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Recent Advances in Ma
Recording Materials

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INTRODUCTION

Technological advances have created an ever-increasing demand on the information storage capacity of digital magnetic recording systems. This demand is aimed toward increasing the linear bit density and the lateral track density by improving the characteristics of the recording surface and by improving the resolution of the read-back transducer.

In this paper we discuss briefly the limitations imposed by the transducer; in more detail, we pursue the role of the properties of the recording medium in an attempt to define the ultimate characteristics of the recording surface for high density digital recording. Finally, we discuss the properties of some new and promising recording media that are bidding to replace the traditional γ-Fe_2O_3 particles. Projections are indicated which should optimize their high density recording performance.

THE RECORDING PROCESS

THE WRITING PROCESS

Magnetic recording of data involves the storage and processing of digital information, utilizing two states of magnetization which are capable of being differentiated. High-density resolution in magnetic recording implies that the transition between oppositely magnetized regions on the tape must be as narrow as possible.

The simplest, and perhaps the most significant, method of examining these effects on density-dependent behavior of different tapes is to record by driving the head with a square-wave generator at increasing frequencies. This corresponds to the "all ones" pattern in the NRZ recording. If this pattern is recorded at very low densities so that the individual pulses are widely separated, then we can examine the position, shape and amplitude of the isolated pulse as a function of thickness and magnetic properties. We can also attempt to reproduce coded patterns by superimposing the isolated pulses and compare the results of this superposition with observed output from the coded pattern on the tape. Thus, the detailed study of an isolated pulse and its dependence on the properties of the tape is probably the most fundamental experiment which we can perform in digital recording.

The output pulse shape depends on the characteristics of the reading head, the separation between tape and head, and on the width of the transition region in the tape between areas of opposite magnetization. The transition region in turn depends on (a) the shape of the hysteresis loop of the recording surface; (b) the writing transducer field gradient and (c) the ratio H_c/I_rt which reflects the trailing edge field gradient and demagnetization. A simple model showing the creation of a transition region is shown in Figures 1a, 1b, and 1c.

