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Yu, M.; Liu, Yi; Moser, A.; Weller, D.; and Sellmyer, David J., "Nanocomposite CoPt:C films for extremely high-density recording" (1999). *David Sellmyer Publications*. 68.

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Nanocomposite CoPt:C films for extremely high-density recording

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(Received 26 May 1999; accepted for publication 26 October 1999)

Nanocomposite CoPt:C films were investigated as potential media for extremely high-density recording. An annealing temperature of over 600 °C is necessary to form nanocomposite CoPt:C films consisting of C matrix and fct CoPt nanocrystallites with grain sizes of 8–20 nm and coercivities of 3–12 kOe. Coercivity and grain size increase with increasing annealing temperature and decreasing C concentration and they are insensitive to film thickness. The average activation volumes are about $0.9 \times 10^{-18} \text{ cm}^3$. The properties of these nanocomposite CoPt:C films can be tailored to satisfy the thermal stability, coercivity, and media noise requirements for extremely high-density recording. © 1999 American Institute of Physics. [S0003-6951(99)00951-1]

The areal density of longitudinal magnetic recording has been increasing 60% annually and the trend is predicted to continue in the near future.^{1–3} At present, using Co-based media, areal density of more than 10 Gb/in.² has been achieved in commercial hard-disk drives and several 20 Gb/in.² and above demonstrations were reported recently.⁴ Extremely high-density recording (EHDR), defined here as an areal density of about 100 Gb/in.², is sought for implementation in a few years. In order to have low media noise, EHDR media would need to have coercivity (H_c) of about 4 kOe (Ref. 5) and weakly exchange-coupled grains of less than 10 nm in size according to very simple estimates.⁶

For grain size $d \approx 10 \text{ nm}$ ($V \approx d^3 = 1 \times 10^{-18} \text{ cm}^3$), the issue of thermal stability has to be considered. The magnetization of a grain decays due to thermal fluctuations. At temperature T the relaxation time τ is given by⁷

$$1/\tau = f_0 \exp(-E_B/k_B T), \quad (1)$$

where f_0 ($\sim 10^9 \text{ Hz}$) is the attempt frequency and E_B is the energy barrier, a function of applied field H . Based on the Stoner–Wohlfarth (SW) model with a low-field approximation, it can be shown that

$$E_B = K_u V (1 - H/H_A) \approx K_u V, \quad (2)$$

where V is the grain volume, K_u is the uniaxial anisotropy constant, and $H_A = 2K_u/M_s$ is the anisotropy field (M_s is the saturation magnetization). It is usually required that the relaxation time of the grains in recording media be at least ten years. Thus, from Eqs. (1) and (2) it is required that $K_u V/k_B T > 40$. This requirement increases to

$$K_u V/k_B T > 60 \quad (3)$$

in a typical 40 Gb/in.² recording environment,⁸ due to non-negligible interbit stray fields. For Co-based media, $K_u \approx 2$

$\times 10^6 \text{ erg/cm}^3$. As grain sizes become smaller than 10 nm, it is clear that Eq. (3) cannot be satisfied at room temperature. So, it is interesting to investigate media materials with K_u higher than that of Co-based media.

The ordered fct CoPt phase has $K_u \approx 5 \times 10^7 \text{ erg/cm}^3$, thus Eq. (3) can be well satisfied even with $d = 4 \text{ nm}$ ($V = 6.4 \times 10^{-20} \text{ cm}^3$). Large H_c , which originate from the high K_u value, were reported in CoPt bulk samples,⁹ CoPt films,¹⁰ CoPt nanoparticulates grown on quartz substrates,¹¹ and CoPt/Ag films.¹² For the purpose of forming small CoPt grains with weak exchange coupling, C would be an ideal isolation material between neighboring CoPt grains because there exist neither stable Co nor Pt carbides.

