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Overwrite in Thin Film Disk Recording Systems

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Abstract—Overwrite in thin film rigid disk recording has been studied experimentally using disks with a wide range of magnetic moment and coercivity. Standard f_2/f_1 overwrite was investigated in detail at various recording currents and different flying heights. A theoretical model was developed using simple analytical approximations that relate demagnetization-field-induced position shift (hard transition shift) to the measured overwrite. The demagnetization fields due to the leading edge transitions were calculated analytically including a good approximation to the gapped head image. The results compare well with experimental measurements. A new overwrite measurement technique using the second harmonic component of a $0.5 f_1$ signal is also described in this work.

I. INTRODUCTION

IN digital magnetic recording, new information is stored in media by simply writing over the old data without a previous separate erasure. Substantial erasure of the old information during the write process must be ensured to achieve satisfactory performance. To meet the challenge of high density recording, new systems are designed to have a smaller head-medium spacing and media are made with higher coercivity and reduced magnetic moment. In this work, the dependence of overwrite on these recording and medium parameters is discussed. A simple theoretical model is also developed to give insight into this process. Overwrite is generally characterized by an f_2/f_1 ratio. Here f_1 represents an "all ones" pattern ([1 1 1 1]) at frequency f_1 . Overwrite is then defined as the ratio of the remaining f_1 level to the original f_1 signal level after overwriting the f_1 signal with an f_2 square wave pattern. The frequency ratio of $f_2/f_1 = 2$ is commonly used. This ratio varies for different coding schemes. For example, an f_2/f_1 ratio of $8/3$ is often used in a (2, 7) code [1].

A number of authors have investigated different aspects of overwrite [2]–[7]. Overwrite arises from three predominant mechanisms: residue, modulation and track edge effect. When the recording current is not sufficient, the previous f_1 signal is not completely removed, yielding a residue f_1 signal detected during playback (residue). Even if the current is sufficient, the magnetostatic field generated by the old f_1 magnetization modulates the head field at a frequency of f_1 and yields an f_1 frequency component to the f_2 magnetization (modulation). Further, it is reported that the unerased f_1 signal can be concentrated near the track edge (track edge effect). The track edge effect is

somewhat independent of head writing current. However, in thin film media with a nominal trackwidth the modulation overwrite process dominates at operating currents.

This paper presents the results of overwrite measurements combined with a theoretical analysis of overwrite in thin film media. The disks used have a wide range of coercivity and magnetic moment and overwrite were measured at different flying heights. The detailed experimental set-up is described in Section II. In Section III, a simple analytical model of overwrite modulation is presented includes the proper gap image for the total magnetostatic field. The model is applied to the experimental disk and head configurations and the results are compared with measurements in Section IV. Finally, Section V describes a new overwrite measurement technique based on direct correlation between the remaining f_1 signal and the second harmonic component of a $0.5 f_1$ signal. This proportionality is also used to verify the dominance of modulation in overwrite.

II. EXPERIMENTAL DETAILS

The experiments were performed on a rigid disk test bed. The disk linear speed was varied from 200 to 800 ips to achieve different flying heights. The read-write amplifier had a $0.8 \text{ nV}/\sqrt{\text{Hz}}$ noise floor and a 30 MHz bandwidth. A thin film head with 23 turns was used both for record and playback. The gap length and head efficiency were determined from the playback power spectrum to be $32 \pm 2 \mu\text{m}$ and 75%, respectively. The track width was $600 \pm 40 \mu\text{m}$ (quoted from manufacture). The flying height, measured by using an interferometric flying height analyzer, varied from $2.4 \mu\text{m}$ to $7.8 \mu\text{m}$ as disk speed changed from 200 ips to 800 ips. Including half the magnetic layer thickness, the disk overcoat and head pole tip recession, the total magnetic spacing were determined to be from $4.7 \mu\text{m}$ to $10.1 \mu\text{m}$. The medium characteristics used in this work are shown in Table I. All the magnetic properties were measured on a vibrating sample magnetometer (VSM).

