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Suppression of exchange bias by ion irradiation

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The exchange bias effect in ferromagnetic/antiferromagnetic sandwich structures is generally believed to be sensitive on the interface exchange interaction, the magnetization, and the thickness of the ferromagnetic layer. Also the interface structure plays a crucial role. We show that, by irradiating samples with He ions, we can manipulate the exchange bias field in a controlled manner. Depending on the dose (10^{14}–10^{17} ions/cm^2) and the acceleration voltage (10–35 kV) of the ions, the shift of the hysteresis can be reduced or even fully suppressed. Potential applications of this effect for magnetic patterning on the nanoscale will be discussed. © *2000 American Institute of Physics.* [S0003-6951(00)03608-1]

Ion irradiation of magnetic multilayer structures is known to alter their magnetic behavior.[1,2] Recently it has been shown that the perpendicular interface anisotropy of Co/Pt multilayers can be modified by He ion irradiation leading to a change in the easy direction of magnetization from perpendicular to in-plane with respect to the film plane.[3,4] The authors attribute this effect to a small amount of atoms displaced by the irradiation. Thus the perpendicular interface anisotropy is reduced and the magnetization reversal is governed by the shape anisotropy, which favors an in-plane orientation of the magnetization. One main conclusion is that perpendicularly magnetized samples, important for magneto-optic storage devices, can be magnetically patterned on a length scale below 50 nm, without changing the topography of the sample.[4]

We report a magnetic patterning process based on ion irradiated exchange bias films, where the patterning is achieved already at very low doses.

The exchange bias effect manifests itself in a shift of a hysteresis loop with respect to the applied magnetic field axis. When a sandwich of a ferromagnetic (F) and an antiferromagnetic (AF) layer is prepared in an applied magnetic field, or when it is heated above the Néel temperature (which is lower than the Curie temperature) and subsequently cooled in a field, the spin arrangement in the AF layer contains information about the direction of magnetization in the F layer. The exchange interaction at the interface acts as an internal field and the magnetization reversal of the F layer is shifted by a so-called exchange bias field, H_{eb}. This effect has been known for a long time[5] and a number of different models[6–9] have been proposed to explain its nature. Since the exchange bias effect is very sensitive to the interface,[10] small modifications could cause considerable changes in the exchange bias field and the coercive field.

In this letter, we present experimental results demonstrating that the value of the exchange bias field as well as the coercivity can be modified over a large range by ion irradiation in a controlled manner by adjusting the dose and the acceleration voltage of the ions. A suppression of the exchange bias field to a desired value is achievable. A mechanism for the suppression of the exchange bias field will be presented.

We chose the well known FeNi/FeMn exchange bias system as a model system.[11] All samples were prepared in a ultrahigh vacuum (UHV) system with a base pressure of 5×10^{-10} mbar. As a substrate, we used chemically cleaned, thermally oxidized Si wafers with a 20 nm FeMn buffer layer. Subsequently a sandwich of a 5 nm FeNi (F) and a 10 nm FeMn (AF) layer were grown on top. Finally a 2 nm Cr layer was deposited to prevent the samples from oxidation. Note that the FeMn buffer has been chosen in order to create symmetric interfaces and that the use of a Cu buffer has been shown not to alter the main conclusions drawn. The thicknesses and composition of the films were carefully controlled by a calibrated quartz crystal oscillator. All constituent layers of the structure but the FeNi layer (200 °C) were grown at room temperature. During the growth, a magnetic field of 50 Oe was applied in the film plane in order to create a single domain state in the F layer and thus to generate the exchange bias field. After the preparation, the magnetic properties, especially their homogeneity, were controlled *ex situ* by laterally resolved longitudinal magneto-optical Kerr-effect (MOKE) measurements.

