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On the comparison of the polarisation behaviour of exchange-biased AF/F NiMn/$Fe_{37}Co_{48}Hf_{15}$ bi-layer and multi-layer films with increased ferromagnetic cut-off frequencies

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ABSTRACT

Antiferromagnetic/ferromagnetic (AF/F) NiMn/$Fe_{37}Co_{48}Hf_{15}$ films were investigated with respect to their exchange bias, in-plane unidirectional anisotropy, polarisation and high frequency behaviour. After deposition, carried out by r.f. magnetron sputtering, the films were post-annealed for 4 h at 300 °C in a static magnetic field, in order to induce exchange-bias, which results in a unidirectional anisotropy. Dependent on the presence of a bi-layer or multi-layer sandwich structure the films show a different exchange-bias field–ferromagnetic inter-layer thickness behaviour with exchange-bias fields $\mu_0{}^*H_{eb}$ between 2 and 10 mT. The in-plane uniaxial (single film) or unidirectional anisotropy fields $\mu_0{}^*H_{UF}$ were between 4 and 18 mT. This results in a significant increase of the cut-off frequency in the GHz range in comparison to a single $Fe_{37}Co_{48}Hf_{15}$ film, which is shown by frequency-dependent permeability plots. High damping in the imaginary part of the permeability, i.e., high resonance line broadening could be observed for films with high coercivity $\mu_0{}^*H_c$ of around 7 mT in the easy axis of magnetisation.

1. Introduction

The discovery of exchange-bias between antiferro- and ferromagnetic materials in 1956 [1] has clearly influenced research and development activities in a wide range, in order to understand the physical mechanisms at the interface of these materials. Especially, the data storage industry has started to benefit from the first evidence of exchange-bias in thin Fe/NiO films [2] and the ensuing detection of the GMR effect [3], which opened the era of spintronics. As a further application, potential interest for ferromagnetic films has developed for incorporating them in high frequency microelectronic devices like micro-inductors, micro-transformers and electromagnetic noise absorbing components to improve their performance [4,5]. In the present paper, we like to focus our attention on high cut-off or resonance frequencies beyond 2.5 GHz. In order to reach higher ferromagnetic resonance frequencies of ferromagnetic films produced by simple magnetron sputtering, an additional exchange-bias field, beside an in-plane uniaxial anisotropy, has to be generated by the combination of antiferro- and ferromagnetic layers [6,7]. The best antiferro- and ferromagnetic exchange-bias effect can usually achieved by smooth, i.e., unperturbed interfaces. NiMn seems to be one of the most promising candidates for, e.g., spin valve devices [8], and even films with high frequency suitability [9] due to its appropriate corrosion properties and thermal stability [10]. The investigation of antiferromagnetic/ferromagnetic single- and multi-layer films with high frequency permeability characteristics has marginally been carried out by now. Therefore, it ought to be theoretically as well as experimentally discussed by considering the exchange-bias and ferromagnetic resonance frequency behaviour, diffusion and resonance line broadening due to precession damping of magnetic moments.

2. Experimental procedures

Soft ferromagnetic Fe-Co-Hf films with good high frequency permeability properties were produced in a "two-step-process" [11]. The films were deposited onto Si (100) substrates with 1 μm silicon oxide (5 mm × 5 mm × 0.375 mm) by reactive r.f. magnetron sputtering in an Ar atmosphere at a constant pressure of 0.5 Pa and at a sputtering power of 250 W. For the deposition, a 6 in. target (target composition: $Fe_{37}Co_{46}Hf_{17}$) was used in a Leybold Heraeus Z550 sputtering set-up which resulted in the composition $Fe_{37}Co_{48}Hf_{15}$. The antiferromagnetic NiMn layers were deposited by employing the identical target diameter and sputtering parameters. The composition was measured by the

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electron probe micro analysis (EPMA) and the Auger electron spectroscopy (AES).

The magnetic polarisation J ($\mu_0{}^*H_{ext}$) loops of the bi-layers in-plane easy and hard direction was determined by Magneto Optical Kerr Effect (MOKE) measurements. The polarisation loops of the multi-layers were measured with a vibrating sample magnetometer (VSM). J_s, the saturation polarisation, the exchange-bias field $\mu_0{}^*H_{eb}$ and the unidirectional anisotropy field $\mu_0{}^*H_{UF}$ were determined by these polarisation curves. An improved measurement procedure was applied [12] to carry out the in-plane frequency characterisation with the high frequency field perpendicular to the easy direction of polarisation by means of a strip-line permeameter, which was coupled to an Agilent 8753 ES vector network analyser [13]. The frequency-dependent permeability could be determined after evaluating the one port S_{11}-parameter from 100 MHz up to 6 GHz.

