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Discontinuous Resistance Change and Domain Wall Scattering in Patterned NiFe Wires With a Nanoconstriction

S. Lepadatu and Y. B. Xu

***Abstract*—A nonlinear current-voltage (I–V) characteristic was observed in patterned NiFe wires with a central "bow-tie" point contact constriction. By passing a dc current through the wire, a sharp resistance drop was obtained for current densities in the range of 1.1–1.4 $\times 10^7$ A/cm^2. This is attributed to current-induced domain wall drag, resulting in displacement of a domain wall away from the constriction. A maximum current-induced resistance change of 0.079% was obtained for a 100-nm constriction, which is comparable with the magnetoresistance due to domain wall scattering in NiFe.**

***Index Terms*—Domain wall movement, domain wall scattering, magnetoresistance, nanoconstriction.**

I. Introduction

RESEARCH into spin electronics devices has mainly focused on two methods of switching the magnetic configuration, generating a magnetic field by use of an external current line or by passing a current through the device. There are several drawbacks associated with the use of external magnetic fields, the most important being crosstalk and high power consumption. This has generated growing interest in the use of current-switched magnetic devices. Following theoretical predictions by Slonczewski [1] and Berger [2], magnetization reversal has been observed in multilayered devices [3]. A spin-polarized current is passed perpendicular to two magnetic thin films separated by a metallic spacer, resulting in a rotation of the magnetization of the free layer. This was explained by a spin-transfer torque mechanism [3]. Another method of switching the magnetic configuration was demonstrated recently [4], where the current-induced domain wall motion was used to unpin a domain wall from a constriction in a spin-valve structure. This effect was predicted theoretically by Berger [5]. In ferromagnetic metals, the interaction between itinerant electrons and a domain wall can give rise to domain wall motion due to the s-d exchange torque exerted by the current carrying electrons on the domain wall magnetic configuration. Gan *et al.* [6] have demonstrated this effect in NiFe thin films by using magnetic force microscopy (MFM) imaging to show the displacement of Bloch walls when dc current pulses are applied. It was found that current densities of the order 10^7 A/cm^2 are required to displace a domain wall and its motion is always in the direction of the current carriers. In this paper, we report the observation of a nonlinear I–V characteristic in patterned NiFe wires with a central nanoscale constriction. This current-induced change in resistance is shown to be attributable, in both sign and magnitude, to the domain wall resistivity associated with current-induced domain wall motion.

II. Sample Fabrication and Measurements

The devices were fabricated on Si(100) using e-beam lithography and liftoff technique. Polymethylmethacrylate (PMMA) was spin coated at a speed of 2000 r/min and baked for 5 min on a hot plate at 150 °C. Using electron beam lithography (FEI Sirion), a set of straight wires and necked wires were defined on the same substrate with the length and the width fixed at 400 and 1 μm, respectively. For the necked wires, a constriction was defined halfway along the wire, forming "bow-tie" point contacts of nominal widths 100, 200, and 300 nm, respectively. Following thermal evaporation of $Ni_{80}Fe_{20}$, 30 nm thick, and an Au capping layer, 2 nm thick, at a pressure of 10^{-5} mBar, ultrasonic assisted liftoff in acetone was used to obtain the samples. A second level of lithography was used, following PMMA spin coating and baking as for the first level, to define the electrical measurement pads. Thermal evaporation was used to deposit 150-nm Al at a pressure of 10^{-5} mBar followed again by ultrasonic assisted liftoff. A sample with a 100-nm constriction is shown in Fig. 1 together with the measurement pads. A standard four-point dc measurement method was used by bonding with Al wires to the pads, with the voltage measurement pads 4 μm apart, centered on the constriction. The applied current was in a range of about 1.5 mA with a 10-μA step. The I–V measurements were performed at zero applied magnetic field after reversal from saturation in the transverse configuration. All the measurements were carried out at room temperature.

