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INVITED PAPER

TEMPERATURE DEPENDENCE OF SWITCHING FIELD AND ITS DISTRIBUTION IN BISTABLE MAGNETIC MICROWIRES

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The switching field distribution of the bistable amorphous Fe-based microwires has been investigated at different temperatures. The mean value and width of the switching field distribution decrease with the temperature. From this study, two mechanisms have been found to be responsible for the switching process in amorphous microwires namely, long range order pinning arising from magnetoelastic anisotropy mainly coming from the coating stresses, and short range order pinning at atomic scale defects. The shape of the switching field distribution is solved in terms of the thermoactivated model. Two contributions are also found to form the potential of the closure domain. The temperature dependence of the switching field distribution width has also been solved in terms of the thermoactivated model and was found to be proportional to the switching field.

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1. Introduction

Amorphous glass coated microwires are excellent materials to study the magnetization processes [1,2]. The domain structure of the microwires with positive magnetostriction consists of one large domain with axially oriented magnetization and an outer shell with transversely oriented magnetization [3]. Additionally, closure domains appear at the ends in order to decrease the magnetostatic energy. This unique domain structure gives rise to square shaped hysteresis loops characteristic of bistable magnetic behaviour. The magnetization process of these microwires runs in one large Barkhausen jump coming from the wall displacement of a single wall depinning from the above mentioned closure domain structures. This is very important for applications as well as for theoretical studies since it gives us the possibility to study the movement of one domain wall without any interaction with other domains.

By subsequent measuring of remagnetizing cycles a distribution of the switching field has been experimentally determined in recent works [4,5] instead of a single valued switching field. This distribution gives us information about the thermodynamics of the closure domain wall potential.

In the present work, the temperature dependence of the switching field distribution of various Fe-based microwires with and without coated glass have been measured in the temperature range from 77 K up to 450 K.

2. Experimental

The study has been performed on amorphous magnetic microwires with nominal composition $Fe_{77.5}Si_{7.5}B_{15}$ prepared by the Taylor-Ulitovsky method. The as-cast microwires have a diameter of metallic nucleus of 11 μm and a total diameter of 29 μm including a Pyrex-like glass

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coating. For the study of microwires without cover, they were plunged into 40% HF solution for 2 min. Afterwards, the homogeneity of the glass removal was checked by optical microscopy. The length of the samples for measurements was 17 mm.

A specially designed device was employed to measure the switching field. It consists of two coaxial coils, a bigger – magnetizing one and another smaller pick-up one for sensing. The set is placed inside a cryostate that allows measurements in the temperature range from 77 to 300 K. The sharp voltage pulse appears at the end of the pick-up coil during the magnetization reversal. The time behaviour of both voltages in magnetizing and pick-up coil is recorded by an oscilloscope connected to a PC. The maximum axial applied field was 41 Oe, high enough not to influence the changes of the switching field with the temperature. The hysteresis cycles were taken at the frequency of 30 Hz. The distribution of switching field was obtained by evaluating 2000 consecutive switching processes. Additionally, magnetization measurements were performed in a Vibrating Sample Magnetometer under a nearly saturating maximum field of 1 T in order to evaluate the temperature dependence of saturation magnetization.

3. Results and discussion

Fig. 1 shows the distribution of the switching field of the amorphous FeSiB microwires at different temperatures after removal of the glass coating. The distribution width decreases with the temperature and its position is shifted towards lower fields. A similar dependence was previously found for the FeSiB microwire with glass coating [4].

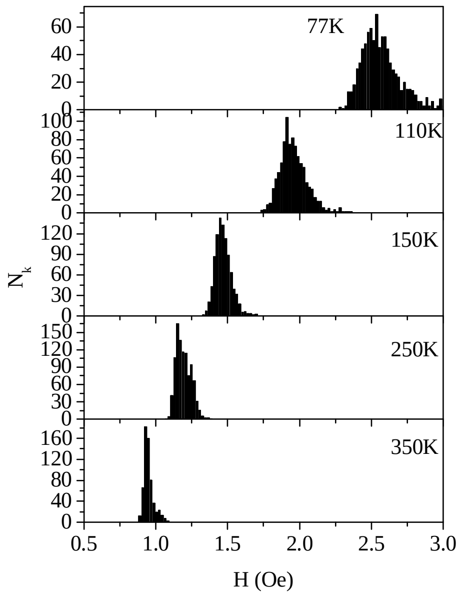

Fig. 1. Switching field distribution of the FeSiB microwire after glass coating removal.

