

Ion-beam-assisted growth of CoPt₃ films

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CoPt₃ films are known to exhibit room-temperature perpendicular magnetic anisotropy when grown between 200 °C–400 °C. We have used Ar ion-beam-assisted growth of CoPt₃ films in an effort to enhance the anisotropy and also lower the temperature range where it occurs. We present a systematic study of the dependence of magnetic properties of the films on substrate temperature during growth, ion beam energy, and ion to atom arrival ratio, R , at the substrate. We find a significant increase of the anisotropy in films grown at 100 °C compared to the $R=0$ value resulting in perpendicular anisotropy at moderate growth temperatures. At 250 °C and 400 °C, however, there is a monotonic decrease in anisotropy with R for all energies. © 2001 American Institute of Physics. [DOI: 10.1063/1.1412430]

It is known that vapor deposited films of CoPt₃ exhibit perpendicular magnetic anisotropy (PMA) when grown at temperatures between 200 °C and 400 °C despite a nominally cubic structure.^{1–3} The PMA is believed to be due to the presence of thin Co platelets in a Pt-rich matrix; the platelets form by a surface equilibrium effect, which drives a surface phase separation during growth.⁴ The limited bulk mobility of the condensing atoms at growth temperatures where PMA occurs causes the platelets to remain trapped in the film without homogenization in the bulk. The occurrence of PMA is accompanied by enhancements in the Curie temperature T_C by 200 °C for films grown at 400 °C, providing evidence of Co atom clustering in the film.⁴ X ray and transmission electron microscope characterization of the films with PMA indicate a random face-centered-cubic (fcc) solid solution, implying that the Co-rich and Pt-rich regions are smaller than the coherence length of the x rays and electrons. Below 200 °C, the films are not epitaxial, appear to be truly disordered fcc and exhibit no PMA. If PMA occurred at low growth temperatures, it would be technologically important for CoPt₃ as a potential perpendicular recording media.

Ion-beam-assisted deposition (IBAD) is a powerful and versatile tool used to control thin-film microstructure.⁵ Previous work^{6,7} using IBAD of CoPt₃ films was carried out at ambient temperatures and at energies ≥ 100 eV (up to 500 eV) and for relatively large R (~ 2). They reported no change in microstructure and no observation of PMA in their films. We have used IBAD of CoPt₃ to answer the following two questions: (1) at low growth temperatures (below 200 °C), could the ion beam increase surface mobility to the condensing atoms and enhance the surface phase segregation into Co platelets, leading to PMA? and (2) at a higher temperature, between 200 °C and 400 °C, could the use of an ion beam enhance the PMA? We find, that yes, the ion beam induces PMA by forming thin Co platelets at temperatures lower than 200 °C but that at higher temperatures, the ion beam reduces the PMA and eliminates it completely for high ion flux. We suggest that this may be because the interfaces between the

Co platelets and the Pt-rich matrix are rather fragile and easily destroyed.

Epitaxial (100) and (111) CoPt₃ films were grown on (100) MgO and (0001) Al₂O₃, respectively, by electron-beam coevaporation from Co and Pt sources. The substrate temperature during growth was maintained at 100 °C, 250 °C, or 400 °C. A 3 cm Kaufmann-type ion gun from Commonwealth Scientific was used to produce 50 or 100 eV Ar ions. The background pressure in the chamber was 3×10^{-10} Torr. The Ar flow rate was 9 sccm, resulting in a pressure of 1×10^{-4} Torr during deposition. The deposition rate, as well as the ion current, were varied to obtain different values of ion/atom ratio, R , specifically, R was varied between 0 and 4 by varying the deposition rate between 0.5 and 0.05 A/s and the ion current between 0 and 50 mA.

Reference samples were made without ion assistance at each growth temperature in flowing Ar gas but no beam current. The properties of these $R=0$ samples are the same as those grown without Ar. Using *in situ* reflection high-energy electron diffraction, films were found to be epitaxial at all growth temperatures. All films were nominally 600 Å thick. The imposition of the ion beam did not significantly affect the composition of the films. We also did not find any trace of Ar within the detection limit of energy dispersive analysis by x rays ($< 1\%$).

Room-temperature, saturation magnetization, M_s , was obtained from $M(H)$ loops using a vibrating sample magnetometer (VSM). For both (111) and (100) films, the anisotropy constant K_u was determined from the area enclosed between the easy and hard axis in the $M(H)$ curves. For (111) films, K_u was also determined from the peak torque measured at room temperature in a torque magnetometer. Values of K_u obtained by the two methods agreed to within 10%.

The Curie temperature, T_C , was determined using the VSM. Each sample was first saturated along the easy axis or plane of magnetization at room temperature in a field of 10 000 Oe. Magnetization curves $M(T)$ were then measured upon heating in a temperature controlled flowing Ar gas in a field of 200 Oe.

