First publ. in: Journal of Applied Physics 103 (2008), 07C102

A model of the temperature dependence of exchange bias in coupled ferromagnetic/antiferromagnetic bilayers

B. Craig, R. Lamberton, and A. Johnston
Seagate Technology, 1 Disc Drive, Springtown Industrial Estate, Derry BT48 0BF, United Kingdom
U. Nowak, R. W. Chantrell,[a] and K. O'Grady
Department of Physics, The University of York, York YO10 5DD, United Kingdom

A granular level model of the magnetic properties of coupled ferromagnetic/antiferromagnetic layers is used to calculate the temperature dependence of the exchange bias. The predicted results are in good qualitative agreement with experiment. Agreement with experiment requires the introduction of the temperature dependence of the anisotropy constant of the antiferromagnetic layer.

I. INTRODUCTION

Exchange coupled ferromagnetic (F)/antiferromagnetic (AF) bilayers are important components of read sensors for magnetic recording, providing a bias for the pinned layer of the sensor. Thermal stability of the AF layer is necessary for the operation of the device. The AF layers generally consist of small grains, and thermal stability is achieved through the anisotropy energy barrier, $K_{AF}V$, of the AF grains. Consequently the anisotropy constant K_{AF} of the AF layer is an important material property. This quantity is often investigated by measurement of the blocking temperature T_B of the AF layer, which for vibrating-sample magnetometer measurement time scales is taken as $T_B = K_{AF}V/25k$; thus, measurement of T_B and the grain volume V allow the determination of K_{AF}. The blocking temperature can be measured from the temperature dependence of the exchange field H_e; however, repeated cycling around hysteresis loops at increasing temperatures is subject to the training phenomenon which affects the measured values of $H_e(T)$. Recent measurements[1] show that it is possible to determine $H_e(T)$ in a "training-free" measurement procedure in which hysteresis loops are measured at the same (thermal activation free) low temperature after raising the system to increasingly high temperatures, which reverses part of the AF layer in the exchange field from the ferromagnet. During this procedure, $H_e(T)$ changes sign and the blocking temperature is determined as $H_e(T_B)=0$. Recently,[2,3] we have used a computational model to study thermal instability of exchange bias. In particular, we investigated the temperature dependence of the exchange field and coercivity[2] and the angular dependence of magnetic properties.[3] Each investigation involved the application of conventional histories of temperature and field. In this paper, we present a computational model of the temperature dependence $H_e(T)$ in the training-free approach described in Ref. 1. It is shown that the model gives results in good agreement with experimental data. This agreement, however, requires the introduction of the temperature dependence of K_{AF}, showing that the energy barrier distribution of the AF layer has a nontrivial temperature dependence, which significantly affects the thermal stability of the AF layer at elevated temperatures. In addition, it is shown that the measured value of the blocking temperature T_B is dependent on the strength of the interlayer exchange coupling.

II. COMPUTATIONAL MODEL

The model is essentially that described in detail in Refs. 2–4. The model is based on Monte Carlo techniques and is capable of predicting the time and temperature dependence of the magnetic properties as required for the current investigation. The F/AF layers are modeled by sets of grains coupled (as appropriate) by magnetostatic and exchange interactions. The microstructure of each layer is created using a Voronoi construction. The microstructure of the F and AF layers is taken to be the same. Each grain is then assigned an anisotropy field from a log-normal distribution function. The F layer is treated in a standard micromagnetic model, with the cell size being the grain size. The magnetic state is determined via minimization of the total energy, comprised of exchange, anisotropy, magnetostatic, and Zeeman terms. Minimization is achieved using a conjugate gradient solver. The AF layer is relatively magnetically "hard" which of course is necessary to provide the stable exchange bias. As a result, the AF layer is treated using a kinetic Monte Carlo method. All grains have an intrinsic energy barrier determined by the anisotropy constant and grain volume in addition to the orientation of the grain with respect to the local magnetic field. The model used here allows thermally activated magnetization reversal with a probability based on the Arrhenius–Néel law,[5] with a numerical solution for stationary states and the Pfeiffer approximation[6] to the energy barrier. The AF grains are subjected to an exchange field from the neighboring grain in the F layer. The model includes the temperature dependence of the AF anisotropy (assumed uniaxial) under the assumption that $K_{AF}(T)=K_{AF}(0)$

[a]Electronic mail: rc502@york.ac.uk.

