



## 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 22–41 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.

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### 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 DW scattering due to the inability of electron spin to travel across the DW adiabatically when its length is comparable to the Fermi wavelength [3]. This opened the possibility of using DWs as the source for a large magnetoresistance effect. Experiments on domain wall magnetoresistance (DWMR) showing a positive effect have been reported using different ferromagnetic structures such as thin films [4], cross-shaped junctions [5], zigzag wires [6], constricted wires [7,8], and micrometre-sized elements [9]. Micromagnetic simulation studies of constricted wires and nanobridges have already been carried out [10,11]. In the latter, we reported the possibility to reduce the DW length down to 11 nm using a nanobridge geometry when taking into account a weak in-plane anisotropy.

In this study, the process for the fabrication of nanostructures with the nanobridge geometry is presented. Furthermore, micro-

magnetic simulation studies were performed to estimate the width of the DWs on the fabricated structures and the results are presented. The anisotropic magnetoresistance (AMR) effect for the nanobridge geometry is calculated numerically using the actual dimensions observed in the fabricated structures. Since our aim is to carry out experimental measurements of DWMR on nanobridges in future work, 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 SiO<sub>2</sub> 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/cm<sup>2</sup>. Development of the exposed wafer was done using a MIBK:IPA process. Subsequently,

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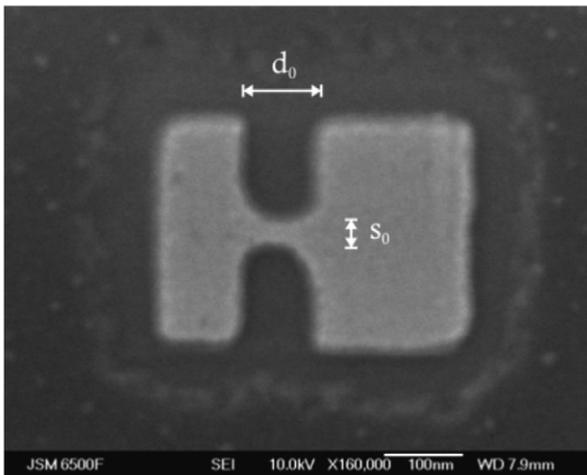
E-mail address: [dgc04r@ecs.soton.ac.uk](mailto:dgc04r@ecs.soton.ac.uk) (D. Claudio-Gonzalez).

the wafer was wet etched with buffered hydrofluoric acid (BHF) (7:1) for 42 s in order to create an undercut in the SiO<sub>2</sub> layer. Electron-gun evaporation (at a pressure of 10<sup>-7</sup> 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.

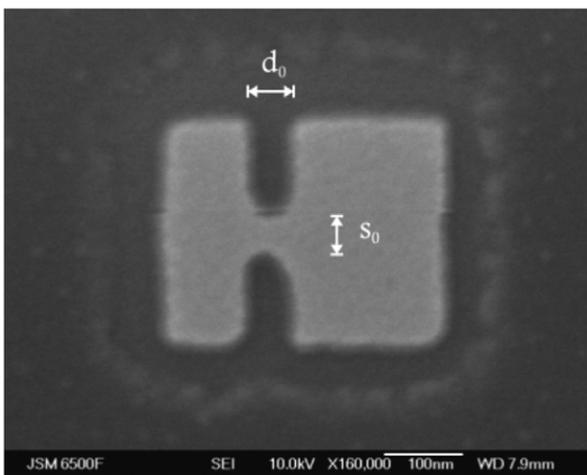
The nanobridge geometry consists of a constriction connecting two rectangular pads as shown in Figs. 1a and b. Left and right pads are 300-nm-wide with lengths of 100 and 200 nm, respectively. This difference in the pad lengths is proposed to facilitate a magnetic configuration in which a DW is formed at the constriction due 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/m, where  $M_s$  is the saturation magnetization, and  $A$  is the exchange stiffness. The cell size was 5 nm<sup>3</sup>. 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 Fig. 1), were simulated using the aforementioned parameters.