3. Film constitution and theoretic background

3.1. Exchange-bias field

In theory, antiferromagnetic/ferromagnetic (AF/F) films are originally considered to be ideally single crystalline with nearly flawless uncompensated interfaces as well as nearly compensated AF- and uncompensated F-layers (Fig. 1a). In reality, they are often polycrystalline and their interfaces are not perfectly smooth. They must be widely regarded as a more complex structure including stress, disorder by grain boundaries, thermal disorder, interfacial roughness, domains in the AF and interdiffusion (Fig. 1b). Additionally, the presence of local crystallographic orientation and magnetic frustration, which do not allow a perfectly uncompensated coupling between the AF and F, should lead to a discrepancy of the theoretical exchange-bias field and the experimentally determined exchange field H_{eb}. But for all theories describing ideal or imperfect films, H_{eb} is always proportional to $1/t_F$ where t_F is the thickness of the ferromagnetic layer [14]. The dependence of the AF layer thickness is described as being more complicated [15]. Dependent on the used material system, e.g., for more than 20 nm, H_{eb} is independent of the AF layer thickness. If thickness is strongly reduced, H_{eb} declines to zero [16].

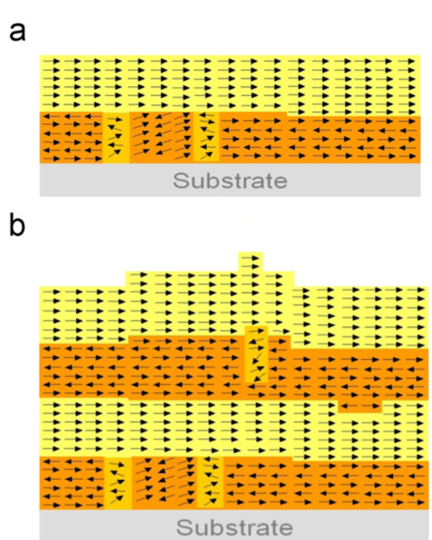

Fig. 1. a: Schematic model of an nearly ideally and perfectly structured anti-ferromagnetic/ferromagnetic (AF/F) NiMn/$Fe_{37}Co_{48}Hf_{15}$ bi-layer film. The moments of the ferromagnetic layer are assumed to be fully uncompensated. b: Schematic model of a more complex structured antiferromagnetic/ferromagnetic (AF/F) NiMn/$Fe_{37}Co_{48}Hf_{15}$ multi-layer film. The moments of the ferromagnetic layers are assumed to be fully uncompensated.

In order to roughly explain our experiments and to discuss the hypothesis of an influenced exchange-bias behaviour due to a possible diffusion process between the multi-layer films to a certain extent, we tried to introduce the AF layer thickness by a phenomenological theoretic model in a simple way. The approach can be made by a simple consideration of the total energy per unit area:

$$\begin{aligned} E_{tot} &= E_Z + E_{UF} + E_{AF} + E_{int} \\ &= -\mu_0 H_{ext} M_F t_F \cos(\alpha-\beta) + K_{UF} t_F (1-\cos^2\beta) \\ &\quad + K_{AF} t_{AF} (1-\cos^2\gamma) - J_{net}\cos(\beta-\gamma) \end{aligned} \tag{1}$$

of the exchange-bias system similar to [15,17] in which the energy contribution E_{AF} of the AF layers will not be neglected. The evolution of magnetic domains are not considered. The first term is the Zeeman energy where H_{ext} is an applied external field, M_F is the magnetisation of the ferromagnetic layer and t_F is its thickness. The second and third term represent the anisotropy energy of the ferromagnetic and antiferromagnetic layer with the anisotropy coefficients K_{UF} and K_{AF}, respectively. The variable t_{AF} describes the thickness of the AF layer. J_{net} is the net exchange-bias constant due to the interface defects mentioned above which represents the mean interface exchange energy E_{int}. α, β and γ are the angles between an applied external field H_{ext} and K_{UF}, between M_F and K_{UF} and between M_{AF} and K_{AF}, respectively. The minimum energy can be obtained by the approach

$$\frac{\partial E_{tot}}{\partial \beta} = -\mu_0 H_{ext} M_F t_F \sin(\alpha-\beta) + K_{UF} t_F 2\cos\beta\sin\beta + J_{net}\sin(\beta-\gamma) = 0 \tag{2}$$

$$\frac{\partial E_{tot}}{\partial \gamma} = K_{AF} t_{AF} 2\cos\beta\sin\beta - J_{net}\sin(\beta-\gamma) = 0 \tag{3}$$

The energy derivatives are solved for $\alpha=\beta=\gamma\to 0$ for which we assume the minimum energy of the film system. By resolving eq. (2) into the external field H_{ext} one obtains

$$\mu_0 H_{ext} = \frac{2K_{UF}\cos\beta\sin\beta}{M_F\sin(\alpha-\beta)} + \frac{J_{net}\sin(\beta-\gamma)}{M_F t_F\sin(\alpha-\beta)} \tag{4}$$

whereas eq. (3) can be changed to the following form:

$$K_{AF} t_{AF} = \frac{J_{net}}{2}\frac{\sin(\beta-\gamma)}{\cos\beta\sin\beta} \tag{5}$$

