Structural phase transformations in annealed Pt/Mn/Fe trilayers

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Introduction

Chemically ordered $L1_0$-FePt is a very interesting magnetic material providing a variety of different applications. For instance, FePt thin films are currently implemented as storage material for application as heat-assisted magnetic recording (HAMR) media with ultra-high density. Furthermore, high perpendicular magnetic anisotropy (PMA) and Curie temperature as well as excellent corrosion resistance are distinctive to this phase allowing for further applications in perpendicular magnetic tunnel junctions [1], magnetic micro-electro-mechanical systems (MEMS) [2], and new-type thermopiles [3, 4]. Althought, the reduction in Curie temperature while maintaining strong PMA is still a relevant task for FePt film applications. In this regard, Mn was considered as a doping element for $L1_0$-FePt [5]. However, solid-state reactions and diffusion regularities in FePt-Mn films requires further studies.

In this study, as-deposited Pt/Mn/Fe trilayers were post-annealed to different temperatures up to 620 °C and the various stages in binary and ternary phase formation initiated by interlayer diffusion were investigated.

Methodology

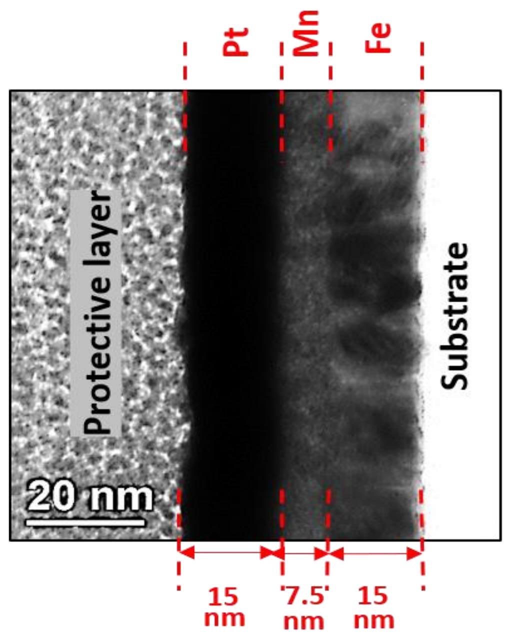

Figure 1. *Cross-section TEM image of the as-deposited Pt/Mn/Fe film sample.*

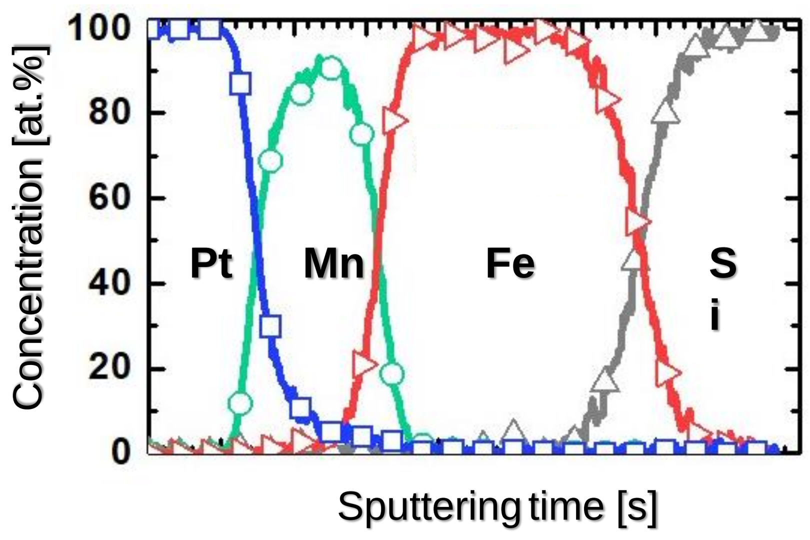

Figure 2. *SNMS composition-depth profile of the as-deposited Pt/Mn/Fe film sample.*

Pt(15 nm)/Mn(7.5 nm)/Fe(15 nm)/sub. thin films were deposited by dc magnetron sputtering on thermally oxidized Si(100) substrates with a 100 nm-thick amorphous SiO_2 layer at room temperature. As-deposited films were annealed in the temperature range of 155-620 °C in vacuum (10^{-3} Pa) with an average heating rate of 0.5 °C/s. Sequence of thermally-activated phase transitions in Pt/Mn/Fe thin films was investigated by combination of x-ray diffraction (XRD), transmission electron microscopy (TEM), energy-dispersive x-ray spectroscopy (EDX) point scanning, secondary neutral mass spectrometry (SNMS) depth profiling, atomic force microscopy (AFM), and magnetic properties measurements.

