Media for 10 Gb/in.^{2} hard disk storage: Issues and status (invited)

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Future 10 Gb/in.^{2} recording densities represent submicron trackwidths and sub-100 nm bit lengths. This requires extremely small magnetic switching units and very high coercivities of the media to satisfy the signal-to-noise ratio requirements. At the same time the question of magnetic thermal stability and the lack of transducers capable of performing at these densities makes it difficult to evaluate media. An uncoupled, highly uniform magnetic grain size of about 10 nm is a compromise toward maintaining an adequately low media noise and yet maintaining magnetic stability. Here we discuss current media construction, the detrimental role of substrate roughness, the role of new media structures and alloys on microstructure and magnetic properties as well as techniques for evaluating media performance prior to the availability of the required playback heads. © *1996 American Institute of Physics.* [S0021-8979(96)39908-9]

I. INTRODUCTION

The introduction of sputtered thin-film media, onto electrolessly plated NiP on an Al substrate, has lead to a substantially smoother surface enabling record and playback heads to become closer to the medium—the single most important characteristic in magnetic recording. These advances have recently lead to an approximate 60% compound annual growth rate for areal densities[1] plus three demonstrations of areal densities in the Gb/in.^{2} range.[2–4] The technology which is commercially available today incorporates 0.4–0.8 Gb/in.^{2} areal densities and is on the 60% growth curve.

In 1992, Murdock *et al.*[5] described several possible recording formats and outlined the required mechanical, magnetic, and recording performance requirements to achieve 10 Gb/in.^{2} areal densities. The selection and matching of the head and media components as well as the tracking and signal processing techniques is currently a complex iteration process and the evaluation of each of these individual components is hampered by the lack of the other. Here, we review and describe some of the hard disk media issues and a philosophy for developing future media when advanced recording and playback heads are not available. By example, we will try to put into perspective where media technology is today and what limits its performance.

II. RECORDING FORMAT AND MAGNETIC REQUIREMENTS

Over a period of several years disk drives have maintained a fairly constant recording trackwidth to linear bit density ratio. Hence, scaling the current areal density to a 10 Gb/in.^{2} system yields a format entirely consistent with Murdock *et al.*'s projections. One format would call for 25 400 tpi (0.5 μm read head width) and a linear density of 400 000 bpi. A 4/3's rate code would then dictate a 300 Kfci linear density.

It is assumed that high moment inductive heads will be available for recording while spin valve head[6] technology will be available for playback. The playback head dynamic range and head-medium spacing, then determines the desired moment of the medium. Scaling arguments[5] indicate that for a 30–40 nm head to the center of medium spacing, a $M_r\delta = 0.4$ to 0.6 memu/sq cm is needed to optimize head response while preventing head saturation nonlinearities during playback. From a medium noise view point, it turns out to be especially advantageous to lower the recording head to medium spacing. Fortunately, the low $M_r\delta$, that spin valve head technology requires, minimizes the transition demagnetization effects to allow higher linear bit densities. As a rule of thumb the flux reversal spacing is limited to approximately πa_x.[7] Hence, to achieve 300 Kfci density, one requires that $a_x < 27$ nm. The coercivity of the medium should approach 3000 Oe while δ should be less than 15 nm.

As usual it is anticipated[6] that the medium noise will slightly dominate the head noise and so an isolated signal pulse to broad band media noise of 27–30 dB is required for 10 Gb/in.^{2} (Ref. 5). Fortunately, we have the experience of particulate recording media as a guide in understanding the media noise issues. Baugh *et al.* and Belk *et al.*[8,9] showed that media noise, measured in the frequency domain, is the smallest when the magnetic regions are composed of small, well-isolated, magnetic particles. For particulate media they found that the noise power was nearly a constant, as a function of transition density, and the smallest at high recording densities. For thin-film media, the noise power increases linearly with increasing transition density and then increases supra linearly.

The magnetic playback head samples a finite volume of the medium determined by the head field distribution. Hence, when a particulate medium is dc erased, the particles are magnetized, largely, all in one direction and fluctuations in the magnetization sensed by the head are due to either nonuniformities in the density of particles or in the random orientation of their magnetic axes. These statistically independent fluctuations yield a Gaussian probability distribution. This gives a noise power proportional to the number of particles, while the signal power is proportional to the square of the number. Hence, the lowest particulate medium noise results when the particles are small so that the number of particles sensed by the head field is maximized and when the size and orientation distribution of the particles is uniform. For the Baugh type of plot, the lowest noise is observed when the medium is in the ac-erased state as the magnetization of individual particles orient to a flux closure condition which minimizes the external fields that the head senses.

