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Brillouin light scattering investigations of exchange biased (110)-oriented NiFe/FeMn bilayers

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All contributing magnetic anisotropies in (110)-oriented exchange biased $Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$ double layers prepared by molecular beam epitaxy on Cu(110) single crystals have been determined by means of Brillouin light scattering. Upon covering the $Ni_{80}Fe_{20}$ films by $Fe_{50}Mn_{50}$, a unidirectional anisotropy contribution appears, which is consistent with the measured exchange bias field. The uniaxial and fourfold in-plane anisotropy contributions are largely modified by an amount, which scales with the $Ni_{80}Fe_{20}$ thickness, indicating an interface effect. The strong uniaxial anisotropy contribution shows an in-plane switching of the easy axis from [110] to [001] with increasing $Ni_{80}Fe_{20}$-layer thickness. The large mode width of the spin wave excitations, which exceeds the linewidth of uncovered $Ni_{80}Fe_{20}$ films by a factor of more than six, indicates large spatial variations of the exchange coupling constant. © *1998 American Institute of Physics.*
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The exchange bias effect, which results from exchange coupling between adjacent ferromagnetic (F) and antiferromagnetic (AF) layers, which are either deposited in a magnetic field or cooled down in a magnetic field after heating above the Néel temperature, is a well-established phenomenon.[1] It manifests itself in a shift of the hysteresis loop along the axis of the applied field, the so-called exchange bias field, H_{eb}, and it is often described as an in-plane unidirectional anisotropy. Although exchange bias systems have been extensively studied,[2–5] the microscopic origin of the exchange bias effect still remains unclear. The most advanced models propose the formation of magnetic domains in the AF layer causing a macroscopic exchange coupling strength of the experimentally observed size,[6,7] which is two orders of magnitude smaller than the atomic F-AF exchange coupling strength. Key issues to be tested experimentally are, (i) to prove the assumption of large local spatial variations of the F-AF coupling, and (ii) apart from the detection of the unidirectional anisotropy, to search for possible additional anisotropy contributions of higher order induced by the exchange coupling mechanism.

We have chosen to study the (110)-oriented system of $Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$ bilayers, since the lowest order in-plane anisotropy contributions, which are of unidirectional, uniaxial, and fourfold symmetry, can be separately determined for simple symmetry reasons. An unexpected large uniaxial anisotropy contribution caused by the FeMn coverage has already been reported for this orientation.[5,6] We have used Brillouin light scattering (BLS) from dipolar spin waves (Damon–Eshbach modes) propagating in the F film parallel to the surface to extract the anisotropy constants.[8]

Two molecular beam epitaxy (MBE) grown staircase-shaped samples have been prepared on Cu(110) single crystal substrates. The samples consist of $Ni_{80}Fe_{20}$ films with thicknesses of 27, 34, 50, and 70 Å for the first, and 18, 24, 37, and 90 Å for the second staircase-shaped sample. Half of each sample was covered by an 80 Å thick $Fe_{50}Mn_{50}$ layer. At this thickness the exchange bias effect is saturated.[4] Finally, both samples were covered with a 20 and 30 Å thick protective Au layer, respectively. The samples were characterized using low energy electron diffraction, and their chemical cleanliness was checked by Auger electron spectroscopy. An analysis of the process parameters revealed that the residual oxygen content in the gas used for sputter cleaning was significantly larger during preparation of the second sample compared to the first. Evaporation on a slightly contaminated surface can therefore not be excluded for the second sample. During growth a magnetic field of ≈250 Oe was applied in the film plane along the [110] direction to induce exchange biasing. We note that the (110)-oriented $Fe_{50}Mn_{50}$ surface is an uncompensated plane with a resultant in-plane magnetization along the ±[001] directions.[4]

The Brillouin light scattering experiments were performed with the external field applied in the film plane and in magnetic saturation to ensure a one-domain state of the F film. Light of an Ar^+ ion laser with a wavelength of 514.5 nm and power of 50 mW was focused onto the sample. The