Results

XRD

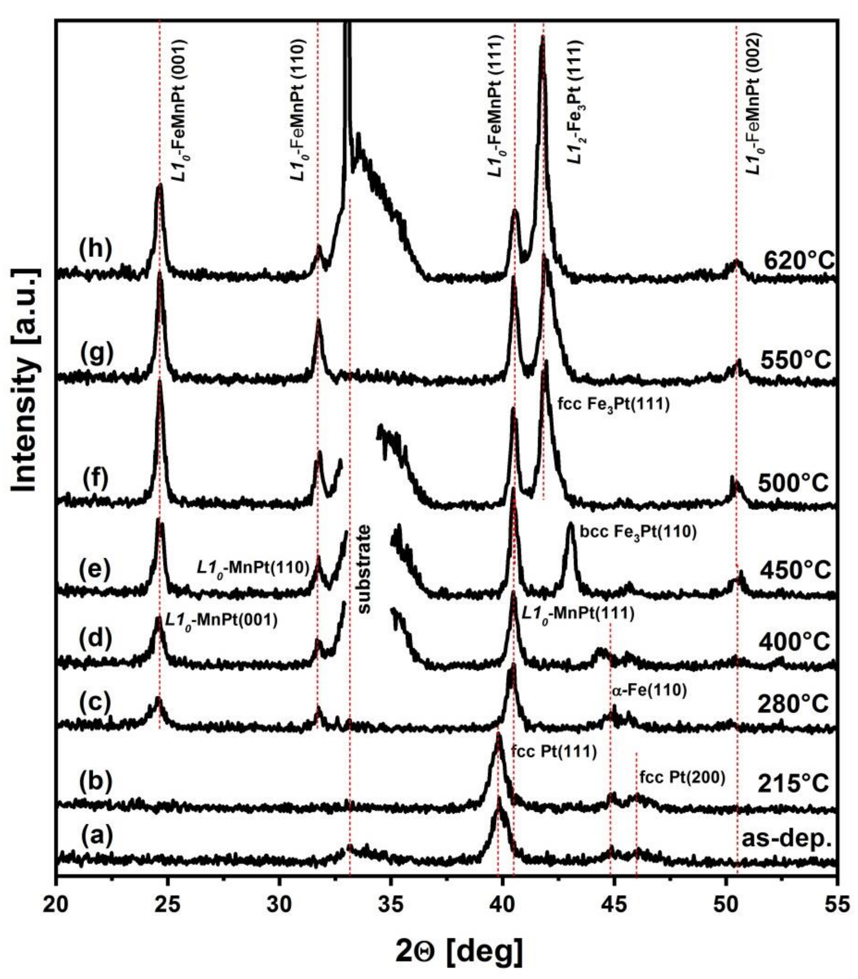

Figure 3. *(a-h) XRD (θ−2θ) scans of Pt(15 nm)/Mn(7.5 nm)/Fe(15 nm) films after deposition and post-annealing at different temperatures.*