By applying the angles $\alpha=\beta=\gamma\to 0$ and substituting J_{net} in eq. (4) by relation (5) one obtains

$$\mu_0 H_{ext} - \frac{2K_{AF} t_{AF}}{M_F t_F} = \frac{2K_{UF}}{M_F} \tag{6}$$

which demonstrates the field displacement of the magnetisation loop of the easy axis of magnetisation due to the exchange-bias field. The term on the right hand side bears the in-plane uniaxial anisotropy field $\mu_0{}^*H_{UF}=2^*K_{UF}/M_F$, which possesses a unidirectional character. The exchange-bias field can now be expressed by the following formula:

$$\mu_0 H_{eb} = 2\frac{\mu_0 K_{AF} t_{AF}}{J_F t_F} \tag{7}$$

which depends on the antiferromagnetic and ferromagnetic layer thickness. Here, J_F is regarded as the saturation polarisation J_s of the ferromagnetic layers, and μ_0 is the magnetic field constant. A theoretic plot of the exchange-bias field $\mu_0{}^*H_{eb}$ in arbitrary units computed by eq. (7) is shown in Fig. 2. It was also experimentally determined that the AF layer thickness does not impact the exchange-bias effect to such an extent [16].

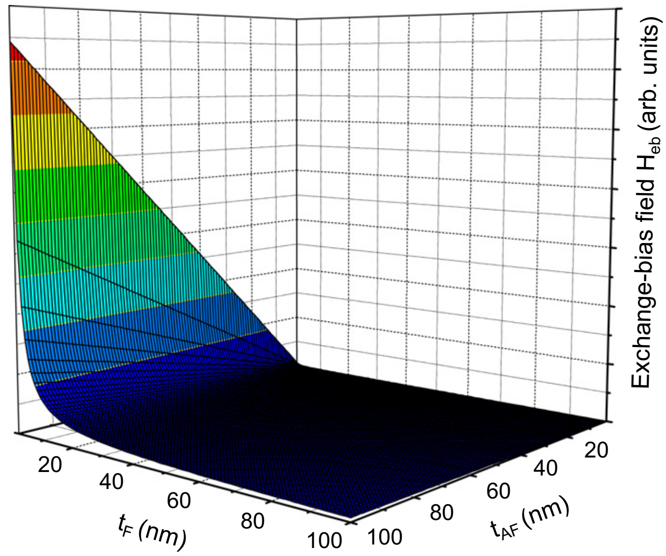

Fig. 2. Computed exchange-bias field dependent on the antiferromagnetic and ferromagnetic inter-layers thickness according to formula (7).

3.2. Frequency-dependent permeability and cut-off frequency

In brief, the frequency-dependent permeability is very well described by the Landau-Lifschitz -Gilbert (LLG) differential equation:

$$\frac{\partial M}{\partial t} = -\gamma M \times H_{eff} + \frac{\alpha_{\text{eff}}}{M_s}\left(M \times \frac{\partial M}{\partial t}\right) \tag{8}$$

in combination with the Maxwell equations to consider eddy-currents, that we have frequently applied to fit the permeability spectrum of single films [18]. α_{eff} is the effective damping parameter, which represents intrinsic and extrinsic line broadening [19,20]. In order to identify the influence of the exchange-bias field H_{eb} to the ferromagnetic resonance frequency (FMR):

$$f_{FMR} = \frac{\gamma}{2\pi}\mu_0 H_{eff} \tag{9}$$

the effective field H_{eff} inside the film, which keeps the magnetic moments in a quasi-uniform precession mode while being subjected to a high frequency field, can be deduced by the following approach:

$$\begin{aligned}\vec{H}_{eff} &= \vec{H}_{UF} + \vec{H}_{eb} + \vec{h} + \vec{H}_d \\ &= \begin{pmatrix}0\\0\\H_{UF}\end{pmatrix} + \begin{pmatrix}0\\0\\H_{eb}\end{pmatrix} + \begin{pmatrix}h_x\\0\\0\end{pmatrix} + \begin{pmatrix}-N_x m_x\\-N_y m_y\\-N_z M_s\end{pmatrix} \\ &= \begin{pmatrix}h_x - N_x m_x\\-N_y m_y\\(H_{UF}+H_{eb}) - N_z M_s\end{pmatrix}\end{aligned} \tag{10}$$

H_d is the demagnetising field vector with the saturation magnetisation M_s and the magnetisation components m_x, m_y of the magnetisation vector defined in the z-direction. $h=(h_x, 0, 0)$ is the high frequency field, which we assume in the x-direction. For films with lateral dimensions much higher than their thickness, the demagnetisation factors are $N_x=N_z=0$ and $N_y=1$. Assuming a weak high frequency field ($h_x \to 0$) the squared magnitude of the effective magnetic field is

$$|H_{eff}|^2 = (H_{UF}+H_{eb})^2 + m_y^2 \tag{11}$$

The last term can be considered as a "fictitious" or imaginary magnetisation, which arises from the demagnetisation effect or shape anisotropy in the y-direction, although the magnetic moments are directly exited by h_x in the x-direction. After a long calculation procedure m_y^2 can be expressed by

