Magneto-transport measurements of domain wall propagation in individual multi segmented cylindrical nanowires

Hanan Mohammed, Enrique Vilanova Vidal, Yurii P Ivanov, Jürgen Kosel

Computer, Electrical and Mathematical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

Magnetotransport measurements were performed on multisegmented Co/Ni nanowires fabricated by template-assisted electrodeposition. Individual nanowires were isolated and electrodes patterned to study their magnetization reversal process. The magnetoresistance reversal curve of the multisegmented nanowire exhibits a step in the switching field. Micromagnetic simulations of the magnetization reversal process are in agreement with the experimental findings and attribute the step at the switching field to the pinning of a domain wall at the interface of the Co/Ni nanowire.

Index Terms—Domain Wall, Magnetoresistance, Multisegment Nanowire, Pinning.

I. INTRODUCTION

The controlled movement of domain walls along a nanostripe using spin polarized currents has spurred considerable interest in the field of magnetic data storage [1], [2]. The lithographically patterned nanostripes could be replaced by a three-dimensional architecture using cylindrical nanowires (NWs), which are fabricated in densely packed 3D arrays [3]. In addition to the 3D architecture, theoretical predictions on the absence of Walker breakdown in a cylindrical NW points to potentially faster devices [4]. The realization of such a cylindrical-NW based device relies on the demonstration of reliable pinning sites for the domain walls (DW) along the NW. In this paper we study the magneto-transport properties of an anisotropy modulated NW for a novel approach of creating a periodic potential along a NW for DW pinning. The multi segmented NW consists of segments of fcc nickel and hcp cobalt, which have a low and high magneto crystalline anisotropy respectively. Magnetoresistance (MR) measurements of the Co/Ni NW reveal a step in the MR curve during the magnetization reversal, which we attribute to DW pinning. Our micromagnetic simulations give an insight into the complex reversal mechanism in the multisegmented NWs and indicate DW pinning at the interface of the segments.

II. EXPERIMENTAL PROCEDURES

A. Fabrication of multisegmented cobalt/nickel nanowires

Template assisted electrodeposition is a relatively easy and cost-effective approach for the fabrication of cylindrical nanowires. Anodic aluminum oxide (AAO) is commonly used as a template as it exhibits a highly ordered hexagonal pore structure with controllable pore diameter and inter-pore distances [5]. In this paper, AAO templates are prepared in-house by a two-step anodization process of highly pure (99.9995%) Al discs. Prior to anodization, the Al discs are electropolished for 2 min in a bath of 1:4 volume mixture of perchloric acid and ethanol at 6 °C to remove any contaminants and defects present on the Al disc. The electropolished discs are then anodized at 40 V for 24 hours in

a 0.3 M oxalic acid solution at 1.6 °C with the Al disc as the anode and the platinum mesh as the cathode. This anodization step yields an alumina layer with randomly oriented pores. In order to obtain a more distributed pore orientation, the alumina layer is etched away using a solution of chromic acid (0.2 M) and phosphoric acid (0.4 M) at 40 °C for 12 hours. This etching process reveals highly ordered dimples on the surface of the Al disc, which facilitates the growth of ordered pores upon another anodization step. A second anodization is thus performed in the same conditions as before resulting in a highly ordered hexagonal pore structure with a pore diameter of 40 nm and a pore center-to-center distance of ~105 nm. In order to perform electrodeposition, the aluminum back layer is etched away using copper solution. The pores are then opened and widened up to 80 nm using a 5 % phosphoric acid solution. A 200 nm thick Au layer is sputtered onto the back of the template to serve as the electrode for electrodeposition. Electrodeposition of nickel is carried out using an electrolyte containing 300 g/L NiSO₄, 46 g/L NiCl₂ and 40 g/L H₃BO₃ at a constant DC voltage of -1.0 V (versus Ag/AgCl) at room temperature under constant stirring. In order to deposit cobalt, the electrolyte solution is changed to a bath containing 250 g/L CoSO₄, 40 g/L H₃BO₃ and electrodeposition is performed at -1 V (versus Ag/AgCl) at room temperature and under constant stirring. The electrodeposition time is tuned to grow 15 μm long multisegmented cobalt/nickel NWs with a diameter of 80 nm consisting of 750 nm long segments each. Finally, the Au back layer is removed by ion milling and the multisegmented NWs are chemically released from the membrane using NaOH solution at 40 °C for 24 h and subsequently stored in ethanol.

