Physica B 454 (2014) 98–101

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Single domain wall dynamics in ferromagnetic wire with circular magnetization and conductive cover

J. Kravčák*

Department of Physics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Park Komenského 2, 042 00 Košice, Slovakia

ARTICLE INFO

Article history:
Received 17 June 2014
Accepted 24 July 2014
Available online 4 August 2014

Keywords:
Domain wall mobility
Eddy currents
Ferromagnetic wire
Circular magnetization reversal
Maxwell equations

ABSTRACT

The circular magnetization reversal process in a long ferromagnetic wire with a non-ferromagnetic conductive cover is theoretically analysed. The model of a single thin rigid 180° domain wall (DW) is used so that the wire is divided crosswise into two magnetic domains with opposite circular magnetization. It is presumed that after switching on direct electric current in the wire, the circular magnetization reversal occurs by means of the DW movement through the wire. The induced electric field and the eddy current power losses in all conductive parts are calculated in the model, from which the DW mobility is determined. It is shown that DW mobility is very sensitive to the thickness and the conductivity of the non-ferromagnetic cover. An experimental procedure for measuring DW mobility through the non-ferromagnetic conductive cover is proposed.

1. Introduction

From experimental practice it is well known that a combination of tension and dc Joule annealing of amorphous ferromagnetic wire CoFeSiB with negative magnetostriction induces circumferential magnetic anisotropy [1,2]. It is presumed that strong circumferential magnetic anisotropy causes homogeneous circular orientation (circular saturation) of spontaneous magnetization in the wire. There are two possible processes during reversal of the circular magnetization in the wire, either of which may occur: the first process involves creation (nucleation) of a single thin 180° domain wall (DW), for example at one end of the wire, followed by DW movement through the wire (see Fig. 1); the second process involves homogeneous magnetization rotation to the opposite circular orientation in the whole volume of the wire [3]. In the presented model the first process is theoretically investigated when an already-created rigid 180° DW with negligible thickness moves through the wire. The approximation of negligible domain wall thickness used in this article is valid considering the real, very long, ferromagnetic cylindrical wire with strong circumferential magnetic anisotropy and diameter at least 10 μm described in Section 2. The deposition of a non-ferromagnetic conductive cover gives the possibility of changing the mobility of the rigid 180° DW, which is theoretically described in model. Providing that the DW velocity is sufficiently small, four assumptions are made in the present article: firstly a quasi-static approximation is introduced and the time delay between the wall displacement and the establishment of eddy currents is neglected; secondly the time derivation of circular magnetization $d\vec{M}/dt \neq 0$ is different from zero, but only at the DW position; thirdly the influence of skin effect on eddy current density is also neglected, considering that the permeability within domains is μ_0; fourthly the eddy current distribution has cylindrical symmetry. The very long wire is used for minimization of wire-end influence. All effects near the wire ends and the measuring voltage contacts resulting for instance in DW acceleration due to asymmetrical eddy current distribution around the DW [4] are neglected.

2. Description of the model

Fig. 1 shows the model of the ferromagnetic wire indicated as FMW with the non-ferromagnetic conductive cover (NFC). Taking into account the cylindrical shape of the wire and its cover, it is convenient to introduce the cylindrical coordinates (r, φ, z) with z axis coincident with the longitudinal axis of the wire. We suppose that the FMW is homogeneously magnetized in a circular direction with circular magnetization $\vec{M} \equiv (M_r, M_\varphi, M_z) = (0, M_s, 0)$ due to strong circumferential magnetic anisotropy. The application of a constant external electric field of intensity $\vec{E}_0 = (0, 0, E_{0z})$ along the z axis creates direct electric current flowing in the wire with current density $\vec{j}_0 = (0, 0, j_{0z})$ given by Ohm's law $j_{0z} = \gamma_1 E_{0z}$, where γ_1 is the FMW conductivity. Consequently it results from Ampere's law that the circular magnetic field strength $\vec{H} = (0, H_\varphi, 0)$ is inhomogeneous, where H_φ linearly increases with r and is connected with j_{0z} or E_{0z} by