$$m_y^2 = M_s(H_{UF}+H_{eb}) \tag{12}$$

The effective magnetic field consequently results in

$$H_{eff} = \sqrt{(H_{UF}+H_{eb})^2 + M_s \cdot (H_{UF}+H_{eb})} \tag{13}$$

After inserting relation (13) into (9) one obtains the ferromagnetic resonance formula:

$$f_{FMR} = \frac{\gamma}{2\pi}\sqrt{\mu_0^2 (H_{UF}+H_{eb})^2 + J_s \mu_0 (H_{UF}+H_{eb})} \tag{14}$$

which simultaneously depends on the unidirectional anisotropy and exchange-bias field. This formula is almost identical to the exact Kittel resonance formula. Beside an in-plane uniaxial or unidirectional anisotropy field, the exchange-bias field should cause an additional increase of the ferromagnetic resonance or cut-off frequency of exchange-biased AF/F multi-layer films.

4. Experimental results and discussion

4.1. Magnetic polarisation, in-plane anisotropy and exchange-bias field

The in-plane unidirectional anisotropy and the exchange-bias field can be generated if the tetragonal AF phase in NiMn is present [21]. In order to keep diffusion between layers as low as possible, an annealing temperature of 300 °C was chosen. For a NiMn film one can observe that the tetragonal AF phase slightly develops for an annealing time from 3 h at 300 °C and becomes more distinctive when annealing time is increased (Fig. 3). By recording polarisation loops exchange-bias can be made visible. This is expressed by the easy direction loop shifts to the negative external field axis in the amount of the exchange-bias field H_{eb}. In Fig. 4a, the common easy and hard axis polarisation of a single $Fe_{37}Co_{48}Hf_{15}$ film with an in-plane uniaxial anisotropy field $\mu_0{}^*H_{UF}$ of about 5 mT and a saturation polarisation of 1.4 T is exhibited. The combination of such a film material with the antiferromagnetic NiMn yields a marked displacement with an increased coercitive field of the easy direction of magnetisation, shown for a bi-layer configuration. As expected, the exchange-bias

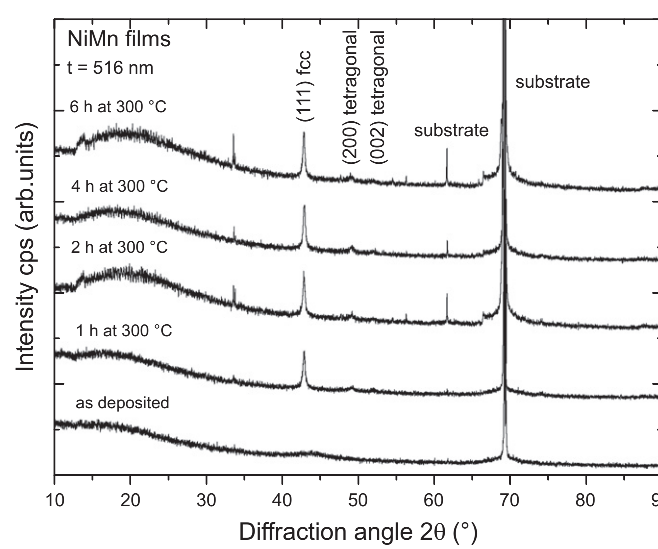

Fig. 3. X-ray diffraction scans of NiMn 516 nm thick films, as deposited and annealed at a temperature of 300 °C for 1 to 6 h, in order to identify the evolution of the tetragonal AF phase.

