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Thermally assisted reversal of exchange biasing in NiO and FeMn based systems

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The stability of the exchange bias field H_{eb} has been studied for magnetron sputtered NiO/$Ni_{66}Co_{18}Fe_{16}$ and $Ni_{66}Co_{18}Fe_{16}$/FeMn bilayers. A forced antiparallel alignment of the ferromagnetic magnetization to H_{eb} results in a gradual decrease of H_{eb} as a function of time for NiO as well as FeMn based samples. The observed decrease of H_{eb} increases with temperature and is interpreted as a thermally assisted reversal of magnetic domains in the antiferromagnetic layer. © *1998 American Institute of Physics.* [S0003-6951(98)02204-9]

Direct exchange coupling at the interface between a ferromagnetic (F) layer and an antiferromagnetic (AF) layer may result in exchange biasing,[1] i.e., in a shift of the hysteresis loop of the F layer along the field axis characterized by an exchange bias field H_{eb}. Exchange biasing is used in device structures for magnetic domain stabilization in magnetoresistive sensors[2] as well as for pinning an F layer in magnetoresistive spin valves[3].

For device applications the long term stability of H_{eb} is an important issue. The effect of temperature on the magnitude of exchange biasing has been studied extensively. Generally H_{eb} decreases with temperature and becomes zero at a temperature called the blocking temperature, T_B.[4,5] However, studies of time effects, i.e., the stability of H_{eb} at a given (operating) temperature and magnetic field have not been reported. Recent calculations have shown that, due to demagnetization effects, the magnetization direction of the pinned F layer of a microstructured GMR spin valve is tilted at the edges.[6] These spin valves are operating at elevated temperatures (approximately 100 °C) due to heating by the sense current. Therefore, the stability of the exchange biasing under these conditions is an important issue with respect to long term stability of GMR read heads.

In this letter, we will report on the stability of H_{eb} at constant temperature for an anti-parallel alignment of the magnetization of the F layer with respect to the direction of H_{eb} using NiO and FeMn AF layers, which are frequently used in biasing structures. We will show that a gradual but sizable reduction and even a reversal of H_{eb} may result. The results can be understood by a macroscopic two-level model in which the anisotropy of the AF layer and the grain size distribution play an important role.

Samples with structure Si (100)/60 nm NiO/5 nm $Ni_{66}Co_{18}Fe_{16}$/5 nm Ta and (borosilicate) glass/3 nm Ta/5 nm $Ni_{66}Co_{18}Fe_{16}$/10 nm FeMn/5 nm Ta were grown at room temperature in an applied field of 10–15 kA/m by a multisource sputter apparatus. The metallic layers were deposited by dc magnetron sputtering at a pressure of 5 mTorr Ar and the NiO layers were deposited by rf magnetron sputtering from a NiO target in an Ar pressure of 1 mTorr. After deposition, the NiO based samples were annealed up to 500 K after which the samples were field cooled down to room temperature in about 10 h in order to improve the exchange biasing.

A variable temperature magneto-optical Kerr effect apparatus was used for magnetic characterization of the samples. H_{eb} was determined as a function of time in the situation of a forced antiparallel alignment of the magnetization of the F layer and H_{eb}. To this end the sample is heated from room temperature to the desired temperature with an external field applied parallel to H_{eb}. Subsequently, the applied field of about 45 kA/m and thereby the magnetization direction of the F layer is reversed and H_{eb} is measured as a function of time at constant temperature. Note that H_{eb} is obtained from an hysteresis loop measurement during which the applied field (and the magnetization direction of the F layer) is varied. This implies that relaxation contributions to H_{eb} faster than half the hysteresis loop measurement time of 12 s cannot be observed.