After characterizing the samples in the as-deposited

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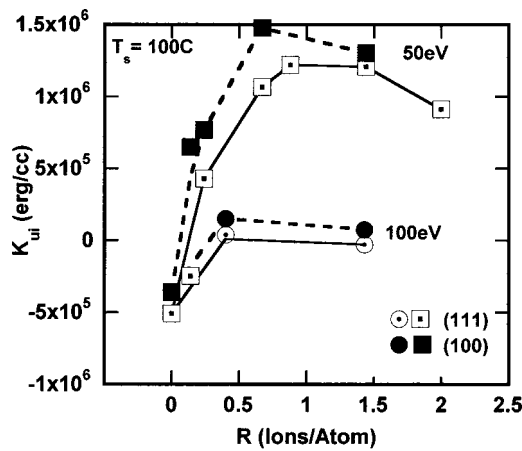


FIG. 1. K_{ii} as a function of R for 50 and 100 eV Ar ion-assisted growth of $\text{CoPt}_3(111)$ and (100) films at 100°C . Lines are drawn as a guide for the eye.

state, films were annealed at 750°C for a period of 30 min. This annealing temperature is above the order-disorder temperature for CoPt_3 and has been shown to eliminate growth induced effects such as Co platelets, resulting in a film with no PMA and T_C and M_s values corresponding to the bulk fcc chemically disordered state.⁴

Figure 1 shows K_{ii} as a function of R for (111) and (100) films grown at 100°C . The shape anisotropy $2\pi M_s^2$ has been subtracted from the measured anisotropy, K_u , to obtain the intrinsic anisotropy constant K_{ii} . In the reference sample, $R=0$, K_{ii} is negative implying that the film has an intrinsic hard perpendicular axis. As R is increased, K_{ii} increases and changes sign, indicating that the easy axis now lies perpendicular to the film. The enhancement in K_{ii} compared to the reference value is small for 100 eV Ar ions. However, for 50 eV Ar ions, there is a significant increase with a maximum of 1.2×10^6 erg/cc at $R=0.8$. The (100) film has a slightly larger K_{ii} than the (111) film at all values of R . The films show a perpendicular remanent moment, but perpendicular remanence is less than the saturation magnetization.

$M(T)$ in the as-deposited films is broad with an enhanced T_C compared to the bulk value of 210°C for CoPt_3 , similar to films with PMA grown at higher temperature without ion assistance.^{3,4} The broad transition suggests the presence of Co platelets of varying size and thickness, each with its own value of T_C . After annealing at 750°C for 30 min, $M(T)$ sharpens and T_C drops to the value expected for the bulk fcc structure. M_s in the as-deposited state is similarly enhanced above the fcc value. This is also consistent with the picture of Co clustering into thin platelets causing an increase in M_s due to enhancements in both Pt and Co orbital moments.⁴ In Fig. 2, we plot the T_C and M_s enhancement in the as-deposited (111) films grown at 100°C . $T_C(M_s)$ enhancement was calculated by subtracting the $T_C(M_s)$ of the annealed sample from $T_C(M_s)$ of the as-deposited films. We note that M_s and T_C enhancements are completely correlated with the occurrence of PMA in the ion-beam-assisted films just as was found in films grown at a higher temperature without ion assistance.^{3,4}

To summarize, by using IBAD, we have been able to bring about the formation of Co platelets in CoPt_3 films

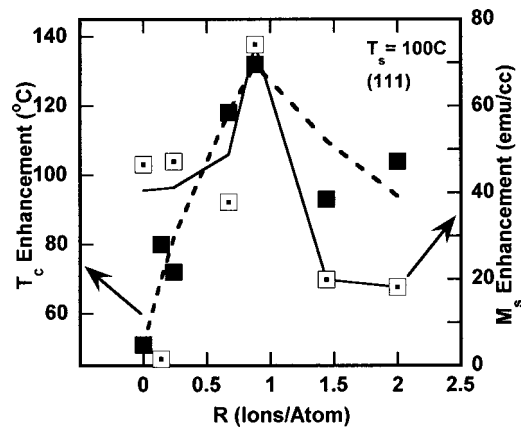


FIG. 2. Enhancement in T_C (solid symbols) and M_s (open symbols) plotted vs R for (111) CoPt_3 films grown at 100°C . Lines are drawn as a guide for the eye.

grown at 100°C , as is strongly suggested by our magnetization measurements. The formation of these platelets is accompanied by the appearance of PMA, enhancement in Curie temperature, T_C , and enhancement in saturation magnetization, M_s , all of which are signatures of the presence of these platelets on a very local scale.⁴ Films exhibit perpendicular anisotropy including perpendicular remanent moment, although the largest PMA is still only 20% of the anisotropy obtained for CoPt_3 films grown at 400°C without any ion assistance.⁴

We have also grown films at 250°C and 400°C with simultaneous Ar ion bombardment. The results at 250°C are shown in Fig. 3. There is a rather large scatter in the data due most likely to the fact that K_{ii} is a steep function of the growth temperature near 200°C .^{3,4} Nevertheless, it is clear that K_{ii} decreases with R at 50 eV and even faster at 100 eV. The magnitude of K_{ii} for the (100) film is again larger than that for the (111) film at all values of R as was observed in the data for $T_s=100^\circ\text{C}$.

