DOMAIN WALL DEPINNING PROCESS IN BISTABLE GLASS-COATED MICROWIRE

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ABSTRACT

A simple analytically solvable model for description of dynamics of the domain wall depinning process from the closure domain structure in bistable microwires was proposed. In this model closure domain structure is modelled by a single domain wall located in quadratic potential well. Critical parameters of rectangular magnetic field pulse needed to release this wall from the potential well were calculated. Theoretical dependence obtained in this way was fitted to experimental data measured on glass-coated $Fe_{77.5}B_{15}Si_{7.5}$ *microwire. Information about the order of closure domain structure dimension and about the mass of the domain wall, which is depinned from the wire end were obtained in this way.*

Keywords: *microwire, bistable, magnetization reversal, domain wall, switching field*

1. INTRODUCTION

Glass-coated amorphous ferromagnetic microwires are very promising materials for technical application as well as for basic research due to their magnetic properties and simple and cheap fabrication [1,2,3].

A large single Barkhausen jump is typical for magnetization reversal process in Fe-based microwires. It is a result of strong axial anisotropy due to high positive magnetostriction, internal mechanical stresses originating from rapid quenching and presence of glass coating. Stray field causes that closure domain structures is formed at the wire ends. Axial magnetization reversal starts by depinning of domain wall from the wire end and subsequently the reversal continues by propagation of a single domain wall along the wire. Velocity of this domain wall can be very high and so this phenomenon can be very interesting for technical applications. On the other hand the study of a single domain wall dynamics can give important information for understanding the process of magnetization reversal [4-8] and about dynamic characteristics of a single domain wall [9,10].

In the presented paper a simple model, which gives possibility to obtain information about characteristic dimension of closure domain structure as well as about dynamic parameters of a domain wall, is described. Model is confronted with experiment results.

2. MODEL

A simple analytically solvable model is proposed for description of single domain wall depinning from the wire end. In the framework of this model closure domain structure at the wire end, in which the wall is initially trapped, is modelled by parabolic potential well. The wall is set into motion by applied homogeneous magnetic field pulse. If parameters of the field pulse (length and magnitude) are large enough, the wall is released from the potential well at the wire end. Inertial motion of the wall after switching off the pulse is taken into account.

Free energy G of the wire is given by:

$$G = E_p + E_H \tag{1}$$

$$E_p = \frac{1}{2}Kx^2 + const \qquad E_H = -2S\mu_0 M_s H x , \tag{2}$$

where E_p is potential well energy (Taylor series of potential energy around its potential minimum at $x = 0$ up to the third term), E_H is contribution of an external field H to the wire energy; K is a positive constant and x is a displacement of the wall from its equilibrium position, S is the area of the wall projection onto a plane perpendicular to the wire, μ_0 is magnetic constant and M_s is saturation magnetization. It is also considered that the potential well has characteristic dimension x_0. In other words the Eq. (1) describes G only in the interval $(-x_0, x_0)$. For $x \geq x_0$ we assume that $E_p \leq E_p(x_0)$. Free energy as function of the wall position x is depicted in Fig. 1. At the figure bottom corresponding position of the wire is plotted.

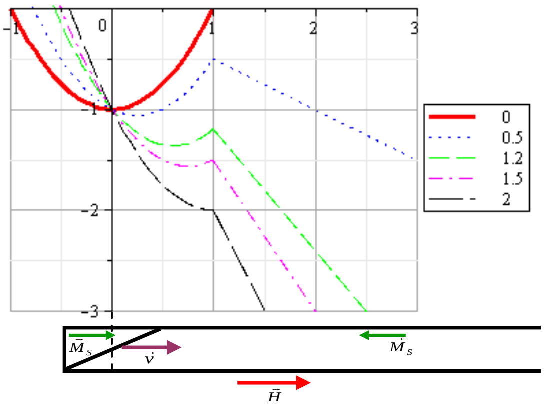

Fig. 1 Free energy as function of normalized horizontal coordinate x/x_0 (x_0 – position of right well border, i.e. half-width of the well), vertical axis unit equals to the depth of the well. Legend: the slope of function E_H (see Eq. (2))

As can be seen in Fig. 1 application of external field causes that the well depth with respect to its right border decreases. If magnitude of the field pulse is high enough the wall propagating under the action of this field to the right can reach the right well border. However, there is some minimum pulse magnitude under which it is not possible. If the wall does not rich the right border during the pulse there are two possibilities. The first one is the case when at the instant when the pulse is switched off the wall velocity is high enough for the wall to travel to the right well border due to its inertial motion and the wall can be released from the well. If this is not the case the wall remains trapped in the well.

