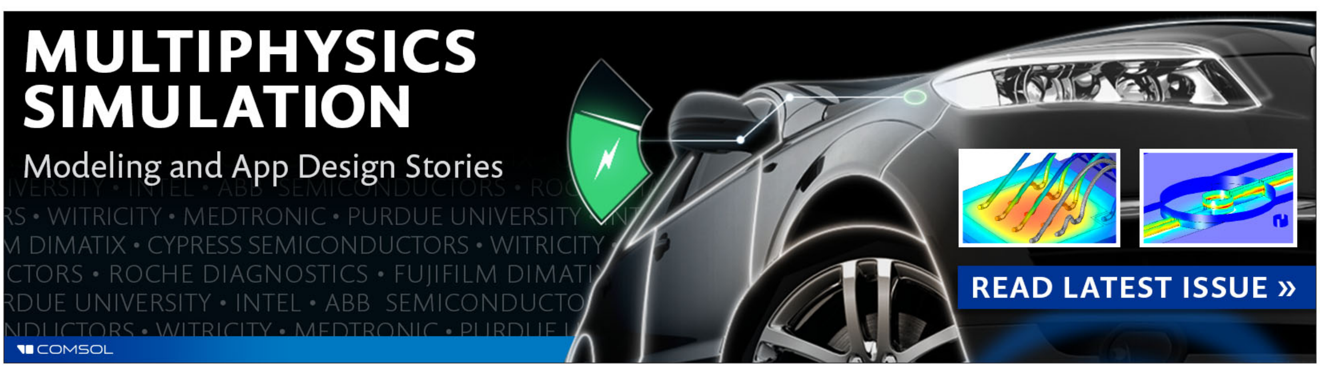
AIP Applied Physics Letters

In-plane current induced domain wall nucleation and its stochasticity in perpendicular magnetic anisotropy Hall cross structures

P. Sethi, C. Murapaka, G. J. Lim, and W. S. Lew

Citation: Applied Physics Letters **107**, 192401 (2015); doi: 10.1063/1.4935347
View online: http://dx.doi.org/10.1063/1.4935347
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/19?ver=pdfcov
Published by the AIP Publishing



In-plane current induced domain wall nucleation and its stochasticity in perpendicular magnetic anisotropy Hall cross structures

P. Sethi, C. Murapaka, G. J. Lim, and W. S. Lew[a)]
School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371

(Received 16 August 2015; accepted 27 October 2015; published online 9 November 2015)

Hall cross structures in magnetic nanowires are commonly used for electrical detection of magnetization reversal in which a domain wall (DW) is conventionally nucleated by a local Oersted field. In this letter, we demonstrate DW nucleation in Co/Ni perpendicular magnetic anisotropy nanowire at the magnetic Hall cross junction. The DWs are nucleated by applying an in-plane pulsed current through the nanowire without the need of a local Oersted field. The change in Hall resistance, detected using anomalous Hall effect, is governed by the magnetic volume switched at the Hall junction, which can be tuned by varying the magnitude of the applied current density and pulse width. The nucleated DWs are driven simultaneously under the spin transfer torque effect when the applied current density is above a threshold. The possibility of multiple DW generation and variation in magnetic volume switched makes nucleation process stochastic in nature. The in-plane current induced stochastic nature of DW generation may find applications in random number generation. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4935347]

