INFLUENCE OF NON-FERROMAGNETIC COVERS ON PROPERTIES OF AMORPHOUS FERROMAGNETIC WIRE

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1. Introduction

From experimental practice it is well known that a combination of tension and dc Joule annealing of an amorphous ferromagnetic wire 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 M_s 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° circular domain wall (CDW) for example at one end of the wire, followed by CDW 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 eddy currents model, Fig.1, the first process is theoretically investigated when an already-created rigid 180° CDW with negligible thickness moves through the wire with deposited non-ferromagnetic conductive cover.

Considering giant magneto−impedance (GMI) effect, which is mainly a surface effect, is very sensitive to the rotation of magnetization in the shell of a wire [4]. For this reason GMI measurements are often used to determine surface magnetic properties of CoFeSiB amorphous thin wire with glass cover. A quasistatic model based on the minimization of the free energy of domain structure was developed [5] to explain the existence of peaks in the GMI dependence in Fig.3, if only a reversible magnetization rotation is present.

2. Eddy currents model

The circular magnetization reversal process in a long ferromagnetic wire (FMW) of the radius R_0 with a non-ferromagnetic conductive cover (NFC) of the overall radius R is theoretically analysed. The model of a single thin rigid 180° CDW 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 field intensity E_{0z} in the wire, the circular magnetization reversal occurs by means of the CDW movement through the wire. The induced electric field $\boldsymbol{E}=(E_r,E_z)$ and the eddy current power losses P in all conductive parts are calculated in the model [6] from which the CDW mobility S is determined. It is shown that CDW mobility is very sensitive to the thickness R-R_0 and the conductivity γ_2 of NFC.

A simple experiment can be performed by putting two measuring voltage contacts A and B on the NFC surface at a fixed distance $\Delta z=z_B-z_A$, which allows induced voltage $\Delta u_i\ (t)$ to be detected between A and B during the circular magnetization reversal of the FMW. The Δu_i (t) is acquired from the axial component E_z of induced electric field $\boldsymbol{E}$ by path integral

$$\Delta u_i(t) = -\int_{z_B}^{z_A} \left(E_z(R,z) - E_{0z}\right)\mathrm{d}z \tag{1}$$

at the time t from the interval when the CDW starts its movement at the left-hand end until it reaches the right-hand end of the FMW. The calculated shape of $\Delta u_i\ (t)$ in Fig.1 (right) determines the positions of the CDW at A or B by inflexion points at times t_A or t_B respectively. Then the CDW velocity v_z is given by $v_z = \Delta z/(t_B - t_A)$, and the time integral of $\Delta u_i\ (t)$ in the time interval from t_A to t_B is always constant $2\mu_0\ M_s\ R_0\ \Delta z$.

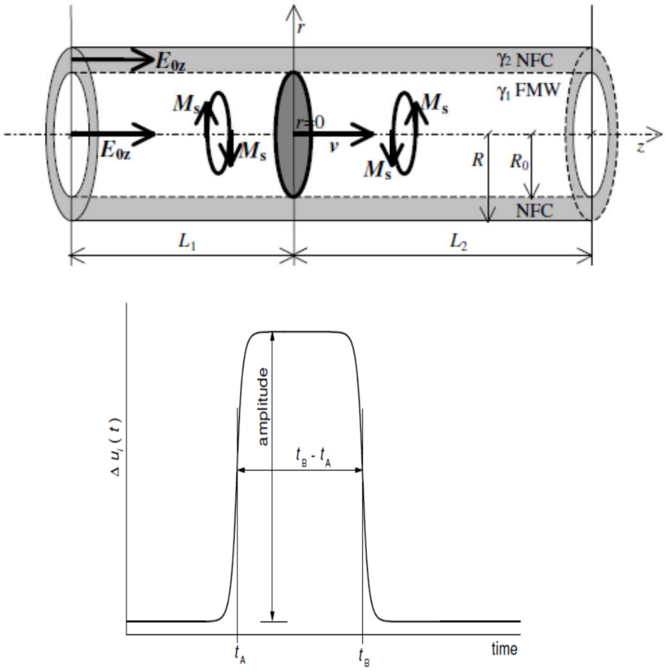

Fig.1: *The scheme of the ferromagnetic wire (FMW) of radius R_0 with circular magnetization and conductivity γ_1, where the circular magnetization reversal occurs by means of CDW movement with velocity* **v**. *(Symbols of* $\boldsymbol{M_s}$ *loops indicate circular magnetization orientation parallel and opposite with circular magnetic field strength $H_{0\phi}(r) = j_{0z}\, r/2$ connected with direct electric current density $j_{0z}=\gamma_1\ E_{0z}$).The calculated shape of the induced impulse by moving CDW during magnetization reversal (right).*