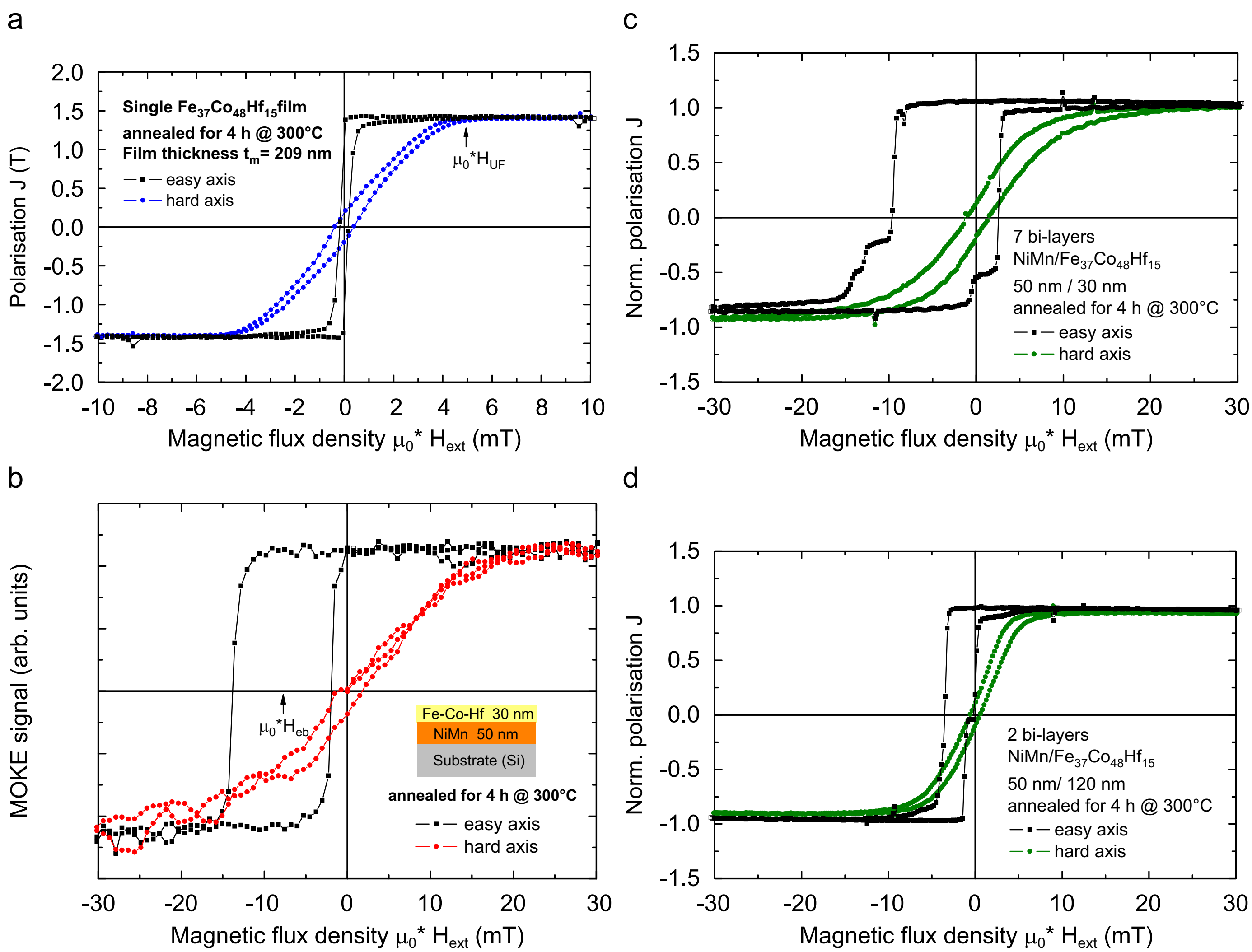

Fig. 4. a: Hard and easy axis polarisation curves of a 209 nm thick $Fe_{37}Co_{48}Hf_{15}$ film annealed at 300 °C for 4h in a static magnetic field measured by VSM. The in-plane uniaxial anisotropy field $\mu_0 {*} H_{UF}$ is indicated. b: Hard and easy axis magnetisation curves of a NiMn/$Fe_{37}Co_{48}Hf_{15}$ (50 nm/30 nm) bi-layer film annealed at 300 °C for 4 h in a static magnetic field measured by MOKE. The in-plane unidirectional anisotropy field field $\mu_0 H_{UF}$ can be denoted to about 18 mT. The exchange-bias field $\mu_0 {*} H_{eb}$ is indicated and gives a value of about 7 mT.c: Hard and easy axis magnetisation curves of a NiMn/$Fe_{37}Co_{48}Hf_{15}$ (50 nm/30 nm) multi-layer film (7 bi-layers) annealed at 300 °C for 4 h in a static magnetic field measured by VSM. The in-plane unidirectional anisotropy field field $\mu_0 {*} H_{UF}$ can be denoted to about 10 mT. The exchange-bias field $\mu_0 {*} H_{eb}$ gives a value of about 3 mT. d: Hard and easy axis magnetisation curves of a NiMn/$Fe_{37}Co_{48}Hf_{15}$ (50 nm/120 nm) multi-layer film (2 bi-layers) annealed at 300 °C for 4 h in a static magnetic field measured by VSM. The in-plane unidirectional anisotropy field field $\mu_0 {*} H_{UF}$ can be denoted to about 8 mT. The exchange-bias field $\mu_0 {*} H_{eb}$ gives a value of about 2 mT.

field trails away when the thickness of the ferromagnetic layer is increased. This is shown by means of normalised magnetisation MOKE measurements (Fig. 4b) at which $\mu_0{*}H_{eb}$ results in, e.g., 8 mT for an AF(50 nm)/F(30 nm) bi-layer configuration. Turning on the attention to the huge increase of the in-plane unidirectional anisotropy, it can be assumed that the exchange stiffness, as a consequence of exchange coupling, is transmitted into the unidirectional anisotropy, which leads to its strong enhancement. Additionally, due to the thin ferromagnetic layers and their subsequently small in-plane demagnetisation effect low fluctuations may also support a strong in-plane uniaxial anisotropy. But it should be noted that the exchange-bias and unidirectional anisotropy do not correlate with each other, which, however, may account for the inhomogeneity of pinning through the ferromagnetic layer [9]. In Fig. 4c, the multi-layer arrangement reveals a similar behaviour. In both film formations the in-plane unidirectional anisotropy depends on the exchange-bias field. With declining exchange-bias the unidirectional anisotropy reduces from 12 mT to a uniaxial anisotropy value of about 5 mT according to a single F film. But regarding the normalised easy polarisation direction of the multi-layer configuration with a high coercitive field ($\mu_0{*}H_c \approx 7$ mT for, e.g., sevenfold AF(50 nm)/F(30 nm)) in Fig. 4c a clear asymmetry between the positive and a kink-afflicted negative polarisation quadrant could be found for several F layer thickness. The kinks virtually vanish for thicker F layers ($t_F = 120$ nm, Fig. 4d). This can be attributed to a two-stage magnetic process [22]. This means, that the polarisation states are not fully reversible at around $J \rightarrow 0$. Within this polarisation process the magnetic moment is in a metastable state at 90°, and then switches to 180°, i.e., in external field direction. In particular, the coherent rotation process of magnetic moments is reversible, but the domain processes are irreversible due to the absence of domain wall nucleation and propagation. At this point, a simple model of a multi-domain state could be assumed and would explain the observed behaviour due to switching the magnetisation at slightly different external magnetic fields.