III. Results and Discussion

Fig. 2(a)–(d) shows, respectively, the resistance versus the current for four different samples: the straight wire, and the wires with 100-, 200-, and 300-nm constriction width. For the straight wire, the resistance does not change with applied current, as expected. For the necked wires, however, a sharp drop in resistance is observed as the current exceeds a critical value. By comparing the areas at the constriction for the 100-, 200-, and 300-nm point contacts with their switching currents—460,

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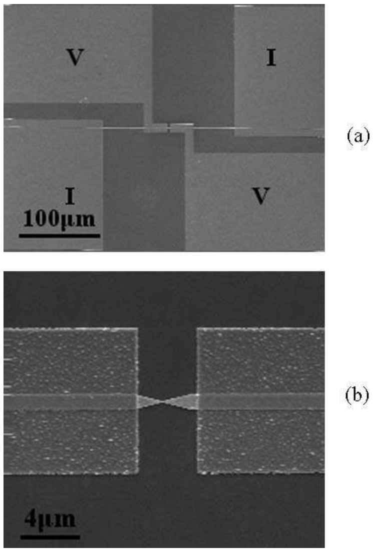

Fig. 1. SEM images of the sample with 100-nm constriction width showing (a) measurement pads geometry and (b) junction area geometry.

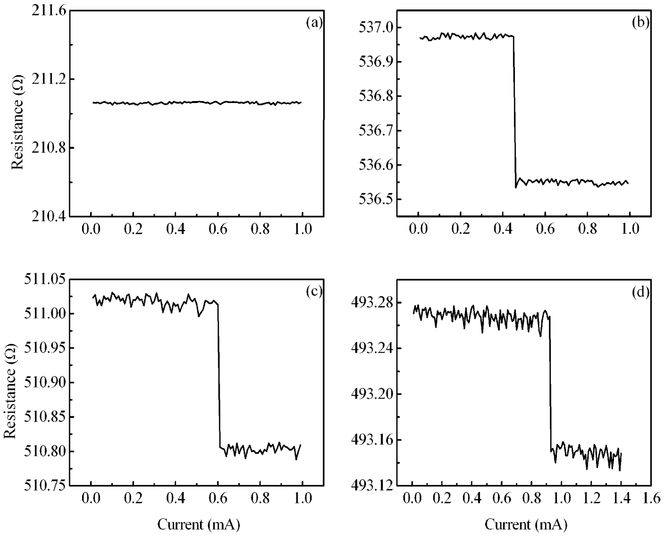

Fig. 2. Resistance versus applied current plots for the (a) straight wire and the necked wires with constriction width of (b) 100 nm, (c) 200 nm, and (d) 300 nm.

610, and 930 μA, respectively—it is found that the current density at the constriction required to change the resistance is in the range of 1.1–1.39 $\times 10^7$ A/cm^2 for all the necked wires. The percentage changes in resistance, calculated with respect to the higher resistance state, show a decrease with increasing point contact width, 0.079%, 0.042%, and 0.024% for the 100-, 200-, and 300-nm point contacts, respectively.

Extensive micromagnetic simulations on similar necked wires [7] have shown the presence of a domain wall at the constriction, which was also demonstrated experimentally [4]. We have also performed extensive micromagnetic simulations on the geometry of our samples, and these have revealed the formation of a 180° domain wall at the narrowest part of the constriction at zero applied magnetic field—accessible reversibly from saturation—as shown in Fig. 3. The rotation of magnetization occurs in plane, as for a Néel wall, since the thickness of the ferromagnetic layer prevents any Bloch walls from forming. It is well known that domain walls contribute an additional magnetoresistance, called domain wall scattering, in ferromagnetic materials. This subject is still an open area of research with both positive contributions of domain walls to resistance [8] and negative contributions [9] reported. García *et al.* [10] have also shown that both negative and positive magnetoresistance may be obtained in an electrodeposited Ni nanocontact, dependent on the combination of applied current and magnetic fields, which was discussed in terms of movement of domain walls in the contact region. Several theoretical models have been proposed to account for positive contributions [11] and negative contributions [12]. Of particular interest is the model proposed by Levy and Zhang [11], which suggests that positive contributions of domain walls are due to spin-dependent impurity scattering of conduction electrons at the domain wall. By comparing the percentage changes of resistance for the 100-, 200-, and 300-nm point contacts, respectively 0.079%, 0.042%, and 0.024%, the change in resistance is seen to decrease for larger point contact widths. As the point contact width increases, the density of the domain wall at the constriction decreases, resulting in smaller contributions to resistance due to domain wall scattering. We have found in a previous publication [8] a positive domain wall resistance of around 0.03% in a 30-nm-thick $Ni_{80}Fe_{20}$ submicron cross. The current-induced resistance changes observed here are in excellent agreement with the magnetoresistance of the domain wall scattering in both sign and magnitude. Thus, we suggest that the drop in resistance, as shown in Fig. 2, is due to the removal of a domain wall from the constriction by current-induced domain wall motion.