The induced eddy currents field in the model provides the viscous damping of the CDW motion

$$v_z = S.H_\phi = S.\frac{1}{\pi R_0^2}\int_0^{R_0} H_{0\phi}(r)\,2\pi r\,\mathrm{d}\,r = S.\frac{j_{0z}\,R_0}{3} = S.\frac{\gamma_1 E_{0z}\,R_0}{3}\,, \tag{2}$$

where the constant of proportionality S is the CDW mobility and H_ϕ is an average value of inhomogeneous circular field of strength over the FMW cross-section.

3. GMI effect

As cast glass-covered ferromagnetic amorphous $Co_{70.5}Fe_{4.5}Si_{15}B_{10}$ thin wire (microwire) of a diameter of 17.8 μm with small negative magnetostriction has been prepared by Taylor-Ulitovski technique. The relatively small negative magnetostriction results in the creation of a wide almost circularly magnetized shell domain structure and a narrow axially magnetized core [2]. The preferential orientation of the spontaneous magnetization (magnetic anisotropy) in the microwire is given by magnetostriction and shape anisotropy. Different mechanical properties of the ferromagnetic metallic central part and of the glass cover of the microwire are responsible for deviation of spontaneous magnetization from circumferential (circular) direction in the shell of the microwire (helical magnetic anisotropy) [7]. Additional removing of the glass cover gives the possibility to decrease the helical anisotropy. Details of the metallic surface of the microwire, studied by means of SEM, revealed surface defects (pits), where the glass cover is bonded to metal [8].

4. Results and discussion

Calculated eddy current field intensity creates a symmetrical vortex on both sides of CDW, and this results in maximal damping effect of the eddy current [6]. The amplitude of eddy current field intensity exponentially decreases with the distance $|z|$ from CDW. During reversal process described in the model the average value of inhomogeneous circular field of strength H_ϕ is constant and the CDW starts its motion almost instantly with constant velocity v_z, Eq.(2), in the long middle part of the FMW. The rigid CDW keeps the same shape in inhomogeneous magnetic circular field $H_{0\phi}(r)$. Fig.2 shows that the mobility S rapidly decreases with the increasing relative thickness R/R_0 of deposited conducting NFC in the interval $R/R_0 \leq 1.3$. This can be explained by the stronger eddy current damping effect due to the enlarged conducting area. Further for the given ratio γ_2/γ_1 the mobility S exhibits the tendency to saturate in the interval $1.5 \leq R/R_0$ and if $R/R_0 \to \infty$, it approaches the finite value. The explanation is the strong localization of eddy current vortex in the limited volume around the moving CDW $r < 2R_0$ and $|z| < 2R_0$.

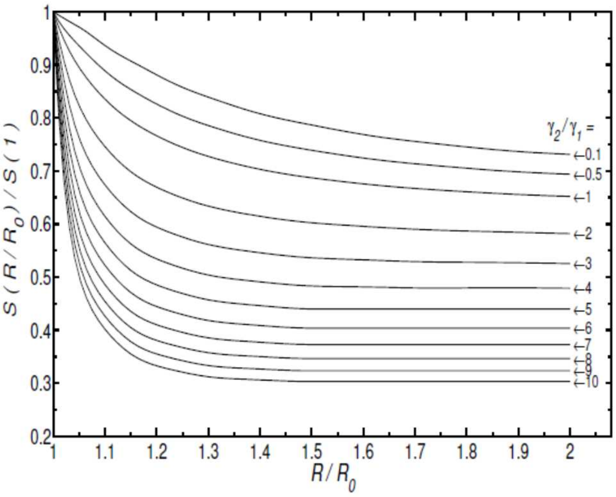

Fig.2: *The calculated dependence of CDW mobility S on the variable R/R_0 for ratios γ_2/γ_1. The wire without conductive cover corresponds to $R/R_0=1$.*

The measured GMI dependences of as-cast $Co_{70.5}Fe_{4.5}Si_{15}B_{10}$ microwire with glass cover [7] and after glass cover removing in Fig.3 displays the double-peak behaviour. The theoretical explanation is that for very low amplitudes i_{ac} (or circular field strength h_ϕ) any reversible domain wall motion at higher frequencies (≥1 MHz) is negligible due to strong damping process [7] and magnetization rotation takes place only in the shell of the microwire. The positions of the couple of sharp peaks ($H = \pm H_m$) are always symmetrical with respect to zero external magnetic fields strength $H=0$ and correspond to the critical field of irreversible magnetization rotation. The dispersion of the critical field altogether with local variation of the easy axis of magnetization affects the peaks shape.