The motion of domain wall (DW) using spin transfer torque (STT)[1–3] has paved the way for research in novel non-volatile magnetic memories[4–6] and logic devices.[7,8] There are reports to indicate that current induced DW motion in nanowires with perpendicular magnetic anisotropy (PMA)[9–12] requires much lesser threshold current for driving compared with their in-plane anisotropy counterparts. Moreover, the magnetization of PMA materials is more uniform and does not suffer from thermal instability.[13] Co/Ni multilayer has proven to be an attractive system due to its large perpendicular anisotropy, low depinning field, and large spin polarization, which can be tuned by varying layer thicknesses.[14,15] DW velocities of the order of 750 m/s have been reported in multilayer of such systems coupled via synthetic antiferromagnetic material.[16] The technique proposed to inject DWs in such nanowires involves generation of local Oersted field by injecting a pulsed current through a non-magnetic metallic stripline.[17,18] Recently, there have been reports of an alternate method of DW nucleation in trilayer stacks by passing an in-plane current. One report suggests spin orbit torque induced perpendicular switching and chirality dependent DW motion in Pt/Co/AlO_x stack;[19] another report suggests joule heating assisted DW nucleation in Pt/CoFeB/MgO stack.[20] Magnetization reversal in Co/Ni multilayer through spin orbit torque induced by spin Hall effect in heavy metal underlayer has also been reported.[21] This method employs an in-plane magnetic field along with an in-plane current to induce magnetization reversal. Phung *et al.* have reported an efficient method of DW nucleation in Co/Ni multilayers using an in-plane current, where they introduce anisotropy gradient at the injection site using ion-irradiation.[22] In this study, we demonstrate that by injecting an in-plane pulsed current in a Co/Ni nanowire with a magnetic Hall cross structure, DWs can be nucleated in the vicinity of Hall cross junction, without the need of an Oersted field. We attribute the DW nucleation in these nanostructures to a combination of higher demagnetization energy at the Hall junction and STT effect.

Figure 1(a) shows the scanning electron microscopy (SEM) image of the fabricated device. The film stack Ta(3)/Pt(3)/Co(0.25)/[Ni(0.5)/Co(0.25)]$_4$/Pt(3)/Ta(3), thicknesses are in nm, was sputter deposited on thermally grown SiO_2 substrate at a base pressure of 2×10^{-8} Torr. The hard-axis anisotropy field H_K was measured to be 5 kOe. A 300-nm-wide Co/Ni nanowire was fabricated using electron beam lithography and Ar-ion milling techniques. Two Ta (5 nm)/Cu (100 nm) electrodes, labeled A and B, were formed at both ends of the wire to generate local Oersted field and flow current through the magnetic wire. The presence of DW was detected using anomalous Hall effect (AHE).[5,23,24] The Hall resistance (R_{Hall}) was measured using a Hall cross structure between the two electrodes. R_{Hall}, which is proportional to the perpendicular magnetization of Hall probe, was measured using a constant 50 μA bias current. The separation between electrode A (B) and the Hall probe was 3.8 μm. Figure 1(b) shows the normalized R_{Hall} measured by sweeping an external magnetic field along the out-of-plane direction. As per our convention, +1 normalized R_{Hall} corresponds to field saturation along the $-z$-direction and 0 R_{Hall} corresponds to saturation along the +z-direction (out-of-plane). A square hysteresis loop was observed, indicating a perpendicular easy axis of magnetization of the nanowire. The nanowire coercivity was found to be 1 kOe. Figure 1(c) shows the normalized R_{Hall} measured by sweeping an external field after injecting a DW. In order to inject a DW,[10,17] the nanowire was first saturated by applying a large (3 kOe) out-of-plane external field along the $-z$-direction, followed by an application of a current pulse (85 mA, 50 ns) to electrode A. The local Oersted field generated by the pulsed current nucleates a DW near the electrode A. An external magnetic field was applied to drive the DW. As the magnetic field was gradually increased along the $+z$-direction, two

[a)]Author to whom correspondence should be addressed. Electronic mail: wensiang@ntu.edu.sg

