Mn doping effect on structure and magnetism of epitaxial 
(FePt)$_{1-x}$Mn$_x$ films

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We study the structure and perpendicular magnetism of molecular beam epitaxy grown (FePt)$_{1-x}$Mn$_x$ films with doping concentration $x = 0, 1\%, 2\%, 3\%, 4\%,$ and 5\%. The (FePt)$_{1-x}$Mn$_x$ films were made by multilayers growth of [Fe/Pt/Mn]$\times N$ at 100°C and annealed at 600°C. X-ray diffraction scans indicate that relatively better $L1_0$ ordered structure for low Mn doping ($x < 2\%$). The (001) and (003) superstructure peaks decrease with the increase of the Mn doping for $x > 2\%$, and a significant (111) peak appears for $x > 3\%$. The perpendicular magnetic anisotropy effect of the (FePt)$_{1-x}$Mn$_x$ films tends to decrease with the increase of Mn doping for $x > 1\%$. However, the $x = 1\%$ doped films possess slightly better perpendicular magnetic anisotropy effect than the zero doped film. The perpendicular magnetic anisotropy constant are of about $1.3 \times 10^6$ and $1.6 \times 10^6$ erg/cm$^3$ for $x = 0\%$ and $x = 1\%$, respectively. © 2003 American Institute of Physics.

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FePt film displays a large perpendicular magnetic anisotropy (PMA) and is a promising material for perpendicular, high-density magnetic recording. The strength of the PMA effect is often strongly correlated with the crystal structure and $L1_0$ ordering in FePt alloy. A marked PMA effect in FePt alloy is often attributed to the symmetry breaking at the interface between the Pt and Fe monolayer (ML) in $L1_0$ structure.

Doping of Mn into magnetic materials can often result in a remarkable change of their structural and/or magnetic properties. For better composition control (of three elements), (FePt)$_{1-x}$Mn$_x$ films were then prepared by a multilayer growth of [Fe($t_{Fe}$)/Pt($t_{Pt}$/Mn($t_{Mn}$))]$_N$ at 100°C. The thickness of $t_{Fe}$ and $t_{Pt}$ were chosen as 5 ML each, and $t_{Mn}$ was designed to fit the desired Mn doping concentration $x$. Note that employing larger $t_{Fe}$ and $t_{Pt}$ makes the interdiffusion among the Fe/Pt/Mn interface difficult. Using less $t_{Fe}$ and $t_{Pt}$, on the other hand, makes good evaluation of Mn material impractical. We have not carried out the study of $x < 1\%$ because the amount of Mn material is too little to be precisely controlled. In this work pure (99.99%) Fe and Pt materials were evaporated from a separate electron-beam source, and Mn from an effusion cell. The crystal structure was studied by in situ reflection high-energy electron diffraction (RHEED) and ex situ x-ray diffraction (XRD). The morphology of magnetic domains was analyzed by atomic force microscopy (AFM) and magnetic force microscopy, respectively. Magnetic property was investigated by polar magneto-optical Kerr effect (PMOKE) and vibrating sample magnetometer (VSM) at room temperature.

On MgO(001) substrate the Pt seed layer was grown as a nice (001) structure, as evidenced by the RHEED streaks shown in Fig. 1(a). Note that it is essential to have the Pt seed layer to obtain the pure $L1_0$ (001) structure and large PMA effect for FePt films, and similar for the (FePt)$_{1-x}$Mn$_x$ films studied here. Figures 1(b)–1(c) show the RHEED patterns of Fe and Pt in the first repeat of [Fe/Pt/Mn]$\times N$ multiplayer grown at 100°C. The first repeat ($N = 1$) of Fe and Pt layer grew as Fe(001) and Pt(001) structure. Indeed, Fe/Pt multiplayer can grow well till the final repeat ($N = 15$) without Mn doping. However, as Mn deposited on Pt for growth of (FePt)$_{1-x}$Mn$_x$ films, the RHEED pattern became broader and weak, as shown for example in Fig. 1(d). The crystal structure deteriorated as the multiplayer repeat increased. After the growth of the [Fe/Pt/Mn]$\times N$ multiplayer, the sample was annealed at 600°C. Annealing for about 1 h, the structure order was

