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Magnetic Anisotropy of Co Films Annealed by Laser Pulses

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Abstract. The magnetic properties of an ultrathin cobalt film were modified by a focused femtosecond pulsed laser beam. The Co wedge, with a thickness ranging from 0 to 2 nm, sandwiched by Au films was prepared using ultra-high vacuum magnetron sputtering on a mica substrate. The modifications of the laser induced magnetic anisotropy were investigated using magneto-optic Kerr microscopy and MFM/AFM techniques. The laser induces: (i) local reorientation of magnetization from an in-plane to a perpendicular state and (ii) an increase of the coercivity field. A corresponding increase of the perpendicular magnetic anisotropy is discussed considering an improvement of the Co/Au interfaces.

Introduction

Ferromagnetic ultrathin films with perpendicular magnetic anisotropy have been intensively studied in recent years because of their unique properties and applications for high density data recording [1]. For higher thicknesses the magnetic dipolar anisotropy forces magnetization into the plane of the film. However, when the film thickness is decreased, a relative increase of the surface contribution leads to perpendicular magnetic anisotropy. Thickness controlled spin reorientation transition (SRT) from an in-plane to a perpendicular preferential magnetization direction can be realized [2, 3]. A wide thickness range with perpendicular magnetization is obtained for films with high quality interfaces. Tuning the SRT is possible by changes in the overlayer [2], the underlayer, and interface roughness [4], post-deposition annealing [5, 6], the ion [7], and electron bombardment [8]. The purpose of this paper is the study of the influence of intense femtosecond laser pulses on the magnetic properties of a Co ultrathin film. The ultrafast laser is a unique tool for irreversible modification of nanostructures (e.g. melting, disintegrating) [9, 10] and for reversible control of magnetism (e.g. by inverse Faraday effect in magnetically ordered materials) [11]. Moreover, a femtosecond pulse laser can be applied to produce periodic patterning by use of interference phenomena [12, 13]. In comparison with usual thermal annealing, laser annealing is a more precise technique allowing higher spatial, energy, and time resolution; additionally, due to the short action on the top layer it significantly reduces undesirable diffusion from the sample bulk. In this paper the irreversible changes of ultrathin Co film structures and magnetic properties are reported

Experimental details

The following structure was deposited by UHV magnetron sputtering onto a mica substrate with a Au(300 nm) buffer: (i) Au(1.5 nm); (ii) a Co wedge with thickness *d* changing linearly from 0 to 2 nm on a 15 mm long sample; (iii) Au(3 nm). The sputtering rates were 0.06, and 0.045 nm/s, for Au and Co, respectively. X-ray diffraction investigations performed on similar samples [14] reveal that the films are (111) textured. The Ti:Sapphire femtosecond pulse laser (Chameleon Ultra, Coherent) was used for local modification of the magnetic properties of the Co. The pulse width is 140 fs and the TEM_{00} mode output beam was linearly polarized. The wavelength was adjusted to 700nm and in the corresponding time the average power reached 1.9 W with a pulse repetition rate of 90 MHz. The laser beam was focused on the sample surface using a plan-convex lens and the light spot diameter was estimated at $2w_0 \sim 10$ µm. The sample was irradiated using a computer controlled motorized *xy*-positioning of the sample and the automatic inner shutter of the laser to adjust the exposure time Δ_L. The magnetization distribution was studied at room temperature using the polar Kerr effect using an optical microscope equipped with xenon lamp illumination and a high sensitivity cooled CCD camera connected to a computer by a frame grabber [2, 3]. The normalized differential image was calculated as $[I(H) – I(-H_{max})]/[I(H) + I(-H_{max})]]$, with all images acquired in a zero field: the $I(H)$ image was obtained after the positive perpendicular magnetic pulse H (usually a series of 2 s positive H pulses were applied to the initially saturated sample by $-H_{max}$), the reference $I(-H_{max})$ image registered after a -578 Oe field pulse. MFM measurements were carried out with a Ntegra Prima scanning probe microscopes (NT-MDT) using the “Tapping mode” for topography imaging and the “Lift Mode” (height 50 nm) for magnetic imaging. The MFM setups have the possibility for application for the permanent external magnetic field (either in-plane or out-of-plane direction). Low magnetic moment MESP-LM probes (Veeco) and home-deposited low coercivity 50 nm Co probes were used to visualize the sample’s magnetic structure.