The disk was dc erased before writing the initial square wave. Then, without changing the recording current, the second square wave was written over the first. The recording current was varied up to values corresponding to deep gap fields of about 5–6 times the disk coercivity (assuming no head saturation). The writing signal frequency was adjusted to ensure the same bit separation at different disk speeds. An HP3585A spectrum analyzer was used for data acquisition. Background noise was subtracted out every time a data point was taken.

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TABLE I
MEDIUM PROPERTIES

Disk	$M_r \delta$ memu/cm ² (KG · μ")	H_c (Oe)	S^*
1	6.30 (31.2)	650	
2	6.48 (32.1)	950	0.92
3	4.20 (27.8)	1250	0.87
4	4.00 (19.8)	1400	0.94

III. THEORETICAL MODEL

Modulation overwrite is discussed in detail in this section. Hard transition shift dominates modulation and an analytical approach to determine this dominant shift is presented. The model utilizes solely longitudinal head and magnetostatic field components. All formula are in the SI unit system.

Modulation Shift

It is generally believed that modulation dominates the overwrite process in thin film media at high recording currents. When writing the f_2 magnetization pattern, the total magnetic field acting on the medium is a combination of head field and a relatively small magnetostatic field generated by the existing magnetization patterns on the medium. Since a transition is nominally written at a location where the total field equals to medium coercivity, the additional magnetostatic field shifts the writing location from that given solely by the head field. The magnetostatic field originates from two sources: the down-stream magnetization leaving the gap region (newly written f_2 magnetization), and the up-stream magnetization entering the gap region (previously written f_1 magnetization and a possible extra transition near the leading edge of the head). Magnetostatic fields generated by the former (down-stream) exhibit a fundamental frequency of f_2 and, as a consequence, shift the newly written transition away from the gap center in the direction of head to medium motion and an equal amount of shift occur for every transition written at the frequency f_2 . Therefore, the overall result of the magnetostatic field generated by the newly written pattern f_2 is to yield a systematic shift. During playback, this shift (only leads to a constant phase shift) is not detected by a power spectrum measurement. Thus it is neglected in the theoretical analysis. However, this transition shift due to f_2 magnetization, also referred to as nonlinear bit shift, is very important in high density recording analysis.

The up-stream magnetization is composed of both the original f_1 magnetization and a possible extra transition near the leading edge of the head. This extra shift occurs if the head field is in a different direction from the previously written f_1 magnetization entering the gap region (A transition written in the presence of this extra transition is called a "hard transition." Similarly, a transition written in the absence of this extra transition is called an "easy transition"). The magnetostatic fields generated by both magnetization yield modulation. Hereafter, the transition

shifts due to the original f_1 magnetization and the extra transition if a hard transition is written are referred to as the f_1 shift and hard transition shift, respectively. Both shifts contain f_1 frequency components. Therefore, during playback a residual f_1 signal is detected in addition to the dominant f_2 signal. Generally, the f_1 shift is negligible compared with the hard transition shift because the magnetostatic fields from f_1 pattern consist of a decreasing sum, alternating in sign. In particular, since the transition locations are beyond the gap, each term in the sum is well imaged (reduced) by the high permeability head (This imaging effect is stronger at lower flying heights). Thus the f_1 shift is neglected in the following discussion.

The modulation process (with only hard transition shift) is discussed in more detail [7], [10] in this paragraph. For simplicity, only the standard $f_2 = 2f_1$ case will be presented. Figs. 1(a)–(d) show the writing process of two complete cycles of an f_2 magnetization pattern. The bit cell length of f_2 is B . Two cycles of f_2 correspond to one cycle of f_1 magnetization with a bit length of $2B$. The length of the writing zone, which is defined as the region over the head gap in which the total field is greater than the medium coercivity (as shown between the vertical dotted lines) is denoted by r . In Fig. 1(a), a hard transition is written since the head field is in the opposite direction to the magnetization entering the writing zone. Therefore a hard transition shift (Δx_h , later denoted as Δ) occurs. In Fig. 1(b), the medium is moved to the right by a distance B and the head field reverses its direction. Note that the head field is in the same direction as the magnetization entering the writing zone. An easy transition is then written and no hard transition shift occurs. The medium is then further moved to the right by a distance B (a shift of $2B$ from the pattern in (a)) in Fig. 1(c). The head field again reverses and the f_1 magnetization entering the writing zone reverses simultaneously. Consequently, an easy transition is written similar to (b) (without hard transition shift). Using the same analysis, Fig. 1(d) (the magnetization pattern is shifted a distance $3B$ from that in Fig. 1(a)) is similar to Fig. 1(a): the hard transition shift occurs. Since only hard transition shift is considered, the detailed phase relation between the f_1 and f_2 magnetization patterns is irrelevant to the overwrite.