B. Electrical probing of an individual nanowire

Electrical probing of individual nanowires allows to gain an insight into the magnetization reversal process within the nanowire. There exists two approaches to electrically address a single NW [6]-[10]. In the first approach, the NWs are kept embedded in the AAO membrane and electrodes are patterned on either side of the membrane, taking care to contact a single NW [6], [7]. The second approach is based on contacting released nanowires [7]-[10]. This ex-situ approach can be realized either by dispersing NWs onto a substrate with

Fig. 1. Schematic of the process for establishing electrode contacts onto an individual cylindrical nanowire.

prefabricated electrodes/alignment marks or by patterning electrodes onto dispersed NWs. The advantages of the ex-situ approach are that NWs can be chosen selectively under a microscope, which allows to probe any structural deformities along the length of the NW. In addition to the selectivity of the NW, measurements are not limited to two-point geometry and different sections of the same NW (as small as 500 nm) can be probed. Also Magnetic Force Microscopy (MFM) and Magneto-Optical Kerr Effect Microscopy can be performed on the same NW, thus allowing its extensive electrical and magnetic characterization [11]. In this paper, we present a nanofabrication method based on the ex-situ approach to contact individual NWs. Instead of lithographically patterning electrodes/alignment marks prior to NW dispersal [8], we disperse NWs onto a substrate and carefully select a NW under a Scanning Electron Microscope (SEM) and utilize Focused Ion Beam (FIB) to mark the position of the selected NW. This method has the advantages of selecting a NW with high precision, as well as contacting only a single NW with no additional metallic structures in the vicinity of the NW.

Firstly, a drop of ethanol containing the NWs is dispersed onto a 1 cm^2 Si/SiO₂ (525 $\mu\text{m}/100 \text{ nm}$) substrate. The number of dispersed NWs is controlled by the concentration of the NW stock solution and it is essential to obtain sufficiently isolated NWs spread over the substrate. The substrate is then viewed under a SEM equipped with a FIB to locate and mark the position of an isolated NW. The FIB markings serve as alignment marks for the subsequent lithography process. The marking procedure is performed such that the FIB marks are

200 μm away from either side of the NW to minimize any contamination. A series of crosses and lines with a minimal value of current are patterned at a depth of 400 nm to ensure their visibility in the subsequent lithography steps. A bilayer resist approach is implemented using resists LOR5B and 950 PMMA (A4) from Microchem. Strong Van der Waals forces that exist between the substrate and dispersed NWs ensure that the NWs are not displaced during the nanofabrication steps.

Fig. 2. Scanning Electron Microscope image of a NW with Au electrodes patterned by Electron-beam lithography.

Using FIB alignment marks, the required electrode design is patterned by Electron-beam lithography (Crestec CABL-9520C) and later developed. The development process is performed in two steps. In the first step, a mixture of MIBK: isopropyl alcohol (1:3) is used for 30 s. In the second step, a

mixture of AZ 726 MIF: Deionized water (1:1) is used for 15 s, with MIBK and AZ726 MIF purchased from Microchem. Prior to metal deposition, an etch step is performed in-situ to remove the NW oxide layer at the resist openings. The etching process is optimized by systematically controlling the etch time to avoid over or under etching of the NW. This step is crucial as it provides a low resistance contact between the NW and the patterned electrodes. The pressure of the chamber is maintained at 10^{-7} T in order to minimize the oxide growth while transferring from the etch chamber to the deposition chamber of the tool. Chromium and gold are deposited to a thickness of 10 nm and 200 nm respectively. Finally, the lift-off process is performed using the resist stripper Remover PG from Microchem at 50 °C for 10 minutes followed by an IPA rinse and N_2 dry.

III. CHARACTERIZATION

A. Magnetotransport measurements

The NW-based device is bonded onto a custom built carrier, which is mounted in between the poles of an electromagnet. Electrical grounding of the device is crucial to avoid any electrical discharge through the NW, which would otherwise result in melting the NW. Prior to measurement, the NW is saturated by applying a magnetic field of 4 kOe along the NW in both directions. The magnetoresistance measurements were performed at room temperature by applying a constant current of 500 nA (Keithley 6221A) in both directions and recording the average voltage (2182A Nanovoltmeter) while the magnetic field is ramped in steps of 2 Oe. Each point of the measurement is a result of the average value of current in both directions. The red curve in Fig. 3 depicts the magnetization reversal in the NW upon applying a magnetic field in one direction while the reverse field direction is denoted by the black curve.

Fig. 3. Magnetoresistance measurement of a Ni NW.

