Magnetic patterning of exchange-coupled multilayers

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The local modification of antiferromagnetic (AF) interlayer exchange coupling by focused ion-beam irradiation has been studied experimentally in the epitaxial Fe/Cr/Fe(001) trilayer systems. Square ferromagnetic (FM) areas of $200\times200\ \mu m^2$ were created in the initially AF trilayer by ion irradiation with a fluence of 10^{15} ions/cm^2. It was found, that in the range of the external magnetic field of about ±200 Oe, the change of magnetic properties at the boundaries separating FM and AF areas occurs within distances of less than 200 nm. This fact allows the use of the technique for magnetic patterning of antiferromagnetically coupled trilayers on the submicrometer scale.
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The antiferromagnetic (AF) interlayer exchange coupling (IEC) between two ferromagnetic (FM) layers separated by a thin nonmagnetic spacer was discovered in 1986 by Grünberg *et al.*[1] Since then, this phenomenon has been intensively studied (for a recent review, see Ref. 2) because of its potential for the creation of antiferromagnetically coupled media for high-density magnetic recording[3,4] and artificial antiferromagnets that are used as hard magnetic electrodes in magnetic memory elements[5,6] and magnetoresistive sensors.[7] The IEC is mediated by the long-range interaction between the magnetic moments of two FM layers separated by a nonmagnetic spacer via conduction electrons of the latter. This coupling leads to the alignment of the magnetic moments of the two layers parallel, antiparallel, or at a certain angle relative to each other depending on the thickness of the spacer and on the states of the interfaces between the magnetic layers and the nonmagnetic spacer.[2]

Recently it was shown[8] that the type of the IEC between two iron layers separated by a chromium spacer can be easily modified by ion irradiation. This modification is a result of the atomic intermixing at the Fe/Cr interface caused by the dissipation of energy of ions due to their collisions within the crystalline lattice. The intermixing at the Fe/Cr interface leads to the appearance of microscopic "magnetic bridges" that connect the two iron films and provide strong direct local FM coupling between them. With increase of the irradiation fluence, the quantity of magnetic bridges increases and the type of interlayer coupling changes to the FM one. Since the direct coupling through a bridge is about hundred times stronger than that via conduction electrons, the density of bridges and, consequently, the ion fluences necessary to change the type of coupling are very small.[8] It is obvious that the modification of the IEC by means of ion irradiation provides a very convenient tool for local modification of magnetic properties of antiferromagnetically coupled trilayers. Due to the possibility to focus the ion beam down to very few tens of nanometers, the proposed technique opens the way for the creation of artificial magnetic media such as thin-film structures containing nanoscaled areas having different magnetic susceptibility. Moreover, due to the moderate ion penetration depth into standard photoresist, which usually does not exceed 50–100 nm, one can realize the ion nanopatterning using standard photoresist mask technology.

In this article, we present experimental results on the laterally resolved ion-beam modification of the IEC in Fe/Cr/Fe trilayers.

For the experimental investigation, samples were prepared consisting of two 10-nm-thick Fe(001) films separated by a 0.7-nm-thick Cr spacer. This particular thickness of the Cr spacer was chosen such that the AF coupling between the Fe layers was strong. The Fe/Cr/Fe(001) trilayers were epitaxially grown using an UHV molecular-beam epitaxy system on a MgO(001) substrate with a 80-nm-thick Cr buffer and covered by 3 nm of Cr in order to avoid corrosion. Finally the samples were irradiated using a focused ion-beam lithography machine. Irradiation with a fluence of 6.25×10^{15} ions/cm^2 was performed with 50-keV Ga^+ ions without an applied external magnetic field, with the samples being kept at room temperature. The ion beam focused down to approximately 100 nm was scanned along the surface of the sample, forming square-shaped irradiated areas with dimensions of $200\times200\ \mu m^2$ separated by 150-μm-wide nonirradiated space.[9] The diagonals of the irradiated squares were aligned along the easy magnetic axes of the fourfold magnetic anisotropy of the Fe(001) films.

The samples as prepared were studied using magneto-optical Kerr-effect (MOKE) magnetometry. The hysteresis loops were measured at different points of the samples. A magnetic field of up to 1.5 kOe was applied parallel to the easy magnetic axis. Typical results of the MOKE measurements are presented in Fig. 1, where the two hysteresis loops shown in parts (a) and (b) correspond to nonirradiated and irradiated areas, respectively. In order to illustrate the rotation of magnetization in the sample, the vector diagram is added to Fig. 1(a) showing the relative orientation of the

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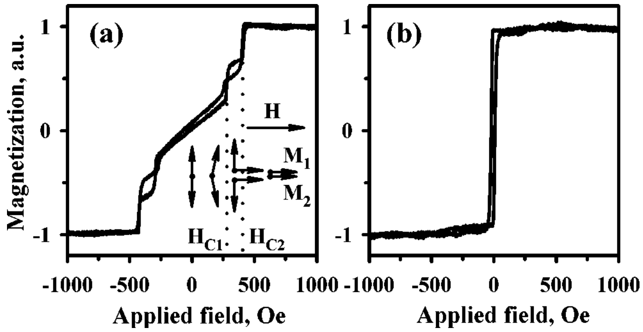