From the temperature dependence of the maximum of the switching field we can find two contributions to the coercivity mechanism of the amorphous microwires:

i) Magnetoelastic pinning of the domain wall on the stress centers, and
ii) Pinning of the domain wall at atomic scale defects.

The magnetoelastic contribution to the switching field H_{sw}^{σ} can be expressed as [4]:

$$H_{sw}^{\sigma} \propto pM_s^{3/2}(1+r(\Delta T))^{1/2}, \tag{1}$$

where M_s is the saturation magnetisation, $p \approx const.\sigma_r$, and $r \approx E(\alpha_g-\alpha_m)/\sigma_r$. Here we have assumed a temperature dependence of the magnetostriction through the scaling law [6]. Also, we consider the temperature dependence of the stresses arising from the different thermal expansion coefficients of the Pyrex, α_g, and metallic nucleus, α_m, σ_r are residual intrinsic stresses coming from quenching and drawing, and E is Young's modulus.

The relaxation contribution H_{sw}^{p} arising from the pinning of the domain wall on the atomic scale defects can be expressed as [7]:

$$H_{sw}^{p}(T) \propto \frac{1}{M_s}\frac{\varepsilon_p^2 \rho_p}{kT} G(T,t)\,, \tag{2}$$

where ε_p corresponds to the interaction energy of the mobile defects with the spontaneous magnetisation, ρ_p is the density of the mobile defects and $G(T,t)$ is a relaxation function [8]: $G(T,t) = (1 - e^{(-t/\tau)})$, where t is the time of measurement and τ is the relaxation time, which is given by the Arrhenius equation: $\tau = \tau_0 e^{Q/kT}$. Here, τ_0 is a pre-exponential factor given elsewhere [8] and Q corresponds to the activation energy of the mobile defects.

The general expression for switching fields in amorphous microwires can be then expressed as the sum of the above given contributions:

$$H_{sw}(T) = H_{sw}^{\sigma} + H_{sw}^{p}(T), \tag{3}$$

Considering eqs. (1) and (2) and applying them into (3) leads to:

$$H_{sw}(T) = pM_s^{3/2}(1+r(\Delta T))^{1/2} + n\, G(T,t)/(M_s T), \tag{4}$$

where $n \approx (\varepsilon_p^2 \rho_p/k)$ is proportional to the number of the defects and $G(T,t)$ is assumed to be a monotonicaly increasing function of the measuring temperature at the measured times and temperatures [9]. Fig. 2 shows the temperature dependence of the switching field of glass-coated microwires and after glass removal. In both cases, it includes the experimental points and their fitting to eq. (4). Curves corresponding to the magnetoelastic, eq. (1), and to the pinnint at defects, eq. (2), are also included. As observed, a reasonable fitting has been achieved confirming that the assumed two contributions are sufficient for describing the temperature dependence of the switching field in amorphous microwires. In the case of the microwire without glass, it should be emphasized that the pinning on the atomic scale defects is the determining contribution to the switching mechanism. It is also responsible for the increase of the switching field at low temperatures. On the other hand, glass coating increases the stresses applied on the microwire through the different thermal expansion coefficients of the metallic nucleus and the glass coating. This results in the increase of the role of magnetoelastic contribution to the switching mechanism at intermediate temperatures (150-400 K). These stresses probably enhance the relaxation at higher temperature which results in the increase of the relaxation contribution at higher temperature.

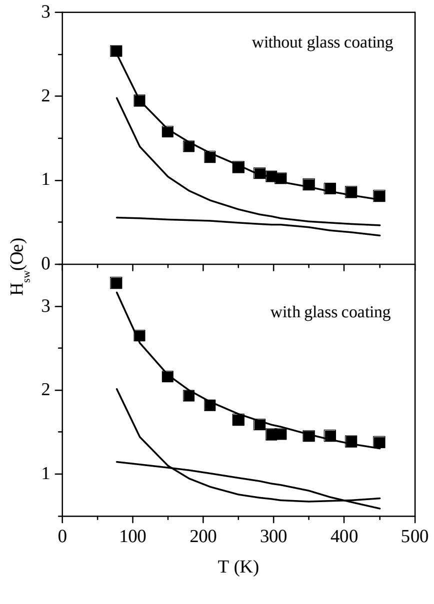

Fig. 2. The temperature dependence of the mean switching field for FeSiB microwire with and without glass coating. Magnetoelastic (eq.1) and defects (eq.2) pinning contributions are also given.