Thin film media are usually composed of closely packed, randomly oriented grains which are either magnetically

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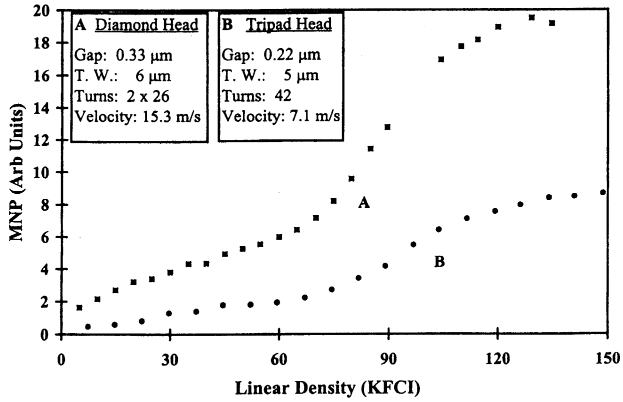

FIG. 1. Effect of record head field gradient on medium noise power for a commercially available CoCrTa hard disk.

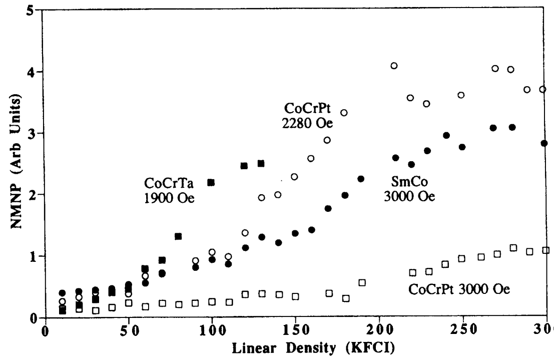

FIG. 2. Medium noise power vs linear density for CoCrTa, CoCrPt, SmCo, and CoCrPt hard disks. The data was normalized by the power in the isolated pulse signal.

exchange-coupled at the grain boundary, grouped as exchange-coupled clusters of grains, or, at best, grains which are somewhat isolated by nonmagnetic material. The latter behaves as particulate media, while the former behaves as large regions of continuous magnetization. For the former, the dc-erased state is the lowest noise situation as the media can be viewed as one large domain with no flux leakage from the media surface. However, at a flux reversal, the fluctuation amplitude manifests as large medium noise. Hence, a medium in which the grains are exchange-coupled exhibits a noise power that is associated with the transition and the noise power increases linearly with the transition density until the transitions are so closely spaced that they begin to interact[10] and the noise power increases supra-linearly. Practically, for a medium noise limited system, the flux spacing, πa_x is usually set to be at or slightly beyond the onset of this supra-linear regime. Therefore the following three simultaneous conditions are desired in a Baugh plot: (1) Small isolated magnetic units to give a low slope in the linear regime. (2) Small, uniform, uncoupled grains to give a low dc noise. (3) A recording transition density chosen to occur prior to the onset of the supra-linear regime.

It should be pointed out that the transition fluctuation amplitude is largely determined by the dispersion in the media characteristics (uniformly of grain size, orientation, exchange coupling, stress, etc.) and these fluctuations are exacerbated by a poor record head field gradient. That is, if the head field gradient is poor, then both a_x (Ref. 7) and the fluctuation (noise) of the transition location will be large.[10,11] Figure 1 shows two non-normalized recording results, on the same medium, where the record head field gradient has been varied. The lower-noise curve B was obtained using a 5-μm-wide Read Rite Tripad head with a 0.22 μm gap and flying at approximately 25 nm (at 7.1 m/s velocity) while the higher-noise curve A was generated using a 6-μm-wide Quantum Diamond head with a 0.33 μm gap and flying at approximately 100 nm. Note that, not only does the supra-linear noise regime begin earlier, but the slope of the linear noise regime is larger for the recordings with the poor record field gradient. Obviously it is difficult to evaluate medium noise without the ideal head and fly height, since medium noise dependents upon the head field gradient. The practical approach, then, is to use a head with the smallest available gap and to fly it as low as possible. The measured medium noise will then be an upper bound. Since the noise power is mostly contained in the low-frequency spectrum,[9,11,12] the playback system does not need to perform to the same linear densities as the recording test system. In brief, we see that the medium grains must be small, magnetically isolated, and of uniform size to minimize the noise, the film moment must be chosen to maximize the spin valve response without overdriving it, the coercivity must be high enough to prevent demagnetization, and the medium structure must be extremely smooth to allow low fly heights both to write low noise transitions and to resolve the playback pulses.

