Thin-Film Recording Media on Flexible Substrates for Tape Applications

Hwan-Soo Lee, Lin Wang, James A. Bain, and David E. Laughlin

***Abstract*—Co-based alloys were investigated as candidates for sputtered thin-film magnetic tape media. Magnetic media on polymeric substrates having acceptable magnetic properties were obtained by applying NiAl/CrMn underlayers prior to CoCrPt deposition with a nonmagnetic CoCrTa intermediate layer. Typical sputtered tape media deposited on traditional polymeric substrates at room temperature revealed sideband modulation noise and large intergranular exchange coupling. A substantial improvement in surface roughness by utilizing smooth polymeric substrates eliminated this modulation noise and accounted for the signal dependent broad-band noise power. This suggests that transition noise is a dominant component of medium noise in sputtered tape media. Additionally, substrate bias is shown to be effective in producing grain decoupling that is necessary for good signal-to-noise ratio.**

***Index Terms*—Intergranular exchange coupling, polymeric substrates, sideband modulation noise, sputtered thin-film magnetic tape media, substrate bias.**

I. Introduction

IN RECENT years, the explosion in the storage, retrieval, and dissemination of information has considerably increased the market demand for high capacity and high performance data storage systems. Magnetic tapes are likely to continue to dominate the area of large capacity mass storage (backup and archival data applications) due to their cost and volumetric density advantages over hard disk storage [1]. Undoubtedly, future higher density recording tape media will need to achieve large increases in linear and track densities and reduction in media thickness to reach a volume storage density goal of 10 Tbyte/in^3, set by the information storage industry consortium (INSIC), for magnetic tape recording [2].

At present, the materials under consideration for future advanced recording tapes are principally acicular metallic particles (MP) and metal evaporated films (ME). In particular, the dramatic improvement in MP properties in recent years [3], using a double-coating technology, has provided thinner magnetic layers and imparted a continuing advantage to the particulate media which may postpone the consideration of alternative materials. In the longer term, however, sputtered tape media can offer the best solution as the next generation tape media. In particular, sputtered films address the concern that increasing shedding and drop-outs might cancel the benefits of further magnetic layer reduction in current MP coating technologies.

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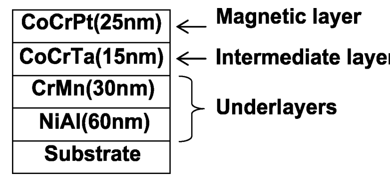

Fig. 1. Typical sample structure: substrate/NiAl (60 nm)/CrMn (30 nm) /CoCrTa (15 nm)/CoCrPt (25 nm).

In this study, an overview of our recent work on producing thin-film longitudinal media for tape substrates is presented. The reasons for using various underlayers and intermediate layers to produce high coercivity longitudinal recording media are explained. Features of the flexible substrate unique to tape, such as the substrate roughness, and their effects on their magnetic properties are also discussed along with the associated recording performance.

II. Experiment

All of the films discussed in this paper were deposited by radio frequency (RF) diode sputtering in a Leybold Z-400 sputtering system on a variety of polymeric substrates, such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN), aromatic polyamide (ARAMID), and polyimide. Polyimide (KAPTON) is used as an exploratory substrate because it can withstand high temperatures, when necessary. Special smooth versions of PEN and ARAMID were used in addition to standard versions of these materials. Glass substrates were also used as a standard substrate for comparison. Films were deposited on either small coupons of substrate ($\sim$1 in) or short lengths of tape ($<$10 cm), which are sufficiently large enough for some recording measurements.

Film stacks were composed of a CoCrPt magnetic layer, a nonmagnetic CoCrTa intermediate layer, and NiAl/CrMn underlayers as shown in Fig. 1. The deposition conditions of the three nonmagnetic layers were chosen to optimize the coercivity of the CoCrPt films. The CoCrTa layer was deposited with fixed substrate bias of -140 V while the CoCrPt layer was prepared under various substrate bias conditions. Other details of the sputtering conditions are described elsewhere [4]. As shown above, the process examined here is likely to be expensive to commercialize. Reduction in stack thickness is highly favorable in terms of realistic fabrication conditions. Future work will address this.