Results and discussion

Figure 1 shows the remanent image of the laser irradiated cobalt wedge obtained as the difference between two images after the pulses of positive and negative maximal field. The region without the laser treatment (the lower region marked as B) will be considered first. For a simplified description of Co ordering, three magnetization states could be distinguished in the discussed thickness range: superparamagnetic, out-of-plane, and in-plane [2, 3]. The out-of-plane state with a square hysteresis loop exists between the thicknesses denoted as d_L and d_H (the white area on the remanent image). In this case these characteristic thicknesses for the as deposited Co region are: $d_L = 0.41$ nm and $d_H = 0.93$ nm. The image intensity is proportional to the Kerr rotation angle φ_{max}. On increasing *d,* the image intensity almost linearly increases in this region [2], which is related to the linear dependence of φ_{max} on thickness in the ultrathin-film range. The black area on the remanent image represents: (i) the superparamagnetic state below d_L or (ii) the in-plane magnetization state above d_H. The transition between white (left) and black (right) area represents the SRT between the perpendicular and in-plane magnetization state.

The laser modified regions are shown in the upper part of the remanent image, Fig. 1b. A regular array of irradiated spots with the exposure time ranging from 0.2 s to 5 s and two continuous irradiated lines are clearly visible in the remanent image. The lower and upper lines were produced by continuous motion of the sample at a speed of 30 and 150 µm/s, respectively. One can distinguish two types of laser induced magnetization changes – above and below the SRT of the non-irradiated sample. Above the SRT ($d > d_H$) there is clear evidence of the creation of the perpendicular magnetization state (the white areas).