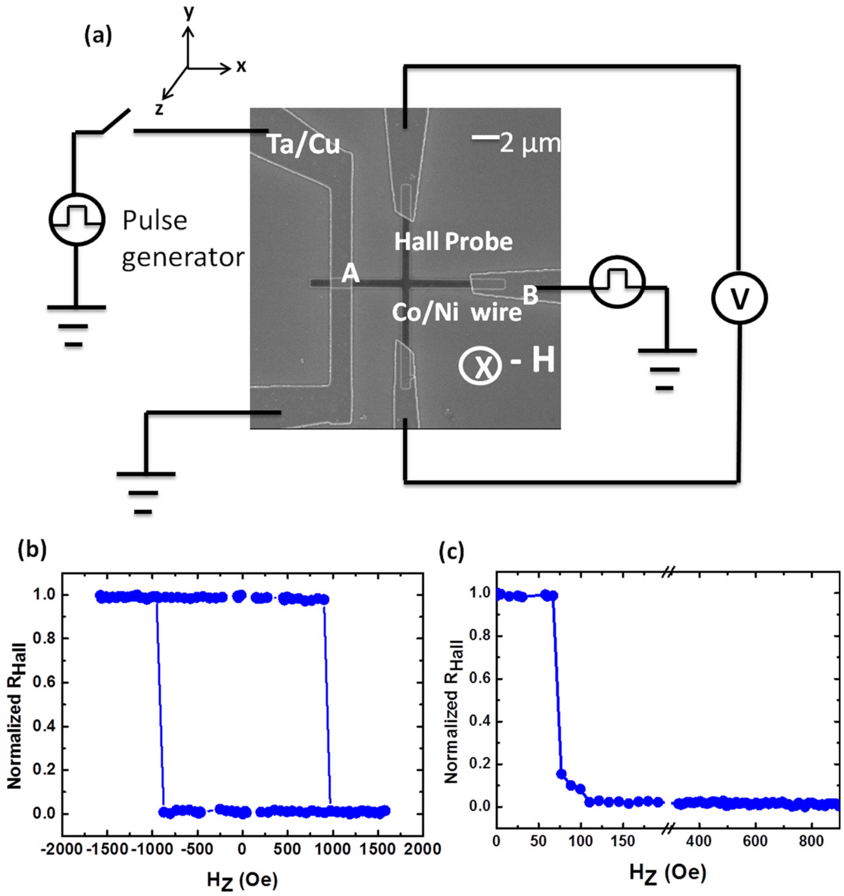


FIG. 1. (a) Schematic of the measurement set-up. Scanning electron microscopy (SEM) image of the fabricated device. (b) Dependence of normalized Hall resistance (R_{Hall}) on external magnetic field (R-H loop). (c) Measurement of normalized R_{Hall} after introducing a domain wall in the nanowire using Oersted field generated from current carrying strip-line.

steps were observed in R_{Hall}. First step at 60 Oe corresponds to DW propagation and pinning at the junction between Hall probe and the nanowire; the second step at 100 Oe corresponds to DW depinning[25] at the Hall probe and propagation through the nanowire and the Hall probe.

In order to study the effect of in-plane current on the magnetization reversal of the nanowire with no DW, a pulsed current was applied from electrode B to A after saturating the nanowire in the $-z$-direction. The magnitude of the pulsed current was varied from 6.8×10^{11} A/m^2 to 1.52×10^{12} A/m^2 while keeping the pulse width constant at 50 ns. After the pulse injection, the external magnetic field was gradually increased in the $+z$-direction, and change in the R_{Hall} was observed, as shown in Figure 2(a). When the applied current density was relatively low, there was no significant change in the magnitude of R_{Hall}, indicating no change in the magnetization of the nanowire. However, when the current density was increased to 8.7×10^{11} A/m^2, a drop in R_{Hall} was observed at field strength of 150 Oe. This indicates change in the magnetization of the nanowire at the Hall probe. The probability of DW nucleation is higher near the junction of Hall probe and the nanowire due to higher demagnetization energy (Kerr images of the reversed magnetization at the Hall junction are shown in the supplementary material[26]). The higher demagnetization energy lowers the anisotropy at the corners due to canting of spins. This in turn generates a gradient of the anisotropy within the nanowire near the junction much like artificial generation of anisotropy gradient by Phung *et al.*[22] It is more favorable to reverse the magnetization in the vicinity of Hall probe via DW nucleation than switching the magnetization of the entire nanowire. With the increase in the applied current density, the drop in R_{Hall} was found to be at lower field strengths. When the current density was increased above a critical current density corresponding to 1.08×10^{12} A/m^2, the application of current pulse itself reduced the magnitude of R_{Hall} without the need of external magnetic field after the current pulse injection. The magnitude of R_{Hall} depends on the magnetic volume switched at the junction.