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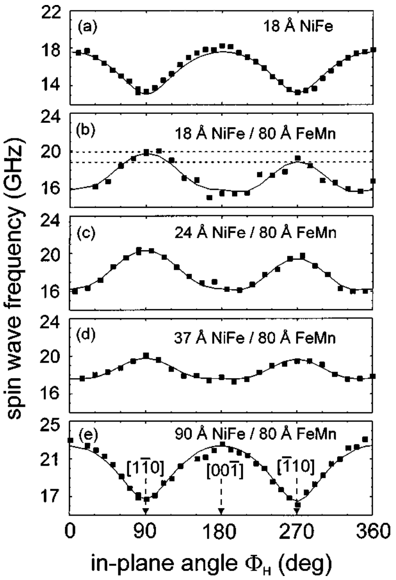

FIG. 1. Spin wave frequencies as a function of the angle of the in-plane applied field, ϕ_H, with the in-plane [001] direction for the Cu(110)/Ni$_{80}$Fe$_{20}$/(80 Å Fe$_{50}$Mn$_{50}$)/Au staircase-shaped sample with Ni$_{80}$Fe$_{20}$ layer thicknesses of 18, 24, 37, and 90 Å. The errors in the frequency positions are smaller than the symbol size. The full lines are least-squares fits. The difference in frequency of the spin wave maxima for the covered Ni$_{80}$Fe$_{20}$ layer of 18 Å thickness, representing the unidirectional anisotropy contribution, is indicated by the dashed horizontal lines. The applied field was 3 kOe.

light inelastically scattered from thermally excited Damon–Eshbach modes was frequency analyzed using a fully automated tandem Fabry–Perot interferometer. A multiparameter least-squares fit was used to accurately determine the frequency positions within ±0.3 GHz. To obtain the anisotropy constants the following expression for the free energy density, F_{ani}, was used:

$$F_{ani}=-K_S^{(2)}\cdot\cos^2\theta+K_p^{(1)}\cos(\phi-\phi_{\text{uni}})\cdot\sin\theta +K_p^{(2)}\cos^2\phi\cdot\sin^2\theta+K_p^{(4)}\cdot\cos^2\phi\cdot\sin^2\phi \cdot\sin^4\theta. \tag{1}$$

with $K_S^{(2)}$ the perpendicular anisotropy constant, $K_p^{(1)}$, $K_p^{(2)}$, and $K_p^{(4)}$ the in-plane anisotropy constants of unidirectional, uniaxial, and fourfold symmetry, respectively, and ϕ the in-plane angle of the direction of magnetization. ϕ_{uni} describes the reference direction of the unidirectional anisotropy. All in-plane angles are measured relative to the [001] direction. θ is the out-of-plane polar angle. We have measured the spin wave frequencies $\nu(\phi_H)$ as a function of the in-plane angle, ϕ_H, of the external field. Using Eq. (1) and a spin wave model[8] the spin wave frequencies were analyzed by fitting simultaneously all $\nu(\phi_H)$ data points for a given Ni$_{80}$Fe$_{20}$ layer thickness using a multiparameter least-squares fit with the anisotropy constants as the fit parameters. Care has been taken to determine the statistical errors of the results and the parameter correlations.

First we discuss the uncovered Ni$_{80}$Fe$_{20}$ staircase-shaped samples for reference. The measured spin wave frequencies as a function of ϕ_H are displayed in Fig. 1(a) for $d_{\text{NiFe}}=18$ Å. For all layer thicknesses a nearly identical spin wave dependence on ϕ_H is obtained with a large uniaxial anisotropy contribution. The spin wave maxima which are present for the ±[001] directions indicate that the easy axis of magnetization is along [001]. The corresponding anisotropy field of about 600 Oe is much larger than the value of 5 Oe usually found in polycrystalline Ni$_{80}$Fe$_{20}$ films grown in an external field. Its origin is still unclear though it may well be of magnetoelastic origin and caused by the Ni$_{80}$Fe$_{20}$ growth mode of long (500 Å), narrow islands with a length-to-width ratio of approximately 10 lying along the magnetically hard [110] direction, as has been shown by scanning tunneling microscopy.[6]