Magnetic properties of the samples were measured by alternating gradient magnetometer (AGM) and vibrating sample magnetometer (VSM). Surface roughness of bare polymer substrates and those coated with magnetic stacks was measured

TABLE I
SPECIFICATIONS OF MEDIA AND WRITE/READ HEADS

<Write head>	
Type	Metal-in-Gap
Gap length (μm)	0.2
Track width (μm)	17
<Read head>	
Type	Shielded AMR
Bias scheme	Soft adjacent layer biased
MR element height (μm)	2.7
MR thickness (nm)	25
Track width (μm)	8
Shield to shield distance (μm)	0.23
Azimuth angle (degrees)	25
<Media>	
Type	CoCrPt sputtered
Coercivity (Oe)	2400
Thickness of mag. layer (nm)	25
Mr·δ (memu/cm^2)	1.2

using an atomic force microscope (AFM). The global film composition was determined by energy dispersive X-ray fluorescence (EDXRF) analysis. Film textures and microstructures were characterized by an X-ray diffractometer (Philips X'pert Pro with X-ray lens) using Cu K_α radiation and by a transmission electron microscope (TEM) operating at 200 kV and an analytical TEM equipped with a nano-probe energy dispersion X-ray (EDX) analyzer.

For protecting the head-tape interface during recording measurements, carbon nitride (CNx) overcoats were reactively deposited using an Anelva SPF-730 sputtering system. The carbon nitride was seen to provide more robust interface for testing although the head-tape was sufficient for short testing without it. However, further investigations will be required for the wear of the sputtered tape media in contact recording [5]–[7]. The recording measurements were done on a drum tester at a head-medium velocity of 6.8 m/s, using a metal-in-gap (MIG) write head with an effective gape length of 0.2 μm and a track width of 17 μm, and an anisotropic magnetoresistive (AMR) read head with a shield-to-shield distance of 0.23 μm and a track width of 7 μm. The sense current of the AMR head was 10 mA. Table I shows the details of the sputtered tape media and the write/read heads employed in the experiment. The resolution bandwidth (RBW) for the measurement was chosen to be 10–30 kHz for the spectral analysis.

III. RESULTS AND DISCUSSION

A. Microstructure on Flexible Substrates

NiAl/CrMn underlayers were used in order to induce a smaller grain size and to promote better epitaxial growth of the hcp structure without substrate heating [8], [9]. In-plane c-axis orientation in CoCrPt films having high Pt content can be preserved on NiAl/CrMn underlayers by introducing a CoCrTa intermediate layer [10]. This nonmagnetic CoCrTa intermediate layer is believed to offer hexagonal symmetry to promote the (10.0) texture and perhaps reduce stacking fault density.

The CoCrPt (10.0) oriented media on tape substrates typically exhibit significantly wider range in orientation than media on rigid substrates due to the flexible substrates unique to tape.

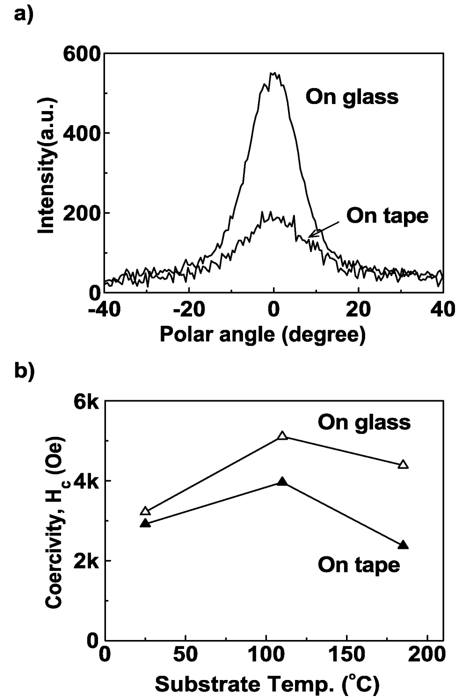

Fig. 2. Structural and magnetic properties of CoCrPt films on glass and tape (KAPTON) substrates: (a) rocking curves for (10.0) oriented media and (b) in-plane coercivity (H_c) as a function of substrate temperature.

