Magneto-resistance in a lithography defined single constrained domain wall spin valve

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We have measured domain wall magnetoresistance in a single lithographically constrained domain wall. An H-shaped Ni nano-bridge was fabricated by e-beam lithography with the two sides being single magnetic domains showing independent magnetic switching. The connection between the sides constraining the domain wall when the sides line up anti-parallel. The magneto-resistance curve clearly identifies the magnetic configurations that are expected from a spin valve-like structure. The value of the magneto-resistance at room temperature is around 0.1% or 0.4 Ω. This value is shown to be in agreement with a theoretical formulation based on spin accumulation. Micromagnetic simulations show it is possible to reduce the size of the domain wall further by shortening the length of the bridge.

Keywords: Spin-valve, Single constrained domain wall, Domain wall magnetoresistance, DWMR

The research of spin-based logic will not only benefit the understanding of physics but also give possibility to fabricate faster and denser memory devices[1,2]. Domain wall magneto-resistance (DWMR) occurs when electrons travel from one side of the magnetic domain wall to another non-adiabatically. The DWMR is reported in many different structures such as ring structure[3–5], line structure[6–11], atom-contact structure[12,13], zigzag structure[14,15]and bridge structure[16,17]. In line-shape devices, the magneto-resistance effect of the domain wall is relatively small because the classic resistance of the line hides the DWMR effect. In the point connecting structure the magnetoresistance can be very large due to the ballistic transport of the electrons, but the fabrication procedures such as mechanical break junctions[18],electrical break junctions[19] and electrochemical junctions[20] are not suitable for the industrial fabrications[21], and the measurements are subject to artefacts[22].

In 1999, Bruno[23] proposed that in nano-structured devices the domain wall width can be constricted by geometric means. A sudden large expansion of the magnetic area will constrict the domain wall as the cost of increasing the area of the domain wall outweighs the exchange interaction. In this letter we report the experimental realization of this proposed structure and show magneto-resistance in a lithographically defined constrain domain wall structure in between two independently switching single magnetic domains. This is the first in-plane transport measurement of an individual nano-magnetic structure.

The device was fabricated on a Si p-type < 100 > wafer with 17-33 Ωcm resistivity. A 50 nm-thick SiO_2 layer was thermally grown on the front side of the wafer. Two layers of Au were deposited by photo lithography and metal lift-off. The thickness of the first gold layer was 22 nm allowing to contact the e-beam defined layers later on, while the second layer was 200 nm to allow probing. The third layer of Au wires which was 22 nm-thick and 200 nm-wide was patterned by a JEOL e-beam lithography system on PMMA and Copolymer bi-layer e-beam resist. The Au was deposited at a pressure 5×10^{-6} mbar and deposition rate 1 Å/s. The lift-off took place in N-Methyl-2-pyrrolidone (NMP) for 30 mins at room temperature. The 20 nm-thick Ni nano-structure constituted the fourth metal layer. The Ni deposition had

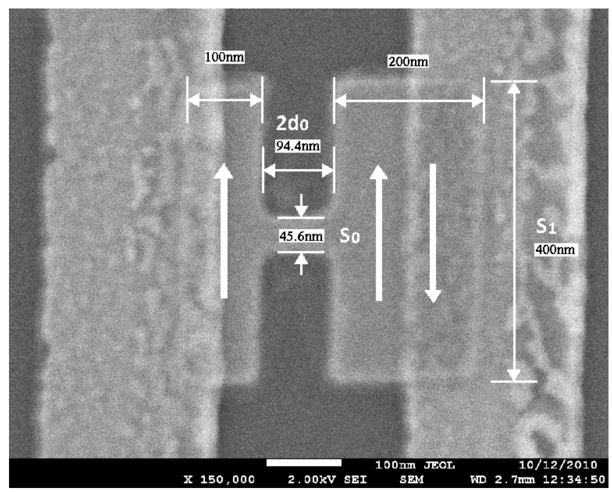

FIG. 1. SEM micrograph of the Ni domain wall structure with the Au contact lines. The bridge length $2d_0 = 94.4$ nm and width $s_0 = 45.6$ nm. The left domain whose size is 100×400 nm^2 can be seen as a pinned pad of the spin-valve, and the right domain 200×400 nm^2 is a switchable pad.