A real magnetic film, such as a recording medium, is generally very different from a collection of identical isolated SW grains because of intergrain interactions, grain-size distribution, and incoherent rotation in magnetization reversal. For such a system, Eq. (3) is generally not applicable since $E_B(H)$ is different from Eq. (2). The magnetic activation volume V^* can be regarded as the effective or average unit volume of magnetic moments that switch together in magnetization reversal regardless of the magnetization reversal model.^{13,14} This idea is supported by the fact that media noise for Co-based films is proportional to $M_s V^*$.¹⁵ It can be shown that^{6,16}

$$V^* = -(\partial E_B / \partial H) / M_s. \quad (4)$$

For isolated identical SW grains, $V^* \approx V$ if $H \ll H_A$. For a real system, Eq. (4) shows that V^* is not directly related to V , but rather depends explicitly on $E_B(H)$. Nevertheless, it is V^* instead of V that should be considered in thermal relaxation, so that V in Eq. (3) should be replaced by V^* .⁶ In this letter, V^* was derived from its relationship with magnetic viscosity and irreversible susceptibility.^{14,17}

CoPt:C films were cosputtered onto water-cooled Si(100) substrates from pure Co, Pt, and C targets. The atomic ratio of Co and Pt is fixed at 1:1 and the C concentration ranges from 30 to 80 vol%. The base pressure is

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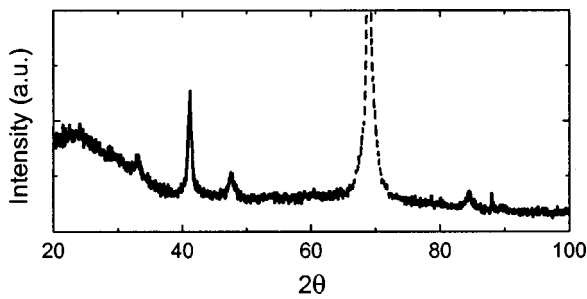


FIG. 1. XRD patterns of a 100 nm CoPt:C film with 30 vol % C annealed at 650 °C. The peak of the dashed line is from the Si(100) substrate.

better than 3×10^{-7} Torr and the Ar pressure is 10 mTorr. The thickness of CoPt:C film is varied from 3 to 100 nm and the C underlayer and overcoat are both 20 nm. All as-deposited films were annealed in vacuum for 1 h at various temperatures. The structural properties were analyzed by x-ray diffraction (XRD) and transmission electron microscopy (TEM). The magnetic measurements were performed on an alternating gradient force magnetometer and a superconducting quantum interference device magnetometer parallel to the film plane unless specified otherwise. The recording experiments were carried out on small sample pieces using a drag tester.

All as-deposited films are magnetically soft with H_c less than 100 Oe. They most likely consist of disordered fcc CoPt,⁹⁻¹² which is the high-temperature phase, and/or amorphous CoPt in addition to C matrix. Since fct CoPt is the low-temperature phase, appropriate annealing leads to the transition from the fcc CoPt phase to the fct CoPt phase in CoPt:C films. As a typical example, Fig. 1 shows the XRD patterns of 100 nm CoPt:C films with 30 vol % C annealed at 650 °C. Excluding the peak from the Si(100) substrate (dashed line at $2\theta = 69.2^\circ$), all visible peaks can be attributed to the fcc CoPt or fct CoPt phase. This indicates that most C remains as a pure element matrix rather than forming any carbide phases. The grain size d is about 12 nm, as estimated by Scherrer's formula¹⁸ from the (111) peak width. It is difficult to distinguish between fct CoPt and fcc CoPt phases only from XRD measurement because their XRD patterns are very similar and all peaks are considerably broadened due to the very small grain sizes. The development of large H_c can best indicate the formation of the fct CoPt phase. The annealing temperature (T_A) dependence of H_c and d of 100

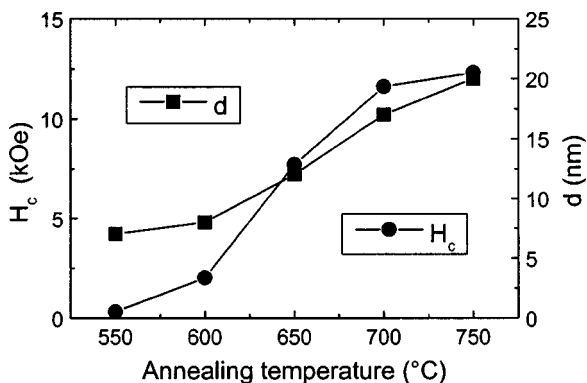


FIG. 2. H_c and d of 100 nm CoPt:C films with 30 vol % C annealed at various temperatures.

