Engineering the Microstructure of Thin Films for Perpendicular Recording

David E. Laughlin, S. Kumar, Yingguo Peng, and Anup G. Roy, *Member, IEEE*

***Abstract*—In this paper we discuss various microstructural features that control the recording properties of thin films used in perpendicular recording. These microstructure features include crystallographic texture, grain size, grain size distribution, grain to grain magnetic isolation, grain to grain composition variation and in the case of $L1_0$ materials the grain to grain variation in the degree of atomic order. We discuss recording media comprised of continuous thin films as well as granular thin films. We discuss media composed of either *hcp* Co alloys or FePt $L1_0$ alloys. Methods of controlling the microstructural parameters are discussed as is their effects on recording properties. Examples from our recent research will be used to illustrate these microstructural aspects of perpendicular recording media.**

***Index Terms*—Co-alloy, crystallographic texture, grain distribution, grain isolation, grain size, granular oxide, $L1_0$ alloy, microstructure, order parameter.**

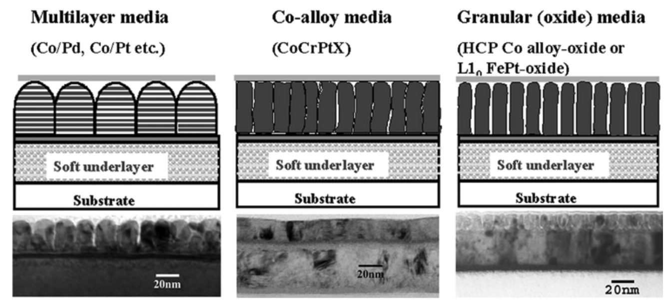

Fig. 1. Schematic structures and cross section microstructures of three types of perpendicular media.

I. Introduction

As MAGNETIC recording changes to the perpendicular paradigm, it remains important to understand which of the various features of the thin film microstructure control the recording properties. The role of microstructure in longitudinal recording media previously has been reviewed [1], [2] and a review on perpendicular media by Victora also has been written [3] in which he cites five important requirements of perpendicular media, as follows.

1) The coercivity should be in the range of 15–20 kOe to fully exploit perpendicular recording.
2) There should be perfect remanence, or a squareness of unity, implying a negative nucleation field.
3) Small grain size.
4) Small exchange interaction between grains.
5) Small spacing between the soft underlayer and the media to minimize the effective spacing loss.

In this review, we focus on the microstructural features related to these requirements. Three types of thin film constructions will be discussed, namely, multilayer, continuous thin film, and granular thin films. These are shown schematically in Fig. 1.

In the multilayered media, a magnetic element (Co) is deposited alternatively with a transition metal such as Pd or Pt. The Co layers are deposited with their closed packed layers in the plane of the film and the Pd or Pt layers are formed epitaxially on these layers giving rise to strong perpendicular anisotropy, by means of interface anisotropy [4]. The layer between the soft magnetic underlayer and the Co/Pd multilayer is usually an amorphous material, which allows the Co to form with its growth texture [5].

The Co alloy continuous thin film media is grown either on an amorphous intermediate layer or on a textured layer of an hcp material such as Ru. The granular media is formed by co-sputtering an oxide (e.g., SiO_2) and a magnetic alloy (either a Co based one or perhaps an $L1_0$ alloy with high magnetocrystalline anisotropy). The mixture of these two materials can form columns of the magnetic alloy separated by an oxide phase [6], [7].

The best type of perpendicular media has not yet been determined. Early in the search multilayers were heavily investigated [3], [8] as was Barium Ferrite media [9], [10] but these no longer seem to be in the forefront of research, mainly because of the difficulty of obtaining small grain sizes. The high coercivity requirement is a difficult one for Co based hcp materials to reach but can be easily met by FePt thin films, multilayer and by Barium ferrite media. The negative nucleation field is fulfilled by the multilayer media [3]. However it is not easy to obtain films with small grains associated with high coercivity and small exchange coupling in either multilayer or Barium Ferrite media. Columnar Co alloy films with segregation to the boundary for magnetic isolation and granular mixtures of the magnetic media (either $L1_0$ or Co alloy) and an oxide which acts so as to isolate the grains, are the two types of media that appear to offer the best combination of properties. Granular media can be produced with very small grains, and seems to be the current media of choice for perpendicular media. Whether it remains in this favored position depends on the relative advances in the other type of media.

