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Tailoring out-of-plane magnetic properties of pulsed laser deposited FePt thin films by changing laser energy fluence

Ying Wang [a], T.L. Tan [a], K.S. Tan [a], P. Lee [a], Hai Liu [b], Boluo Yadian [b], Ge Hu [b], Yizhong Huang [b], R.V. Ramanujan [b], R.S. Rawat [a,*]

[a] NSSE, NIE, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, Singapore
[b] School of Material Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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ABSTRACT

Magnetic properties of pulsed laser deposited (PLD) FePt thin films are investigated at three different laser energy fluences of 51, 136 and 182 J/cm^2. Deposition at lower laser energy fluence (51 J/cm^2) yields softer out-of-plane coercivity ($\leq$0.4 kG), whereas deposition at higher laser energy fluence (136 and 182 J/cm^2) results in harder out-of-plane coercivity ($\geq$5.0 kG). The improved coercivity is found to be attributed to the formation of vacancy defects in thin films, which is indicated by stress change from tensile to compressive form with increasing laser energy fluence. Maximum out-of-plane saturated magnetization of 615 emu/cm^3 and remanent squareness ratio of 0.88 are achieved for 16 nm thick FePt thin films deposited at moderate laser energy fluence of 136 J/cm^2, making them suitable for high density perpendicular data storage applications.

1. Introduction

Magnetic nanoparticles (NPs) like FePt are of high interest both in basic research and applications. They have been extensively studied due to their potential applications in magnetic data storage, drug deliveries, biomedical imaging, etc. [1]. Face centered tetragonal (fct) FePt nanoparticles are especially of immense technological importance in high density magnetic storage media applications because of its high uniaxial magnetocrystalline anisotropy ($K_u = 6.6 \times 10^7$ J/m^3) and thermal stability [2]. FePt nanoparticles can be magnetically stable up to the size of 4 nm. They can also exhibit large coercivity of 10–20 kOe, a value of which, however, is unsuitable for recording media due to the limitation of the writing head [2–4]. For magnetic storage media, FePt nanoparticles should have coercivity lower than 10 kOe (for data bit to be easily written) and high magnetization (for better data readability) [2,3]. This requires a composite of hard and soft magnetic phases being strongly exchange coupled in FePt nanoparticles. Moreover, perpendicular orientation is preferred for high density storage application as compared to longitudinal orientation, because perpendicular magnetic recording has narrower transition region between recording bits and therefore a higher recording density [5]. Shen et al. [6] reported an achievement of out-of-plane squareness (~1) and out-of-plane coercivity (9–15 kOe) for FePt thin films with a thickness of 5–15 nm prepared by dc magnetron sputtering. Chen et al. also obtained perpendicular magnetic anisotropy in FePt films of 10 nm thickness, while in-plane magnetic anisotropy are found to be preferred in FePt films with thickness over 20 nm [7]. Thus, films thinner than 20 nm are deposited in this work. In pulsed laser deposition (PLD), the orientation texture of the thin films is found to be associated with the energetic nature of the ablation plume. Nakano et al. [8–10] and Chang et al. [11] reported the dependence of composition, structure and magnetic properties on ablation laser power for FePt films deposited by pulsed laser deposition (PLD). Nakano et al. reported a transition from isotropic films to perpendicular anisotropic films with increasing laser power from 5 to 7 W [9]. Chang et al. varied the laser photon energy by changing laser wavelength (1064, 532, 355 to 266 nm) [11], but laser pulse energy and laser energy fluence was kept constant. They report an evolution of deposition mechanism from thermal evaporation (for wavelength of 1064 and 532 nm) to ablation (for wavelength of 266 nm) [11]. Compared to composition of target, Pt-rich FePt films are deposited in thermal evaporation mode while stoichiometric FePt films are prepared in ablation mode [11]. The changed composition for different wavelength leads to different structural and magnetic properties [11]. Our previous work [12] also showed that the ablation laser fluence plays a key role for the formation of impurities in FePt thin films and consequently affects their magnetic properties. All these studies [8–10] demonstrate the importance of ablation laser energy to

* Corresponding author. Tel.: +65 6790 3930/3908; fax: +65 6896 9414.
E-mail address: rajdeep.rawat@nie.edu.sg (R.S. Rawat).