Magnetostatic Field

The transition writing process is illustrated in Fig. 2, where d is the medium head spacing (flying height plus head recession, disk overcoat and half the medium thickness), g is the gap length and r is the length of writing zone which is set by $H_{head}(r/2, d) = H_c$. Here, instead of the total field, the head field is used because the demagnetization field is small to the first order. An analytical expression for r , derived from the Karlquist longitudinal head field function [12] is given by (for $H_0 > 2H_c$):

$$r = 2 \sqrt{\frac{dg}{\tan\left(\frac{H_c \pi}{H_0}\right)} + \frac{g^2}{4} - d^2}. \quad (1)$$

located at (x', y') is

$$\left(\frac{\partial q}{\partial x}\right)_{\text{surface}} = -\frac{dq}{\pi(y'^2 + (x - x')^2)} \quad (7)$$

where y' is the spacing between the source charge and the head surface ($y = 0$). x' is the charge location along the surface. As sketched in Fig. 3 this charge distribution is maximum under the source charge. A good approximation to the exact image is to simply remove the charge over the gap surface (shown between the vertical dashed line in Fig. 3). Thus with this proper imaging, the longitudinal demagnetization field due to image charges at (x, y) is given, to the first order, by

$$H_{di}(x, y) = \frac{dq}{2\pi^2} \left(\int_{-\infty}^{-g/2} dx' + \int_{g/2}^{\infty} dx' \right) \cdot \frac{x' - x}{((x' - x)^2 + y^2)((x' + x)^2 + y^2)} \quad (8)$$

Under the assumption $a \ll r$, the extra magnetic transition near the head leading edge can be treated as a line source with $q = 2M_r \delta$. The magnetostatic field at head trailing edge generated by the image of this extra transition is then derived from (8) by replacing both y' and y by d , x' by $-r/2$ and x by $r/2$:

$$H_{di}(r/2, d) = \frac{dM_r \delta}{\pi^2} \left(\int_{-\infty}^{-g/2} dx' + \int_{g/2}^{\infty} dx' \right) \cdot \frac{x' - r/2}{((x' - r/2)^2 + d^2)((x' + r/2)^2 + d^2)} \quad (9)$$

The total magnetostatic field due to the extra transition is then the field in (4) minus the field in (9). The closed form expression of the field is

$$H_d(r/2, d) = \frac{M_r \delta}{\pi r} \left(\frac{4d^2}{r^2} - \frac{dr}{\pi(4d^2 + r^2)} \right) \cdot \left(\ln \left(\frac{(r/2 - g/2)^2 + d^2}{(r/2 + g/2)^2 + d^2} \right) + \frac{r}{d} \cdot \left(a \tan \left(\frac{r - g}{2d} \right) - a \tan \left(\frac{r + g}{2d} \right) \right) \right) \quad (10)$$

This field is plotted in Fig. 4. For comparison, the fields with no image and perfect image are also plotted in the same figure. For $r < g$, corresponding to a writing zone less than the gap length when both the written transition and the extra leading edge transition are over the gap, the field approaches that of no image. For $r > g$, both transitions are over the head pole tips and the field approaches that of perfect image. It can be seen from Fig. 4 that using a proper gapped head image is very important, especially when the length of the writing zone is close to the gap length. This approximation follows very closely the re-

Fig. 3. Schematic of induced magnetic charge distribution on a gapless head surface due to a line charge. To correct for the gap, simply remove the charge over the gap (between the dashed lines).

Fig. 4. Magnetostatic field along the surface of a head with a finite gap due to a line charge distribution. The field is measured at trailing edge side of the writing zone ($r/2$) while the line charge is at the leading edge side of the writing zone ($-r/2$). Only the right side of a symmetric head is shown.

sults of Green's function analysis [9]. Further improvement can be made by adding very small line charges along the gap edges.