This is in part attributable to the difficulty in producing well-oriented NiAl/CrMn (112) underlayers on tape substrates. Quantitative information on the difference in (10.0) orientation quality can be seen from X-ray rocking curves as shown in Fig. 2(a). The (10.0) orientation of the CoCrPt films on tape substrates is highly dispersed about the sample normal (FWHM of 25°). This distribution is about 10° wider (at FWHM) than those on glass substrates. In this figure, the planes which diffract are parallel to the film surfaces at zero degrees on the horizontal axis, and the polar angle indicates the tilt from the normal direction of the film of the grains being measured. In Fig. 2(b), the resulting in-plane coercivity (H_c) for the sputtered media on tape and glass substrates is shown as a function of substrate temperature. The 20%–30% lower H_c is observed on tape substrates at typical working temperature (RT and 110 °C).

In Fig. 3, the X-ray diffraction spectrum of samples having the structure of NiAl/CrMn/CoCrTa/CoCrPt films is shown. The NiAl/CrMn underlayers have two characteristic X-ray peaks: (110) at 44.3° and (112) at 81.4° in a $\theta - 2\theta$ scan. The sputtered tape media have a good lattice match to obtain a strong Co (10.0) growth texture, and contain a weak Co (00.1) orientation. The NiAl/CrMn cell on the (112) plane and the CoCrTa cell on the (10.0) plane is 0.250 nm × 0.408 nm and 0.253 nm × 0.409 nm, respectively, while the CoCrPt cell on the (10.0) plane is 0.263 nm × 0.420 nm as measured from X-ray diffraction.

In bright-field TEM images of the sputtered tape media, well-defined grains with average grain size less than 20 nm were seen. Grain-to-grain epitaxy at the NiAl/CrMn, CrMn/CoCrTa, and CoCrTa/CoCrPt interfaces of the layered structure in Fig. 1 could be observed from the cross-sectional TEM images. In neither view, however, can any clear physical separation (amorphous phase or voids) between grains be observed.

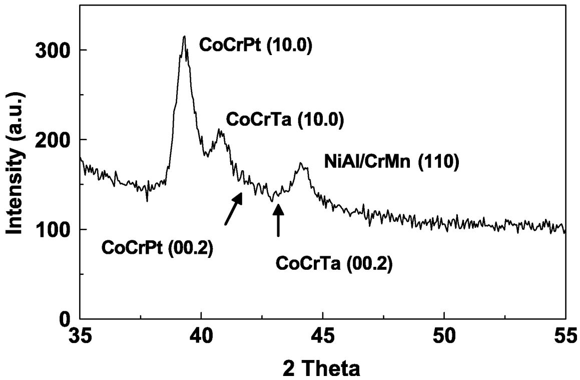

Fig. 3. The X-ray diffraction spectrum shows a weak Co (00.2) peak along with a strong Co (10.0), indicating the prominence of (10.0) texture.

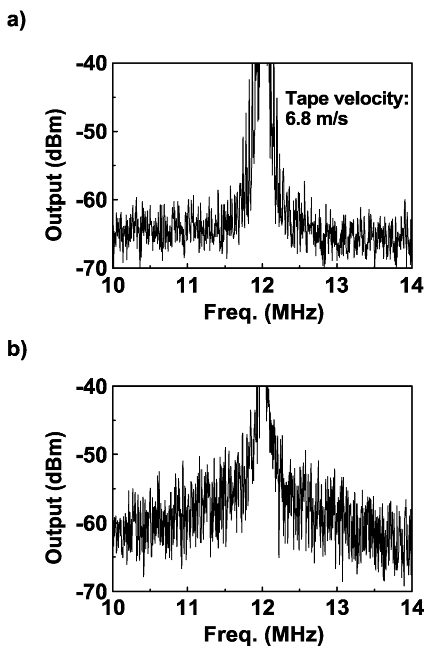

Fig. 4. Spectrum of 90 kfci density signal. The sidebands of the fundamental component of the sputtered tape media deposited on (a) a smooth base film (ARAMID) and (b) a conventional base film (PEN). The RBW of the measurement was 10 kHz.

