On the mechanism of irradiation-enhanced exchange bias

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PACS. 75.70.Cn – Magnetic properties of interfaces.
PACS. 61.80.Jh – Ion irradiation effects.
PACS. 75.30.Gw – Magnetic anisotropy.

Abstract.

By means of layer resolved ion irradiation the mechanisms involved in the irradiation driven modifications of the exchange bias effect in NiFe/FeMn bilayers have been investigated. It is shown that not only the locations of the defects but also the magnetic coupling between both layers during the irradiation process is of crucial importance. This requires an extension of current models accounting for defects in exchange bias systems.

Introduction.

The magnetic exchange interaction between an antiferromagnetic (AF) and a ferromagnetic (F) layer can lead to the so-called exchange bias effect [1]. The most prominent feature is a shift of the hysteresis loop along the field axis. It is widely exploited in applications like angular sensors and magnetic memory cells to provide a fixed reference direction in one of the two magnetic layers of a magnetoresistive device.

Several models have been proposed that account for various related phenomena [2,3,4,5,6], taking into account domains in the AF layer either parallel or perpendicular to the layer plane. Though a complete understanding of the effect on the microscopic scale is still under discussion, it is generally agreed upon that exchange bias is very sensitive to the structural properties of the AF layer and its interface to the F layer. A good demonstration of this sensitivity has been performed either by diluting the AF layer with non-magnetic atoms [7,8] or by ion irradiation of the whole layer system with light ions of several keV energy [9]. In both cases an enhancement of the exchange bias field over the initial value was observed. Additionally, it has been demonstrated that irradiation can be used to adjust the pinning direction of the exchange bias effect [9].

In order to understand the ion dose dependence of the exchange bias field, a phenomenological model has been proposed [9]. It takes into account structural effects in the AF layer, similar to the suggestions in Ref. [7], as well as at its interface with the F layer.

In the present work we focus on the mechanisms responsible for the change of the exchange bias field magnitude during ion irradiation. By performing the irradiation process between deposition steps without breaking the UHV environment, the effects of bombardment are limited to specific regions of the layer stack. Thus, a first experimental proof of the role of the defect position within the bilayer as suggested in the proposed model [9] is provided.

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addition to this model, irradiation experiments at elevated temperatures demonstrate that the enhancement of the exchange bias field is driven by the magnetic coupling between the layers. An alternative approach to the modification mechanisms is suggested.

Before going into the details of the experiments, we will provide a short summary of the model described in Ref. [9]. It is assumed that the ion induced modifications have different effects on the exchange bias depending on their vertical placement within the layer stack. Defects created in the volume of the AF layer are supposed to act as pinning sites for AF domain walls. These pinning sites reduce the energy necessary to create new domain walls, thus increasing the density of walls upon irradiation and decreasing the average size of the domains. According to random-field models this leads to a larger shift field, see, e.g., Ref. [2]. In first approximation, this is described by the relation 

\[ H_{eb}(n) \propto (1 + aptn), \]

with \( n \) the ion dose, \( t \) the AF layer thickness, \( p \) the efficiency of defect creation and \( a \) describing the efficiency of a volume defect to change the bias field. \( p \) is calculated using the SRIM code [10].

Second, the ion bombardment leads to a mixing of the AF/F interface which will suppress the exchange bias due to broken exchange interaction across the interface. This is described by an exponential decay with dose: 

\[ H_{eb}(n) \propto \exp(-b_I n), \]

with \( b_I \) describing the efficiency of an interface defect to change the bias field. The total dose dependence therefore is given by

\[ H_{eb}(n)/H_{eb}(0) = (1 + aptn) \cdot \exp(-b_I n). \]  

For a more detailed description see Ref. [9].

Experiments. – The studied samples are polycrystalline and have been prepared by thermal evaporation in a UHV system with a base pressure of \( 5 \cdot 10^{-10} \) mbar. A 150 Å thick Cu buffer layer has been deposited on top of an oxidized Si substrate. For the F (AF) layer, 50 Å (100 Å) of Ni\textsubscript{81}Fe\textsubscript{19} (Fe\textsubscript{50}Mn\textsubscript{50}) has been used. The stacking sequence of these two layers has no significant effect on the observed exchange bias or the dose dependence after irradiation. Finally the sample is covered with 20 Å of Cr to protect it from oxidation. For the ion bombardment a commercial sputter gun has been used which is attached to the same vacuum system and is operated with 5 keV He ions. The base pressure during irradiation is \( 5 \cdot 10^{-8} \) mbar. The sample is exposed to different ion doses at several areas by scanning the ion beam and changing exposure time. The ion current is controlled by a Faraday cup. Transmission electron microscopy (TEM) studies have been performed to check for changes in microstructure and texture after irradiation of the whole layer stack. At a dose of \( 2 \cdot 10^{15} \) ions/cm\(^2\) giving the maximum enhancement no changes have been detected.

