PHYSICAL REVIEW B, VOLUME 63, 060409(R)

Local manipulation and reversal of the exchange bias field by ion irradiation in FeNi/FeMn double layers

A. Mougin, T. Mewes, M. Jung, D. Engel, A. Ehresmann, H. Schmoranzer, J. Fassbender,* and B. Hillebrands
Fachbereich Physik and Forschungs- und Entwicklungsschwerpunkt Materialwissenschaften, Erwin-Schrödinger-Straße 56, Universität Kaiserslautern, 67663 Kaiserslautern, Germany
(Received 20 November 2000; published 23 January 2001)

Both the direction and the strength of the exchange bias field H_{eb} of an FeNi/FeMn double layer are manipulated locally by He ion irradiation in an applied magnetic field. The magnitude of H_{eb} is enhanced over its initial value in the low ion dose regime. Above a threshold irradiation dose a reduction and eventually a suppression of H_{eb} is found. The direction of H_{eb} is initialized by the field direction during irradiation. These observations are discussed considering the structural modifications caused by the ion bombardment. The data are well described by a model, which is based on the competition between the enhancement of the exchange bias field strength due to defect creation in the antiferromagnetic layer and the decrease induced by intermixing at the ferromagnet/antiferromagnet interface.

DOI: 10.1103/PhysRevB.63.060409 PACS number(s): 75.70.Cn, 61.80.Jh, 75.30.Gw, 85.70.−w

The exchange bias effect results from the magnetic exchange interaction between two adjacent ferromagnetic (F) and antiferromagnetic (AF) layers and expresses itself in various intriguing phenomena. For a recent review see Ref. 1. The ferromagnetic hysteresis loop is shifted by the so-called exchange bias field and exhibits an enhanced coercivity compared to that of the respective single F layer if the sample is either prepared in a magnetic field or cooled down through the Néel temperature of the AF layer in a field. The exchange bias effect has been known for a long time[2] and is nowadays widely used in devices.[3,4] Many authors have undertaken attempts to model the effect.[2,5–10] An enhancement of the exchange bias effect was found experimentally and by Monte Carlo simulations using a diluted AF layer.[11]

Recently, it has been demonstrated for Co/Pt multilayers[12–14] and for FePt alloys,[15] that ion irradiation is an excellent tool to modify magnetic properties locally, without modifying the sample topography. Ion irradiation induces atomic displacements and hence causes remanent modifications of the magnetic properties. In the case of exchange bias systems it was shown that ion irradiation of a sample showing exchange biasing can modify the bias field strength, depending on the ion dose and energy.[16,17]

In this communication, we report on ion irradiation experiments on an exchange bias system in the presence of an external field. We illustrate that the exchange bias field can be designed both in direction and magnitude. Its direction is adjusted by the direction of the external field during irradiation. Depending on the ion dose the strength of the exchange bias field can be enhanced or reduced compared to the initial strength after preparation. The results are discussed by introducing a phenomenological model to describe the dependence of the bias field on the density of defects created by bombardment in the bulk AF layer and at the F/AF interface. Our results have implications on the understanding of the interaction between impinging ions and the spin distribution in the exchange bias system. Moreover, from the technological point of view, the effect allows to tailor the direction of exchange biasing and thus the orientation of the pinned layer in a spin-valve, in, e.g., a magnetic sensor element.

We chose the FeNi/FeMn exchange bias system.[16,17] The samples were prepared in an ultrahigh vacuum system with a base pressure of 5×10^{-10} mbar. A 5 nm thick $Fe_{0.19}Ni_{0.81}$ layer (F) and a 10 nm thick $Fe_{0.5}Mn_{0.5}$ (AF) layer were grown onto a thermal oxidized Si substrate with a 35 nm thick Cu buffer layer. Finally, a 2 nm thick Cr layer was deposited to prevent the samples from oxidation. All layers were grown at room temperature. The samples are polycrystalline with a strong (111) texture. After the deposition the samples were heated and subsequently cooled in a magnetic field $H_{prep}=500$ Oe below the Néel temperature to initialize the exchange bias field.