B. Modulation Noise in Sputtered Tape Media

Sideband modulation noise about the signal peak which was previously reported in [11] can be dramatically reduced in sputtered media deposited on smooth substrates, as shown in Fig. 4. The typical spectrum of the signal components for the sputtered tape media at 90 kfci reveals that the sputtered tape medium on a smooth substrate (ARAMID) in Fig. 4(a) is nearly free of modulation noise. In contrast, the sidebands of the fundamental component for the sputtered tape medium on a conventional substrate (PEN) are clearly visible in Fig. 4(b). The range of frequencies shown in Fig. 4(b) extends about 2 MHz on either side of the signal peak. Thus, for the 6.8-m/s head-to-tape speed, these outer frequencies correspond to a modulation wavelength of 3.4 μm. Clearly, in Fig. 4(b), a small amount of the modulation noise extends even to this short spatial wavelength, though most of the modulation noise power in this sample is confined to longer wavelengths (closer to the fundamental tone). In both the

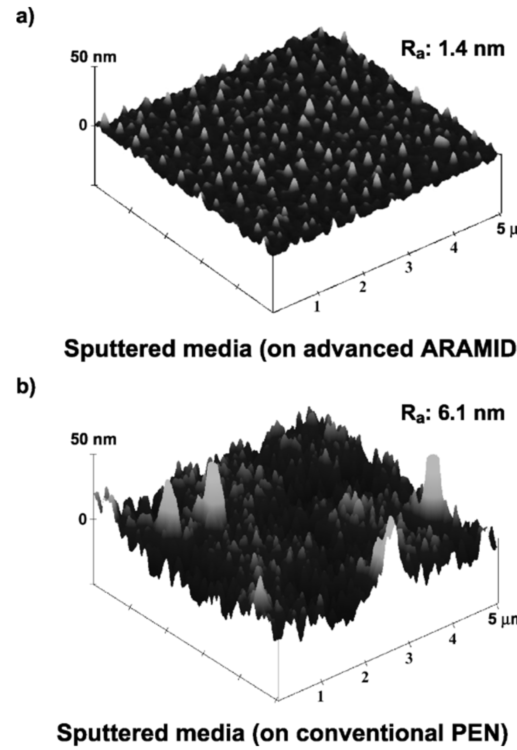

Fig. 5. Measured roughness properties of sputtered media on (a) advanced ARAMID with R_a of 1.4 nm and (b) conventional PEN with R_a of 6.1 nm.

rough and smooth substrate cases, head-to-tape spacing fluctuations are assumed responsible for the modulation noise, generated by the roughness of the tape surfaces as discussed below.

In Fig. 5, the topography of sputtered tape media on the two different types of substrates described above is shown. The tape surface for smooth ARAMID [Fig. 5(a)] consisted of fine protrusions that were uniformly distributed with a height of 10 nm and a diameter of 100 nm. The standard (rough) PEN [Fig. 5(b)], in contrast, includes both large spikes and fine protrusions. Through a comparison of the two tape surfaces, it is evident that the spike peaks on the tape surface are significantly less for the film on the smooth substrates. This is critical to modulation noise because, the peak height of the tape surface determines the interface with the recording head. Note that the average roughness is about an order of magnitude less than the actual head-to-tape spacing dictated by peak height.

Spectral analysis of AFM measurements of the sputtered tape media also indicated correspondingly lower surface roughness in this range of spatial frequencies. Specifically, we have used power spectral density (PSD) measurements to identify the spatial wavelengths that contribute most to the surface topography. As shown in the PSD plot in Fig. 6, spatial wavelengths between 0.5 and 10 μm for sputtered tape media deposited on conventional substrates contribute 100 times more "roughness power" than that for sputtered tape media deposited on smooth substrates. These spectral measurements or roughness correspond to part of the range of spatial wavelengths seen in the sidebands in Fig. 4 (3.4 to $\sim$ 60 μm), suggesting, as has been shown previously, that surface roughness is the source term for modulation noise in MP media [13]. In addition to the reduction in modulation noise discussed above, we also observed a reduction in the

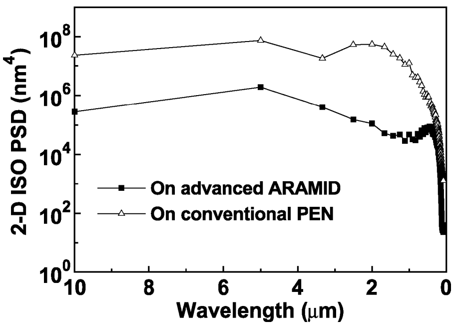

Fig. 6. Measured power spectral density and curve fitting for media (on advanced ARAMID) and media (on conventional PEN).