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The authors are with the Department of Material Science and Engineering, Electrical and Computer Engineering, and Data Storage Systems Center, Carnegie Mellon University, Pittsburgh, PA 15213 USA (e-mail: laughlin@cmu.edu; kumar2@andrew.cmu.edu; yingguo@andrew.cmu.edu; agroy@ece.cmu.edu).

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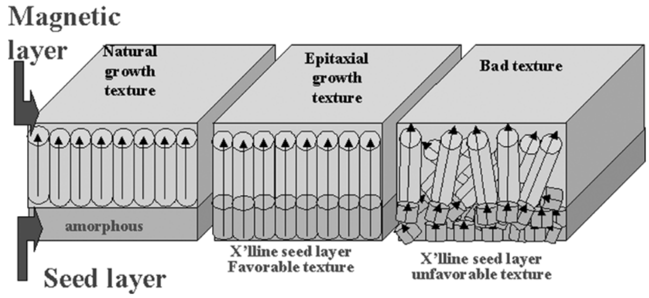

Fig. 2. Schematic representations of the growth of Co grains on different intermediate layer structures.

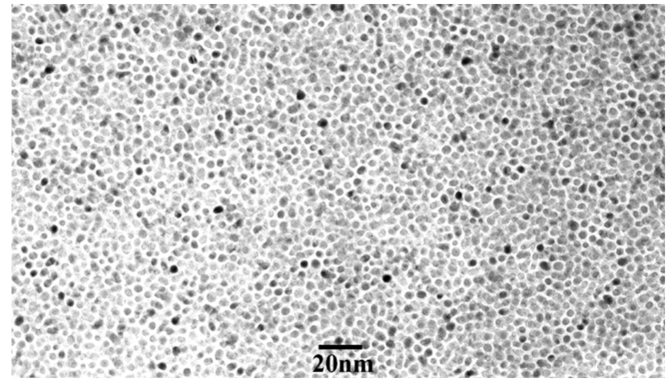

Fig. 3. Granular media displaying 3.5 nm grains.

II. Crystallographic Texture

Perpendicular recording requires that the easy axis of magnetization be out of the plane of the film. For multilayer films this occurs naturally, as the film interface anisotropy is perpendicular to the modulated structure. For Co/Pd multilayers, the Co close packed plane comes down in the plane of the film if the intermediate layer is amorphous. For continuous Co based hcp alloy films the natural growth texture is the perpendicular [0001]. In this case, the role of underlayers is to enhance the growth texture. This may be done by epitaxy or it may be done by using an amorphous underlayer [11]. See Fig. 2. If the amorphous layer has some crystallinity, or if the crystalline intermediate layer loses its texture the magnetic films lose their strong crystallographic texture. The texture can be observed by x-ray diffraction in which only the $(000l)$ Co diffraction peaks should be present (l an even number) or by plan view electron diffraction in which only the $(hk.0)$ rings of the Co should be present.

The growth of the granular microstructure with texture is not as well understood. However, it is clear that such growth can lead to perpendicular anisotropy if the magnetic materials either nucleates or grows with the correct crystallographic orientation. In the case of Co based alloy granular media, the Co alloy should attach itself first to the intermediate layer before the oxide does. If an $L1_0$ media is being used (e.g., FePt) its texture must be set up by epitaxy, so the intermediate layer must have one of its cubic $\langle 100 \rangle$ axes perpendicular to the plane of the film. An intermediate layer of Pt can be placed between the MgO and the FePt. Pt has a lattice parameter between those of MgO and FePt, and can be used to control the amount of epitaxial strain. This strain can be utilized to produce the [001] texture. Other ways of obtaining this texture include the use of Cr interlayers between the media and MgO, and the use of Cr with the [001] texture as an underlayer. This is discussed below.

