Fabrication and simulation of nanostructures for domain wall magnetoresistance studies on Nickel

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ABSTRACT

We report the use of electron beam lithography and a bilayer liftoff process to fabricate magnetic Ni nanostructures with constriction widths in the range of 22 to 41 nm. The structures fabricated correspond to the nanobridge geometry. Reproducibility and control over the final nanostructure geometry were observed when using the fabrication process introduced, these two qualities are important in order to carry out a more systematic analysis of domain wall magnetoresistance (DWMR). On the other hand, micromagnetic simulations of structures with the nanobridge geometry were carried out using not only the dimensions of the fabricated nanostructures but also smaller dimensions thought to be achievable with further optimization of the fabrication process. It was found that domain walls with a reduced length of 42.5 nm can be obtained using the nanobridge geometry. Furthermore, the anisotropic magnetoresistance (AMR) effect was calculated numerically and it was found to be smaller than the DWMR, this makes the nanobridge geometry a good candidate for future measurements of the magnetoresistive effect due to domain wall scattering.

1. Introduction

The importance of studying magnetic domain walls (DWs) is due to the variety of physical phenomena arising from their interaction with magnetic fields and electric currents. As shown by Bruno [1], DWs can be tailored by defining constrictions in a ferromagnetic structure. Garcia et al. [2] reported large values of magnetoresistance which were attributed to domain wall scattering due to the presence of a DW in the nanobridge constriction. In this paper, the simulation of the AMR was done to assess whether AMR was higher than DWMR in these structures. This is accomplished by comparing the AMR effect, as obtained from simulations, to the analytical prediction of the DWMR effect. These results suggest that future magnetoresistance measurements will reflect the scattering due to the presence of a DW in the nanobridge constriction.

2. Experimental

For the fabrication of the nanostructures presented in this paper we used Si n-type <100> wafers with resistivity 17-33 Ω-cm as a substrate. A 20-nm-thick layer of SiO2 was then thermally grown on the front side of the wafer. The adhesive agent hexamethyldisilazane (HDMS) was used as a primer layer before the spinning of a 250-nm-thick layer of anisole-based resist ZEP520-A. Patterning was done with electron beam lithography (EBL) using a JEOL Electron Beam Pattern Generator (JBX-9300FS) at 100 keV with a dose of 115 μC/cm². Development of the exposed wafer was done using a MIBK:IPA process. Subsequently, the wafer was etched with buffered hydrofluoric acid BHF (7:1) for 42 sec in order to create an undercut in the SiO2 layer. Electron-gun evaporation (at a pressure of 10⁻⁷ mbar) was used to deposit a 10-nm-thick layer of Ni and a 1-nm-thick Au capping layer without breaking the vacuum. Liftoff was carried out in acetone on a wobbler.

The nanobridge geometry consists of a constriction connecting two rectangular pads as shown in Figures 1a and 1b. Left and right pads are 300-nm-wide with lengths of 100, and 200 nm respectively. This difference in the pad lengths is proposed to facilitate a magnetic configuration in which a domain wall is formed at the constriction due

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Fig. 1. SEM micrographs of nanostructures with a nanobridge geometry. Nominal lengths of the constrictions were $d_0 = 100$ nm (a), and $d_0 = 60$ nm (b). Nominal width for both structures was $s_0 = 20$ nm. Although the obtained constriction lengths are virtually the same as the nominal values, the observed widths are: $s_0 = 22$ for the case of (a), and 41 nm for (b).

to the different coercivities at which the magnetization in the pads switches.

To study the magnetic behaviour of the fabricated structures, we used the micromagnetics code based on finite difference method OOMMF [12]. Common parameters for Ni were used: $M_s = 490$ kA/m, and $A = 9 \times 10^{-12}$ J/m². Where $M_s$ is the saturation magnetization, and $A$ is the exchange stiffness. The cell size was 5 nm$^3$. The magnetization reversal of the nanobridges for fields from +100 to -100 mT with 5 mT steps applied along the $y$ axis (as displayed in Figure 1), were simulated using the aforementioned parameters.

Magnetization distributions of the nanobridge at fields where a DW is pinned in the constriction were used to estimate the width of the DW. The DW profiles obtained from such simulations are shown in Figure 2 along with their respective widths which were calculated using the method introduced in our previous work on nanobridges [11]. Simulated DW lengths for the nanostructures featured in Figure 1, are displayed as an inset in Figure 2. For the calculation of the anisotropic magnetoresistance (AMR) plotted in Figure 3b we used nmag (a multiphysics package based on the finite element method developed at Southampton University [13]) and followed the methodology employed by Bordignon et al. in Reference [14]. The advantage of using this method is, that it takes into account the back reaction of the AMR effect onto the current distribution hence it provides a more accurate AMR estimation. The plots shown in Figures 3a and 3b correspond to the magnetization reversal and the AMR numerically calculated of a nanobridge with the dimensions of the structure depicted in Figure 1a. This calculation was carried out using an experimental resistivity ($\rho_0 = 52 \, \Omega \cdot \text{cm}$) obtained from I-V measurements.