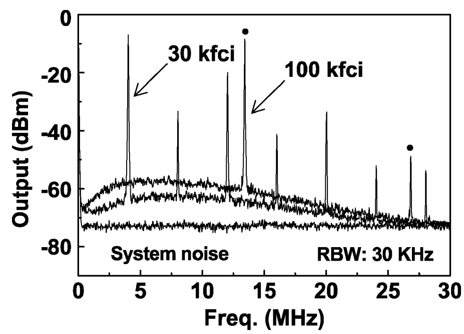

Fig. 7. Spectrum for recording square wave. The broad-band noise level increases at higher recording density.

head-to-tape spacing on the smoother substrate, which raised the head field gradient and significantly improved the linear bit density. We estimate that this benefit to signal-to-noise ratio (SNR) was as large as or larger than that caused by the modulation noise improvements. This will be addressed in detail in a subsequent paper.

Another interesting trend in the sputtered tape media is the signal-dependent broad-band noise. Electronic noise and readback noise spectra for signals recorded at different recording densities are shown in Fig. 7. In this figure, the fundamental signal peaks and several harmonics are shown with the broad-band noise. It is clearly seen that the broad-band noise power increases as the recording density increases. This behavior suggests that the noise arises from mainly irregular domain boundaries in the transition, namely, a transition noise dominated system, as seen in media on rigid substrates for disk drives [12]. In conventional MP tape media, however, this trend does not occur and the broad-band noise power *decreases* as the recording density increases [13].

The distinction between the noise power trend of the MP and the thin-film media arises from different origin of their randomness. The transition noise of thin-film media results from the magnetization fluctuation concentrated near the recorded transition centers. The noise power increases with recording density because more transitions occur per length of medium at higher density. At even higher density, the amount of noise in the transitions increases rapidly due to magnetostatic interactions that cause percolation between adjacent transitions.

On the other hand, the noise power versus density trend of MP is determined almost completely by the spatial characteristics of the head-to-medium spacing fluctuations. The MP tape

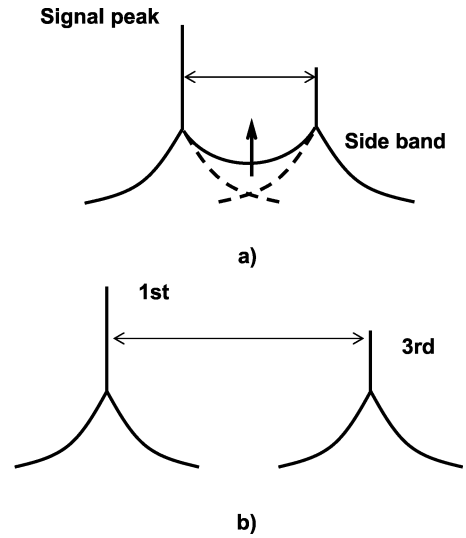

Fig. 8. Illustration of spectral plot of amplitude modulation sideband noise. For lower recording density, less separation between the fundamental harmonics occurs, yielding folded sidebands between the two harmonics. (a) Long wavelength. (b) Short wavelength.

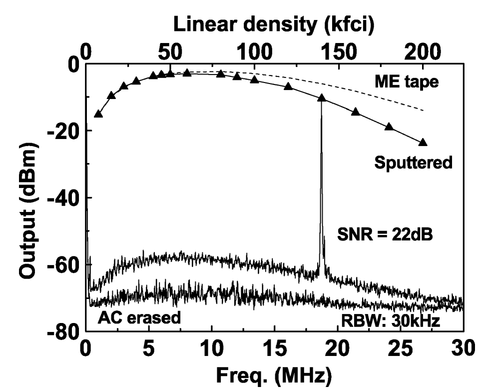

Fig. 9. Spectra of signal and noise for the sputtered tape media with the AMR head. The SNR showed about 22 dB at channel density (D_{50}) of 140 kfci. An experimental ME medium is also shown for comparison.

medium noise is characterized by narrower sideband noise and the broad-band noise spectra. These sidebands in MP can be thought of as extending to very short wavelengths (very large frequencies) about the fundamental harmonics. These sidebands about the harmonics are summed to produce the measured playback power spectral density. As shown in Fig. 8, the broad-band noise produced by the head-to-medium fluctuations decays with increasing separation of the harmonics. Accordingly, the noise in the recorded transition decreases as the record density increases, contrary to the characteristics of transition-noise-dominated thin film. Another way to envision this is to consider a surface roughness correlation length and compare it to the density of recording. Once the spacing between bits is smaller than this length, further increases in density will increase transition to transition correlation and decrease noise.

