APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 11 12 MARCH 2001

Patterning ferromagnetism in $Ni_{80}Fe_{20}$ films via Ga^+ ion irradiation

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(Received 3 April 2000; accepted for publication 30 December 2000)

We demonstrate that focused Ga^+ ion irradiation can comprehensively modify the ferromagnetic properties of $Ni_{80}Fe_{20}$ thin films. Magneto-optic Kerr effect measurements at room temperature and magnetoresistance measurements at temperatures between 1.5 and 270 K characterized the irradiation effects. Irradiation steadily reduced the films' room temperature coercivity, and a dose of 1.0×10^{16} ions/cm^2 at 30 keV was found sufficient to cause a loss of ferromagnetism at room temperature in films of thickness up to 15.5 nm. *In situ* end-point detection and postirradiation atomic force microscopy confirmed that the sputtering which accompanied doses up to 1.0×10^{16} ions/cm^2 did not compromise the protective caps on these $Ni_{80}Fe_{20}$ films. We therefore conclude that the modification of ferromagnetic properties occurred primarily because of direct Ga^+ ion implantation. From these results, we speculate that focused Ga^+ ion irradiation could be a convenient tool for the nanoscale patterning of magnetic properties in 3d transition metal thin films.
[DOI: 10.1063/1.1351519]

In reports over the last three years, ion irradiation has emerged as a promising tool for the nanoscale patterning of highly structured magnetic thin film systems such as ultrathin Co/Pt multilayers[1–8] and chemically-ordered FePt superlattices.[8–10] In this letter, we demonstrate the promise of ion irradiation for patterning two important thin film systems that are not so highly structured and thus so fragile with respect to irradiation: $Ni_{80}Fe_{20}$ and $Ni_{80}Fe_{20}/Cu/Ni_{80}Fe_{20}$. Specifically, we demonstrate that focused 30 keV Ga^+ irradiation can comprehensively modify the magnetic properties of $Ni_{80}Fe_{20}$ ($\leqslant$15.5 nm) thin films up to and including rendering them non-ferromagnetic at room temperature. (Previous research on the ion irradiation of $Ni_{80}Fe_{20}$ has used films that were an order of magnitude thicker than those used here and thus found comparatively more minor irradiation effects.[11])

The samples employed were a series of $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) films and $Ni_{80}Fe_{20}$(9.0 nm)/Cu(8.0 nm)/$Ni_{80}Fe_{20}$(9.0 nm)/$Ni_{80}Cr_{20}$(9.0 nm) trilayers grown by thermal evaporation at $<10^{-6}$ mbar onto room-temperature GaAs(100). The samples were then homogeneously irradiated with a commercial 30 keV Ga^+ focused ion beam system (FEI Corporation 200 xP® focused ion beam workstation).

Such Ga^+ ion irradiation can sputter 3d transition metal targets rather quickly. The relatively thick 9.0 nm cap of $Ni_{80}Cr_{20}$ was chosen to ensure that the ions did not sputter through to the underlying magnetic film. Ion beam sputtering was monitored *in situ* by end-point detection.[12] With this method, it was determined that a dose of 2.3×10^{16} ions/cm^2 sputtered away the entire 9.0 nm $Ni_{80}Cr_{20}$ cap. Computer simulations using the TRIM-90 program by Ziegler and Biersack[13] closely corroborated this empirical figure, calculating that 2.0×10^{16} ions/cm^2 on average would completely remove the cap. The maximum dose used in these experiments was only 1.0×10^{16} ions/cm^2, and therefore the remaining $Ni_{80}Cr_{20}$ cap should have always been ample, having a mean thickness between 4.5 and 5.2 nm.