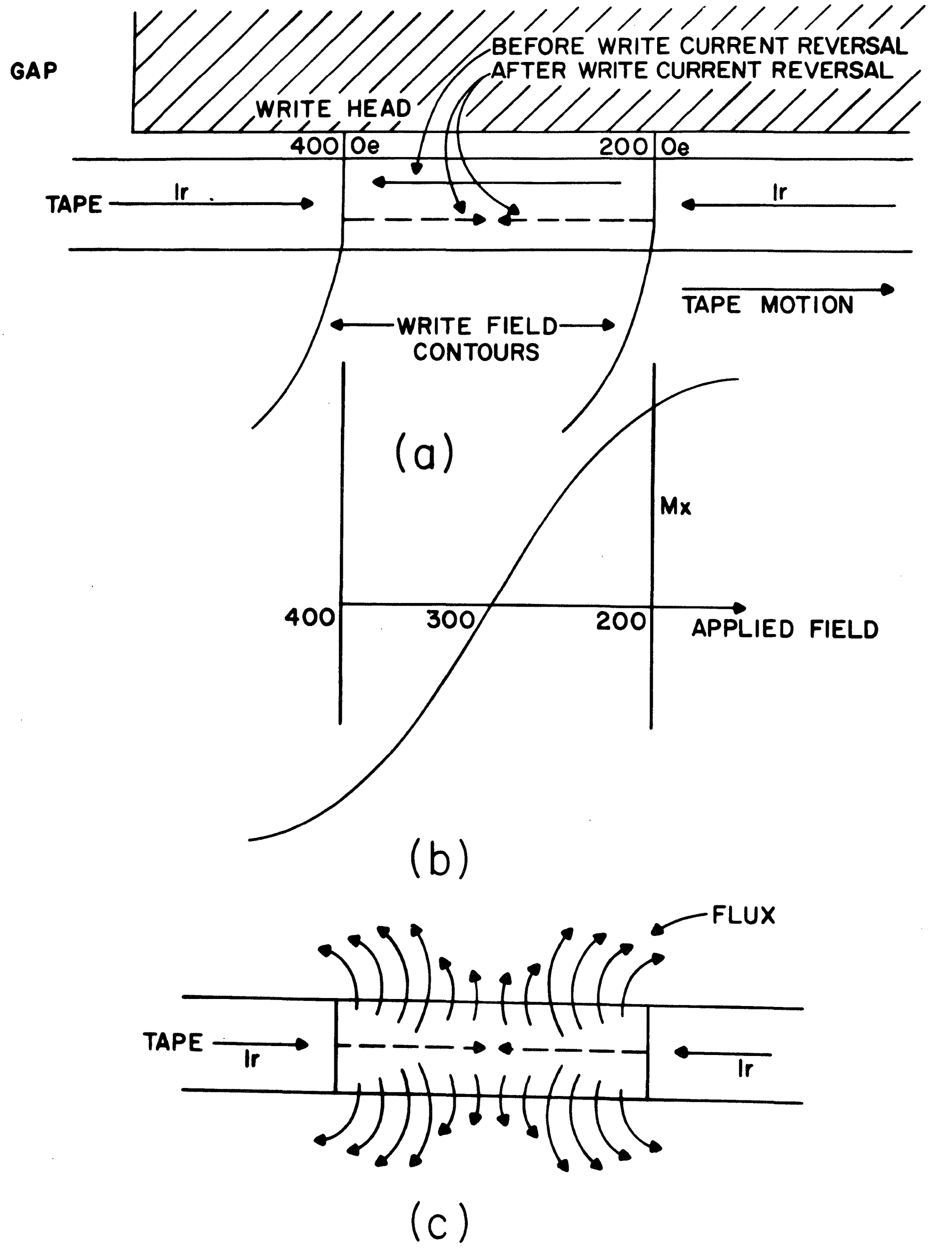

FIGURE I

A. THE INTERACTION OF THE WRITE GAP FIELD GRADIENT AND THE RECORDING SURFACE.

B. TRANSITION REMANENCE MAGNETIZATION DISTRIBUTION (MX).

C. FINAL TRANSITION REGION.

Figure la shows typical oxide tape that is pre-saturated and passed under a write transducer where sufficient write current is applied so that the 200 and 400 Oe contours of the head penetrate the tape. The write current is then suddenly reversed through zero to an equal value in the opposite direction to give a transition region shown in Figure lc. Hence, each small increment ΔL_0 (Figure lc) along the transition length will experience a different effective reversing field from 200 Oe to 400 Oe for the oxide example. Therefore, the remanence magnetization (M_x) distribution in the transition region is an arc-tangent function similar to the tape's remanence magnetization curve determined for a sample whose geometry is identical to the bit geometry that is written. This is assuming there is little effect from the transition flux to demagnetize the bit.

The basic writing process was adequately explained in the previous discussion pertaining to the formation of a transition region. Other factors, not to be included in this discussion, could have a profound influence on the ability of any medium to sustain high densities. Factors such as write current, write gap, head field gradient and the distance from the gap center line where writing occurs will be discussed in a forthcoming publication.

THE READ PROCESS

A significant loss factor in high density recording is imposed by the read back transducer in that it limits the signal magnitude and resolution of a given recording surface. When the read gap is zero, or an integral multiple of twice the bit length, there is zero head output. The signal output of a read head is proportional to the effective track width, the half power of the coercivity-remanence-thickness product of the tape, the velocity of the tape, and the number of turns on the read back coil. Hence, there is an optimum read head gap, which will result in maximum head output signal when the head parameters such as head core length and permeability are fixed and the bit length specified.

Using a typical metal lamination head, the read gap was varied between 40 and 150 micro inches. Frequency response curves were determined for the various oxide and plated surfaces utilized in this study. Figures 2 through 4 show the effect of a 40 micro inch read gap on plated and oxide samples, while Figures 5 through 7 are for the 150 micro inch read gap. For each read gap, the absolute value of the output signal as well as the normalized values are plotted.

In general these curves show for both plated and oxide surfaces that at low densities the thicker the sample, the higher the output, and at high densities the thicker the sample the lower the output. When the samples are normalized we see that the thinner the sample, the better the frequency response.