The obtained MR curves are attributed to the anisotropic magnetoresistance (AMR), which has its origin in spin orbit interaction and depends on the relative orientation of magnetization and electric current. Ni and Co exhibit small values of AMR ($\sim 1\%$) [7]. Fig 3 depicts the magnetization reversal curve of a Ni NW. At saturation, the magnetic

moments are aligned parallel to the direction of current. Reversal of the magnetic field results in a decrease of resistance as the magnetic moments continuously rotate away from the direction of current. At a distinct value of the magnetic field referred to as the switching field H_{sw} , there occurs an abrupt reversal of the magnetic moments, which is indicated by a sudden jump of resistance as depicted in Fig. 3.

Fig. 4. Magnetoresistance measurement of a multisegmented Co/Ni NW. Insets depict the plateaus at the switching field.

An important aspect of the MR curve is its insight into the switching behavior of NWs. We find that the magnetoresistance curve of the multi segmented Co/Ni NW depicted in Fig. 4 differs from that of the Ni NW in Fig 3. Instead of the distinct jump at H_{sw} , it displays a plateau during the jump (Fig. 4 insets). The plateau indicates that the magnetization does not reverse at once, and magnetization reversal proceeds only upon further increase of the magnetic field. This region of the curve is indicative of the pinning of a domain wall, which continues to propagate upon further increase in the magnetic field. Also the Co/Ni NW displays several periodic jumps, but these are not attributable to the switching of the NW magnetization as they occur before the switching event itself.

B. Magnetization reversal in Co/Ni nanowires

Previous studies revealed that the magnetization reversal in fcc Ni and hcp Co NWs occurs through the nucleation of vortex domain walls at the NW ends followed by subsequent depinning and propagation along the NW in a parallel field configuration [11]. In the case of fcc Ni NWs, the magnetization reversal is determined by the high value of shape anisotropy, which is a consequence of the high aspect ratio (length/diameter) of the NW. This leads to an easy axis parallel to the NW's longitudinal axis at remanence [12]. Whereas hcp Co ($d = 80$ nm) has a more complex structure due to the high value of magneto crystalline anisotropy, which is oriented in the plane of the NW's diameter. At remanence, the magnetic structure consists of a vortex like state along the NW with a core parallel to the direction of the initial applied field. Also the high aspect ratio (length/diameter) of the NW would lead to the presence of more than one vortex with alternating

chirality (clockwise and anticlockwise) [12] [13].

To study the effect of DW pinning on the magnetotransport measurements, we performed micromagnetic simulations by using Landau-Lifshitz Gilbert (LLG) software [14]. We chose the following geometrical parameters for simulation of the magnetization reversal process of a multisegmented Co/Ni NW: two segments of cobalt and nickel each 750 nm long with a diameter of 80 nm in a magnetic field applied parallel to the NW long axis. The NW was discretized into a cubic mesh with a size of 2 nm. The magnetic parameters of fcc Ni and hcp Co (with magneto crystalline anisotropy in-plane of the NW's diameter) were taken from Ref. [13].

Fig. 5. Simulation of magnetization reversal in a Co/Ni NW. Stage (a) and (m) of the simulations exhibit opposite states of magnetization with DW pinning at the interface occurring in stage (g).

The simulation proceeds from a saturated state of the multisegmented NW, which is depicted in stage (a) of Fig. 5. Upon decreasing the field, open vortex states form at the ends of the segments. The open vortex state of the Co segment differs from the Ni segment, by forming a vortex state along the entire length of the Co segment. The Co segment in stage (d) of the magnetization reversal process consists of a core magnetized along the length of the NW possessing two different chirality. In stage (e-f) the Ni segment shows a pronounced open vortex at its end and a subsequent reversal of magnetization of the Ni segment is observed in stage (g). At this point of reversal of the multi segmented NW, we note that the Ni segment has switched its magnetization whereas the Co segment remains relatively unchanged. This differential

switching of the segments lead to the pinning of a domain wall at the Co/Ni interface as depicted in stage (g). The magnetization reversal proceeds with the switching of one of the cores of Co segment subsequently switching its shell magnetization direction. In stage (k) the entire NW has completely reversed its magnetization direction.

Fig. 6. Simulation of magnetoresistance of a Co/Ni NW.

Fig. 6 depicts the magnetoresistance curve extracted from the micromagnetic simulations. The labels (a-m) correspond to those in Fig. 5. While stages (g)-(j) of the simulation depicts possible sites for domain wall pinning, stage (g) which corresponds to DW pinning at the Co/Ni interface, displays a much larger value of pinning strength. Thus we assume that the plateau observed in the MR measurements (Fig. 4) points to stage (g) of the simulation. In addition to the MR measurements, domain wall pinning was observed only at the Co/Ni interface in our Magnetic Force Microscopy (MFM) studies, as shown in Fig. 7.

Fig. 7. MFM of domain wall pinned at a Co/Ni interface.