Eq. (1) can be used to derive corresponding force acting on the wall:

$$F_p(x) = -\mathrm{grad}E_p = -Kx \tag{3}$$

$$F_H = -\mathrm{grad}E_H = 2S\mu_0 M_S H \tag{4}$$

For a moving wall also damping force has to be taken into account

$$F_\beta = -\beta v \tag{5}$$

where β is damping coefficient (it will be considered as constant in this model) and v is wall velocity. The net force acting on the wall is equal to $F_p + F_H + F_\beta$, so using Eqs. (3,4,5) the wall equation of motion can be expressed as

$$m\frac{\mathrm{d}^2(x)}{\mathrm{d}t^2} = -Kx + kH - \beta\frac{\mathrm{d}x}{\mathrm{d}t} \tag{6}$$

where m is inertial mass of the wall.

After some rearrangements this equation can be written in the form

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + 2b\frac{\mathrm{d}x}{\mathrm{d}t} + \omega_0^2 x = h \tag{7}$$

where

$$2b = \frac{\beta}{m}, \quad \omega_0^2 = \frac{K}{m}, \quad h = \frac{k}{m}H, \quad k = 2S\mu_0 M_s .$$

Using substitution $y = x - h/\omega_0^2$ equation for damped harmonic oscillator is obtained from Eq. (7). So solution of Eq. (7) for the domain wall position x and the wall velocity v as a functions of time are given by the expressions

$$x = A\mathrm{e}^{-bt}\sin(t\sqrt{\omega_0^2 - b^2} + \varphi) + \frac{h}{\omega_0^2} \tag{8}$$

$$v = A\mathrm{e}^{-bt}\left[-b\sin\left(t\sqrt{\omega_0^2 - b^2} + \varphi\right) + \right. \\ \left. + \sqrt{\omega_0^2 - b^2}\cos\left(t\sqrt{\omega_0^2 - b^2} + \varphi\right)\right] \tag{9}$$

Constants A and φ can be obtained from initial conditions.

Two different situations should be considered:

I. $\omega_0 > b$, for which $\omega = \sqrt{\omega_0^2 - b^2}$ is real and solution of Eq. (7) can be expressed by harmonic functions, as written in Eqs. (8,9).

II. $\omega_0 < b$, for which $i\omega = \sqrt{\omega_0^2 - b^2}$. The solution of Eq. (7) in this case can be expressed by hyperbolic functions. This expression can be obtained directly from Eqs. (8,9) substituting $i\omega$ (i is the imaginary unit, ω is real) for the square root expressions. Formulas are formally the same only harmonic functions sin and cos are replaced by hyperbolic function sinh and cosh. This holds for all relevant expressions in the article, if not mentioned otherwise.

We do not know which kind of solution corresponds to our experiment; both possibilities will be discussed in the next section, in which the results obtained from the theoretical model will be compared with experimental data.

Since the inertial motion of the wall after switching off the field pulse is taken into account the Eq. (7) was solved for two time intervals:

1. $t \in \langle 0, \tau_c \rangle$ for which $H = H_{pc}$ and initial conditions at $t = 0$ are $x = 0$ and $v = 0$. The wall reach a position x_p ($x_p \le x_0$) with velocity v_p at the time τ_c.
The obtained solution is

$$x_1 = \frac{h}{\omega_0^2}\left[1\text{-}\mathrm{e}^{-bt}\left(\frac{b}{\omega}\sin(\omega t) + \cos(\omega t)\right)\right] \tag{10}$$

$$v_1 = \frac{h}{\omega}\mathrm{e}^{-bt}\sin(\omega t) \tag{11}$$

2. $t \in \langle \tau_c, t_0 + \tau_c \rangle$, for which $H = 0$ and initial conditions at the beginning of this interval are $x = x_p$ and $v = v_p$. At the end of this time interval the wall just reaches the well border x_0 with zero velocity.
Solution obtained for this interval is

$$x_2 = \frac{h}{\omega_0^2}\mathrm{e}^{-bt}\left[\left(\frac{b}{\omega}\sin(\omega t) + \cos(\omega t)\right) - \right. \\ \left. -\mathrm{e}^{-b(t+\tau_c)}\left(\frac{b}{\omega}\sin\left(\omega(t+\tau_c)\right) + \cos\left(\omega(t+\tau_c)\right)\right)\right] \tag{12}$$

$$v_2 = \frac{h}{\omega}\left[\mathrm{e}^{-b(t+\tau_c)}\sin\left(\omega(t+\tau_c)\right) - \mathrm{e}^{-bt}\sin\left(\omega t\right)\right] \tag{13}$$