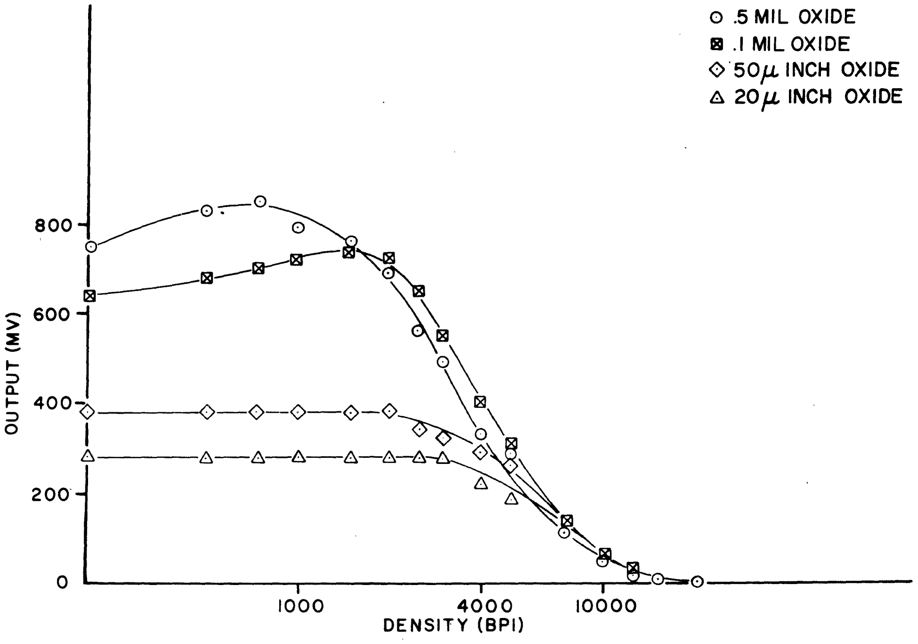

FIGURE 2

SATURATION DENSITY RESPONSE CURVES FOR OXIDE TAPES OF VARIOUS THICKNESS UTILIZING A 40μ INCH READ GAP

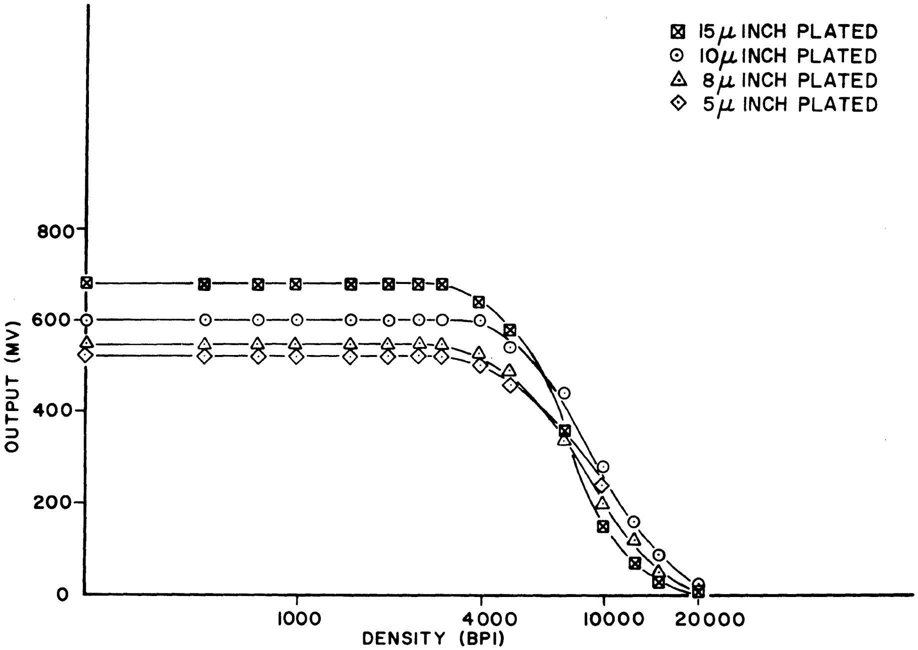

FIGURE 3

SATURATION DENSITY RESPONSE CURVES FOR PLATED TAPES OF VARIOUS THICKNESS UTILIZING A 40μ INCH READ GAP

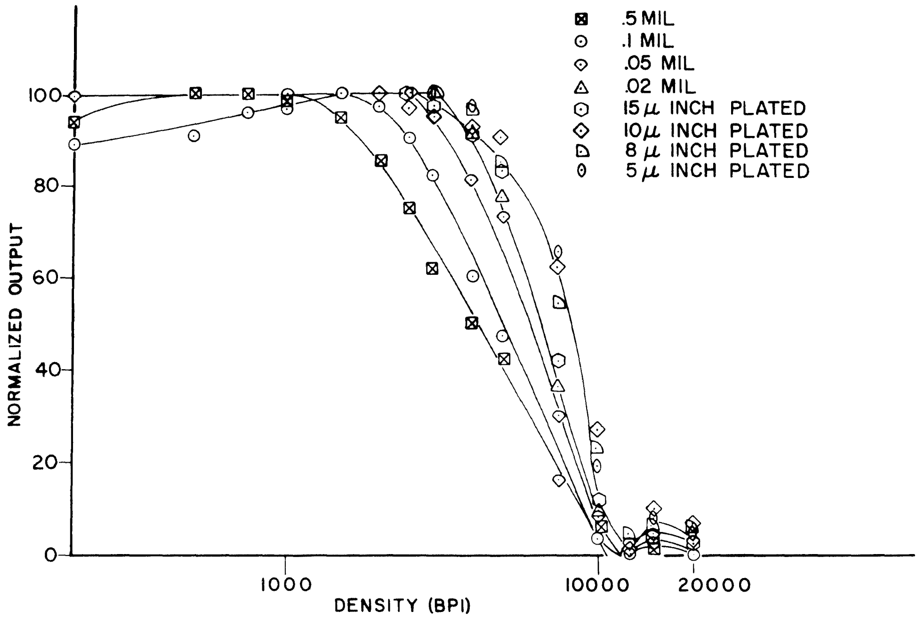

FIGURE 4
NORMALIZED SATURATION DENSITY RESPONSE CURVES FOR PLATED AND OXIDE TAPES OF VARIOUS THICKNESS UTILIZING A 40μ INCH READ GAP

