Micromagnetic simulation of domain wall motion in magnetic nano-wires

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Abstract. The magnetization reversal process of magnetic nano-wires was investigated using a moving mesh finite element method. The nucleation and expansion of reversed domains is calculated solving the Gilbert equation of motion. For a wire diameter of d = 20 nm either a transverse wall or a vortex wall is formed, depending on the strength of the initial applied field. Once a reversed domain is nucleated, the wall configuration remains the same during the complete reversal process. The vortex wall moves faster than the transverse wall. The domain wall velocities are in the order of 300 m/s to 800 m/s for an external field in the range from 300 kA/m to 600 kA/m for a Gilbert damping constant α = 1. The domain wall velocity increases with increasing wire diameter and decreasing damping constant, reaching 2000 m/s for d = 40 nm, α = 0.05, and an applied field of 250 kA/m.

Keywords. magnetic nano-wires, domain wall motion, domain wall velocity, micromagnetics

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1. Introduction

Magnetic nano-wires are of great practical and theoretical interest. Future magneto-electronic devices and magnetic sensors may be based on the magneto-resistance of domain walls moving in nano-wires. [1-4]. Lee and co-workers [1] investigated the nucleation of domain walls in NiFe wire junctions using magnetic force microscopy and micromagnetic calculations. Domain walls nucleate in the wider part and are trapped in the junction area. Based on these results the authors suggest structures which may be used to launch domain walls into wires with a controlled external field. Ono and co-workers [2] investigated magnetization reversal in NiFe/Cu/NiFe trilayers using the giant magneto-resistance effect. The time variation of the resistance was measured to estimate the domain wall velocity. Taniyama and co-workes [3] reported a negative magneto-resistance due to domain walls in Co zig-zag wires.
McMichael and co-workers [4] used micromagnetic simulations to investigate the motion of transverse head-to-head walls within a domain wall trap consisting of a a shaped NiFe wire with two wide ends. The influence of Bloch lines and vortices on domain wall motion in prismatic wires was investigated by Nakatani and co-workers [5]. They calculated domain wall velocity as a function of the wire dimensions solving the Landau-Lifshitz Gilbert equation. The possible wall structures of head-to-head walls in thin permalloy films were numerically computed by McMichael [6]. Hertel and Kronmüller applied an adaptive finite element method to calculate domain configurations and vortex motion in thin film elements [7].
This work uses a finite element technique to calculate the domain wall motion in cylindrical Co nano-wires. The domain wall velocity is calculated numerical as a function of the external field, the wire diameter and the Gilbert damping constant. Section 2 introduces the adaptive finite element method used for the calculations. Section 3 treats the influence of the wall structure on the domain wall velocity.

2. Moving mesh micromagnetics

The simulations starts from the total magnetic Gibbs free energy

$$E_t = \int \left[A \sum_{i=1}^{3} (\nabla\beta_i)^2 - K_u(\mathbf{u} \cdot \boldsymbol{\beta})^2 - \frac{1}{2}\boldsymbol{J} \cdot \boldsymbol{H}_\mathrm{d} - \boldsymbol{J} \cdot \boldsymbol{H}_\mathrm{ext} \right] dV, \tag{1}$$

A is the exchange constant, β_i denote the direction cosines of the magnetic polarization vector, $\boldsymbol{J} = (\beta_1,\beta_2,\beta_3)J_s$. K_u and $\boldsymbol{u}$ are the magneto-crystalline anisotropy constant and the anisotropy direction. $\boldsymbol{H}_{ext}$ is the external field. The demagnetizing field, $\boldsymbol{H}_d$, follows from a magnetic scalar potential. The magnetic scalar potential solves the magnetostatic boundary value problem and can be effectively computed using a hybrid finite element boundary method [8]. The variational derivative of (1) gives the total effective field $\boldsymbol{H}_{eff}$ acting on the magnetic polarization. In equilibrium the torque, $\boldsymbol{J} \times \boldsymbol{H}_{eff}$, vanishes and the magnetic polarization is at rest. Once a sufficiently large reversed field is applied a domain wall will nucleate and propagate through the wire. The dynamic response of the system follows from the Gilbert equation of motion

$$\frac{\partial \boldsymbol{J}}{\partial t} = -|\gamma| \boldsymbol{J} \times \boldsymbol{H}_\mathrm{eff} + \frac{\alpha}{J_s} \boldsymbol{J} \times \frac{\partial \boldsymbol{J}}{\partial t} . \tag{2}$$