Figure 2(b) shows micromagnetic simulation configuration depicting the magnetization of the nanowire and Hall probe junction when four DWs are nucleated due to magnetization reversal at the junction. At relatively low magnetic field strength and low current density, the portion marked "red" in Figure 2(b) (with reversed magnetization) would be less in volume. This indicates less switched magnetic volume at the Hall probe. As magnetic field is increased in the out-of-plane direction, the DWs would move away from each other and the magnetization of the Hall probe would also switch. This would be detected as drop in the R_{Hall}. When the field was swept in the $+z$-direction, the normalized R_{Hall} dropped in two steps indicating the switched domain expansion and depinning at the Hall probe. When the magnetic volume at the junction between Hall probe and nanowire junction is completely switched, as shown in Figure 2(b), the external field that is required to switch the Hall probe should be the same for all current densities. The Hall bar is switched

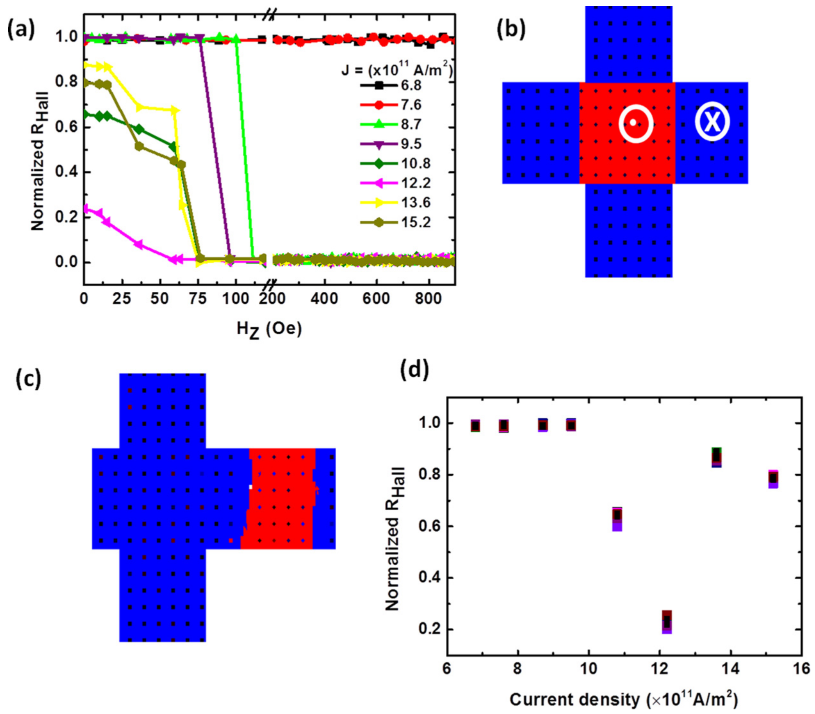


FIG. 2. Anomalous Hall effect (AHE) measurements on device with relatively lower hard-axis anisotropy field (=5000 Oe). (a) Measurement of R_{Hall} with external magnetic field as a function of current density after the application of current pulses. (b) Simulated magnetization state of the system when DWs are nucleated and the entire magnetic volume at the Hall probe is switched (c) Simulated magnetization state of the system, when the DWs are driven away from the Hall probe upon application of pulsed current. (d) Statistical distribution of R_{Hall} as a function of current density.