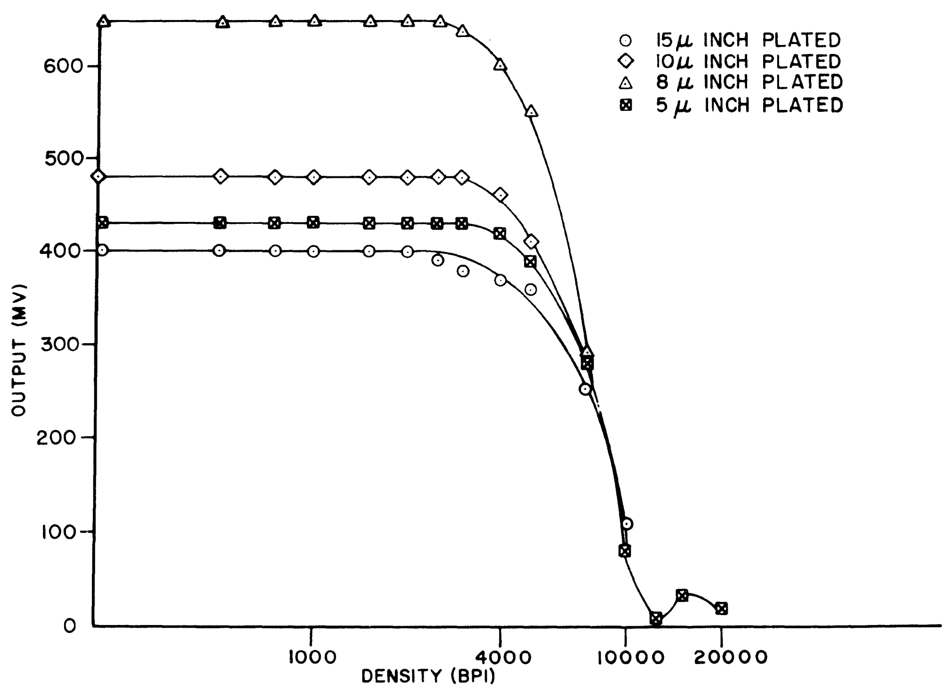

FIGURE 5
SATURATION DENSITY RESPONSE CURVES FOR PLATED TAPES OF VARIOUS THICKNESS UTILIZING A 150μ INCH READ GAP

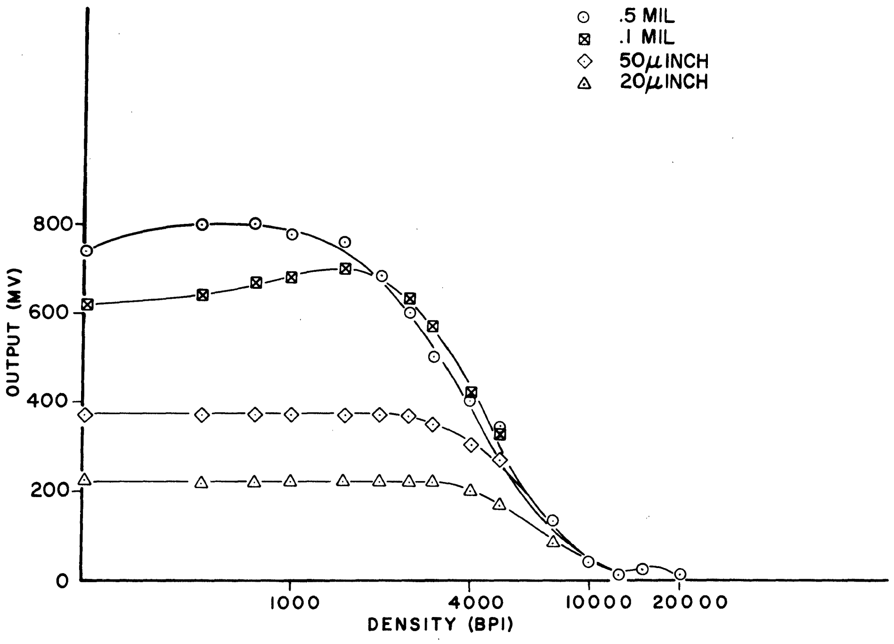

FIGURE 6
SATURATION DENSITY RESPONSE CURVES FOR OXIDE TAPES OF VARIOUS THICKNESS UTILIZING A 150μ INCH READ GAP

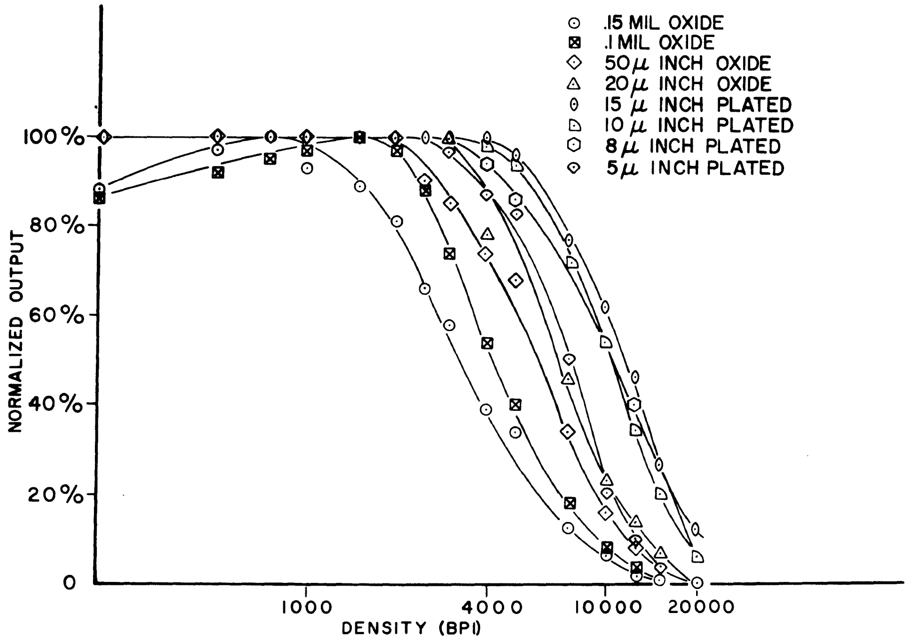

FIGURE 7
NORMALIZED SATURATION DENSITY RESPONSE CURVES FOR PLATED AND OXIDE TAPES OF VARIOUS THICKNESS UTILIZING A 150 μ INCH READ GAP

The two samples giving the best resolution were plated and their absolute output and normalized output are shown in Figures 8 and 9, respectively. The significant difference between the two samples is their coercivity where the coercivity of one is twice the other. It is seen that the sample with the higher coercivity is much better for all considerations.

