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Exchange bias in FeF_2–Co/Pt heterosystems with perpendicular anisotropy

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Abstract

The exchange bias effect is measured in heterosystems with perpendicular anisotropy consisting of Co/Pt multilayers on top of the (0 0 1) face of a FeF_2 single crystal. The resulting exchange field H_E exhibits a strong dependence on temperature and the axial freezing field, H_F. Within the framework of an Ising-type model, the H_E vs. T as well as the H_E vs. H_F data are explained in terms of the microscopic spin structure at the interface. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Exchange biasing; Perpendicular anisotropy; Ising model; Antiferromagnetism

Based on recent progress in the technology of e.g. magnetic field sensors and spin valves [1], there is a renewed interest in the exchange bias effect in layered ferromagnetic (FM)/antiferromagnetic (AF) heterosystems. One of the favored model systems consists of single crystals or textured films of FeF_2 which are covered with metallic FM films [2–4]. After field-cooling to below the Néel temperature of FeF_2, $T_N = 78$ K, the exchange bias effect shifts the hysteresis loop of the FM film by an amount H_E towards the field direction which points opposite to the applied freezing field, H_F. In the case of antiferromagnetic exchange coupling between the FM and AF interface layer, the sign of H_E can change with increasing H_F if the Zeeman energy of the AF interface overcomes the coupling energy. Such competition effects are well known from compensated FeF_2(1 1 0)–Fe bilayers [4]. Recently, we observed a similar decrease of $|H_E|$ with increasing freezing field in the case of uncompensated FeF_2(0 0 1) surfaces covered with FM Co/Pt-multilayers [5]. They are deposited at $T = 500$ K under UHV conditions by thermal (Co) and electron beam evaporation (Pt) onto the (0 0 1) surface of the FeF_2 crystal which has been polished to optical flatness with 2.5 μm diamond paste before transferring the single crystal into the UHV chamber. Such systems exhibit strong uniaxial perpendicular magnetic anisotropy. Hence, freezing fields are applied along the easy axis which points perpendicular to the plane of the Co/Pt-multilayer. In accordance with the drastic reduction of the degrees of freedom of the spin variables, less complex spin structures are involved in the formation of the FM/AF interface in comparison with the planar anisotropic case. Hence, uniaxial heterosystems are useful candidates for simple Ising-type model considerations, although the observed exchange bias fields of $|\mu_0 H_E| < 9$ mT are surprisingly small.

Fig. 1b shows a hysteresis loop of FeF_2(0 0 1)/Pt15 Å (Co3.5 Å/Pt12 Å)$_5$/Pt8 Å measured by SQUID magnetometry after cooling the heterosystem in an axial magnetic field $\mu_0 H_F = 0.1$ T from $T = 150$ to 10 K. In order to eliminate all background influences, the exchange bias is safely determined by subtracting the ascending and descending branches of the loops. Fig. 1c shows the result of the subtraction procedure (circles) together with a best Lorentzian fit (solid line). Thus, the exchange bias field H_E is determined with high accuracy from the small shift of the fitting curve with respect to $H_F = 0$.

Fig. 1a shows the freezing field dependence of H_E measured at $T = 10$ K. In addition, Fig. 2 exhibits the temperature dependence of H_E. The underlying hysteresis

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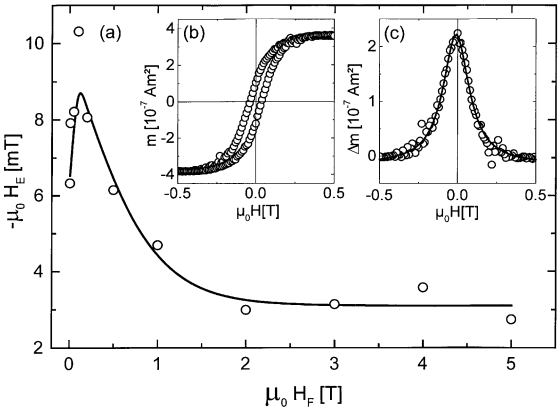

Fig. 1. (a) Experimental data (circles) of the exchange bias H_E obtained from hysteresis loops m vs. $\mu_0 H$ at $T = 10$ K for various freezing fields H_F and the corresponding best fit of Eq. (1) (solid line). Inset (b) shows the hysteresis loop m vs. $\mu_0 H$ after field cooling at $\mu_0 H = 0.1$ T from $T = 150$ to 10 K. Inset (c) shows the subtraction of the ascending from the descending branch of the m vs. $\mu_0 H$ loop (circles) and the corresponding best Lorentzian fit (solid line).