In the first experiment, the influence of ion bombardment on the AF/F interface was studied. For this purpose, a sample was prepared with the F layer grown before the AF layer. Growth of the AF layer was stopped at a thickness of 15 Å. At this thickness the interface is well defined but the sample exhibits neither a bias shift nor an enhancement of coercivity yet. Several areas with ion doses ranging from \( 9 \cdot 10^{13} \) to \( 2 \cdot 10^{16} \) ions/cm\(^2\) were irradiated. During the bombardment a field of 30 Oe was applied to saturate the F layer. Next, the deposition of the AF layer was completed to obtain a total thickness of 100 Å. A scheme of the experiment is shown in Fig. 1. After growth the sample was heated above the blocking temperature to 200°C and cooled in an applied field of 250 Oe to initialize the exchange bias. Magnetic characterization was performed by longitudinal magneto-optical Kerr effect (MOKE) magnetometry. It should be stated that the absolute value of \( H_{eb} \) at zero dose is reduced to 80 Oe in this sample compared to typical values of 180 Oe in cases where growth of FeMn has not been interrupted. This is probably due to a residual contamination of the surface during irradiation reducing the overall coupling. However, this value is still one order of magnitude larger than anisotropies which have been reported in single Ni\textsubscript{81}Fe\textsubscript{19} films [11]. Therefore,
Fig. 1 – Scheme of the experiments for investigation of defects in (a) the interface region only, (b) the volume AF layer only.

this does not affect the conclusions drawn in the following. In Fig. 2 the dose dependence of the normalized exchange bias field compared to a sample which has been irradiated after completed deposition is shown. An enhancement of the exchange bias field is only observed for the sample where all layers have been irradiated. In the case where the irradiation can only cause intermixing an enhancement is completely absent. This is the behaviour as expected from the model.

In a complementary experiment the effect of bombardment on the volume AF layer was studied. Therefore, the AF layer was grown first and irradiated with the same dose pattern as

Fig. 2 – Dose dependence of $H_{\text{eb}}$ normalized to the as-prepared value. The closed squares correspond to a sample that has been irradiated completely. The open circles belong to a sample where only the interface region has been modified, and triangles denote selective irradiation of the AF layer.
Fig. 3 – Dose dependence of $H_{eb}$ for a sample irradiated after complete preparation. The data represented by closed squares has been obtained by irradiating at room temperature, open circles correspond to irradiation at 260°C.

described above. Then the NiFe layer and the Cr protective layer were deposited. The sample was annealed under the same conditions as described above. It exhibits a shift field of 180 Oe on the non-irradiated areas. The exchange bias field has only a weak dependence on the ion dose in this case (Fig. 2 triangles). Especially, it does not decay to zero like it is observed in the previous experiment where the AF/F interface was present during irradiation (cf. Fig. 2 circles). Only a slight reduction of the bias field is observed.

This result leads to the conclusion that the F layer has to be present during irradiation for the enhancement mechanism to work. The question remains how the F layer affects the modification process. A pure thermal effect has already been ruled out by the fact that the enhancement of the shift field remains after an annealing process in opposite field direction [9]. Thus, only structural changes remain possible. The F layer can cause elastic stress/strain that influences the interaction of the atoms with the ions. Another reason could be that the magnetic interaction between both layers is required. In order to answer these questions, a third experiment was carried out.

A sample with the F layer deposited first was grown completely in one step and annealed afterwards. First, half of the sample area was irradiated at room temperature. Second, the other area of the sample was irradiated in an applied field at a temperature of 260°C. This temperature is above the Néel temperature of FeMn and thus the coupling between the AF spins is eliminated, whereas elastic forces, if existent, will persist. Afterwards, the whole sample was cooled in the same applied field to initialize the exchange bias effect. The resulting dose dependencies of $H_{eb}$ for both cases are shown in Fig. 3. Only the part of the sample which was irradiated with the antiferromagnetic order present shows an enhancement of the exchange bias field. The areas that were irradiated at 260°C only show a decay. Therefore elastic strains can be ruled out as the origin of the discussed enhancement mechanism.

Discussion. – The mechanism for reduction and suppression of the exchange bias effect by ion irradiation in the NiFe/FeMn system has clearly been identified to be caused by interactions of the ions with the atoms in the vicinity of the F/AF interface. This effect can be attributed to interface mixing. The modifications that cause the enhancement of the bias
field take place in the volume of the AF layer. These findings are consistent with the models proposed in Refs. [9,17].

