Effects of Polymeric Substrate Roughness on Head–Medium Spacing and Recording Properties of Sputtered Magnetic Tape

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We investigated the spacing dependence of recording characteristics on head–medium spacing due to the surface roughness of substrates. CoCrPt-sputtered tape media with a magnetic thickness of 25 nm were deposited onto polymeric substrates possessing very different roughnesses for this investigation. The degradation in the write and read processes due to spacing was a significant limiting factor at high densities. By utilizing smooth polymeric substrates, a substantial improvement in system bandwidth as well as effective write field gradient can be achieved. As a result, overwrite performance was also considerably improved over the frequency range of interest.

***Index Terms*—Effective write field gradient, overwrite, smooth polymeric substrates, spacing dependence, sputtered tape media.**

I. Introduction

ONE OF THE barriers to increasing achievable data rates of current magnetic data tape systems has been signal-to-noise ratio (SNR). Surface roughness modulates the head-to-medium contact spacing and yields head field fluctuations in both the recording and the playback processes. The critical importance of spacing variations arising from media surface roughness is associated with two fundamental components: modulation noise and spacing dependent output.

In current tape systems, amplitude modulation plays a dominant role in determining the noise introduced during the magnetic recording. Head-to-medium spacing fluctuations are responsible for this modulation and create sidebands about the signal peak [1]. The long wavelength fluctuations during writing create the sidebands (modulation noise), while short wavelength fluctuations contribute a broad-band noise source (tone noise).

Average spacing between head and medium can change due to a number of causes, such as surface topography, pole tip recession, the head contour or the tape rigidity. However, in tape contact recording systems, a major contribution arises from the medium surface roughness. A large spacing broadens the transition width during the writing and attenuates the high frequency content of the read signal, which will result in a degradation of the SNR [2]. Therefore, in order to boost achievable linear density, achieving smooth recording surfaces in tapes is crucial. The playback signal is maximized with reducing head-to-tape spacing as much as possible.

Previously, it has been reported that modulation noise, present as sidebands about the signal peak, is seen in sputtered tape media deposited directly on a rough polymeric substrate, at level similar to that observed in metal particle (MP) tape [3] while use of smooth substrates was shown to dramatically reduce modulation noise about the carrier frequency [4]. In this study, head-to-tape spacing caused by substrate topography is further related to recording performance during the write and read processes.

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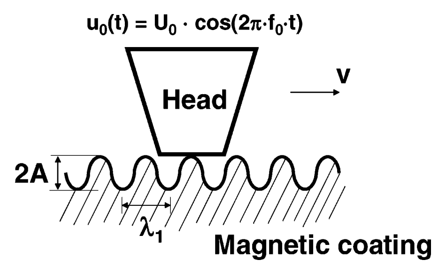

Fig. 1. Schematic of a head–medium interface. A magnetic head is in contact with a coating surface of which the contour varies sinusoidally.

II. Phenomena Due to Media Roughness

A. Modulation Noise

Wierenga *et al.* [5] showed that spacing variations arising from media surface roughness are the major cause of modulation noise in short wavelength recording. Consider a mathematical model of modulation noise by assuming the head-to-medium distance that varies sinusoidally with amplitude (A) and wavelength (λ_1) as shown in Fig. 1.

The spacing loss factor of the reproduced signal of wavelength (λ_0) having frequency f_0, is given by

$$\text{Loss factor} = \exp\left[-\frac{2\pi}{\lambda_0}(A + A\cos(2\pi \cdot f_1 \cdot t))\right] \quad (1)$$

where t is time, and f_1 is the frequency corresponding to λ_1. In a situation where the spatial frequencies are much smaller than the recording frequencies and recording wavelengths are sufficiently larger than the relevant roughness amplitudes $(\lambda_0 \gg A)$, the readback signal $u_0(t)$ from a recorded sine wave signal can be approximated by

$$u(t) = u_0(t)\exp\left[-\frac{2\pi}{\lambda_0}(A + A\cos(2\pi \cdot f_1 \cdot t))\right]$$
$$\cong U_0\cos(2\pi \cdot f_0 \cdot t) - \frac{\pi A f_0}{V}$$
$$\cdot U_0\{\cos(2\pi \cdot (f_0 - f_1) \cdot \mathrm{t}) + \cos(2\pi \cdot (f_0 + f_1) \cdot \mathrm{t})\} \quad (2)$$