IV CONCLUSION

In this paper, we have demonstrated the magnetoresistance measurements of electrodeposited individual multisegmented Co/Ni nanowire. The anisotropy modulated nanowires create a periodic potential for domain wall pinning at the Co/Ni

interface. Incorporating conventional lithography techniques as well as LLG simulations, we have explored the magnetization reversal behavior in the multisegmented nanowires. Our magnetoresistance measurements as well as magnetic force microscopy studies are in agreement with the micromagnetic simulations, which indicate that domain wall pinning can be achieved at the interfaces of multisegmented Co/Ni nanowires. The ability to tailor such pinning sites along a nanowire is a crucial step towards controlled domain wall manipulation in cylindrical nanowires.

ACKNOWLEDGMENT

This work was supported by King Abdullah University of Science and Technology (KAUST) and in part by Saudi Basic Industries Corporation (SABIC).

REFERENCES

- [1] S. S. P. Parkin, M. Hayashi, L. Thomas, "Magnetic Domain-Wall Racetrack Memory," *Science*, vol. 320, no. 5873, pp. 190-194, Apr. 2008.
- [2] L. Berger, "Emission of spin waves by a magnetic multilayer traversed by a current," *Phys. Rev. B.*, vol. 54, issue 13, pp. 9353-9358, Oct. 1996.
- [3] H. Masuda and K. Fukuda, "Ordered Metal Nanohole Arrays Made by a Two-Step Replication of Honeycomb Structures of Anodic Alumina," *Science*, vol. 268, no. 5216, pp. 1466-1468, Jun. 1995.
- [4] R. Hertel, M. Yan, A. Kákay, S. Gliga, "Beating the Walker Limit with Massless Domain Walls in Cylindrical Nanowires," *Phys. Rev. Lett.*, vol. 104, pp. 057201, Feb. 2010.
- [5] L.G. Vivas, Y.P. Ivanov, D.G. Trabada, M.P. Proenca, O. Chubykalo-Fesenko, M. Vázquez, "Magnetic properties of Co nanopillar arrays prepared from alumina templates," *Nanotechnology*, vol. 24, issue 10, pp. 105703, Feb. 2013.
- [6] S. Fusil, L. Piroux, S. Mátéfi-Tempfli, M. Mátéfi-Tempfli, S. Michotte, C. K. Saul, L. G. Pereira, K. Bouzehouane, V. Cros, C. Deranlot, "Nanolithography based contacting method for electrical measurements on single template synthesized nanowires," vol. 16, issue 12, pp. 2936-2940, October 2005.
- [7] A. Fert, L. Piroux, "Magnetic Nanowires," *Journal of Magnetism and Magnetic Materials*, Vol. 200, pp. 338-359, 1999.
- [8] L. Vila, L. Piroux, J. M. George, G. Faini, "Multiprobe magnetoresistance measurements on isolated magnetic nanowires," *Appl. Phys. Lett.*, vol. 80, no. 20, pp. 3805, May 2002.
- [9] M. E. Toimil Molaes, E. M. Hohberger, Ch. Schaefflein, R. H. Blick, R. Neumann, C. Trautmann, "Electrical characterization of electrochemically grown single copper nanowires," *Appl. Phys. Lett.*, vol. 82, no. 13, pp. 2139, March 2003.
- [10] M. Tanase, D. M. Silevitch, C. L. Chien, D. H. Reich, "Magnetotransport properties of bent ferromagnetic nanowires," *J. Appl. Phys.*, vol. 93, issue 10, pp. 7616, May 2003.
- [11] E. V. Vidal, Yu. P. Ivanov, H. Mohammed, J. Kosel, "A detailed study of the magnetization reversal in individual Ni nanowires," *Appl. Phys. Lett.*, vol. 106, pp. 032403, 2015.
- [12] Yu. P. Ivanov, M. Vázquez, O. Chubykalo-Fesenko, "Magnetic reversal modes in cylindrical nanowires," *J. Phys. D: Appl. Phys.*, vol. 46, pp. 485001, 2013.
- [13] Yu. P. Ivanov, D. G. Trabada, A. Chuvilin, J. Kosel, O. Chubykalo-Fesenko, M. Vázquez, "Crystallographically driven magnetic behaviour of arrays of monocrystalline Co nanowires," *Nanotechnology*, vol. 25, no. 47, pp. 475702, November 2014.
- [14] W. Scholz, J. Fidler, T. Schrefl, D. Suess, R. Dittrich, H. Forster, V. Tsiantos, "Scalable Parallel Micromagnetic Solvers for Magnetic Nanostructures," *Comput. Mater. Sci.*, vol. 28, pp. 366-383, 2003.