Materials Science-Poland, Vol. 24, No. 3, 2006

Analysis of magnetization reversal at the exchange -biased interface using the Ising approach

T. BŁACHOWICZ*, M. WIEJA

Department of Electron Technology, Institute of Physics, Silesian University of Technology, Krzywoustego 2, 44-100 Gliwice, Poland

The paper provides the results of exchange-biased simulations of a single ferromagnetic (FM) layer coupled to a quenched antiferromagnetic (AFM) region using the Random field Ising model (RFIM). From the RFIM algorithm, the shapes of exchange-biased hysteresis loops and featuring perpendicular magnetic anisotropies were obtained. Providing a possible explanation for this effect, the recognized stable part of an interface magnetization, represented by unreversed spins at the interface, was evidently simulated. The obtained results are consistent with the domain state model (DSM) model, in which a part of the AFM interface magnetization is stable during hysteresis loop creation.

Key words: *spintronics; exchange-bias; magnetization reversal*

1. Introduction

The simulation of exchange-biased phenomena is important for intensive theoretical and experimental research whose results have already been applied to magnetoelectronics and will soon be used in novel devices where electron-spin plays an important role [1–4]. One of the most important components of spintronic devices are exchange-biased magnetic thin layers. The phenomenon of importance can be described as shift of the hysteresis loop of a ferromagnetic material along the field axis and as enhancement of the coercive field, observed in coupled ferromagnetic (FM) and antiferromagnetic (AFM) thin films after being deposited in a magnetic field or field cooling below the Néel temperature of the AFM. This effect, which exists at the ferromagnetic/antiferromagnetic (FM/AFM) interface, can be tailored on the atomic scale by structural modifications in the AFM bulk [5–6]. Such efforts have been adequately described within the domain state model (DSM) of exchange-bias [7, 8] and experimentally confirmed by crystal structure dilution [5] and ion irradiation [9]. The DSM approach is based on Monte Carlo calculations using the

*Corresponding author, e-mail: Tomasz.Blachowicz@polsl.pl

heat-bath algorithm [10]. Apart from the DSM, other numerical methods can be applied. One of them is based on the random field Ising model (RFIM) [11–13]. Presented here are the results obtained from numerical simulations using the RFIM algorithm. In particular spin reversibility influenced by atomic roughness at the interface was analysed.

2. Simulations

The RFIM approach can be used to simulate the bias of the FM layer by the AFM region. It has been applied by Illa [14] who intended to reproduce the properties of a single layer of ferromagnetic spins placed on a totally quenched AFM. We propose a similar approach, our results, however, can be interpreted in the scope of perpendicular magnetic anisotropies.

In the current simulation, in order to block spins, the exchange constant between neighbouring FM spins was enhanced at randomly distributed positions from its normal value of 1 to a larger value, for example 10. Thus, the complete magnetic field at a given lattice point i was calculated as

$$H_i = \sum_{j=1}^{j=4} (J_{ij} S_j) + h_i^G + H_{\text{ext}} \tag{1}$$

where J_{ij} is the exchange constant (coupling constant) randomly enhanced to $J_E > J_{ij} = 1$, S_j is the spin with the value of +1 or –1, h_i^G is the Gaussian distributed field representing atomic roughness at the interface, and H_{ext} is the externally applied magnetic field. During simulations, when the total field changed its algebraic sign at a given point, the spin flipped into the opposite orientation. Further, the magnetization of the system was calculated as the ratio of the algebraic sum of spins and the total system square dimension. All simulations started from a saturation state, in which all spins were at +1 positions. The simulation was carried out using one-dimensional periodic conditions of the Born-Karman type. Additionally, numerical experiments were carried out with 2-dimensional periodic conditions, and even with no periodic conditions, but this did not change the obtained results. The results were averaged over many trails, the averages attaining constant values after about 20 replications. Details of the influence of boundary conditions, the dimensions of the investigated system, and the number of disorder realizations on the performance of the RFIM can be found in the author's other work [15]. Calculations were carried out on a computer cluster consisting of 16 PCs to increase numerical performance. The time needed to make and to average 10^3 trails was about 40 minutes for a 50×50 spin system.