The magnetic properties were investigated *ex situ* by longitudinal magneto-optical Kerr-effect (MOKE) magnetometry. Initially, the samples were characterized prior to the irradiation process. The exchange bias field, H_{eb}, and the coercive field, H_C, were found to be homogeneous across each sample. Figure 1(a) shows a typical hysteresis loop measured parallel to the preparation field direction, H_{prep}. The preparation field is indicated in all figures by a bold arrow. An initial exchange bias field, $H_{eb,initial}$, of -190 Oe is found. The half width of the hysteresis loop is 22 Oe, which is considerably enhanced over the coercive field of the respective single FeNi film value.

After magnetic characterization 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 sample were realized by adjusting the beam current (10–100 n*A*) and by varying the irradiation time (3–120 s), covering the ion dose range (2×10^{13}–10^{16}) ions/cm^2. During the ion irradiation process an external magnetic field of $\approx$1000 Oe was applied in the film plane either parallel (H_P) or antiparallel (H_{AP}) to H_{prep}, indicated by thin arrows, in Figs. 1–3. In order to reduce the experimental error in the results caused by the use of different samples, consecutive ion doses are prepared on different areas of the same sample.

In Figs. 1(b) and 1(c) hysteresis curves are shown after He irradiation in an external magnetic field in the geometries parallel (H_P) and antiparallel (H_{AP}) to H_{prep}, as sketched