III. Grain Size and Distribution

It is important to obtain small grains with a narrow distribution of size in perpendicular media to reduce the transition noise and to support large recording densities. For a given mean grain size value, a wider grain size distribution gives rise to a higher transition noise. The grains with larger size than the average produce a wider zigzag boundary, while the smaller grains are thermally less stable (or in the ultimate case, superparamagnetic), which decay faster in magnetization and cause noise over time. In addition, as discussed in Section V, small grains have a larger composition dispersion, which may entail a larger H_k distribution, and hence give rise to an extra source of transition noise.

Small grains are easily obtained in the granular media; in fact, sometimes the grain size is too small. See Fig. 3, which is the microstructure of a Co based alloy with SiO_2 that displays a grain size of about 3.5 nm and grain center to center distance of about 4.5 nm. This sample displayed a very low coercivity.

The variables involved in granular media include the volume fraction of the two phases, the rate of sputtering and the back pressure. These must be carefully controlled if the film is to contain grains that can be ferromagnetic (as opposed to superparamagnetic) and contain magnetically isolated grains.

IV. Grain Isolation

Granular media has excellent grain to grain isolation as the oxide phase surrounds the grains over their entire boundaries. This enables each grain to respond to applied magnetic fields independently which in turn gives rise to high coercivity and low noise. See Fig. 4, where the grain size is about 5 nm.

The grains in the continuous thin film Co alloy films can be isolated by chemical segregation, as in the longitudinal media. Cr is known to segregate to the boundary and various other elements alloyed with the underlayer can also be used [12], [13] if they can diffuse along the grain boundaries. Thus, the segregation may be from within the grains or through the grain boundaries from the underlayers. Fig. 5 illustrates grain segregation in a Co alloy film. Electron energy loss mappings are shown for a thin film of Ti\CoCrPt\ CrMn which had been annealed at 450 °C for 5 min. The lighter regions in (b), (c) and (d) are more enriched by Cr, Mn and Co, respectively. Some of the Cr enrichment also comes from segregation to the boundaries of the Cr in the alloy film. Such composition profiles greatly improve the grain to grain magnetic isolation [13].

Grain isolation seems to be a major problem for the multilayer media. The multilayers form a columnar microstructure, but it seems difficult to have chemical segregation to the grains as in the Co based thin films. If multilayers are to be utilized as perpendicular media it will be necessary to obtain smaller magnetic cluster sizes in the films.

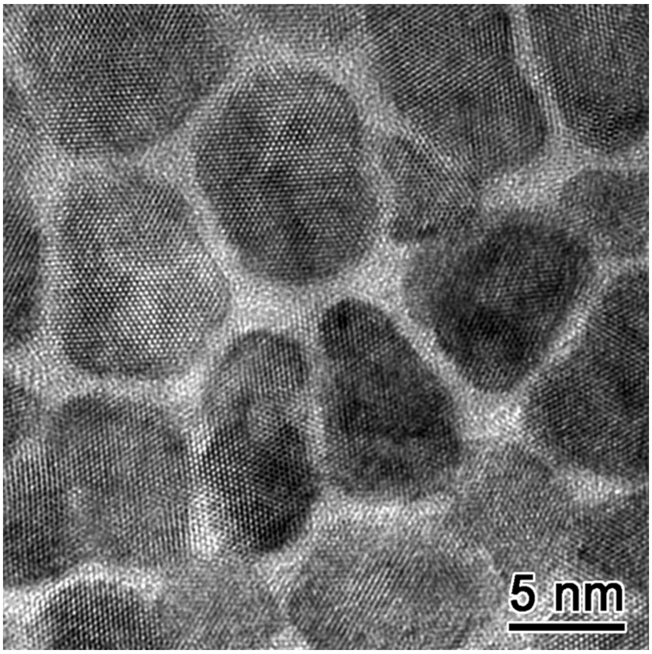

Fig. 4. HRTEM of a Co based granular media with grain size of about 5 nm. This media displays high coercivity and has good grain to grain magnetic isolation due to the continuous film of oxide at the Co boundaries.