$\times[M(T)/M(0)]^n$, where M is the AF sublattice magnetization (here, calculated using mean-field theory) and n is an exponent here taken as 3.

The simulation couples the FM and AF layers via and exchange field calculated as follows. The interlayer exchange energy is[7]

$$E_{\text{exch}} = -J_s ac\hat{m}_{\text{F}} \cdot \hat{m}_{\text{AF}}, \tag{1}$$

where J_s is the interfacial exchange constant, a is the grain area, and c is the contact fraction. The $\hat{m}$'s are unit vectors representing the orientations of the F and AF spins, respectively. The exchange field acting on the FM layer is

$$H_e = \frac{\partial E_{\text{exch}}}{\partial \mu_{\text{F}}} = \frac{J_S c\hat{m}_{\text{AF}}}{M_s t} = H_e^{\text{int}}\hat{m}_{\text{AF}}, \tag{2}$$

where the moment of the ferromagnetic grain is $\boldsymbol{\mu}_F = M_s V\hat{m}$ with M_s the saturation magnetization, $V=at$ is the FM grain volume, and t is the thickness of the FM layer. H_e^{int}, representing the intrinsic exchange field acting on the FM layer, is given by

$$H_e^{\text{int}} = \frac{J_s c}{M_s t}. \tag{3}$$

We now calculate the energy barrier of the AF grains. The energy of the AF grains is

$$E_{\text{AF}} = -adK_{\text{AF}}(\hat{e} \cdot \hat{m}_{\text{AF}})^2 - J_s ac\hat{m}_{\text{F}} \cdot \hat{m}_{\text{AF}} \tag{4}$$

where $\hat{e}$ is the easy direction of the AF grain and d is the thickness of the AF film. Normalizing with respect to $2K_{\text{AF}}ad$ and using Eq. (3), we can write Eq. (4) as

$$\frac{E_{\text{AF}}}{2K_{\text{AF}}ad} = -\frac{1}{2}(\hat{e} \cdot \hat{m}_{\text{AF}})^2 - \frac{H_e^{\text{int}} M_s t}{2K_{\text{AF}}d}\hat{m}_{\text{F}} \cdot \hat{m}_{\text{AF}}. \tag{5}$$

Equation (5) is identical to the *S-W* expression with a local field $H_e^{\text{int}}t/d$ acting on grains with an effective anisotropy field $H_K^{\text{eff}} = 2K_{\text{AF}}/M_s$. The simulation uses the parameters H_e^{int} and H_K^{eff} to represent the FM/FM coupling.

III. RESULTS

We first calculate the temperature variation of the exchange bias H_e. This is done following the training-free measurement procedure[1] on a biased AF layer.

(1) Go to a low temperature T_l such that thermal effects are unimportant and measure the hysteresis loop. This first cycle is done twice in order to remove any "athermal" training effect.
(2) The material is then cycled to negative saturation of the FM layer.
(3) Here the temperature is raised to some temperature T.
(4) The temperature is then lowered to T_l where a hysteresis loop is measured. From this, the exchange field H_{exch} is measured.

This procedure is repeated as a function of T, leading to measurements of the temperature dependent exchange bias field $H_{\text{exch}}(T)$.

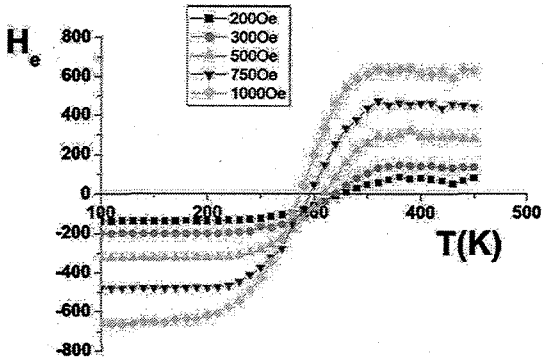

FIG. 1. (Color online) Variation of H_e with T for a system with a grain diameter of 6 nm. Calculations are given for various values of H_e^{int} as indicated in the legend.

