MFM studies of magnetic multilayers patterned using ion beams.

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The antiferromagnetic interlayer exchange coupling between two ferromagnetic layers separated by a thin nonmagnetic spacer is mediated by the long range interaction between the magnetic moments of two ferromagnetic layers via conduction electrons of the spacer. Recently it was shown,[1] that the type of the interlayer exchange coupling 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 ferromagnetic coupling between them. With increase of the irradiation fluence the quantity of magnetic bridges increases and the type of interlayer coupling changes to the ferromagnetic 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 is very small.[1] It is obvious that the modification of the exchange interlayer coupling 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 novel artificial magnetic media such as thin-film structures containing nano-scaled 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 nano-patterning using standard photoresist mask technology.

In this talk we present experimental results on the laterally resolved ion beam modification of the interlayer exchange coupling 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 antiferromagnetic coupling between the Fe layers was strong. The Fe/Cr/Fe(001) trilayers were epitaxialy grown using an ultra high vacuum 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 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 200×200 μm^2 separated by 150 μm wide non-irradiated space.[2] The diagonals of the irradiated squares were aligned along the easy magnetic axes of the four-fold 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 in 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 the parts (a) and (b) correspond to a non-irradiated and an irradiated area, 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 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 non-irradiated trilayer structure exhibits typical antiferromagnetic 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 to increase slowly with the increase of the field strength. As soon as the strength of the magnetic field reaches the critical value H_{C1}≈250 Oe, the total magnetization of the trilayer starts to increases stepwise. Such a behavior can be explained by a weak 90-degree interlayer exchange coupling[3] coexisting in our samples with the strong antiferromagnetic one. As a result, the orientation of the magnetic moments of the layers at 90 degree 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}≈450 Oe the trilayer becomes completely

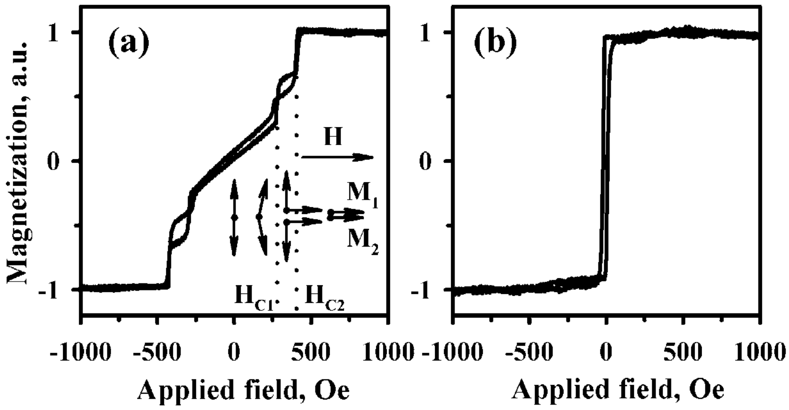

FIG. 1. Hysteresis loops for a non-irradiated (a) and an irradiated (b) area.

saturated. In contrast to the complicated magnetic behavior of the non-irradiated Fe/Cr/Fe trilayer the irradiated trilayer simply exhibits a typical ferromagnetic 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 non-irradiated 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 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 non-irradiated ones.

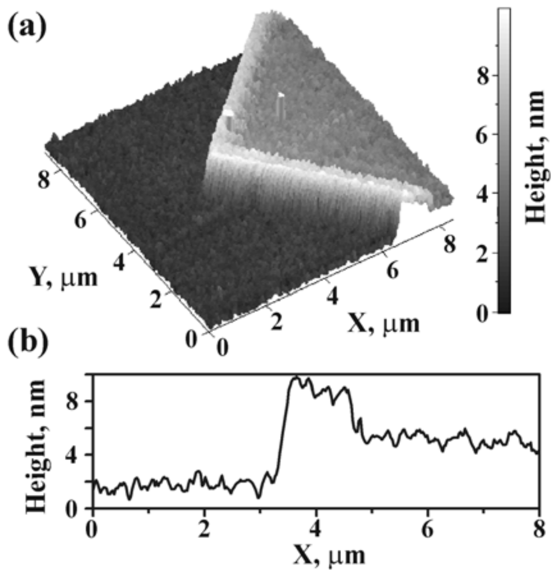

FIG. 2. Topography of a corner of the irradiated area measured by an atomic-force microscope. (a) – the general 3D view, (b) – the profile along the X-direction.

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 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.

