Magnetic domain walls in constrained geometries

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Magnetic domain walls have been studied in micrometer-sized Fe$_{20}$Ni$_{80}$ elements containing geometrical constrictions by spin-polarized scanning electron microscopy and numerical simulations. By controlling the constriction dimensions, the wall width can be tailored and the wall type modified. In particular, the width of a 180° Néel wall can be strongly reduced or increased by the constriction geometry compared with the wall in unconstrained systems.

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For almost a century, the width of magnetic domain walls (DWs) has been believed to be determined by material properties only. However, recent investigations on DWs in nanometer-scale systems have revealed new physical properties due to the geometrical confinement of the magnetization. A reduction of the Bloch wall width has been predicted and observed in nanometer-sized constrictions. This effect is thought to be the origin of the large magneto-resistance measured in nanocontacts, and explained by ballistic transport through a narrow constriction. Furthermore, domain walls are now being investigated as tiny individual magnetic objects that can be manipulated in view of their potential for application in novel magnetic logic or memory devices.

The prediction of DW narrowing in a constriction was based on a ferromagnetic model system containing a planar Bloch wall. Because dipolar contributions in the constriction were neglected, the problem was one-dimensional and could be solved analytically. The vast majority of small elements, however, exhibits DWs of Néel type, with a nonvanishing magnetization component perpendicular to the wall. In these walls, the dipolar energy determines the wall profile to a large extent, and hence the problem is more intricate.

In this paper, we investigate Néel-type walls in elements containing constrictions of controlled dimensions. The experimental results obtained by scanning electron microscopy with spin analysis (spin-SEM and SEMPA) are compared with micromagnetic simulations. We demonstrate how the wall properties can be tuned both by the element size and the constriction dimensions. Constraining a DW in a micrometer-sized element strongly reduces the wall width compared with the width in an infinite film. By appropriately tuning the constriction dimensions, the Néel wall width can further be decreased, or alternatively, increased until the wall splits into two separate walls.

The constrictions were fabricated in thin, micrometer-sized rectangular elements by using electron-beam lithography and Ar dry etching of Fe$_{20}$Ni$_{80}$ thin films. These films were produced by sputter deposition on SiO$_2$/Si(100), resulting in (111)-textured Fe$_{20}$Ni$_{80}$ films with a grain size of about 2 nm diameter, as determined from x-ray measurements. The crystalline anisotropy of the film was measured to be a superposition of a uniaxial term $K_u = 160$ J/m$^3$ and a cubic term $K_1 = -150$ J/m$^3$. The anisotropy is so low that it has no influence on the magnetic patterns in this study, as verified by micromagnetic simulations. All simulations were carried out using the OOMMF code. The material parameters used for the simulations are the commonly employed values for Fe$_{20}$Ni$_{80}$, an exchange constant $A_{exch} = 13 \times 10^{-12}$ J/m and a saturation magnetization $M_s = 800$ kA/m. The discretization cell size was 5 nm.

![FIG. 1: (a) Topographic image of a 10 µm × 4 µm × 7.5 nm Fe$_{20}$Ni$_{80}$ element with constriction dimensions $d_0 = 225$ nm and $S_0 = 500$ nm. (b) Corresponding magnetic configuration after ac demagnetization as determined by spin-SEM. The arrows indicate the magnetization direction. (c) Schematic of the rectangular magnetic element with constriction. (d) Magnetic configuration calculated for an element having the same dimensions.](image-url)
We quantify the mean Néel wall density multiplied by the total length. The wall width results from the minimization of the energy density, and is solely determined by the material parameters. A DW located in a constriction, however, is affected by the constriction geometry. At the constriction edges, the magnetization is forced to lie parallel to the sides to minimize the surface dipolar energy, and hence the wall width locally corresponds to $d_0$. To minimize its total energy in such a geometry, the DW deforms in the constriction area, i.e., the local wall width depends on the distance from the constriction center, and the wall adopts a two-dimensional shape. We consider the two limiting cases of small and large $d_\text{0}$. The relevant length scale to compare with is the wall width without constriction, $w_0$, which deviates from the wall width in an extended film. The wall adopts a two-dimensional shape. We consider the two limiting cases of small and large $d_0$. The relevant length scale to compare with is the wall width without constriction, $w_0$, which deviates from the wall width in an extended film. The wall adopts a two-dimensional shape.
value of $S_0 \simeq 250$ nm, a reduction of $w^*$ is observed with decreasing $S_0$, which becomes most pronounced for small $S_0$.

For $2d_0 > w_0 \simeq 200$ nm, the wall width at the constriction edges expands and the wall deforms inward (see inset on the right in Fig. 4). The same energy arguments as above apply: For small $S_0$, the wall at the center stretches, resulting in an increase of the measured $w^*$. The larger $S_0$ the stronger the confinement of the wall deformation to the edge region, and consequently the increase of $w^*$ is postponed to larger $d_0$ values.