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the properties of PLD deposited FePt films. However, films reported by Nakano et al. and Chang et al. are of tens μm and 100 nm thick, respectively, while thin films of less than 20 nm are of interest in this work. Our previous work [12] focused on elimination of impurities in FePt thin films instead of systematical studies of effect of laser energy fluences. Since crystalline structures of FePt films also depend on film thickness as reported by Shen et al. [6] and Chen et al. [7], it is interesting to investigate the effect of ablation laser energy on thinner films as it might be different from that on thicker films (100 nm and tens μm ones). Thus, the effects of laser energy fluences on morphological, crystalline and magnetic properties of PLD synthesized FePt thin films (of 5–16 nm thick) are worth studying in detail.

In this work, FePt films thinner than 20 nm are deposited using PLD to form perpendicular orientation in samples. Various laser energy fluences (51, 136 and 182 J/cm^2) are used to study their effect on the morphological, crystalline and magnetic properties of FePt thin films.

2. Experimental details

FePt thin films of thickness 5, 10 and 16 nm are produced at room temperature in vacuum at background pressure better than 5.7×10^{-6} mbar by PLD using a Lotis-TII (LS-2137U) 2nd harmonic Nd:YAG laser (532 nm) with laser energy fluences (LEF) of 51, 136 and 182 J/cm^2 and a pulse repetition rate of 10 Hz. The LEF on the target surface is varied using the method reported in our previous paper [13] in which neutral density filters of different transmission values were used for fixed laser pump energy and fixed laser spot size. The diameter of the laser spot size on the target surface is kept constant at 264 μm. This method of controlling the LEF on target surface is most reliable as by keeping the laser pump energy same the laser pulse width also remains the same as it is well known that changing the laser pump energy also changes the laser pulse length. The average deposition rate for LEF of 51, 136 and 182 J/cm^2 is estimated to be about 0.14, 0.18 and 0.22 nm/min, respectively. At fixed ablation LEF, the thickness of thin films is controlled by the number of laser shots. The as-deposited samples are uniform thin films with a few laser droplets as the scanning electron microscopy (SEM) image shown in Fig. 1(a). The compositions of as-deposited FePt thin films tend to reduce the amount of Fe by 2–9 at.% compared with that of target material ($Fe_{50}Pt_{50}$). As shown in Fig. 1(b), the average Fe at% for as-deposited samples deposited at LEF of 51, 136 and 182 J/cm^2 is 45.4, 48.2 and 40.9 at%, respectively. This indicates Pt-rich composition for all the samples. The as-prepared samples were post-annealed at 600 °C for 60 min in a 95% Ar/5% H_2 flowing gas atmosphere. The silicon (Si) substrates were placed in the deposition system at a distance of 5 cm normal to the ablation target. The FePt target (50:50 at% with 99.99% purity, Ø 2.5 cm), which is purchased from Kurt J. Lesker, is polished and ultrasonically cleaned before being fixed in the PLD chamber. The Si substrates were cleaned sequentially in acetone, ethanol and deionized water for 10 min each in an ultrasonic bath. The commercial purchased Si substrates were of N type and with ⟨1 0 0⟩ orientation.