3. Results and discussion

Figure 1a and its inset provide the results of simulation carried out for a 50×50 lattice, the standard deviation of the random fields being σ = 1.65, the enhanced exchange constant J_E = 20, the fraction of enhanced bounds f = 0.03, and the external magnetic field intensity ranging from –2.7 to 8. Figure 2a and its inset provide results

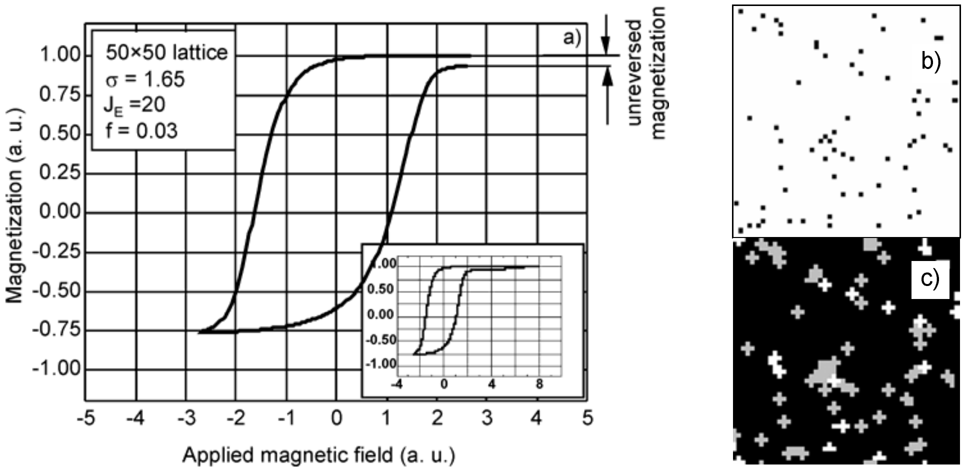

Fig. 1. Simulation of exchange-bias for a system with σ= 1.65. The simulation starts from saturation under the applied magnetic field 8 a. u, ranging between 8 a. u. and –2.7 a.u. Other input data are given in the figure: a) hysteresis loop with unreversed part of magnetization (Inset: the whole loop), b) randomly distributed locations for the enhanced exchange constants J_E, c) completely unreversed spins in +1 positions (grey squares), spins not reversed from –1 orientations for a field intensity of 2.7 (white squares), and fully reversed spins (black region)

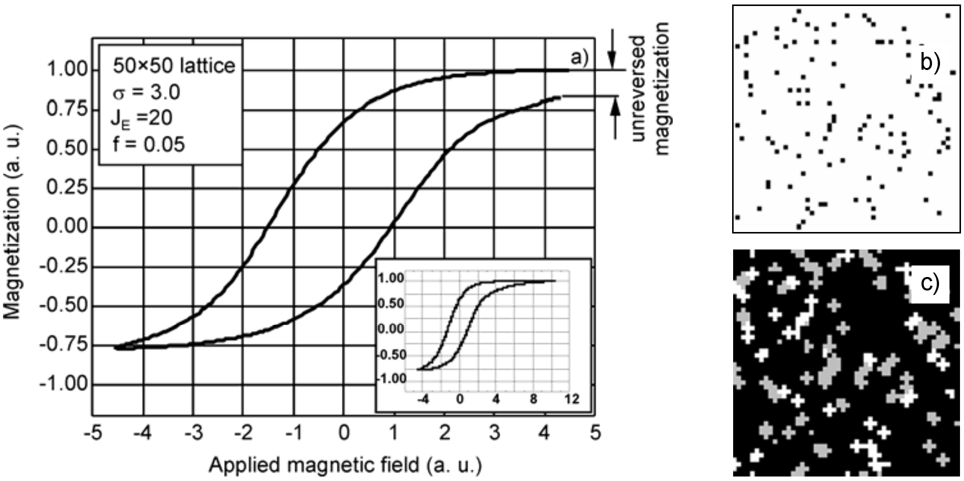

Fig. 2. Simulation of exchange-bias for a system with σ= 3.0. The simulation starts from saturation under the applied magnetic field 10.5 a. u. ranging between 10.5 a. u. and –2.7 a.u. Other input data are given in the figure: a) hysteresis loop with unreversed part of magnetization (Inset: the whole loop), b) randomly distributed locations for the enhanced exchange constants J_E, c) completely unreversed spins in +1 positions (grey squares), spins not reversed from –1 orientations for a field intensity of 4.5 (white squares), and fully reversed spins (black region)

for a standard deviation of the random fields $\sigma = 3$, the fraction of enhanced bounds $f = 0.05$, and the external magnetic field intensity ranging from –4.5 to 10.5.