FIG. 1. Hysteresis loops for a nonirradiated (a) and an irradiated (b) area.

magnetic moments M_1 and M_2 of the two Fe layers for different values of the external magnetic field H. As seen from Fig. 1(a), the nonirradiated trilayer structure exhibits typical AF magnetization curves in the range of the external magnetic field of ± 250 Oe. In this range, the application of a magnetic field leads to a weak deviation of the magnetic moments M_1 and M_2 from their original antiparallel state, which results in the total magnetization of the trilayer increasing slowly with the increase of the field strength. As soon as the strength of the magnetic field reaches the critical value $H_{C1} \approx 250$ Oe, the total magnetization of the trilayer starts to increases stepwise. Such a behavior can be explained by a weak 90° IEC[10] coexisting in our samples with the strong AF one. As a result, the orientation of the magnetic moments of the layers at 90° with respect to each other becomes favorable in the range of magnetic fields from 250 to 450 Oe, and M_1 and M_2 lie in the directions of magnetic easy axes [see the vector diagram in Fig. 1(a)]. Finally, when the strength of the external magnetic field exceeds $H_{C2} \approx 450$ Oe, the trilayer becomes completely saturated. In contrast to the complicated magnetic behavior of the nonirradiated Fe/Cr/Fe trilayer, the irradiated trilayer simply exhibits a typical FM hysteresis loop [see Fig. 1(b)], with the coercive field equal to 20 Oe.

Next, magnetic force microscopy (MFM) measurements were performed in the regions situated close to the boundary between the irradiated and nonirradiated areas. For this purpose, a multifunctional scanning probe microscope was used (Solver AFM-MFM produced by NT-MDT Co.). The microscope contains a built-in electromagnet, which allows one to investigate the domain structure of samples placed in an external magnetic field.

Figure 2 shows the topography of a corner of the irradiated area. Figure 2(a) shows the general three-dimensional (3D) view of the corner, whereas Fig. 2(b) demonstrates the topographical profile along the X direction, as indicated in the figure. As seen from Fig. 2, in the irradiated areas, the surface of the film structure is elevated by about 2–3 nm relative to the nonirradiated ones. Close to the boundary, this elevation is stronger and amounts to about 6–8 nm. The observed elevation can be explained by crystalline defects appearing due to the penetration of the Ga ions into the crystalline lattice of the sample. Computer simulations of the irradiation process show that for the chosen irradiation parameters, most ions pass both magnetic layers and are stopped in the Cr buffer layer. Therefore, the magnetic layers are not significantly disturbed by the irradiation process, and

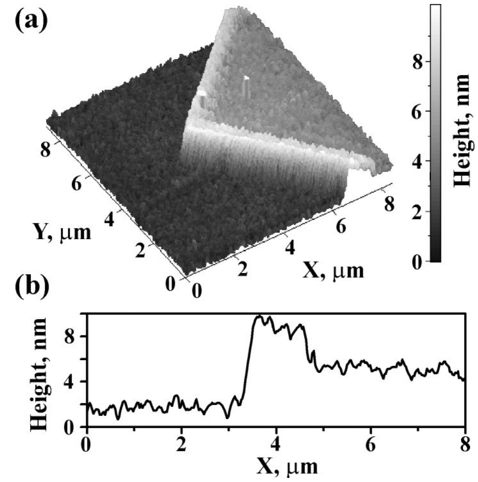

FIG. 2. Topography of a corner of the irradiated area measured by an atomic-force microscope. (a) The general 3D view. (b) The profile along the X direction.

the observed elevation of the surface does not indicate that considerable crystalline defects appear in the Fe/Cr/Fe trilayer. Instead, most of the defects are concentrated inside the Cr buffer layer, which becomes locally expanded.

Figure 3 presents the MFM images of the corner of the irradiated area obtained in weak external magnetic fields that do not significantly exceed the coercive field of the irradiated area. The four panels (a), (b), (c), and (d) of Fig. 3 correspond to the strengths of the applied magnetic field H equal to -30, 0, 5, and 30 Oe, respectively. The magnetic field was applied along one of the magnetic easy axes, which are shown in the figure by black arrows. As seen from Fig. 3(a), in the magnetic field of -30 Oe, the boundary between the irradiated and nonirradiated areas provides very strong magnetic contrast, whereas the remaining surface is magnetically uniform. Such a behavior is understood by the strong differ-