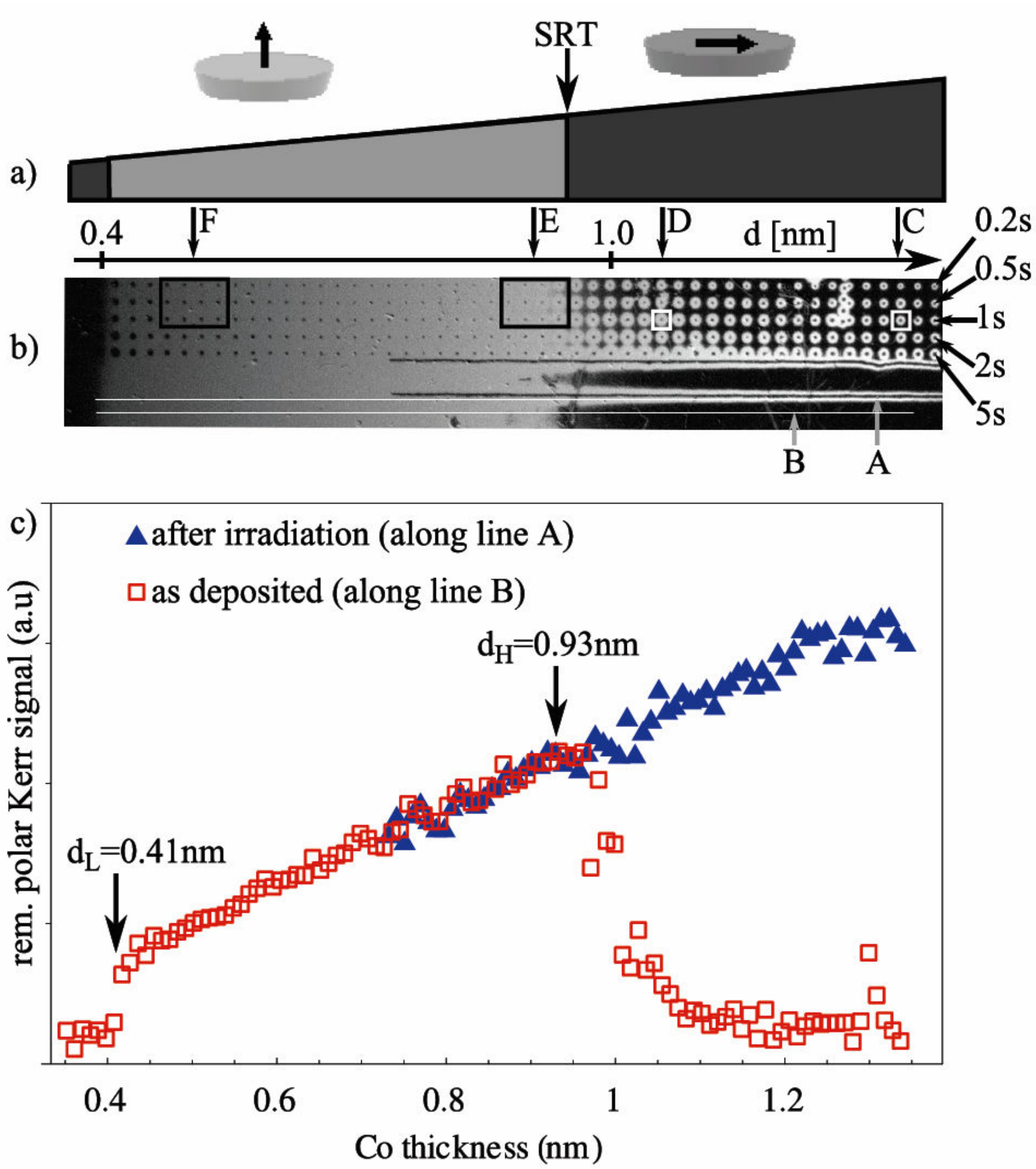

Figure 1. a) schematic side view of the sample;
b) remanence polar Kerr image of array of irradiated spots and two lines;
c) profiles of relative remanence magneto-optic Kerr effect on Co wedge, along irradiated line (triangles, marked A in remanence image) and as-deposited line (squares, marked B).

Figure 2 illustrates evolution of the magnetization reversal process in two selected spots, indicated with arrows C and D in Fig. 1b (in the third row with the exposition 1 s). The process starts with a reversed domain nucleation close to a spot edge – the SRT region. On increasing the applied field pulse H the "white" domain area increases by propagation of the domain wall from the spot edge toward the centre. Finally magnetization is reversed in the whole spot except the central region. The lowest panels in Fig. 2 show the remanent images. The magnetization reversal process is similar to that described for the as-deposited wedge type of ultrathin Co [3]. The "black" area inside any spot has no remanence and seems to be related to the presence of a non-ferromagnetic phase. Even with the field pulse as high as 4 kOe it does not increase magnetic contrast of the central region. The "white" spot area represents the laser-induced change from the in-plane to the perpendicular magnetic state. It decreased with increase of d and decrease of the exposure time Δ_L.

Figure 3 shows magnetization processes in the two regions below the SRT, marked with rectangles F and E in Fig. 1b. For the non-irradiated sample the coercivity field reaches a maximum of about 50 Oe at $d = 0.8$ nm. Cobalt thickness regions were selected: (i) in Fig. 3a - below the coercivity field peak, where the direction of magnetization reversal process ("white" area growth) goes from the low to the high cobalt thickness - from left into right in Fig. 3a; (ii) in Fig. 3b - above the coercivity peak close to SRT, the direction of magnetization reversal goes from the high to the low cobalt thickness region- from right into left in the Fig. 3b. Details of magnetization reversal in the as-deposited Co wedge are discussed in reference [3]. The laser annealed areas are reversed in the higher magnetic field. Moreover, the domain sizes in the laser irradiated area are larger than those in the reference as-deposited regions. The laser irradiation induces an increase of coercivity, which is usually related to the higher perpendicular magnetic anisotropy.