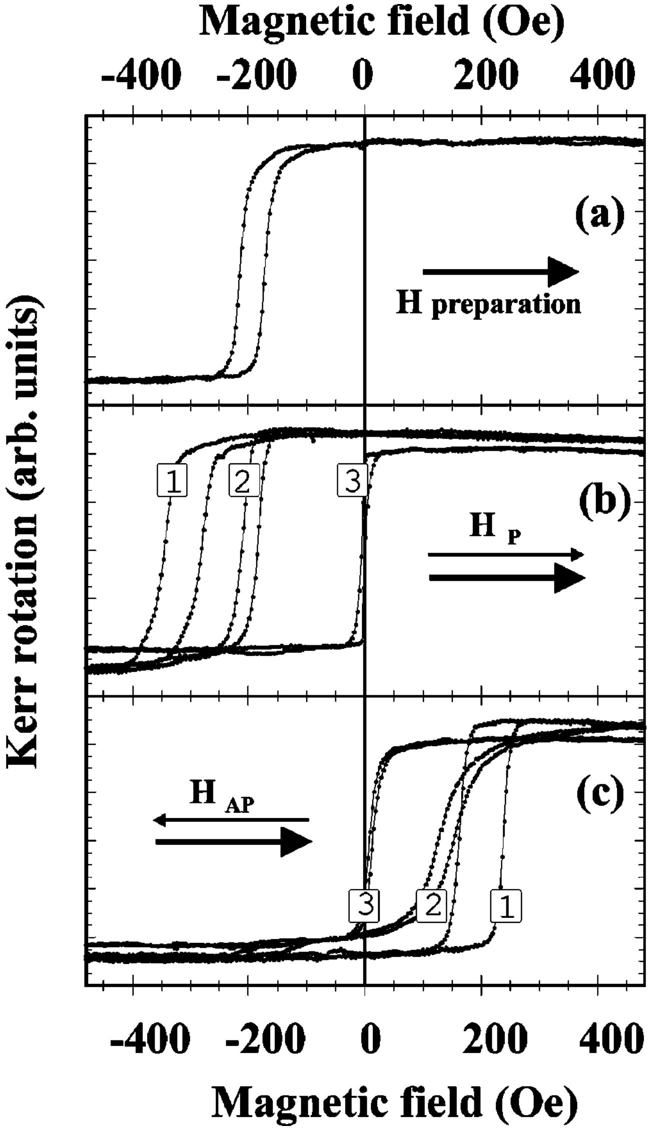

FIG. 1. Hysteresis curves for FeNi/FeMn exchange bias samples measured at room temperature. (a): hysteresis curve of a sample prior to He irradiation. The field direction during preparation is indicated by a bold arrow. (b) and (c): hysteresis curves after irradiation in an external field parallel H_P and antiparallel H_{AP} to the preparation field direction H_{prep}. The field directions applied during irradiation are indicated by a thin arrow. The numbers correspond to different doses. In (b) (irradiation field parallel to H_{prep}): 1: 0.25×10^{15} ions/cm^2, 2: 1.32×10^{15} ions/cm^2, and 3: 9.5×10^{15} ions/cm^2. In (c) (irradiation field antiparallel to H_{prep}): 1: 0.25×10^{15} ions/cm^2, 2: 0.9×10^{15} ions/cm^2, and 3: 9.5×10^{15} ions/cm^2.

in the figure. The numbered curves correspond to successively increasing ion doses as listed in the caption. When the irradiation is performed in the H_P geometry [Fig. 1(b)], a low ion dose of 2.5×10^{14} ions/cm^2 (1) leads to an enhanced shift of the hysteresis loop with respect to the initial one [cf. Fig. 1(a)], similar to the results of irradiation without any external field.[17] A further increase of the ion dose leads to a reduction (2) and finally to a full suppression (3) of the absolute exchange bias field.

In the H_{AP} geometry, as is displayed in Fig. 1(c), the

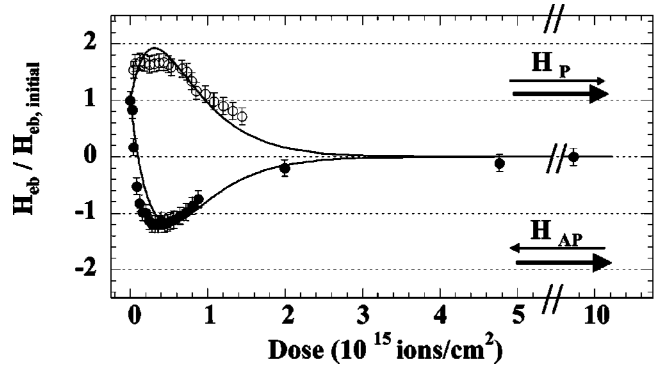

FIG. 2. Normalized exchange bias field, $H_{eb}/H_{eb,initial}$, as a function of ion dose. Open (full) symbols are extracted from the hysteresis curves measured for samples irradiated in an external field parallel (H_P) and antiparallel (H_{AP}) to the preparation field, H_{prep}. The solid lines are the result of a model fit as discussed in the text.

hysteresis loops are remarkably shifted to the opposite side with respect to that of the as-grown sample. Note that the value of the exchange bias field is enhanced in the low dose regime (1) compared to the initial absolute value. A further increase of the ion dose leads to a reduction of the absolute exchange bias field value (2). Finally, for a high ion dose the exchange bias field is fully suppressed (3). Irrespective of the sign, the overall course of the exchange bias field is similar