The formation of a secondary small GMI peaks (inset in Fig.3) has been observed after glass cover removing. The theoretical explanation is that the blade-shaped domains, displayed in Fig.3 (right), are formed on both sides of surface defects (pits) to minimize magnetostatic energy. The blade-shaped domains are also responsible for hysteresis observed in GMI dependence.

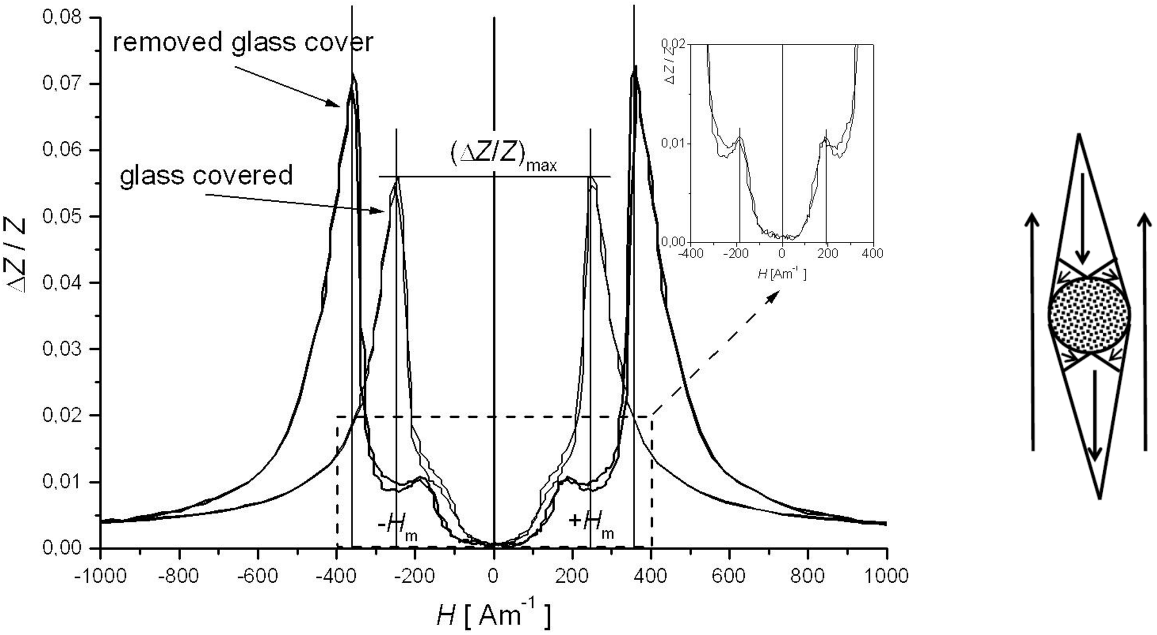

Fig. 3: *GMI dependence measured at the frequency of 1 MHz and at the amplitude* $i_{ac}=1$ *mA in as-cast* $Co_{70.5}Fe_{4.5}Si_{15}B_{10}$ *microwire of a diameter* $d = 8.1$ *μm with glass cover and after glass cover removing. Scheme of the blade-shaped domains on the surface of the wire closing the defect (right).*

5. Conclusion

Experimental procedure to measure the CDW mobility through the non-ferromagnetic conductive cover is proposed. Considering the relative ratio γ_2/γ_1 is known parameter then the calculated decrease of CDW mobility displayed in Fig.2 gives possibility to determine the thickness of the conductive cover during its deposition on ferromagnetic wire.

The removing of the glass cover reduces tensile stresses in the microwire and changes the induced helical anisotropy. This results in increasing of the critical field H_m and the maximum value of GMI ratio $(\Delta Z/Z)_{max}$ in Fig.3 (left).

A residual domain structure formed around local surface defects (pits) on the microwire surface manifests itself in hysteresis and formation of the secondary small GMI peaks (inset in Fig.3).

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