Hard Transition Shift

The magnetostatic field discussed above affects both the hard transition shape and the center location. In most recording systems, the shape difference between a hard and an easy transition is negligible. However this magnetostatic field introduces a noticeable amount of hard transition center shift. An analytical derivation on this position shift is presented below.

With the magnetostatic field taken into account, the hard transition center is set by

$$H_c = H_h(x_0 + \Delta) + H_d(2x_0 + \Delta) \quad (11)$$

Where x_0 is the transition center determined solely by the head field, Δ is the hard transition position shift, H_h is the head field (centered at $x = 0$) and H_d is the magnetostatic field due to the extra transition at the opposite side of the writing zone ($2x_0 = r$). Expansion of (11) to the first or-

Fig. 1. Schematic of magnetization pattern during f_2/f_1 overwrite. Configurations at four positions are shown. The medium has moved to left each position by a distance B .

Fig. 2. Schematic of transition written process. The new bit is written at the trailing edge side of the writing zone. An extra transition occurs at the leading edge side if a hard transition is written.

Where E is the head efficiency, N is the number of turns in the write head, I is the writing current and $H_0 = NIE/g$ is the deep gap field. If a hard transition is written (Figs. 1(a) and (d)), an extra transition is formed at the leading edge side of the writing zone and shifts the transition being written toward the gap center via the magnetostatic field. The separation between the extra transition and the transition being written is r .

A reasonable approximation to a recorded transition is of the arctangent form:

$$M(x) = \frac{2M_r}{\pi} \operatorname{atan} \left(\frac{x - x_0}{a} \right) \quad (2)$$

where x is measured along the track, x_0 is the center location, " a " is the transition length and M_r is the saturation remnant magnetization. Assuming a uniform longitudinal magnetization distribution through the recording medium thickness, the longitudinal demagnetization field along the medium center line without head imaging is:

$$H_d(x) = -\frac{2M_r}{\pi} \left(\operatorname{atan} \frac{a + \delta/2}{x - x_0} - \operatorname{atan} \left(\frac{a}{x - x_0} \right) \right) \quad (3)$$

where δ is the medium thickness. The magnetostatic field generated by the extra leading edge transition at the lo-

cation where the f_2 transition is written (a distance r from the extra transition center), assuming $\delta, a \ll r$, is

$$H_d(r) = -\frac{M_r \delta}{\pi r}. \quad (4)$$

In this approximation, the precise form of the transition shape is irrelevant.

Finite Gap Imaging

Due to the high permeability of the head material, $\mu/\mu_0 \approx 500-2000$, extra magnetic charges are induced on the head surface if there is a charge distribution above the head. The induced charges, which are opposite in sign to the source charges, reduce the magnetostatic field. Simple imaging, assuming induced charges distributed along the entire head surface (infinite pole tip and gapless head), is considered first. The image charges in this case are equivalent to "mirror charges," charges whose distribution are symmetric to that of the source charges with respect to the head surface. The magnitude of the field, h_{di} , generated by these induced charges then equals the demagnetization field from the magnetization transition outside the medium at a distance $2d$:

$$H_{di}(x) = \frac{M_r}{\pi} \left(\operatorname{atan} \frac{a + 2d + \delta/2}{x - x_0} - \operatorname{atan} \left(\frac{a + 2d - \delta/2}{x - x_0} \right) \right). \quad (5)$$

If a finite relative permeability of the head, $\mu_r = \mu/\mu_0$, is considered, a proportional constant $\mu_r - 1/\mu_r + 1$ appears in (5). However, unless in the case of severe head saturation, this factor is very close to unity and thus is neglected in the analysis. With a perfect image the net demagnetization field in the medium is the field in (3) (or (4)) minus the field in (5). Assuming the spacing is small, $d \ll r$, this net field is given approximately by

$$H_d(r) = -\frac{4M_r \delta d^2}{\pi r^3}. \quad (6)$$

However, in reality, due to the geometry of the head, especially the finite gap length, head imaging is much more complicated. The exact imaging for this approximation (or Green's function analysis) can be calculated via conformal mapping methods [9]. An approximation to the exact solution to include the effect of a finite gap length is described here in a 2 D approach assuming infinite head length and width.

