phys. stat. sol. (a) **169**, 139 (1998)

Subject classification: 75.60.Ch; 76.50.+g; S1.1; S1.3

Anomalous Coercivity in Hysteresis Loops of Antiferromagnetically Coupled Fe/Ag/Fe Trilayers on MgO(001) Substrates

T. TOLIŃSKI and J. BASZYŃSKI

Institute of Molecular Physics, Polish Academy of Sciences,
Smoluchowskiego 17, PL-60-179 Poznań, Poland
Phone: (48-61) 8612-432, Fax: (48-61) 8684-524, e-mail: tomtol@ifmpan.poznan.pl

(Received March 24, 1998; in revised form June 26, 1998)

A numerical simulation of the demagnetization process (hysteresis loop) is performed in order to evaluate the bilinear and biquadratic coupling in the MgO/[Fe/Ag/Fe]/Ag trilayer. The proposed approach is intermediate between the model assuming that the system always reaches the Global Energy Minimum (GEM) and the model considering the situation when the system follows the Local Energy Minimum (LEM). The intermediate approach is realized by defining the energy barrier parameter E_b determining the transition between the local energy minima. The value of E_b can be obtained using reference (uncoupled) samples. The numerical algorithm applied to the GEM, LEM and the intermediate model is described. The bilinear J_1 and biquadratic J_2 coupling parameters are determined from the ferromagnetic resonance and hysteresis loop measurements.

1. Introduction

Indirect interlayer exchange coupling between magnetic sublayers through a nonmagnetic spacer has been studied extensively since its discovery in 1986 [1]. The antiferromagnetic (AF) coupling is typically observed by ferromagnetic resonance (FMR) or hysteresis loop measurements [2 to 4]. We have recently shown that for Fe/Ag/Fe samples the iron sublayers should have strongly different magnetic properties in order to reveal the additional, so called optical mode within the FMR spectrum [5]. The distance between the main and the secondary mode is a measure of the interlayer coupling. However, the asymmetry of the trilayer leads to complex demagnetization processes. Thus, adjustment of the hysteresis loop and FMR measurements requires employment of adequate models. Usually demagnetization processes in AF coupled trilayers are interpreted by making the assumption that the system always finds the global energy minimum (GEM) [6] due to domain nucleation and domain wall movement or follows the local energy minimum (LEM) [7] *via* coherent rotation. It was emphasized by Dieny and Gavigan that in real samples an intermediate case may be realized [6,7]. The aim of this paper is to study a phenomenological model falling between the GEM and LEM approaches and to apply it to the asymmetric MgO/[Fe(t_1)/Ag(t_{Ag})/Fe(t_2)]/Ag trilayers.

2. Experimental

The samples studied were obtained by evaporation from two electron guns under a vacuum of about 10^{-4} Pa and at room temperature. The substrate wafers were obtained from single MgO crystals by cleavage.

The deposition rates of the Fe and Ag films were about 0.013 nm/s as was monitored by a crystal quartz oscillator. The hysteresis loops were measured using a vibrating sample magnetometer (VSM) at room temperature.

The surface of the substrates is *step-like* with the step width of about 1000 nm and the height of about 4.1 nm as observed by atomic force microscopy [8]. The steps are flat within one monolayer accuracy, that is the accuracy of the AFM measurements.

The Fe films grow epitaxially on MgO and have the b.c.c. (001) orientation with the [100] *in-plane* axis rotated by 45° with reference to the MgO [100] direction.

The *in-situ* conductance was detected just after deposition of the first 2 to 3 monolayers of Fe which indicates a high density of nucleation sites on the substrate surface. We could observe a characteristic inflexion on the thickness dependence of the resistance at the iron thickness of about 4 nm which is in good agreement with the height of the substrate steps.

3. Phenomenological Model

Probing the static response of a system to an external magnetic field applied along the *in-plane* direction of easy magnetization one can expect that the magnetization reorientation will occur in the field $H_K = 2K/M$, where K is the cubic anisotropy constant. For the films obtained on the *step-like* MgO substrates we have found that the coercivity H_C (measured by VSM) is strongly reduced in comparison with the anisotropy field determined from FMR ($H_K \cong 10H_C$) [9]. The reduction of the coercivity value is known as a Brown' s paradox and results from the existence of a freely moving domain wall [10]. The domains are nucleated at pinning sites characterized by a locally enhanced anisotropy [11]. In the films obtained on MgO the pinning sites could be located at the steps of the substrate surface.