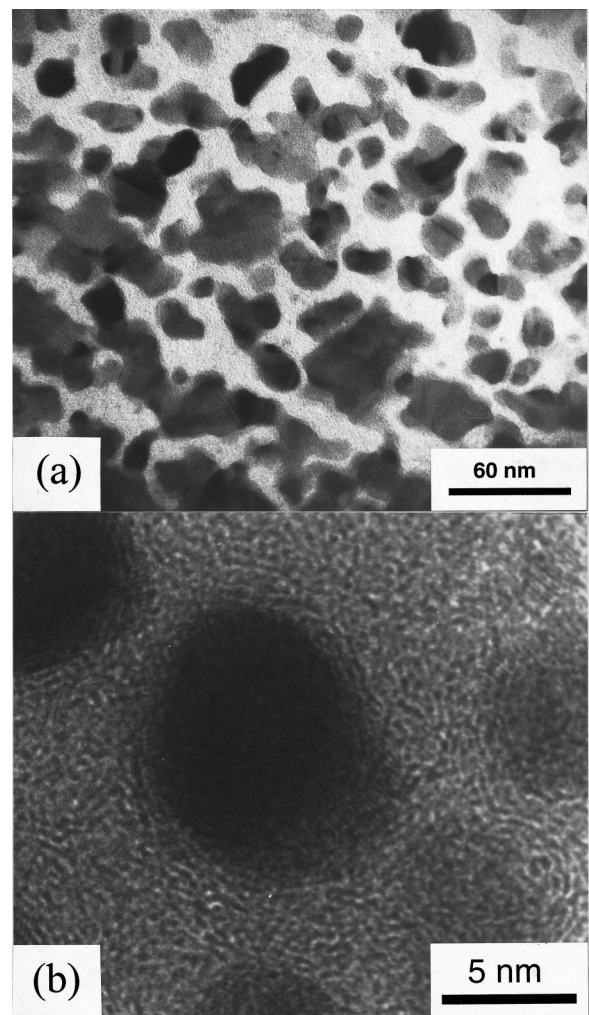


FIG. 3. (a) Bright-field and (b) high-resolution TEM pictures of a 100 nm CoPt:C film with 30 vol % C annealed at 650 °C.

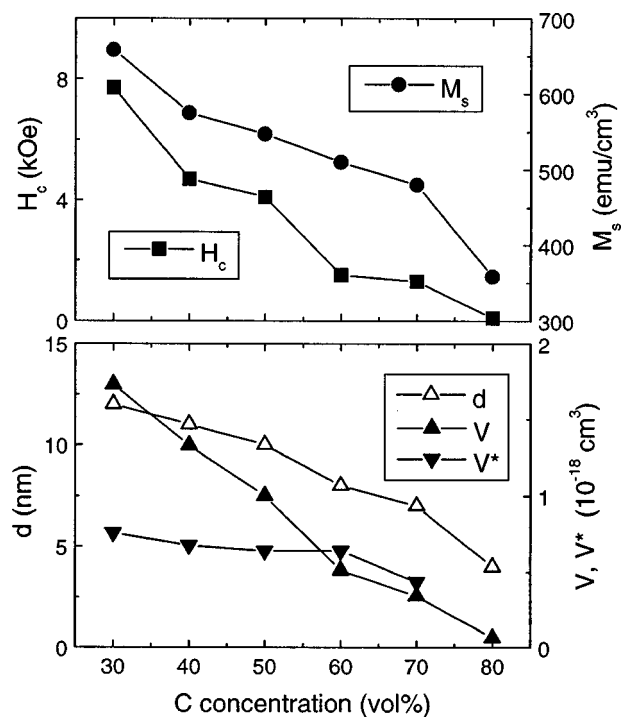


FIG. 4. H_c , M_s , d , $V = d^3$, and V^* of 100 nm CoPt:C films annealed at 650 °C with various C concentrations.

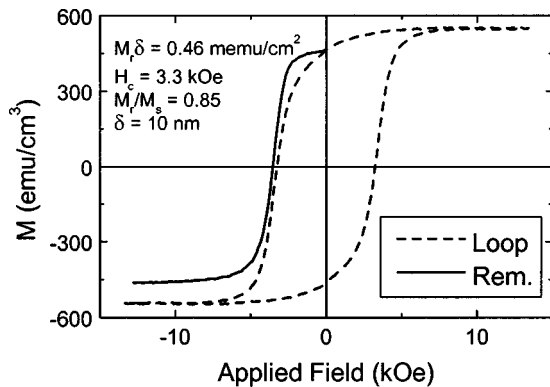


FIG. 5. Hysteresis loop and dc remanence curve of a 10 nm CoPt:C film with 50 vol % C annealed at 600 °C.

nm CoPt:C films with 30 vol % C are plotted in Fig. 2. While d increases steadily with increasing T_A , H_c increases first dramatically, from 2.0 to 11.9 kOe, when T_A increases from 600 to 700 °C, then slowly when T_A is further increased. The rapid increase of H_c around T_A of 650 °C can be explained only by the formation of the fct CoPt phase. The slow increase of H_c when T_A is higher than 700 °C is most likely due to the growth of fct CoPt crystallites.