For single-domain Stoner–Wohlfarth particles, the coercivity is determined by both orientation and crystalline anisotropy energy. Also, as the grain size is reduced and the thermal energy fluctuations threaten the stability of the recorded bit it is important to maximize the magnetic crystalline anisotropy. Charap and Lu's[13] modeling indicated that for 400 Kfci recording and cobalt parameters ($K_u = 4\times10^6$ erg/cc, $M_s = 900$ emu/cc), a grain size below 8 nm would tend to be thermally unstable. A 10 Gb/in.^{2} medium should then have magnetic units in the 10–12 nm diameter range. The quest then is to achieve isolated grains of this size while maximizing the anisotropy. An approach to achieving high anisotropy is to build grains of such crystalline perfection that the magnetocrystalline anisotropy is maximized. The alignment of the anisotropy axis along the record track direction will also help to maximize the coercivity. However, there is modeling evidence that this type of orientation may increase medium noise.[14]

III. STATUS OF CURRENT MEDIA DEVELOPMENT

Figure 2 provides a comparison of the normalized medium noise power for a number of media designed for various recording densities. Table I lists the magnetic properties of each of these media. An all ones pattern was recorded on each of these media using a Read Rite Tripad head with the head to medium velocity (7.1 m/s) adjusted such that the head was flying just beyond contact of the disk. The medium

TABLE I. Magnetic properties and surface roughness details of high coercivity hard disks.

Media		Magnetic properties		Substrate			Overlayer thickness (nm)
Type	material	H_c (Oe)	$M_r t$ (memu/cm^2)	Material	State	Roughness R_{rms} (nm)	
A	CoCrTa	1900	2.1	NiP/Al	Textured	8.7	15(C)
B	CoCrTa	2200	1.0	NiP/Al	Textured	5.0	15(C)
C	CoSm	3000	0.6	Glass	Smooth	1.3	7(Cr) 10(C)
D	CoCrPt	3000	0.55	NiP/Al	Super Smooth	0.4	5(C)

noise power was obtained using the technique described earlier.[8,9,12] Medium A (CoCrTa) was removed from a modern commercial drive operating at 0.4 Gb/in.^{2} density. In Fig. 2, one can observe the supra-linear noise regime beginning at approximately 50 Kfci. Medium B (CoCrPt) is a commercially emerging medium designed for approximately 1–1.2 Gb/in.^{2} density. We observe a lower slope and the supra-linear behavior at 125–150 Kfci indicating a superior medium. Sample C is a SmCo medium[12,15] with a grain size of about 20 nm, while sample D is a CoCrPt medium with a grain size of approximately 15–20 nm. Using this close flying head neither of these latter two media appear to possess a supra-linear noise regime when recorded up to 300 Kfci. However, the linear regime's nonzero slope indicates that these media are still transition noise limited and have exchange coupling. Eventually, at higher densities the supra-linear noise behavior should be observed. A gap null occurs at 230 Kfci. A significantly sharper head field gradient should decrease the transition noise for these media provided the inherent transition noise is limited by the head field gradient and not by the media microstructure.