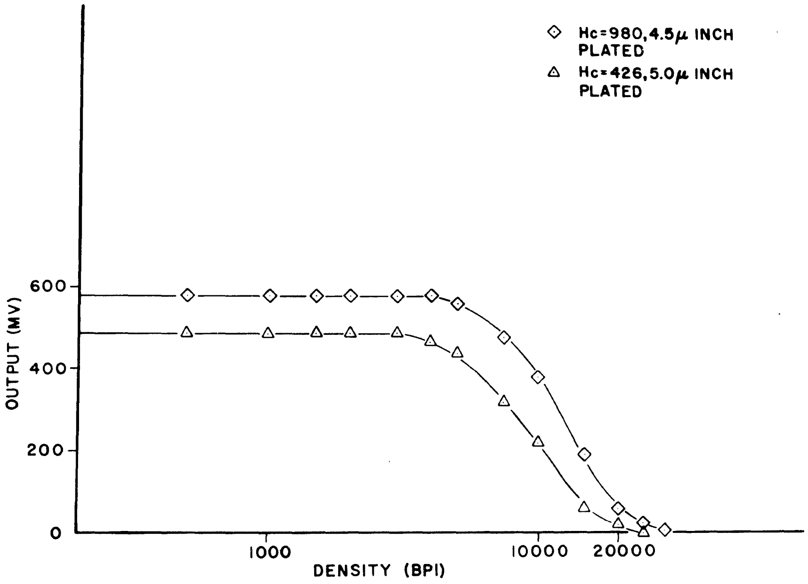

FIGURE 8
DENSITY RESPONSE CURVES FOR TWO PLATED SURFACES

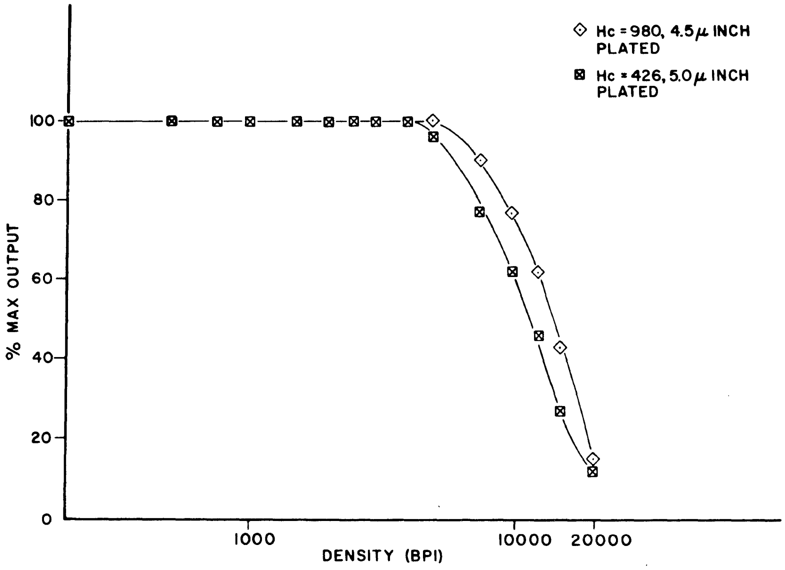

FIGURE 9
NORMALIZED DENSITY RESPONSE CURVES FOR TWO PLATED SURFACES

Therefore, for maximum resolution in high density recording, the read gap and tape thickness should be as small as necessary while the coercivity should be as large as that which the write head can saturate.

PEAK SHIFT

In order to achieve high density recording, the inter-bit resolution of the recording system has to be of such a nature as to minimize peak shift. The phenomenon of peak shift is the outward displacement of the pulses from two consecutive ones followed by several zeros. When bits are written close together on the tape, the possibility arises that the reading head is not able to discriminate completely between the adjacent transitions leading to an interaction of the bit flux in the read transducer causing a reduction in the amplitude of the pulse and, of more importance, a shift in the position of the output voltage peaks in coded patterns. Therefore, to analyze the effect of the properties of plated and oxide tapes the influence of the read transducer must be minimized. For this experiment, as stated previously, the read gap was 40 micro inches.

Figures 10 and 11 give a composite picture of experimentally determined peak shift of oxide and plated surfaces as a function of bit density. For the oxide examples, it is interesting to note, that the percent peak shift is a direct function of the sample thickness, and that if the write current is optimized for maximum output, (non-saturation recording), a thick sample will give a radical reduction in peak shift. Due to the thinness of the plated samples, they exhibit much less peak shift than any oxide surface, with the 50 micro inch oxide surface being somewhat comparable to the worst plated surface.