In the GEM model [6] the system always finds the global energy minimum due to the domain nucleation processes and the magnetization curve is fully reversible. In the LEM model [7] the system stays in the local energy minimum and when it disappears the system slides along a path on the energy surface to the next minimum (Fig. 1). The coercivity attains its maximum and the hysteretic behaviour is revealed.

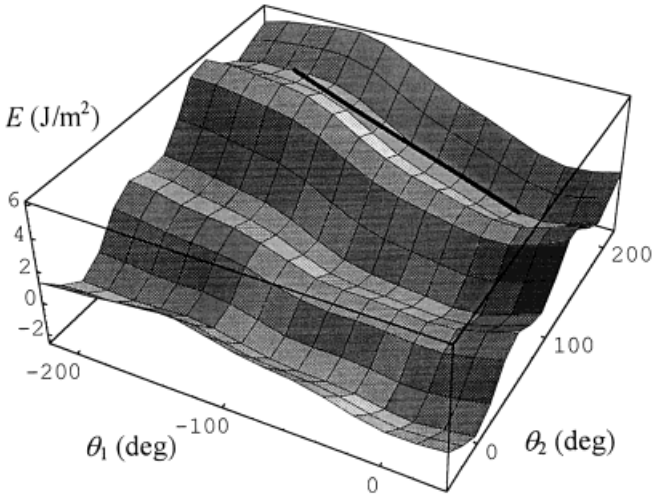

Fig. 1. Example of energy surface $E = f(\theta_1, \theta_2)$ for orientation (first order) transition of the magnetizations $(-180°; 180°) \rightarrow (0°; 180°)$. Reduced parameters: $J_1 = -1$ J/m^2, $J_2 = 0$, $M_1 = M_2 = 1$ T, $t_1 = t_2 = 1$ m, $K_1 = 1.4$ J/m^3, $K_2 = 8.0$ J/m^3, $H = 1.72$ A/m

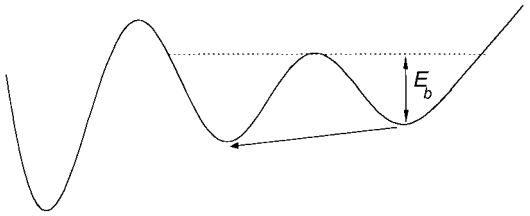

Fig. 2. Schematic (1D) model describing the rule of changing the local energy minimum. The value of the E_b parameter determines the coercivity of the hysteresis loop if the anisotropy fields are known from FMR

In the intermediate approach we define the parameter E_b describing the energy barrier (Fig. 2). If the depth of the local minimum becomes smaller than the assumed value of the E_b parameter the system switches to a lower energy minimum if it exits below the barrier level $E_{min} + E_b$, where E_{min} is the energy value in the actual minimum.

The free energy describing the asymmetric trilayer for the external magnetic field H parallel to the *in-plane* easy axis is

$$E = -J_1 \cos(\theta_1 - \theta_2) - J_2 \cos^2(\theta_1 - \theta_2) - t_1 M_1 H \cos\theta_1 - t_2 M_2 H \cos\theta_2 + K_1 t_1 \cos^2\theta_1 \sin^2\theta_1 + K_2 t_2 \cos^2\theta_2 \sin^2\theta_2 , \quad (1)$$

where J_1, J_2 are the bilinear and biquadratic coupling parameters, t_1, t_2 and K_1, K_2 are the thicknesses and cubic anisotropy constants of the iron sublayers. θ_1 and θ_2 are the *in-plane* angles between the magnetizations M_1, M_2 and the easy axis Fe [100], respectively. The magnetizations are assumed to lie in the film plane. In real samples it is not true and we have found that the simulation of the hysteresis loop is sufficiently reliable and consistent with experimental results if the effective values of the magnetizations ($M_{eff} = M - 2\mu_0 K_\perp / M$, where $K_\perp$ is the perpendicular surface anisotropy constant) determined from FMR are considered.