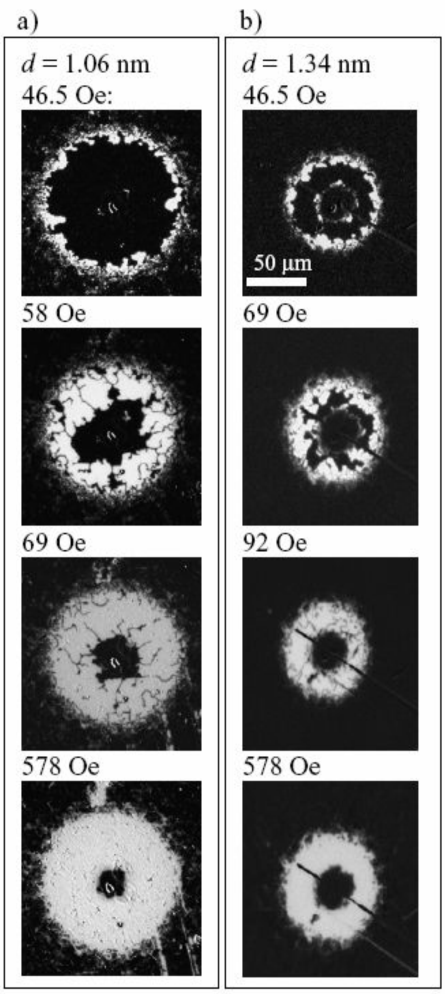

Figure 2. Magnetization reversal of irradiated spots for Co thickness of 1.06 nm (a) and 1.34 nm (b) above SRT (pointed by arrows D and C, respectively, in Fig. 1b, with the 1 s exposition).

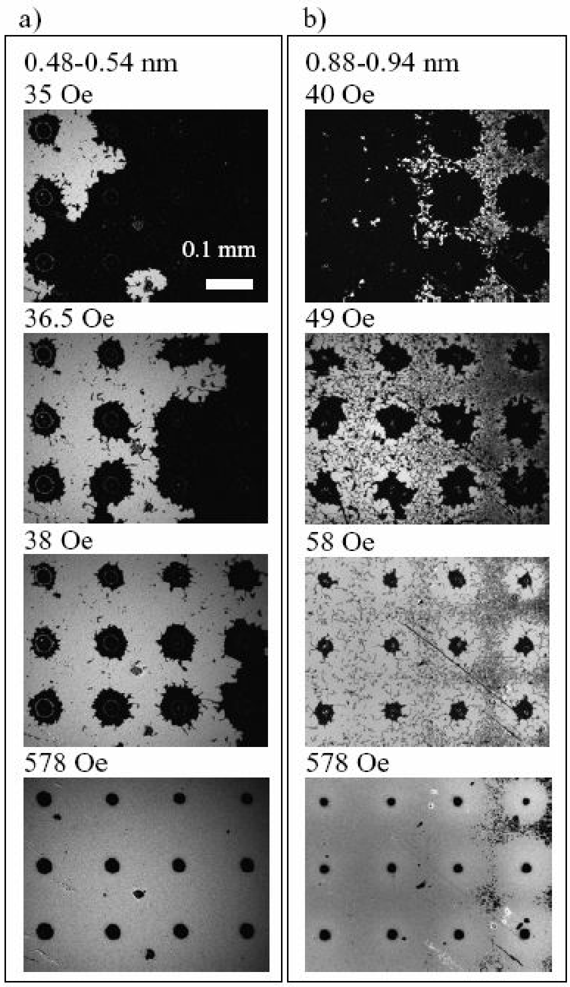

Figure 3. Magnetization reversal of regions for Co thickness below SRT (marked as rectangles F and E in Fig. 1b). Three lines of spots correspond to the exposition 0.2 s, 0.5 s, and 1 s.