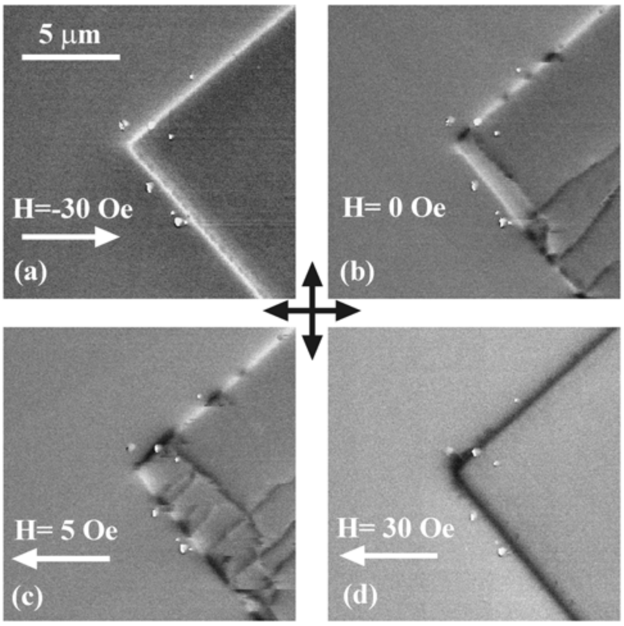

FIG. 3. MFM images of a corner of the irradiated area obtained in weak external magnetic fields: -30 Oe (a), 0 Oe (b), 5 Oe (c), 30 Oe (d). The black arrows indicate the easy axes of the four-fold magnetic anisotropy of the Fe(001) films.

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 strength of 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 non-irradiated areas provides very strong magnetic contrast, whereas the remaining surface is magnetically uniform. Such a behavior is understood by the strong difference in magnetizations of the irradiated and non-irradiated areas. The completely saturated irradiated area produces strong magnetic stray fields at its edges when surrounded by the non-irradiated 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 non-irradiated area remains uniform. As the magnetic field changes its direction and its strength increases again [see Fig. 3(c) and 3(d)] the domain structure in the irradiated area changes and finally disappears in a field exceeding 20 Oe, whereas the non-irradiated 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 non-irradiated areas is seen very sharply. This indicates that the strong magnetic moment of the irradiated ferromagnetic area does not have any considerable influence on the magnetization of the non-irradiated antiferromagnetic area in the boundary regions and, as a result, the change of magnetic properties at the boundaries between the irradiated and non-irradiated 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.

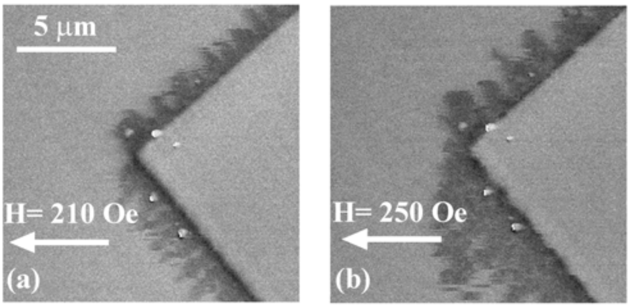

FIG. 4. MFM images of a corner of the irradiated area obtained in strong external magnetic fields: 210 Oe (a), 250 Oe (b).

Of particular interest is the change in the properties of the boundaries between the irradiated and non-irradiated 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 non-irradiated trilayer experiences a strong influence of the irradiated area. This phenomenon can be explained by an instability of magnetization of antiferromagnetically coupled non-irradiated trilayer in magnetic fields lying close to H_{C1}. Due to the presence of the 90-degree coupling the alignment of the magnetic moments of the two Fe layers at 90 degree becomes favorable in the range of magnetic field between H_{C1} and H_{C2}. The strong magnetic stray field of the irradiated area stimulates the nucleation of the 90-degree phase in the non-irradiated area close to the boundary. On the other hand the similar domain behavior was observed by Kusinski, et al.[4] for the case of ion-patterned Co/Pt multilayers. Therefore, further investigations are needed in order completely to understand the nature of this phenomenon.

[1]S. O. Demokritov, C. Bayer, S. Poppe, M. Rickart, J. Fassbender, B. Hillebrands, D. I. Kholin, N. M. Kreines, and O. M. Liedke, Phys. Rev. Letters **90**, 97201-1 (2003).
[2]The relatively large size of the irradiated squares was chosen in order to allow local magnetooptical measurements of hysteresis loops in different areas.
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[4]G. J. Kusinski, K. M. Krishnan, G. Denbeaux, G. Thomas, B. D. Terris, and D. Weller, Appl. Phys. Lett. **79**, 2211 (2001).