by the two DWs motion in opposite directions along it, i.e., stretching the magnetization of the Hall bar. This value corresponds to the DW depinning in Hall bar and is close to 75 Oe for all the subsequent applied current densities, as shown in Figure 2(a). At an applied current density of 1.22×10^{12} A/m^2, the R_{Hall} reached a minimum indicating the switching of large volume of the Hall cross junction. When four DWs are present at the junction of Hall probe and the nanowire, the spin configuration in the magnetic Hall probe is also affected. Further increase in the current density reduces the drop in R_{Hall}, indicating the DW displacement away from the Hall probe. The above can be explained by considering the pinning and de-pinning strength of the DWs at the Hall probe. It has been shown that DW would experience repulsion at the magnetic Hall probe[25] and precess until the field is strong enough to de-pin the DW from the Hall probe. At low enough current density, the DW is not able to overcome the potential due to Hall probe and is pinned in the vicinity of the Hall probe. At this current density (1.22×10^{12} A/m^2), the R_{Hall} drops to its minimum value. When the current density increases beyond this threshold value, the DWs are de-pinned from the Hall probe and are able to propagate further in the nanowire as shown by the simulated configuration in Figure 2(c). At this point, the DWs are nucleated and driven simultaneously by STT effect. A similar process of DW nucleation and motion has been reported by Phung *et al.*,[22] where they attribute the DW nucleation in the PMA region to the process of extraction of DW from in-plane magnetized (IMA) to PMA region by STT. The 90° magnetization boundary formed between the PMA and IMA region due to anisotropy gradient introduced by ion-irradiation acts as the nucleation site for the DW. In our Hall structure, the anisotropy gradient is naturally generated at all the four edges. This indeed produces a non-uniform magnetization at the corners of the Hall-cross. The canted spins resulted due to the fringing field at the four corners are driven by STT effect and are responsible for domain wall nucleation and propagation. After the DW is de-pinned from the Hall probe, the spin configuration inside the Hall probe reverts to the original magnetization state and the R_{Hall} recovers to the original value. When the current direction is reversed, R_{Hall} again drops indicating motion of reversed domains towards the Hall junction, and the detailed results are shown in the supplementary material.[26] Figure 2(d) shows the plot of normalized R_{Hall} after the application of current pulse. Each of these measurements was repeated 20 times to check for repeatability. The extent of spread in R_{Hall} indicates the non-uniformity in reversed magnetization volume at the junction which clearly exhibits the presence of stochasticity in DW nucleation process. Moreover, we cannot eliminate the possibility of multiple DW generation contributing to stochasticity. One such scenario where multiple DWs are generated can be seen in Kerr images presented in the supplementary material.[26]

Next, the effect of pulse width modulation on R_{Hall} was studied keeping the current density constant. Figure 3(a) shows the variation in normalized R_{Hall} as magnetic field is swept after the application of current pulse, for various pulse widths keeping the current density constant at 1.22×10^{12} A/m^2. The trend in R_{Hall} is similar to the one obtained previously in Figure 2(a). When the pulse width is low (10 ns), the reduction in R_{Hall} occurs at larger field strength. This implies that at low operating power, current alone is insufficient to reverse the magnetization in the nanowire; it requires assistance of external field. Once the DWs are nucleated, the field required to de-pin it from the Hall probe is less than 100 Oe. The drop in

