DOMAIN WALL MOBILITY IN Co-BASED AMORPHOUS WIRE

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Summary Dynamics of the domain wall between opposite circularly magnetized domains in amorphous cylindrical sample with circular easy direction is theoretically studied. The wall is driven by DC current. Various mechanisms which influence the wall velocity were taken into account: current magnitude, deformation of the mowing wall, Hall effect, axially magnetized domain in the middle of the wire. Theoretical results obtained are in a good agreement with experiments on Co-based amorphous ferromagnetic wires.

1. INTRODUCTION

Amorphous ferromagnetic wires have been investigated during the last 15 years with a view to understanding both the basic behavior and to the potential for application (especially in new computer technologies). The absence of magnetocrystalline anisotropy gives some new possibilities in forming magnetic properties of these materials.

Stress annealed Co-based amorphous wire with circular easy direction provides possibility to create conditions for study of circular domain wall (CDW) - boundary between circularly magnetized domains [1]. Some results of the theoretical study of CDW dynamics are reviewed in this paper.

CDW is driven by the “external” circular magnetic field created by DC electric current flowing through the sample. Conductivity of amorphous wires is high and consequently eddy currents around the moving CDW can be a dominant mechanism responsible for damping CDW motion. In accordance with experiments, we assume that a single wall moves along the wire with a constant velocity and the radius of the sample is big enough for existence of eddy currents. Various kinds of influences were taken into account in the study of the CDW velocity:

a) The fields in the place of a moving wall (circular field and eddy currents field) are so inhomogeneous, that it is necessary to take into account the wall deformation [2].

b) The abrupt reversal of the internal magnetic field across the wall and corresponding reversal of the Hall electric field causes additional non-uniformity in the wall vicinity not only due to the eddy currents. This creates additional net force “domain-drag effect“ (DDE). Experimental data shows that the mobility of the wall moving in the current direction differs (of order of several percent for a low current) from the mobility of the wall moving in the direction opposite to the current direction [3].

c) Due to exchange interaction, a non-circularly magnetized core in the middle of a cylindrical sample exists. The CDW velocity was studied also in the presence of the axially magnetized core [4].

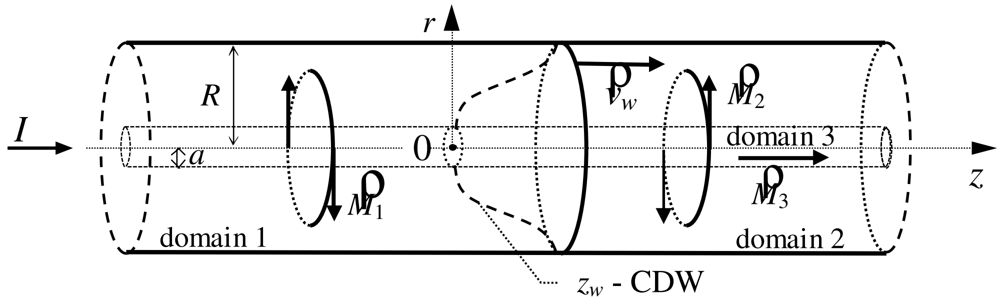

Fig. 1. The model of a sample with a single CDW moving at constant velocity v_w along z axis

2. MODEL

We consider a single CDW moving in *z* direction along a long cylindrical sample as shown in Fig.1. We ignore the thickness of the CDW (it is small in comparison with the radius *R* of the cylinder) and capacitive effect ($\operatorname{div}\vec{j} = 0$). The magnetization inside domains: $\vec{M}_1 = -\vec{M}_2 = (0, M_S, 0)$ and $\vec{M}_3 = (0, 0, M_S)$, where M_S is the saturation magnetization. For ferromagnetic wires $\vec{B} \approx \mu_0 \vec{M}$, where μ_0 is permeability of vacuum. The calculations were done in a cylindrical coordinate system with the origin 0 in the wall symmetry center. Subscripts 1, 2, and 3 refer to domains 1, 2 and 3, respectively (Fig.1).