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almost recovered as shown in Fig. 1(e), indicative of good alloying in the interface of the Fe/Pt/Mn multilayer. The samples were annealed at 600 °C for about 2 h. Extensive annealing time was not used to prevent significant interdiffusion between the (FePt)\textsubscript{1-x}Mn\textsubscript{x} film and the Pt seed layer. The same treatment was done and a similar trend in the structure evolution was observed for different Mn doping. Figure 3 shows XRD scans of the (FePt)\textsubscript{1-x}Mn\textsubscript{x} films by annealing [Fe/Pt/Mn]\texttimes N multilayers at 600 °C. The results indicate that relatively better L\textsubscript{10} ordered structure for low Mn doping (x<2%) of the (FePt)\textsubscript{1-x}Mn\textsubscript{x} films. The (002) fundamental peak and (001) and (003) superstructure peaks decrease with the increase of the Mn doping x \geq 2%. In addition, a significant (111) peak around 2θ = 40° appears for x>3%. The difference in the (003) reflection in x=3% sample could be related to the structure transition (at about x=3%) from a L\textsubscript{10} (001) structure to a mixed structure [L\textsubscript{10}(001)+(111)]. Note that the broader peaks on the left side of (001) and (003) are also due to the MgO substrates as shown in Fig. 2. The Pt(002) seed layer

FIG. 1. Subsequent RHEED images of (a) 5 ML Fe, (b) 5 ML Pt, and (c) 0.4 ML Mn grown on a Pt (150 Å) seed layer on MgO(001) at 100 °C. (d) RHEED image of (FePt)\textsubscript{0.2}Mn\textsubscript{0.8} after annealing the [Fe(15 ML)/Pt(10 ML)/Mn(1 ML)]\texttimes 15 multilayer at 600 °C for 1 h. The RHEED beam was directed parallel to the underlying MgO[1-10] azimuth.

FIG. 2. X-ray diffraction spectra of the [Fe(15 ML)/Pt(10 ML)/Mn(1 ML)]\texttimes 15 multilayer prepared at 100 °C. S represents the peaks from the MgO substrate.

FIG. 3. X-ray diffraction spectra of (FePt)\textsubscript{1-x}Mn\textsubscript{x} films after annealing the [Fe(15 ML)/Pt(10 ML)/Mn(1 ML)]\texttimes 15 multilayer at 600 °C for 2 h. S and P represent the peaks come from the MgO substrate and Pt seed layer, respectively.
peaks (indexed as P in Fig. 3) remain clear for all the (FePt)$_{1-x}$Mn$_x$ films.

The polar MOKE measurements reveal that the PMA effects of the (FePt)$_{1-x}$Mn$_x$ films tend to decrease with the Mn doping for $x > 1\%$, as shown in Fig. 4. However, the $x = 1\%$ doping films possess slightly better PMA effect than the zero doping film. The Kerr rotation for both $x = 0\%$ and $x = 1\%$ are of about 0.32°. The saturation magnetization of both $x = 0\%$ and $x = 1\%$ are of about 790 and 770 emu/cm$^3$, as measured by VSM. However, the polar coercivity of $x = 1\%$ ($-5$ kOe) is larger than $x = 0$ ($-3.5$ kOe). The perpendicular magnetic anisotropy constant is of about $1.5 \times 10^7$ erg/cm$^3$ and $1.6 \times 10^7$ erg/cm$^3$ for $x = 0\%$ and $x = 1\%$, respectively.

To further study the effect of Mn doping on the structure of the (FePt)$_{1-x}$Mn$_x$ films, we carry out AFM scans for these samples. For FePt film ($x = 0\%$), there are holes typically of 0.05 μm in size, as shown in Fig. 5(a). This structure is likely due to the postannealing process of the Fe/Pt multilayer. The morphology of the FePt film ($x = 0\%$) is in marked contrast to the $x \geq 1\%$ samples which show clear grains instead of holes, as shown for example in Fig. 5(b) for the $x = 1\%$ sample. Since the total thickness (300–320 Å) varies within 10% for all the (FePt)$_{1-x}$Mn$_x$ films (0–5%), the difference of grain structure is likely due to the Mn doping (under the same annealing process). The mean roughness of $x = 0\%$ and $x = 1\%$ samples are 14 and 22 Å, respectively. The surface roughness of the (FePt)$_{1-x}$Mn$_x$ film increases with the increasing of Mn doping concentration for $x \geq 1\%$. Holes in the FePt ($x = 0\%$) sample could offer as magnetic pinning centers and results in a decrease of the PMA. Mn doping tends to suppress the growth of the holes. That could be one of the reasons why the $x = 1\%$ sample shows a better PMA than the zero doping sample. However, the increasing surface roughness [and appearance of the (111) phase] for higher Mn doping tends to decrease the PMA effect.

In summary, we have demonstrated in this work that high ($x \geq 2\%$) Mn doping results in an increase of the (111) component and surface roughness of the (FePt)$_{1-x}$Mn$_x$ film, thus resulting a decrease of the PMA effect. However, Mn doping at $x = 1\%$ in (FePt)$_{1-x}$Mn$_x$ film shows a better PMA effect than zero doping sample. For future work, we will carry out careful work on the Mn doping concentration within 1%.

9 Without using the Pt seed layer, a large component of FePt(111) in addition to the $L_1_1$(001) structure is often observed.
10 Indeed, the streak RHEED patterns can be recovered for annealing at 500 °C for 1 h.