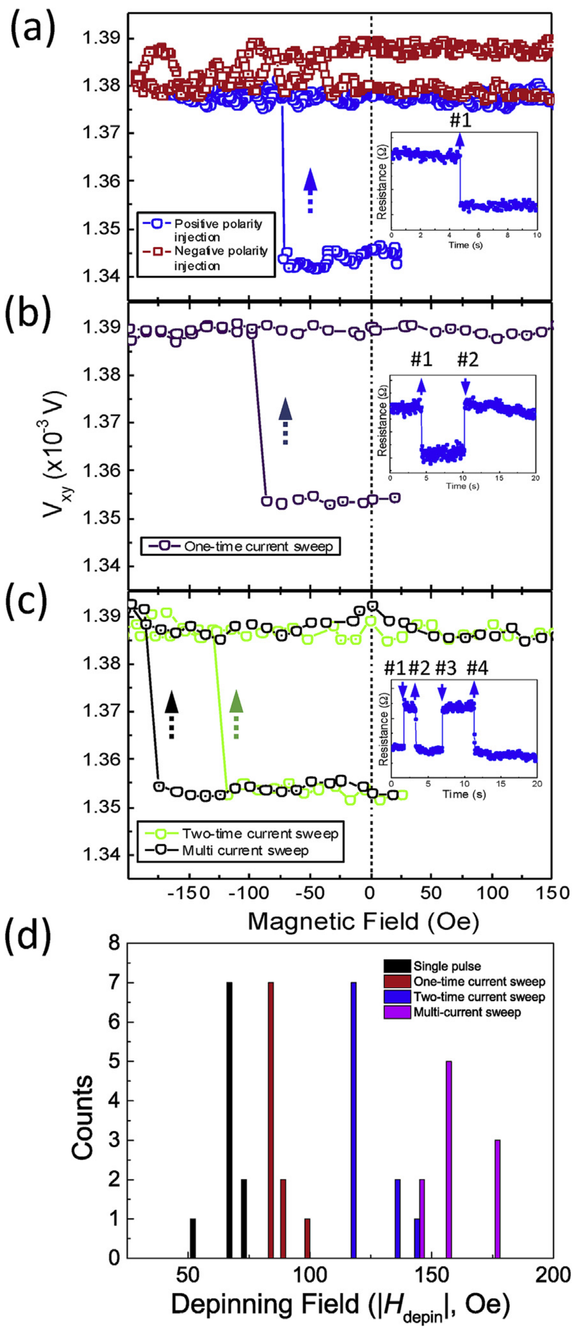

Fig. 3. The AHE induced by DW injected into the nanowire system. The labeled numbers #1, #2, #3, and #4 correspond to the number of current pulse injections, with each successive pulse having alternating polarity. (a) Inset: DW injected using a single pulse with positive polarity. Applying a negative field induces a reversal of the magnetization of the nanowire. Subsequent pulsing using a negative polarity does not induce any DW in the system. (b) DWs induced with a bipolar pulse exhibit a larger field. (c) DWs injected using multiple current pulses with alternating polarity exhibit an increase in the switching field as seen from the AHE. (d) Histogram depicting the distribution in the DW depinning fields as a function of the number of current pulse injections.

domain or DW at the Ta Hall bar. Following the change in the Hall signal, the external field is increased along the +z direction. The fact that the Hall signal does not exhibit any change with increasing field along the +z direction indicates that the domain or DW is not present or may have been removed by the magnetic field sweep. For DW created with a single positive pulse, we observed consistent detection of DW (blue arrow dash line) at the Hall bar at an external field of −72 Oe as detected by the AHE in Fig. 3(a). For the domain (two DWs) created using a combination of positive/negative pulses, we observed that the DW detection at the Hall bar exhibits a large field distribution with V_{xy} switching fields from −90 Oe to −180 Oe (blue, green, black arrow dash line) in Fig. 3(c). For each set of current pulse, the measurements were repeated 10 times. Fig. 3(d) shows the histogram of the depinning field as a function of current pulses. The change in Hall voltage is consistent with $\Delta V_{xy} \approx 30$ μV for all Hall voltage change in the AHE measurements, as shown in Fig. 3. The result is attributed to the asymmetric nature of the two DWs at the domain edges propagating within the nanowire as the external field is applied. Two DWs emanating from the domain have opposite chirality; up-DW-down and down-DW-up. In addition, the propagation of the DWs results in an expanding domain as the external perpendicular field is applied. Using the DW injection condition in the inset of Fig. 3, we obtain a low field switching of Hall voltage by AHE as shown in Fig. 3. The field is swept until the Hall voltage switching exhibits the maximum ΔV_{xy} change. The arrival of the DW at the Hall bar is then determined by the Hall voltage switching. This process is able to initialize the DW or domain at the Hall bar.