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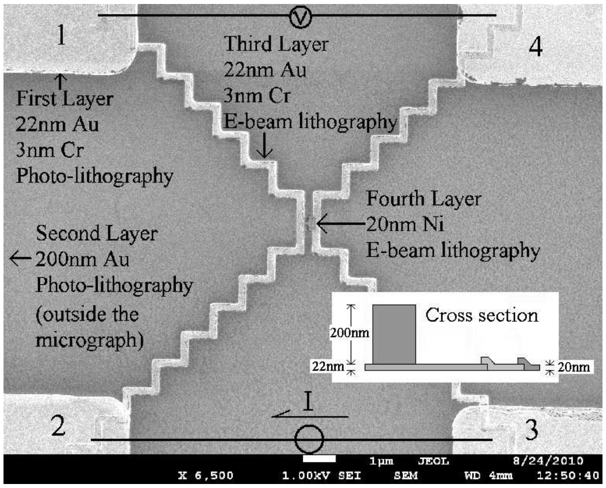

FIG. 2. SEM micrograph showing top view of the whole device structure including four-point probe measurement set up and insert showing cross section view. The ordered number in cross section shows the fabrication sequence. The pads numbered 1-4 indicate the probes' connection during our measurement $R_{dev} = V_{14}/I_{23}$.

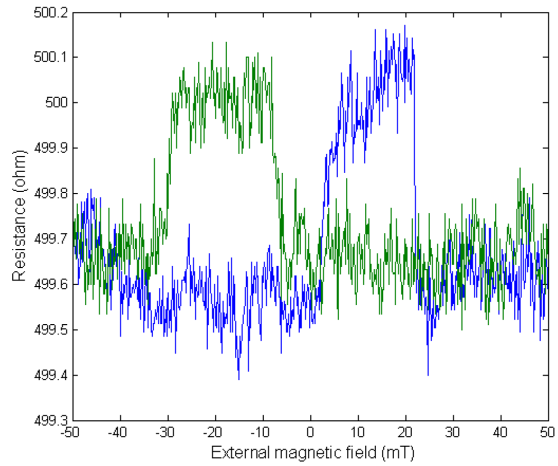

FIG. 3. Room temperature magneto-resistance curves of the Ni nano-bridge. The blue curve shows the device resistance when increasing magnetic field, while the green curve shows the decreasing field. Data are averaged over 6 individual measurements.

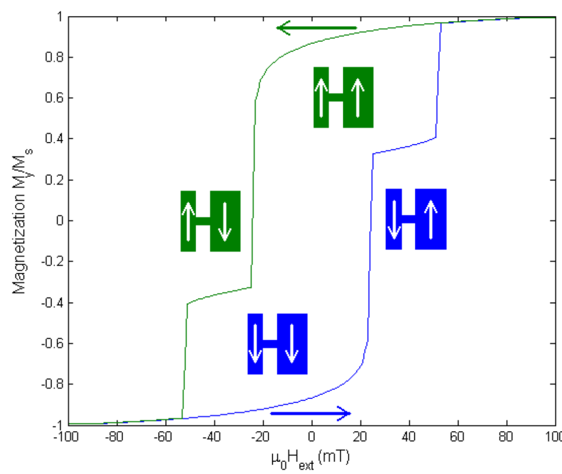

FIG. 4. OOMMF magnetization - magnetic field hysteresis loops. The model's geometrical size is based on the fabricated device shown in Fig. 1. The simulation parameters for Ni, exchange stiffness $A = 9 \times 10^{-12}$ J/m, and saturation magnetization $M_s = 490$kA/m are used. The curve shows both the parallel and anti-parallel states of our device.

the same condition as the Au deposition except for the deposition rate, which was 0.5 Å/s. Fig. 1 shows the Ni nano-bridge together with the e-beam defined Au layer. The critical alignment between the two layers shows an alignment tolerance of better than 20 nm.

The Au structure allows a four point measurement technique to be employed in the measurement of the domain wall structure such that only the Ni structure contributes to the resistance as shown in Fig. 2. Room temperature MR measurement were performed with a Lakeshore EMTTP4 magnetic probe station and an Agilent B1500 semiconductor parameter analyser.