* Tel.: +421 55 6022601; fax: +421 55 6330115.
E-mail address: Jozef.Kravcak@tuke.sk

http://dx.doi.org/10.1016/j.physb.2014.07.066
0921-4526/

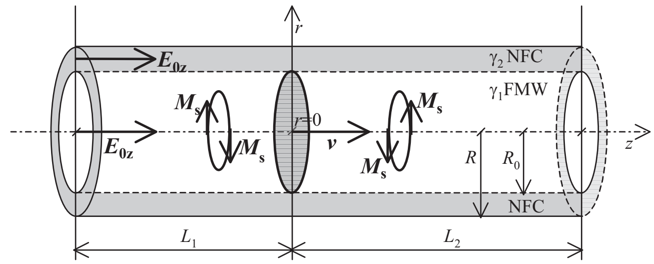

Fig. 1. The scheme of ferromagnetic wire (FMW) with circular magnetization and conductivity γ_1, where circular magnetization reversal occurs by means of DW movement with velocity v. (Symbols of M_s loops indicate circular magnetization orientation parallel and opposite with circular magnetic field strength $\vec{H}$ connected with direct electric current density $j_{0z}=\gamma_1 E_{0z}$ (1).)

the relation:

$$H_\varphi(r)=j_{0z}\frac{r}{2}=\gamma_1 E_{0z}\frac{r}{2} \tag{1}$$

The direct electric current also flows in the conductive cover with current density $j_{z2}=\gamma_2 E_{0z}$, where γ_2 is the NFC conductivity. Regardless of this, the contribution of j_{z2} to H_φ in the FMW is equal to zero.

Considering the opposite circular orientation of applied H_φ with respect to the circular magnetization of the FMW, magnetization reversal in the FMW occurs due to the movement of a single rigid 180° DW with velocity v in the z direction from the end of the wire, as displayed in Fig. 1. Let the origin of the coordinate system be placed in the center of the moving DW ($z=0$). The radius of the FMW is denoted R_0. The overall radius of the FMW together with the NFC is R. The movement of the DW along the FMW induces eddy current flow which can be described by electric field intensity $\vec{E}(r,\varphi,z)$ circulating around the DW. The Maxwell–Faraday equation states

$$(\mathrm{rot}\,\vec{E})_\varphi=-\mu_0\left(\frac{\mathrm{d}\vec{M}}{\mathrm{d}t}\right)_\varphi=-\mu_0 2M_s v, \tag{2}$$

for $z=0$ and $0\le r\le R_0$.

In the quasi-static approximation, Maxwell's equations produce a set of partial differential equations valid for $\vec{E}(r,\varphi,z)$ in all conductive volumes (FMW and NFC), where $z\neq 0$ or $R_0<r$

$$\mathrm{rot}\,\vec{E}=0,\quad \mathrm{div}\,\vec{E}=0,\quad \nabla^2\vec{E}=0 \tag{3}$$

with two boundary conditions: the first one is (2), because the FMW is separated into two magnetic domains by the moving DW, and the second one is $E_n=0$, the normal component of $\vec{E}(r,\varphi,z)$ on the outer conductive surface, where $r=R$, is equal to zero. Taking into account the cylindrical symmetry of the FMW and NFC, the partial derivatives with respect to φ are equal to zero, and the last equation in (3) can be rewritten in the form of Laplace's equations:

$$(\nabla^2\vec{E}(r,\varphi,z))_r=\nabla^2 E_r-\frac{E_r}{r^2}=0$$
$$(\nabla^2\vec{E}(r,\varphi,z))_z=\nabla^2 E_z=0 \tag{4}$$

The method of separation of variables yields the solution $\vec{E}(r,\varphi,z)=[E_r(r,z),0,E_z(r,z)]$ of equations (4) for the above described model in the form of a Fourier-Bessel series:

$$E_r(r,z)=\mp\sum_{n=1}^{\infty}D_n\mathrm{J}_1(\lambda_n r)\,\mathrm{e}^{-\lambda_n|z|}$$
$$E_z(r,z)=\sum_{n=1}^{\infty}D_n\mathrm{J}_0(\lambda_n r)\,\mathrm{e}^{-\lambda_n|z|}+E_{0z} \tag{5}$$