The image effect in general is caused by the magnetic charges along the head surface that are induced by the high permeability recording head. The exact solution is to find the induced charge distribution and then to calculate the magnetostatic field generated by these charges. In a 2 D case with an infinite planar surface (gapless head), the image charge distribution for an line charge source q

der yields:

$$\Delta = - \frac{H_d(r)}{\left. \frac{\partial H_h}{\partial x} \right|_{x=r/2}}. \quad (12)$$

The negative sign of Δ yields a shift that is always toward the gap center. For the Karlquist head field function at a relatively small spacing ($d \ll g$):

$$\frac{\partial H_h}{\partial x} = \frac{QH_c}{d}. \quad (13)$$

Q is almost a constant [12], close to 0.8, when recording current is set to give a maximum head field gradient. In (13), the effects of head field rise time is neglected. In general, a finite head field rise time effectively deteriorates the head field gradient. Using (6) to (13), the hard transition shift is:

$$\Delta = \frac{M_r \delta d}{H_c \pi Q r} F(d, g, r). \quad (14)$$

Where $F(d, g, r)$ is a function of head medium spacing, gap length and the length of writing zone only (Because of (1), $F(d, g, r)$ can also be interpreted as a function of spacing, gap length and writing current only). For different recording limits, $F(d, g, r)$ is given in Table II. For a thin film head with a typical trackwidth and pole tip length, this approximation holds very well. If one considers a more general head image, for example taking into account a finite pole tip length, (14) still holds with only a slight modification in $F(d, g, r)$.

Overwrite (f_1/f_2 Playback Analysis)

Fig. 5(a) illustrates one cycle of the f_1 playback signal before overwrite. Since it is recorded on a previously dc erased medium, the hard transitions suffer both shape distortion and position shift. Here $h(x)$ and $e(x)$ stand for the playback voltages corresponding to hard and easy transitions, respectively. The playback signal after overwrite is shown in Fig. 5(b). The detailed process was explained in the previous section: Two hard transitions are separated by two consecutive easy transitions in one period.

For the f_1 signal, the spectrum of the playback waveform is

$$V_{f_1} = h_{4B}(k) \exp(ik\Delta) - e_{4B}(k) \exp(ik2B) \quad (15)$$

where k , the wave number, $h_{4B}(k)$ and $e_{4B}(k)$ are the Fourier transforms of a sequence $h(x)$ and $e(x)$ equally separated by a distance of $4B$, respectively. Δ is the hard transition shift which only transfers to a constant phase shift in the spectrum. Measured at the corresponding f_1 frequency, $k_{f_1} = 2\pi/4B$, the signal level is

$$V_{f_1}(k_{f_1}) = h_{4B}(k_{f_1}) \exp(ik_{f_1} \Delta) + e_{4B}(k_{f_1}). \quad (16)$$

After overwrite, the modulated f_2 playback signal can be

TABLE II
MAGNETOSTATIC FIELD FUNCTION $F(d, g, r)$ FOR DIFFERENT IMAGING MODEL

$F(d, g, r)$	Limits
1	no image
$\frac{4d^2}{r^2}$	perfect image
$\frac{4d^2}{r^2} - \frac{dr}{\pi(4d^2 + r^2)} \left(\ln \left(\frac{(r/2 - g/2)^2 + d^2}{(r/2 + g/2)^2 + d^2} \right) + \frac{r}{d} \left(\text{atan} \left(\frac{r-g}{2d} \right) - \text{atan} \left(\frac{r+g}{2d} \right) \right) \right)$	proper image

Fig. 5. Schematic of playback signal for (a) before overwrite and (b) after overwrite. The hard transition if no hard transition shift occurs are shown in dashed curves.

analyzed in the same fashion:

$$V_{f_2}(k) = h_{4B}(k) \exp(ik\Delta) - e_{4B}(k) \exp(ikB) + e_{4B}(k) \exp(ik2B) - h_{4B}(k) \exp(ik(3B + \Delta)) \quad (17)$$