Ion-induced roughening of the cap, potentially a major concern as it hypothetically could have compromised the cap with pinholes, was not a problem. Atomic force microscopy confirmed that the ion beam did not significantly roughen the surface of the targets. At the doses used ($\leqslant1.0\times10^{16}$ ions/cm^2) the root-mean-square (rms) roughness of the irradiated regions never exceeded 0.9 nm. In comparison, the rms roughness of the samples as grown averaged 0.7 nm. Given that at the maximum dose used, 1.0×10^{16} ions/cm^2, both *in situ* end-point detection and computer simulations imply that $\geqslant$4.5 nm of $Ni_{80}Cr_{20}$ cap remained on average

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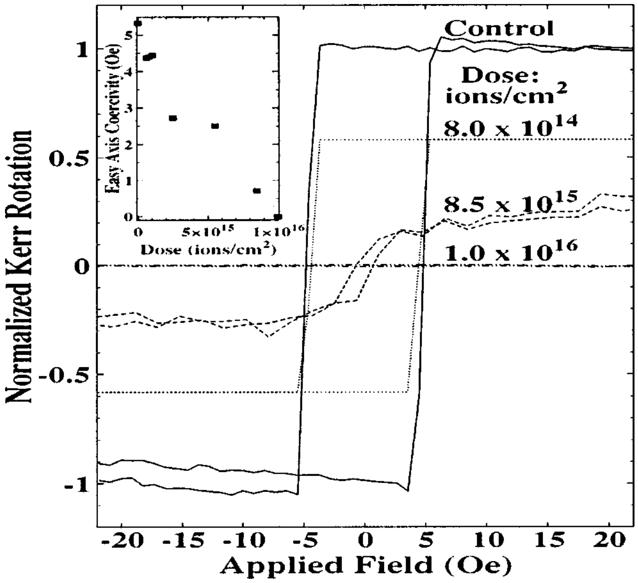

FIG. 1. Longitudinal Kerr microscopy at 290 K of easy axis magnetization reversal in 10 μm×100 μm mesas of $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) that were homogeneously irradiated with 30 keV Ga^+ ions. Measurements were dc, and each plotted curve represents the average of 20 magnetization loops. Full magnetization loops for a control and three representative doses are plotted. The inset displays coercivity vs dose, as determined from Kerr microscopy on all samples (control, plus seven doses between 6.0×10^{14} and 1.0×10^{16} ions/cm^2, inclusive).

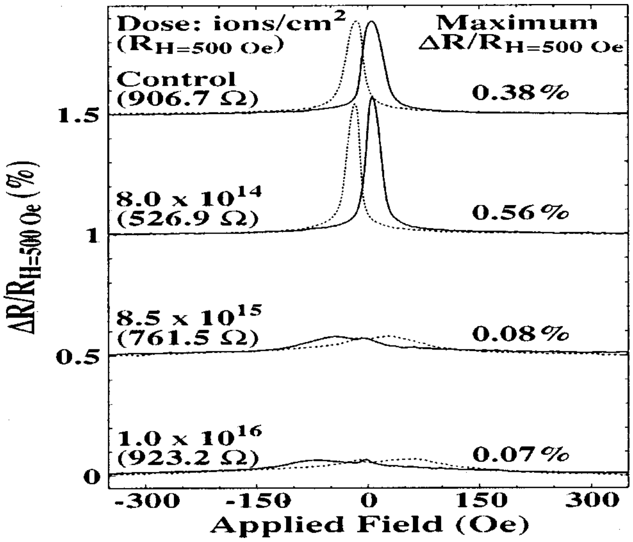

FIG. 2. Magnetoresistance response at 40 K of the same 10 μm×100 μm mesas of $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) homogeneously irradiated with 30 keV Ga^+ ions as Fig. 1. Traces from different doses are offset for clarity. The applied field was always perpendicular to the current and in the plane of the mesa.

(i.e., mean cap thickness $\geqslant 5\times$rms roughness), ion-induced pinholing of the cap should have been negligible.

Figure 1 outlines how irradiation reduced the room temperature MOKE response of the $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) films to nil within experimental accuracy. All samples dosed with $\leqslant 8.5\times10^{15}$ ions/cm^2 possessed a clearly hysteretic MOKE response. At a dose of 1.0×10^{16} ions/cm^2, which was the next highest dose performed, there was a complete absence of any measurable hysteresis. Therefore, the minimum dose necessary to destroy ferromagnetism at room temperature in the $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) films employed here was between 8.5×10^{15} and 1.0×10^{16} ions/cm^2.