The local minima have to fulfil the standard conditions for functions of two variables, namely [6,7]

$$\frac{\partial E}{\partial \theta_1} = 0 , \qquad \frac{\partial E}{\partial \theta_2} = 0 , \quad (2)$$

$$\frac{\partial^2 E}{\partial \theta_1^2} + \frac{\partial^2 E}{\partial \theta_2^2} > 0 , \quad (3)$$

$$\frac{\partial^2 E}{\partial \theta_1^2} \frac{\partial^2 E}{\partial \theta_2^2} - \left(\frac{\partial^2 E}{\partial \theta_1 \, \partial \theta_2} \right)^2 > 0 . \quad (4)$$

Finally, in the intermediate (between GEM and LEM) phenomenological model the demagnetization process is simulated according to the following procedure:

1. A high enough value of the field H is chosen to put the system into saturation ($\theta_1 = -180^\circ$, $\theta_2 = 180^\circ$).

2. The value of H is reduced and a new equilibrium position of the magnetizations is localized (Eqs. (2) to (4)) within a small neighbourhood of the previous solution.

3. In the case of a significant change of the angles θ_1 and θ_2 (beyond the small neighbourhood) a small step is done in the direction of the highest slope (gradient) on the energy surface. The gradient direction is controlled after each step. The steps are repeated until the change of the gradient sign (crossing the local minimum). Subse-

quently, the position of the minimum is defined precisely using the Eqs. (2) to (4). The points 2 and 3 are repeated until the saturation of the sample in the opposite direction ($\theta_1 = 0^\circ$, $\theta_2 = 0^\circ$) is reached.

4. The above algorithm affords possibilities for simulation of the hysteresis loop in LEM model. In the case of the intermediate approach the depth of the local energy minimum is investigated numerically before the value of the field is changed. If the depth is smaller than E_b the area below the barrier level $E_{min} + E_b$ is searched for the lowest energy minimum (Fig. 2). Obviously, for high values of E_b the GEM model will be reproduced.

Fig. 3 shows the experimental hysteresis loop measured for the MgO/[Fe(8.3 nm)/Ag(1.5 nm)/Fe(3.7 nm)]/Ag(10 nm) trilayer and the numerically simulated demagnetization curves for GEM, LEM and the intermediate model. The spacer thickness $t_{Ag} = 1.5$ nm corresponds to the first AF peak we had observed in the interlayer coupling oscillations. The parameters J_1 and J_2 were estimated by fitting to the shape of the experimental hysteresis loop and to the resultant coupling parameter $J_{1,2}$ ($J_{1,2} = J_1 + 2J_2 = -0.14 \times 10^{-3}$ J/m^2) evaluated from FMR measurements. The obtained values $J_1 = 0.02 \times 10^{-3}$ J/m^2 and $J_2 = -0.08 \times 10^{-3}$ J/m^2 are comparable with the result of Celinski et al. [2] for the first AF peak ($J_1 = 0.053 \times 10^{-3}$ J/m^2, $J_2 = -0.070 \times 10^{-3}$ J/m^2). Fig. 3