The obtained asymmetrical minor loops (Figs. 1a, 2a) point to the existence of unreversed spins during loop creation. What should be emphasized is that these spins can be divided into two parts. The first set of spins can be distinguished as the field decreases from its maximum to minimum value, and where some spins are unreversed (grey squares in Figs. 1c, 2c). The other part can be recognized when the field increases back to its maximum value – these spins were reversed when the field decreased, but some of them were not reversed back (white squares in Fig.1c, 2c). Obviously, the spins that are unreversed during this first period of the hysteresis loop remain unreversed until the end of a given simulation of the hysteresis loop. In this way, the current effects differ from those provided by X. Illa, where under the same assumptions and applied algorithm, FM spins seem to be completely reversible from their –1 orientations. For clarity, the black regions in Figs. 1c, 2c represent +1 orientation of spins – these spins are completely reversible from +1 to –1 and back to +1. Figs. 1b, 2b provide information on the randomly distributed locations of the enhanced exchange constants J_E.

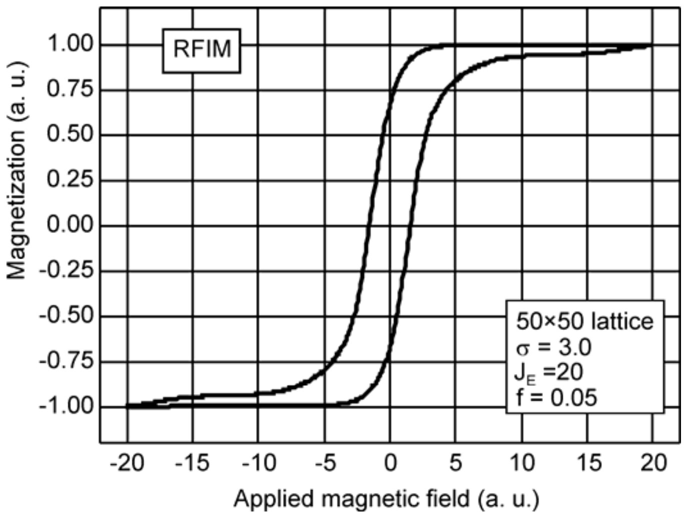

Fig. 3. Simulation of the total loop for the external magnetic field ranging from –20 to 20

The results reported here are consistent with the DSM model [16, 17], where a part of the AFM interface magnetization is stable during creation of the hysteresis loop and leads to the up-shift of the AFM hysteresis loop with open ends. In the DSM model which recognizes this phenomenon, the irreversible part of the interface magnetization of the AFM acts as an additional effective field influencing the FM, and is a source of exchange bias and unidirectional in-plane magnetic anisotropy. Thus, the RFIM results provided here and the DSM results provide information about the stable part of AFM/FM interface magnetization. Furthermore, the results provided here possess equivalents in experimental reality. The AFM crystal lattice dilution, using different atom substitutions, and exchange-bias in the AFM/FM system, were realized technologically in CoO/Co bilayers – the AFM CoO structure was modified by inserting non-magnetic substitutions of the $Co_{1-x}Mg_xO$ type [18].

Figure 3 provides results of a total loop, for which the external magnetic field intensity ranges from –20 to 20, the standard deviation of the random fields being $\sigma = 3$, the enhanced exchange constant $J_E = 20$, and the fraction of enhanced bounds $f = 0.05$. This proves that the effects observed in these simulation correspond to minor loops.

4. Conclusions

What can be concluded from the RFIM results shown here, is the existence of unreversed spins of two types: unreversed from the +1 orientation and unreversed from the –1 orientation. Importantly, the examination of the data provided here indicates a correlation with results obtained within the DSM model of exchange-bias for the AFM layer at the AFM/FM interface.

