phys. stat. sol. (c) **1**, No. 12, 3702–3705 (2004) / **DOI** 10.1002/pssc.200405538

Hard magnetic FePt films for atom chips

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Received 27 June 2004, accepted 14 October 2004
Published online 20 December 2004

PACS 68.55.Jk, 75.50.Ww, 75.70.Ak

In this work FePt hard magnetic films were prepared with a thickness of 250 and 500 nm for making atom chips. We choose FePt because it has high magnetocrystalline anisotropy as well as high saturation magnetization. The FePt films were deposited at room temperature and at 350°C using Molecular Beam Epitaxy on a Si substrate. After post annealing, the samples have high in-plane and out-of-plane coercivity (H_c = 8.0 kOe and 8.34 kOe, respectively) and remanent magnetization (M_r/M_s = 0.90, 0.93, respectively). Whereas the samples deposited at room temperature have many cracks on the surface, the samples deposited at 350 °C are free of cracks and their surfaces are mirror-like. The magnetized sample keeps the magnetization after baking in vacuum at 170 °C for 24 hours. A calculation shows that such samples can be used to trap cold atoms after lithographic patterning.

1 Introduction Atom chips are planar microstructures that generate magnetic fields in which laser-cooled atoms can be trapped. Nowadays most of the atom chip designs are using current carrying wires to produce the minimum of the magnetic field [1, 2]. If the laser-cooled atoms are in low-field-seeking states, they can be trapped by the minimum of the magnetic field. Hard magnetic films have great potential [3, 4] as atom chips and have several advantages over current-carrying wires: more stable magnetic stray field, larger field gradient, no ohmic heating, and absence of current noise. Also some interesting patterns are topologically impossible with current-carrying wires.

This application of hard magnetic film poses specific requirements: the thickness of the magnetic layer should be at least 200 nm in order to produce enough stray field; the magnetic moments should be completely in-plane or out-of plane and have high coercivity; the surface should be mirror-like to reflect lasers for cooling down the atoms. Finally the film should also be homogeneous, stable and bakeable.

FePt has been studied extensively both in bulk [5, 6] and thin film [7–11] form since it combines high magneto-crystalline anisotropy with high M_s [12] and corrosion resistance. The FePt phase diagram shows a disordered face-centered cubic (fcc) structure at high temperature, which is magnetically soft. At lower temperatures, the Fe and Pt order in an atomic multilayer structure. This face-centered tetragonal (fct or $L1_0$) phase has very high magneto-crystalline anisotropy and coercivity.

It has been shown [13] that annealing of the soft fcc material produces nanocrystallites of the fct phase that are exchange coupled to the soft phase, resulting in a material with the optimum properties desired here.

2 Experimental The 250 nm and 500 nm $Fe_{50}Pt_{50}$ films were co-evaporated by Molecular Beam Epitaxy (MBE) from Fe and Pt targets on a Si (111) substrate at room temperature and 350 °C. The samples were post-annealed in vacuum at different temperatures in order to get hard magnetic properties.

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The phase composition was examined with XRD and the surface was checked with SEM and optical microscopy. The magnetic properties were measured with SQUID magnetometry.

3 Results and discussion

3.1 FePt films grown at room temperature Figure 1 shows the XRD patterns of FePt films deposited at room temperature before and after annealing. From this figure one can see there are only fcc reflections from the as-deposited sample, indicative of a disordered fcc phase. After annealing the disordered fcc phase transformed to the ordered fct phase.

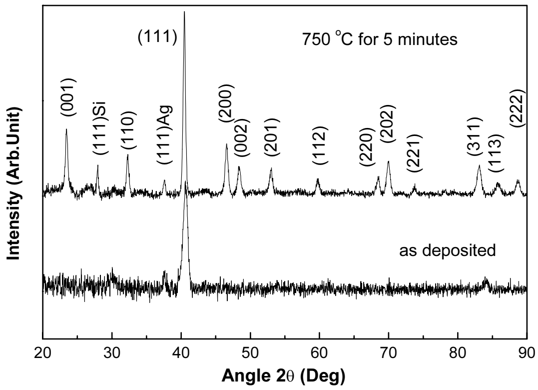

Fig. 1 XRD patterns of $Fe_{50}Pt_{50}$ deposited at room temperature before and after annealing

SQUID measurements show that the as-deposited sample is magnetically soft with high saturation magnetization. The coercivity H_c and M_s are 80 Oe and $1.16x10^6$ A/m, respectively. The best hard magnetic properties were obtained after annealing at 750 °C for 5 minutes, giving a coercive field H_c = 8.0 kOe and a remanent magnetization ratio of M_r/M_s = 0.90.