Figure 4 illustrates the complexity of the DW in the constriction. The wall is two-dimensional and asymmetric, in good agreement with the calculated configuration. In the constriction region, the magnetization has to undergo a $180^\circ$ rotation. As exchange forces the spins to remain as closely aligned with each other as possible, the $180^\circ$ turn happens over a larger distance in the outer part of the turn. This explains the asymmetry of the DW configuration. We emphasize that the complex two-dimensional structure of a DW is not restricted to the Néel wall. We have also simulated Bloch walls and find similar features: bent walls and complex two-dimensional patterns. The assumption that a Bloch wall can be treated as a one-dimensional object is only justified for $d_0 \ll S_0$. Otherwise, dipolar contributions force the Bloch wall configuration to adopt a Néel-type arrangement.

Figure 4 also reveals the presence of a small intermediate domain nucleated at one constriction edge. This results from a strong preference for low-angle DWs in the case of Néel walls: Energy can be gained by replacing the $180^\circ$ domain wall by two $90^\circ$ walls and an intermediate domain. The splitting into two $90^\circ$ walls is local at first and will not affect the average DW profile significantly. But as $d_0$ approaches $S_0$, this domain expands to the constriction center, leading to the complete separation of the $180^\circ$ wall into two $90^\circ$ walls. This is experimentally visible in the average wall profile, as shown in Fig. 5 for a constriction of dimensions $S_0 = d_0 = 250$ nm. Thus, an additional condition needs to be fulfilled to avoid wall splitting and to pin a narrower $180^\circ$ DW in a constriction. Apart from $S_0$ being small, also $d_0 < S_0$ is required.

Figure 5: Wall profile determined in a wide constriction with $S_0 = 250$ nm and $d_0 = 250$ nm showing the splitting of the wall into two individual $90^\circ$ walls. Experimental data are shown as a solid line, the simulation as a dashed line; element dimensions: $10 \mu m \times 4 \mu m \times 7.5$ nm.

Having considered the effect of the constriction dimensions on the DW width, let us discuss the influence of the element size. In an infinitely extended 10-nm-thick Fe$_{20}$Ni$_{80}$ film, the Néel wall width has been determined to be on the order of 100 nm$^{21,22}$ with tails extending several micrometers beyond the core. In our small magnetic element, however, the tails are limited by the element width $2d_1$, leading to modified profile and wall width. Compared with the unconstrained extended film, the magnetostatic charges need to be modified within the Néel wall. This rearrangement of charges is rather complex and has not yet been described theoretically.$^{22}$ Figure 4 shows the variation of the wall width $w_0$ determined for rectangular elements of varying lateral size. Both, our experimental results and micromagnetic simulations demonstrate that a strong reduction of $w_0$ occurs when decreasing $2d_1$, owing to the confinement of the wall in the micrometer-sized element. Such a dependence on the magnetic-element dimensions is specific of the Néel wall and is not expected to occur for a Bloch wall.

Finally, let us comment on the small discrepancy observed between the experimental and calculated DW widths at small $d_0$. This is reminiscent of other experimental DW profile measurements in which the DW width was found to be much larger than the simulated values.$^{22}$ It was proposed that the magnetocrystalline anisotropy is smaller and/or the exchange constant larger than assumed in the calculations. Anisotropy can be ruled out in our case. The fact that the discrepancy arises only at small $d_0$, at which exchange is predominant, corroborates that exchange might be underestimated in the simulations.

In conclusion, we have investigated the configuration of $180^\circ$ Néel walls pinned in patterned constrictions, both
FIG. 6: Evolution of the average DW width $w^\ast$ as a function of the rectangle’s lateral size $2d_1$, with experimental results (empty circles) and calculations (filled circles). While a constriction was needed to pin a $180^\circ$ Néel wall its dimensions are such that $w^\ast$ equals $w_0$ (see Fig. 3): $S_0 = 250$ nm and $d_0 = 50$ nm. The element thickness is 20 nm.

Because of the extended tails in the Néel walls, the wall width in micrometer-sized elements can be strongly reduced, compared with the infinitely extended thin film. The width decreases when the lateral size of the magnetic element $2d_1$ decreases. In addition, by tuning the constriction dimensions, the Néel-wall width can also be modified continuously. Owing to significant dipolar contributions at the constriction edges, the domain wall can be stretched to wide profiles for large constriction widths $2d_0$. For small $d_0$, on the other hand, the domain wall is strongly confined when the constriction length $2S_0$ decreases. The ability to control domain-wall profile properties through geometrical constraints calls for further investigation of other domain-wall properties such as the magnetoresistance, or the displacement of constrained magnetic domain walls.

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