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# Control of the axis of chemical ordering and magnetic anisotropy in epitaxial FePt films

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Growth of epitaxial films of the $L1_0$ phase of FePt, with the tetragonal $c$ axis along either the film normal or in-plane, is described. Films were grown by coevaporation of Fe and Pt, under ultrahigh vacuum conditions, onto a seed film of Pt grown on MgO or $SrTiO_3$ substrates. The perpendicular or in-plane orientation of the $c$ axis was controlled by selecting the (001) or (110) substrate plane, respectively. Nearly complete chemical ordering was achieved for growth at 500 °C for both orientations. Magnetic and magneto-optical characterization of these films confirmed the huge magnetic anisotropy expected for this phase. In the most highly ordered films, anisotropy fields in excess of 120 kOe were measured. © *1996 American Institute of Physics.* [S0021-8979(96)34108-9]

The magnetic and magneto-optical properties of intermetallic FePt alloy films are of current interest. The magnetic anisotropy, and magneto-optical Kerr rotation of FePt both correlate[1] with the degree of chemical ordering and the magnetic anisotropy energy $K_u$ is predicted[2] to reach a value of $>10^8$ erg/cc for complete ordering. This is one of the highest predicted[2] anisotropy energies of transition metal alloys and results from spin-polarization of the Pt $5d$ bands combined with the large spin-orbit coupling for Pt. Chemically ordered FePt films with their $c$ axis oriented along the film normal have been prepared by annealing sputtered epitaxial films,[3] cosputtering onto heated substrates,[4] and by molecular beam epitaxy (MBE).[1,5] The $c$-axis normal configuration was obtained by growing FePt onto (001) Pt seed films on MgO(001) substrates to symmetry match the fourfold FePt basal plane with the Pt. The lattice misfits for FePt(001)/Pt(001) and Pt(001)/MgO(001) are $-1.8\%$ and $-7.3\%$, respectively. Despite these large misfits FePt grows epitaxially with perpendicular mosaic spreads of only ~1°, as we report in this paper. Up until now, there have been no reports of growth of FePt epitaxy with the $c$ axis in plane. In view of the technological interest[6] in $L1_0$ FePt films for longitudinal magnetic recording media, there is a need to control the orientation of the $c$ axis. In this article we describe the growth and characterization of FePt films with the $c$ axis either perpendicular or in-plane.

The films were grown by coevaporation in a VG Semicon V80M MBE system using $e$-gun sources for both Fe and Pt. The fluxes were controlled by Leybold Inficon Sentinel III rate monitors and film growth rates of Pt and FePt were ~0.1 and 0.2 Å/s, respectively. Film growth was characterized, *in situ* using both reflection high-energy electron diffraction (RHEED) and low-energy electron diffraction (LEED). Following growth, the films were characterized by x-ray diffraction, vibrating sample and torque magnetometry, and magneto-optical Kerr studies. MgO(001) and (110) substrates were supplied by Harrick Inc.; $SrTiO_3$(110) by Marketech Inc. They were polished on one side using a syton finish and prepared as described earlier[7] for sapphire substrates.

We have earlier reported[1] growth of FePt films on 150-Å-thick Pt template films on MgO(001) substrates. Much thinner Pt films also act effectively as templates for FePt(001) growth. Pt films ~7 Å thick, grown at a substrate temperature of 700 °C, exhibited ''spotty'' RHEED patterns, consistent with transmission electron diffraction through (001)-oriented Pt islands. Overgrowth of FePt[8] resulted in a progressive transition to elongated streaks in the RHEED pattern at ~100 Å consistent with growth of a smooth, con-