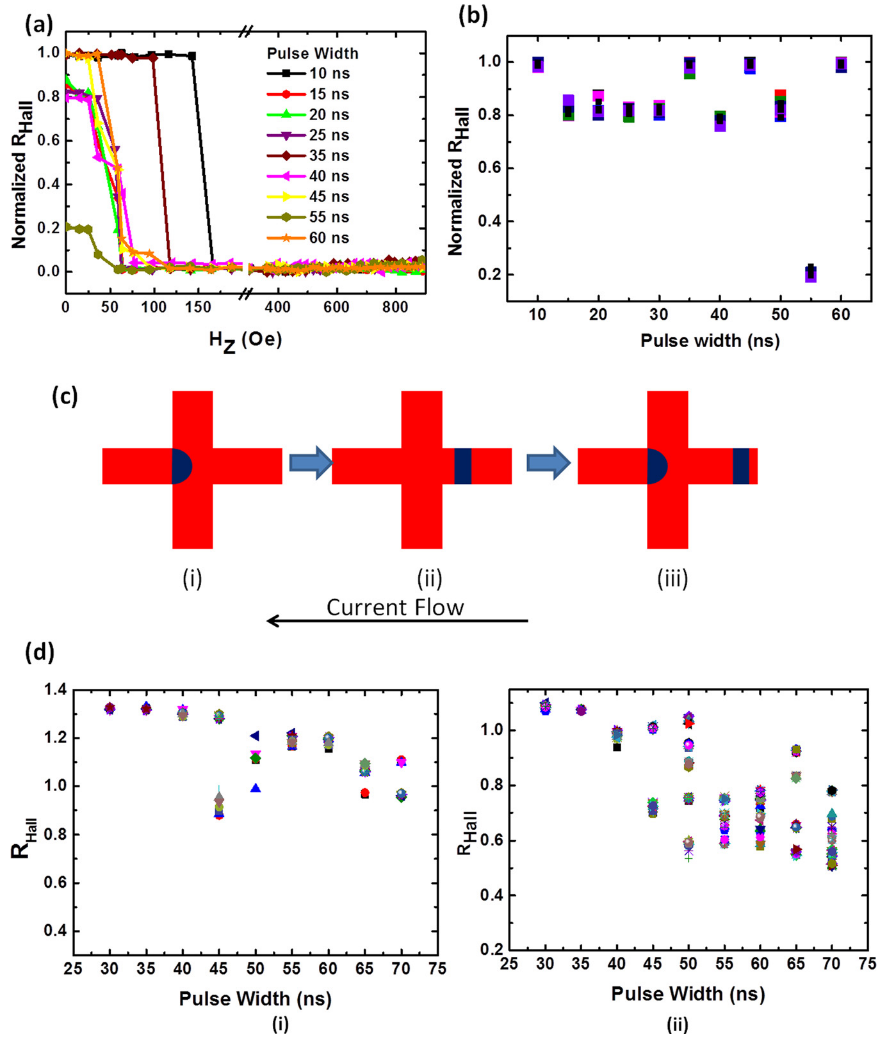


FIG. 3. AHE measurements on device with relatively lower hard-axis anisotropy field (=5000 Oe). (a) Measurement of R_{Hall} with external magnetic field as a function of pulse width after the application of current pulses. (b) Statistical distribution of R_{Hall} as a function of pulse width. Each measurement was repeated 20 times. (c) Schematic depicting a possible scenario showing multiple DW nucleation and propagation across the Hall junction: (i) DW nucleation via expansion of reversed magnetic domains at the Hall junction; (ii) depinning and propagation of DW away from the Hall junction; (iii) nucleation and expansion of second DW at the Hall junction. (d) Statistical distribution of R_{Hall} as a function of pulse width for larger nanowire dimensions (i) 2 μm (ii) 1.5 μm.

R_{Hall} to 0 occurs at around 75 Oe as observed from the previous result. Figure 3(b) shows the plot of normalized R_{Hall} measured immediately after the application of current pulse (no external field applied after the current pulse). Each of these measurements was repeated 20 times to check for repeatability. From the plot, it is observed that for pulse width less than 15 ns there is no drop in R_{Hall}, indicating no DW nucleation at the junction. When the pulse width is between 15 ns and 50 ns, the R_{Hall} varies between 1 and 0.8 indicating either no reversal or slight reversal at the corners of the junction. At 55 ns, R_{Hall} drops to its minimum value indicating maximum reversal of magnetic domains at the Hall junction. By increasing the pulse width further to around 60 ns, the R_{Hall} recovers to its maximum value indicating de-pinning of the DWs from the Hall bar similar to the one observed in Figure 2(c). This also indicates a possibility of multiple DW generation as shown in the schematic of Figure 3(c). Distribution of R_{Hall} indicates the presence or the absence of DWs at different pulse widths and current densities. Additionally, measurements with respect to pulse width for two different dimensions of the nanowire corresponding to 2 μm and 1.5 μm have also been performed and are shown in Figures 3(d-i) and 3(d-ii). It is observed that when the pulse width is less than 40 ns there is no change in the R_{Hall} indicating no DW nucleation at the junction. As the pulse width increases, there is a drop in the R_{Hall}. The measurements were repeated 20 times at each pulse width. The magnitude of drop is different for different set of measurements as indicated by the spread in the resistance values. Even though there is no clear trend in the plots, it appears slightly skewed indicating larger drop at larger pulse widths. The large spread in the R_{Hall} indicates variation in the reversed domain volume with current pulses near the Hall junction. These results suggest the possibility of stochasticity in the DW generation process using in-plane pulsed current.