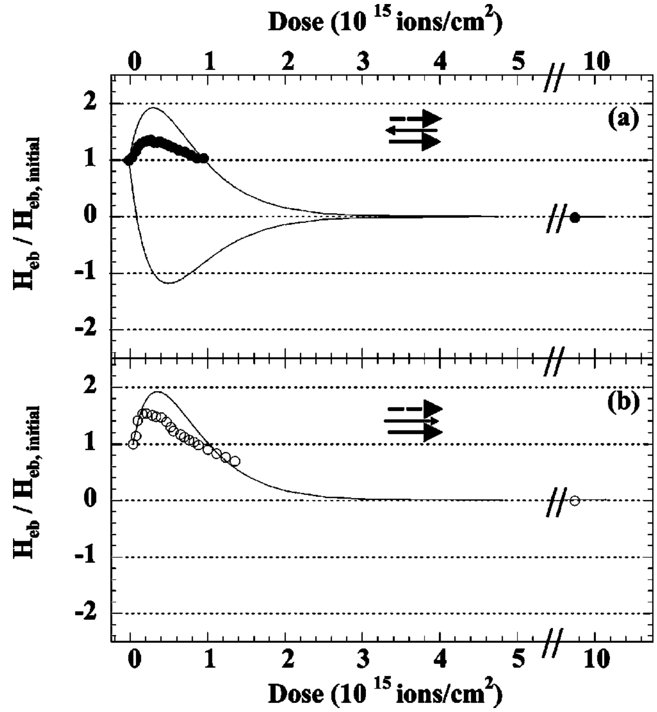

FIG. 3. Normalized exchange bias field as a function of ion dose. After completing the magnetic characterization shown in Fig. 2 the samples were annealed at 230 °C in an applied field parallel to H_{prep}. The annealing field direction is indicated by the dashed arrows. Full (open) symbols are extracted from the corresponding hysteresis curves after the annealing process for the H_{AP}(a) and H_P (b) cases. For comparison the thin solid lines represent the results of the fits from Fig. 2.

in both irradiation configurations. Measurements at different elevated temperatures show that the blocking temperature is 155 °C regardless of the ion dose.

In order to analyze the experimental findings more quantitatively the exchange bias field normalized to the field before ion irradiation, $H_{eb}/H_{eb,initial}$, is plotted as a function of ion dose in Fig. 2. Open (full) symbols denote the H_P (H_{AP}) irradiation geometry. Two different regimes are identified in the H_P geometry: (i) in the low dose regime a pronounced increase by about 75% of H_{eb} is found. (ii) For doses larger than 7.5×10^{14} ions/cm^2 the evolution is reversed and H_{eb} is reduced. In the H_{AP} geometry very low ion doses are sufficient to change the sign of H_{eb}. Upon irradiation with an ion dose of 2×10^{14} ions/cm^2 the initial absolute value of H_{eb} is recovered with the opposite sign. A maximum of the absolute value of the exchange bias field is found for 3.5×10^{14} ions/cm^2. A successive increase of the ion dose leads to a similar suppression of the effect as in the H_P geometry. The dependence of the coercive field (cf. Fig. 1) on the ion dose is similar to that of the exchange bias field.

The experimental observations can be understood considering the ion induced structural modifications. The ions loose progressively energy along their trajectories. In the case of He ions accelerated by 10 kV along its trajectory each ion only displaces a few tens of atoms by nuclear collisions and stops at about 90 nm beneath the sample surface deep in the substrate.[18]

Next, we model the experimental findings. In the following, n_V and n_I denote the normalized densities of defects in the bulk AF layer and at the interface. If all atoms of the AF volume have been displaced, $n_V=1$. We make the following two assumptions: (i) the magnitude of the exchange bias effect is linearly proportional to the number of displaced atoms in the bulk of the AF layer. This is in agreement with current models of the exchange bias effect, which assume domain walls in the AF layer and predict, that H_{eb} is proportional to the number of domain walls.[11] The domain-wall number is proportional to the number of defects generating them.[11] (ii) Defects created at the interface (normalized defect density n_I) are mostly exchanges of atoms across the interface (interfacial mixing), which reduce the effective exchange coupling across the F/AF interface.[16] We model this effect by an exponential decrease of the exchange coupling as a function of n_I.[19,20] Then the normalized exchange bias field can be written as:

