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Influences on relaxation of exchange biasing in $\text{NiO}/\text{Ni}_{66}\text{Co}_{18}\text{Fe}_{16}$ bilayers

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Influences on relaxation of exchange biasing in NiO/Ni₆₆Co₁₈Fe₁₆ bilayers

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The stability of the exchange biasing field, H_{eb} has been studied for NiO/Ni₆₆Co₁₈Fe₁₆ bilayers. A forced antiparallel alignment of the ferromagnetic magnetization to H_{eb} results in a gradual decrease and even a reversal of H_{eb} . The decrease of H_{eb} increases with temperature and is independent of the external field and NiO layer thickness. This decrease can be interpreted by a thermally assisted relaxation process. A new effect of the relaxation process on H_{eb} is demonstrated by using different cooling rates. © 1998 American Institute of Physics. [S0021-8979(98)18111-2]

I. INTRODUCTION

Direct exchange coupling at the interface between a ferromagnetic (F) layer and an antiferromagnetic (AF) layer may result in exchange biasing,¹ which induces a unidirectional anisotropy of the F layer. The unidirectional anisotropy gives rise to a shift of the hysteresis loop of the F layer along the field axis, which is equal to the exchange biasing field, H_{eb} . The magnitude of H_{eb} depends on temperature and becomes zero at a temperature called the blocking temperature, T_B . It is known that directing the external field (and thereby the magnetization of the F layer) antiparallel to H_{eb} while cooling at temperatures below T_B results in a decrease of H_{eb} .^{2,3}

Recently, we have shown that an antiparallel alignment of the magnetization of the F layer to H_{eb} at a constant temperature results in a gradual decrease and even a reversal of H_{eb} .⁴ The observed behavior of H_{eb} is interpreted by a macroscopic two-level model. The two-level model can result from an AF layer consisting of AF domains with uniaxial anisotropy, which are laterally decoupled and exchange-coupled to the F layer following Fulcomer and Charap.⁵ This results in an absolute and a local energy minimum for the sublattice (staggered) magnetization direction of an AF domain, see insets of Fig. 1. After cooling the sample in an applied magnetic field from above T_B to a certain temperature below T_B , the staggered magnetization directions of the AF domains are assumed to be distributed over the two energy minima according to the Boltzmann distribution function. This situation (at $t=0$) gives rise to the observed ex-

change biasing field and is shown in the inset (a) of Fig. 1. The forced antiparallel alignment of H_{eb} and the magnetization of the F layer after $t=0$ results in an interchange of the two energy minima. Subsequently, a thermally assisted redistribution of the now nonequilibrium distribution of the staggered magnetization directions of the AF domains occurs [see inset (b) of Fig. 1] and, therefore, a relaxation of H_{eb} . Among others, the relaxation time of an AF monodomain

FIG. 1. The time dependence of H_{eb} at 425 K for Si(100)/40 nm NiO/5 nm Ni₆₆Co₁₈Fe₁₆/5 nm Ta. At $t=0$ the external field is reversed, forcing an antiparallel alignment of the magnetization of the F layer and H_{eb} (circles). After 42 h (2520 min.), the direction of the external field and thereby the magnetization of the F layer is reversed again (squares). The line after $t=2520$ min. represents the inverted data for H_{eb} after $t=0$. The insets show a schematic representation of dependence of the energy per unit area, E_s , on the angle ϕ of the staggered magnetization of an AF domain with uniaxial anisotropy, which is exchange coupled to a F layer with the magnetization directed along $\theta=0$ (a) and π (b). The circles represent the distribution over the two minima at thermal equilibrium, $t=0$ (a) and just after the reversal of the magnetization of the F layer (b).

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increases with thickness, which is assumed to be correlated to the grain size.

Here, we report to which extent the Fulcomer–Charap model provides an at least qualitative description of the observed decrease of H_{eb} after reversing the applied field (and thereby the magnetization direction of the F layer) at $t=0$. The implications of the model for the observed $H_{eb}(t)$ are demonstrated by experiments using different cooling rates from above T_B to room temperature.