In order to estimate the resistance change due to the presence of a DW in our constricted nanostructures we employed the equation proposed by Ieda et al. [15].

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

Where $P$ is the polarization of the conduction spin, $\rho_0$ is the normal 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 $\frac{w}{\lambda_F}$ where $w$ is the length of the DW. A spin polarization of $P = 20\%$, and a spin diffusion length $\lambda_F = 21$ nm for Ni as determined by recent experiments [17,18] were considered. If we add this change of resistance to the resistance measured in similar structures without an applied magnetic field ($R \approx 345 \pm 0.1 \, \Omega$), we can then estimate the MR ratios presented in Table 1.
Fig. 3. (a) Magnetization reversal of a nanobridge with constriction dimensions: \( s_0 = 22 \text{ nm} \) and \( d_0 = 100 \text{ nm} \) for magnetic fields applied along the y axis. (b) AMR effects of \( 4.9 \times 10^{-4} \) and \( 2.37 \times 10^{-3} \) are expected at -15 and 15 mT fields. These are the fields at which a domain wall is formed at the constriction, this is represented by the steps in the magnetization reversal shown in (a).

3. Results and discussion

From the structures shown in Figure 1 we can observe that the nanobridge geometry is very well defined. The correlation between the actual and nominal dimensions, more remarkably over the rectangular pads, can be readily seen. This constitutes evidence that a high degree of control over the final structures is possible thanks to the fabrication process introduced above. Similar results were observed for different samples featuring the same structure, this ensures the reproducibility required in order to carry out a more systematic analysis of DWMR. From the inspection of the plot shown in Figure 3a one can observe steps in the magnetization reversal at \( \pm 15 \text{ mT} \) fields. By inspecting the simulated magnetization distribution corresponding to this fields, it was found that such steps correspond to the pinning of a DW at the constriction. The profiles of the DWs are shown in the inset of Figure 2. For a nanobridge with the dimensions showed in Figure 1a (\( s_0 = 22 \text{ nm}, d_0 = 100 \text{ nm} \)), the length of the DW is \( w = 70 \text{ nm} \). For this constriction length, it is more favourable for the magnetization to split into two \( 90^\circ \) DWs [11], as reflected by the profiles observed. Since our aim is to experimentally achieve smaller DW lengths, we studied the effect that further reduction of the constriction dimensions has on the resulting DW length. In order to do so, we calculated the DW width for constrictions with widths \( s_0 = 20 \text{ nm} \) and lengths \( d_0 = 20, 60, \) and \( 100 \text{ nm} \). Such results are shown in Figure 2. When comparing the DW widths from this plot with those of the inset it becomes evident that constrictions with smaller widths have greater influence on the DW length than constrictions with just shorter lengths. This is an important finding because, from an experimental point of view, it means that we still need to optimize our fabrication process to realize smaller constriction widths, and hence shorter DW lengths. From the results shown in Figure 2 we observe that a DW with length \( w = 42.5 \text{ nm} \) is expected for a constriction with dimensions \( s_0 = 20 \text{ nm} \) and \( d_0 = 20 \text{ nm} \). Nonetheless, a constriction with dimensions \( s_0 = 20 \text{ nm} \) and \( d_0 = 60 \text{ nm} \) seems more plausible. The estimated values of DWMR using equation 1 are presented in Table 1. From these results, we observe that DWMR can be higher than AMR.

<table>
<thead>
<tr>
<th>DW length (nm)</th>
<th>Constriction dimensions (( s_0 \text{[nm]},d_0 \text{[nm]} ))</th>
<th>AMR</th>
<th>DWMR</th>
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<tr>
<td>70</td>
<td>22,100</td>
<td>1.11</td>
<td>2.37 \times 10^{-3}</td>
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<tr>
<td>79</td>
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<td>0.6</td>
<td>1.1 \times 10^{-3}</td>
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<td>20,60</td>
<td>1.53</td>
<td>4.4 \times 10^{-3}</td>
</tr>
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</table>

Table 1

Estimated DWMR as a function of the DW lengths obtained from simulations of nanobridges with different constriction lengths. A shorter DW length means a higher contribution to the MR effect.

4. Conclusions

We succeeded in fabricating nanostructures with constriction widths in the range of 22 to 41 nm using a nanobridge geometry. Domain walls with reduced widths down to 42.5 nm can be obtained by using this geometry. Both AMR and DWMR have been estimated using numerical and micromagnetic simulations. It was found that DWMR is higher than AMR, this makes the nanobridge geometry a good candidate to carry out further studies on the topic of domain wall magnetoresistance. Experimental work is taking place to obtain DWMR measurements on such structures. D. Claudio-Gonzalez acknowledges support from the Mexican Council of Science and Technology (CONACYT). We also thank Mir Mokthari from Mir Enterprises Limited and Enrico Gili for their contribution to the fabrication of the experimental samples.

References