The velocity of the CDW can be estimated by two procedures [2,5]. In the Method I the wall velocity is obtained by equating the losses due to eddy currents around the wall to the power supplied by applied field acting on the wall. In the Method II, the velocity is calculated as that for which the mean total field over the wall area (eddy current field plus applied field), which is proportional to the force acting on CDW, is equal to zero. Due to the symmetry of the sample we assume that components of current density

$$j_\varphi = 0,\ j_r = j_r(r,z),\ j_z = j_z(r,z)\cdot \quad (1)$$

Under these assumptions, the electric field $\vec{E}$ and the current density $\vec{j}$ satisfy the following Maxwell's equations for all points not located on the wall

$$\operatorname{rot}\vec{E} = 0,\ \operatorname{div}\vec{j} = 0,\ \vec{E} = \hat{\rho}\vec{j}, \quad (2)$$

where $\hat{\rho}$ is the resistivity tensor. Solution for the current density has to satisfy the following boundary conditions

$$j_r(z \to \pm\infty) = 0,\ j_z(z \to \pm\infty) = \frac{I}{\pi R^2} = j_0, \quad (3)$$
$$j_r(r = R) = j_r(r = 0) = 0.$$

3. RESULTS

a) We estimated the degree of CDW distortion and its influence on the wall mobility [6] for model, where the thin inner domain was ignored ($a = 0$) and the Hall's effect was not taken into account (the resistivity ρ is scalar). For a flexible wall the equation of motion is

$$C\varepsilon - \mu_0(H_{\text{on CDW}})(M_2 - M_1) = 0, \quad (4)$$

where C is the wall curvature and ε is the wall energy per unit area. All terms in this equation refer to the forces normal to the wall. The CDW profile can be obtained as one for which variations of the inhomogeneous field on the wall are balanced by variations of its curvature. The boundary conditions on CDW are

$$\vec{t}\vec{j}_1 = \vec{t}\vec{j}_2 + 2\mu_0 M_S v_N / \rho,$$
$$\vec{n}\vec{j}_1 = \vec{n}\vec{j}_2 \quad (5)$$

where $\vec{t}, \vec{n}$ are tangential and normal unit vectors to the wall in the zr plane, v_N is a normal component (to the wall) of the wall velocity v_w. Using these conditions, the current density was obtained from Maxwell's equations. This is a function of v_w and the shape z_w of the CDW. On the other hand, v_w and z_w can be calculated if the components of current density are known. An iteration procedure was used to solve this problem up to the first order approximation. In the zero order approximation for a planar CDW the current density $\vec{j}^{(0)}$ and velocity $v_w^{(0)}$ were obtained. Then the profile of the wall in first order approximation $z_w^{(1)}(r)$ was calculated, and velocity in the first order approximation $v_w^{(1)}$ was determined. The formula for critical current I_c above which the curvature of CDW can no longer compensate field variations was derived in this approximation. This value is close to the upper limit for single CDW experiments. The obtained results are depicted in Figs. 2,3. Taking into account wall distortion the velocity versus current (circular field) dependence deviates from the linear one. For higher currents (i.e. for higher degrees of wall distortion) the velocity is higher than for planar CDW.

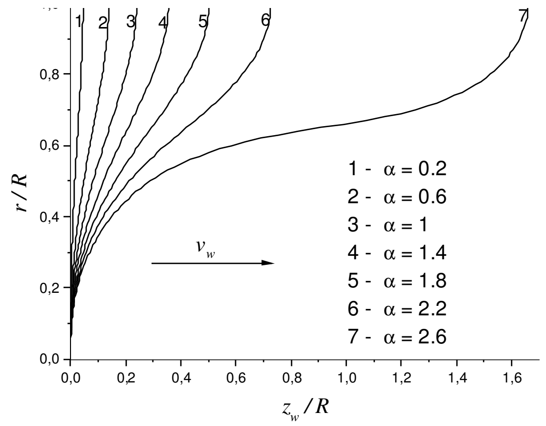

Fig. 2. CDW profiles for different values of parameter $\alpha = \frac{\mu_0 M_S}{3\pi\varepsilon} I$