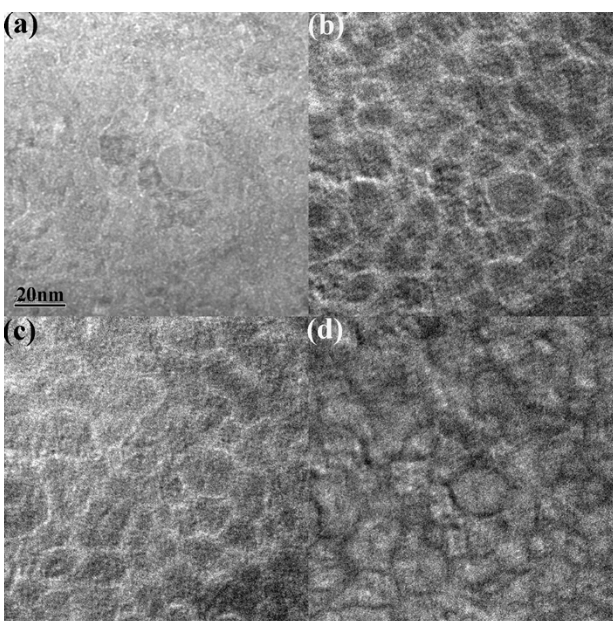

Fig. 5. EELS spectra of Co alloy media: (a) is zero energy loss spectrum, (b), (c), and (d) are Cr, Mn, and Co mapping of (a), respectively.

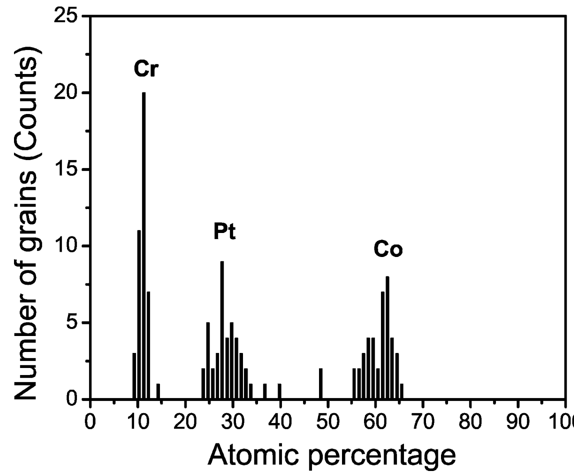

Fig. 6. Composition variation of grains in a nominal Co-11Cr-28Pt thin film. Note that the Cr composition has a narrower distribution than the Pt distribution.

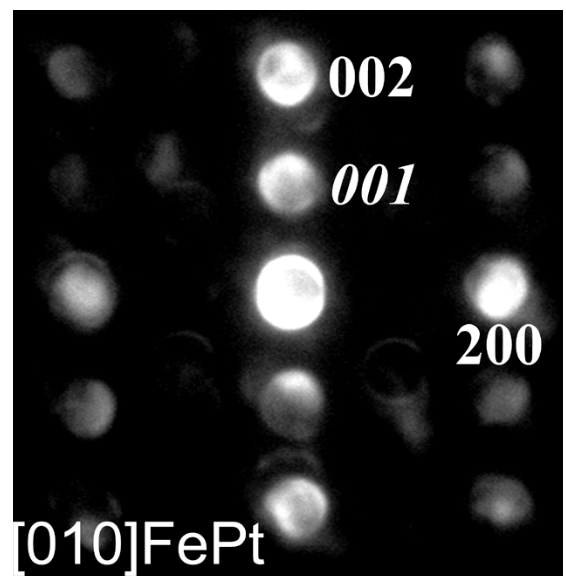

Fig. 7. A nano beam electron diffraction pattern of $L1_0$ FePt thin film taken in cross section. The film has perpendicular texture.