To explain the change of the distribution parameters with temperature we have applied the thermoactivated mechanism model [10-12]. It is based on the fact that the energy barrier of the domain wall can be overcome by thermal activation even at fields lower than the switching field (see Fig. 3). This model assumes a simple analytical approximation for the field dependence of the energy barrier $\Delta G(H)$ [12,13]:

$$\Delta G(H) = G_0(1-H/H_{sm})^{3/2} = G_0\Delta h^{3/2}, \tag{5}$$

where H_{sm} is the highest observed switching field and $\Delta h=(H_{sm}-H)/H_{sm}$. The probability, dp, of switching at an external field H whose amplitude lies between ΔH and $\Delta H + d(\Delta H)$ is then given by [12,14]:

$$\Delta p = A \exp(-\Delta G/kT)d(\Delta H) \tag{6}$$

where A is a constant given by the normalization condition $\int_0^{H_{sm}} dp = 1$, and $\Delta H=H_{sm}-H$. Assuming that the free energy of a domain wall can be expanded in power of the increment of its magnetic moment up to the cubic terms, the dependence of ΔG on applied field given in eq. (5) can be rewritten as:

$$\Delta G(H) = \frac{8}{3}\chi_0\sqrt{H_{sw}}(\Delta H)^{3/2} \tag{7}$$

where χ_0 is the initial susceptibility coming from the closure domain wall at zero applied field.

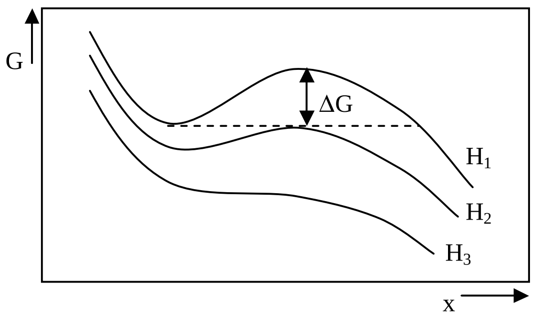

Fig. 3. Schematic representation of the thermoactivated mechanism model. Dependence of the free energy of the domain wall on its position at applied fields.

Anyhow, this model predicts the increase of the switching field as well as its distribution width with the temperature [13,15], in opposition with our results, where both values decrease with temperature. The thermoactivated model predicts the shape of the switching field distribution: The linear dependence of the logarithm of the probability density dp to observe the Barkhausen jump in the field range Δh and $\Delta h+d(\Delta h)$ on the reduced switching field $(\Delta h)^{3/2}$ [10, 12]:

$$\ln(dp/d(\Delta h)) = \beta - \alpha(\Delta h)^{3/2}, \tag{8}$$

where

$$\alpha = (8/3)\chi_0 H_{sw}^{2}/kT \tag{9}$$

$$\beta = (2/3)\ln(\alpha)-\ln(2)-\ln[y(\alpha^{1/3})] \tag{10}$$

and

$$y(\alpha^{1/3}) = \int_0^{\alpha^{1/3}} z\exp(-z^3)dz \tag{11}$$

The linear dependence given in eq. (8) is very useful since it gives us the possibility to check the model with the experimental data. It was shown previously [10,12] that probability density $dp/d(\Delta h)$ can be evaluated from the distribution given in Fig.1 as:

$$\frac{dp}{d(\Delta h)} = \left[\sum_{k=1}^{k_m} \frac{N_k}{\sum_{i=k}^{k_m} N_i} \right]^{-1} \frac{N_k}{\delta h \sum_{i=k}^{k_m} N_i}, \tag{12}$$

where $\delta h = (H_{max}-H_{min})/k_m$ and k_m is the number of divisions of the interval (H_{min};H_{max}). Eq. (12) takes into account the fact that conditions for appearance of large and small fluctuations are non-equivalent due to the experimental method.

