AIP | Applied Physics Letters

Demonstration of edge roughness effect on the magnetization reversal of spin valve submicron wires

T. W. Chiang, L. J. Chang, C. Yu, S. Y. Huang, D. C. Chen, Y. D. Yao, and S. F. Lee

Citation: Applied Physics Letters **97**, 022109 (2010); doi: 10.1063/1.3463459
View online: http://dx.doi.org/10.1063/1.3463459
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/97/2?ver=pdfcov
Published by the AIP Publishing

Demonstration of edge roughness effect on the magnetization reversal of spin valve submicron wires

T. W. Chiang,[1,2] L. J. Chang,[1,3] C. Yu,[1] S. Y. Huang,[1] D. C. Chen,[1] Y. D. Yao,[4] and S. F. Lee[1,a)]

[1]*Institute of Physics, Academia Sinica, Taipei 115, Taiwan*
[2]*Department of Physics, National Taiwan University, Taipei 106, Taiwan*
[3]*Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu 300, Taiwan*
[4]*Institute of Applied Science and Engineering, Fu Jen University, Taipei 242, Taiwan*

(Received 23 March 2010; accepted 18 June 2010; published online 15 July 2010)

We prepared submicron wide trilayer spin valve wires designed with periodic "spikes" as artificial roughness. The height and the pitch of the spikes were varied systematically. No obvious dependence was found between the roughness and the domain wall velocity when the spikes were smaller than a threshold of 30 nm for NiFe. The average velocity was slowed down when the height of the spikes were larger than the threshold. In-plane transverse magnetic fields help to reduce the critical current density for current induced domain-wall motion. Our results could be attributed to the space modulation of the local magnetization. © *2010 American Institute of Physics*. [doi:10.1063/1.3463459]

In contemporary nanotechnology, domain wall devices attract lots of attention in information storage and processing. These devices utilize domain wall displacements at the boundary of different magnetizations by means of keeping at least one domain wall within the device and manipulating its motion.[1] Applications such as magnetic logic devices[2] and racetrack memories[3] have been proposed. For these applications to be competitive with the present devices, the domain wall dynamics must be fast and reliable. Therefore, determination of the domain wall velocity in submicron or nanometer magnetic wires is one of the crucial topics of interest not only for fundamental research but also for applications.

There have been studies of the domain wall velocity in magnetic materials.[4–8] The domain wall velocity $v=(\gamma D/\alpha)H$ at a low field viscous regime is proportional to the applied field H, where γ is the gyromagnetic ratio; D the domain width; α the Gilbert damping parameter. When the magnitude of an external field is equal to the Walker field,[4] one can find the maximum velocity of the domain wall. As the field is increased over the Walker field, the domain wall velocity reduces significantly and begins to move in an oscillatory manner due to the nucleation of vortices inside the domain wall. Before the domain wall begins to propagate again in a submicron wide wire, the nucleation must transit the width of the wire.[5–7] To overcome the velocity breakdown, several simulation reports showed that fields perpendicular to the wire plane and edge roughness can enhance the domain wall velocities at a field larger than the Walker field.[5,9–13] Experimental results also showed the suppression of the Walker breakdown and enhancement of domain wall velocity below the Walker field.[14] Domain wall motions can be induced by an external field or by high current density (J_c).[15–17] In the current induced domain-wall motion (CIDM) effect, reducing the critical current density is another important issue for application. Law *et al.* described a strategy to reduce the J_c in CoFe/Pd-based perpendicular anisotropy spin valves by the insertion of an in-plane spin polarizer.[18]

As the line width gets narrower, roughness on the edges of the nanowires cannot be ignored. There have been experimental results of domain wall mobility reported.[12,19] The discrepancies among the experimental results and with theoretical calculations were usually attributed to the roughness. Reports studying the roughness effect on magnetic nanowires suggested that the edge roughness would obstruct the domain wall motion.[10,11,20,21] However, it was proposed theoretically that roughness could decrease the switching field and increase the domain wall velocity at high fields.[21,22] When wires have rough edges, the decrease of velocity due to distorted domain walls in the turbulent regime under high fields was suppressed from numerical simulation.[22] It was then proposed that roughness should be engineered rather than avoided when fabricating domain wall nanostructure devices.

With the advent of modern nanolithography techniques, nanoscale patterns with better defined shapes are achievable in order to study the physical properties at this length scale. Since there are both pros and cons related to the roughness effect on the domain wall mobility,[19,23] we would like to study this effect systematically. Also will be shown is the roughness effect on the critical current density for current-induced magnetization switching.