Further, we have investigated the effect of pulse current on R_{Hall} for devices with larger anisotropy field. The layer thicknesses of Co/Ni thin film stack were tuned to obtain hard-axis anisotropy field of 7 kOe. The thin film was patterned into Hall cross structures similar to the one shown in Figure 1(a). The R_{Hall} was measured by sweeping the out-of-plane magnetic field; a square hysteresis loop was obtained indicating perpendicular easy axis of magnetization (not shown here). The coercivity of the nanowire obtained was 650 Oe. Figure 4(a) shows the variation of normalized R_{Hall} as magnetic field is swept

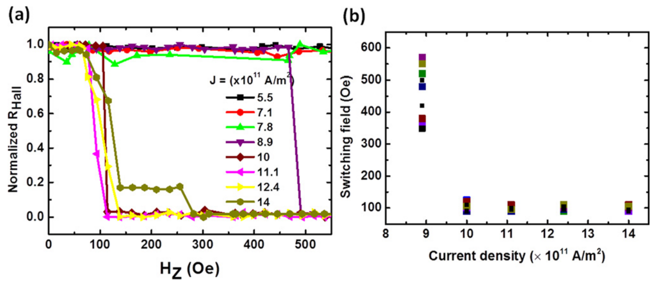


FIG. 4. AHE measurements on device with relatively larger hard-axis anisotropy field (=7000 Oe). (a) Measurement of R_{Hall} with external magnetic field as a function of current density after the application of current pulses. (b) Switching field distribution as a function of current density.

after the application of current pulse in the nanowire. The current density was varied from 5.5×10^{11} A/m^2 to 1.4×10^{12} A/m^2. There was no change in the R_{Hall} till the current density was kept below 7.8×10^{11} A/m^2. When the applied current density was 8.9×10^{11} A/m^2, there was a drop in R_{Hall} at field strength of 480 Oe. This indicates that the set current density may initiate changes in the spin orientation but it is not high enough for magnetization reversal at the Hall probe, which occurs at relatively high field strength. As the current density was increased to 1×10^{12} A/m^2, the drop in R_{Hall} occurred at much lower field strength (100 Oe). Thus, there is a sudden transition in the magnetization reversal process. The trend in R_{Hall} was similar to the one observed previously as the current density was increased. In all the above results, it is to be noted that there is no change in the magnitude of R_{Hall} without field sweep after the pulse injection, unlike in the previous case of lower anisotropy field devices, where the R_{Hall} was reduced by the application of current itself. This observation points to the fact that magnetization reversal can occur more readily for devices with lower anisotropy field strength. Figure 4(b) shows the plot of switching field distribution of the R_{Hall} at different applied current density values. Each of these measurements was repeated 20 times to get the distribution of the field at which R_{Hall} switches. At current density value of 8.9×10^{11} A/m^2, the switching field appeared to have larger spread. As the current density increased, there was a drop in the switching field and the spread also became narrower. The spread in R_{Hall} would depend on the sample geometry and surface irregularities. The nucleation of DWs would be preferably triggered at geometrical in-homogeneities or at the junction of Hall probe and the nanowire. The details of the effect of pulse width modulation on the R_{Hall} keeping the current density constant are provided in the supplementary material.[26] The results are similar to the one obtained in Figure 4(a), where the R_{Hall} drops at larger pulse width and current alone is not sufficient to cause magnetization reversal.

In summary, we demonstrate nucleation of multiple DWs at the Hall cross in a Co/Ni nanowire by the application of in-plane pulsed current without using local Oersted field. This phenomenon was more apparent in material with lower magnetization anisotropy. For the material with higher anisotropy strength, current alone was not sufficient to cause magnetization reversal. These observations may have been ignored by the previous studies where the focus is on DW nucleation using Oersted field. The magnitude of the applied current density and pulse width was found to control the R_{Hall} by modulating the reversed magnetic volume at the Hall junction. The large spread indicating variation in reversed domains and nucleation of multiple DWs manifests the stochastic nature of DW generation process. It shows that the signal at the Hall bar varies for each measurement. With multiple Hall cross structures fabricated on a single nanowire, the stochastic nature of the DW nucleation leads to random number generation at each Hall bar when an in-plane current is applied. Therefore, we believe that the current work may lead to the research on magnetic Hall bars for random number generator applications.

This work was 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. WSL is a member of the Singapore Spintronics Consortium (SG-SPIN). We would like to thank Mr. Gan Weiliang for assistance in Kerr imaging setup.