Fig. 3 shows the room temperature magneto-resistance effect of the nano-bridge. The resistance-field pattern shows the typical step-like behaviour of a spin-valve like magneto-resistance (MR) structure in which both sides switch independently. The high coercive side (100×400 nm^2 domain; left side in Fig. 1) switches at around 25mT and the low coercive side (200×400 nm^2 domain) switches near 5 mT. These experimental values are slightly smaller than those derived from an OOMMF[24] simulation as shown in Fig. 4. Nevertheless, a clear plateau is identified in the MR curve in which the domains are anti-parallel leading to a domain wall in the nano-bridge and hence domain wall magneto-resistance of around 0.1% or 0.4 Ω. This magnitude is similar to those in Ni necked wires reported by Lepadatu and Xu[25].

Ieda et al.[26] provide an equation to explain the DWMR effect based on spin accumulation:

$$\Delta R = 2P^2 \rho_0 \lambda_F A^{-1} F(\xi) \quad (1)$$

where P is the polarization of the conduction spin, ρ_0 is the classic resistivity, λ_F is the spin diffusion length, A is the cross sectional area of the constriction, and $F(\xi)$ is a function of the ratio w/λ_F in which w is the domain wall width. Reduction of the domain wall width will increase the $F(\xi)$'s value[26].

We have previously shown[27] using a micromagnetic simulation that the domain wall width can be reduced by scaling the geometrical size of the bridge either through a reduction of the s_0/s_1 ratio or through limiting the bridge length $2d_0$. Using the experimental ratio of $s_0/s_1 = 0.10$, we can calculate the value of the domain wall width once demagnetization effects are taken into account. The calculations as displayed in Fig. 5 show that our current value of the domain wall width is 42 nm. Entering this

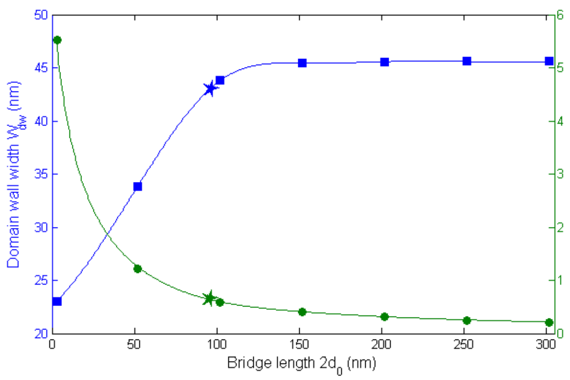

FIG. 5. OOMMF micromagnetic simulation results and corresponding theoretical MR values. The squares (left hand curve, blue) show the constrained domain wall length as a function of $2d_0$ for fixed ratio $s_0/s_1 = 0.10$. The circles (right hand curve, green) show the MR ratio corresponding to the simulated domain wall width calculated using Equation 1. The stars indicate the experimental dimensions of the bridge and corresponding MR value of the domain wall.

value in to the Equation 1 together with a spin polarization of $P = 20\%$, $\lambda_F = 21$ nm and $\rho_0 = 520$ nΩm[17] we arrive at a value of $\Delta R = 0.402\ \Omega$ which is close to our measurement result. The contact resistance between Au and Ni reduces the experimental MR ratio, and removing this contribution gives an experimental MR ratio of the domain wall of 0.6%, idential to the theoretical value. Further reduction of the length of the bridge will significantly enhance the magneto-resistance as shown on the right y-axis of Fig. 5. It should be noted that the current simulation gives a Néel-wall which is similar as the result at micrometer range reported by Jubert et al at 2004[28], but energy difference between the magnetic configurations is quite small[29] with experimental verification required by for instance magnetic transmission x-ray microscopy[30].

We have measured the domain wall magnetoresistance in a single lithographically constrained domain wall. The value of the magneto-resistance at room temperature is around 0.1% or 0.4 Ω in agreement with a theoretical formulation based on spin accumulation. Micromagnetic simulations show it is possible to reduce the size of the domain wall further by shortening the length of the bridge allowing larger MR ratio and a quantitative test of the effect of a reduction of the domain wall on the magneto-resistance.

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