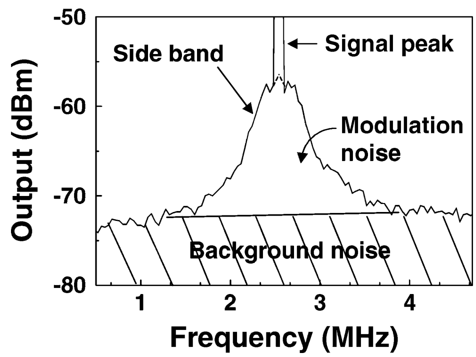

Fig. 2. Typical modulation noise spectrum from readback. Shaded area is the integrated background noise.

where $u_0(t)$ is the reproduced voltage for a perfectly smooth coating and V is the relative speed between head and tape. It shows the reproduced signal is amplitude-modulated by the sinusoidally varying surface and has a characteristic wavelength that introduces noise terms in the reproduced signal at frequencies $(f_0 - f_1)$ and $(f_0 + f_1)$. Consequently, the head-to-media spacing variations lead to skirt-shaped sidebands on either side of the signal peak. The area between the skirts is called "modulation" noise. Typical modulation noise from readback spectrum is shown in Fig. 2. The figure indicates, schematically, the relevant features in the spectrum: a signal peak, a sideband, a modulation noise, and a background noise having a broad band.

B. Spacing Loss

Here, an expression of spacing loss due to media surface roughness is presented. This will be used to assess the head-to-tape spacing difference between two types of sputtered tape media in later section.

The ratio of the playback voltage V_1 at the head-to-medium spacing of d_1 to the voltage V_{ref} at the spacing of d_{ref} for readback at the wavelength of λ can be written

$$\frac{V_1}{V_{\mathrm{ref}}} \propto \exp\left(-\frac{2\pi}{\lambda}\cdot((a_1+d_1)-(a_{\mathrm{ref}}+d_{\mathrm{ref}}))\right) \quad (3)$$

where a is the arctangent transition parameter, and the subscript on a indicates the spacing during writing.

If we define $\mathrm{LF}(\lambda,\Delta d)$ as the loss function (in decibels) for the readback signal at wavelength λ and spacing d_1, as compared to the signal at wavelength λ and spacing d_{ref}, we have, from (3)

$$\mathrm{LF}(\lambda,\Delta d) \equiv 20\log_{10}\left(\frac{V_1}{V_{\mathrm{ref}}}\right) = -55\left(\frac{\Delta d}{\lambda}+\frac{\Delta a}{\lambda}\right) \quad (4)$$

where Δd is defined as $d_1 - d_{\mathrm{ref}}$ and Δa as $a_1 - a_{\mathrm{ref}}$, such that LF is positive when d_1 and a_1 increase and signal level decreases relative to the reference level.

The first term occurs due to the exponential decay of the magnetic field in the readback process [6]. The second is due to what is typically called "writing loss" [7] and results from a poorer head field gradient at greater spacing, which broadens transitions, as shown in Fig. 3. This term, $\Delta a/\lambda$, has been estimated in [7] to be about $0.8\cdot\Delta d/\lambda$, for media with demagnetizing field