Figure 1c shows the profiles of remanent image, taken along irradiated ("white" area) and reference non-irradiated lines (lines A and B, respectively), plotted as the dependency on Co-thickness. The magnetization states in the irradiated and non-irradiated states are similar below d_H – as both dependencies overlap. Above d_L the remanence MO effect of the irradiated area monotonically increases with Co thickness. The thickness dependence of remanence shows that the laser irradiation does not give rise to a change of the polar magneto-optic Kerr effect. Consequently, it was deduced that the laser annealing in the region discussed does not significantly modify the film's structure and the magnetic moment density of the Co film.

From the above experimental results it was deduced that the laser irradiation related effects are responsible for the increase of the perpendicular magnetic anisotropy observed in both thickness ranges. The increase of the magnetic anisotropy seems to be related to the improvements of Co/Au interfaces after the laser annealing. A similar effect was observed [15] for Co/Au ion sputtered multilayers where annealing at only 300ºC, however for a significantly longer period, led to an increase in the magnetic anisotropy. A strong temperature increase is expected during the laser pulse and drastic laser induced changes of the morphology of the film's nanostructure were reported for different materials [12]. Melting of the metal was expected in the laser's focus spot. The results of AFM measurements support this hypothesis - the large and regular crystallites are observed inside the focusing spot which indicates, that during the exposure, film melting and recrystallization occurred (Fig. 4).

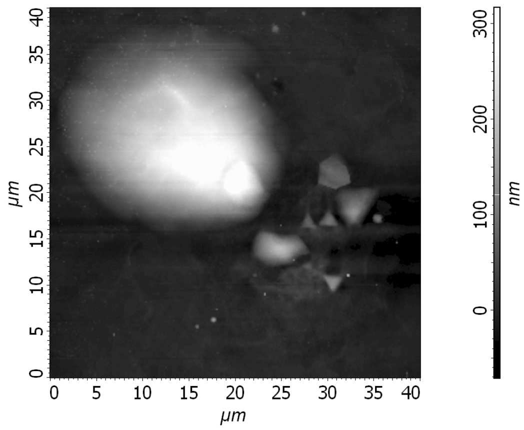

Figure 4. AFM Image of laser irradiated area (1.9 W for 1 second) with black spot inside. Triangular shaped crystal and tall 300nm high mica swelling are visible.

If the laser power is significantly reduced to 0.3 W with a slightly prolonged exposure time of 20 s the effect of laser annealing, but without visible surface changes can be observed (Fig. 5). It means that using a focused laser beam as a tool it is possible to make longitudinal pattering of the magnetic properties of a cobalt film without any visible changes to the surface topography.

a) b) c)

