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Extrinsic control of the exchange bias

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Abstract

A new control mechanism for the exchange bias effect in magnetic heterostructures is proposed. It takes advantage of the magnetoelectric effect which takes place in the antiferromagnetic pinning layer. In contrast with the pioneering AC measurements of the magnetoelectric effect, we investigate the magnetic response of the prototypical magnetoelectric compound Cr_2O_3 on static electric fields. The linear dependence of the magnetic moment on the applied axial electric field and the temperature dependence of the corresponding slopes $\alpha_{\parallel}$ are measured by DC SQUID magnetometry. The contribution of the field-induced surface magnetization and its impact on the exchange bias effect is estimated.

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Keywords: Magnetoelectric effect; Exchange bias; Thin films

It is now widely accepted that the antiferromagnetic (AF) interface magnetization S_{AF} plays a crucial role for the exchange bias effect in magnetic heterostructures. The temperature and field dependence of S_{AF} as well as its robustness against consecutive magnetization reversal of the ferromagnetic (FM) top layer are decisive for the understanding of the temperature and field dependence of the exchange bias field $\mu_0 H_e$ and its training. This becomes obvious already in the framework of the phenomenological Meiklejohn–Bean approach [1]. It predicts a linear dependence of $\mu_0 H_e$ on S_{AF} in the elementary case of infinite AF layer thickness t_{AF} and anisotropy K_{AF}, but becomes a more sophisticated $\mu_0 H_e$ vs. S_{AF} dependence in the case of finite t_{AF} and K_{AF} [2]. The simplest generalized expression which can be derived in the limit of strong anisotropy under the assumption that the magnetic freezing field is applied along the FM and AF easy axes reads

$$\mu_0 H_e = -\frac{J S_{AF} S_{FM}}{M_{FM} t_{FM}} + \frac{J^3 S_{AF}^3 S_{FM}^3}{8 K_{AF}^2 M_{FM} t_{FM} t_{AF}^2} \qquad (1)$$

where J, t_{FM}, M_{FM} and S_{FM} are the exchange coupling, the thickness, the saturation and interface magnetization of the FM top layer, respectively. In the typical experimental situation where the Curie-temperature of the FM layer is much larger than the Néel-temperature T_N of the pinning layer, basic thermodynamic considerations suggest, that the enigmatic microscopic details of the exchange bias phenomenon are related to S_{AF}, which establishes on cooling the heterostructure in an applied magnetic field to below T_N. From the experimental point of view it is, hence, a challenging task to control S_{AF} which, on the one hand, allows to tune $\mu_0 H_e$ and, on the other hand, allows to check theoretical predictions like, e.g., Eq. (1).

Variations of the freezing field [3] and the temperature are typical methods in order to modify S_{AF} during and after the freezing process, respectively. However, the origin of S_{AF} cannot unambiguously be clarified by such experiments. Recently, a random-field domain state model of the AF pinning layer has been proposed [4]. Alternatively, weak ferromagnetism which, e.g., is created by the piezomagnetic effect gives rise to a frozen moment $m_z^p = \lambda \sigma_{xy} l_z / |\underline{l}|$, which contributes to S_{AF} at $T < T_N$. Here, the AF order parameter $\underline{l}$ sets in and the degeneracy of the sublattice magnetization is lifted by shear stress σ_{xy}. The qualitative dependence of $\mu_0 H_e$ on

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σ_{xy} has recently been shown in the heterostructure $Fe_{0.6}Zn_{0.4}F_2(1\,1\,0)$/Fe/Ag [5].

The electric control of S_{AF} is the ultimate step in order to obtain easy access to a continuous control parameter of the exchange bias field. In order to estimate the realizability of an electric tunable exchange bias heterosystem on the basis of the magnetoelectric (ME) effect we investigate the magnetic response of Cr_2O_3 on static electric fields $|\underline{E}| \leqslant 170$ kV/m. They are applied along the (0 0 0 1)-axis which is defined by the corundum structure of the crystal. The E-fields correspond to applied voltages U across the sample of thickness $t = 1$ mm. The ME-effect of Cr_2O_3 is determined by $\underline{M} \propto \underline{Q}\,\underline{E}$, where $\underline{M}$ the induced magnetization and $\underline{Q}$ is the diagonal response tensor with $Q_{xx} = Q_{yy} \propto \alpha_\perp$ and $Q_{zz} \propto \alpha_\parallel$ in accordance with the symmetry given by the magnetic point group $\bar{3}\underline{m}$ [6].