The created domains from the multiple current pulses are also investigated within a 30 μm long nanowire comprising of two magnetic Hall bars and a Π-shaped cross as a DW trap in the structure. The extended length of the wire from 6 μm to 30 μm allows clear MFM imaging of the created domains within the device. Additionally, the device enables the measurement of magnetoresistance (MR) change within the local area of the wire between the two magnetic Hall bars. The Hall bar also acts as an artificial pinning site across the nanowire.

Domains are first created by performing two bipolar current pulse injections. The MFM image shows four domains with alternate dark and bright contrast (white and black boxes with dash line) in the nanowire, as shown in Fig. 4(b). The domains are trapped between the different pinning sites introduced in the wire. For DWs (domains) created by the current pulses, a large pinning field (−140 Oe, labeled #1 in hysteresis loop) is obtained by AHE measurement as seen in Fig. 4(c) (black line). On the other hand, the MR curve combined with the switching of Hall resistance (R_{xy}) is shown in Fig. 4(c) (blue line). The MR signal increases with step resistance changes (blue arrows) as seen from the hysteresis loop in AHE measurement, as the perpendicular field is swept from 0 Oe to negative and to positive direction. We note that the #1 switching ($+\Delta R_{xy}$) in hysteresis loop is to reverse the spins in the nanowire swept by the locally created domains. The switching of #2 ($-\Delta R_{xy}$) and #3 ($+\Delta R_{xy}$) at ~ ± 350 Oe reflects the magnetized nanowire without the created domains by pulses. We note that the abrupt switching in resistance with field sweep reflects the magnetization with domain creation at the nanowire across the Hall bars. The abrupt resistance changes in AHE (black) and MR (blue) exhibit the same as $\Delta R_{xy} = R_{MR} \approx \pm 0.4\ \Omega$ in Fig. 4(c). Consequently, this result explains why the cyclic resistance change due to the current pulses is combined with the increment of the nominal resistance, as shown in Fig. 2(a) and (b). The multiple pulse injections are enabled to create multiple domains to induce an increment of MR with the magnetization in the nanowire.

3. Summary

In summary, we present a DW injection technique, which is a combination of Oersted field and spin transfer torque by current pulse injection. The DWs are directly sensed via the change in the anisotropic magnetoresistance. Step-wise resistance change is caused by the creation and annihilation of DWs. The winding

