14th Czech and Slovak Conference on Magnetism, Košice, Slovakia, July 6–9, 2010

Domain Wall Dynamics in Bistable Ferromagnetic Laminations

J. Kravčák* and V. Šuhajová

Department of Physics, FEEI, Technical University of Košice, Park Komenského 2, 041 54 Košice, Slovakia

The presented article deals with a model of magnetic reversal in conducting lamination with a one central ferromagnetic layer and two outer non-ferromagnetic layers. Considering a single rigid 180° domain wall spreading through the axially magnetized ferromagnetic layer the calculation of induced eddy currents in lamination is performed. The dependence of single domain wall mobility on the thickness of ferromagnetic layer is displayed. The effect of non-homogeneous magnetic field intensity generated by eddy currents is also discussed.

PACS numbers: 75.60.Ch, 75.60.Ej, 75.60.Jk

1. Introduction

The eddy currents distribution for a single plane domain wall moving in a rectangular ferromagnetic bar was studied by Williams et al. [1]. Based on this work the extended model was developed containing a central rectangular ferromagnetic layer — core — and two conducting non-ferromagnetic layers — shell (see Fig. 1) [2]. The movement of a single domain wall was also studied by Colaiori et al. [3] by means of diffusion equation for eddy currents field, i.e. there is a finite time delay between the wall displacement and the establishment of the eddy currents. In this article the quasi-static approximation is introduced, where permeability μ_0 is within domains, and reduced Maxwell differential equations are used in Sect. 2. The influence of domain wall non-zero thickness on eddy currents losses produced during wall movement through the sample is very small in case of a strong uniaxial magnetic anisotropy [4]. For this reason the approximation of the zero domain wall thickness is fully valid for the model described below.

2. Model description and eddy currents calculation

We introduce a rectangular sample with dimensions $x \in [-L_1, L_2]$, $y \in [-h/2, h/2]$, and infinite in the z direction. The sample contains three conducting layers, two outer layers are not ferromagnetic (NFL) and the central one is ferromagnetic (FML) with uniform antiparallel magnetization with respect to z direction. If an external magnetic field of intensity H is applied in z direction, magnetic reversal of FML occurs by the propagation of a single rigid plane 180° domain wall (DW) from the left to the right sample boundary as displayed in Fig. 1. The origin of the coordinate system is placed in a centre of the moving DW ($x = 0$). It should be pointed out that L_1 and L_2 are variable distances of the DW from left and right sample boundary, respectively.

* corresponding author; e-mail: jozef.kravcak@tuke.sk

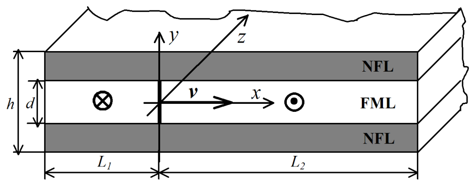

Fig. 1. Magnetic reversal (domain wall movement) in FML. The rectangle width is $L_1 + L_2 = 2$.

Thus the sample width is $L_1 + L_2$. The FML thickness is denoted by d.

Generally, the theory of eddy currents is based on a diffusion equation solution [3]. The following calculations are done on the assumption that electric and magnetic fields are propagated instantaneously (displacement current is neglected). The current density $\boldsymbol{j}$ is the solution of the differential equations: $\nabla^2\boldsymbol{j} = 0$, $\mathrm{rot}\boldsymbol{j} = 0$, $\mathrm{div}\boldsymbol{j} = 0$.

Using the boundary condition: $\boldsymbol{j}_n = 0$, normal component of $\boldsymbol{j}$ is equal to zero on all outer sample surfaces, gives

$$j_x(x,y) = \sum_{n=1}^{\infty} D_n \sinh\left(\frac{n\pi}{h}(L_{1,2} - x)\right) \times \cos\left(\frac{n\pi}{h}\left(y - \frac{h}{2}\right)\right),$$
$$j_y(x,y) = \sum_{n=1}^{\infty} D_n \cosh\left(\frac{n\pi}{h}(L_{1,2} - x)\right) \times \sin\left(\frac{n\pi}{h}\left(y - \frac{h}{2}\right)\right), \quad (1)$$

where L_1 is for interval $x \le 0$ and L_2 is for interval $x \ge 0$. Additional boundary condition should be applied within the sample at the domain wall position ($x = 0$): $\mathrm{rot}\boldsymbol{j} = -\gamma\mu_0\,\mathrm{d}\boldsymbol{M}/\mathrm{d}t$, where $\mathrm{d}\boldsymbol{M}/\mathrm{d}t$ is a rate of magnetization change, γ is the sample conductivity and μ_0 is magnetic permeability and it yields the coefficients

$$D_n = \mp\frac{4\gamma\mu_0 M_{\mathrm{S}} v \sin(n\pi/2)\sin(n\pi d/(2h))}{n\pi\cosh(n\pi L_{1,2}/h)}, \quad (2)$$

for $n = 1, 2, 3, \ldots$, where v is domain wall velocity and the + sign is valid for $j_y(x,y)$ with L_1 in interval $x \leq 0$ only.