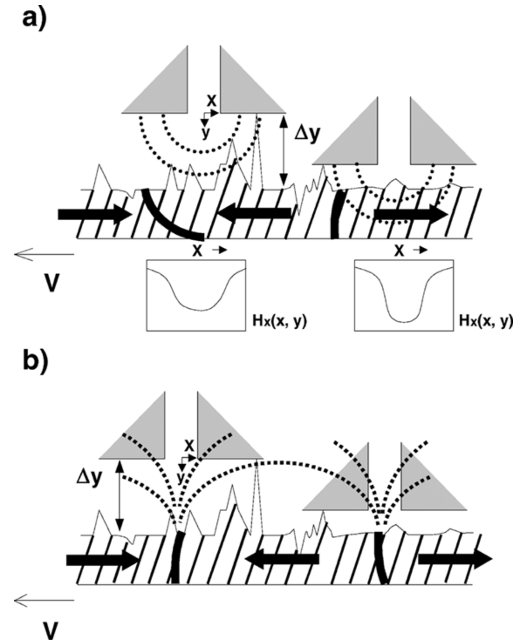

Fig. 3. Illustration of (a) transition broadening and (b) output loss, resulting from surface roughness. Peak asperity lifts the head away from the tape, resulting in spacing fluctuation Δy. $H_x(x,y)$ represents the x component of the head field produced by a write head.

to coercivity ratio (m_r/H_c) of 2–3. This yields an overall loss factor, $\mathrm{LF}(\lambda,\Delta d)$ of

$$\mathrm{LF}(\lambda,\Delta d) = -99\cdot\frac{\Delta d}{\lambda}. \quad (5)$$

The value Δd can therefore be determined from a plot of $\mathrm{LF}(\lambda,\Delta d)$ versus $1/\lambda$ plot, as will be shown next.

III. Experimental Procedure

$Co_{62}Cr_{15}Pt_{23}$ thin films were sputter-deposited on polyethylene naphthalate (PEN) substrates possessing very different roughnesses. A nonmagnetic $Co_{69}Cr_{29}Ta_2$ (15 nm) intermediate layer and NiAl (60 nm)/$Cr_{92}Mn_8$ (30 nm) underlayers were deposited prior to depositing the CoCrPt layer. Other details are described elsewhere [8]. The magnetic layer was 25 nm thick having a protective carbon nitride $(\mathrm{CN_x})$ layer with a thickness of 5 nm. The $\mathrm{CN_x}$ thin film was deposited by a reactive sputtering process in an environment of pure nitrogen [9]. The surface roughness was measured using an atomic force microscope (AFM). The typical measurement area was 10 μm $\times$ 10 μm. Noise measurements were made at a head–medium velocity of 6.8 m/s, using a metal-in-gap (MIG) write head with a track width of 17 μm and an anisotropic magnetoresistive (AMR) read head with a track width of 7 μm.

In the frequency domain measurements, the resolution bandwidth (RBW) and video bandwidth (VBW) were chosen to be 10–30 kHz and 3–10 kHz, respectively. Square waves were used to study spacing dependent recording characteristics. The signal and noise spectra were measured using an Advantest R3132 spectrum analyzer. The recording current was set to optimize the write saturation curve measurement at each linear density. The total broad-band noise was estimated in the conventional way.

TABLE I
PROPERTIES OF THE MEDIA USED IN THE MEASUREMENT

Medium	Medium R_a (nm)	H_c (Oe)	S^*	Base film	Substrate R_a (nm)
A	1.3	2400	0.90	Advanced PEN	1.3
B	5.0-7.0	2300	0.91	Standard PEN	5.0-7.0

The signal peaks and sidebands (if present) were removed from the signal power spectrum using a simple straight line interpolation. The integrated broad-band noise was then obtained by subtracting the measured electronic noise from each spectrum. For SNR, the signal power is defined as the harmonic peak, and the noise power as the area under the spectrum excluding the signal peak. Magnetic properties of the samples were measured by alternating gradient magnetometry (AGM) and vibrating sample magnetometry (VSM).

IV. RESULTS AND DISCUSSION

The roughness data of sputtered tape media A and B are listed in Table I, which includes the magnetic properties for each medium. The roughness of sputtered tape medium A is lower (by a factor of 4–5) than that of sputtered tape medium B due to the use of smooth polymeric substrates. Sputtered films were conformal with substrates and their surface roughnesses agreed within 10%–20% with those of the plain substrates. Note that the peak height of the tape surface determines the interface with the recording head. The average roughness is, in general, about an order of magnitude less than the actual head-to-tape spacing dictated by peak height.