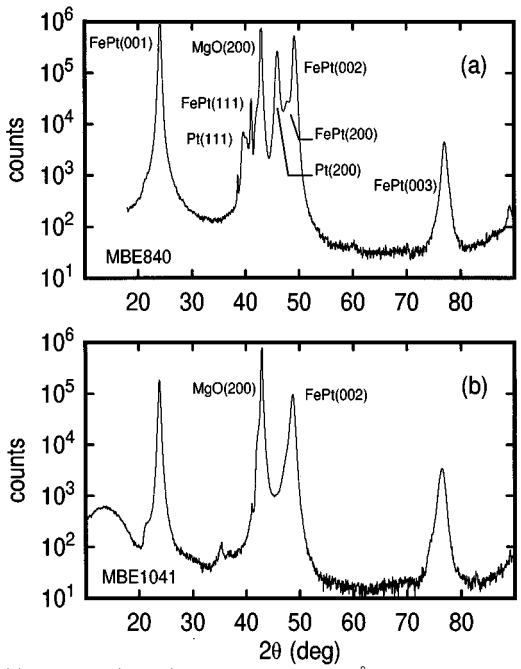


FIG. 1. (a) Specular ($\theta-2\theta$) x-ray scan of 1000-Å-thick film of FePt(001)/MgO(001). The complete structure was 18 Å $Pt/Fe_{0.52}Pt_{0.48}$/150 Å Pt/MgO(001). (b) Specular x-ray scan of 943-Å-thick film of FePt(001)/MgO(001). The complete structure was 18 Å $Pt/Fe_{0.50}Pt_{0.50}$/7 Å Pt/MgO(001).

TABLE I. Compositions, long-range order parameters and mosaic spread for FePt(001) films.

| Seed film | FePt (%Fe) | $S_{max}$ | $S_{meas}$ | ⊥ mosaic (°) (001) | ⊥ mosaic (°) (002) | ⊥ mosaic (°) (003) |
|---|---|---|---|---|---|---|
| 150 Å Pt/MgO(001) | 52 | 0.96 | 0.93±0.02 | 1.05 | 0.78 | 0.84 |
| 7 Å Pt/MgO(001 | 50 | 1.0 | 0.92±0.02 | 2.49 | 1.99 | 2.08 |

tinuous epitaxial (001)-oriented film. The RHEED pattern showed little change as the film increased in thickness from 100 to 1000 Å. Specular x-ray diffraction scans for FePt films with thick and thin Pt seed layers are shown in Figs. 1(a) and 1(b). The intense (001) and (003) superstructure peaks in both scans indicate a high degree of chemical ordering with the tetragonal *c* axis along the film normal. However, structural differences between the two samples are evident from these data. For example, minority structural domains with the tetragonal *c* axis in plane or inclined to the film plane are indicated by the presence of FePt(200) and (111) specular peaks, respectively, in Fig. 1(a) (thick Pt). For the film of Fig. 1(b) (thin Pt) these minority domains are absent. The long-range order parameter,[1] *s*, for the two samples was quantified using integrated intensities for the (001), (002), and (003) peaks extracted from fits to scans over these peaks using a high-resolution diffractometer. This procedure is described in detail elsewhere.[8] Here we point out that the mosaic spread of each of the peaks was included in the calculation and an experimental Debye–Waller factor ($\sigma$=0.136 Å) was used. Differences in mosaic spread for the superstructure and fundamental peaks are considerable and must be included in the calculation of *S* for meaningful results. The agreement between *S* determined from the (001)/(002) and (003)/(002) intensity ratios was within 4%. Table I summarizes film compositions, maximum possible order parameters at these compositions and perpendicular mosaic spreads (FWHM of rocking curves) for the (001), (002), and (003) peaks. The order parameter for both samples is close to the maximum possible values at the compositions stated.

FePt(110) films were prepared in two different ways. Initially, $SrTiO_3$(110) substrates were used with a seed film of 30 Å Pt(110). The growth of this structure has been described earlier.[9] Unfortunately, the cubic perovskite structure of $SrTiO_3$ gives rise to a (110) peak which makes extraction of the FePt(110) superstructure intensity imprecise. MgO has no (110) peak and was used as an alternative substrate. In this case a 7-Å-thick Pt seed film was used. RHEED studies[9] showed facetted Pt(110) film growth on the $SrTiO_3$ and islanded growth of Pt(110) on MgO(110). X-ray specular scans for films grown at 500 °C on $SrTiO_3$ and MgO are