Figure 1 shows the calculated variation of H_e with T and H_e^{int} for a system with a grain diameter of 6 nm, and an anisotropy constant $K_{\text{AF}}=3\times10^6$ erg/cm^3 with a log-normal distribution with standard deviation $\sigma=0.3$. The AF layer has a Néel temperature of $T_N=500$ K. The results are in good qualitative agreement with experiment, with reasonable values for the blocking temperature T_B. It is interesting to note that the value of T_B is predicted to decrease with the exchange coupling between the layers as represented by H_e^{int}. This point will be discussed further later, but first we consider the effect of the temperature dependence of K_{AF}.

Figure 2 shows the calculations for the same physical parameters as 1 with the exception that K_{AF} remains constant (temperature independent). In order to highlight the effect of the temperature variation of K_{AF}, Fig. 2 shows the exchange field normalized to the zero temperature value for each value of H_e^{int}. It can be seen that the form of $H_e(T)$ assuming constant K_{AF} is asymmetric for small H_e^{int}, which is not the case for the data of Fig. 1, which are calculated taking into account the temperature variation of K_{AF}.

The temperature variation of H_e involves the switching of the direction of the AF spins from the negative to the positive direction. For a constant K_{AF}, the AF spins are not switched (for low values of H_e^{int}) even at temperatures as high as 400 K. However, the temperature variation of K_{AF} lowers the energy barrier sufficiently to allow switching at

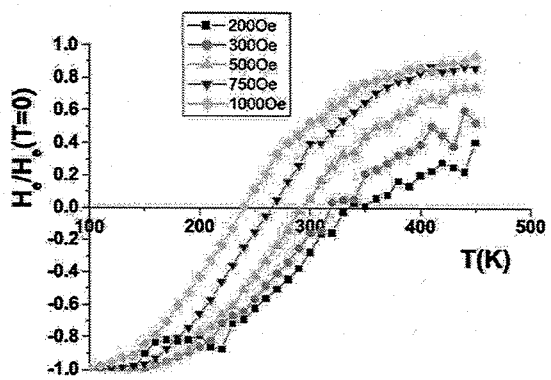

FIG. 2. (Color online) Variation of H_e with T for a system with a grain diameter of 6 nm and constant (temperature independent) K_{AF}. Calculations are given for various values of H_e^{int} as indicated in the legend.

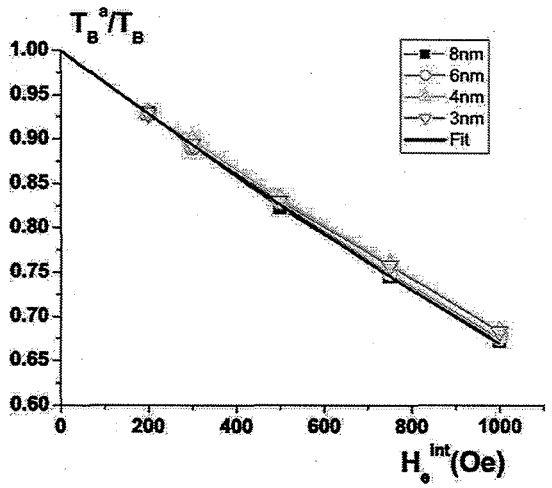

FIG. 3. (Color online) The variation of the apparent blocking temperature T_B^a (normalized to the intrinsic blocking temperature T_B) with H_e^{int} for various particle diameters as given in the legend. K_{AF} is taken as monodisperse.

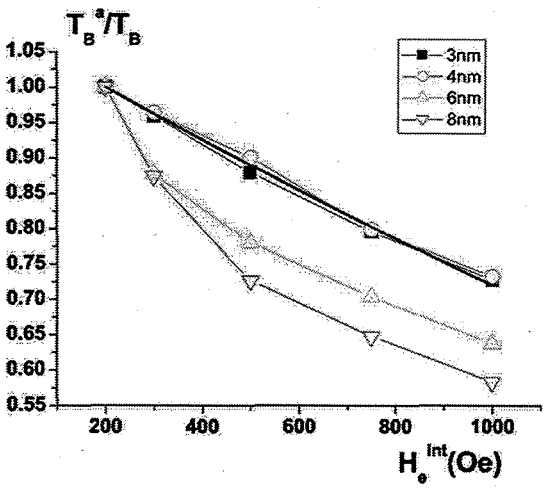

FIG. 4. (Color online) The variation of the apparent blocking temperature T_B^a (normalized to the intrinsic blocking temperature T_B) with H_e^{int} for various particle diameters as given in the legend. K_{AF} has a standard deviation of $\sigma=0.5$.

high temperatures, contributing to the complete reversal of the exchange field observed experimentally.[1] We note also that extremely large values of H_e^{int} also lower the energy barrier sufficiently to allow complete reversal.