Where the four terms correspond to the recording configurations in Figs. 1(a)–(d). Extra hard transition shifts occur in a and d . The remaining f_1 signal strength, again measured at $k_{f_1} = 2\pi/4B$, is

$$V_{f_2}(k_{f_1}) = (1 + i)(h_{4B}(k_{f_1}) \exp(ik_{f_1} \Delta) - e_{4B}(k_{f_1})). \quad (18)$$

The overwrite ratio measured by spectral analysis is therefore the ratio of (17) to (15):

$$OW = 20 \log \left| \frac{(1 + i)(h_{4B}(k_{f_1}) \exp(ik_{f_1} \Delta) - e_{4B}(k_{f_1}))}{h_{4B}(k_{f_1}) \exp(ik_{f_1} \Delta) + e_{4B}(k_{f_1})} \right|. \quad (19)$$

In most magnetic recording systems, the shape difference between a hard and an easy transitions is negligible. Thus, we can simplify (18) by setting $h_{4B}(k) = e_{4B}(k)$, to:

$$OW = 20 \log \left(\frac{\sqrt{2} \pi}{4B} \Delta \right) \quad (20)$$

Here each k_{f_1} has been replaced by $2\pi/4B$. Therefore, the

overwrite ratio including (14), is given by:

$$OW = 20 \log \left(\frac{\sqrt{2} M_r \delta d}{4 B Q H_c r} F(d, g, r) \right) \quad (21)$$

where r , and $F(d, g, r)$ are given, respectively, in (1) and Table II.

IV. DISCUSSION

The dependence of overwrite ratio on recording parameters is given clearly in (21). The overwrite ratio varies linearly with $M_r \delta / H_c$. Note that a similar monotonic dependence is found for the transition length: $a = \sqrt{M_r \delta d / \pi Q H_c}$ [12].

Reducing the medium magnetic moment $M_r \delta$, reduces the magnetostatic field. Increasing the medium coercivity results in increasing the head field gradient at the writing location. Both approaches improve the medium overwrite capability, since the hard transition shift is the ratio of the demagnetization field to the head field gradient.

In addition to the linear spacing factor, d , in (21), both the writing zone length, r , and $F(d, g, r)$ are functions of spacing. Under practical recording conditions, the dependence of r on d is relatively weak. But $F(d, g, r)$ can be a strong function of d (for example in the perfect image case, this function is $4d^2/r^2$). Therefore the dependence of overwrite on head medium spacing can be strong. Reducing the spacing results in an increased head field gradient as well as a reduced total magnetostatic field due to enhanced imaging. The overwrite ratio then decreases. Both the length of writing zone, r and $F(d, g, r)$ also are functions of gap length, g . But their dependence on g are different from that on d . r varies almost linearly with g for a typical gap length and spacing while $F(d, g, r)$ is a weak function of g . Increasing the gap length, in general further separates the f_1 transition and the extra leading edge transition. Therefore, the demagnetization field from the extra transition is reduced as well as overwrite ratio.

The relation between the overwrite ratio and writing current is more complicated. First, by increasing the current, the writing zone expands, resulting in an increased r and consequently a reduced overwrite ratio. Secondly, $F(d, g, r)$ generally decreases with an increased r , also yields a reduced overwrite ratio. Q , the head field gradient coefficient, often treated as a constant, but varies slightly with the writing current. $Q \approx 0.8$ is the maximum value when recording at a maximum head field gradient, and decreases with further increasing writing current. The overwrite ratio increases with a reduction in Q . As a result of these competing factors r , $F(d, g, r)$ and Q , overwrite generally decreases with increasing recording current. The f_2/f_1 overwrite ratio also decreases with increasing bit length (B) of the magnetization pattern.

V. RESULTS AND DISCUSSIONS

Measured f_2/f_1 overwrite ratio versus deep gap head field for disk no. 1 (Table I) is plotted in Fig. 6. The horizontal axis is the normalized by the medium coercivity.