Figure 3(a) is a bright-field TEM image of a 100 nm CoPt:C film with 30 vol % C annealed at 650 °C. Some CoPt grains are well separated from each other while some appear aggregated. Figure 3(b) is a high-resolution TEM image showing a CoPt grain separated from others. This image also shows that the C matrix is amorphous and the CoPt grain is a single crystal. The average grain size observed from Fig. 3 is about 11 nm, which is in good agreement with the result obtained from Scherrer's formula.

The effect of C concentration was investigated for CoPt:C films annealed at 650 °C. Figure 4 shows H_c , M_s , and d , along with $V=d^3$, and V^* of 100 nm films as functions of C concentration. As expected, M_s decreases almost linearly with increasing C concentration. So does d because more C certainly slows the growth of CoPt grains. Presumably, the primary reason for the decrease of H_c with increasing C concentration is due to a decreasing K_u value resulting from incomplete transition from the fcc CoPt phase to the fct CoPt phase. The decrease of d may also contribute to the decrease of H_c . For C concentration of less than 60 vol %, V^* is almost constant, at about $0.68 \times 10^{-18} \text{ cm}^3$, and it is considerably smaller than V , suggesting incoherent rotations. For higher C concentrations V^* is close to V and decreases with C concentration.

A large variation of film thickness δ has little effect on H_c and V^* of annealed CoPt:C films. For those with 50 vol % C annealed at 600 °C, H_c remains almost constant, at about $3.3 \pm 0.7 \text{ kOe}$ when $\delta \geq 5 \text{ nm}$. When $\delta = 3 \text{ nm}$, H_c decreases to 1.5 kOe, probably resulting from the decreased grain volume due to reduced dimension. V^* appears to be a constant, at about $(1.1 \pm 0.1) \times 10^{-18} \text{ cm}^3$, for the whole thickness range ($\delta = 3 - 100 \text{ nm}$).

Recording experiments were performed on selected samples. The results of a 10 nm CoPt:C film with 50 vol % C

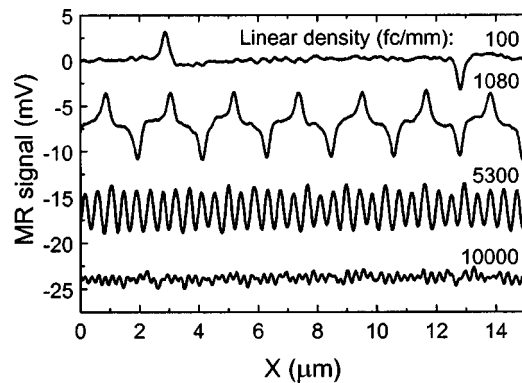


FIG. 6. Magnetoresistance (MR) head read-back signals of individual tracks at various linear densities of a 10 nm CoPt:C film with 50 vol % C annealed at 600 °C (X denotes the distance along the track direction).

annealed at 600 °C are given here as an example. This sample has $d < 10 \text{ nm}$ and $V^* \approx 1.1 \times 10^{-18} \text{ cm}^3$. The hysteresis loop and dc remanence curve are shown in Fig. 5. The read-back signals of individual tracks at various linear densities are shown in Fig. 6. With a C overcoat of 20 nm, clear read-back signals at linear densities of at least 5000 fc/mm can be obtained. Much higher densities may be expected if the C overcoat thickness is reduced to less than 10 nm.

In summary, we are able to synthesize nanocomposite CoPt:C films with controlled nanostructure and magnetic properties so that parameters suitable for EHDR media can be obtained. In addition, both CoPt and C phases have excellent chemical stability. Therefore, nanocomposite CoPt:C film is a very promising media candidate for extremely high-density recording.

The authors thank Professor S. H. Liou and C. P. Luo for their generous help. This work is supported by NSIC and NSF/DMR-9623992.

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