II. EXPERIMENTAL DETAILS

Samples consisting of Si(100)/40 or 60 nm NiO/5 nm $\text{Ni}_{66}\text{Co}_{18}\text{Fe}_{16}$ /5 nm Ta were grown at room temperature in an applied field of 10–15 kA/m by a multisource sputter apparatus. Pressure prior to deposition was typically 10^{-8} Torr. 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 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.

The experiments were carried out using a variable temperature Magneto-Optical Kerr Effect (MOKE) apparatus. The sample was heated from room temperature to the desired temperature in an external field, which was applied parallel to H_{eb} . Subsequently, H_{eb} was measured as a function of time at a constant temperature and external field. Note, that H_{eb} was obtained from a hysteresis loop measurement during which the direction of the applied field (and the magnetization of the F layer) was varied. This implies that relaxation contributions to H_{eb} faster than half the hysteresis loop time of 12 s cannot be observed.

III. RESULTS AND DISCUSSION

The blocking temperature for the NiO/ $\text{Ni}_{66}\text{Co}_{18}\text{Fe}_{16}$ bilayers is 480 K, as determined from the temperature dependence of H_{eb} ,⁴ which is similar to the results obtained by others.³ Figure 1 shows H_{eb} as function of time at 425 K for Si(100)/40 nm NiO/5 nm $\text{Ni}_{66}\text{Co}_{18}\text{Fe}_{16}$ /5 nm Ta. At $t=0$ an external field is applied, which forces an antiparallel alignment of the magnetization of the F layer and H_{eb} . A gradual decrease of H_{eb} is observed resulting in zero exchange biasing within 2 h after which H_{eb} changes sign and becomes negative. After 42 h the external field and thereby the magnetization direction of the F layer is reversed, which results in an increase of H_{eb} . The increase of H_{eb} as a function of time is identical to the inverted behavior of H_{eb} observed after $t=0$. The reversibility of the time dependence of H_{eb} upon the reversal of the external applied field (and thereby the magnetization direction of the F layer) implies a magnetic origin and not some structural cause for the change in H_{eb} .

Within the Fulcomer–Charap model the relaxation of H_{eb} arises from the redistribution of the staggered magnetization directions of the AF domains due to the exchange coupling between the AF domains and the F layer. However, the magnetization directions of the AF domains may also be

FIG. 2. The time dependence of H_{eb} at 425 K for Si(100)/40 nm NiO/5 nm $\text{Ni}_{66}\text{Co}_{18}\text{Fe}_{16}$ /5 nm Ta applying different magnitudes of the external field antiparallel to H_{eb} . The magnetization of the F layer is directed parallel to H_{eb} for an external field of -6 kA/m (up triangles) and antiparallel to H_{eb} for external fields of -45 kA/m (squares) and -125 kA/m (circles). The inset shows the hysteresis loop measurement at $t=0$.

influenced by an external applied field, e.g., if an AF domain possess a small magnetic moment due to finite size effects^{6,7} and the exchange coupling energy at the AF and F interface is smaller than the Zeeman coupling energy of the AF domain.⁸ Figure 2 shows the time dependence of H_{eb} for different magnitudes of the external field applied antiparallel to H_{eb} . The figure shows that a decrease of H_{eb} is only observed if the magnetization direction of the F layer is antiparallel to H_{eb} , but is independent of the magnitude of the (small) external field.