The temperature dependence of the initial H_{eb} is shown in Fig. 1 for the samples with 60 nm NiO and 10 nm FeMn,

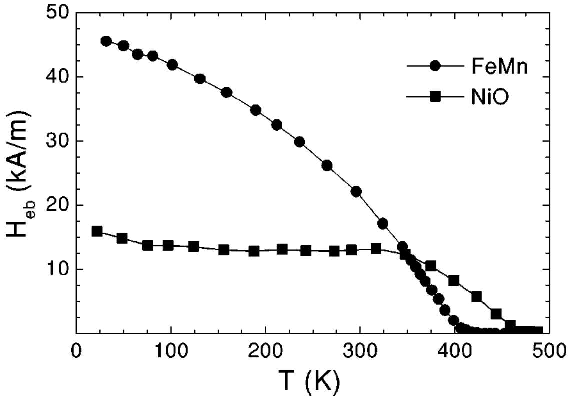

FIG. 1. The temperature dependence of the exchange bias field H_{eb} for Si (100)/60 nm NiO/5 nm $Ni_{66}Co_{18}Fe_{16}$/5 nm Ta (squares) and glass/3 nm Ta/5 nm $Ni_{66}Co_{18}Fe_{16}$/10 nm FeMn/5 nm Ta (circles).

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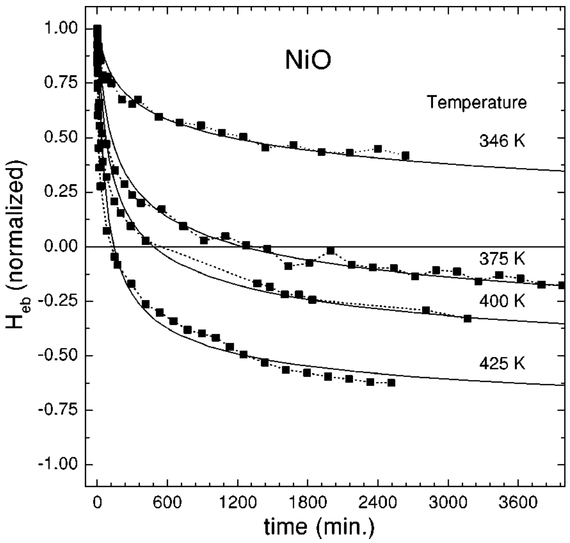

FIG. 2. The time dependence of the exchange bias field H_{eb} during a forced antiparallel alignment of the magnetization direction of the F layer and H_{eb} at several temperatures for Si (100)/60 nm NiO/5 nm $Ni_{66}Co_{18}Fe_{16}$/5 nm Ta. The solid lines represent the fit of the data at different temperatures as described in the text.

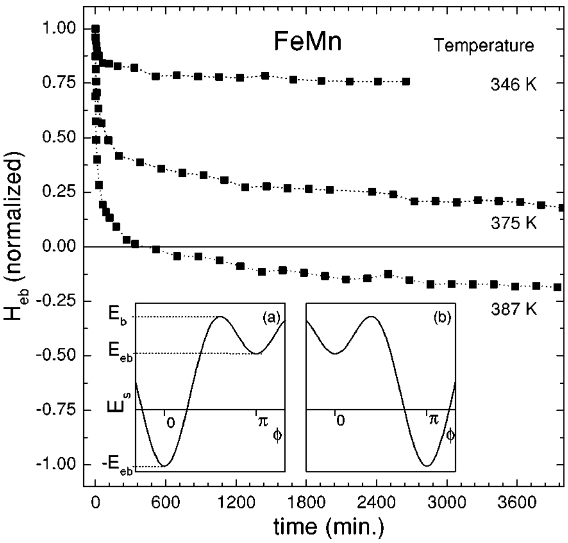

FIG. 3. The exchange bias field H_{eb} as function of time during a forced antiparallel alignment of the magnetization direction of the F layer and H_{eb} at several temperatures for glass/3 nm Ta/5 nm $Ni_{66}Co_{18}Fe_{16}$/10 nm FeMn/5 nm Ta. The insets show a schematic representation of the angular (ϕ) dependence of the energy per unit area, E_s of an AF layer with uniaxial anisotropy and exchange coupled to a F layer with the magnetization directed along 0 (a) and π (b).