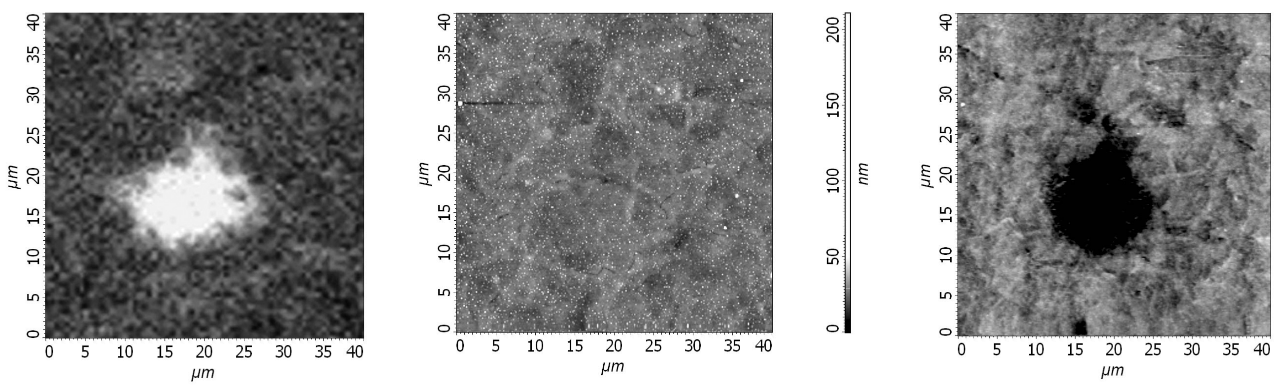

Figure 5. Irradiated spot (0.3 W during 20 s) for Co thickness of 1 nm imaged with:
a) magneto-optic remanence Kerr effect;
b) AFM;
c) MFM. MFM image was obtained in zero external field after 2 s pulse of perpendicular magnetic field 950 Oe. No visible changes in sample surface were detected by AFM.

Conclusion

In conclusion, annealing with femtosecond laser pulses induces an increase in the perpendicular magnetic anisotropy of an ultrathin Co film sandwiched between Au layers. The laser beam induced: (i) inside the focused spot – a nonferromagnetic region with crystallites on the film surface; (ii) outside the focusing spot – a reorientation from in-plane magnetization state into the out-of-plane state. The magnetic anisotropy increase was explained by considering that improvements of the quality of the Co/Au interfaces contributed to the surface magnetic anisotropy. The effects discussed could be used for magnetic pattering which are important for technical applications.

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References

[1] B. D. Terris and T. Thomson, J. Phys. D: Appl. Phys. 38, R199 (2005).
[2] M. Kisielewski, A. Maziewski, M. Tekielak, A. Wawro, and L. T. Baczewski, Phys. Rev. Lett. 89, 087203 (2002) and references therein.
[3] M. Kisielewski, Z. Kurant, M. Tekielak, W. Dobrogowski, A. Maziewski, A. Wawro, and L. T. Baczewski, phys. stat. sol. (a) 196, 129 (2003).
[4] J.-R. Jeong, J. A. C. Bland, J.-W. Lee, Y.-S. Park, and S.-C. Shin, Appl. Phys. Lett. 90, 022509 (2007).
[5] A. Wawro, Z. Kurant, L. T. Baczewski, P. Pankowski, J. Pelka, A. Maneikis, A. Bojko, V. Zablotskii, and A. Maziewski, phys. stat. sol. (c) 3, 77 (2006).
[6] M. Urbaniak, F. Stobiecki, and B. Szymanski, J. Alloys Compd. p. (in press) (2007) and references therein.
[7] J. Ferre, T. Devolder, H. Bernas, J. P. Jamet, V. Repain, M. Bauer, N. Vernier, and C. Chappert, J. Phys. D: Appl. Phys. 36, 3103 (2003).
[8] R. Allenspach, A. Bischof, U. Durig, and P. Grutter, Appl. Phys. Lett. 73, 3598 (1998).
[9] D. S. Ivanov and L. V. Zhigilei, Phys. Rev. B 68, 064114 (2003).
[10] P. Lorazo, L. J. Lewis, and M. Meunier, Phys. Rev. B 73, 134108 (2006).
[11] A. V. Kimel, A. Kirilyuk, F. Hansteen, R. V. Pisarev, and T. Rasing, J. Phys.: Condens. Matter 19, 043201 (2007).
[12] C. Favazza, J. Trice, H. Krishna, R. Kalyanaraman, and R. Sureshkumar, Appl. Phys. Lett. 88, 153118 (2006).
[13] J. B. Kim, G. J. Lee, Y. P. Lee, J. Y. Rhee, K. W. Kim, and C. S. Yoon, Appl. Phys. Lett. 89, 151111 (2006).
[14] M. Urbaniak, F. Stobiecki, B. Szymanski, A. Ehresmann, A. Maziewski, and M. Tekielak, J. Appl. Phys. 101, 013905 (2007).
[15] F. J. A. den Broeder, D. Kuiper, A. P. van de Mosselaer, and W. Hoving, Phys. Rev. Lett. 60, 2769 (1988).

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