Fig. 6. Measured overwrite ratio verse H_0 for disk no. 1 at 4.7μ head medium spacing.

ity. The bit length of the f_2 square wave magnetization, $B = 50 \mu$. The net magnetic spacing was 4.7μ . The overwrite ratio decreases generally with increasing writing current. The same trend is found for other spacings as well as other disks. For comparison, a plot of isolated pulse peak voltage versus recording current (I/O curve) is shown in the same figure with an arbitrary vertical units. It is seen that the medium magnetization is saturated when the head field exceeds approximately $3H_c$ for disk no. 1 at this flying height. Modulation overwrite dominates for $H_0 > 3H_c$ because the head field is sufficient (larger than the switching fields of the magnetic grains) to erase the f_1 magnetization pattern.

For $H_0 < 3H_c$, the residual overwrite dominates the yields extremely large overwrite ratio. When $H_0 \approx 1.6 H_c$, the overwrite curve shows a "shoulder," which has been noted previously [5]. This is due to a reduction in total writing field at the gap center during the writing process. The total magnetic field is the sum of head field and the demagnetization field from the extra leading edge transition if a hard transition is written. Due to a finite coercivity distribution, a transition (both transition if a hard transition is written) starts to form when the maximum head field at the medium surface reaches approximately H_c . The demagnetization field generated by the extra transition at this point increases rapidly resulting in a reduction in the total field. The field reduction causes insufficient erasure of the f_1 pattern and hence increases overwrite.

Results from the analytical model are compared quantitatively with measurements in Fig. 7. In the modulation region, the overwrite ratio decreases slightly with writing current. This confirms the dominance of r and $F(d, g, r)$ over Q in (21). To clarify the importance of proper imaging, results from (21) for disk no. 1 are shown for three cases: no image, perfect image and proper gapped image. It is evident that results from both the no image and the perfect image cases do not agree with experiment. The gapped image case, on the other hand, gives a reasonable prediction of the modulation dominated, high current region. The importance of using a proper gapped image can also be seen from Fig. 4. For a range of deep gap field from $3.0 H_c$ to $5.0 H_c$, the length of the writing zone, r ,

Fig. 7. Comparison of theoretical model and measurement. Data are shown for disk no. 1 at $4.7 \mu\text{m}$ spacing.

Fig. 8. Dependence of overwrite ratio on head medium spacing for disk no. 1 at $H_0 = 4.0 H_c$.

calculated from (1) varies from 1.2 g to 1.4 g. In this case, the gapped imaging from Fig. 4 is neither close to that of no imaging nor to that of perfect imaging and therefore must be used in a proper overwrite calculation.

Overwrite measurements were performed at different flying heights. Results for disk no. 1 are shown in Fig. 8, where the overwrite ratio is plotted versus head-medium spacing. The writing current was carefully chosen to achieve a deep gap field equal to $4.0 H_c$ at all flying heights. Strong dependence of overwrite on head-medium spacing is evident. Reducing the effective spacing from $10.1 \mu\text{m}$ to $4.7 \mu\text{m}$ cause the overwrite ratio to reduce from -24 dB to -36 dB . Results for other disks and deep gap fields show the same trend. In the same figure, theoretical calculations are shown using a gapped image.

Overwrite ratios are plotted versus $M_r \delta/H_c$ in Fig. 9 for disks with varying coercivity and magnetic moment.

Fig. 9. Overwrite ratio versus $M_r \delta/H_c$ for disks no. 1 to no. 4 at $7.7 \mu\text{m}$ head medium spacing.

Again the deep gap field was fixed in each case at $4.0 H_c$. The net spacing was $7.7 \mu\text{m}$. The overwrite ratio decreases with decreasing $M_r \delta/H_c$. The dependence of overwrite on $M_r \delta/H_c$ is weak in contrast to its strong dependence on spacing. Reducing $M_r \delta/H_c$ from $50 \mu\text{m}$ to $17 \mu\text{m}$, the ratio changes from -31 dB to -36 dB . The theoretical results with proper imaging are also plotted in the Fig. 9 (solid line). Reasonable agreement with experimental measurement occurs except for the disk with the lowest $M_r \delta/H_c$ (disk no. 4 in Table II); This deviation may be due to head saturation during the recording process.