Observation of the sample with SEM and optical microscope shows that there are a lot of cracks in the as-deposited layers. It indicates the stress in the magnetic layer is very high and couldn't be released during deposition. The stress comes from either the difference of the lattice parameters of Si and FePt or the disordered fcc phase itself. The force in the FePt layer accumulates during growth until cracks appear at a critical point.

Although the magnetic properties of these samples could satisfy the requirements of atom chips after annealing, they were not suitable to make atom chips because of those cracks. In order to release the stress during deposition we tried growth at higher temperatures.

3.2 FePt films grown at 350 °C Figure 2 shows the XRD patterns of the sample made at 350 °C before and after annealing. It shows that the peaks of the as-deposited film are broadened. This indicates that some intermediate cubic structure, $L1_2$-type cubic crystal structure, was formed [5]. This struc

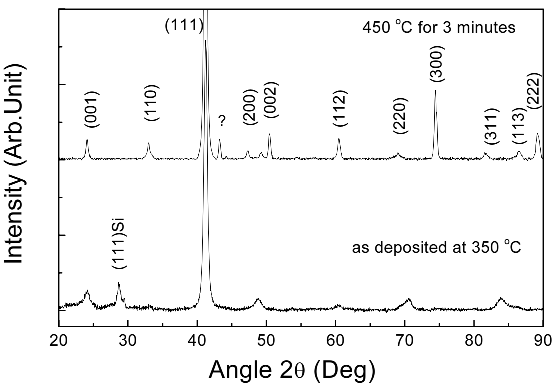

Fig. 2 XRD patterns of $Fe_{50}Pt_{50}$ deposited at 350 °C before and after annealing

ture can be also called ordered fcc phase, in which there is some atomic ordering but not strong enough to form tetragonal phase. After annealing the ordered fct phase was formed. SEM and optical microscope show that the surface of these films is free of micro-cracks.

The annealing temperature dependence of M_r/M_s and H_c for both in and out-of plane is shown in Fig. 3. From this figure one can see that the as-deposited sample is magnetically hard, which is in good agreement with the ordered fcc phase observed in the XRD results. This is also in agreement with the investigation that 350 °C substrate temperature is the starting point for formation of fct phase [14]. With increasing annealing temperature, for the in-plane magnetization loops, M_r/M_s and H_c peak at 500 °C. For the out-of-plane magnetization loops, M_r/M_s reached a maximum at 450 °C but H_c at 500 °C.

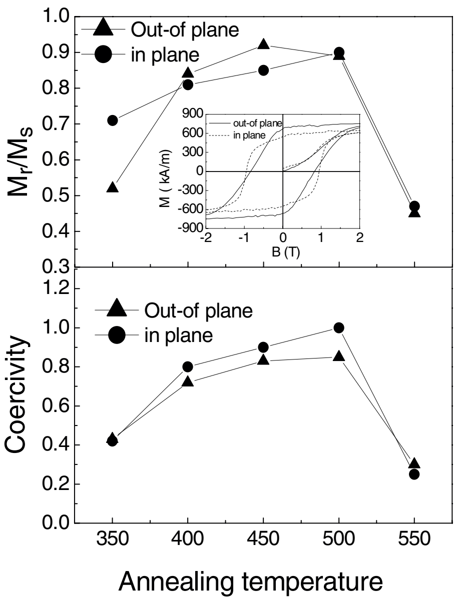

Fig. 3 M_r/M_s and H_c of the FePt film as a function of annealing temperature (350 °C is the as-deposited sample). Inset shows the hysteresis loop of FePt film annealed at 450 °C for 3 minutes.