The magnetic wire is divided into tetrahedral finite elements. Within each element the direction cosines β_i are interpolated by a linear function. In order to resolve a magnetic domain wall the element size has to be smaller than the characteristic length, l_c, given by the minimum of the exchange length, l_{ex} and the Bloch parameter δ_0

$$l_\mathrm{c} = \min(l_\mathrm{ex},\delta_0) = \min\left(\sqrt{\frac{2\mu_0 A}{J_s^2}}, \sqrt{\frac{A}{K_\mathrm{u}}} \right). \tag{3}$$

If the element size is too big a so-called domain wall collapse [9] will occur: The magnetization becomes aligned anti-parallel at neighboring nodes and the torque on the magnetization vanishes. A high number of finite elements is required for the study of wall motion in magnetic wires using a uniform fine grid with an element size $h \le l_c$. In order to keep the number of finite elements small and avoid the domain wall collapse, an adaptive refinement scheme can be applied. The finite element grid is adjusted to the current wall position during the solution of the Gilbert equation of motion. The mesh is refined in regions with non-uniform magnetization, whereas elements are taken out where the magnetization is uniform. Thus the fine grid move together with the wall, as the mesh can be coarsed as soon as the wall has passed by. Fig. 1 shows the flow chart of the corresponding algorithm. After each time step an error indicator is computed for each finite element. A reliable refinement indicator is based on the constraint condition for the norm of the magnetization vector which successfully identifies the regions with non-uniform magnetization [10]. If the error is too large the time step is rejected and the finite element mesh is refined in regions with large errors. Otherwise the time integration is continued on the given grid. Thus the simulation proceeds in time only if the space discretization error is below a certain threshold. Numerical studies [11] showed that the moving mesh reduces the total CPU time by more than a factor of 4. Fig. 2 shows a sequence of grids during the simulation of domain wall motion in a Co-wire. The mesh size in the coarse region is 20 nm, whereas the mesh size at the wall position approaches l_c, which is 4.3 nm for the investigated Co wire.

3 Results and discussion

Fig. 3 gives the model system used for the simulations. The magnetic wire of a length of 600 nm is composed of two parts, a soft magnetic part with a length of 100 nm and a hard magnetic part with a length of 500 nm. The soft magnetic fraction has zero magnetocrystalline anisotropy. The hard magnetic part has a uniaxial anisotropy parallel to the long axis of the wire. The domain wall velocity significantly depends on the wall structure. The nucleation process determines the wall structure and thus has to be an inherent part of the simulation model. The soft region provides an easy way to control the nucleation of a domain at one side of the wire. In the simulations the external field is applied parallel to the long axis. A small external field leads to the nucleation of a reversed domain within the soft magnetic part. A head-to-head domain wall forms and moves towards the interface between the different phases. Once the domain wall reaches passes the interface between the different regions we measure the decay of the magnetic polarization parallel to the long axis as a function of time. The domain wall velocity is obtained from the slope of this curve. Fig. 4 illustrates this procedure for different applied fields, leading to the domain wall velocity, v_D, as a function of the external field, H_{ext}. The bottom plot gives $v_D(H_{ext})$ for a wire with a diameter of 10 nm and a Gilbert damping constant of $\alpha = 1$. For all applied fields a so-called transverse wall forms. In the center of the wall the magnetization points normal to the long axis of the wire. This structure remains the same during the motion of the domain wall through the wire.