While a signal-to-noise ratio could be obtained by extrapolating out to 300 Kfci, MFM images can provide more accurate information plus insight into the microstructural properties. Figures 3–5 show MFM images of transition patterns at different densities for three of the four media of Fig. 2. Clearly, just as was shown in the noise power curve, the onset of the exchange coupled transition-transition interaction has occurred for the CoCrTa medium well prior to the 150 Kfci density, Figs. 3(a)–3(c). An atomic force microscope (AFM) image, Fig. 3(d), shows the film's roughness and grain clustering due to the mechanical texturing of the substrate. Close examination of the large magnetic switching units observed in the dc-erased areas of the MFM images correlate to the AFM observed grain clusters. To avoid this noise source, future media should be prepared using smooth substrates having a smooth data zone surface.[16]

Experimental media C and D were prepared on a smooth glass substrate and a supersmooth NiP-Al substrate, respectively. The MFM images of these disks [Figs. 4(a)–4(c) and Figs. 5(a)–5(c), respectively] show well-resolved transitions into the 200 and the 250 Kfci regimes, respectively. The smaller magnetic unit size correlates to the substrate quality shown in Figs. 4(d) and 5(d). Other MFM features worth noting are the quiet dc-erased backgrounds, as well as, the small substrate scratch in the center of the 250 Kfci track in medium D. Even though the magnetic switching unit size of this latter medium is largely determined by the underlayer microstructure, the roughness of the scratch dominates the

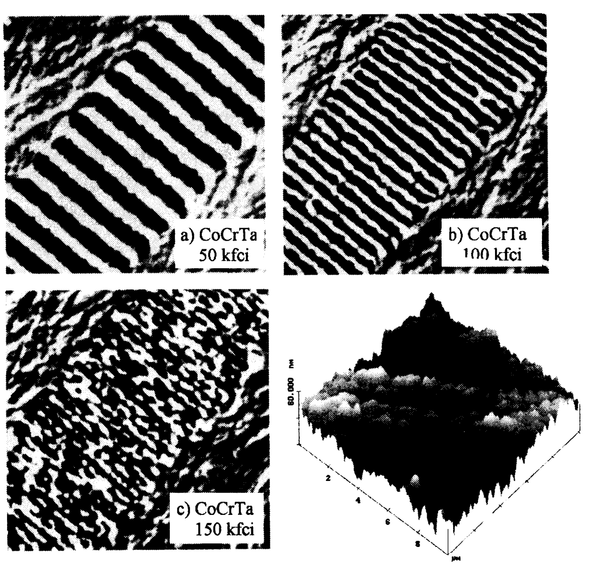

FIG. 3. (a)–(c) MFM images of magnetic transitions and (d) AFM image of the surface in a CoCrTa hard disk. The substrate was mechanically textured.

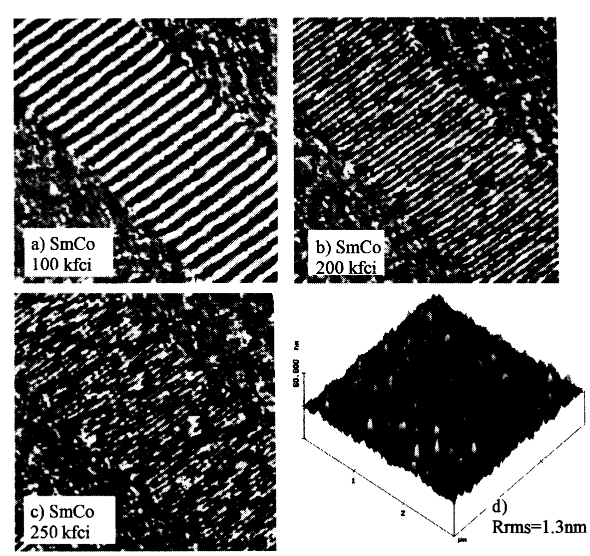

FIG. 4. (a)–(c) MFM images of magnetic transitions in a SmCo hard disk and (d) AFM image of the smooth blank glass disk substrate.

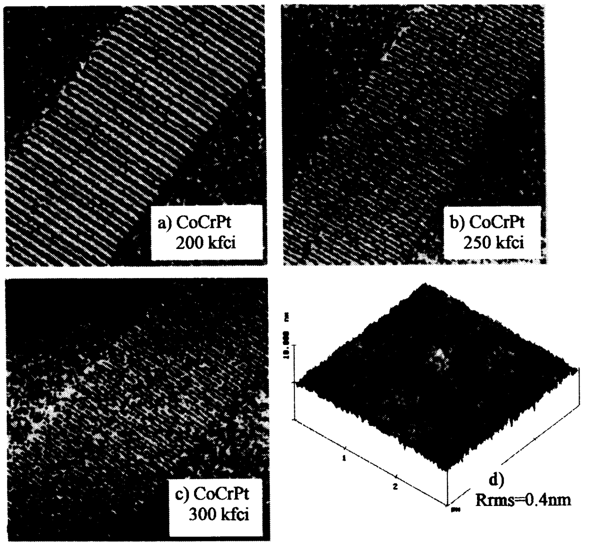

FIG. 5. (a)–(c) MFM images of magnetic transitions in a CoCrPt (medium D) hard disk and (d) AFM image of the supersmooth NiP/Al disk substrate.