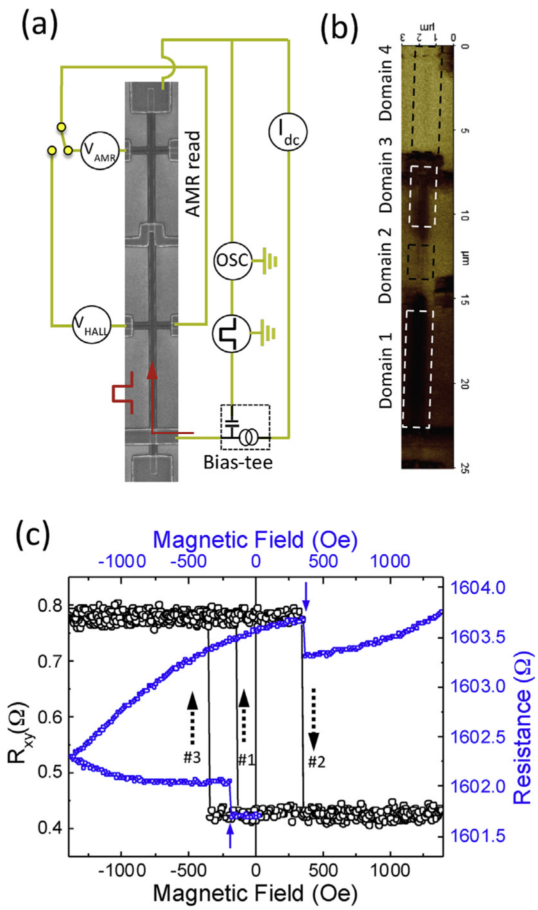

Fig. 4. (a) Schematic illustration of the current pulse injection and anisotropic magnetoresiatance (AMR) measurement along the nanowire. The magnetic hysteresis loop from the AHE measurement is also measured at one of the magnetic Hall bars. The Π-shaped Hall cross transverse to the nanowire is used for a trap of created domain. (b) The MFM image is obtained after the current pulses are injected from injection line to nanowire (red arrow). (c) The hysteresis loop from AHE measurement (black circle line). The switching sequences in the hysteresis loop follow the labeled numbers #1, #2, and #3 with switching directions (black dot arrows). The AMR curve (blue circle line) having abrupt switching (blue arrows) is measured between the two magnetic Hall bars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

direction of the local Oersted field associated with the current pulse polarity leads to the creation of DW and shifting of DW (domain) with spin transfer torque effect. For the DW motion, we observe a constant depinning field of −72 Oe for DW created with a single current pulse. For two DWs within the system, the depinning field exhibits large field distribution. This is attributed to the fact that the two DWs in the domain having the chirality are comprised of down-DW-up and up-DW-down configurations, leading to a propagation of the DWs in the nanowire and consolidation of domains in the nanowire.

Acknowledgments

The work was supported by a MOE-AcRF Tier 2 Grant (MOE 2013-T2-2-017). The work was also supported by the Singapore National Research Foundation, Prime Minister's Office, under a Competitive Research Programme (Non-Volatile Magnetic Logic and Memory Integrated Circuit Devices, NRF-CRP9-2011-01), and an Industry-IHL Partnership Program (NRF2015-IIP001-001). WSL is a member of the Singapore Spintronics Consortium (SG-SPIN).