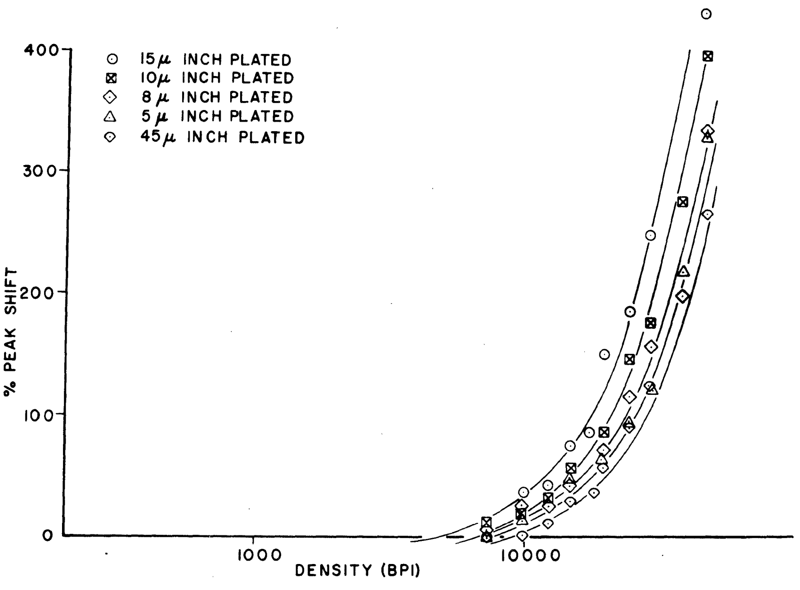

FIGURE 10
PERCENT PEAK SHIFT VS BIT DENSITY FOR PLATED SURFACES

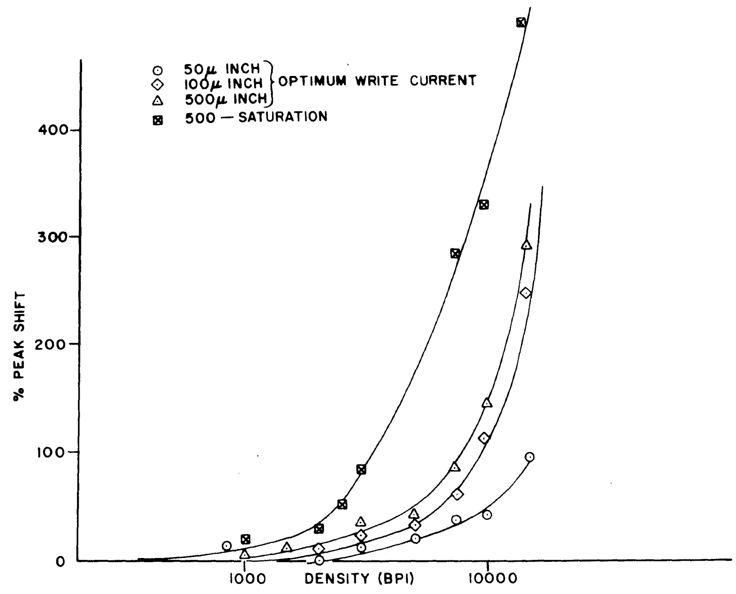

FIGURE 11
PERCENT PEAK SHIFT VS BIT DENSITY FOR OXIDE SURFACES

Comparing the normalized frequency response curves of both oxide and plated surfaces in Figure 12, we can see that again thinness is a prime prerequisite for high density recording.