transition location. Transitions at 300 Kfci were clearly visible for medium D, but Fig. 5(c) indicates that the medium SNR is unacceptable for a 0.5 μm trackwidth.[6,17]

IV. CURRENT MEDIA STRUCTURE APPROACH

Modern commercial media are prepared by sputter deposition and consist of a structure of a lubricant, a carbon overcoat, a magnetic layer, and a Cr underlayer, on a substrate. The carbon overcoat and the lubricant are used to provide mechanical and chemical protection to the underlying metals. Daval and Randet[18] showed that an underlayer of Cr could significantly improve the magnetic properties of a Co alloy thin film. Since then, much work has been published on how the Cr underlayer influences the Co alloy microstructure and magnetic properties. The medium's coercivity and noise performance are largely determined by the Co alloy composition, grain size, and crystal orientation, perfection, and isolation. The underlayer largely effects the latter of these via promoting epitaxial growth onto the Cr crystallites. Likewise, the substrate surface strongly influences the Cr growth via both surface bonding energy[19] and roughness.

In brief, depending upon the growth conditions[19–21] the bcc Cr tends to develop with a variety of crystallographic textures. The closest packed planes are {110} and so at low substrate temperatures, or when prepared with a substrate bias, the low-energy state (110) texture is obtained which promotes an epitaxial (10.1) cobalt texture. Since the atomic sizes of Cr and Co are similar, the atomic spacing of the atoms at these two surfaces approximately match and so, on a small grain size scale, an epitaxial growth results. This places the magnetic easy axis (c axis) of the HCP Co tilted approximately 28° from the film plane. Since the Cr axes are random in-plane, the in-plane magnetization components of the Co crystallites are random in-plane. On the other hand, under higher-temperature deposition conditions, it is possible to obtain (002) Cr texture from which epitaxial growth yields a (11.0) textured Co film. Since this texture calls for the HCP

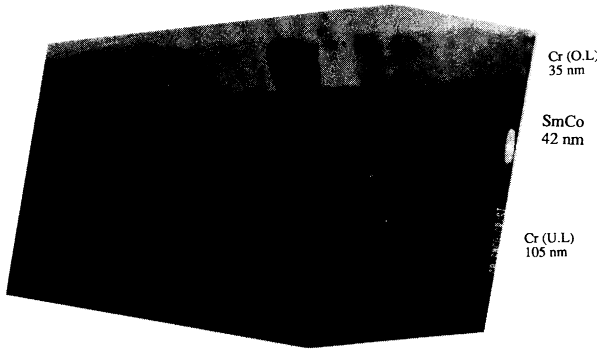

FIG. 6. Cross-sectional TEM image of the SmCo/Cr interface.

c axis to lie totally in the film plane higher coercivities usually result. Less often reported, but still commonly observed, is a (10.0) Co texture which is now believed to be due to a (112) underlayer texture.[23] Peng *et al.*[22] recently showed that epitaxial growth alone is not sufficient to achieve high coercivity. If the grain size of the Cr underlayer is large enough and the processing conditions are such to promote cobalt alloy bi- and quadcrystal structures,[24] then the effective magnetocrystalline anisotropy is compromised and, hence, the coercivity is degraded.

Due to the Cr surface roughness and grain boundaries the Co grains tends to replicate the Cr grain size. Hence, provided the Co grains do not grow together, and enable the Co to connect at the interfaces, the magnetic switching unit size is largely determined by the underlayer grain size. To decouple the grains and to keep the magnetic switching unit small various Co alloys have been studied to provide a nonmagnetic grain boundary phase. For example, in CoCrTa and in CoCrPt, it has been argued that preparation of the films at elevated temperatures causes Cr segregation to the grain boundaries. However, compared to the influence of the underlayer, it is hard to conceive how this mechanism could set the basic grain size.