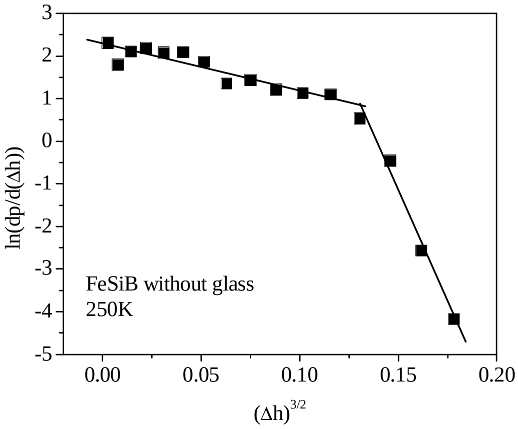

Fig. 4. Dependence of the probability density on the reduced magnetic field.

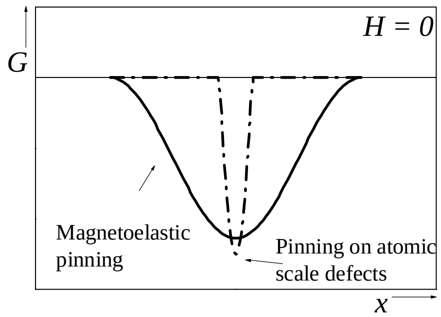

Fig. 5. Schematic view of the two domain-wall potentials that contribute to the switching mechanism.

The field dependence of the probability density given in eq. (8) is shown in Fig. 4, where instead of a single dependence, the sum of two linear dependencies is found. This can be explained in terms of the sum of two potentials which would correspond to the two contributions to the switching mechanism of the microwires. The magnetoelastic pinning of a domain wall coming from the long range interaction and its potential is wide shaped, whereas the pinning on the atomic scale defects has a short range origin and its potential is narrow (see Fig. 5). The minimum of the domain wall free energy is given by the sum of the above mentioned potentials. According to the thermoactivated model, the temperature dependence of the switching field distribution width is given by [11]:

$$\Delta H = (1/\alpha)^{2/3} Q H_{sm}, \tag{17}$$

where Q is a constant. As observed in Fig. 6, the distribution width is proportional to the switching field in a first approximation, particularly for the case of the microwire without glass. On the other hand, we have to keep in mind that α can also be temperature dependent. Moreover, we have two contributions to the coercivity with a different temperature dependence which results in the intersected distribution.

4. Conclusions

The switching field distribution of bistable amorphous FeSiB microwires with and without glass coating has been investigated at different temperatures. It is found that the switching field decreases with the temperature. Two contributions to the switching mechanism are identified from the study of the temperature dependence of the mean switching field: the magnetoelastic pinning of the domain wall on the stress centers, and the pinning of the domain wall on atomic level defects.
The switching field distribution width also decreases with the temperature. The distribution shape has been solved in terms of the thermoactivated model. Based on this model, the distribution shape can be explained by introducing two potentials: i) Magnetoelastic one which results from long-range interaction, and ii) Relaxation one which results from short-range relaxation of the atomic defects.

According to the thermoactivated model, the temperature dependence of the distribution width is found to be proportional to the coercivity.

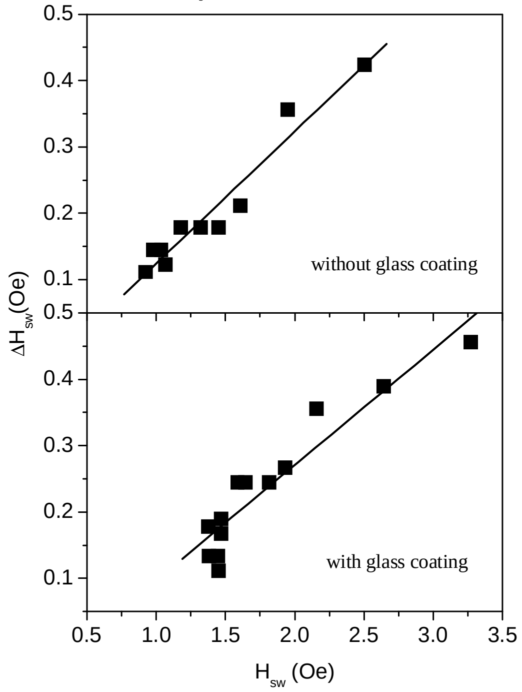

Fig. 6. Dependence of the switching field distribution width on the switching field at different temperatures for glass-coated microwire and after glass-removal.

Acknowledgements

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