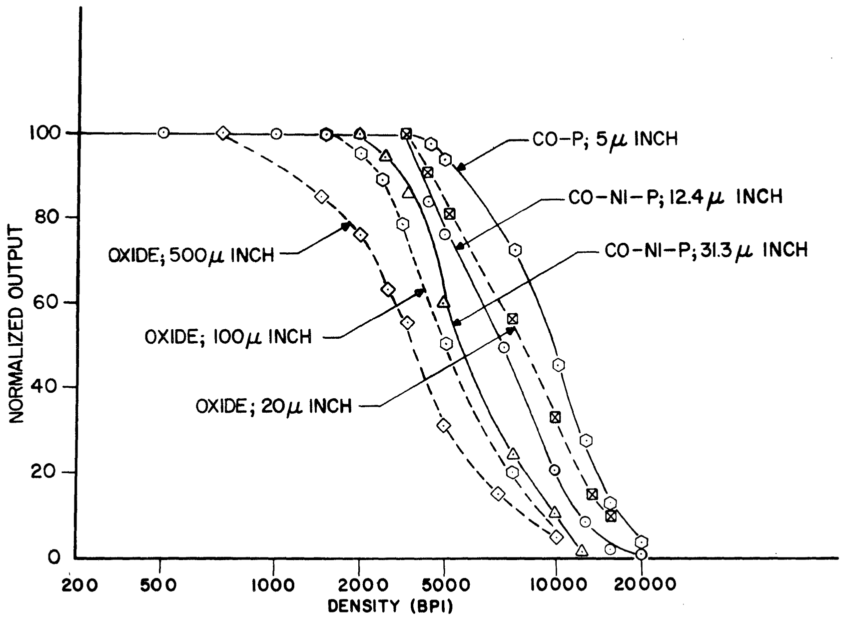

FIGURE 12
NORMALIZED FREQUENCY RESPONSE CURVES FOR OXIDE AND PLATED SURFACES

THE ROLE OF THE MAGNETIC PROPERTIES

In digital magnetic recording a bit is defined by a magnetization reversal on the recording surface. The extent of this magnetization transition region is primarily determined by the writing transducer field gradient and the demagnetization of the recording medium. This in turn is controlled by the magnetic properties and the thickness of the medium. The width and amplitude of the pulse that one reads back from such a transition are in general a function of the magnetization transition region, the medium thickness, the medium-to-transducer spacing, and the characteristics of the read transducer. In general, any one of these parameters can dominate the pulse characteristics, depending on their relative magnitudes. To determine the significance and emphasize the importance of the magnetic properties and the thickness of the recording medium, one should minimize the playback transducer effects by using a very narrow read gap (1 micron in our experiments) and as close as possible contact between transducer and medium. Under these circumstances, the length of the magnetization transition region, which is determined primarily by the magnetic properties and the thickness of the recording medium, can become the most important parameter in the width and amplitude of the read back pulse. It affects the width of the pulse because the read transducer scans the flux distribution emanating from the transition region. It also affects the pulse amplitude because the magnetic charge density in the transition region, and therefore the flux density over the transition region, is essentially inversely proportional to the length of the magnetization transition.

The resultant transition region in a recording surface is primarily determined by demagnetization effects, particularly for the case of thin recording surfaces where the writing transducer plays only a minor role. Consequently, the dependence of the resultant transition region on the magnetic properties and the thickness of the recording surface is described by the ratio[1]:

$$\left[\frac{I_r d}{H_c}\right]^n \qquad (1)$$

Where, I_r is the remanent magnetic dipole moment per unit volume, d is the recording surface thickness, and H_c is its coercivity. The exponent n depends on the I_r/H_c ratio of the material. For small I_r/H_c ratios, n is approximately 1/2, and it increases gradually to 1 for large I_r/H_c ratios.

The correlation between the magnetic properties and the recording performance of magnetic recording surfaces is a subject of very active and current interest in magnetic recording.[2-5] Our findings,[6] based on an experimental investigation of the recording characteristics of a large number of thin metallic surfaces with widely different magnetic properties, lead us to the following conclusions regarding the width and amplitude of a pulse read back from an isolated magnetization transition:

$$\text{half pulse width} \propto \left[\frac{t}{H_c}\right]^{1/2} \qquad (2)$$

and,

$$\text{pulse amplitude} \propto \left[H_c I_r t\right]^{1/2} \qquad (3)$$

Whereas these relationships were established for thin metallic surfaces, there are experimental indications that they are approximately valid for thicker particulate surfaces as well.

A striking fact, apparent in the above relationships, is the absence of the remanent magnetization from relationship (2) which defines the resolution of a recording surface, while the remanence does apparently enter in relationship (1) which defines the magnetization transition region. However, the validity of relationship (2) has been experimentally demonstrated to extend over a wide range of samples for both continuous metallic and particulate coatings. While, with very large variations in magnetic properties and thickness, it seems to break down only for very low coercivities (below 150 Oe) where the half pulse width exhibits an increasing dependence on the remanent magnetic moment with decreasing coercivity.

Relationships (2) and (3) shall form the basis of our subsequent discussion of the evolution of magnetic recording media and the properties which they should possess for optimized recording performance.

THE EVOLUTION OF RECORDING MEDIA

Traditionally, the ferromagnetic constituent of magnetic recording surfaces has been a dispersion of single-domain γ-Fe_2O_3 particles immersed in an organic binder, and coated on to substrates to a thickness of 12.5 microns. Coercivities fall in the range of 260-280 Oe, and remanent induction in the range of 800-900 gauss. These surfaces have been used successfully for recording digital densities up to 3200 flux reversals per inch; however, technological demands for higher storage densities have stimulated studies to remove the present material and transducer limitations and approach more closely the optimized conditions. These conditions, from the point of view of the medium, are indicated by relationships (2) and (3), which, as was pointed out earlier, hold quite well for thin metallic surfaces, but are also good approximations for thicker particulate coatings.

The obvious approach to high density recording surfaces is quite clear:

a. Increase the coercivity of the recording surface to the maximum value, consistent with the field capabilities of the writing transducer (somewhere in the vicinity of 600-700 oersteds for contact recording with conventional metal lamination transducers). Any advantages that might be gained by using coercivities higher than 600-700 oersteds, are usually offset by the deterioration of the writing transducer field gradient due to the large write currents. This limitation, however, can be essentially removed by using high saturation magnetic moment laminations in the writing transducer. The optimum value of the coercivity also depends to some degree on the thickness of the recording surface--it is larger for thinner surfaces. Increasing the coercivity of the recording surface should increase both its signal output and its resolution, according to relationships (2) and (3).

b. Increase the remanent magnetization of the recording surface to the maximum possible value. Provided that the coercivity is not very low ($H_c > 150$ Oe), increasing the remanent magnetic dipole moment results in an increase in output without any appreciable deterioration in resolution, particularly for thin recording surfaces.

c. Decrease the thickness of the recording surface to the minimum possible value, consistent with acceptable output signal, good surface finish, uniformity of coating, and good wearability. The thickness of the recording surface adversely affects its resolution in two primary roles. First, it enters in the demagnetizing factor and broadens the magnetization transition region. This effect is the one mainly reflected in relationship (2) which was established for thin metallic surfaces. In addition to its effect on demagnetization, the thickness plays another very important role in the read back process by introducing an effective spacing between the transducer and the medium, which again adversely affects the resolution. If we consider the recording medium to consist of a number of thin layers parallel to its surface, then we can superpose the contribution of each layer to obtain the total read back pulse. It is then evident that the contributions of the layers further away from the read transducer will be smaller in amplitude and broader in width. This effect becomes the more important with increasing thicknesses. Of the three primary properties of a recording surface--coercivity, remanence, and thickness--it is the thickness which allows for true optimization for any given application, since it adversely affects the resolution, while it beneficially affects the output. However, it is our belief that digital recording surfaces of today, as well as those of the foreseeable future, are primarily limited by resolution and not by output. If we are right, it would seem that one should strive for the thinnest possible recording surface, while relying on optimized coercivity and remanence to assure acceptable signal output.