Clearly, it can be argued that when the lateral scale of the substrate roughness is similar to the desired magnetic unit scale media noise can be decreased.[25,26] Likewise, a very smooth substrate could tend to promote large grain features were it not for the underlayer microstructure taking over and controlling the resulting magnetic unit size. As an example of the controlling effect of the underlayer a fairly uniform roughness results when 28 nm of SmCo is deposited upon a 100 nm (110) textured Cr layer prepared at room temperature on a smooth substrate.[25] Without the controlling Cr underlayer identically prepared SmCo films result in nonuniform, enlarged grains and a noisy media. The uniform roughness provided by the Cr underlayer leads to, a uniform SmCo unit size, a delineation between magnetic units, and consequently a lower-noise medium. Further evidence of this delineation is shown in the transmission electron microscope (TEM) cross section, Fig. 6. This structure is composed of a Cr underlayer, a SmCo magnetic layer, and a Cr overlayer. The underlayer grain structure clearly propagates not only into and through the SmCo layer, but continues into the Cr overlayer. A high-resolution TEM image of this film is shown in Fig. 7.

FIG. 7. High-resolution TEM cross-sectional image at the SmCo/Cr interface.

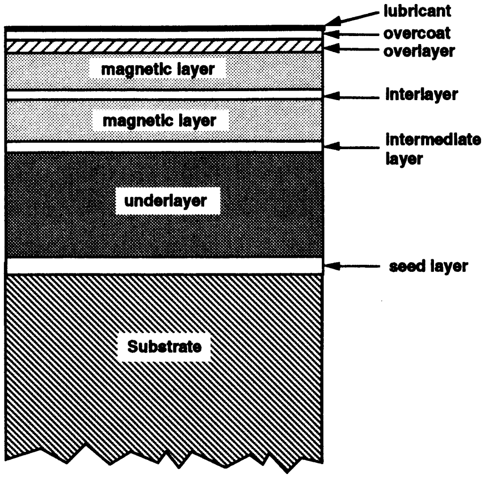

FIG. 8. Thin-film layer structure in novel high coercivity media with multiple magnetic and nonmagnetic layers.

Here, the Cr grain structure is clearly evident and close examination shows the shadowing of the SmCo units at the Cr grain boundaries continuing through the film thickness. At first glance, it appears that the SmCo layer is amorphous, which is consistent with the reported high temperatures (>600 °C) needed to crystallize the films.[27] However, close examination shows that a large number of SmCo nanocrystallites (2–5 nm size) grow even at room temperature when prepared on the Cr underlayer. Epitaxial growth between the Cr and the SmCo interface is also weakly visible. Bright-field, plane-view TEM microstructural images of this film shows a clear separation between the grains while the selected area electron diffraction pattern shows evidence that a lattice matched crystallinity exists in the SmCo. The underlayer has strongly influenced the magnetic switching unit size and has also induced at least partial crystallinity into the, otherwise, amorphous, SmCo film. This results in the low-noise performance indicated in Fig. 2.

V. NEW MEDIA STRUCTURE APPROACH

In order to further minimize medium noise, even smaller magnetic switching unit sizes need to be achieved while more perfect crystals are needed to maintain coercivity. One approach is to use sputtered multiple epitaxial layers. Figure 8 depicts such a structure. If the substrate is assumed to be perfectly smooth, then the first sputtered layers will dominate the magnetic film's microstructure. Each of the layers can have multiple purposes, but the following gives a simplified picture of their roles: The seed layer is to provide an initial texture, while still providing a smooth surface to the underlayer. This way the underlayer texture is formed early during film growth. The underlayer is to control the fundamental grain size and, also, to transfer a high quality texture via epitaxial growth to the latter layers. The intermediate layer can provide both chemical effects and a buffer interface to promote a better Co layer texture as we shift from a BCC lattice to the HCP. The magnetic layers provide the storage mechanism while the interlayer has been used in the past to double the number of magnetic particles.[28,29] The overlayer, overcoat, and lubricant are to provide their normal protective functions.