where sign $-$ is valid for $z\le 0^-$ and sign $+$ is for $z\ge 0^+$. For $n=1,2,3\ldots$, $\mathrm{J}_0(\lambda_n r)$ and $\mathrm{J}_1(\lambda_n r)$ are Bessel functions of the first kind [5]. λ_n denotes a root (zero) of equation $\mathrm{J}_1(\lambda_n R)=0$. Note that Bessel functions of the second kind [5] were excluded in (5), because the solutions must be finite when $r=0$. The value of coefficients D_n in (5) is given by

$$D_n=\frac{\mu_0 2M_s v\Phi_1(\lambda_n R_0)}{\lambda_n^2 R^2\mathrm{J}_0^2(\lambda_n R)},$$

$$\Phi_1(\lambda_n R_0)=\frac{\pi\lambda_n R_0}{2}[\mathrm{J}_1(\lambda_n R_0)\mathrm{H}_0(\lambda_n R_0)-\mathrm{J}_0(\lambda_n R_0)\mathrm{H}_1(\lambda_n R_0)] \tag{6}$$

where function $\Phi_1(\lambda_n R_0)$ is defined by Struve functions $\mathrm{H}_0(\lambda_n R_0)$ and $\mathrm{H}_1(\lambda_n R_0)$ [5].

The proper boundary conditions have to be applied to $\vec{E}(r,\varphi,z)$ at the inner interface between the FMW and NFC with different conductivities. The tangential component is continuous $E_z(R_0^-,z)=E_z(R_0^+,z)$ and the normal component E_r is discontinuous, determined by $\gamma_1 E_r(R_0^-,z)=\gamma_2 E_r(R_0^+,z)$ [6].

3. Calculation of eddy current power loss and domain wall mobility

The eddy current power loss P generated during DW movement along the z-direction P consists of two parts, P_1 and P_2, corresponding to the FMW and NFC respectively. Taking into account the boundary conditions, P_1 and P_2 can be calculated from the electric field intensity (5)

$$P_1=\gamma_1\int_0^{R_0}2\pi r\int_{-\infty}^{\infty}(\vec{E}(r,\varphi,z)-\vec{E}_0)^2\,\mathrm{d}z\,\mathrm{d}r$$
$$P_2=\gamma_2\int_{R_0}^{R}2\pi r\int_{-\infty}^{\infty}(\vec{E}(r,\varphi,z)-\vec{E}_0)^2\,\mathrm{d}z\,\mathrm{d}r \tag{7}$$

Due to minimization of the magnetostatic energy of the FMW, the rigid DW is impelled (accelerated) in the z direction by the inhomogeneous circular magnetic field of strength (1), expressed as an average value of $\langle H_\varphi\rangle$ over the FMW cross-section area:

$$\langle H_\varphi\rangle=\frac{1}{\pi R_0^2}\int_0^{R_0}H_\varphi 2\pi r\,\mathrm{d}r=\frac{j_{0z}R_0}{3}=\frac{\gamma_1 E_{0z}R_0}{3} \tag{8}$$

On the other hand the DW is damped (decelerated) by an eddy current magnetic field of strength H_e acting on the DW. If the inertia of the DW is negligible, the equilibrium $H_e=-\langle H_\varphi\rangle$ is established almost instantly and the eddy current loss of the DW is equal to the rate

$$P=2\mu_0 M_s v\int_0^{R_0}H_\varphi 2\pi r\,\mathrm{d}r=2\mu_0 M_s v\frac{\pi j_{0z}R_0^3}{3} \tag{9}$$

Thus the velocity of the DW v is directly proportional to $P=P_1+P_2$. The indicated integrations (7) and (9) provide the eddy current damping, which has viscouse character:

$$v=S.\langle H_\varphi\rangle, \tag{10}$$

where the constant of proportionality S is the DW mobility.

4. Results and discussion

4.1. DW mobility

Experimentally the uniform electric field E_{0z} and the direct electric current $j_{0z}=\gamma_1 E_{0z}$ are supplied by two source voltage contacts placed at the left and right ends of the wire. Because the dimension of the contacts (small drops of conductive material) is larger than the diameter R, practically it is very difficult to eliminate the influence of the contacts on the mobility of the DW near the FMW ends. For this reason the mobility S is