SQUID magnetometry

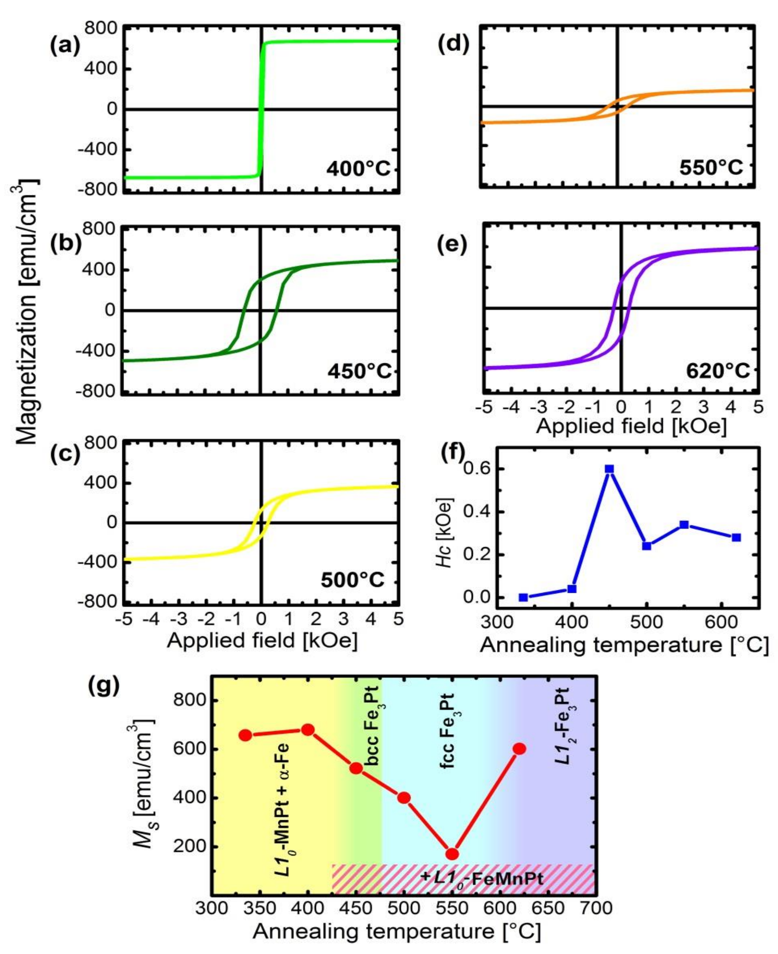

Figure 4. *(a-e) In-plane M-H hysteresis loops of Pt/Mn/Fe films after deposition and post-annealing at different temperatures. (f) Coercivity and (g) saturation magnetization at room temperature as function of annealing temperature.*

Results

SNMS depth profiling

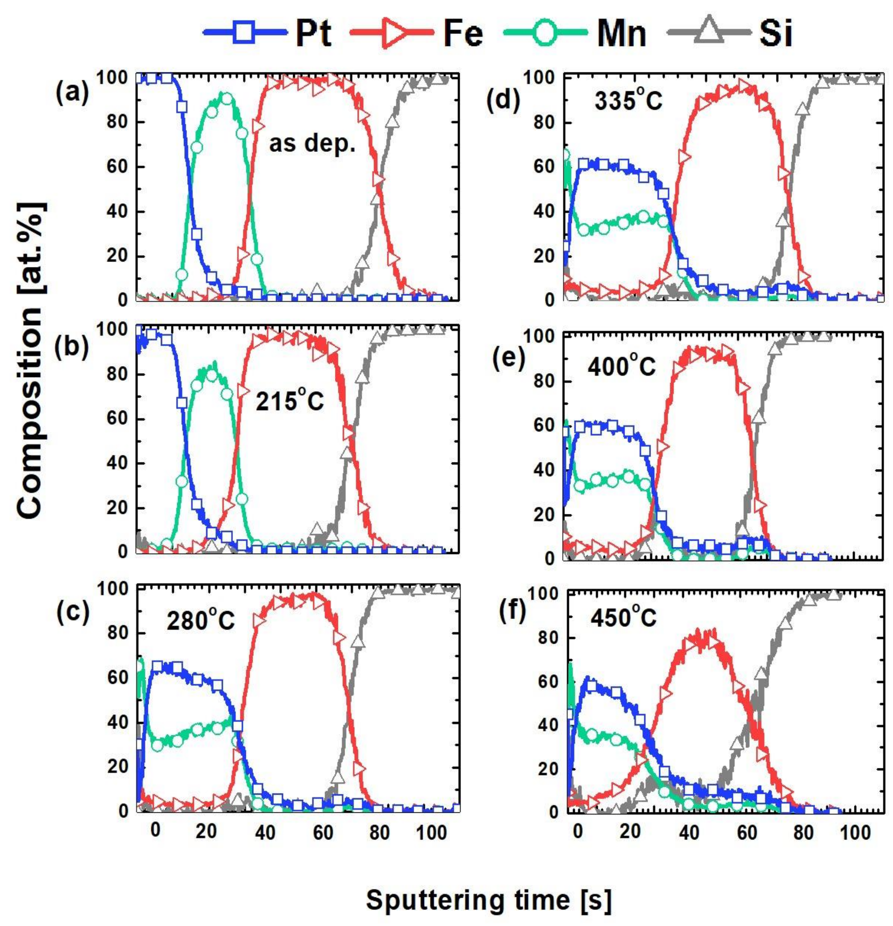

Figure 5. *(a-h) SNMS composition-depth profiles of Pt/Mn/Fe films after deposition and post-annealing at different temperatures.*