We now discuss two media structures which follow this format. The first consists of an alternative underlayer with $B2$-type crystal structure.[23] The $B2$ is a derivative structure of the bcc Cr and for NiAl the atomic spacing is almost identical to that of Cr thus providing a potential epitaxial match for HCP Co.[23] Because the sputtered NiAl grain size is more uniform and about half that of Cr,[23] there is the potential for smaller Co grains and lower media noise. When CoCrPt (or CoCrTa) is deposited onto NiAl or Cr underlayers, using identical processing conditions, very similar coercivities are obtained provided the NiAl is thicker. However, if even a very thin, 2.5 nm, intermediate layer of Cr is used on the NiAl then the coercivity is even greater than for the medium with a Cr underlayer. The dramatic effect of the intermediate layer is believed to be due to a smoother atomic interface resulting in a more perfect Co crystallite. Preliminary measured values of noise have shown a significant improvement.[30] Other evidence of the benefit of an intermediate layer is the use of a thin layer of CoCrTa between a Cr underlayer and a Pt-rich $Co_{72}Cr_{10}Pt_{18}$ alloy.[31] By using 5-nm-thick CoCrTa as an intermediate layer on Cr, a HCP template was provided for the epitaxial growth of the larger lattice constant $Co_{72}Cr_{10}Pt_{18}$ and the coercivity increased by over 30% (>4000 Oe).

The second approach is to use a seed layer to initialize the underlayer crystal texture which may in turn enhance crystal perfection by minimizing internal lattice defects. Nakamura and Futamoto[32] demonstrated that Cr could be epitaxially grown on single-crystal [001] MgO. For this $B1$-type crystal the {001} planes have the lowest surface energy.[33] Hence, we have found that even very thin layers of sputtered MgO are (001) textured. This surface matches well with the bcc Cr[34] to induce a strong (002) Cr texture, Fig. 9, even when the films are prepared without preheating the substrate. Coercivities greater than 4000 Oe have been achieved for CoCrPt magnetic layers grown on this structure.[34] A similarly impressive effect on coercivity is found when NiAl is used as the underlayer on the MgO seed layer.[35]

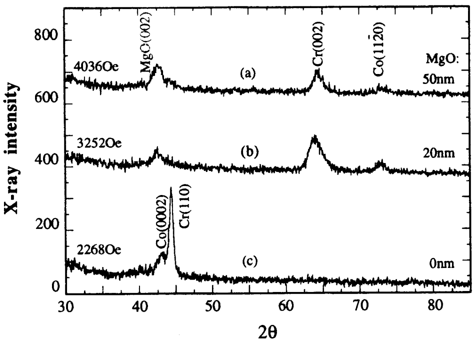

FIG. 9. X-ray diffraction patterns of CoCrPt films grown on 100-nm-thick Cr underlayers sputtered onto MgO seed layers of (a) 50 nm, (b) 20 nm, and (c) zero thicknesses.

VI. BEYOND 10 Gb/in^2

Here we have compared current hard disk media to experimental media approaching 10 Gbit/in.^{2} densities. We have shown that apparent media noise is tied to the recording head field gradient as well as to the substrate and underlayer smoothness. In addition, we have outlined epitaxial procedures for developing media with both higher coercivities and smaller magnetic switching units.

It may very well be possible to continue on the current technology path to recording densities even beyond 10 Gbit/in.^{2} However, it is hard to see how recording densities can increase another order of magnitude without a considerably different approach.[36] If a medium with uniformly placed magnetic units is conjectured, many of today's technical limitations are eliminated. If a bit is defined as either a single, or a fixed number of magnetic switching units, then the noise issues change from asking how many particles are in a bit to whether or not manufacturing inaccuracies spatially misplaced the magnetic units. The system noise may then be dominated by tracking and transducer sensitivity limits. Hence, a uniform array of magnetic particles, each just larger than the superparamagnetic size limit, would represent the ultimate recording medium. For uniaxial cobalt alloys, 8-nm-diameter particles centered on a 10 nm array spacing should provide stable data bits. This corresponds to a recording density of over 6000 Gbit/in.^{2} Clearly producing this array of sublithographic particles will require novel patterning or self assembly techniques and depending upon the transducers it may be important to have a single magnetic orientation. This raises entirely new challenges for those who will develop the tracking and signal processing technologies. Nevertheless, these technologies are within the realm of imagination and lend support to a continuity of the 60% areal density growth curve.

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