The data for films grown at 400°C are shown in Fig. 4. As seen at 250°C , the decrease in anisotropy with increasing R is very steep at 100 eV, while 50 eV bombardment leads to a more gradual decrease in K_{ii} .

Based on M_s and T_C at $T_s=100^\circ\text{C}$ for $R=0$, the film is

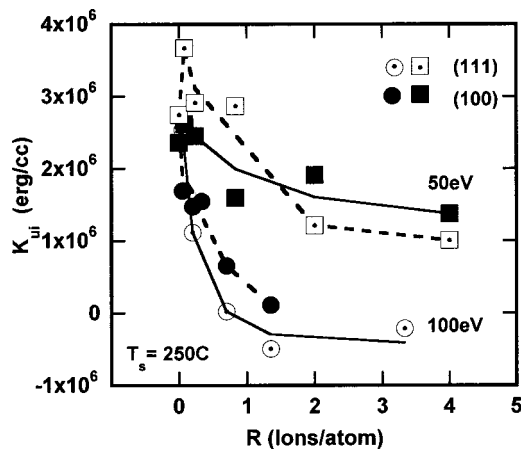


FIG. 3. K_{ii} as a function of R for 50 and 100 eV Ar ion-assisted growth of $\text{CoPt}_3(111)$ and (100) films at 250°C . Lines are drawn as a guide for the eye.

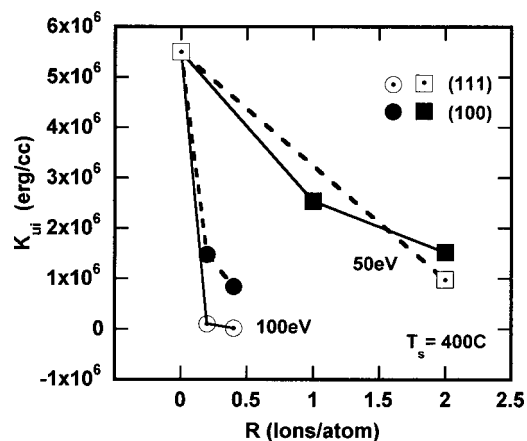


FIG. 4. K_{ii} as a function of R for 50 and 100 eV Ar ion-assisted growth of CoPt_3 (111) and (100) films at 400 °C. Lines are drawn as a guide for the eye.

a homogeneous chemically disordered fcc structure even on a local scale with no phase separation into Co platelets. As the ion current is increased, i.e., for higher ion-to-atom arrival ratios, more energy is transferred to the condensing atoms, leading to increased surface mobility. This enhances surface phase separation into Co platelets and leads to perpendicular anisotropy. The effect is maximized at $R=0.8$, above which K_{ii} is reduced. We suggest that this is due to a competition between two effects; enhanced surface mobility which increases platelet formation and subsurface damage which reduces the sharpness of the interfaces. At $R=0.8$, we have the optimum sharpness for the interfaces between the Co platelets and the Pt-rich matrix for the given conditions of growth, therefore K_{ii} is a maximum.

At 250 °C and 400 °C, PMA is reduced by ion bombardment. It is possible that the surface is still producing Co platelets, but as a result of the ion bombardment, there is

sufficient subsurface mobility so that the Co platelets are eliminated by homogenization in the layers just below the surface. A comparison of Figs. 3 and 4 leads us to conclude that the effect of the ion bombardment is more dramatic at 400 °C than at 250 °C, since at higher temperatures, the already higher mobility of the atoms with the additional imparted energy from the ions leads to increased homogenization.

In summary, we have carried out Ar IBAD of CoPt_3 films. For films grown at 100 °C, we find a significant enhancement of the PMA using a 50 eV Ar ion beam and a moderately low ion flux ($R=0.8$). Previous work^{6,7} reported no changes in anisotropy using IBAD of CoPt_3 . This is consistent with our results since their study was for room-temperature growth, 100 eV ion energy, and relatively high R (~ 2). At 250 °C and 400 °C, we find that the effect of the ion beam is to decrease the PMA compared to the reference value at all energies.

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