The edge roughness due to the fabrication technique has been on the order of 10 nm for nanowires with width on the order of 100 nm.[19] Our sample wires consisted of a spin valve structure, NiFe(24 nm)/Cu(10 nm)/NiFe(12 nm), and their widths were fixed at 400 nm. Different edge "roughness" was designed by e-beam lithography as periodic spikes along both sides of the samples. The height of the spikes was varied up to 60 nm and the pitches (period) were varied up to 400 nm. Samples were deposited by dc magnetron sputtering onto Si substrates. Figure 1 shows four typical NiFe samples with (a) no designed roughness, measured edge roughness about 7 nm; (b) 26 nm spike height, 200 nm pitch; (c) 33 nm spike height, 100 nm pitch; and (d) 51 nm spike height, 200 nm pitch.

a)Electronic mail: leesf@phys.sinica.edu.tw.

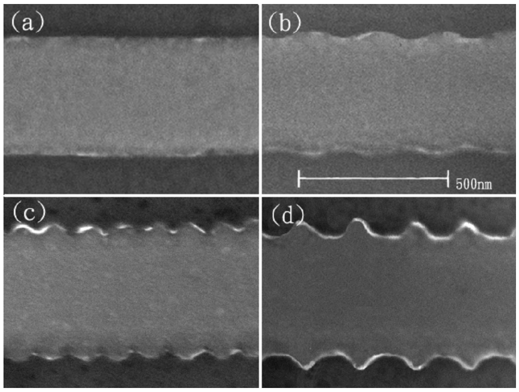

FIG. 1. Scanning electron microscope images of the NiFe samples with (a) no designed roughness, (b) 26 nm spike height, 200 nm pitch, (c) 33 nm spike height, 100 nm pitch, and (d) 51 nm spike height, 200 nm pitch.

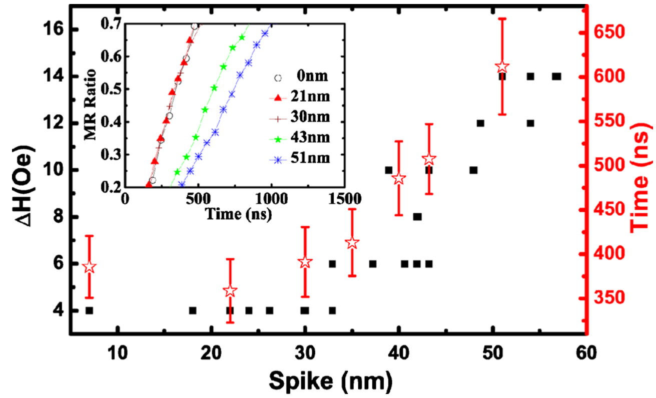

FIG. 3. (Color online) Transition width ΔH vs spike height (square). The rising time vs spike height (star). The inset shows the MR vs time of no roughness, spike 21 nm, spike 43 nm and spike 51 nm samples.

Sample resistance was measured with a four-probe technique at room temperature. Magnetoresistance values are normalized to the saturation values ($MR=[R(H)-R(H_S)]/R(H_S)$). The sweeping rate of the applied magnetic field was kept at 10^5 Oe/s (10 Oe/100 μs) for all measurements. In Fig. 2, we present the MR curves of the four samples in Fig. 1. Unlike the large size thin film spin valve structures, in which thick layers usually had smaller coercive fields and switched first upon the reversal of the magnetic field, thin layers switched first in nanowires.[20] The large shape anisotropy in nanowires causes the domain wall formation and propagation responsible for magnetization reversal and domain walls in thin wires cost less energy. The sample without the designed roughness showed fast transitions between low and high resistance states, resulting in a square MR curve. The switching fields decreased when the spikes were introduced, indicating that the formation of the domain walls became easier. As the spike height increased, the switching field also increased, suggesting that large enough spikes had stronger binding strength to the domain walls. Apart from the difference in MR ratios and in the switching fields, the transitions of the MR curves on the low field side were smoother when the spike height increased. This was due to the difference of the domain wall displacements in the magnetic layers. Thus, we could study qualitatively the average domain wall velocities as functions of designed spike heights and pitches with the transition widths ΔH, which is the field range of 10% to 90% changes on the MR curves. When the pitch became longer, no systematic change on the MR, switching field, and ΔH was observed. The transition width ΔH versus spike height are presented in Fig. 3. When the spikes are smaller than 30 nm, the roughness provides nucleation sites around which reverse domains can easily form to reduce the switching field and to stabilize the wall structure.[21,22] The smaller roughness on the scale of the exchange length makes the domain wall propagate stably. When the spike becomes larger, it creates a pinning effect on the magnetic domain walls and a stronger applied field is needed to overcome the local anisotropy so that the switching field and the ΔH are increased.[24] We also performed a time-domain dynamic measurement by using a 10 GHz oscilloscope. A home-made pre-amplifier was needed since the voltage drops across our metallic samples were small. The time variations of the signals rising from 20% to 70% MR at 10 Oe are presented in the inset of Fig. 3. Since the measurement is performed in a much shorter time scale than the field variation, the magnetic field can be taken as a constant. The mobility μ is 3.9 ± 0.4 m/s Oe, similar to the value of 2.6 ± 0.2 m/s Oe reported by Ono *et al.*[20] The slopes of the linear response versus spike height showed the same tendency as shown in Fig. 3. As the spike height decreased, domain wall motion was unhindered. As spike height increased, more time was necessary for the domain wall to travel through the sample. There were sometimes transient states, at which the voltages were constant for up to 100 ns, for large spike samples (not shown in the figure). The 30 nm of spike height was a critical value above which slower domain wall motion can be clearly observed.