The structure, morphology, composition and magnetic properties of samples were investigated by various characterization techniques. The surface morphology and thickness of samples were measured by field emission scanning electron microscopy (FE-SEM, JEOL JSM-6700F). The compositions of thin films were obtained by FE-SEM attached with Oxford Instrument's energy dispersive X-ray (EDX) spectroscopy. Magnetic properties of the films were measured by the vibrating sample magnetometer (VSM, Lake Shore 7400) with a maximum field up to 14 kG. The phase composition of the coatings was identified using thin-film X-ray diffractometer (XRD, Shimadzu 6000) with Cu Kα radiation of 1.5418 Å wavelength with a scan speed of 0.016°/s. The microstructure and images of magnetic nanoparticles were obtained on a JEOL 2100F transmission electron microscope (TEM).

3. Results and discussion

The in-plane and out-of-plane hysteresis loops of samples deposited at different laser energy fluences (LEF) (51, 136 and 182 J/cm^2) are shown in Fig. 2(a) and (b) for film thickness (t) of 5 nm and in Fig. 2(c) and (d) for t = 10 nm. Samples deposited at LEF of 51 J/cm^2 show small coercivity values for both in- and out-of-plane hysteresis loops indicating low perpendicular and longitudinal anisotropy (K_u). The samples synthesized with LEF of 136 and 182 J/cm^2, on the other hand, exhibit much larger perpendicular anisotropy (K_u) than the longitudinal samples, as the area under the out-of-plane hysteresis loops is much larger than that of in-plane loops. The larger K_u is attributed to the strong (0 0 1)-preferred orientation induced by thinner thin films (t < 15 nm) [6] and increased ablation laser energy density [14]. The presence of longitudinal K_u grains in samples, indicated by the observed in-plane hysteresis loops, may originate from the relaxation of stress that favors the formation of perpendicular K_u FePt [15,16]. However, there

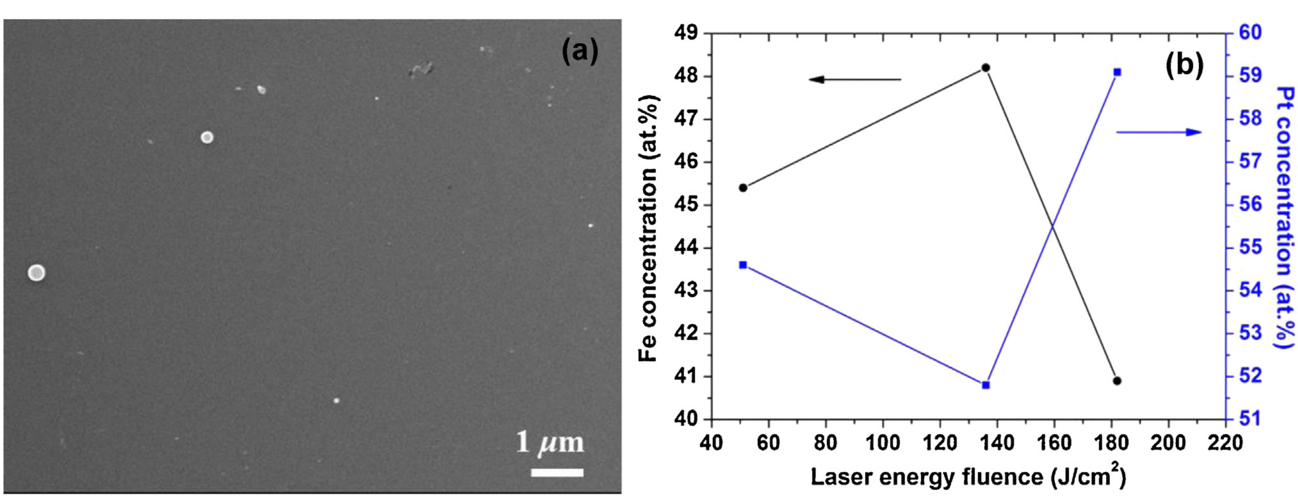

Fig. 1. (a) SEM image of as-deposited sample at LEF of 51 J/cm^2; (b) Fe and Pt concentrations of as-deposited FePt thin films as a function of laser energy fluences. The composition of the target is $Fe_{50}Pt_{50}$.