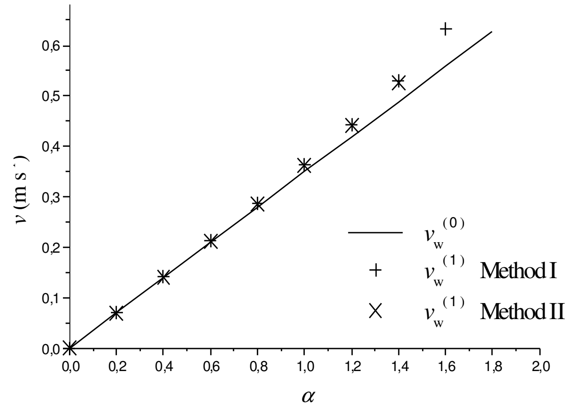

Fig. 3. $v_w^{(0)}(\alpha)$ *- velocity of planar CDW,* $v_w^{(1)}(\alpha)$ *- velocity of distorted CDW:* + *refers to Method I,* × *refers to Method II*

b) Full understanding of experimental data requires to take into account also DDE, i. e., the contribution of non-diagonal components of resistivity tensor [7]. Then electric field is

$$\vec{E}_i = \left(\rho j_r + \rho\beta\, j_z M_i / M_S,\ 0,\ \rho j_z - \rho\beta\, j_r M_i / M_S\right), \quad (6)$$

where i = 1,2 and β is tangent of Hall angle. We ignore thin inner domain (a = 0). Problem is solved for planar CDW (low current I). The boundary conditions on CDW are $E_{r1} = E_{r2} + 2\mu_0 M_S v_w$ and $j_{z1} = j_{z2}$. Then the current density from Maxwell's equations can be obtained. Then using Method II velocity of CDW can be expressed

$$v_w = I\frac{\rho}{\mu_0 M_S}\frac{1}{\pi R^2}\left(\pm\frac{1}{3\pi^2\tilde{\Omega}} + \beta\right), \quad (7)$$

where $1/\left(3\pi^2\tilde{\Omega}\right) \approx 1.5$. For small β and I, the $\tilde{\Omega}$ values are practically the same. Experimental results for $\beta = 0.02$ are in good agreement with this v_w. For $\beta = 0$ expression is the same as $v_w^{(0)}$ in a).

c) An influence of an axially magnetized core on the CDW velocity was studied for the planar shape of CDW and $\beta = 0$ [4]. The radius a of inner domain 3 is assumed to be constant in the stress annealed sample. The radial component of current density on CDW has discontinuity $j_{r1} = j_{r2} + 2\mu_0 M_S v_w / \rho$. Solving Maxwell's equation and using Method II the CDW velocity $v_w = v_w(a)$ was obtained.

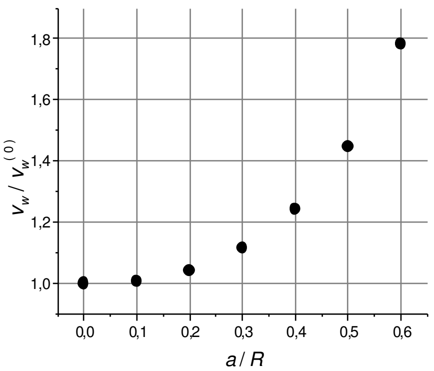

Fig. 4. *Dependence* $v_w / v_w^{(0)}$ *on normalized core radius* a / R

In Fig. 4 we can see that for small core radii, the increase of the CDW velocity can be comparable with other studied phenomena.

4. CONCLUSION

The linear dependence of the wall velocity on current was obtained for a low current value, for higher current values the dependence deviates from the linear one due to the increasing distortion of the moving wall. The expression for the critical current value for existence of a single wall was obtained. The expression for the wall velocity influenced by the Hall effect in a low current region was obtained. It was shown that the wall velocity differs if the wall propagation is parallel and anti-parallel with respect to the current flow. Presence of an axially magnetized inner domain also increases the wall mobility. For small core radii, the increase of the CDW velocity is comparable with other studied phenomena. All theoretically obtained results are in good agreement with experiments on Co-based amorphous ferromagnetic wires.

Acknowledgement

Presented research work has been supported by S.G.A. projects No. 1/8128/01 and 1/1013/04.

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