which is obtained by measuring hysteresis loops at increasing temperatures after cooling the sample from room temperature to 20 K in about 2 h with an external field applied parallel to H_{eb}. The figure shows that H_{eb} becomes zero at T_B of 480 K and 425 K for the NiO and FeMn based samples, respectively. The observed temperature dependence of H_{eb} is similar to that reported by others.[4,5]

Figure 2 shows the normalized exchange bias fields as function of time, t, for several temperatures during a forced antiparallel alignment of the magnetization of the F layer and H_{eb} for a NiO based sample. The exchange bias fields are normalized to the initial value of H_{eb} at $t = 0$ shown in Fig. 1. Figure 2 shows that at 400 K (well below T_B) H_{eb} becomes zero after 8 h and then H_{eb} changes sign and becomes negative. This decrease of H_{eb} increases with temperature. The solid lines shown in Fig. 2 represent fits which are discussed later.

Further experiments[7] using a 40 nm instead of a 60 nm NiO layer show an identical decrease of H_{eb} as a function of time for several temperatures. The decrease of H_{eb} is a reversible magnetic process, i.e., reversing the external applied field and thereby the magnetization direction of the F layer during an experiment, thus restoring the original biasing configuration, resulting in an increase of H_{eb}. Experiments using different magnitudes of the applied field show that the decrease of H_{eb} is only observed if the applied field is sufficiently large to reverse the magnetization of the F layer, but is independent of the magnitude of the applied field once the magnetization is reversed. This implies that the observed decrease of H_{eb} is only induced by the forced reversal of the F layer magnetization due to the resulting frustration of the exchange coupling at the F/AF interface and is independent of the influence of the (small) external applied field on the AF layer.

Figure 3 shows that the decrease of H_{eb} as a function of time is also observed for a FeMn based sample. For temperatures close to T_B, the observed decrease of H_{eb} is similar to that of the NiO based samples, but at lower temperatures the decrease of H_{eb} compared to that of NiO based samples is somewhat less pronounced.

The decrease of H_{eb} as a function of time can be understood by a macroscopic two-level relaxation model. Modeling the F and AF layers as magnetic monodomains and assuming an exchange coupled F/AF bilayer with uniaxial positive anisotropies, K_F and K_{AF} for the F and AF layer, respectively, and their easy axes parallel to an external applied field, the energy per unit area is given by

$$E = K_F t_F \sin^2 \theta + K_{AF} t_{AF} \sin^2 \phi - H \mu_0 M_s t_F \cos \theta + E_{eb} \cos(\theta - \phi), \tag{1}$$

in which t_F and t_{AF} are the thicknesses of the F and AF layer, respectively. The exchange bias coupling energy per unit area is given by E_{eb}. The angle between a positive applied field and the (sublattice) magnetizations of the F layer and AF layer (M_s and M_{sa}, respectively) is given by θ and ϕ, respectively. Since the field is applied along the easy magnetization axes, θ is assumed to be either 0 or π. If $K_{AF} t_{AF} > E_{eb}/2$, then an energy barrier appears in the dependence of the energy as function of the sublattice (staggered) magnetization direction of the AF layer [see the insets of Fig. 3 for $\theta = 0$ (a) and $\theta = \pi$ (b)]. The inset (a) of Fig. 3 refers to $t < 0$ for which ϕ is assumed to be 0 (the absolute energy minimum) and exchange biasing is observed if the staggered magnetization direction of the AF layer remains fixed during an hysteresis loop measurement. Reversing M_s at $t = 0$ results in a change of the angular dependence of the AF energy from inset (a) to (b). The energy state of the AF layer can relax towards a lower energy minimum by reversing M_{sa} (from $\phi = 0$ to π), which results in a reversal of the exchange bias field.