$$H_{eb}/H_{eb,initial}(N)=[1\pm a n_V(N)]\times\exp[-b n_I(N)] \quad (1)$$

with N the number of impinging ions and a (b) the efficiency of the volume (interface) defects to modify the exchange bias field magnitude. In the first factor the + (−) sign corresponds to irradiation in an applied field parallel (antiparallel) to H_{prep}. We assume that the exchange bias originates from the imbalance between different domains in the AF layer resulting in a net exchange field acting on the F layer, as commonly used.[6–10] In the H_P geometry the imbalance is reinforced, whereas in the H_{AP} geometry the imbalance is progressively reversed. In the next step the corresponding normalized defect densities have to be determined. n_V is calculated solving the rate equation:

$$\frac{dn_V(N)}{dN}=pt[1-n_V(N)] \quad (2)$$

with p the probability of displaced atom per incoming ion and per length unit calculated from TRIM simulations,[18] and t is the AF layer thickness. In the limit $n_V\ll1$ we obtain: $n_V\approx ptN$. pt is evaluated from a simple integration over the total AF thickness.[18] Since each impinging ion penetrates through the interface, the normalized interface defect density is given by $n_I(N)=\gamma N$ with γ a proportionality factor. Then, the normalized exchange bias field satisfies the equation

$$H_{eb}/H_{eb,initial}(N)=(1\pm aptN)\times\exp(-b_I N) \quad (3)$$

with $b_I=\gamma b$. Only two free parameters (a, b_I) are needed in a fit procedure to reproduce the two sets of data points simultaneously in the H_P and in the H_{AP} geometry. The solid lines in Fig. 2 correspond to this model with $a=2.7$ and $b_I=2.5$. In the low dose regime the formation of bulk defects in the AF layer is responsible for the increase of H_{eb}, whereas interfacial mixing is only of minor importance. This enhancement of H_{eb} is in agreement with recent studies by Miltenyi *et al.*,[11] which showed that the increase of H_{eb} is caused by the creation of pinning sites in the AF layer generated by a low concentration of nonmagnetic defects. A successive increase of the ion dose leads to an enhanced amount of interfacial mixing that reduces the exchange coupling and thereby reduces H_{eb}. When H_{eb} is suppressed, an observed slight reduction of the Kerr rotation and small angle x-ray data are consistent with the interfacial mixing process between the F and the AF layer.[16]

Finally to rule out temperature effects we address the problem of the degree of irreversibility of the irradiation induced modifications of the exchange bias field. The experimental procedure involves two steps: First the sample is initialized and then irradiated in the H_{AP} or the H_P geometry. Second, the sample is annealed at 230 °C in an applied field parallel to H_{prep} to reinitialize the exchange bias field in its original direction. The obtained normalized exchange bias field is displayed as a function of the dose in Fig. 3. Full (open) symbols correspond to the H_{AP} (H_P) geometry. For comparison, thin solid lines represent the result of the calculations that reproduce the experimental data of Fig. 2. Results for the H_{AP} geometry are shown in Fig. 3(a). By the reinitialization process the exchange bias field, which was reversed by irradiation in the first step, is again switched back into the initial direction. The thermal annealing process acts as thermal magnetic initialization. Nevertheless, most of the pinning sites in the bulk of the AF layer generated in step one are preserved, and thus the overall dependence of the exchange bias field on the irradiation dose remains. This is also the case for the H_P geometry [Fig. 3(b)]. However, in both cases, in the dose regime $(0.1-1.5)\times10^{15}$ ions/cm^2 a reduction of the absolute normalized exchange bias field is observed in comparison to the data in Fig. 2. In order to fit the set of data after annealing with the above described model, the parameter a, describing the efficiency of an impinging ion to modify the exchange bias field via bulk defects in the AF layer, is decreased to $a = 1.7$, whereas the b_I parameter, describing the interfacial mixing contribution, is preserved, as expected. The reduction of a is attributed to a partial removal of the pinning sites caused by the annealing process. In order to understand the intrinsic mechanisms on the atomic level further investigations are required. Probably induced local strains and magneto-elastic effects have to be considered.[21]

In conclusion, we have demonstrated that the exchange bias field can be tailored both in direction and in magnitude by He ion irradiation. The dependence of the exchange bias field as a function of ion dose is consistent with a simple model based on a competition between defect creation in the AF layer and interfacial mixing .