We used the 3-dimensional micromagnet simulation OOMMF (Ref. 25) to simulate the magnetization configurations of the trilayer spin valve wires with different spikes. The magnetizations of the samples were determined by solving the Landau–Lifschitz–Gilbert equation. The parameters used were the exchange constant 3×10^{11} J/m, saturation moment 8.6×10^5 A/m, no crystalline anisotropy, damping parameters 0.5, and mesh size $10\times10\times12$ nm^3. From the simulation, the vortex wall was created at one side of the wire when the magnetic field was diminished from the saturation and reversed. When the spike was small, the local moments near the wire edge were rotated and aligned with

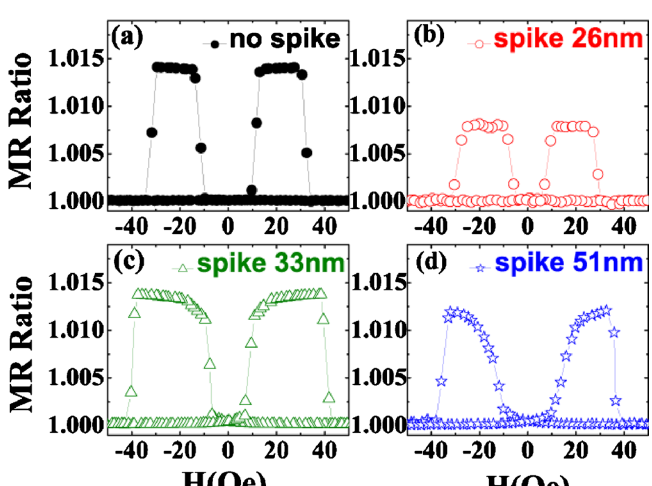

FIG. 2. (Color online) Magnetoresistance ratio curves of the four samples in Fig. 1.

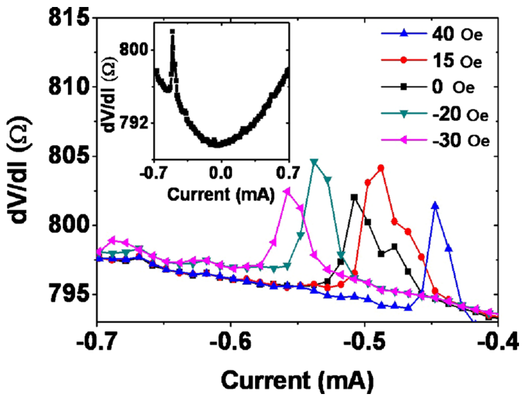

FIG. 4. (Color online) The differential resistance vs current curves shows the current induced magnetization switching at low fields after a −3000 Oe saturation field transverse to the wire. Different symbols represent data at various fields as indicated. The inset shows the full spectrum at zero field.

the spike shape but the moments at the center were not affected. When the spike was large enough, the shape anisotropy fields could create space modulation of the local moments across the line width from the spikes before the domain started to propagate. The anisotropy fields would affect the domain propagation and decrease its velocity.

The CIDM effect was also investigated in these samples. When the external field was applied along the wire, the samples showed CIDM within a narrow field range smaller than the coercive field, as we have found in other kinds of submicron wires.[26,27] When the field was zero, we could not find CIDM with the J_c up to 1×10^9 A/cm^2. When the field was applied in the transverse direction of the samples with designed roughness, the CIDM was clearly observed at and around zero field. Figure 4 shows the differential resistance dV/dI spectra of a sample with spikes height of 56 nm and pitch of 215 nm. The measurements were made by the differential technique.[28] When a −3000 Oe saturation field was applied along the hard axis of the wire and then reduced to zero, a magnetization reversal characteristic peak in dV/dI was observed when the current I was increased. This can be explained by local domain formation near the roughness due to the shape anisotropy. The critical current density is on the order of 1 to 3×10^6 A/cm^2 at zero field, which is one order of magnitude smaller than the typical reported value.[15–17] Thus, roughness can be engineered to reduce the critical current density in the CIDM effect.