C. Media Noise in Sputtered Tape Media

In Fig. 9, the roll-off curves for a sputtered tape medium and an experimental ME tape medium are shown. The maximum output from the sputtered tape medium having a thickness δ

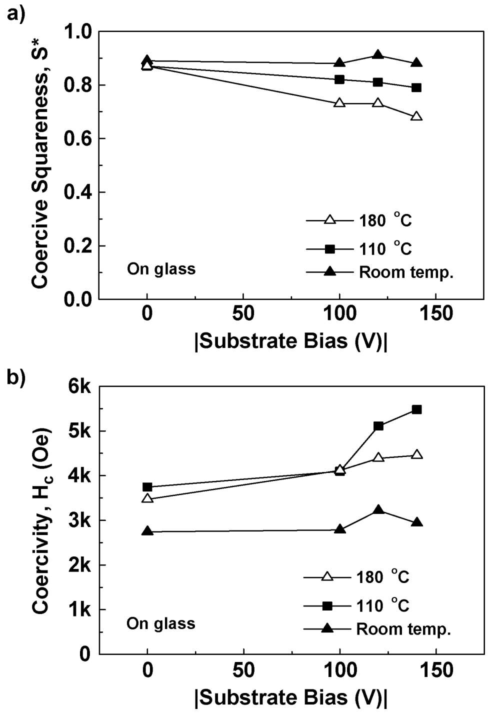

Fig. 10. The variation of magnetic properties of the CoCrPt media on glass versus substrate bias and temperature: a) S^* and b) H_c.

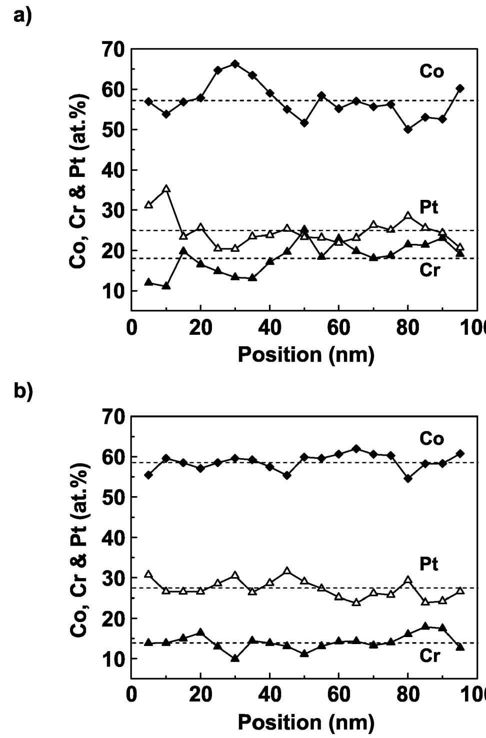

Fig. 11. Variation of Co, Cr, and Pt concentration measured in a plan-view TEM image of the CoCrPt layer: (a) $Co_{57}Cr_{16}Pt_{27}$ films bias-sputtered and (b) $Co_{59}Cr_{15}Pt_{26}$ films sputtered without bias.

of 25 nm was comparable with that of the experimental ME which is 40 nm thick. The similar output voltage comes from the similar value of $M_r \cdot \delta$ for the two media. A D_{50} value (the density which produced 50% of the maximum output voltage from the AMR head) for the sputtered tape medium is of 140 kfci while a D_{50} of 160 kfci is shown for the ME tape medium [14]. The isolated readback pulse from the sputtered tape media is shown to have a pulsewidth at 50% of maximum amplitude (PW_{50}) of 0.31 μm. Consistent with this frequency response, the medium noise floor at the maximum for the ME tape medium was 10 dB lower at a higher linear density. At a linear density of 180 kfci, the integrated noise power of the ME tape media (3.5 $[\mathrm{mV}]^2$) was unambiguously smaller than that for the sputtered tape media (30.2 $[\mathrm{mV}]^2$), which leads to higher SNR and D_{50} for the ME tape medium.