Following the assumptions of Refs. [9,17], one expects a strong enhancement of the exchange bias field for the case of the latter experiment. Due to the induced defects, after a field-cooling procedure the AF layer should develop more domains compared to the as-prepared case and therefore exhibit stronger bias, especially as the suppression effect of interface mixing is avoided in this experiment. The F layer is not involved in this scenario at all. Yet, this behavior is not observed experimentally (see Fig. 2). Therefore, we conclude that the F layer has to be present during irradiation. The last experiment shows unambiguously, that the exchange bias enhancement is not due to potential elastic effects caused by the presence of the F layer. In contrast, we conclude that both the magnetic order in the AF layer and the exchange coupling to the F layer are necessary for the enhancement mechanism to work.

Our results can be understood in terms of the proposed model if one assumes that the placement and/or type of defects is not completely random but to some extent steered by the anisotropic forces in the AF. In the creation process of a pinning site it arranges in a way, that minimizes the total energy of the system. Because of the exchange coupling this also includes the energy of the F layer in a field. Since in all experiments the F layer was saturated either by the internal bias field or an external field, the arrangement of the defects will take place in a fashion where the total energy is minimized resulting in a higher shift field [9]. If the spin system of the AF layer is disordered during irradiation or, equivalently, the F layer is missing, defect placement occurs randomly. In the first case the disordered AF layer fails to couple to the saturated F layer providing the preferred direction. In the second case, there is no preferred direction. In both cases no enhancement is observed. This data fits to recent simulations where defects were modeled as local enhancement of the uniaxial anisotropy of the AF layer [12]. An enhancement of the bias field was only found when the anisotropy axes are aligned. Defects with random anisotropy axes caused a reduction of the bias field.

The relevance of the magnetic forces is especially intriguing as the amount of energy placed into the layers by the ions (i.e. several eV/monolayer according to SRIM simulations [10]) is large compared to the magnetic energies involved. The exact mechanism of the interactions between ions and target atoms in these structures needs to be determined.

In conclusion, we have shown that the observed enhancement of the exchange bias field in irradiated NiFe/FeMn bilayers is caused by modifications of the bulk AF layer. It cannot be explained in terms of a pure statistical domain size argument, and in this point it differs from the phenomena observed in diluted antiferromagnets. The influence of the magnetic exchange force across the F/AF interface has to be taken into account. The suppression of the exchange bias effect is attributed to changes at the F/AF interface.

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Fruitful discussions with R. L. Stamps and M. D. Stiles are gratefully acknowledged. We thank D. McGrouther and S. Blomeier for valuable help with the TEM studies. The work is supported in part by the European Communities Human Potential programme under contract number HPRN-CT-2002-00296 NEXBIAS and by the Deutsche Forschungsgemeinschaft.

REFERENCES

[1] Meiklejohn W. H. and Bean C. P., Phys. Rev., 102 (1956) 1413.
[2] Malozemoff A. P., Phys. Rev. B, 35 (1987) 3679.
[3] Koon N. C., Phys. Rev. Lett., 78 (1997) 4865.
[4] Schulthess T. C. and Butler W. H., *J. Appl. Phys.*, **85** (1999) 5510.
[5] Kiwi M., Mejia-Lopez J., Portugal R.D and Ramirez R., *Appl. Phys. Lett.*, **79** (1999) 3995.
[6] Nowak U., Usadel K. D., Keller J., Miltényi P., Beschoten B. and Güntherodt G., *Phys. Rev. B*, **66** (2002) 014430.
[7] Miltényi P., Gierlings M., Keller J., Beschoten B., Güntherodt G., Nowak U. and Usadel K. D., *Phys. Rev. Lett.*, **84** (2000) 4224.
[8] Shi H., Lederman D. and Fullerton E., *J. Appl. Phys.*, **91** (2002) 7763.
[9] Mougin A., Mewes T., Jung M., Engel D., Ehresmann A., Schmoranzer H., Fassbender J. and Hilebrands B., *Phys. Rev. B*, **63** (2001) 060409R.
[10] Ziegler J. F., Biersack J. P. and Littmark U., *The Stopping and Range of Ions in Solids* (Pergamon, New York, Oxford) 1985.
[11] Woods S. I., Ingvarson S., Kirtley J. R., Hamann H. F. and Koch R. H., *Appl. Phys. Lett.*, **81** (2002) 1267.
[12] Kim J. V. and Stamps R. L., *Appl. Phys. Lett.*, **79** (2001) 2785.