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

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We have successfully measured domain wall magnetoresistance in a single lithographically constrained domain wall. A H-shaped Ni nano-bridge was fabricated by e-beam lithography with the two sides being single magnetic domains showing independent magnetic switching and 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

I. INTRODUCTION

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. 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,7–6, line structure,7–12, atom-contact structure,13,14, zigzag structure,15,16, and bridge structure.17,18. 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,19, electrical break junctions20 and electrochemical junctions21 are not suitable for the industrial fabrications,22, and the measurements are subject to artefacts.23

In 1999, Bruno24 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 realisation of this proposed structure and show magnetoresistance 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 magnetic structure completely at the nano-scale using standard methods.

II. EXPERIMENTAL

The device was fabricated on a Si p-type <100> wafer with 17-33 Ωcm resistivity. A 50nm-thick SiO₂ 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 22nm allowing the contact 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 were patterned by a JEOL e-beam lithography system on PMMA and Copolymer bi-layer e-beam resist. The Au deposition was done at pressure 5 × 10⁻⁶
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 $R_{dc} = V_{41}/I_{23}$.

mbar and deposition rate 1 Å/s. The lift-off was done in N-Methyl-2-pyrrolidone (NMP) for 30 mins at room temperature. The 20 nm-thick Ni nano-structure was build in the fourth metal layer. The Ni deposition had 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.

III. RESULT AND DISCUSSION

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 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 25 mT 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$^{25}$ 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 which is similar to the result in Ni necked wires reported by Lepadatu and Xu in 2004$^{26}$.

Ieda et al.$^{27}$ provided an equation to explain the DWMR effect based on spin accumulation:

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

(1)

where P is the polarization of the conduction spin, $\rho_0$ is the classic resistivity, $\lambda_F$ is the spin diffusion length, A is the cross sectional area of the constriction, and $F(\xi)$ is a function of the ratio $w/\lambda_F$ in which w is the domain wall width. The reduction on the domain width will increase the $F(\xi)$’s value$^{27}$.

We have previously shown$^{28}$ using a micromagnetic simulation that the 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 demagnetisation effects are taken into account. The calculations as displayed in Fig. 5 show that our current value of the domain wall width is 42nm. Entering this value in to the Equation 1 together with a spin polarization of \(P = 20\%\), \(\lambda_F = 21\) nm and \(\rho_0 = 520\) n\(\Omega m\)\(^{18}\) we arrive at a value of \(\Delta R = 0.402\) \(\Omega\) which is close to our measurement result. Further reduction of the length of the bridge will significantly enhance the magneto-resistance.

**IV. CONCLUSION**

We have successfully measured 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 \(\Omega\) 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 and a quantitative test of the effect of a reduction of the domain wall on the magneto-resistance.

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