Using Eqs. (10, 11) we can obtain the lowest possible value of the field pulse magnitude $H_{pc\ \mathrm{min}}$ for which the wall can be released from the potential well if the length of this critical pulse τ_0 is long enough. For $H_{pc\ \mathrm{min}}$ in the instant of its switching off τ_0 the wall just reaches position $x_1(t = \tau_0) = x_0$ with velocity $v_1(t = \tau_0) = 0$. (For higher field the velocity is higher than zero at the well border, for lower field with the same length of pulse the wall never reaches the right well border at position $x = x_0$). So, from boundary conditions at time τ_0: $x_1 = x_0$ and $v_1 = 0$ using Eqs (10,11) we obtain in the case:

I. ($\omega_0 > b$)

$$\tau_0 = \frac{\pi}{\omega} \tag{14}$$

$$h_{pc\min} = x_0\omega_0^2 \frac{1}{1+\exp\left(-\pi\frac{b}{\omega}\right)} \tag{15}$$

where $h_{pc\ \min} = H_{pc\ \min}\, k\ /\ m$. For the pulse with the length τ satisfying condition $\tau < \tau_0$ there exists some value of the field pulse magnitude $H_{pc} > H_{pc\ \min}$ for which the wall reaches position x_0 with zero velocity. In this case also the second solution (inertial motion after the field pulse) has to be taken into account.

II. ($\omega_0 < b$)
In this case, equations corresponding to Eqs. (10,11) are

$$x_1 = \frac{h}{\omega_0^2}\left[1\text{-e}^{-bt}\left(\frac{b}{\omega}\sinh(\omega t)+\cosh(\omega t)\right)\right] \tag{16}$$

$$v_1 = \frac{h}{\omega}\mathrm{e}^{-bt}\sinh(\omega t) \tag{17}$$

Using Eqs. (16,17), the corresponding values of critical parameters satisfying the same boundary conditions are

$$\tau_0 \to \infty \tag{18}$$

$$h_{pc\min} = x_0\omega_0^2 \tag{19}$$

Now it is possible for a given value of h_{pc} to calculate the corresponding value of τ_c (i.e. to obtain function $h_{pc} = f(\tau_c)$) for which the wall just reaches the well border at x_0.

Conditions at time t_0 after the end of pulse are: $x_2 = x_0$ and $v_2 = 0$. From these conditions and using Eqs. (12,13) we can obtain expressions for t_0 and $h_{pc} = H_{pc}\, k\ /\ m$ as function of τ_c.

In particular cases we obtain:

I. ($\omega_0 > b$)

$$t_0 = \frac{1}{\omega}\arctan\left(\frac{\sin(\omega\tau_c)}{\mathrm{e}^{b\tau_c}-\cos(\omega\tau_c)}\right) \tag{20}$$

$$h_{pc} = x_0\omega_0^2\left[\frac{\left(1-\mathrm{e}^{-(b+i\omega)\tau_c}\right)^{\frac{b}{i\omega}-1}}{\left(1-\mathrm{e}^{-(b-i\omega)\tau_c}\right)^{\frac{b}{i\omega}+1}}\right]^{\frac{1}{2}} = x_0\omega_0^2\frac{\exp\left[\frac{b}{\omega}\arctan\left(\frac{\sin(\omega\tau_c)}{\mathrm{e}^{b\tau_c}-\cos(\omega\tau_c)}\right)\right]}{\sqrt{2}\,\mathrm{e}^{-\frac{b\tau_c}{2}}\left[\cosh(b\tau_c)-\cos(\omega\tau_c)\right]^{\frac{1}{2}}} \tag{21}$$

II. ($\omega_0 < b$)

$$t_0 = \frac{1}{\omega}\arctan\left(\frac{\sinh(\omega\tau_c)}{\mathrm{e}^{b\tau_c}-\cosh(\omega\tau_c)}\right) \tag{22}$$

$$h_{pc} = x_0\omega_0^2\left[\frac{\left(1-\mathrm{e}^{-(b+\omega)\tau_c}\right)^{\frac{b}{\omega}-1}}{\left(1-\mathrm{e}^{-(b-\omega)\tau_c}\right)^{\frac{b}{\omega}+1}}\right]^{\frac{1}{2}} \tag{23}$$

3. EXPERIMENTAL RESULTS AND DISCUSSION

Glass-coated microwire $Fe_{77.5}B_{15}Si_{7.5}$ prepared by Taylor-Ulitovski method with parameters: length 12 cm, diameter of metallic nucleus about 15 μm, thickness of glass coating about 9 μm was studied in the experiment

Experimental setup is shown in Fig 2. Solenoid (So), 15 cm long can generate homogeneous magnetic field along the wire. The wire end is placed into a narrow coil (PC), 2 cm long with diameter of 1mm, which can generate local magnetic field pulse that can set the wall into motion. At some distance from this wire end a pick up coil (PuC), 1 cm long with diameter of 1mm, is located and gives possibility to obtain information about magnetic state of the wire. Detailed description of the experiment is given in [11].