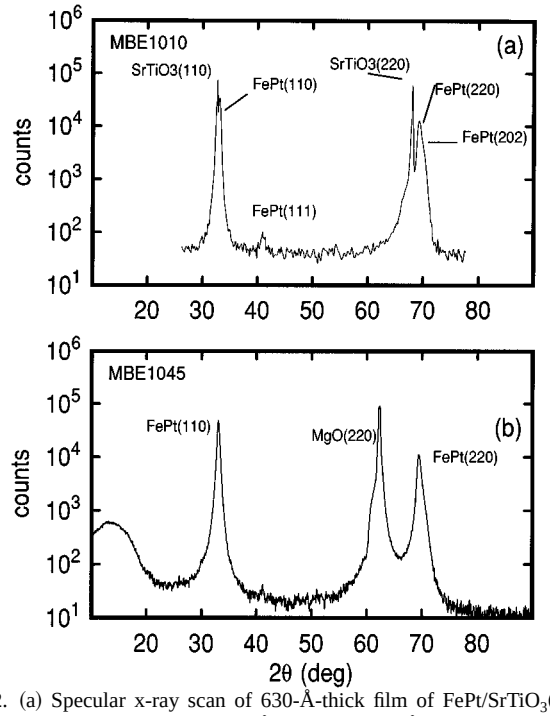


FIG. 2. (a) Specular x-ray scan of 630-Å-thick film of FePt/$SrTiO_3$(110). The complete structure was Pt 18 Å/$Fe_{0.56}Pt_{0.44}$/30 Å Pt/$SrTiO_3$(110). (b) Specular x-ray scan of 830 Å-thick film of FePt(110)/MgO(110). The complete structure was Pt 18 Å/$Fe_{0.58}Pt_{0.42}$/7 Å Pt/MgO(110).

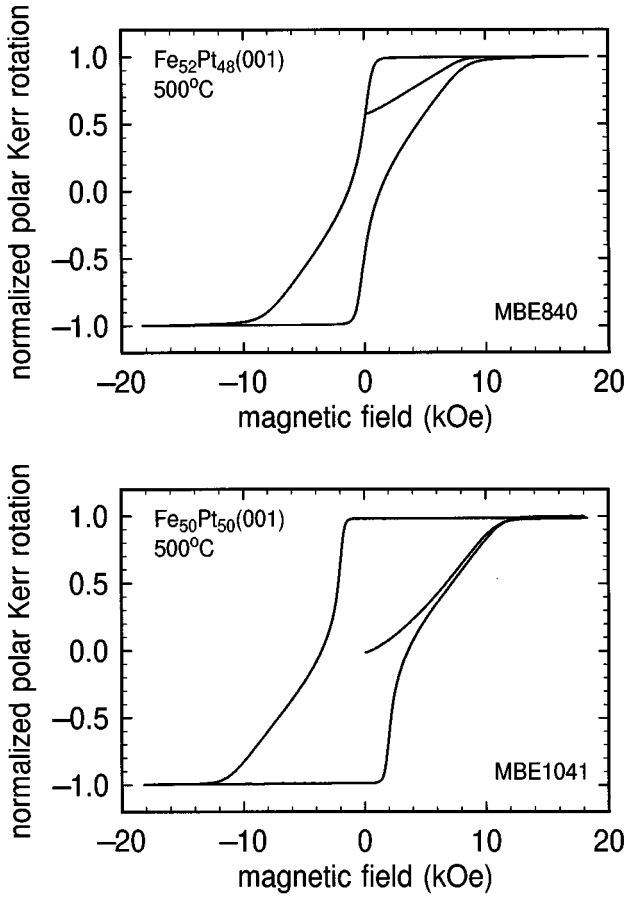


FIG. 3. Magneto-optical polar Kerr loops for FePt(001) films of Figs. 1(a) and 1(b). Laser wavelength 633 nm.

TABLE II. Compositions, long-range order parameters, perpendicular mosaic spread for FePt(110) films.

| Seed film | FePt (%Fe) | $S_{max}$ | $S_{meas}$ | ⊥ mosaic (°) (110) | ⊥ mosaic (°) (220) |
|---|---|---|---|---|---|
| 30 Å Pt/$SrTiO_3$(110) | 56 | 0.88 | 0.78±0.10 | 1.70 | 1.45 |
| 7 Å Pt/MgO(110) | 58 | 0.84 | 0.81±0.02 | 1.64 | 1.22 |

shown in Figs. 2(a) and 2(b), respectively. A high degree of chemical ordering in both samples is evident from the intense FePt(110) peak. However, in the $SrTiO_3$ sample, the FePt(110) peak appears as a shoulder on the $SrTiO_3$ peak. The majority orientation of both FePt films is FePt(110)‖$SrTiO_3$, MgO(110). In this orientation, the *c* axis of the FePt is oriented in the film plane. Both RHEED and x-ray diffraction confirm that: FePt[001]‖Pt, MgO, $SrTiO_3$[001], and FePt[110]‖Pt, MgO, $SrTiO_3$[110]. The presence of a strong FePt(202) shoulder, for the $SrTiO_3$ sample, reveals a minority structural domain with the tetragonal *c* axis inclined at ≃44° to the film plane. Peak fitting suggests that ~30% of the film volume is comprised of the minority domain. A small FePt(111) peak in Fig. 2(a) shows that this film also has a very weak (~0.1% of the sample volume) minority (111) orientation. The long-range order parameter for these two samples is given in Table II. Note that for the sample grown on MgO(110) the long-range order parameter is close to the maximum possible value.