We now return to the dependence of the blocking temperature on H_e^{int}. This dependence suggests that the temperature at which $H_e(T)=0$ does not define the intrinsic blocking temperature $T_B=25kT=K_{\text{AF}}$. This is because the energy barrier of the AF grains is dependent on the exchange field from the F layer. This we define the temperature at which $H_e(T)=0$ as the "apparent" blocking temperature, which we now investigate with a simple semianalytical model. On raising the temperature to the activation temperature T_M, the critical energy barrier becomes $E_c^m(h_{\text{eff}})=25kT_B/(1-h_{\text{eff}})$. At T_M, all AF spins with energy barriers $<E_c^m(h_{\text{eff}})$ are switched into the positive direction, as a result of which it is straightforward to show that

$$H_e(T)=H_e(T=0)\left(2\int_0^{E_c^m(h_{\text{eff}})} f(E_B)dE_B-1\right), \tag{6}$$

where $f(E_B)$ is the energy barrier distribution function. The blocking temperature is defined as the temperature at which $H_e(T)=0$, from which by definition $E_c^m(h_{\text{eff}})=E_m$, where E_m is the median energy barrier. Consequently, $E_m=25kT_B/(1-h_{\text{eff}})^2$, from which the apparent value of blocking temperature is

$$T_B^a=T_B(1-h_{\text{eff}})^2, \tag{7}$$

and the apparent blocking temperature decreases with H_e^{int}, as shown by the numerical calculations.

Figure 3 shows the variation of T_B^a (normalized to T_B) with H_e^{int} for various particle diameters. K_{AF} is taken as monodisperse since as will be shown shortly the simple model fails for wide energy barrier dispersions. According to Eq. (7), T_B^a/T_B should simply scale with $(1-h_{\text{eff}})^2$, independent of the grain diameter. The superposition of the grain size data in Fig. 3 confirms this prediction. In Fig. 3, we also give a fit to Eq. (7). The fit is reasonable using a value of $H_K^{\text{eff}}=5.5$ kOe. This is rather smaller than the actual value of $H_K^{\text{eff}}=7.5$ kOe, which is probably due to the in-plane randomly oriented easy axis distribution in the computational results as opposed to the assumption of aligned easy axes of the analytical model.

Finally, Fig. 4 shows the variation of the numerically calculated apparent blocking temperature T_B^a (normalized to the intrinsic blocking temperature T_B) with H_e^{int} for various particle diameters. In this case, K_{AF} has a standard deviation of $\sigma=0.5$. Clearly, as the grain size increases, the superposition of the grain size data fails for the numerical model, in contrast to the case shown in Fig. 3. The reason for this is not yet understood and is the subject of further investigation.

IV. SUMMARY

We have used a model of an exchange coupled F/AF bilayer to investigate the variation of exchange field with temperature. The model gives good agreement with experiment and reasonable blocking temperatures T_B for the assumed K_{AF} value of 3×10^6 erg/cm^3. It is predicted that the apparent value of T_B depends on the strength of the intrinsic interlayer exchange coupling due to the reduction of energy barriers. However, the measured values of T_B will be only weakly affected for normal values of exchange coupling strength.

[1]L. E. Fernández Outón and K. O'Grady, J. Appl. Phys. **95**, 6852 (2004).
[2]D. Choo, R. W. Chantrell, R. Lamberton, A. Johnston, and K. O'Grady, J. Appl. Phys. **101**, 09E521 (2007).
[3]T. R. Gao, D. Z. Yang, S. M. Zhou, R. Chantrell, P. Asselin, J. Du, and X. S. Wu, Phys. Rev. Lett. **99**, 057201 (2007).
[4]R. W. Chantrell, N. S. Walmsley, J. Gore, and M. Maylin, Phys. Rev. B **63**, 024410 (2000).
[5]L. Néel, Ann. Geophys. **5**, 99 (1949).
[6]H. Pfeiffer, Phys. Status Solidi A **118**, 295 (1990).
[7]E. Fulcomer and S. H. Charap, J. Appl. Phys. **43**, 4190 (1972).