The authors declare no competing financial interest.

[1]L. Berger, J. Appl. Phys. **55**, 1954 (1984).
[2]J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[3]G. Tatara and H. Kohno, Phys. Rev. Lett. **92**, 086601 (2004).
[4]S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008).
[5]J. H. Franken, H. J. M. Swagten, and B. Koopmans, Nat. Nanotechnol. **7**, 499 (2012).
[6]D. Chiba, G. Yamada, T. Koyama, K. Ueda, H. Tanigawa, S. Fukami, T. Suzuki, N. Oshima, N. Ishiwata, Y. Nakatani, and T. Ono, Appl. Phys. Express **3**, 073004 (2010).
[7]W. Zhao, D. Ravelsona, J. O. Klein, and C. Chappert, IEEE Trans. Magn. **47**, 2966 (2011).
[8]P. Xu, K. Xia, C. Gu, L. Tang, H. Yang, and J. Li, Nat. Nanotechnol. **3**, 97 (2008).
[9]S. W. Jung, W. Kim, T. D. Lee, and H. W. Lee, Appl. Phys. Lett. **92**, 202508 (2008).
[10]S. Fukami, T. Suzuki, N. Ohshima, K. Nagahara, and N. Ishiwata, J. Appl. Phys. **103**, 07E718 (2008).
[11]H. Tanigawa, T. Koyama, G. Yamada, D. Chiba, S. Kasai, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, and T. Ono, Appl. Phys. Express **2**, 053002 (2009).
[12]S. Fukami, Y. Nakatani, T. Suzuki, K. Nagahara, N. Ohshima, and N. Ishiwata, Appl. Phys. Lett. **95**, 232504 (2009).
[13]S. Mangin, D. Ravelsona, J. A. Katine, M. J. Carey, B. D. Terris, and E. Fullerton, Nat. Mater. **5**, 210 (2006).
[14]S. Fukami, T. Suzuki, H. Tanigawa, N. Ohshima, and N. Ishiwata, Appl. Phys. Express **3**, 113002 (2010).
[15]G. H. O. Daalderop, P. J. Kelly, and F. J. A. den Broeder, Phys. Rev. Lett. **68**, 682 (1992).
[16]S.-H. Yang, K.-S. Ryu, and S. Parkin, Nat. Nanotechnol. **10**, 221 (2015).
[17]Y. Yoshimura, T. Koyama, D. Chiba, Y. Nakatani, S. Fukami, M. Yamanouchi, H. Ohno, and T. Ono, Appl. Phys. Express **5**, 063001 (2012).
[18]T. Koyama, D. Chiba, K. Ueda, K. Kondou, H. Tanigawa, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, K. Kobayashi, and T. Ono, Nat. Mater. **10**, 194 (2011).
[19]C. Bi and M. Liu, J. Magn. Magn. Mater. **381**, 258 (2015).
[20]K. Narayanapillai, X. Qiu, J. Rhensius, and H. Yang, J. Phys. D: Appl. Phys. **47**, 105005 (2014).
[21]L. Liu, O. J. Lee, T. J. Gudmundsen, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. **109**, 096602 (2012).
[22]T. Phung, A. Pushp, L. Thomas, C. Rettner, S.-H. Yang, K.-S. Ryu, J. Baglin, B. Hughes, and S. Parkin, Nano Lett. **15**, 835 (2015).
[23]M. Yamanouchi, D. Chiba, F. Matsukura, and H. Ohno, Nature **428**, 539 (2004).
[24]D. Ravelosona, S. Mangin, J. A. Katine, E. E. Fulletron, and B. D. Terris, Appl. Phys. Lett. **90**, 072508 (2007).
[25]R. Hiramatsu, K.-J. Kim, T. Taniguchi, T. Tono, T. Moriyama, S. Fukami, M. Yamanouchi, H. Ohno, Y. Nakatani, and T. Ono, Appl. Phys. Express **8**, 023003 (2015).
[26]See supplementary material at http://dx.doi.org/10.1063/1.4935347 for information on additional experiments and detailed analysis.