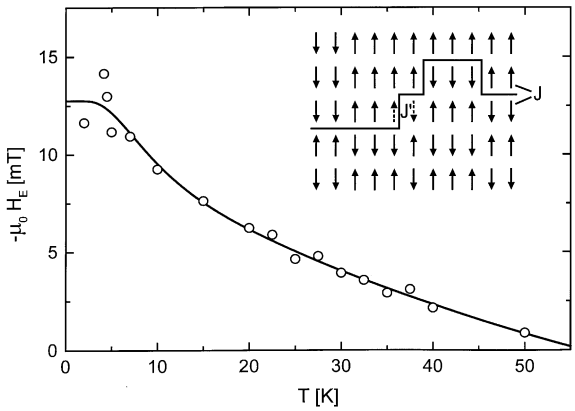

Fig. 2. Experimental data (circles) of the exchange bias H_E for various temperatures T and the corresponding best fit of Eq.(1) extended by the molecular field term H_m (solid line), which enters the magnetic moments $m^{\pm}$ (see text). Inset shows a schematic spin structure of the FM/AF interface (line) with two exchange interactions J and J' (see text). Arrows indicate the magnetic moments of the FM and AF system, respectively.

loops are obtained from measurements at temperatures $2\,\mathrm{K} \leqslant T \leqslant 50\,\mathrm{K}$ after cooling the system in the axial freezing field $\mu_0 H_F = 0.1$ T, which maximizes the exchange bias effect (Fig. 1a). Both H_E vs. H_F and H_E vs. T are described by a simple Ising-type model. It takes into account the microscopic spin structure at the interface, which is established on cooling to below T_N. Once the spin structure at the interface is stabilized, the underlying antiferromagnet develops its domain structure from the interface into the bulk of the structure. This mechanism makes sure that an uncompensated AF interface with structural roughness is able to generate a net magnetic moment. The frozen magnetic moment M_{AF} and the field-induced moment M_F of the AF and FM interface layer determine the exchange field according to [6]

$$H_E \propto J M_{AF} M_F. \tag{1}$$

In our simple model, we determine M_{AF} from a thermodynamic analysis, while M_F is completely determined by the applied field. The non-thermal behavior of M_F reflects the high value of the critical temperature $T_C \approx 600$ K of the Co/Pt multilayer in comparison with the Néel temperature of FeF_2. The thermodynamic analysis of the AF interface is based on the energy function $E = -JS_F S_{AF} - g\mu_B \mu_0 H S_{AF}$, where J is the exchange interaction between spins of the AF interface spin and its fixed FM counterpart. The Zeeman energy of the AF spins competes with the exchange interaction in the case $J < 0$. Finally, a second interaction J' is introduced. It is assumed [5] to rigidly couple edge spins of the AF interface with ferromagnetic spins, which occupy neighboring places of the same atomic layer. Within the framework of these model assumptions the exchange field reads [5]

$$H_E \propto (2n_F^{+} - n_0)\left[n_F^{+}(1-\alpha)\Delta m + (1-\alpha)m^{-} + \frac{J'}{|J'|}\alpha(2n_F^{+} - n_0) \right], \tag{2}$$

where $n_F^{\pm}(H)$ describes the field induced number of up-spins in the ferromagnetic interface. $n_F^{\pm}(H)$ is assumed to be a linear function of H for $|H| < H_S$ which saturates at n_0 for $H > H_S$. $m^{\pm} = g\mu_B \tanh((\pm J + g\mu_B\mu_0 H)/k_B T_N)$ describes the thermal average of an AF-interface moment which couples to an up (+) or down (−) pointing FM moment. Finally, the roughness parameter α is given by the ratio of the number of moments which are located at steps to the total number of interface moments (see inset Fig. 2). After insertion of Eq. (2) into Eq. (1), the resulting function is fitted to our experimental data (Fig. 1a). The following parameters emerge: $J/k_B T_N = -0.11$, $\mu_0 H_S = 0.08$ T, $\alpha = 0.64$ and $g\mu_B/k_B T_N = 1.15\,\mathrm{T}^{-1}$. As expected, the microscopic exchange parameter $J/k_B T_N$ is negative. Hence, AF coupling at the interface is favored. Note that the *Pt*-buffer of 15 Å thickness in FeF_2(0 0 1)/Pt15 Å(Co3.5 Å/Pt12 Å)$_5$/Pt8 Å reduces the strength of the interaction by 81% in comparison with FeF_2(0 0 1)/(Co3.5 Å/Pt12 Å)$_3$/Pt8 Å investigated recently [5].

Within a mean-field approach also the temperature dependence of H_E can be modeled. For that purpose, the field dependence of $m^{\pm} = g\mu_B \tanh((\pm J + g\mu_B\mu_0 H)/k_B T)$ is extended by a molecular field $H_m \propto |T - T_N|^{\beta}$, where

β has been fixed during the fitting process as $\beta = 0.325$, which is the 3d Ising critical exponent of the order parameter. It takes into account the interaction of the AF interface with the subsequent layers of the AF bulk. The molecular field stabilizes the spin structure of the AF interface and, hence, supports the exchange bias field. With increasing temperature H_m decreases which gives rise to a decrease of H_E. However, further investigations are necessary in order to obtain quantitative results.

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