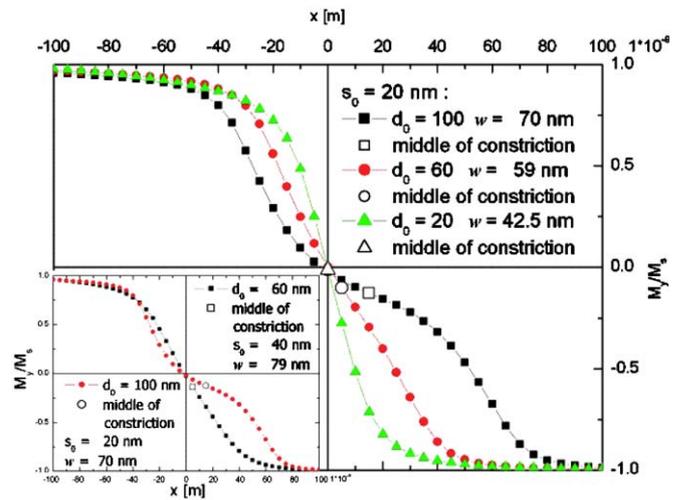
a



b



**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).



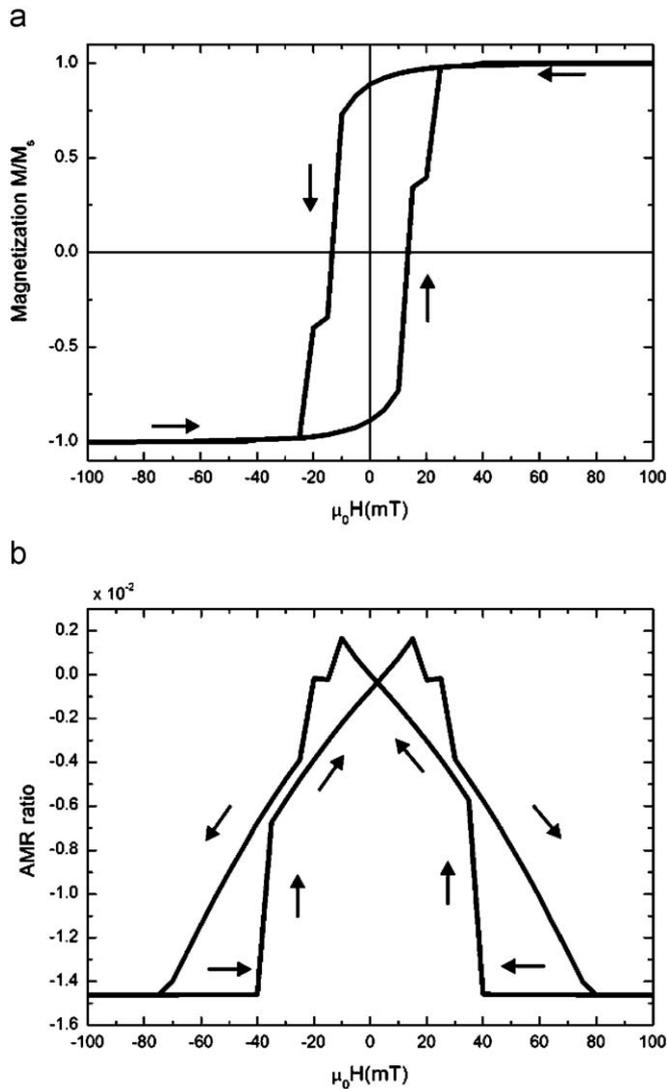
**Fig. 2.** Simulated domain wall profiles in nanobridges as a function of the constriction length. From micromagnetic simulations it was found that a domain wall length of  $w \approx 42.5$  nm, is achievable with the nanobridge geometry (definition of the DW length is the same as the one used in Ref. [11]). This domain wall length corresponds to a constriction of dimensions  $s_0 = d_0 = 20$  nm. In the inset the simulated domain profiles corresponding to the fabricated nanobridges illustrated in Figs. 1a and b are shown. In all cases the position of the DW can be realized by examining the geometric middle point of the constriction indicated for each profile. As the constriction length decreases, the DW is pushed towards the middle of the constriction.

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 Fig. 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 Fig. 1, are displayed as an inset in Fig. 2. For the calculation of the AMR plotted in Fig. 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 Ref. [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 Figs. 3a and b correspond to the magnetization reversal and the AMR numerically calculated of a nanobridge with the dimensions of the structure depicted in Fig. 1a. This calculation was carried out using an experimental resistivity ( $\rho_0 = 52 \Omega \text{ cm}$ ) 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. [16]:

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

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  $w/\lambda_F$  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:  $s_0 = 22$  nm and  $d_0 = 100$  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).

**Table 1**

Estimated DWMR as a function of the DW lengths obtained from simulations of nanobridges with different constriction lengths.

DW length ( $w$ ) (nm)	Constriction dimensions ( $s_0$ (nm), $d_0$ (nm))	$\Delta R$ (Eq. (1)) ( $\Omega$ )	AMR	DWMR
70	22, 100	1.11	$2.37 \times 10^{-3}$	$3.5 \times 10^{-3}$
79	41, 60	0.6	$1.1 \times 10^{-3}$	$1.8 \times 10^{-3}$
60	20, 60	1.53	–	$4.4 \times 10^{-3}$

A shorter DW length means a higher contribution to the MR effect.

### 3. Results and discussion

From the structures shown in Fig. 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 Fig. 3a one can observe steps in the magnetization reversal at  $\pm 15$  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 Fig. 2. For a nanobridge with the dimensions showed in Fig. 1a ( $s_0 = 22$  nm,  $d_0 = 100$  nm), the length of the DW is  $w = 70$  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 width  $s_0 = 20$  nm and lengths  $d_0 = 20, 60,$  and  $100$  nm. Such results are shown in Fig. 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 Fig. 2 we observe that a DW with length  $w = 42.5$  nm is expected for a constriction with dimensions  $s_0 = 20$  nm and  $d_0 = 20$  nm. Nonetheless, a constriction with dimensions  $s_0 = 20$  nm and  $d_0 = 60$  nm seems more plausible. The estimated values of DWMR using Eq. (1) are presented in Table 1. From these results, we observe that DWMR can be higher than AMR.

### 4. Conclusions

We succeeded in fabricating nanostructures with constriction widths in the range of 22–41 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 of the reported structures.

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