The effect of lower doses on room temperature magnetic properties is best seen in the inset to Fig. 1, which plots all the coercivities obtained by MOKE. The coercivity of the films steadily decreased as the ion dose was increased through the entire investigated range of 6.0×10^{14}–1.0×10^{16} ions/cm^2.

Magnetoresistance measurements characterized irradiation effects on low temperature behavior. Figure 2 depicts AMR measurements performed at 40 K on the same samples depicted in Fig. 1. The data of Fig. 2 contain three notable results.

First, by 40 K, ferromagnetism was clearly regained in the $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) film dosed to 1.0×10^{16} ions/cm^2. This sample, which lacked any measurable hysteretic MOKE response at room temperature, demonstrated a readily measurable hysteretic AMR response at 40 K. However, irradiation had reduced the AMR ratio $\Delta R/R_{H=500\ \mathrm{Oe}}$ by over fivefold with respect to the control, while it had increased the baseline electrical resistance, $R_{H=500\ \mathrm{Oe}}$, only by 1.8%.

Second, the samples dosed with $\geqslant 8.5\times10^{15}$ ions/cm^2 possessed much wider AMR responses at 40 K than the control. This is notable because room-temperature MOKE (Fig. 1) measured these highly dosed samples to have lower coercivities than the control. This implies that irradiation reduced the coercive force despite inducing pinning defects. At the same time, the dramatic reduction of Kerr angle in Fig. 1 and AMR ratio in Fig. 2 imply that compositional change resulting from ion implantation reduced the exchange interaction. Such an exchange-reducing compositional change could cause a room temperature coercivity reduction despite the introduction of pinning defects. However, possibly also playing a significant role in the observed magnetization reversal trends could be a reduction of the planar magnetocrystalline anisotropy due to ion-induced displacement cascades that amorphize the sample.

Third, all samples dosed with $\leqslant 8.5\times10^{15}$ ions/cm^2 possessed $R_{H=500\ \mathrm{Oe}}$ values significantly *lower* than that of the control sample. This may seem surprising, as the main effect of such doses was likely to amorphize the film through displacement cascades. However, such amorphization could potentially reduce resistance relative to the control sample if the control had nanometer scale gaps that could be erased by the nanometer-scale displacements induced by the irradiation. This assumption is plausible given that the control sample was deposited onto a room-temperature substrate without undergoing subsequent annealing. Such a mechanism can explain why resistance drops with the lowest doses and then increases with dose. There are hundreds of displacements per incident Ga^+ ion. As there are $\approx 10^{17}$ atoms/cm^2 in the $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) film targets, even a low dose of just $\approx 10^{15}$ ions/cm^2 will have essentially displaced every single atom from its original lattice site. Hence, low doses ($\approx 10^{15}$ ions/cm^2) should have fully achieved whatever benefit amorphization provided. As the dose increased, the growing ion implantation reversed the beneficial effects of these first ion-induced displacements. (Note that calculations show that the actual heating of the