Ion irradiation was performed using a system described in detail elsewhere.[12] He gas is ionized in a penning source and the ions are accelerated by up to 60 kV. An electrostatic single pole lens is used to focus the ion beam on a final aperture close to the sample. To achieve an exact irradiation dose a beam blanker is positioned between the lens and the final aperture. With the aperture set to 1.3 mm diameter, a beam current of 2 μA was achieved, corresponding to an ion dose rate of 10^{15} ions/(s cm^2) at an acceleration voltage of 30 kV. Other doses on the samples have been realized by ad-

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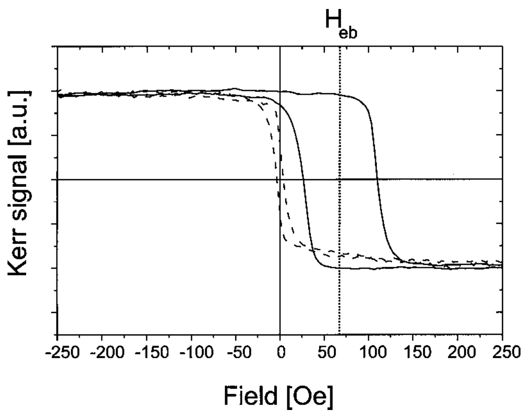

FIG. 1. Typical hysteresis loops of an exchange bias sample before (straight line) and after (dashed line) irradiation. Prior to the irradiation the sample shows an exchange bias field value of $H_{eb}=69$ Oe and a coercive field of $H_c=42$ Oe, whereas for a dose of 8.5×10^{16} ions/cm^2 (dashed line) the exchange bias and the coercive field are reduced to $H_{eb}=0.7$ Oe and $H_c=4$ Oe, respectively. Note that the magnitude of the Kerr rotation remains unaffected by the irradiation.

justing the beam current (0.01–2 μA), depending on the accelerating voltage, and varying the irradiation time (3–300 s). With this parameter set, it was possible to cover the ion dose range from 10^{12} to 10^{17} ions/cm^2. Different ion doses at the same acceleration voltage are applied to one single sample by irradiating different areas of the sample (cf. schematic layout in Fig. 2).

In Fig. 1 the effect of the ion irradiation on the magnetization reversal process can clearly be seen in the MOKE hysteresis loops. As expected, the as-grown hysteresis loop (solid line) exhibits an exchange bias field of $H_{eb}=69$ Oe and a coercive field of $H_c=42$ Oe. In Fig. 1 a hysteresis loop measured after irradiation with a dose of 8.5×10^{16} ions/cm^2 is shown by a dashed line. The exchange bias field vanishes, and the coercive field $H_c=4$ Oe is comparable to an unbiased FeNi film, indicating that irradiation of the F layer itself does not modify the magnetic properties for the doses and energies considered here. Note that the magnitude of the Kerr rotation is not affected by the ion irradiation. After irradiation both values decrease depending on the dose (cf. Fig. 2).

In Fig. 2 a lateral scan across the sample through the

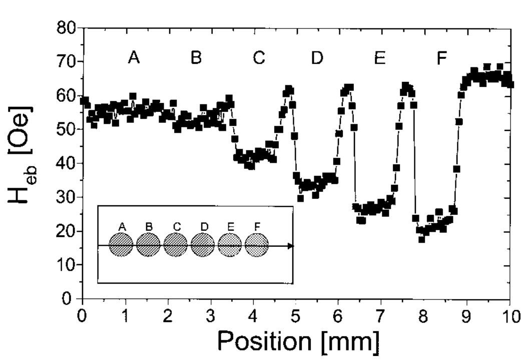

FIG. 2. Lateral scan across the sample through the centers of the irradiated areas. The exchange bias fields are extracted from the measured hysteresis loops and plotted as a function of the position on the sample. The acceleration voltage was 10 kV. The doses are in units of ions/cm^2: A: 1.4×10^{14}, B: 4.7×10^{14}, C: 9.4×10^{14}, D: 1.2×10^{15}, E: 1.9×10^{15}, F: 2.4×10^{15}. The inset shows a schematic sketch of the sample with the lateral scan indicated. The irradiated areas are shown by shaded areas.