This simplified model, assuming a single monodomain in the AF layer would result in an abrupt reversal of H_{eb}

instead of the experimentally observed gradual decrease of H_{eb}. In reality, however, the AF layer has to be modeled as an ensemble of noninteracting AF domains as described by Fulcomer and Charap.[8] At $t=0$, the M_{sa} directions of the AF-domains are assumed to be distributed over $\phi=0$ and π according to the Boltzmann distribution function. The reversal of M_s at $t=0$ results in a gradual change of the distribution in M_{sa} direction towards the new equilibrium distribution (the distribution at $t=0$ inverted) by a thermally assisted relaxation process. The time dependence of H_{eb} is given by:[8] $\exp(-t/\tau)$ with $1/\tau=\nu_0\{\exp[-(E_b-E_{eb})A/k_BT] +\exp[-(E_b+E_{eb})A/k_BT]\}$ in which ν_0 is the characteristic frequency for magnetic domain reversal, A is the area of the AF domain, and E_b is the barrier energy per unit area given by $E_b=K_{AF}t_{AF}[1+(E_{eb}/2K_{AF}t_{AF})^2]$ in the model described by Eq. (1). Analyses of the experimentally observed time dependence of H_{eb} clearly shows that it cannot be described by one single exponential function. This indicates that we are dealing with an ensemble of nonidentical AF domains with a resulting distribution of τ.

The τ distribution can result from a distribution in A, e.g., by a grain size distribution in the AF layer and assuming that an AF-domain coincides with an AF grain.[9] Transmission electron and scanning electron microscopy experiments on the NiO layer show a columnar growth with a distribution in grain sizes. Assuming a log normal grain size distribution,[10] the distribution in the diameter, d, of the grains is given by: $(1/\sqrt{2\pi}\sigma)\times\exp[-\ln^2(d/d_{mean})/2\sigma^2]$, in which σ and d_{mean} are 0.57 and 5 nm, respectively, as estimated from scanning electron microscope (SEM) images. The resulting fits are shown in Fig. 2 by the solid lines. In these fits the initial distribution of M_{sa} over $\phi=0$ and π is assumed to be grain size independent, and E_{eb} is calculated using the data of Fig. 1. To fit the data at different temperatures, a temperature independent value for ν_0 of 0.025 min^{-1} and decreasing values for E_b (via K_{AF}) with temperature are used. This implies that the increase in relaxation rate with temperature as observed in Fig. 2 is not only due to the increase of thermal energy but also due to the decrease of K_{AF}. The fit values obtained for K_{AF} are 11.7, 6.5, 5.2, and 3.4 kJ/m^3 at 346, 375, 400, and 425 K, respectively. These values are rather low compared to the bulk values for K_1, which decrease from 500 to 380 kJ/m^3 for increasing temperatures of 0–430 K.[11] Theoretically, K_{AF} is proportional to the square of the staggered magnetization.[11] A possible explanation for the low fit values of K_{AF} may be found in the fact that the staggered magnetization of the NiO layer is reduced due to finite size effects. This would give rise to a reduced value for K_{AF} and also a distribution of K_{AF}, which is not taken into account in the fits. Note that in the modeling described above, the relaxation of H_{eb} is assumed to arise from a uniform magnetization rotation of an AF domain, while in more recent models of exchange biasing the formation of domain walls in the AF layer plays an important role.[12–14] However, the detailed nature of the exchange biasing mechanism is not important for the interpretation of the data in terms of a macroscopic two-level relaxation model.

We have shown that the forced reversal of the magnetization of the F layer in an exchange biased F/AF system can lead to a significant decrease of the exchange bias field, H_{eb}. In the case of a continuous misalignment this can even lead to a reversal of H_{eb} as monitored in the present study for a $Ni_{66}Co_{18}Fe_{16}$ F layer exchange coupled to a NiO AF layer. The observed decrease of H_{eb} can be interpreted as a thermally assisted reversal of the staggered magnetization directions of magnetic domains in the AF layer. A distribution of laterally decoupled AF domains is needed to describe the decrease of H_{eb} as a function of time. These results suggest that a nonparallel alignment of the magnetization of the pinned F layer and H_{eb} has important consequences for the stability of H_{eb} and should be considered when selecting antiferromagnetic biasing materials for GMR read heads.

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