Fig. 4 indicates that the roughnesses of the tape surfaces as measured by AFM have a strong impact on the recording performance of the sputtered tape media. Typical spectra of the readback signal components for media A and B at 45 kfci are shown. The shapes of the sidebands for these two media are quite different. The sputtered tape medium A on a smooth substrate is nearly free of modulation noise while the sidebands of the fundamental component for the sputtered tape medium B on a conventional substrate are clearly noticeable. In both cases, head-to-tape spacing fluctuations are assumed responsible for any observed modulation noise.

Fig. 5 shows SNR with respect to recording density for the sputtered tape media A and B. For the sputtered tape medium B where sidebands are quite significant, the SNR is plotted both with and without including sidebands in order to estimate the effect of sidebands on SNR. The sideband noise appeared narrow and distinct from the broad-band noise in the spectrum.

The dotted line in Fig. 5 corresponds to the case that the sidebands are excluded during SNR computation. The measurements show that the elimination of sidebands about the fundamental harmonics gives a gain of 4–5 dB in SNR at low density, with its contribution becoming less pronounced at higher recording densities. This is due to the increase in transition noise with recording density. The broad-band noise of sputtered tape media has the character of transition noise and linearly increases with recording density as discussed previously

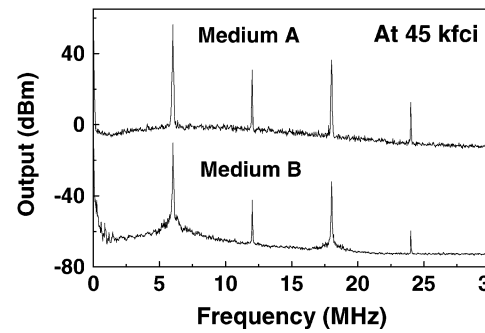

Fig. 4. Spectrum of 45 kfci density signal for media A and B. Use of smooth substrates significantly reduced modulation noise about the carrier frequency. Medium A is nearly free of modulation noise while for medium B, the sidebands of the fundamental component are clearly visible.

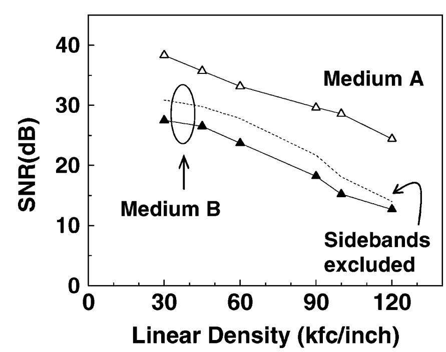

Fig. 5. SNR with increasing recording density for sputtered tape media A and B. The dotted line presents the change in SNR for sputtered tape medium B when the sidebands are excluded during SNR computation.

[4]. The presence of more transitions at higher densities results in more noise in the recording channel. In contrast, sideband noise is less dependent on recording density [10].

Even after accounting for modulation noise, there is still a significant difference in SNR between sputtered tape medium A (solid) and sputtered tape medium B (dotted). This suggests an important additional contribution from spacing in the recording process. In what follows, the effect of this spacing on the recording process as well as the playback process is taken into account.

A large recording field gradient is desirable to obtain a sharp magnetization transition in the write process. In the simple Karlqvist approximation, the longitudinal component of the write field is given by

$$H_x(x,y) = \frac{H_g}{\pi}\left[\tan^{-1}\left(\frac{x+\frac{g}{2}}{y}\right) - \tan^{-1}\left(\frac{x-\frac{g}{2}}{y}\right)\right] \quad (6)$$

where H_g is the deep gap field related to the head geometry and the write current, x is the displacement along data track, and y is the spacing between magnetic medium and head surface. The x component of head field is mostly relevant in the longitudinal recording scheme. The plot in Fig. 6 shows that the spacing dependence of the head field possesses a strong sensitivity to the head-to-tape distance, with shorter head-to-tape distance resulting in a larger gradient. A poor recording field gradient broadens the transition width and directly increases nonlinear distortions in the playback signal [2].