For thicker wires also vortex walls may form. The magnetization rotates in opposite directions within different sections of the wall, leading to the formation of a Bloch line. The transverse and the vortex wall have nearly similar total energy for a diameter of 20 nm. The formation of a vortex reduces magnetic surface charges and thus the magnetostatic energy. On the other hand the exchange energy of a vortex wall is higher than the exchange energy of the transverse wall. For $d = 20$ nm the calculated total energy of the vortex wall is about 1% higher than the total energy of the transverse wall. In the simulations, both types of walls may be formed depending on the applied field during the nucleation process. However, the wall velocity depends on the wall type. Fig. 5 gives the calculated wall velocities for different wire diameters. The two sets of data for $d = 20$ nm refer to the transverse wall (white triangles) and the vortex wall (black triangles). Once the wall nucleates into a certain structure, this structure remains the same during wall motion. Fig. 6 gives the domain structure at different times during the motion of the domain wall. The arrows give the magnetization component within a slice plane parallel to the long axis of the wire. In addition, the grey scale indicates the direction of rotation of the magnetization vector. The black and white regions in the pictures on the right hand side clearly indicate two different directions of rotation within the wall.

For a diameter of 40 nm the gain in stray field energy due to the formation of a vortex is bigger than the expense of exchange energy. Thus only vortex walls are formed. An example of the wall structure can be seen in the inset of fig. 7. The figure compares the domain wall velocity for different damping constants. Small damping increases the wall mobility [12] and thus leads to a significant increase in the wall velocity.

4 Conclusions

Numerical micromagnetic calculations show that the domain wall velocity in magnetic nano-wires significantly depends on the wall structure. For a critical range of the wire diameter, the energy of the transverse and vortex walls are rather similar. Depending on the applied field during the nucleation process, either of the two walls can be formed. The wall velocity of a vortex wall is about 1.3 times higher than the wall velocity of the transverse wall. For a wire diameter $d \geq 40\ \mathbf{m}$ only vortex walls occurs. Thus with low damping ($\alpha = 0.05$) domain wall velocities in the order of 10^3 m/s can be achieved.

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Figure Captions

Fig. 1. Flow-chart of the adaptive mesh micromagnetic algorithm. The simulation proceeds in time only if the space discretization error is below a certain threshold.

Fig. 2. Sequence of meshes during the motion of the domain wall. The pictures give the triangular mesh on the surface of the wire.

Fig. 3. Finite element model of the two-phase wire. The total length of the nano-wire is 600 nm. The soft magnetic part with zero anisotropy facilitates the nucleation of reversed domains. The hard magnetic part has the material parameters of Co (spontaneous magnetic polarization J_s = 1.76 T, exchange constant $A = 1.3 \times 10^{-11}$ J/m, and the magnetocrystalline anisotropy parallel to the long axis, $K_u = 4.5 \times 10^5$ J/m^3).

Fig. 4. Calculation of the domain wall velocity. Top: Total magnetic polarization parallel to the long axis for different applied fields. The different lines refer to different fields in the range from 560 kA/m to 700 kA/m with a step of 14 kA/m. Bottom: Domain wall velocity as a function of the applied field. The wire diameter is d = 10 nm and the Gilbert damping constant is $\alpha = 1$.

Fig. 5. Domain wall velocity as a function of the applied field for different wire diameters. The white symbols and the black symbols refer to transverse walls and vortex walls respectively.

Fig. 6. Domain wall configurations at different wall positions. Left: Transverse wall, right: Vortex wall. The arrows give the magnetization component in a slice plane parallel to the long axis. The grey scale maps the out of plane component of the magnetization. The wire diameter is d = 20 nm and the Gilbert damping constant is $\alpha = 1$.

Fig. 7. Domain wall velocity for different damping constants. Triangles: $\alpha = 0.05$, circles: $\alpha = 1$.The wire diameter is 40 nm. The inset shows the wall structure.