Despite this consistency with the DSM model, however, we have tested several types of boundary conditions imposed on the 2D structure. The results were not sensitive to these in-plane features. We can conclude that we simulated perpendicular out-of-plane magnetization reversal. The observed pinning of ferromagnetic spins was influenced by the AFM. It seems realistic that the obtained unreversed part of interface magnetization can be transferred into another perpendicular direction, a third dimension. Importantly, layered structures with perpendicular magnetic anisotropies have been experimentally realized [19] with IrMn applied to exchange-biased Co/Pt multilayers. The model presented in the present paper can be easily extended onto the 3D type to simulate perpendicularly exchange-biased structures as well.

The authors hope that these results will contribute, at least partially, to full understanding of the exchange bias phenomenon [20]. It seems that much work in this area, however, still remains to be done.

Acknowledgements

The paper is associated with the activities related to Grant No. 3 T11F 015 26 received from the Polish State Committee for Scientific Research.

References

[1] KANAI H., YAMADA K., AOSHIMA K., OHTSUKA Y., KANE J., KANAMINE M., TODA J., MIZOSHITA Y., IEEE Trans. Magn., 32 (1996), 3368.

[2] KANAI H., KANE J., YAMADA K., AOSHIMA K., KANAMINE M., TODA J., MIZOSHITA Y., IEEE Trans. Magn., 33 (1997), 2872.

[3] KANAI H., KANAMINE M., HASHIMOTO A., AOSHIMA K., NOMA K., YAMAGISHI M., UENO H., UEHARA Y., UEMATSU Y., IEEE Trans. Magn., 35 (1999), 2580.

[4] KAKA S., NIBARGER J.P., RUSSEK S.E., STUTZKE N.A., BURKETT S.L., J. Appl. Phys., 93 (2003), 7539.
[5] BESCHOTEN B., TILLMANNS A., KELLER J., GÜNTHERODT G., NOWAK U., USADEL K.D., Adv. Solid State Phys., 42 (2002), 419.
[6] KELLER J., MILTÉNYI P., BESCHOTEN B., GÜNTHERODT G., NOWAK U., USADEL K.U., Phys. Rev. B, 66 (2002), 14431.
[7] NOWAK U., USADEL K.D., Phys. Rev. B, 44 (1991), 7426.
[8] NOWAK U., USADEL K.U., KELLER J., MILTÉNYI P., BESCHOTEN B., GÜNTHERODT G., Phys. Rev. B, 66 (2002), 14430.
[9] MEWES T., LOPUSNIK R., FASSBENDER J., HILLEBRANDS B., JUNG M., ENGEL D., EHRESMANN A., SCHMORANZER H., Appl. Phys. Lett., 76 (2000), 1057.
[10] BINDER K., *The Monte Carlo Method in Condensed Matter Physics*, Springer-Verlag, Berlin, 1995.
[11] SETHNA J.P., DAHMEN K., KARTHA S., KRUMHANSL J.A., ROBERTS B.W., SHORE J.D., Phys. Rev. Lett., 70 (1993), 3347.
[12] BLOSSEY R., KINOSHITA T., DUPONT-ROC J., Physica A, 248 (1998), 247.
[13] NOWAK U., USADEL K.D., ESSER J., Physica A, 250 (1998), 1.
[14] ILLA X., VIVES E., PLANES A., Phys. Rev. B, 66 (2002), 224422.
[15] BLACHOWICZ T., Cent. Eur. J. Phys., 3 (2005), 147.
[16] NOWAK U., MISRA A., USADEL K.D., J. Appl. Phys., 89 (2001), 7269.
[17] NOWAK U., MISRA A., USADEL K.D., J. Magn. Magn. Mater., 240 (2002), 243.
[18] MILTÉNYI P., GIERLINGS M., KELLER J., BESCHOTEN B., GÜNTHERODT G., NOWAK U., USADEL K.D., Phys. Rev. Lett., 84 (2000), 4224.
[19] SORT J., GARCIA F., RODMACQ B., AUFFRET S., DIENY B., J. Magn. Magn. Mater., 272–276 (2004) 355.
[20] MEIKLEJOHN W.H., BEAN C.B., Phys. Rev., 102 (1956), 1413.

Received 1 June 2005
Revised 10 October 2005