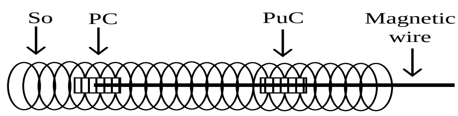

Fig. 2 Schematic view of wire location in the experimental set up. So – solenoid, PC – pulse coil, PuC – pick up coil

The dependence of critical pulse length vs. critical pulse magnitude obtained in experiment is shown in Fig. 3. As can be expected critical pulse magnitude increases with decreasing of critical length of the pulse. Experimental results can be analysed using the simple theoretical model presented in the previous section.

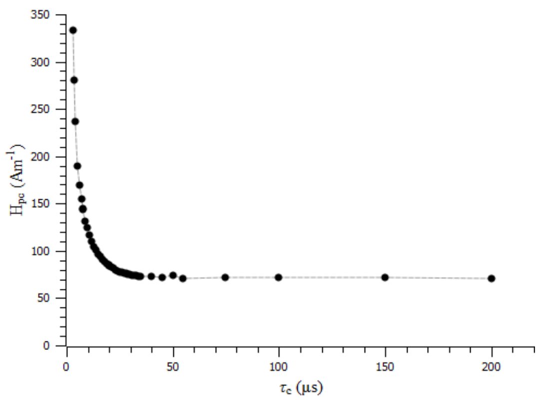

Fig. 3 Dependence of critical pulse parameters magnitude H_{pc} vs. length τ_c for wall depinning

This model gives possibility to obtain parameters b and ω from experimental data using fitting procedure. As can be seen in Fig. 3 the value of minimum magnitude of the field pulse is $H_{pc\ \min} \approx 70$ A/m. For fitting we used dependence $H_{pc\ \min}\ /\ H_{pc} = h_{pc\ \min}\ /\ h_{pc}$. Fitting procedure for the case I ($\omega_0 > b$) was not successful (not convergent). For the case II ($\omega_0 < b$) fitting was successful and it was possible to obtain fitting parameters. The fitting function in this case was obtained using Eqs. (12,23)

$$\frac{h_{pc\,\min}}{h_{pc}} = \left[\frac{\left(1 - e^{-(b-\omega)\tau_c}\right)^{\frac{b}{\omega}+1}}{\left(1 - e^{-(b+\omega)\tau_c}\right)^{\frac{b}{\omega}-1}} \right]^{\frac{1}{2}} \tag{24}$$

Result of the fitting procedure is shown in Fig. 4.

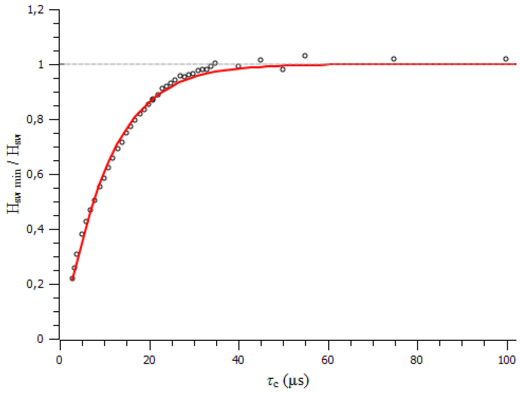

Fig. 4 Experimental dependence (points) and fitting curve $h_{pc\,\min} / h_{pc}$ as function of τ_c

As can be seen the model curve in Fig. 4 is in good agreement with the experimental data. The obtained values for fitting parameters b and ω are

$$b = 384\,000 \text{ s}^{-1}$$
$$\omega = 277\,000 \text{ s}^{-1} \tag{25}$$

In the discussed case II $(i\omega)^2 = \omega_0^2 - b^2$ from which

$$\omega_0 = \sqrt{b^2 - \omega^2} = 266\,000 \text{ s}^{-1} \tag{26}$$

From these fitting parameters it is possible to obtain information about domain wall mass and about typical dimension of potential well.