References

[1] A. Brataas, A.D. Kent, H. Ohno, Current-induced torques in magnetic materials, Nat. Mater. 11 (2012) 372–381.
[2] S. Parkin, S.H. Yang, Memory on the racetrack, Nat. Nanotechnol. 10 (2015) 195–198.
[3] S.S. Parkin, M. Hayashi, L. Thomas, Magnetic domain-wall racetrack memory, Science 320 (2008) 190–194.
[4] D.A. Allwood, G. Xiong, M.D. Cooke, C.C. Faulkner, D. Atkinson, N. Vernier, R.P. Cowburn, Submicrometer ferromagnetic NOT gate and shift register, Science 296 (2002) 2003–2006.
[5] T. Koyama, D. Chiba, K. Ueda, K. Kondou, H. Tanigawa, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, K. Kobayashi, T. Ono, Observation of the intrinsic pinning of a magnetic domain wall in a ferromagnetic nanowire, Nat. Mater. 10 (2011) 194–197.
[6] T. Phung, A. Pushp, L. Thomas, C. Rettner, S.H. Yang, K.S. Ryu, J. Baglin, B. Hughes, S. Parkin, Highly efficient in-line magnetic domain wall injector, Nano Lett. 15 (2015) 835–841.
[7] J.H. Franken, M. Hoeijmakers, R. Lavrijsen, J.T. Kohlhepp, H.J.M. Swagten, B. Koopmans, E. van Veldhoven, D.J. Maas, Precise control of domain wall injection and pinning using helium and gallium focused ion beams, J. Appl. Phys. 109 (2011) 07D504.
[8] J.H. Franken, R. Lavrijsen, J.T. Kohlhepp, H.J.M. Swagten, B. Koopmans, Tunable magnetic domain wall oscillator at an anisotropy boundary, Appl. Phys. Lett. 98 (2011) 102512.
[9] T. Koyama, H. Hata, K.-J. Kim, T. Moriyama, H. Tanigawa, T. Suzuki, Y. Nakatani, D. Chiba, T. Ono, Current-induced magnetic domain wall motion in a Co/Ni nanowire with structural inversion asymmetry, Appl. Phys. Express 6 (2013) 033001.
[10] A.V. Khvalkovskiy, V. Cros, D. Apalkov, V. Nikitin, M. Krounbi, K.A. Zvezdin, A. Anane, J. Grollier, A. Fert, Matching domain-wall configuration and spin-orbit torques for efficient domain-wall motion, Phys. Rev. B 87 (2013) 020402(R).
[11] G. Chen, T. Ma, A.T. N'Diaye, H. Kwon, C. Won, Y. Wu, A.K. Schmid, Tailoring the chirality of magnetic domain walls by interface engineering, Nat. Commun. 4 (2013) 2671.
[12] Alex Hubert, R. Schäfer, Magnetic Domains: the Analysis of Magnetic Microstructures, third ed., Springer, Berlin Heidelberg New York, 2009.
[13] S. Chikazumi, Physics of Ferromagnetism, second ed., Oxford University Press, 1999.
[14] S. Fukami, J. Ieda, H. Ohno, Thermal stability of a magnetic domain wall in nanowires, Phys. Rev. B 91 (2015) 235401.
[15] T. Koyama, K. Ueda, K.J. Kim, Y. Yoshimura, D. Chiba, K. Yamada, J.P. Jamet, A. Mougin, A. Thiaville, S. Mizukami, S. Fukami, N. Ishiwata, Y. Nakatani, H. Kohno, K. Kobayashi, T. Ono, Current-induced magnetic domain wall motion below intrinsic threshold triggered by Walker breakdown, Nat. Nanotechnol. 7 (2012) 635–639.
[16] K.-J. Kim, R. Hiramatsu, T. Koyama, K. Ueda, Y. Yoshimura, D. Chiba, K. Kobayashi, Y. Nakatani, S. Fukami, M. Yamanouchi, H. Ohno, H. Kohno, G. Tatara, T. Ono, Two-barrier stability that allows low-power operation in current-induced domain-wall motion, Nat. Commun. 4 (2013) 2011.
[17] G. Yu, P. Upadhyaya, K.L. Wong, W. Jiang, J.G. Alzate, J. Tang, P.K. Amiri, K.L. Wang, Magnetization switching through spin-Hall-effect-induced chiral domain wall propagation, Phys. Rev. B 89 (2014) 104421.
[18] K.-J. Kim, R. Hiramatsu, T. Moriyama, H. Tanigawa, T. Suzuki, E. Kariyada, T. Ono, Tradeoff between low-power operation and thermal stability in magnetic domain-wall-motion devices driven by spin Hall torque, Appl. Phys. Express 7 (2014) 053003.
[19] S. Fukami, M. Yamanouchi, S. Ikeda, H. Ohno, Depinning probability of a magnetic domain wall in nanowires by spin-polarized currents, Nat. Commun. 4 (2013) 2293.
[20] H. Tanigawa, T. Koyama, G. Yamada, D. Chiba, S. Kasai, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, T. Ono, Domain wall motion induced by electric current in a perpendicularly magnetized Co/Ni nano-wire, Appl. Phys. Express 2 (2009) 053002.
[21] J.H. Franken, M. Hoeijmakers, H.J. Swagten, B. Koopmans, Tunable resistivity of individual magnetic domain walls, Phys. Rev. Lett. 108 (2012) 037205.
[22] M. Hayashi, L. Thomas, R. Moriya, C. Rettner, S.S. Parkin, Current-controlled magnetic domain-wall nanowire shift register, Science 320 (2008) 209–211.
[23] K.-J. Kim, J.-C. Lee, S.-B. Choe, K.-H. Shin, Joule heating in ferromagnetic nanowires: prediction and observation, Appl. Phys. Lett. 92 (2008) 192509.
[24] J.H. Franken, M. Herps, H.J. Swagten, B. Koopmans, Tunable chiral spin texture in magnetic domain-walls, Sci. Rep. 4 (2014) 5248.
[25] P.P. Haazen, E. Mure, J.H. Franken, R. Lavrijsen, H.J. Swagten, B. Koopmans, Domain wall depinning governed by the spin Hall effect, Nat. Mater. 12 (2013) 299–303.
[26] D. Chiba, M. Kawaguchi, S. Fukami, N. Ishiwata, K. Shimamura, K. Kobayashi, T. Ono, Electric-field control of magnetic domain-wall velocity in ultrathin cobalt with perpendicular magnetization, Nat. Commun. 3 (2012) 888.