On increasing the annealing temperature, more and more ordered fct phase is formed. If the grain size of the remaining fcc phase is below the critical size, the fct and fcc phase will be exchange-coupled and forms the so-called nanocomposite magnet [15] which have both high H_c and M_s. When the annealing temperature is higher than 550 °C, M_r/M_s and H_c decrease significantly. This may be due to the growth rate of the grains being higher than the nucleation rate at high temperature, which results in an increase of the grain size of both fcc and fct phases. If the grain size of the fcc phase becomes larger than the critical size, fct and fcc phase will be de-coupled. Depending on the T_{anneal}, the hysteresis loop shows the presence of a few percent of a soft phase, which is magnetically de-coupled from the hard phase. The best results are shown in the inset of figure 3 (T_{anneal} = 450 °C). Since it is impossible to re-magnetize the atom chip after putting it into the ultra-high vacuum trapping system, the atom chip has to keep its magnetization during baking the vacuum system. The measurements show that the magnetized sample still keeps 95% of the remanent magnetization after baking at 170 °C for 24 hours.

4 Conclusion FePt films with 250 and 500 nm thickness were prepared with MBE. Deposition at 350 °C can release stress in the magnetic layer and samples with mirror-like surface were obtained. After annealing the fct and fcc phase in the FePt film were exchange-coupled so that we can get high H_c and M_r/M_s (H_c = 8.0 kOe, M_r/M_s = 0.90 for in-plane magnetization and H_c = 8.34 kOe, M_r/M_s =0.93 for out-of-plane magnetization). Because M_r/M_s is more critical than H_c for atom chips, we choose 500 °C for in-plane magnetization and 450 °C for out-of-plane magnetization as the final annealing temperature. The film deposited at 350 °C can be used in making atom chips and it will be patterned in the very near future.

Acknowledgements This work was supported by Stichting Fundamenteel Onderzoek der Materie (FOM).

References

[1] R. Folman, P. Kruger, D. Cassetttari, B. Hessmo, T. Maier, and J. Schmiedmayer, Phys. Rev. Lett. **84**, 4749 (2000).
[2] J. Reichel, Appl. Phys. B **75**, 469 (2002).
[3] A. I. Sidorov et al., C. R. Acad. Sci. Paris, t. 2, Série IV, 565 (2001).
[4] T. J. Davis, J. Opt. B: Quantum Semiclass. Opt. **1**, 408 (1999).
[5] Q.F. Xiao, E. Brück, Z.D. Zhang, F.R. de Boer, and K.H.J. Buschow, J. Alloys. Compd. **364**, 315 (2004).
[6] P.D. Thand, E. Brück, F. D. Tichelaar, K. H. J. Buschow, and F. R. de Boer, IEEE Trans. Magn. **38**, 2934 (2002).
[7] M.-G. Kim, S.-C. Shin, and K. Kang, Appl. Phys. Lett. **80**, 20 (2002).
[8] C. L. Platt, K.W. Wierman, E.B. Svedberg, R. van de Veerdonk, J. K. Howard, A. G. Roy, and D. E. Laughlin, J. Appl. Phys. **92**, 10 (2002).
[9] M. Weisheit, L. Schultz, and S. Fähler, will be published in J. Appl. Phys., June 2004.
[10] H. Bernas, J.-Ph. Attané, K.-H. Heinig, D. Halley, D. Ravelosona, A. Marty, P. Auric, C. Chappert, and Y. Samson, Phys. Rev. Lett. **91,** 077203 (2003).
[11] M. L. Yan, N. Powers, and D. J. Sellmyer, J. Appl. Phys. **93**, 10 (2003).
[12] D. Weller and M. F. Doerner, Annu. Rev. Mater. Sci. **30,** 611 (2000).
[13] J. P. Liu, C. P. Luo, Y. Liu, and D. J. Sellmyer, Appl. Phys. Lett. **72**, 483 (1998).
[14] Y. Huang, H. Okumura, G. C. Hadjipanayis, and D. Weller, J. Magn. Magn. Mater. **242-245,** 317 (2002).
[15] H. Zeng, J. Li, J.P. Liu, Z.L. Wang, and S.H. Sun, Nature **420**, 395 (2002).