In Fig. 5, the apparent difference between the exchange-bias field of the bi-layer and multi-layer configuration can be observed. In order to fit the measurement data, formula (7) was taken into account. By, e.g., applying a reduced AF layer thickness

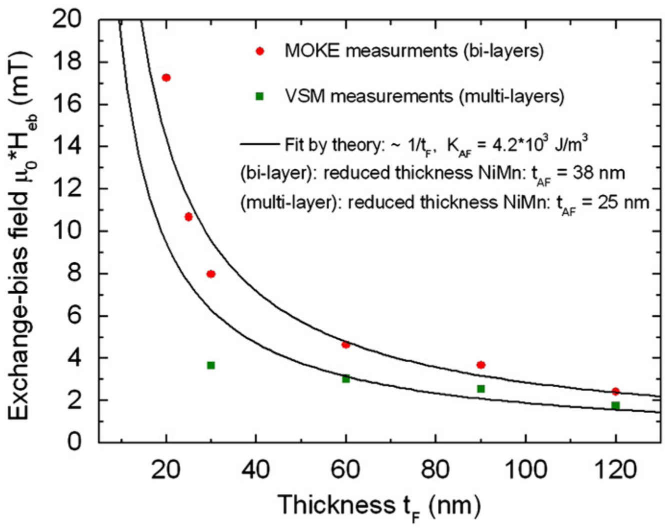

Fig. 5. Comparison between the experimental exchange-bias field data dependent on the ferromagnetic inter-layer thickness of bi-layer and multi-layer arrangements. The solid line represents the theoretic model according to eq. (7).

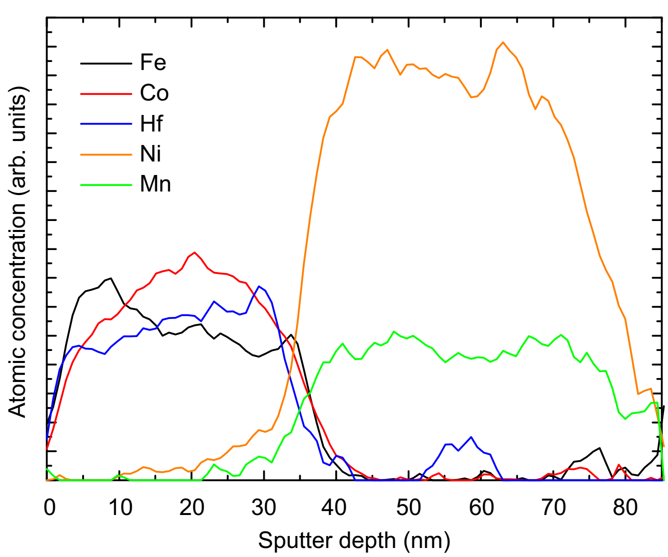

Fig. 6. Atomic concentration depth profile of an $Fe_{37}Co_{48}Hf_{15}$/NiMn 80 nm thick bi-layer obtained by Auger electron spectroscopy (AES). Diffusion of NiMn into $Fe_{37}Co_{48}Hf_{15}$ was estimated to be around 15 nm.

in the multi-layers due to an assumed diffusion process, instead of the nominal thickness of 50 nm, the increase of the exchange-bias field is lower than for the bi-layers. At this point, diffusion of Ni and Mn to a distance of around 10–15 nm into the F layers was estimated by an Auger depth profile (Fig. 6). So, the exchange-bias between the layers seems to be perturbed, and can be put on the level with a reduction of the AF thickness to about 25 nm. But it has to be kept in mind, that this simple theoretic estimation by formula (7) has it limits if interdiffusion affects all film layers. Here, the theory fails for certain regions.