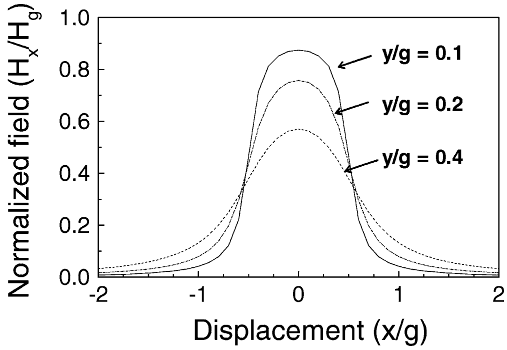

Fig. 6. Normalized Karlqvist head field H_x for different head-to-tape spacing. With a smaller spacing, a sharper write field gradient can be seen by the recording medium.

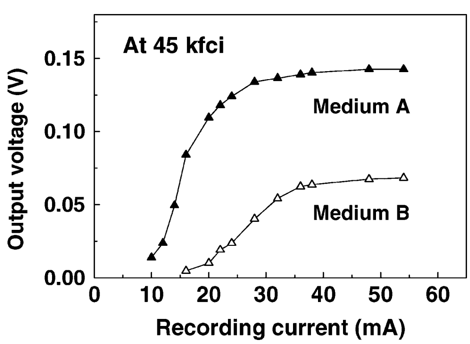

Fig. 7. Saturation curves for media A and B with respect to recording current at linear density of 45 kfci. The lower head-to-tape spacing for medium A led to a better saturation characteristic.

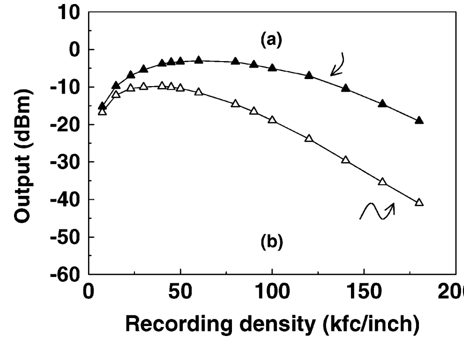

Fig. 8. Dependence of the reproduced output on the substrate roughness. The roughness (Ra) of the sputtered media on (a) smooth PEN substrates is 1.3 nm while 6.1 nm on (b) conventional PEN substrates.

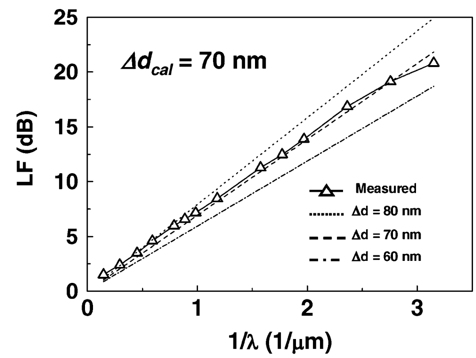

Fig. 9. Measured output difference, loss factor (LF) as a function of wavelength (λ) for media A and B. The mean head-to-tape spacing difference Δd_{cal} for the two was obtained by a best fitting.

Typical playback voltage versus recording current is plotted in Fig. 7. The comparatively lower head-to-tape spacing in medium A gave rise to a greater effective write head field gradient, and leads to a good saturation characteristic. At short wavelengths (100 kfci), some recording demagnetization with increasing write current was seen when currents above the optimum recording current were used.

Fig. 8 shows that the spacing dependence of the reproduced output plays an important role in improving recording density as well. The roll-off curves revealed maximum output of medium A is 7 dB higher compared to that of medium B. This substantial increase in output level for medium A is attributed to the decrease in head-to-tape spacing. The corresponding time-domain isolated characteristic pulse of medium A was also 30% narrower in pulsewidth (PW_{50}) and 40% larger in magnitude. At a recording density of 100 kfci, the difference extended up to 16 dB. Accordingly, this resulted in the density at 50% of the maximum (D_{50}) of 140 kfci in medium A while D_{50} of 90 kfci was observed in medium B. As evidenced by (3), spacing loss increases exponentially with increased separation from the medium as a ratio of the wavelength of the signal; therefore, high frequencies are more susceptible to dropouts.