3. Results and discussion

From Eqs. (1) and (2) we have numerically calculated a non-homogeneous magnetic field intensity $H_z(x,0)$ generated by eddy currents along the x axis ($y=0$) using the Biot–Savart law [5], see Fig. 2. The eddy currents field in-

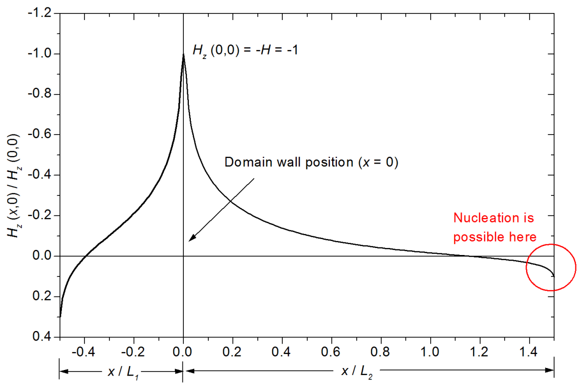

Fig. 2. Distribution of the reduced eddy current field intensity running through the sample in the x axis ($y=0$). The position of the wall ($x=0$) is asymmetric with respect to the left and right sample boundary. Driving field intensity $H=1$.

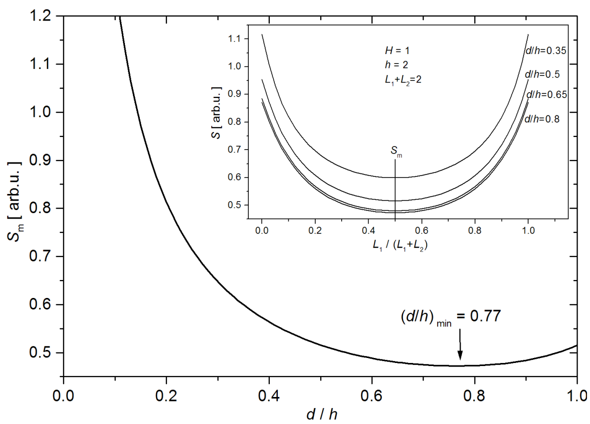

Fig. 3. Dependence of the minimum DW mobility S_{m} at the center of the rectangle on the ratio d/h. Inset shows the calculated dependences of the DW mobility on the DW position (distance L_1) and on the ratio d/h.

tensity at the DW position ($x=0$) $H_z(0,y)$ is antiparallel to external driving field of intensity H, $H_z(0,y)=-H$, and the DW acceleration vanishes (the process known as eddy currents damping). Going further from the DW position, $H_z(x,0)$ rapidly decreases to zero value with x. But there is a transition interval near the left and right side of rectangle where $H_z(x,0)$ changes its antiparallel orientation to the parallel one with respect to external field H. In case of asymmetric position of the DW in Fig. 2, $H_z(x,0)$ is considerably higher in transition interval which is closer to the moving DW. If the sum of $H+H_z(x=L_2,0)$ reaches the nucleation field intensity [6], there is a possibility to create a new DW at the opposite side of rectangle ($x=L_2$), which will move in opposite direction. Neglecting other interactions of DW (e.g. DW pinning, tilting and the Hall effect) a linear dependence of the DW velocity v on driving field intensity H was derived from (1) and (2): $v=SH$ [2], where S is the DW mobility

$$S=(\pi^3 d)/\{4h^2\gamma\mu_0 M_{\mathrm{S}}\sum_{n=1}^{\infty} n^{-3}[\tanh(n\pi L_1/h) + \tanh(n\pi L_2/h)]\sin^2(n\pi/2)\sin^2(n\pi d/(2h))\}\,. \quad (3)$$

The calculated dependences of the DW mobility on the DW position (distance L_1) and on the ratio d/h (the FML thickness to overall sample thickness h) are displayed as inset in Fig. 3. We can see the maximum DW mobility on both sides of the rectangle and the minimum DW mobility S_{m} at the center of the rectangle. The mobility S_{m} rapidly decreases with the ratio d/h in Fig. 3. We observe at the ratio $(d/h)_{\min} = 0.77$ the absolute minimum DW mobility.

4. Conclusions

The presented theoretical model deals with magnetic reversal of the rectangular sample consisting of one central ferromagnetic layer and two outer conductive non--ferromagnetic layers. The magnetic reversal in external magnetic field of low intensity is connected with propagation of one single plane domain wall through the ferromagnetic layer. The proposed geometry of the sample allows us to calculate exactly the eddy currents distribution and to determine the generated eddy currents field in the sample as well. We have shown the theoretical possibility of the nucleation of new DW (moving with a negative velocity) induced by the eddy currents field. This effect can manifest itself in a sudden increase of the DW velocity which could be observable in the Sixtus–Tonks experiment. We have also shown that conductivity and thickness of non-ferromagnetic layers with respect to the thickness of a ferromagnetic layer play a very important role in the DW mobility and the ratio $d/h=0.77$ gives us the absolute minimum DW mobility.

Acknowledgments

This work was supported by the Slovak grant projects VEGA No. 1/0076/09 and VEGA No. 1/0136/10.

References

[1] H.J. Williams, W. Shockley, C. Kittel, *Phys. Rev.* **80**, 1090 (1950).

[2] J. Kravčák, *Acta Phys. Slov.* **56**, 153 (2006).

[3] F. Colaiori, G. Durin, S. Zapperi, arXiv:0706.2122v1 (2007).

[4] R.P. del Real, *J. Magn. Magn. Mater.* **303**, 160 (2006).

[5] J. Kravčák, *Acta Electrotechn. Inform.* **10**, 75 (2010).

[6] R.S. Tebble, D.J. Craik, *Magnetic Materials*, Wiley--Interscience, London 1969.