4.2. Frequency dependent permeability

As depicted in Fig. 7a, the real and imaginary part of the permeability of a single $Fe_{37}Co_{48}Hf_{15}$ film measured up to 6 GHz exhibits a clear ferromagnetic resonance frequency f_{FMR} at approximately 2.4 GHz. With an initial permeability μ_r $(f \to 0)$ of about 230 and an effective damping parameter of $\alpha_{eff}=0.0123$, it can be clearly seen that LLG appropriately matches the measured frequency data. It is assumed that a clear-cut resonance behaviour exists. As theoretically predicted in chapter 3.2 (eq. (14)), the ferromagnetic cut-off frequency of a AF/F multi-layer film, showing a marked exchange-bias field, shifts to higher values (Fig. 7b). In Fig. 7c, the ferromagnetic cut-off frequency reaches about 4.1 GHz which gets along with a stronger exchange-bias due to thinner F layers. The next Fig. 8 shows that the determined cut-off frequency data are close to the computed unidirectional and exchange-bias field dependence (eq. (14)). The decreasing initial static permeability is obvious if one considers the relation

$$\mu_r(f \to 0) = \frac{J_s}{\mu_0 \cdot (H_{UF} + H_{eb})} + 1 \tag{15}$$

Surveying the permeability spectra, increased broadening can be followed, which comes from higher precession damping. This is associated with a relatively weak AF anisotropy when the F couples to the AF, and the precession of the ferromagnetic moments is thereby damped by dragging the AF spins. A correlation with the polarisation loops (Fig. 4a, b and c) is conspicuous for which the coercitive field is increased. Differently speaking, based on the fact that uniform precession of magnons with a wave vector $k \approx 0$ (FMR magnon) are present, their lifetime is destroyed by scattering at the AF interfaces due to a discrepancy or discontinuity of the—perturbed by diffusion—F spin system. As a result, a degenerate magnon with $k > 0$ and the same frequency is generated (two-magnon scattering). The two-magnon energy is then dissipated into the lattice, which results in broadening of the imaginary part of the permeability spectra. If the ferromagnetic layer thickness is increased damping is lowered for a lower antiferromagnetic/ferromagnetic volume-interface ratio. Consequently, the full width at half maximum (FWHM) of the imaginary part of the permeability is decreased [23].

5. Conclusion

Antiferromagnetic/ferromagnetic NiMn/$Fe_{37}Co_{48}Hf_{15}$ films with combined unidirectional and exchange-bias fields were investigated with regard to their exchange-bias–ferromagnetic interface layers thickness dependence and high frequency permeability behaviour. The films were fabricated as bi-layers as well as multi-layers. By means of a simple theoretic concept it could be made comprehensible that assumed diffusion reduces the antiferromagnetic coupling or effectiveness of the antiferromagnetic layer, especially in the multi-layer arrangement due to diffusion from both sides. This could be shown by taking a reduced antiferromagnetic interface layer thickness t_{AF} into account.

For example, it could be also shown by multi-layer films, that beside an in-plane unidirectional anisotropy, which makes the magnetic moments to tend into a defined direction, an additional exchange-bias field leads to higher resonance frequencies. This was previously predicted by deriving the exact theoretic resonance frequency formula, which is close to the Kittel resonance formula. In order to obtain the resonance frequency, an effective field about which the magnetic moments precess was hypothesised by a vector model. It showed, that simply introducing and adding an exchange-bias field to the uniaxial or even to the unidirectional field increases the ferromagnetic resonance frequency. This resulted in higher broadening of the imaginary part of the frequency dependent permeability, which stands for higher losses, i.e., precession damping of magnetic moments by two-magnon scattering processes at non-ferromagnetic, i.e., AF interfaces and perturbed ferromagnetic diffusion zones. As a result, this influences the quality factor, as a general measure of loss, which defines the range of applications. Higher losses are needed where the energy of electromagnetic waves has to be absorbed