Fig. 1

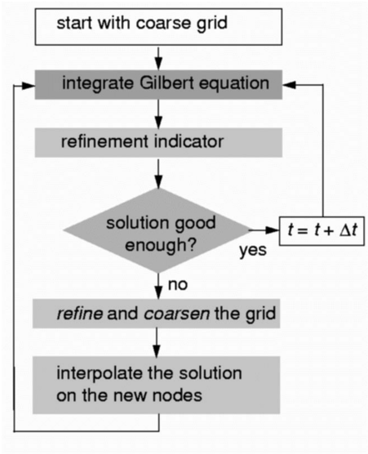

start with coarse grid
integrate Gilbert equation
refinement indicator
solution good enough?
yes
$t = t + \Delta t$
no
refine and *coarsen* the grid
interpolate the solution on the new nodes

Fig. 2

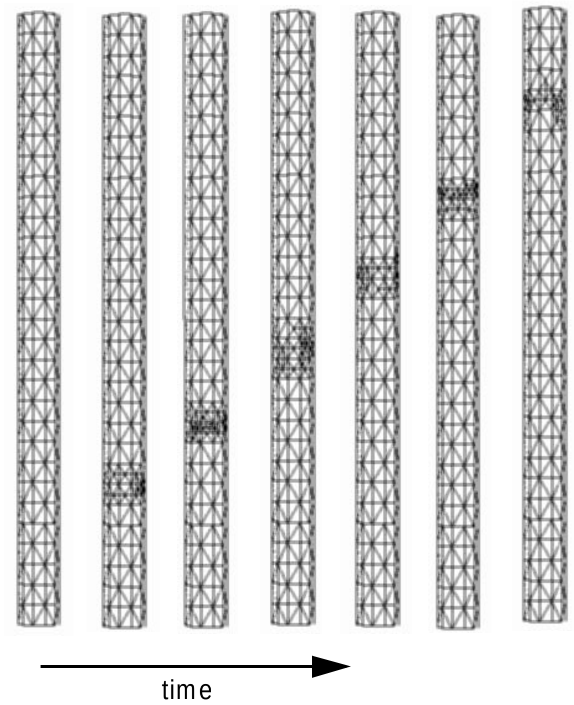


Fig. 3

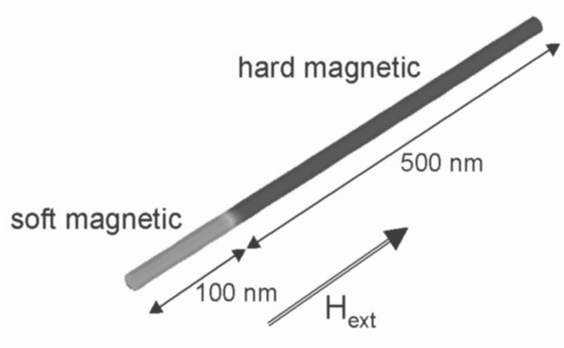
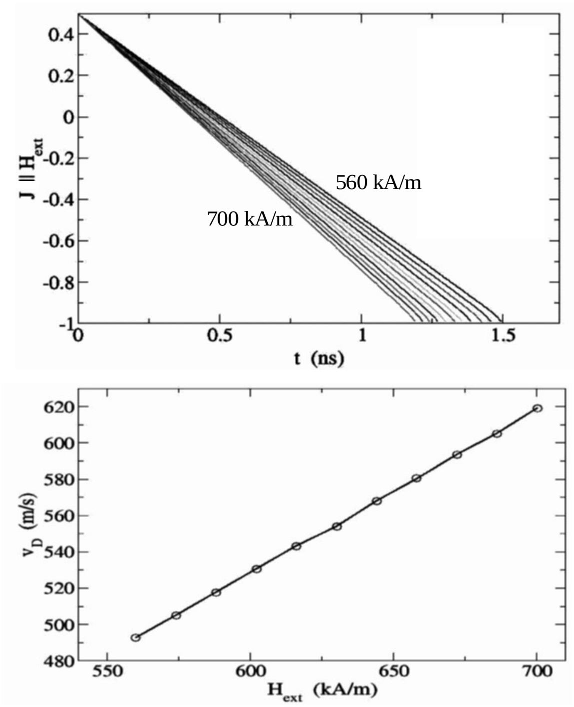


Fig. 4



0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
J ‖ H_ext
560 kA/m
700 kA/m
0
0.5
1
1.5
t (ns)
620
600
580
560
540
520
500
480
v_D (m/s)
550
600
650
700
H_ext (kA/m)