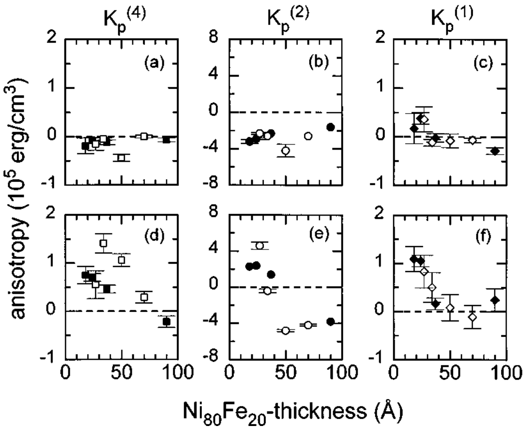

FIG. 2. The obtained anisotropy constants of the two staircase-shaped samples (open and closed symbols for the first and second sample) as a function of the Ni$_{80}$Fe$_{20}$ layer thickness for the uncovered layers (a), (b), (c) and the layers covered by 80 Å Fe$_{50}$Mn$_{50}$ (e), (d), (f).

Entirely different results are obtained upon covering the Ni$_{80}$Fe$_{20}$ layers by an 80 Å thick Fe$_{50}$Mn$_{50}$ layer as displayed in Figs. 1(b)–(e). For the Ni$_{80}$Fe$_{20}$ layer thicknesses of 18–37 Å, the spin wave maxima and thus the easy axes of magnetization are shifted by 90°. Moreover, for the 18 Å thick Ni$_{80}$Fe$_{20}$ layer, and to a lesser degree for the 24 and 37 Å thick films, the two maxima at ϕ_H equal to 90° and 270° do not agree in their spin wave frequencies as indicated in Fig. 1(b) by the dashed horizontal lines. The difference in frequency is a measure for the unidirectional anisotropy. Results of recent Kerr measurements of the exchange bias field as a function of the in-plane direction of the external field corroborate this interpretation.[9] The results of the determination of all anisotropies are displayed in Fig. 2 for the uncovered and covered Ni$_{80}$Fe$_{20}$ films, respectively. Again, first we discuss the uncovered samples [Figs. 2(a)–2(c)]. The in-plane fourfold anisotropy contribution is more or less zero. A large uniaxial in-plane anisotropy of $K_p^{(2)}=(-3\pm1)\cdot10^5$ erg/cm^3 is obtained nearly independent of the Ni$_{80}$Fe$_{20}$ thickness within the error margins. As expected the unidirectional anisotropy parameter, $K_p^{(1)}$, was found to be consistent with a zero value within the error margins.

The anisotropy behavior of the covered Ni$_{80}$Fe$_{20}$ films is displayed in Figs. 2(d)–2(f). All three in-plane anisotropy contributions decrease with increasing Ni$_{80}$Fe$_{20}$ thickness. For large Ni$_{80}$Fe$_{20}$ thicknesses the respective anisotropy values of the uncovered and the covered Ni$_{80}$Fe$_{20}$ films converge, indicating an interface effect. Within the given limited

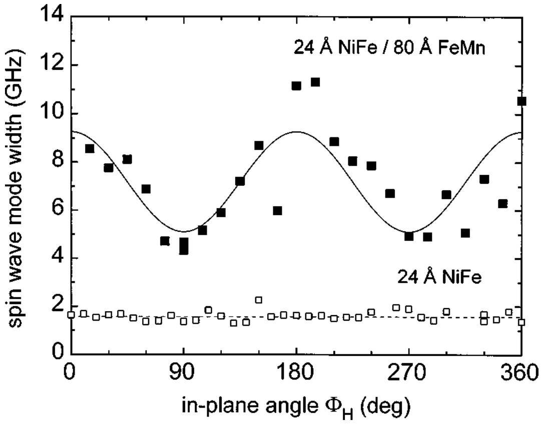

FIG. 3. Spin wave mode widths as a function of the angle of the in-plane applied field, ϕ_H, with the in-plane [001] direction for the 24 Å thick $Ni_{80}Fe_{20}$ layer for the $Fe_{50}Mn_{50}$ covered and uncovered case. The full (open) squares are the data of the covered (uncovered) layer. The full and dashed lines are guides to the eye.