VI. A NEW OVERWRITE MEASUREMENT TECHNIQUE

In this section, a new overwrite measurement technique is presented. It uses the correlation between the remaining f_1 signal after f_2/f_1 overwrite and the second harmonic component of a $0.5 f_1$ signal written on the same dc erased medium. Both analytical derivation and experimental procedure are given in the following discussion. Theoretical analysis is based on the model described in Section III with the same assumption that modulation dominates overwrite at high recording current.

For a $0.5 f_1$ square wave written on dc erased media, the playback signal spectrum, similar to (15), is

$$V_{0.5f_1}(k) = h_{8B}(k) \exp(ik\Delta) - e_{8B}(k) \exp(ik4B) \quad (22)$$

where $h_{8B}(k)$ and $e_{8B}(k)$ are, respectively, the Fourier transforms of a sequence of hard and easy transitions separated equally by a distance $8B$. The hard transition shift, Δ , is given by (14) because it is not frequency dependent. The second harmonic of (22), which corresponds to $k = k_{f_1} = 2\pi/4B$, (22) becomes

$$V_{0.5f_1}(k_{f_1}) = h_{8B}(k_{f_1}) \exp(ik\Delta) - e_{8B}(k_{f_1}). \quad (23)$$

Notice that $h_{4B}(k) = 2h_{8B}(k)$, $e_{4B}(k) = 2e_{8B}(k)$, so that a comparison of (22) and (16) gives

$$V_{f_2}(k_{f_1}) = 2(1 + i)V_{0.5f_1}(k_{f_1}). \quad (24)$$

Fig. 10. Remaining f_1 signal after f_2 overwrite and the second harmonics of $0.5 f_1$ signal written on the same dc erased medium versus H_0 for disk no. at 4.7μ spacing.

This simple relation implies that at high current, the remaining f_1 signal of an f_2/f_1 overwrite process is lower than the second harmonic component of a $0.5 f_1$ signal written on the same dc erased medium by a factor of $2(1 + i)$. ($20 \log(2|1 + i|) = 9$ (dB)). Note here in the derivation of (24), the assumption that hard and easy transitions are of the same shape is not needed.

Experimental results are shown in Fig. 10. The remaining f_1 signal after f_2/f_1 overwrite (solid line) and the second harmonic component of $0.5 f_1$ signal (dashed line) for disk no. 1 are both plotted versus deep gap field. The total head-medium spacing is 4.7μ , and the bit length for f_2 signal remains unchanged, 50μ . At high current, the two curves are virtually parallel and the difference between them is about 8 dB, which is in a good agreement with (24). This also verifies that modulation is the dominant factor in a high current overwrite process.

This proposed method is valid only at high recording current ($H_0 > 3 H_c$). To summarize: First, record a square wave at a particular frequency f . Measure the signal level $V_1(f)$ in dB, then dc erase the medium and record a $0.5 f$ square wave. Measure its second harmonic component, $V_2(f)$ in dB. The f_2/f_1 ($f_2/f_1 = 2$) overwrite ratio can then be calculated by

$$OW_{f_2/f_1} = V_2(f) - V_1(f) + 9 \text{ dB} \quad (25)$$

This method is convenient if the overwrite dependence on writing current is desired. The technique can be expanded to any ratio of f_2/f_1 , by a simple variation of (25).

VII. CONCLUSIONS

Standard f_2/f_1 overwrite has been measured for various recording currents and flying heights. Disks with different magnetic properties, such as coercivity and magnetic moment were used. Results show that at high recording currents, the overwrite process is dominated by modulation, namely, hard transition shifts. A simple analytical model for overwrite at high current is developed. Modulation is assumed to be the dominant mechanism. Proper image of the gapped head was taken into account by simply removing the induced magnetic charges over the gap. Results

compare well with the measurements. Lowering the flying height increases the head field gradient and reduces the magnetostatic field due to increased head imaging. Both these effects decrease hard transition shift and thus overwrite ratio. Decreasing medium demagnetization factor, $M_r \delta/H_c$, reduces magnetostatic and hence the overwrite ratio. However, the reduction in overwrite due to the reduction in magnetostatic field is less than due to the reduction of flying height. A new overwrite measurement technique based on the second harmonic component of a $0.5 f_1$ signal was proposed.

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