6.12 Thermal behavior of the exchange bias effect in NiFe/FeMn double layers modified by He ion irradiation

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Recently, we have reported that both the exchange bias field and the coercive field in FeNi/FeMn bilayers can be reduced or enhanced by He ion irradiation in a controlled manner by adjusting the dose and the energy of the He ions, see preceding Section [1]. In this report the temperature dependence of both the bias field and the coercive field are examined.

The samples were prepared in a UHV-system with a base pressure of $5 \times 10^{-10}$ mbar. A 5 nm thick ferromagnetic (F) Fe$_{0.19}$Ni$_{0.81}$ layer and a 10 nm thick antiferromagnetic (AF) Fe$_{0.5}$Mn$_{0.5}$ layer were grown onto thermally oxidized Si substrates with a 35 nm Cu buffer layer. Finally, a 2 nm Cr layer was deposited to protect the samples from oxidation. The samples were grown at room temperature and show a strong (111) texture. After deposition, the samples were heated and subsequently cooled in an 500 Oe magnetic field below the Néel temperature to initiate the exchange bias effect.

The magnetic properties were initially investigated \textit{ex situ} by longitudinal magneto-optical Kerr-effect (MOKE) magnetometry at room temperature. The exchange bias field and the coercive field were found to be homogeneous across each sample. The initial exchange bias field, $H_{eb,initial}$, is as high as $-190$ Oe. This exchange bias field corresponds to an interface exchange energy of $0.08$ erg/cm$^2$. The respective coercive field, $H_{c,initial}$, is $22$ Oe, which is considerably higher than typical values for single FeNi films ($2 - 3$ Oe). An analysis of the hysteresis curves

![Graph showing variation of bias and coercive fields with ion dose]

**Fig. 1:** Variation of the bias field ratio $H_{eb}/H_{eb,initial}$ (closed squares) and the coercive field ratio $H_{c}/H_{c,initial}$ (open circles) with the ion dose.

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1 In collaboration with M. Jung, D. Engel, A. Ehresmann, and H. Schmoranzer, Fachbereich Physik, Universität Kaiserslautern.
as a function of the in-plane angle of the applied field shows an unidirectional anisotropy, as expected for this system due to the exchange bias effect.

To perform the ion irradiation the samples were inserted into an ion optical bench. He ions were produced in a Penning type source and accelerated by 10 kV. Different doses on the samples were realized by adjusting the beam current ($5 \sim 60 \text{ nA}$), and by varying the irradiation time ($3 \sim 120 \text{ s}$). These values for current, voltage and time allows us to cover the ion dose range from

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Fig. 2: Temperature dependence of the exchange bias field (a) and the coercive field (b). The insets show the same values normalized to the respective value at room temperature.
10^{13} \text{ ions/cm}^2 \text{ to } 6 \cdot 10^{15} \text{ ions/cm}^2. \text{ The effect of different ion doses was studied on a single sample by irradiating different areas of the sample with different parameter sets.}

Next hysteresis loops were measured with a cycle time of 40 s on the different irradiated areas by scanning the MOKE laser beam laterally across the sample through the centers of the irradiated areas. The normalized exchange bias field ratio, \( \frac{H_{eb}}{H_{eb,\text{initial}}} \), and the coercive field ratio, \( \frac{H_c}{H_{c,\text{initial}}} \), are plotted in Fig. 1 as a function of the ion dose. Two different regimes are identified: i) A pronounced increase of \( H_{eb} \) and \( H_c \) is found in the dose regime between \( 10^{13} \) and \( 0.3 \cdot 10^{15} \text{ ions/cm}^2 \). The maximum values are \( H_{eb,\text{max}} = -315 \text{ Oe} \) and \( H_{c,\text{max}} = 56 \text{ Oe} \). ii) For doses above \( 0.3 \cdot 10^{15} \text{ ions/cm}^2 \) the evolution is reversed and \( H_{eb} \) is reduced. The shift of the hysteresis loop decreases continuously with increasing ion dose. Finally, at an ion dose of \( 5.5 \cdot 10^{15} \text{ ions/cm}^2 \), the exchange bias effect is fully suppressed and the coercive field is reduced to a quarter of its initial value. Both the bias field \( H_{eb} \) and the coercive field \( H_c \) follow the same qualitative relationship. For a detailed discussion see [2].

To further examine the correlation between bias and coercivity magnetometry measurements were performed in the temperature range 25 –180 °C. The temperature was stabilized by a closed loop controller. The loops for irradiation in the dose range from \( 10^{13} \) to \( 10^{14} \text{ ions/cm}^2 \) showed no noticeable difference. Therefore, as representative values for this range, the results for \( 5 \cdot 10^{13} \text{ ions/cm}^2 \) are shown. Figure 2a shows the values of \( H_{eb} \) as a function of temperature. The inset shows the same data normalized to the respective values at room temperature. All curves show the same, almost linear decrease with increasing temperature. The deviation from a Brillouin function type relationship, as might be expected at first hand, can be understood on the basis of the grain size distribution [3, 4]. By increasing the temperature smaller grains become unstable first and do not contribute to the bias effect any more. The blocking temperature for all ion doses including the zero dose value is \( T_B = 155 \text{ °C} \) which is significantly lower than the bulk Néel temperature of \( T_N = 220 \text{ °C} \) for FeMn. However, the coercive field \( H_c \) exhibits a plateau around the blocking temperature (Fig. 2b). This can be understood by a weakened AF spin configuration at temperatures near the Néel temperature. The AF spin configuration does not stay fixed on reversal of the F layer. This causes an uniaxial anisotropy instead of an unidirectional one. This phenomenon is comparable to the coercivity enhancement experienced at the onset of exchange bias with increasing AF layer thickness [5].

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References