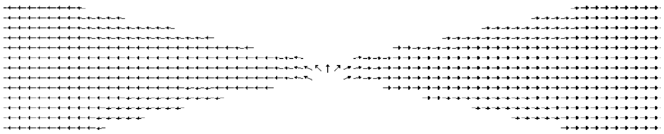

Fig. 3. Micromagnetic simulation for the sample with 100-nm constriction width at zero applied magnetic field, after reversal from saturation in the transverse geometry.

Three mechanisms have been proposed for current-induced domain wall motion [6]. The first is known as the hydromagnetic domain wall drag, which is based on the Hall effect. The direction of domain wall displacement is dependent on the anomalous Hall coefficient and the direction of the applied current. For $Ni_{80}Fe_{20}$ at room temperature, the anomalous Hall coefficient assumes a positive value resulting in domain wall displacement in the same direction as that of the current. This effect is strongly dependent on the thickness of the material, and Gan *et al.* [6] have shown that it becomes the dominant effect responsible for domain wall drag, in NiFe samples with a thickness greater than 1 μm. This reduces to zero for very thin samples, and its effect is negligible in our sample with a thickness of 30 nm. The second mechanism is due to the current-induced magnetic field, which runs in closed loops perpendicular to the direction of current flow, studied by Hung and Berger for NiFe thin films [5]. They have shown that this mechanism is not present in films with a thickness smaller than 35 nm. The third mechanism, predicted theoretically by Berger [5], is due to the exchange interaction between 3d electrons in the material and 4s electrons in the conduction band. A spin-polarized current will exert a torque on the electrons in the domain wall, effectively resulting in a displacement of the domain wall, which is in the same direction as the current flow and its effect is independent of sample thickness. Experimental investigations of this effect [5], carried by applying current pulses to thin film samples and observing the motion of domain walls by Kerr microscopy, have shown that the current density required to move a domain wall is of the order 10^7 A/cm^2, which is in excellent agreement with our results. For our samples, it was not necessary to apply current pulses, as the required current density can be reached by applying dc currents without heating of the wires, due to the small cross-sectional area at the constriction. By varying the width of the constriction, we demonstrate clearly that a critical current density of 1.1–1.4 $\times 10^7$ A/cm^2 is needed to move the domain wall in NiFe wires.

A nonlinear I–V has been reported first in ferrimagnetic nanocontacts of $\mathrm{Fe_3O_4}$, and crystals of $(\mathrm{La_{0.7}Sr_{0.3}})\ \mathrm{MnO_3}$ [13]. The resistance was found to drop gradually as the current exceeds a critical value, which was discussed in terms of domain wall movement due to spin pressure, resulting in a "magnetic balloon effect." For our samples, the resistance drops sharply due to the confined domain wall being completely removed from the constriction at the critical current density. While the resistance change observed here is much smaller than that in $\mathrm{Fe_3O_4}$ [13], the critical current density needed to move the domain wall in NiFe wires is two orders of magnitude smaller. These distinct differences may be due to different materials studied, different contact areas, and possibly different approaches. The ferrimagnetic magnetite crystals [13] were brought together by means of a piezoelectric device to form a nanocontact of 1 nm^2 in area, which allows electrical measurements to be made. By precisely defining the point contact width and device geometry using e-beam lithography, we have determined the critical current density and found a discrete resistance change comparable with domain wall magnetoresistance. In a recent experiment on NiFe rings with a nanoconstriction [14], an applied magnetic field was used to pin and unpin domain walls from the constriction. The observed negative contribution to magnetoresistance was attributed to anisotropic magnetoresistance (AMR). However, in our experiments, we observed a positive contribution to resistance without the use of magnetic fields. This approach has the advantage of canceling any additional contributions, such as AMR and Hall effect contributions, which can lead to misinterpreted domain wall scattering in domain wall magnetoresistance studies.

IV. CONCLUSION

In summary, we have fabricated using advanced e-beam lithography NiFe wires with a "bow-tie" nanoscale constriction and have shown for the first time a discontinuous current-induced resistance change in patterned single-layer ferromagnetic wires. A sharp drop in resistance of up to 0.079% for a 100-nm constriction was observed, and the critical current density was determined to be 1.1–1.4 $\times 10^7$ A/cm^2, attributed to current-induced domain wall movement via s-d exchange interaction. This may serve as a basis for nanomagnetic devices such as magnetic logic gates or magnetic random access memory, where the applied current should be able to switch the magnetic configuration locally.

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