Fig. 1 shows the electric field-induced axial magnetic moment m_z vs. U of Cr_2O_3 in zero applied magnetic field for temperatures $T = 50$ (down triangles), 190 (squares) and 290 K (up triangles) below $T_N = 307$ K, respectively. The vertical shift of the curves with respect to each other reflects the temperature dependence of the magnetization of the bulk antiferromagnet of volume $V = 14\,\text{mm}^3$ in the presence of small magnetic fields. They originate from residual magnetic flux pinned in the superconducting coil of the magnetometer. However, the physics of the ME-effect is represented by the temperature and field dependence of the slope $\alpha_\parallel \propto Q_{zz} \propto \partial m_z/\partial E_z$.

Fig. 2 shows $\partial m_z/\partial U$ vs. T at $\mu_0 H = 0$ (circles) and 0.5T (squares), respectively. The temperature dependence of $\alpha_\parallel \propto \partial m_z/\partial U$ follows the product $\chi_\parallel\ \langle S_z \rangle$ where $\chi_\parallel$ vs. T and $\langle S_z \rangle$ vs. T describe the temperature dependences of the parallel magnetic susceptibility and the AF order parameter, respectively [7]. The shift of $\partial m_z/\partial U$ vs. T at $\mu_0 H = 0.5$ T with respect to the zero field data reflects the suppression of the AF order in an applied homogeneous magnetic field.

From Fig. 2 we estimate that the induced ME moment is given by $m_z \approx 8.5 \times 10^{-9}\,\text{Am}^2$ at $T = 250$ K which corresponds to the magnetization $M_z = 0.61$ A/m. Assuming homogeneous distribution of M_z across the entire sample we obtain $\delta S_{AF} = M_z c = 8.3 \times 10^{-10}$A which is defined by the magnetic moment of the topmost layer of thickness $c = 1.36$ nm divided by the interface area of the sample. The layer thickness is given by the height of the crystallographic unit cell. We compare this induced change δS_{AF} with a typical excess magnetization of a diluted antiferromagnet in a field. It can be estimated according to the rule of thumbs $\Delta M_z/M_z \approx 1/50$ [8]. With $M_z \approx 1 \times 10^4$ A/m and the lattice constant $a = 0.47$ nm of the prototypical random-field system $Fe_{1-x}Zn_xF_2$ we obtain the interface magnetization of $S_{AF} \approx 9 \times 10^{-8}$A. Hence, we estimate, that tuning of the exchange bias in the case of heterostructures involving bulk ME pinning layers yields $\delta(\mu_0 H_e) \approx \mu_0 H_e/100$. However, reduction of the AF layer thickness increases the internal electric field and, hence, the tuning efficiency.

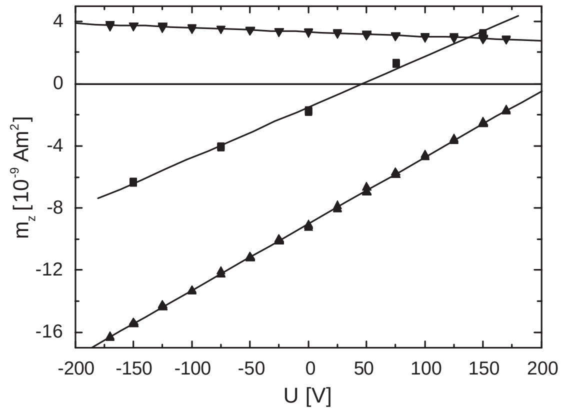

Fig. 1. Magnetic moment m_z vs. U of Cr_2O_3 at $\mu_0 H = 0$ for temperatures $T = 50$ (down triangles), 190 (squares) and 290 K (up triangles) with linear best fits, respectively.

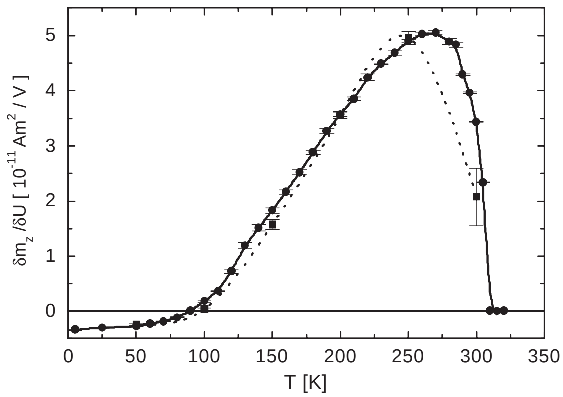

Fig. 2. $\partial m_z/\partial U$ vs. T in $\mu_0 H$ =(circles) and 0.5 T (squares), respectively. The lines are splines.

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