accuracy the differences in the respective anisotropy values are consistent with a $1/d_{\mathrm{NiFe}}$-scaling law for all three in-plane contributions. For the fourfold in-plane anisotropy, $K_p^{(4)}$, the data of the second sample agree only within a factor of two with those of the first sample. This is probably due to a lesser quality in the film-substrate interface due to problems in the sputter cleaning process (see above). However, both samples show the same systematic decrease of this anisotropy contribution with increasing $Ni_{80}Fe_{20}$ thickness. For the uniaxial in-plane anisotropy, $K_p^{(2)}$, a change in sign is obtained for the first sample at (35 ± 5) Å and for the second sample near (50 ± 10) Å. For the unidirectional anisotropy constant, $K_p^{(1)}$, we obtain for $Ni_{80}Fe_{20}$ film thicknesses smaller than about 40 Å (i.e., the range where reliable conclusions can be made) an angle for the reference direction of $\phi_{\mathrm{uni}}=90°$, i.e., the easy direction of the unidirectional and the easy axis of the uniaxial anisotropy contributions are collinear.

While the origin of the unidirectional anisotropy contribution ($K_p^{(1)}$) is likely found in the exchange bias mechanism, the cause of the large modifications to the two other in-plane anisotropies ($K_p^{(2)}$,$K_p^{(4)}$), compared to the uncovered $Ni_{80}Fe_{20}$ films, needs to be discussed. Since these modifications are identified as interface contributions it is very likely that these contributions are also induced by the exchange coupling interaction and compete with the respective intrinsic contributions of the uncovered layer. Indeed, Jungblut *et al.* have recently shown that the exchange bias effect is causing the additional contribution in $K_p^{(2)}$.[6]

We now turn to the measurements of the spin wave linewidths. Mode broadening for propagating spin waves is obtained, if the internal fields vary locally on a length scale, which is of the order of the spin wave wavelength (3000 Å).[10] In our experiments the spin wave modes show a large mode broadening of more than a factor of six upon covering the $Ni_{80}Fe_{20}$ layers by $Fe_{50}Mn_{50}$ for the lower $Ni_{80}Fe_{20}$ layer thicknesses. This is displayed in Fig. 3 for the 24 Å thick $Ni_{80}Fe_{20}$ layer for the covered and uncovered case. For the covered sample the mode width varies within a factor of two as a function of the azimuthal angle, ϕ_H. As can be seen from Figs. 1 and 3 the maximum and minimum values correspond to the hard [001] and easy [110] direction of magnetization, respectively. The linewidth is strongly decreasing with increasing $Ni_{80}Fe_{20}$ layer thickness converging to the width of the uncovered $Ni_{80}Fe_{20}$ films. This is also characteristic for an interface effect.

The large spin wave mode broadening and its dependence on the in-plane angle of the external field can be understood as follows: We assume variations in the local F-AF exchange field on a scale of the atomic terrace width, which is of the order of 50 Å.[6] From the local exchange field the macroscopic, averaged exchange bias field, or equivalently, the unidirectional in-plane anisotropy, are generated. The variations in the F-AF exchange field will cause a broadening of the spin wave linewidth, which is therefore a characteristic fingerprint of the variations.[8,10,11] The broadening is largest, if not only internal field contributions (here the exchange coupling field) vary, but also the direction of magnetization. The latter occurs, if the easy axis of the spatially varying internal field is not collinear with the external field. By changing the direction of the external field, minima and maxima in the linewidth appear at the easy and hard axes of the exchange coupling induced uniaxial anisotropy.

In conclusion, for the (110)-oriented $Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$ exchange bias system large in-plane anisotropy contributions of unidirectional, uniaxial, and fourfold symmetry have been found. In particular we observed an in-plane switching of the easy axis of magnetization with increasing $Ni_{80}Fe_{20}$ layer thickness from the [110]-axis to the [001]-axis. The large spin wave mode width which is observed in the bilayer structures is a clear indication for large local variations of the exchange coupling. The decrease of the mode width with increasing $Ni_{80}Fe_{20}$ layer thickness is consistent with the nature of an interface effect.

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