Fruitful discussions with R.L. Stamps and H. Bernas are gratefully acknowledged. We thank S. Robert, Laboratoire de Physique des Matériaux of Nancy, for assistance in x-ray measurements. This work was partly supported by the EC-TMR program ''Dynaspin'' No. FMRX-CT97-0124.

*Corresponding author. Email address: fassbend@physik.uni-kl.de

[1] J. Nogues and I.K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).

[2] W.H. Meiklejohn and C.P. Bean, Phys. Rev. **102**, 1413 (1956); **105**, 904 (1957).

[3] C. Tsan, J. Appl. Phys. **55**, 2226 (1984).

[4] B. Dieny, V.S. Speriosu, S.S.P. Parkin, B.A. Gurney, D.R. Wilhoit, and D. Mauri, Phys. Rev. B **43**, 1297 (1991).

[5] D. Mauri, H. Siegmann, P.S. Bagus, and E. Kay, J. Appl. Phys. **62**, 3047 (1987).

[6] A.P. Malozemoff, Phys. Rev. B **35**, 3679 (1987); J. Appl. Phys. **63**, 3874 (1988).

[7] N.C. Koon, Phys. Rev. Lett. **78**, 4865 (1997).

[8] T.C. Schulthess and W.H. Butler, Phys. Rev. Lett. **81**, 4516 (1998); J. Appl. Phys. **85**, 5510 (1999).

[9] M.D. Stiles and R.D. Mc Michael, Phys. Rev. B **59**, 3722 (1999).

[10] K. Takano, R.H. Kodama, A.E. Berkowitz, W. Cao, and G. Thomas, Phys. Rev. Lett. **79**, 1130 (1997).

[11] P. Miltenyi, M. Gierlings, J. Keller, B. Beschoten, G. Güntherodt, U. Nowak, and K.D. Usadel, Phys. Rev. Lett. **84**, 4224 (2000).

[12] C. Chappert, H. Bernas, J. Ferré, V. Kottler, J.P. Jamet, Y. Chen, E. Cambril, T. Devolder, F. Rousseaux, V. Mathet, and H. Launois, Science **280**, 1919 (1998).

[13] T. Aign, P. Meyer, S. Lemerle, J.P. Jamet, J. Ferré, V. Mathet, C. Chappert, J. Gierak, C. Vieu, F. Rousseaux, H. Launois, and H. Bernas, Phys. Rev. Lett. **81**, 5656 (1998).

[14] T. Devolder, C. Chappert, Y. Chen, E. Cambril, H. Bernas, J.P. Jamet, and J. Ferré, Appl. Phys. Lett. **74**, 3383 (1999).

[15] D. Ravelosona, C. Chappert, V. Mathet, and H. Bernas, Appl. Phys. Lett. **76**, 236 (2000).

[16] T. Mewes, R. Lopusnik, J. Fassbender, B. Hillebrands, M. Jung, D. Engel, A. Ehresmann, and H. Schmoranzer, Appl. Phys. Lett. **76**, 1057 (2000).

[17] A. Mougin, T. Mewes, R. Lopusnik, M. Jung, D. Engel, A. Ehresmann, H. Schmoranzer, J. Fassbender, and B. Hillebrands, IEEE Trans. Magn. (to be published).

[18] SRIM 2000 code, J.F. Ziegler, J.P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon, New York, 1985).

[19] N.J. Gökemeijer, T. Ambrose, and C.L. Chien, Phys. Rev. Lett. **79**, 4270 (1997).

[20] T. Mewes, B.F.P. Roos, S.O. Demokritov, and B. Hillebrands, J. Appl. Phys. **87**, 5064 (2000).

[21] J. Ferré, B. Briat, R.H. Petit, R.V. Pisarev, and J. Nouet, J. Phys. (France) **37**, 503 (1976).