In summary, we prepared samples with different edge 'roughness' to study the roughness effects on the domain wall displacement. Below a threshold length, 30 nm for 12 nm thick and 400 nm wide NiFe wires, the average domain velocity remained constant. When the spikes were larger, more pining sites were created for the domain walls and slowed down the average velocity. The same space modulation of the magnetization, when the external field was applied and returned to zero in the transverse direction of the wire, helped to reduce the critical current density for current induced domain-wall motion.

We thank Mr. Da Shung Su for his technical assistance. Financial supports of Academia Sinica and National Science Council of Taiwan, Republic of China are acknowledged.

[1] R. P. Cowburn, D. A. Allwood, G. Xiong, and M. D. Cooke, J. Appl. Phys. **91**, 6949 (2002).
[2] D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit, and R. P. Cowburn, Science **309**, 1688 (2005).
[3] S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008).
[4] N. L. Schryer and L. R. Walker, J. Appl. Phys. **45**, 5406 (1974).
[5] A. Kunz and S. C. Reiff, Appl. Phys. Lett. **93**, 082503 (2008).
[6] D. G. Porter and M. J. Donahue, J. Appl. Phys. **95**, 6729 (2004).
[7] M. Hayashi, L. Thomas, C. Rettner, R. Moriya, and Stuart S. P. Parkin, Nat. Phys. **3**, 21 (2007).
[8] Z. Li, J. He, and S. Zhang, J. Appl. Phys. **99**, 08Q702 (2006).
[9] J.-Y. Lee, K.-S. Lee, and S.-K. Kim, Appl. Phys. Lett. **91**, 122513 (2007).
[10] F. Cayssol, J. L. Menéndez, D. Ravelosona, C. Chappert, J.-P. Jamet, J. Ferré, and H. Bernas, Appl. Phys. Lett. **86**, 022503 (2005).
[11] E. Martinez, L. Lopez-Diaz, L. Torres, C. Tristan, and O. Alejos, Phys. Rev. B **75**, 174409 (2007).
[12] D. Atkinson, D. A. Allwood, G. Xiong, M. D. Cooke, C. C. Faulkner, and R. P. Cowburn, Nature Mater. **2**, 85 (2003).
[13] A. V. Khvalkovskiy, K. A. Zvezdin, Ya. V. Gorbunov, V. Cros, J. Grollier, A. Fert, and A. K. Zvezdin, Phys. Rev. Lett. **102**, 067206 (2009).
[14] S. Glathe, I. Berkov, T. Mikolajick, and R. Mattheis, Appl. Phys. Lett. **93**, 162505 (2008).
[15] L. Berger, J. Appl. Phys. **71**, 2721 (1992).
[16] P. Vavassori, V. Metlushko, and B. Ilic, Appl. Phys. Lett. **91**, 093114 (2007).
[17] N. Ohshima, H. Numata, T. Suzuki, S. Fukami, K. Nagahara, and N. Ishiwata, J. Appl. Phys. **103**, 07D914 (2008).
[18] R. Law, E.-L. Tan, R. Sbiaa, T. Liew, and T. C. Chong, Appl. Phys. Lett. **94**, 062516 (2009).
[19] F. Cayssol, D. Ravelosona, C. Chappert, J. Ferre, and J. P. Jamet, Phys. Rev. Lett. **92**, 107202 (2004).
[20] T. Ono, H. Miyajima, K. Shigeto, K. Mibu, N. Hosoito, and T. Shinjo, Science **284**, 468 (1999).
[21] J. Gadbois and J.-G. Zhu, IEEE Trans. Magn. **31**, 3802 (1995).
[22] Y. Nakatani, A. Thiaville, and J. Miltat, Nature Mater. **2**, 521 (2003).
[23] M. T. Bryan, D. Atkinson, and R. P. Cowburn, Appl. Phys. Lett. **85**, 3510 (2004).
[24] C. Yu, S. F. Lee, J. L. Tsai, E. W. Huang, T. Y. Chen, Y. D. Yao, Y. Liou, and C. R. Chang, J. Appl. Phys. **93**, 8761 (2003).
[25] A three-dimensional code to calculate the magnetization configuration and its field evolution is described on http://math.nist.gov/oommf.
[26] J. L. Tsai, S. F. Lee, Y. Liou, Y. D. Yao, T. Y. Chen, and K. W. Cheng, J. Appl. Phys. **97**, 10C710 (2005).
[27] K. W. Cheng, C. Yu, S. F. Lee, Y. D. Yao, Y. Liou, and J. H. Huang, J. Appl. Phys. **105**, 07D115 (2009).
[28] *Low Level Measurements Handbook*, 6th ed. (Keithley Instruments Inc., Cleveland, 2004).