V. Grain to Grain Uniformity

An aspect which has often been overlooked in the examination of media is the need to keep the grain to grain value of H_k as uniform as possible to avoid undue media noise. To do this the composition of the grains must be uniform and in the case of the $L1_0$ media the order parameter of the grains must be the same grain to grain. This is not an easy task and needs to be more thoroughly investigated. Our preliminary work on grain to grain composition variation in Co-Pt-Cr alloys shows that the Pt composition varies more grain to grain than does the Cr composition [8]. See Fig. 6. This seems to be related to the fact that Cr segregates to the grain boundaries and Pt does not. A thermodynamic equilibrium is set up between the composition of the Cr at the boundary and that of the Cr within the grains (Gibbs Adsorption). This equilibrium acts to fix the composition of Cr within the grains. See [15], [16]. Pt does not segregate to the boundaries and hence does not have any thermodynamic constraints on its composition. The difference in Pt composition grain to grain will give rise to a difference in H_k grain to grain and this increases the media noise. This is discussed in more detail in [14].

Sato and Hirotsu have developed a technique for measuring the order parameter of naonparticle FePt. [17] They calculate the ratio of a superlattice reflection (hkl) and $(2h\ 2k\ 2l)$ to determine this value. See Fig. 7 for an example of an electron diffraction pattern taken from a film of FePt. However, the control of the order parameter in $L1_0$ alloys is challenging, especially since a completely ordered grain has too large of anisotropy (and hence H_k) on which to be written. This means that an order

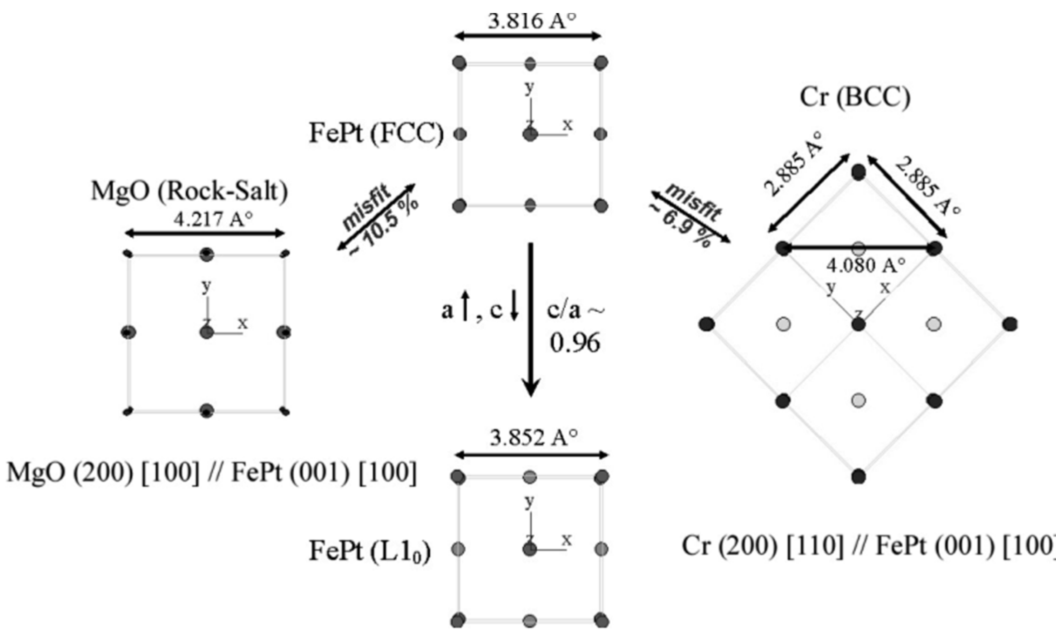

Fig. 8. The epitaxial matching of the FePt lattice with the MgO and the Cr lattices can be used to promote the (001) textured growth of FePt thin films.