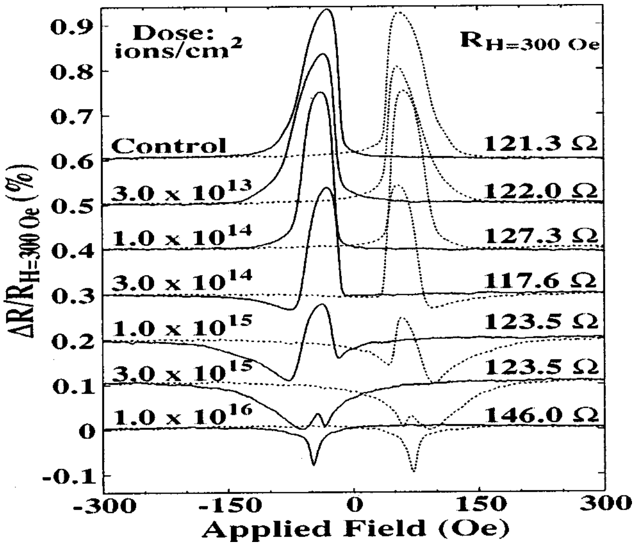

FIG. 3. Magnetoresistance response at 1.5 K of 10 μm×100 μm mesas of $Ni_{80}Fe_{20}$(9.0 nm)/Cu(8.0 nm)/$Ni_{80}Fe_{20}$(9.0 nm)/$Ni_{80}Cr_{20}$(9.0 nm) homogeneously irradiated with 30 keV Ga^+ ions. Traces from different doses are offset for clarity. The applied field was always parallel to the current and in the plane of the mesa.

sample by the ion beam is negligible, and thus the ion beam should not have induced any conventional annealing.)

Further corroboration that 30 keV Ga^+ ion irradiation could dramatically reduce the Curie point of $Ni_{80}Fe_{20}$ films came from electrical measurements at 1.5 K on $Ni_{80}Fe_{20}$(9.0 nm)/Cu(8.0 nm)/$Ni_{80}Fe_{20}$(9.0 nm)/$Ni_{80}Cr_{20}$(9.0 nm) multilayers exhibiting giant magnetoresistance (GMR). Figure 3 encapsulates the results of these experiments.

The remarkable aspect of Fig. 3 is not that the GMR response steadily decreases with increasing ion dose. Ion-induced displacement cascades compromising the $Ni_{80}Fe_{20}$/Cu interfaces readily explain this steady decrease. Instead, the remarkable aspect of Fig. 3 is the *width* of AMR response. The AMR response, which became more and more visible as GMR vanishes, first *broadened* with dose and then suddenly *narrowed* at a dose of 1.0×10^{16} ions/cm^2.

This trend in the AMR cannot be explained by any alteration of the $Ni_{80}Fe_{20}$/Cu interfaces. It also seems counterintuitive. More ion irradiation should have meant more pinning defects and thus a higher saturating field and a wider AMR response. However, the sudden narrowing becomes explainable once it is realized that the bottom $Ni_{80}Fe_{20}$ layer was essentially unirradiated. (TRIM-90 calculates <0.7% of ions penetrate this deep),[13] A narrow AMR response is expected if the relatively pristine bottom $Ni_{80}Fe_{20}$ layer dominated the AMR response. The data shown in Fig. 3 thus imply that the 30 keV Ga^+ ions at some dose between 3.0×10^{15} and 1.0×10^{16} ions/cm^2 rendered the AMR response of the top $Ni_{80}Fe_{20}$(9.0 nm) layer at 1.5 K negligible within experimental accuracy. Therefore, it possible that Ga^+ ion irradiation reduced the Curie point of the top 9.0 nm $Ni_{80}Fe_{20}$ layer to below 1.5 K.

Overall, the experimental results—especially the fact that irradiation steadily reduced room-temperature coercivity despite having created pinning defects—imply that compositional changes from ion implantation were the predominant mechanism for the measured changes in ferromagnetic properties. Some magnetic changes were observed even in mildly dosed samples that could not have received >1 at. % of direct Ga^+ ion implantation (such as the 8.0×10^{14} ions/cm^2 sample depicted in Figs. 1 and 2). Ion-induced mixing of Cr from the $Ni_{80}Cr_{20}$ cap can account for this, because such indirect implantation can be significant even at low doses of $\approx10^{15}$ ions/cm^2 since each incident 30 keV Ga^+ ion can displace hundreds of Cr atoms. However, given the thickness of the films and the fact that TRIM-90 simulations show such indirect Cr implantation would be essentially restricted to within 2 nm of the $Ni_{80}Fe_{20}$/$Ni_{80}Cr_{20}$ interface,[13] direct Ga^+ ion implantation appears to be the decisive factor for the dramatic reduction in Curie points eventually observed with doses of 1.0×10^{16} ions/cm^2.