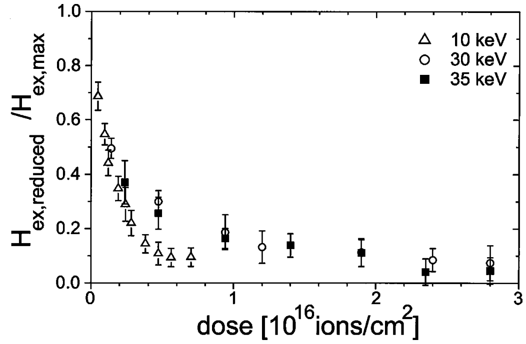

FIG. 3. Normalized exchange bias field as a function of ion dose for different acceleration voltages varying between 10 and 35 kV.

centers of the irradiated areas is shown, as indicated in the inset. The exchange bias field is extracted from the measured hysteresis loops and plotted as a function of the position on the sample. All nonirradiated areas exhibit a value of $H_{eb}=55-68$ Oe, whereas for the irradiated areas the exchange bias field and the coercive field (not shown in Fig. 2) are reduced by the ion dose. A number of scans are performed for samples irradiated at several acceleration voltages of the He ions and dose regimes on various exchange bias samples. The exchange bias fields are extracted by averaging the measured field values within the plateaus of the irradiated areas. Since different samples exhibit a slightly different exchange bias field, we have normalized the exchange bias field to its initial value (nonirradiated areas) in order to achieve a better comparison between the results obtained from different samples.

Figure 3 shows the normalized exchange bias field as a function of the ion dose. For all acceleration voltages of the He ions we find a pronounced decrease of the exchange bias field in the dose regime between 10^{14} and 10^{17} ions/cm^2. Even for a dose as low as 5×10^{14} ions/cm^2 a reduction of the exchange bias field value is observed. The main difference between irradiation with low (10 kV) and high (35 kV) acceleration voltages are the different slopes of the curves in Fig. 3, i.e., for an acceleration voltage of 10 kV lower doses are required for reducing the exchange bias field by the same amount than for 35 kV. This becomes immediately clear by considering the different penetration depths and energy losses for the different ion energies. At 35 kV the penetration depth for an individual ion is typically 350 nm, much larger than the total film thickness of the exchange bias system. By traversing the AF and the F layer, the ion loses energy mainly via electron interactions.[13] Only at the end of the ion trajectory the dominant interaction is via collisions with nuclei leading to a change of the crystallographic structure. Thus, at the interface between the F and AF layers the density of displaced atoms is rather low. For lower acceleration voltages (10 kV) the penetration depth is lower (100 nm), the interaction regime is located closer to the surface and thus the density of displaced atoms is increased (by a factor of 3). The reduction of the exchange bias field can thus be attributed to an increased interface intermixing leading to a decrease of H_{eb}. For Fe/F_2[10] and NiO/NiFe[14] films it was already observed, that an increased roughness leads to a decrease of H_{eb}. Sputtering or a temperature effect can be ruled out. Secondary ion mass spectroscopy (SIMS) measurements showed, that sputtering is only responsible for a tiny amount of milling of the Cr capping layer without any influence on the AF and F layers. Temperature effects have been excluded by two experimental observations: (i) Different areas on the sample were irradiated with a constant dose but with varying irradiation time intervals interrupted by blanking the ion beam for several seconds. No difference in the reduction of the exchange bias effect have been observed in the different areas. (ii) After completing the magnetic characterization the sample was brought back into a vacuum system and annealed at 230 °C in an applied field of the same magnitude (50 Oe) but opposite direction. Due to this procedure the exchange bias was reversed completely, i.e., the irradiated and nonirradiated areas exhibit the same values of the exchange bias field but with respect to the new (opposite) direction. However, the exchange bias field and the coercive field remain reduced in magnitude in the irradiated areas indicating a structural origin of the suppression. In the case of a temperature induced reduction annealing in an applied magnetic field would cause a restoration of the initial value of the exchange bias field.

To use ion irradiation for magnetic patterning[15] of an exchange bias system, the structural origin of the suppression is of large importance because of its local nature. Since the ion beam is collimated close to the surface and the nuclear damage cascade is located deep in the substrate, proximity effects are negligible and patterning becomes possible down to the smallest lateral sizes feasible by focused ion beam or, alternatively, the resolution of mask techniques. Possible applications are in the area of data storage and sensor devices, since for both a control of in-plane magnetized domains is essential. A large advantage is gained since a magnetic patterning is available without a topographic structure.

In summary, our experiments show the pronounced influence of ion irradiation both on the exchange bias field and on the coercive field. Depending on dose and acceleration voltage the values of both fields are reduced. This reduction is understood by the creation of interface intermixing. Potential applications for magnetic device structures have been discussed.

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