AFM

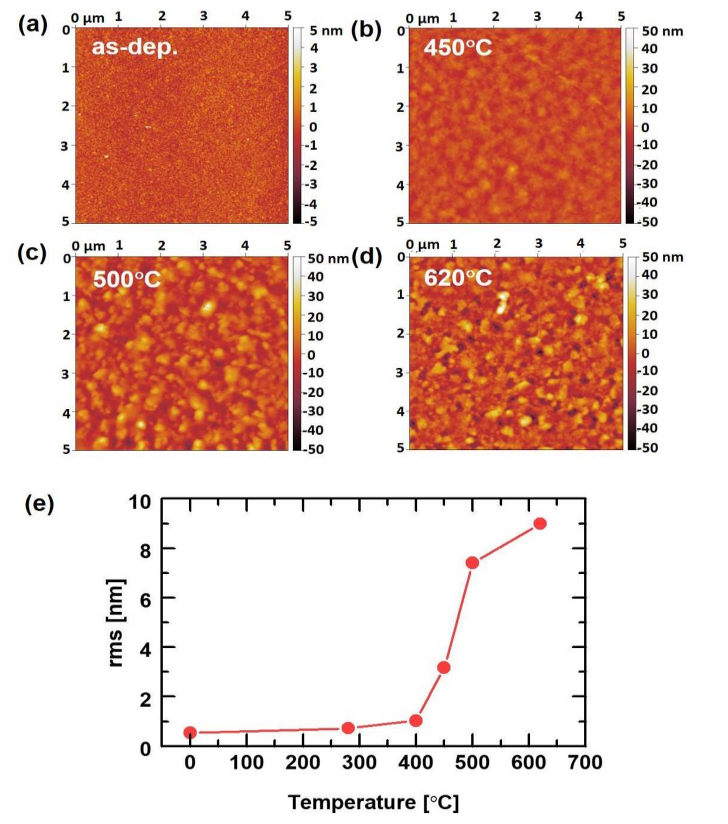

Figure 6. *AFM images of the (a) as-deposited and (b-d) annealed Pt/Mn/Fe film samples and (e) temperature dependence of rms roughness.*

TEM + EDX

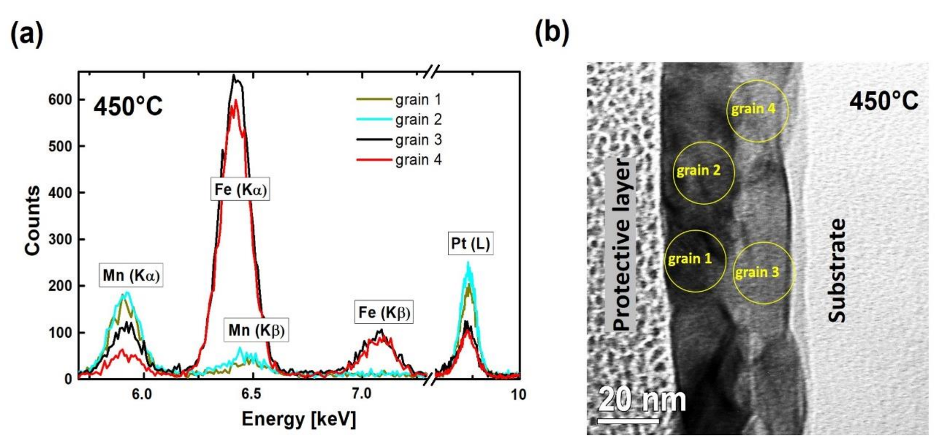

Figure 7. *(a) EDX spectra and (b) corresponding cross-section TEM image of a 450°C post-annealed sample. EDX spectra were taken at specific locations of the TEM lamella as marked in (b)*

To summarize, from the structural and chemical analysis based on XRD, SNMS, and TEM results, the following sequence of main phase transformations with annealing temperature can be proposed:

$$\text{Pt/Mn/Fe} \xrightarrow{280^\circ C} L1_0\text{-MnPt} + \alpha\text{-Fe} \xrightarrow{450^\circ C} L1_0\text{-FeMnPt} + \text{bcc } Fe_3Pt \xrightarrow{500^\circ C} L1_0\text{-FeMnPt} + \text{fcc } Fe_3Pt \xrightarrow{620^\circ C} L1_0\text{-FeMnPt} + L1_2\text{-}Fe_3Pt.$$

Conclusion

The sequence of phase transitions occurring in Pt/Mn/Fe trilayers during post-annealing in vacuum up to 620 °C was investigated. After annealing at 280 °C the ordered binary $L1_0$-MnPt phase was formed and pronounced Mn surface segregation was registered. An unreacted Fe layer remains in the film at these temperatures, dominating the materials magnetic properties. The following increase of the sample temperature up to 450 °C results in the incorporation of Fe to the $L1_0$-MnPt structure and the additional formation of metastable bcc Fe_3Pt. Upon further annealing to 500 °C, the bcc Fe_3Pt structure transforms into the paramagnetic fcc Fe_3Pt structure resulting in a decrease of the saturation magnetization. The following rise in saturation magnetization obtained after annealing at 620 °C is related to the chemical $L1_2$ ordering of Fe_3Pt, which is ferromagnetic at room temperature. The final phase products of $L1_0$-FePtMn and $L1_2$-Fe_3Pt are consistent with the initial elemental concentrations of the Pt/Mn/Fe trilayer.

Acknowledgment

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References

[1] Kohn A. et al. Appl. Phys. Lett. 102 (2013) 062403.
[2] Rhen F.M.F. et al. IEEE Trans. Magn. 39 (2003) 2699.
[3] Mizuguchi M. et al. Appl. Phys. Express 5 (2012) 093002.
[4] Hasegawa K. et al. Appl. Phys. Lett. 106 (2015) 252405J.
[5] Xu D.B. et al. J. Appl. Phys. 109 (2011) 07B747.

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