In conclusion, we have demonstrated that focused Ga^+ irradiation can comprehensively modify the magnetic properties of $Ni_{80}Fe_{20}$ (≤15.5 nm) films, up to and including rendering them non-ferromagnetic at room temperature. We estimate that the beam used here could attain ≤30 nm resolution with a dosage ratio of 100:1 between ''dosed'' and ''undosed'' regions given that it is has a full-width-at-half-maximum of 8 nm and that TRIM-90 simulations predict that ion lateral straggling in $Ni_{80}Fe_{20}$(15.5 nm)/$Ni_{80}Cr_{20}$(9.0 nm) films is only 3.2±2.0 nm (mean ± standard deviation).[13] Combined with the results on Co films from Ref. 8, the work here suggests that focused Ga^+ irradiation can be a convenient tool for the nanoscale patterning of magnetic properties in 3d transition metal thin films.

[1] C. Chappert, H. Bernas, J. Ferré, V. Kottler, J.-P. Jamet, Y. Chen, E. Cambril, T. Devolder, F. Rousseaux, V. Mathet, and H. Launois, Science **280**, 1919 (1998).

[2] H. Bernas, T. Devolder, C. Chappert, J. Ferré, V. Kottler, Y. Chen, C. Vieu, J.-P. Jamet, V. Mathet, E. Cambril, O. Kaitasov, S. Lemerle, F. Rousseaux, and H. Launois, Nucl. Instrum. Methods Phys. Res. B **148**, 872 (1999).

[3] T. Devolder, C. Chappert, Y. Chen, E. Cambril, H. Bernas, J.-P. Jamet, and J. Ferré, Appl. Phys. Lett. **74**, 3383 (1999).

[4] J. Ferré, C. Chappert, H. Bernas, J.-P. Jamet, P. Meyer, O. Kaitasov, S. Lemerle, V. Mathet, F. Rousseaux, and H. Launois, J. Magn. Magn. Mater. **199**, 191 (1999).

[5] B. D. Terris, L. Folks, D. Weller, J. E. E. Baglin, A. J. Kellock, H. Rothuizen, and P. Vettiger, Appl. Phys. Lett. **75**, 403 (1999).

[6] D. Weller, J. E. E. Baglin, A. J. Kellock, K. A. Hannibal, M. F. A. Toney, G. A. Kusinski, S. A. Lang, L. Folks, M. E. Best, and B. D. Terris, J. Appl. Phys. **87**, 5768 (2000).

[7] B. D. Terris, D. Weller, L. Folks, J. E. E. Baglin, A. J. Kellock, H. Rothuizen, and P. Vettiger, J. Appl. Phys. **87**, 7004 (2000).

[8] T. Aign, P. Meyer, S. Lemerle, J.-P. Jamet, J. Ferré, V. Mathet, C. Chappert, J. Gierak, C. Vieu, F. Rousseaux, H. Launois, and H. Bernas, Phys. Rev. Lett. **81**, 5656 (1998).

[9] D. Ravelosona, C. Chappert, V. Mathet, and H. Bernas, J. Appl. Phys. **87**, 5771 (2000).

[10] D. Ravelosona, C. Chappert, V. Mathet, and H. Bernas, Appl. Phys. Lett. **76**, 236 (2000).

[11] J. E. E. Baglin, M. Tabacniks, R. Fontana, A. J. Kellock, and T. Bardin, Mater. Sci. Forum **248–249**, 87 (1997).

[12] That is, a picoampmeter monitored beam→sample→stage current. In a multilayer target, when the beam sputters completely through one layer to reveal a new material, there will be a sudden, sharp change in this current. This effect allows one to determine what dose is necessary to destroy each layer.

[13] Ion ranges were calculated with TRIM-90 computer program, J. F. Ziegler and J. P. Biersack (1990); algorithm presented in J. P. Biersack and L. Haggmark, Nucl. Instrum. Methods **174**, 257 (1980) (TRIM program made available for PCs by J. F. Ziegler, Ziegler@usna.edu).