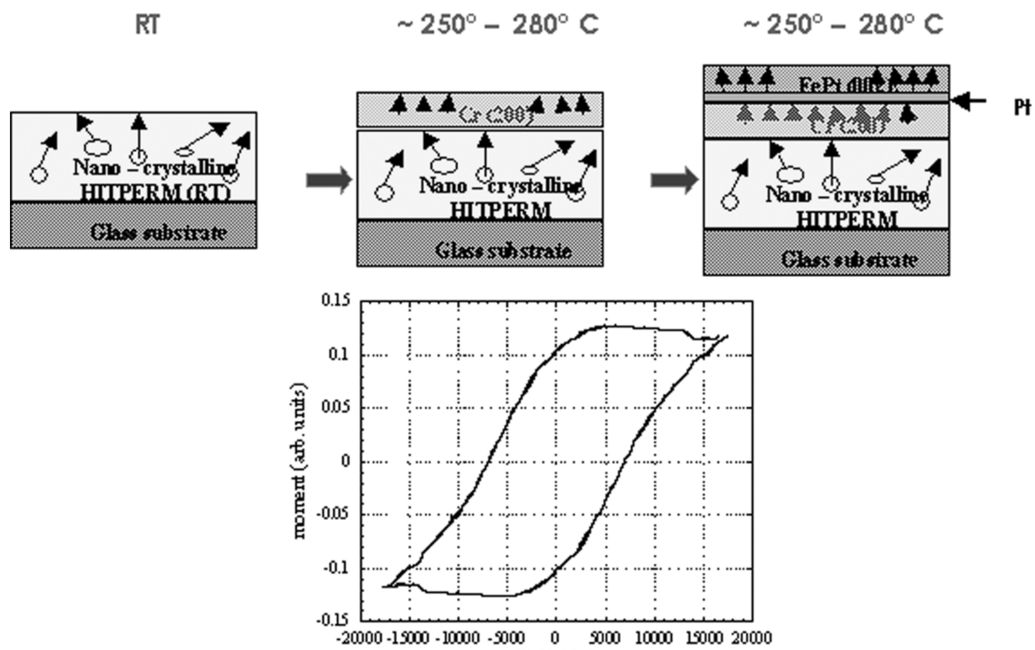

Fig. 9. Schematic representation of the growth of (002) textured FePt on Cr (200) seed layers and with a soft underlayer. Cr develops the required (200) texture only over a narrow range of temperatures. The hysteresis loop was obtained using the anomalous Hall effect. The film structure was Fe-Pt (30 nm)/Pt (3 nm)/Cr (80 nm)/HITPERM (100 nm)/glass substrate.

parameter less than unity must be obtained and it is very difficult to do this grain to grain in a thin film, or for that matter in nanoparticles [14]. We are working on methods of homogeneously ordering the $\mathrm{L1_0}$ grains or nanoparticles, so as to obtain more uniform H_k distribution.

VI. Example of Current Research Media: FePt

FePt thin films with (001) perpendicular texture have been prepared by epitaxial growth on MgO and Cr seed layers (Fig. 8). The misfit of the FePt *fcc* phase with the MgO rock-salt structure is about 10.5%, whereas it is only 6.9% with the Cr *bcc* structure. However, although the $\mathrm{L1_0}$ ordered phase is thermodynamically stable at room temperatures, sputtered thin films do not have the ordered structure because they do not pass the order-disorder transformation at high temperatures during the fabrication process. As a result, these films have to be deposited on a heated substrate or subsequently annealed at high temperatures so as to obtain the ordered $\mathrm{L1_0}$ phase. In this regard, since the $fcc \rightarrow \mathrm{L1_0}$ transformation involves strain (reduction in c/a from 1.0 in the *fcc* phase to $\sim$ 0.96 in the $\mathrm{L1_0}$ phase), a misfit parameter somewhere between that with the Cr and MgO lattices is believed to assist in driving the transformation at lower temperatures. Fig. 9 represents the growth of (002) oriented FePt on Cr seed layers. In this case, we employed nanocrystalline HITPERM soft-magnetic underlayers. The hysteresis loop that is shown was obtained using the anomalous Hall effect and using a methodology that we have introduced [18]. For this given double-layered perpendicular thin film media, the loop shows a coercivity, $H_C \sim 7000$ Oe and a squareness, S ~ 0.80.

VII. Other Recording Schemes

We do not include herein a discussion of heat assisted magnetic recording. Similar microstructural features are involved with that media. Also, perpendicular media could be utilized in tape media. These topics are beyond the scope of this paper.

VIII. Conclusion

In this paper we have discussed some of the important microstructural features of thin film perpendicular magnetic recording media. We believe that such an understanding of the microstructural features will be of great aid in the development of the perpendicular media.

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