From these recording characteristics of the sputtered tape media, one can infer that sputtered CoCrPt tape media grains deposited at room temperature are highly exchange-coupled [11]. This large intergranular coupling observed in these films suggests insufficient Cr segregation due to the room temperature deposition needed to avoid substrate damage. A realistic value, along with the above argument, will help us view the significance of the transition width. The transition parameter a of the sputtered tape media was estimated to be 60–70 nm when the values for the head gap g of 0.176 μm, the head-to-medium spacing d of 20–25 nm, and the medium thickness δ of 25 nm were used. Thus, the transition length of πa is about 200 nm, or 10 grains across the transition.

Most disk media contain fairly high concentration of Cr (16–22 at.%) and require substrate temperatures above 200 °C to get the segregation pronounced by diffusion to the grain boundaries [15]. However, the need to use substrate deposition temperatures below 150 °C or even less for the tape media application of sputtered thin films causes difficulty in getting grain-to-grain isolation. Therefore, for high-density sputtered tape media to achieve acceptable medium noise, the reduction of exchange coupling between neighboring grains through physical separation or compositional segregation must be achieved through methods other than elevated temperature deposition. It should be noted that decoupling between grains in ME tape media is achieved by introducing oxygen during evaporation, resulting in fine Co crystallites separated by CoO crystallites in columnar microstructure [16].

Using bias sputtering to achieving granular isolation at deposition temperatures well below the glass transition temperature of some polymeric substrates such as PEN or ARAMID was recently reported [4]. Fig. 10 shows bias sputtering can aid in achieving this isolation, but also requires some elevation in substrate temperature $(> 100\,°\mathrm{C})$ to be effective, making this technique unsuitable for PET substrates [17]. CoCrPt films (on glass) show substantial decreases in S^* as a function of bias, in the presence of modest temperature increases. The change of S^* and H_c is attributed to a decrease in intergranular coupling as well as an observed increase in the Pt content of the CoCrPt films from 23 to 27 at.%. The effect is not very significant for the samples at room temperature (filled triangles), but becomes more pronounced as the temperature is raised. At 180 °C (open triangles), the effect is quite pronounced. The $\Delta M/M_r$ curve which is associated with a volume of reversal due to cooperative switching also showed the CoCrPt films deposited with higher substrate bias and some elevation in substrate temperature have a smaller $\Delta M/M_r$ peak. The similar behavior was observed in the CoCrPt films deposited on polymer substrates as well.

This trend is thought to be correlated with compositional inhomogeneity observed during bias sputtering. The chemical compositions of the CoCrPt magnetic layer were investigated using TEM equipped with a nanoprobe EDX analyzer. Typically, 5–6 grains for the EDX were selected to investigate the elemental distribution in the CoCrPt media. As shown in Fig. 11, larger compositional inhomogeneity was found in biased CoCrPt films, than in unbiased films. The two CoCrPt films have similar global composition of $Co_{57}Cr_{16}Pt_{27}$ and $Co_{59}Cr_{15}Pt_{26}$, respectively. The Cr content fluctuated from 11 to 24 at.% in the highly biased CoCrPt media (-250 V), while the variation of the Cr extends only 10–17 at.% in the corresponding CoCrPt films deposited without substrate bias. The local composition of the Co and Pt as well as that of the Cr also varies across the grains in a similar fashion. The dotted lines indicate the average concentration of each element. It appears, then that bias sputtering can drive compositional segregation and produce intergranular decoupling at relatively lower deposition temperatures. In these measurements, care was taken to insure that bias sputtering was not simply a source of extra heat. Temperature increases induced by the biasing energy above those maintained by the sample heater, were less than $10\,^{\circ}$C.

IV. Conclusion

CoCrPt sputtered thin-film magnetic tape media have been successfully fabricated and characterized in various aspects. Substrate roughness has been shown to be critical to reducing modulation noise. If this is accomplished, sputtered tape media on appropriate substrates are expected to be inherently smooth and less vulnerable to defects in very thin layers than MP. High coercivity also seems likely to be attainable by leveraging hard media disk technology. The big technical challenges seem to be realizing desirable medium microstructure in longitudinal thin-film media without raising the temperature of the substrate during deposition. Bias sputtering presents one possible mechanism for this.

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