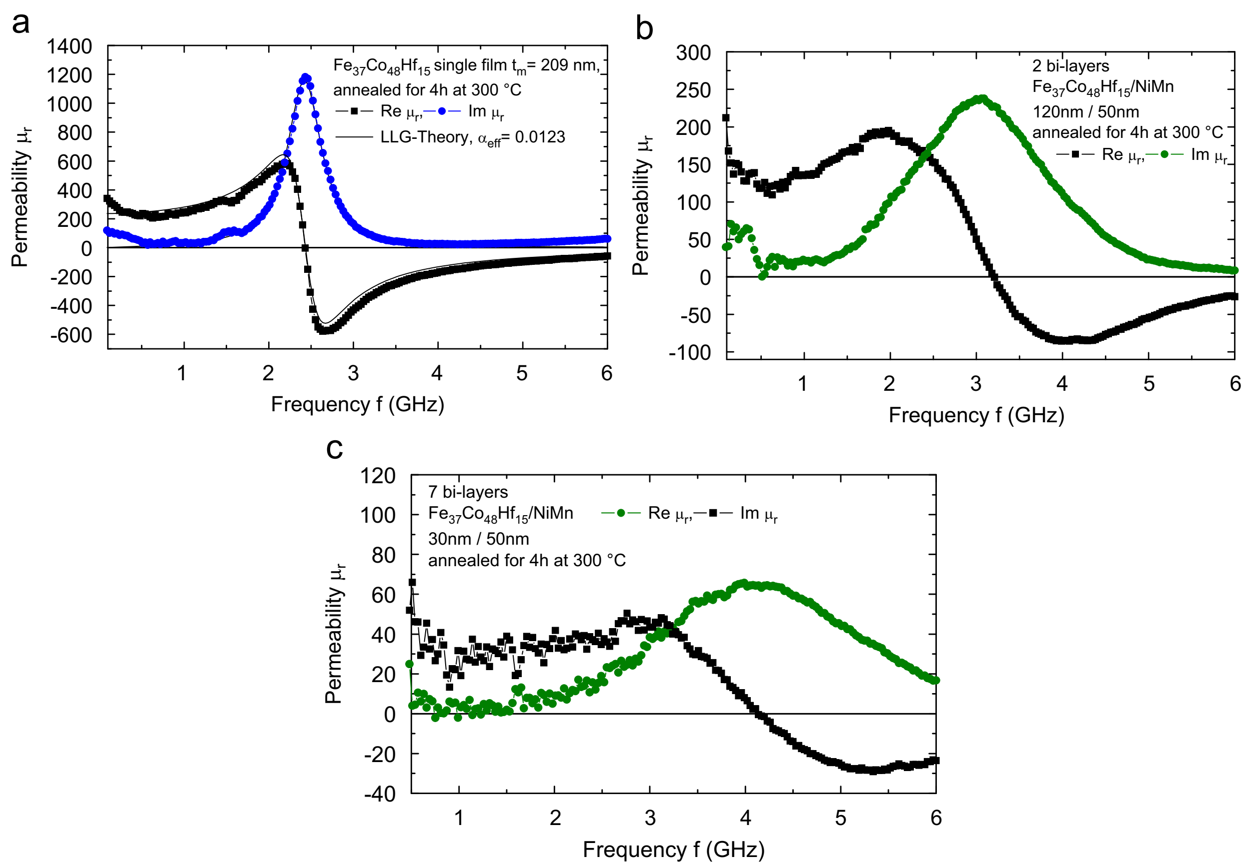

Fig. 7. a: Real and imaginary part of the frequency-dependent permeability of a 209 nm thick $Fe_{37}Co_{48}Hf_{15}$ film annealed at 300 °C for 4 h in a static magnetic field. The solid line shows the modified Landau-Lifschitz-Gilbert theory with an effective damping parameter α_{eff}=0.0123. b: Real and imaginary part of the frequency-dependent permeability of a NiMn/$Fe_{37}Co_{48}Hf_{15}$ (50 nm/120 nm) multi-layer film (2 bi-layers) annealed at 300 °C for 4 h in a static magnetic field. c: Real and imaginary part of the frequency-dependent permeability of a NiMn/$Fe_{37}Co_{48}Hf_{15}$ (50 nm/30 nm) multi-layer film (7 bi-layers) annealed at 300 °C for 4 h in a static magnetic field.

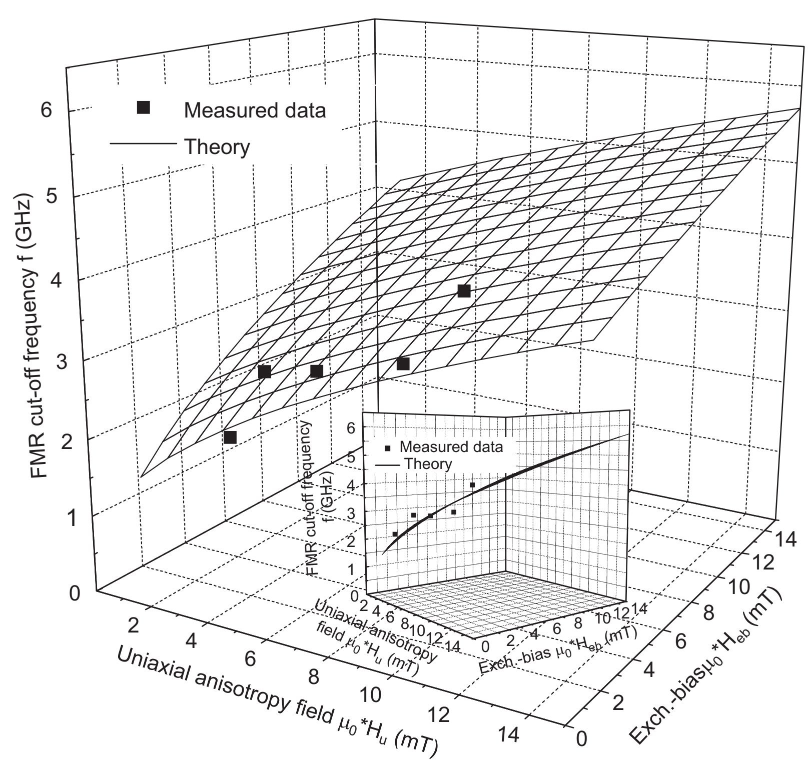

Fig. 8. Experimentally obtained ferromagnetic resonance cut-off frequency data dependent on the in-plane unidirectional anisotropy field and exchange-bias field. The inset demonstrates the deviation between the experiment and theory. The theory is computed by relation (14).

and converted (Electromagnetic Compatibility, EMC). In microelectronic components, e.g., micro-inductors, high losses would reduce their performance.

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