Fig. 5

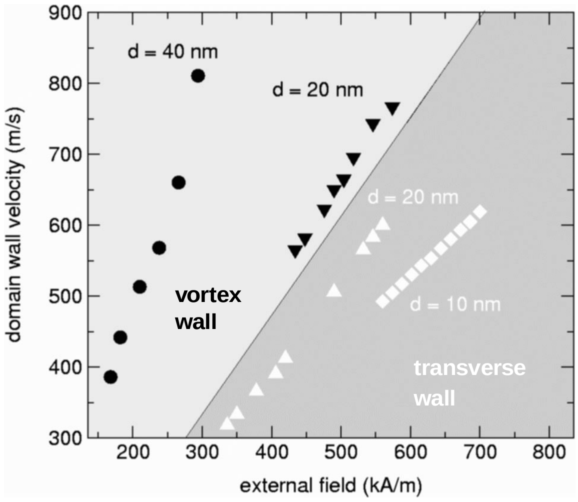

d = 40 nm
d = 20 nm
d = 20 nm
d = 10 nm
vortex
wall
transverse
wall
domain wall velocity (m/s)
external field (kA/m)
900
800
700
600
500
400
300
200
300
400
500
600
700
800

Fig. 6

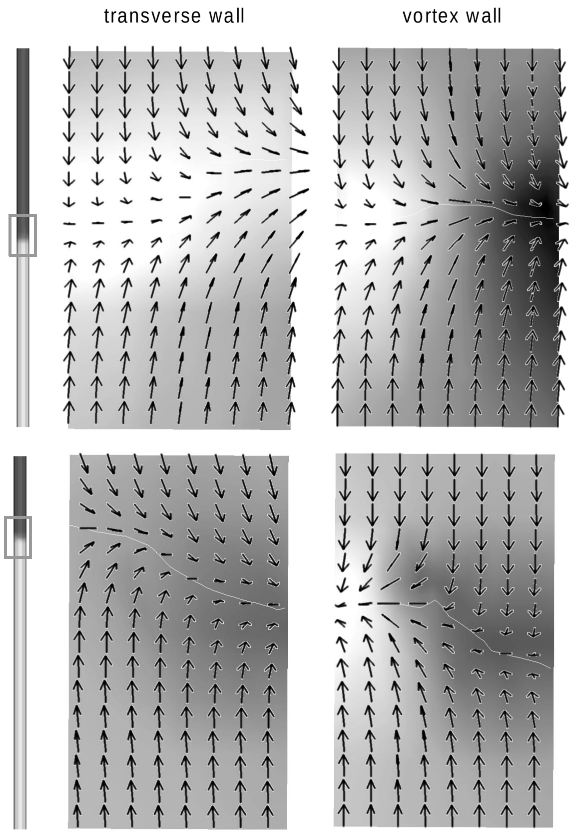
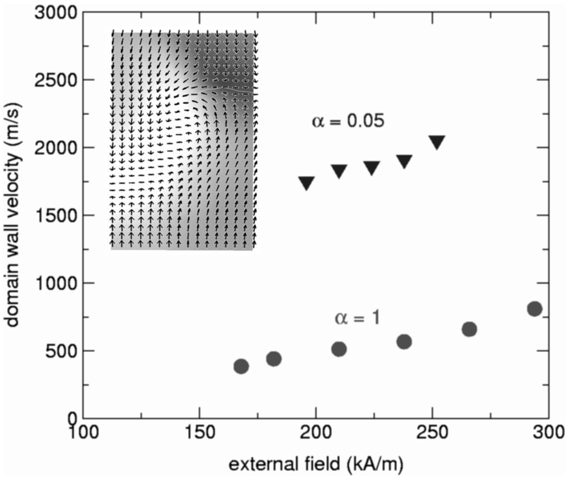


Fig. 7


3000
2500
2000
1500
1000
500
0
100
150
200
250
300
domain wall velocity (m/s)
external field (kA/m)
α = 0.05
α = 1