Figure 3 shows the normalized exchange biasing fields as a function of time during an antiparallel alignment of H_{eb} and the magnetization of the F layer at different temperatures for samples consisting of a 40 to 60 nm NiO layer. The exchange biasing fields are normalized to the initial value at $t=0$. The gradual decrease of H_{eb} increases with temperature, which is discussed elsewhere.⁴ Apart from the curves at 375 K, the decrease of H_{eb} is independent of the AF-layer thickness, which is inconsistent with the assumption that the AF grains are monodomain throughout the entire AF-layer

FIG. 3. The exchange biasing field, H_{eb} as function of time at different temperatures during a forced antiparallel alignment of the magnetization of the F layer and H_{eb} . The squares and circles represent the data of samples consisting 40 and 60 nm NiO/5 nm $\text{Ni}_{66}\text{Co}_{18}\text{Fe}_{16}$ /5 nm Ta grown on Si(100), respectively. The values of H_{eb} are normalized to the initial value $t=0$.

FIG. 4. The figure shows H_{eb} as function of time at 290 K after field cooling from 550 K down to 290 K in 2 min for Si(100)/40 nm NiO/5 nm $\text{Ni}_{66}\text{Co}_{18}\text{Fe}_{16}$ /5 nm Ta. Subsequently, the sample is heated up to 432 K in 20 min after which again the time dependence of H_{eb} is measured. During these experiments the magnetization of the F layer is directed parallel to H_{eb} . Note the break in the time axis.

thickness. In that case the relaxation rate of H_{eb} would be expected to reduce with increasing AF-layer thickness for columnar grown AF layers. Columnar growth has been observed for these NiO layers by transmission electron microscopy experiments.

Interestingly, the distribution of the AF domains over the two energy minima is not only influenced by the magnetization direction of the F layer, but also by a change in temperature. Decreasing the temperature results in a new equilibrium distribution, which will only be attained if the relaxation rate is faster than the cooling rate. This implies that the magnitude of H_{eb} is not only influenced by the direction of the magnetization of the F layer during cooling below T_B , which is already demonstrated by others,^{2,3} but also by the cooling rate. The effect of varying the cooling rate has been investigated by field cooling from above T_B to 290 K in 2 min instead of our standard 10 h. This results in a decreased H_{eb} of 9 kA/m, at $t=0$, instead of 12 kA/m. Figure 4 shows the subsequent variation of H_{eb} as a function of time for a *parallel* alignment of the magnetization of the F layer and H_{eb} after cooling in 2 min. The time dependence of H_{eb} at 290 K shows a constant value for H_{eb} indicating that the thermal energy is too small to relax the nonequilibrium distribution of the AF domains. However, after increasing the temperature to 432 K in 20 min, a relaxation of H_{eb} is observed from 2.7 kA/m to about 4.8 kA/m (see Fig. 4). Subsequent slow cooling to 290 K in about 7 h results in an increased value for H_{eb} of 13 kA/m.

IV. CONCLUSIONS

We have shown that the gradual decrease of H_{eb} during a forced antiparallel alignment of the magnetization of the F

layer to H_{eb} results from the exchange coupling at the F and AF interface and is independent of the (small) external field. The decrease of H_{eb} as a function of time increases with temperature indicating a thermally assisted relaxation process. These three observations are consistent with the model proposed by Fulcomer and Charap in which the decrease of H_{eb} is described by a thermally assisted relaxation process of AF domains, which are mutually decoupled and exchange-coupled to the F layer. However, the similar behavior of H_{eb} for the 40 and 60 nm NiO layers is inconsistent with the assumption that the AF grains are monodomain. This suggests that the mechanism of exchange biasing is more complex than described by the Fulcomer–Charap model, e.g., by the formation of AF domain walls in the AF grains as proposed by more recent models.^{9–11} We note, however, that the detailed nature of the exchange biasing mechanism is not important for the general assumptions on which the macroscopic two-level relaxation model is based.

An new effect of the relaxation process is demonstrated by field cooling from above T_B to 290 K in 2 min instead of 10 h, which results in a decrease of H_{eb} from 12 to 9 kA/m. This effect does not only support the relaxation model, but also shows the importance of using a sufficiently low cooling rate to obtain exchange biasing in spin valve devices when using a magnetic anneal treatment.

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