Magneto-optical polar Kerr loops and *M*-*H* loops for the FePt(001) samples of Figs. 1(a) and 1(b) are shown in Fig. 3. For both samples the easy axis is along the film normal. Perpendicular remanence is 60% and 100%, respectively and the saturation Kerr rotations are 0.71 and 0.75°, respectively. In-plane remanence is small for both samples and in-plane *M*-*H* loops show that the magnetization is not saturated in the maximum applied field of 20 kOe. For these samples the estimated anisotropy fields are ≃75 and 120 kOe, respectively. Figure 4 shows *M*-*H* loops for the FePt(110) samples with the field applied along the easy axis: FePt[001] (parallel) or along the film normal: FePt[110] (perpendicular). The in-plane remanence is 100% for both samples but there is a large difference in the out-of-plane magnetization data. The FePt/$SrTiO_3$ sample has a much larger remanence than the FePt/MgO(110) sample. The anisotropy fields for the samples are ≃75 and 140 kOe, respectively.

The structural and magnetic data for the FePt(001) films confirm that near-complete chemical ordering is achieved for film growth on Pt(001)/MgO for both 150 and 7-Å-thick Pt seed films at 500 °C. There are, however, significant differences in structural quality of the two samples which probably lead to the observed differences in magnetic properties. For example, the minority (111) and (100) structural domains may provide minority magnetic domains which contribute to the reduced remanence seen in the film with the thicker Pt seed film. Kern microscopy[10] reveals reverse-nucleated domains in zero field for this film. Similarly, for the FePt(110) samples the presence of (111) and (101) minority structural domains, in the film grown on $SrTiO_3$, may contribute to the perpendicular remanence and reduced magnetic anisotropy field for this sample. The huge magnetic anisotropy for the FePt $L1_0$ phase is confirmed by the magnetic data for these films. Torque magnetometry data, to be presented in detail elsewhere,[10] confirms $K_u$ to be $\sim 10^8$ erg/cm$^3$ for these films.

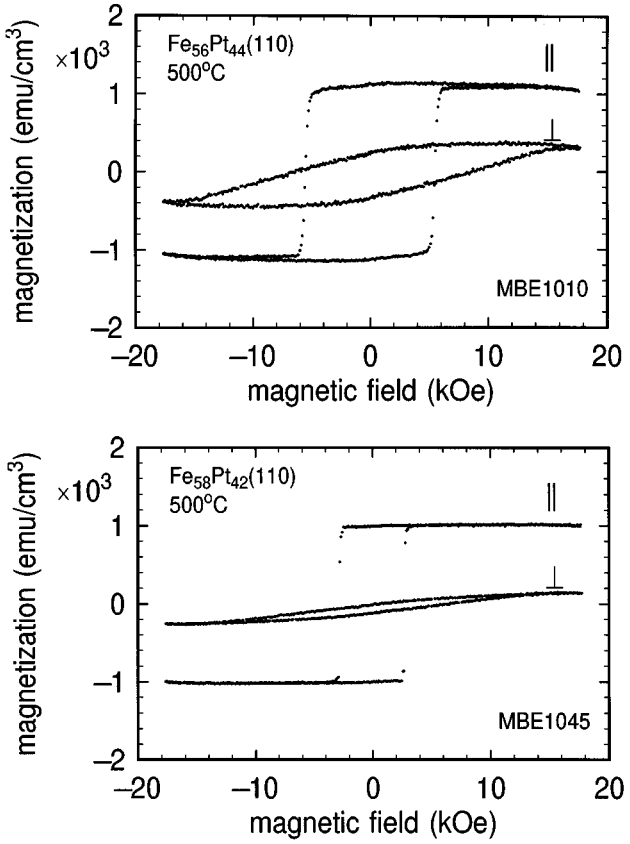


FIG. 4. Magnetization loops for FePt(110) films of Figs. 2(a) and 2(b).

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