To obtain the mass of domain wall we express the wall mobility as a function of the wall mass. In the simplest model of the wall propagating under action of constant homogeneous magnetic field with constant velocity the equation of motion Eq. (7) has a form $2bv = h$. The velocity as function of external field $v = \lambda H$, where λ is mobility, can be measured. Using these equations the expression for wall mobility as function of domain wall mass is

$$\lambda = \frac{\mu_0 M_s}{b m_0} \tag{27}$$

where $m_0 = m / S$. Using the expressions for parameters defined in Eqs. (7,19,27), the following equations for the wall mass and the well half-width can be obtained

$$m_0 = \frac{\mu_0 M_s}{b\lambda} \tag{28}$$

$$x_0 = \frac{2b\lambda}{\omega_0^2} H_{pc\,\min} \tag{29}$$

Using the following experimentally obtained values of parameters $H_{pc\min} \approx 70$ A/m (see Fig. 3), $\lambda \approx 3$ m^{2}A^{-1}s^{-1}, $\mu_0 M_s \approx 1.56$ T [6], Eqs. (25,26) and Eqs. (28,29), the characteristic values of m_0 and x_0 were calculated.

$$m_0 = 1{,}35\,10^{-6} \text{ kg} \tag{30}$$

$$x_0 = 2.23 \text{ mm} \tag{31}$$

These values are in qualitative agreement with known experimental results [9,10,2].

4. CONCLUSIONS

A simple analytically solvable model for description of dynamics of the domain wall depinning process from the closure domain structure in bistable microwires was proposed. In the model the closure domain structure is modelled by quadratic potential well. A comparison with results of experiment, in which critical parameters of the field pulse for which the wall is just released from the closure domain structure, gave possibility to obtain important information about the order of closure domain structure dimension and about the mass of the domain wall which is depinned from the wire end.

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REFERENCES

[1] VÁZQUEZ, M.: Soft magnetic wires, *Physica B: Condensed Matter*, vol. 299, no. 3–4, pp. 302–313, June 2001.

[2] ZHUKOVA, V. – IPATOV, M. – ZHUKOV, A.: Thin magnetically soft wires for magnetic microsensors, *Sensors*, vol. 9, pp. 9216–9240, 2009.

[3] VÁZQUEZ, M.: Advanced Magnetic Microwires. *Handbook of Magnetism and Advanced Magnetic Materials*, vol. 4 *Novel Materials*. John Wiley & Sons, 2007. DOI: 10.1002/9780470022184.hmm418.

[4] KOSTYK, Y. – VARGA, R. – VÁZQUEZ, M. – VOJTANÍK, P.: Domain wall propagation in adiabatic regime, *Physica B: Condensed Matter*, vol. 403, pp. 302–313, 2008.

[5] VARGA, R. – KOSTYK, Y. – ZHUKOV, A. – VAZQUEZ, M.: Single domain wall dynamics in thin magnetic wires, *Journal of Non-Crystalline Solids*, vol. 354, pp. 5101-5103, 2008.

[6] VARGA, R. – GARCIA, K. L. – VÁZQUEZ, M.: Single-Domain Wall Propagation and Damping Mechanism during Magnetic Switchin of Bistable Amorphous Microwires, *Phys. Rev. Lett.*, vol. 94, 017201, 2005.

[7] IPATOV, M. – USOV, N. A. – ZHUKOV, A. – GONZALEZ, J.: Local nucleation field of Fe-rich

microwires and their dependence on applied stresses, *Physica B*, vol. 403, pp. 379–381, 2008. DOI: 10.1016/j.physb.2007.08.054.

[8] ZIMAN, J. – ONUFER, J. – KLADIVOVÁ, M.: DC magnetization processes in bistable glass-coated ferromagnetic microwires, *J. Magn. Magn. Mater*., vol. 323, pp. 3098–3103, 2011. doi.org/10.1016/j.jmmm.2011.06.064.

[9] ZIMAN, J. – ŠUHAJOVÁ, V. – KLADIVOVÁ, M.: Magnetic domain wall dynamics in an inhomogeneous magnetic field, *Physica B*, vol. 407, pp. 3905–3909, 2012. doi.org/10.1016/ j.physb.2012.06.021.

[10] VÁZQUEZ, M. – BASHEED, G. A. – INFANTE, G. – Del REAL, R. P.: Trapping and injecting single domain wall in magnetic wire by local fields, *Phys. Rev. Lett.*, vol. 108, pp.037201, 2012.

[11] ONUFER, J.– ZIMAN, J. – KLADIVOVÁ, M.: Dynamics of closure domain structure in bistable ferromagnetic microwire; *in press.*

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