In this experiment, the combined write/read spacing loss was measured, but it was not possible to separate the writing from the reading spacing losses. However, in an attempt to gain some insight in the output behavior, we assessed the head-to-tape spacing difference from a following analysis. In this analysis, it is presumed that the change is in medium surface topography and not factors other than the medium topography, which can influence the spacing fluctuations. Referring to (5), the change in output signal at each linear density was calculated and plotted as a function of inverse wavelength. The sensitivity of the spacing fitting is shown in Fig. 9. A good fitting from the slope gave the Δd value of 70 nm. This rather large value of spacing difference seems plausible, and can be justified by comparing surface profiles of the two sputtered tape media A and B measured by AFM (see Fig. 10). The maximum vertical distance Δz in medium A is 10 nm while Δz of 90 nm is observed in medium B. This corresponds to the spacing difference of 80 nm, which is in reasonable agreement with the recording measurement $\Delta d = 70$ nm.

The reduction in spacing also results in a reduced effect of the magnetostatic field from overwritten transitions due to the sharper recording field gradient. The overwrite ratio is improved as shown in Fig. 11. Overwrite was defined as the ratio of the amplitude (A) of the residual fundamental frequency component (A_2) to the original signal (A_1) of an overwritten frequency (1F) after recording with an overwriting frequency (2F)

$$\mathrm{OWR} = 20\log_{10}\left(\frac{A_2}{A_1}\right). \tag{7}$$

The 1F was varied and the 2F was taken as 12 MHz ($\lambda_2 = 0.56$ μm). A spacing reduction gives an improvement in overwrite behavior with about 5 dB higher values.

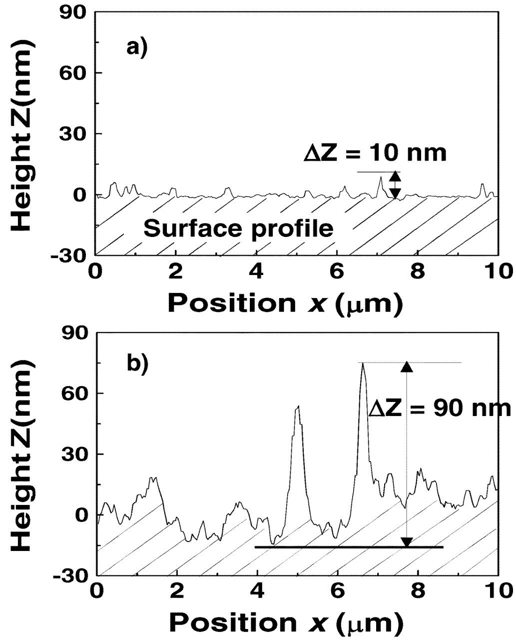

Fig. 10. Typical surface profiles for media A and B measured by AFM. The maximum vertical distance Δz for medium A is 10 nm while Δz of 90 nm is observed for medium B. (a) Medium A. (b) Medium B.

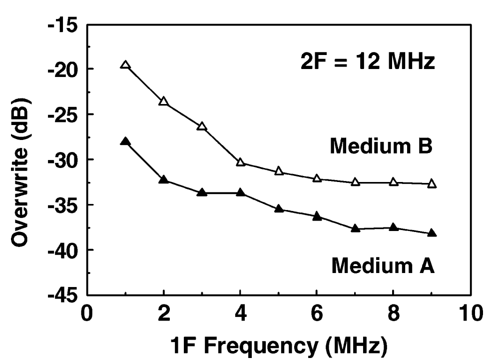

Fig. 11. Overwrite performance for media A and B as a function of the overwritten frequency (1F). The overwriting frequency (2F) is 12 MHz ($\lambda = 0.56\ \mu$m). For medium A, about 5 dB higher values over the whole frequency range were obtained.

V. Conclusion

We have studied tape roughness effects on output and modulation noise of sputtered tape media. Reduction in head-to-tape spacing by utilizing smooth polymeric substrates produces improvements in SNR (~6 dB) comparable to the improvement associated with the elimination of modulation noise (~6 dB) of these sputtered tape media.

This finding will provide the benefits of further improving surface roughness in polymeric substrates. However, a complicating factor in achieving smooth recording surfaces in contact recording systems using tape might be the need to reduce the friction forces arising when the recording head and tape are in contact. Surface roughness can be some desirable attributes of tape media which are required to improve the durability of the magnetic tapes.

Acknowledgment

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