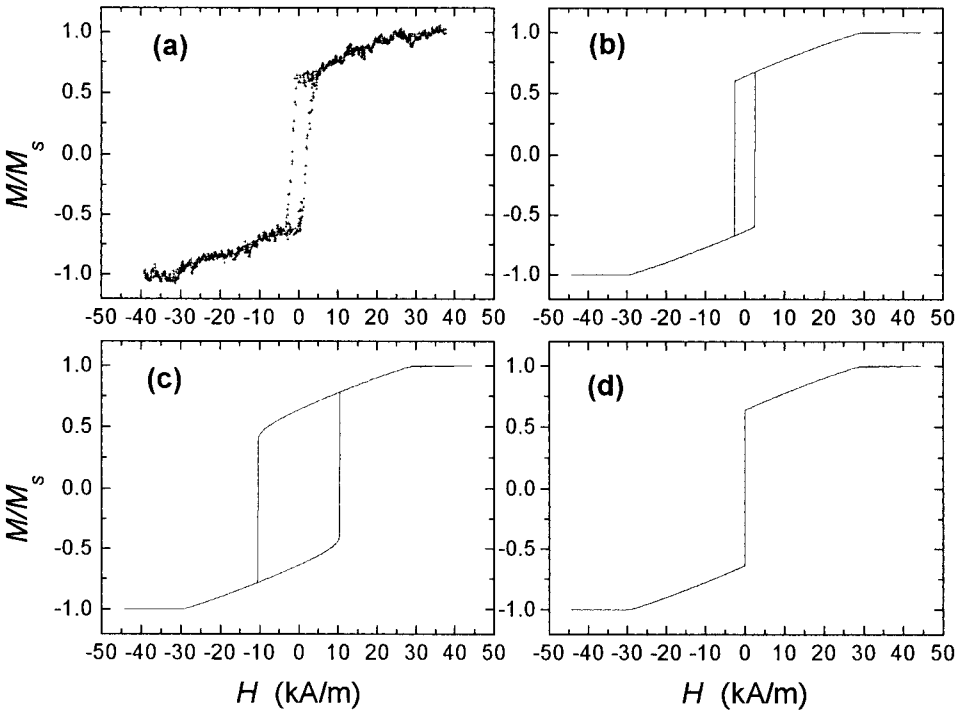

Fig. 3. a) Experimental and b) theoretical hysteresis loop for $t_{Ag} = 1.5$ nm. For the present approach the parameters are: $J_1 = 0.02 \times 10^{-3}$ J/m^2, $J_2 = -0.08 \times 10^{-3}$ J/m^2, $H_{K1} = 23.87$ kA/m, $H_{K2} = 4.77$ kA/m, $M_1 = 1.935$ T, $M_2 = 1.319$ T, and $E_b = 0.03 \times 10^{-3}$ J/m^2. For comparison, c) and d) show the theoretical loops for the case when the system either follows the local energy minimum or always finds the absolute energy minimum, respectively

clearly speaks in favour of employing the intermediate approach. The assumed value of the energy barrier $E_b = 0.03 \times 10^{-3}$ J/m^2 is of the order of the typical domain wall energy for magnetic thin films. In practice it is a good method to apply either the E_b value determined for single magnetic films or for uncoupled trilayers, i.e. for reference samples.

4. Conclusions

Neither the model assuming that the system always falls in the global energy minimum nor the model in which the system follows the local energy minimum is adequate to fit the hysteresis loops measured for the MgO/[Fe/Ag/Fe]/Ag trilayers. Therefore, the intermediate approach has been proposed. It is based on the assumption that the domain nucleation occurs if the depth of the local energy minimum is smaller than the energy barrier.

Acknowledgement This work was supported by the KBN grant No. 2 P03B 050 11.

References

[1] P. Grünberg, R. Schreiber, Y. Pang, M.B. Brodsky, and H. Sowers, Phys. Rev. Lett. **57**, 2442 (1986).
[2] Z. Celinski, B. Heinrich, and J. Cochran, J. Appl. Phys. **73**, 5966 (1993).
[3] H. Yamazaki, J. Magn. Magn. Mater. **125**, 272 (1993).
[4] P.E. Wigen, Z. Zhang, L. Zhou, M. Ye, and J.A. Cowen, J. Appl. Phys. **73**, 6338 (1993).
[5] J. Baszyński, T. Toliński, and P.B. Sczaniecki, phys. stat. sol. (a) **148**, K41 (1995).
[6] B. Dieny and J.P. Gavigan, J. Phys.: Condensed Matter **2**, 187 (1990).
[7] B. Dieny and J.P. Gavigan, J. Phys.: Condensed Matter **2**, 159 (1990).
[8] R. Czajka, Technical University of Poznań (private communication).
[9] T. Toliński and J. Baszyński, J. Physique **8**, 229 (1998).
[10] A.S. Arrott and B. Heinrich, J. Magn. Magn. Mater. **93**, 571 (1991).
[11] A. Moschel, R.A. Hyman, A. Zangwill, and M.D. Stiles, Phys. Rev. Lett. **77**, 3653 (1996).