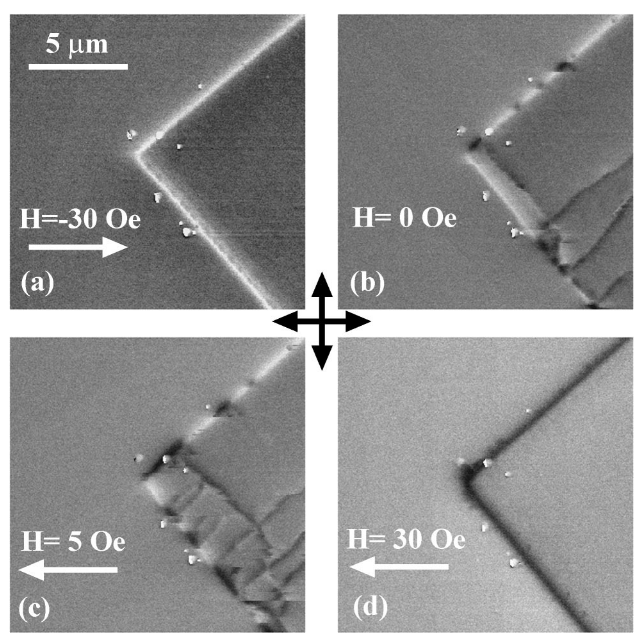

FIG. 3. MFM images of a corner of the irradiated area obtained in weak external magnetic fields: -30 Oe (a), 0 Oe (b), 5 Oe (c), and 30 Oe (d). The black arrows indicate the easy axes of the fourfold magnetic anisotropy of the Fe(001) films.

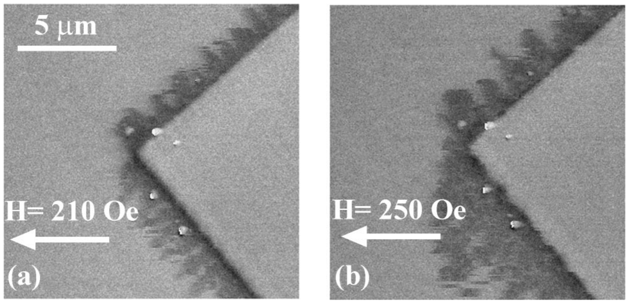

FIG. 4. MFM images of a corner of the irradiated area obtained in strong external magnetic fields: 210 Oe (a) and 250 Oe (b).

ence in magnetizations of the irradiated and nonirradiated areas. The completely saturated irradiated area produces strong magnetic stray fields at its edges when surrounded by the nonirradiated trilayer with small net magnetization. As the external magnetic field decreases to zero [see Fig. 3(b)], the irradiated area breaks up into domains, whereas the nonirradiated area remains uniform. As the magnetic field changes its direction and its strength increases again [see Figs. 3(c) and 3(d)], the domain structure in the irradiated area changes and finally disappears in a field exceeding 20 Oe, whereas the nonirradiated area does not demonstrate any visible change.

It is important to note here that for the whole range of magnetic fields between −30 and 30 Oe, the magnetic boundary between the irradiated and nonirradiated areas is seen very sharply. This indicates that the strong magnetic moment of the irradiated FM area does not have any considerable influence on the magnetization of the nonirradiated AF area in the boundary regions and, as a result, the change of magnetic properties at the boundaries between the irradiated and nonirradiated areas occurs within submicrometer distances. As the upper estimate for the length, on which the change of magnetic properties occurs, the length of localization of the magnetic stray field can be taken. From measurements a value of about 200 nm is estimated. Consequently, one can conclude that ion irradiation provides a useful method for magnetic patterning of Fe/Cr/Fe trilayers with a lateral resolution, which is in any case not worse than 200 nm.

Of particular interest is the change in the properties of the boundaries between the irradiated and nonirradiated areas as a function of the external magnetic field. The MFM measurements show that the magnetic boundaries remain well defined in magnetic fields of up to about ±200 Oe. As the field strength approaches H_{C1} [see Fig. 1(a)], the magnetic images of the boundary regions start to demonstrate qualitative changes. This fact is illustrated by Fig. 4, where the MFM images are shown measured for the strength of the magnetic field equal to 210 Oe (a) and 250 Oe (b). Unfortunately, in strong external magnetic fields, the domain structure of the sample cannot unambiguously be derived from the MFM measurements due to the rotation of magnetization of the MFM tip out of its axis. However, it is clearly seen from Fig. 4 that in the boundary region, the magnetization of the nonirradiated trilayer experiences a strong influence of the irradiated area. This phenomenon can be explained by an instability of magnetization of antiferromagnetically coupled nonirradiated trilayer in magnetic fields lying close to H_{C1}. Due to the presence of the 90° coupling, the alignment of the magnetic moments of the two Fe layers at 90° becomes favorable in the range of magnetic field between H_{C1} and H_{C1}. The strong magnetic stray field of the irradiated area stimulates the nucleation of the 90° phase in the nonirradiated area close to the boundary. On the other hand, the similar domain behavior was observed by Kusinski *et al.*[11] for the case of ion-patterned Co/Pt multilayers. Therefore, further investigations are needed in order completely to understand the nature of this phenomenon.

In conclusion, we have demonstrated that local ion-beam modification of the AF interlayer exchange coupling in Fe/Cr/Fe trilayers can be used for magnetic patterning on the submicrometer scale. Such patterning provides a unique mean to create AF thin-film structures containing submicrometer-size FM areas. The performed investigation shows that the well-defined magnetic boundary between irradiated and nonirradiated areas exists in a large range of the external magnetic field.

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