Thus far we prescribed the directions which should be followed to optimize the properties of recording surfaces. This discussion was restricted to the most important characteristics of the medium--its coercivity, remanence, and thickness. Other parameters, such as squareness, steepness of the sides of the hysteresis loop, and magnetic anisotropy are in our opinion of secondary importance, and are not considered here.

We proceed now to discuss the magnetic properties and the evolution of the various particulate and continuous recording media. In discussing these materials, it should be kept in mind that, whereas the saturation magnetization is a structure insensitive property, which depends primarily on the composition of the material and temperature, this is not the case with the properties of the surface which are most pertinent to the recording process, namely, its remanence, coercivity, and squareness; these are structure sensitive properties; and, in addition to composition, depend on particle size and shape, particle interactions, the various anisotropies present, and the temperature. Any one or more of these mechanisms may be employed, where appropriate, to optimize the magnetic properties of these surfaces. Considering the anisotropies, two in particular are dominant in these materials:

a. Shape anisotropy: This is present in acicular particles and it increases with increasing acicularity. The long axis of the particles becomes the easy or preferred axis for the magnetization. The coercivity associated with shape anisotropy is proportional to the saturation magnetization of the particles, and it exhibits essentially the same temperature dependence as the saturation magnetization. This usually implies good temperature stability of the coercivity, except for materials with low Curie points.

b. Crystalline anisotropy: This depends on the crystal structure of the material and the orientation of the magnetization with respect to the crystallographic axis. It usually exhibits a very large temperature dependence, decreasing rapidly with increasing temperature. The coercivity of these materials is proportional to their crystalline anisotropy, and consequently it will most frequently exhibit a large temperature dependence.

In the following discussion on the properties of various recording media, many of the comments were brought up by several participants in the Workshop on Magnetic Recording that was held during the 1966 INTERMAG Conference in Stuttgart, Germany.

γ-Fe_2O_3

Acicular particles with axial ratio of about 6:1 and shape as the predominant anisotropy. Typical coercivity is $\sim$ 270 Oe. with good temperature stability. To increase the coercivity one or more of the following techniques may be employed:

a. Increase acicularity.

b. Decrease particle size and increase size uniformity to attain more coherent magnetization reversal.

c. Dope with small amounts of Cobalt (1-4%).

The first two steps have provided coercivities up to about 360 Oe. The last step has provided coercivities up to 850 Oe., but with poor temperature stability because these doped particles were non-acicular (they were of "coal" like "cubic" shape). If acicular cobalt-substituted γ-Fe_2O_3 particles could be produced, they should have good temperature stability and be prime contenders for optimized recording surfaces.

The remanence of γ-Fe_2O_3 recording media is about 860 gauss for normal particle to binder loading ratios. To increase the remanence one has to increase the loading, which might be accompanied by some adverse effects on wearability, or go to Fe_3O_4 particles, which in addition to a substantial increase in remanence, offer the advantage of higher coercivity.

One difficulty with γ-Fe_2O_3 acicular particles is that of aligning them along the direction of tape motion to produce more square hysteresis loops. It is believed that this difficulty is due to a large extent to the rough and irregular (dendritic) surface of the particles. If smoother particles could be made we could expect considerable improvement in alignment with the attendant improvement in recording performance.

CrO_2

Very acicular particles with axial ratio as high as 20:1 and shape as the predominant anisotropy. However, the crystalline easy axis almost coincides with the shape easy axis. Typical coercivity is $\sim$ 420 Oe. with poor temperature stability due to the low Curie point ($\sim$125°C). However, the large variation of H_c with T corresponds to a similarly large variation of M_r, rendering the ratio H_c/M_r essentially temperature independent. Since this is the characteristic ratio that determines the demagnetization of recorded magnetization transitions, the recorded signal output recovers almost completely following temperature excursions to 60°C and even higher. To increase the coercivity one would strive for smaller particle size, for improved size and shape uniformity, or doping with other elements. Thus coercivities of 650 Oe and higher have been achieved.

These particles can be aligned quite well to produce recording surfaces with very good squareness. It is believed that the smoothness of the particle surface should be credited primarily for the better alignment of the particles.

The remanence of CrO_2 recording surfaces is about 1450 gauss, almost double that of γ-Fe_2O_3 surfaces.

Fe-Co

The main anisotropy of these particles is believed to be crystalline, but shape also enters as the small particles tend to form "Chains of Spheres". Because of the high magnetic moment of these particles, even a small shape effect would result in a proportionally large contribution to the coercivity. Typical coercivities are about 700 Oe with good temperature stability. To vary the coercivity and remanence of these particles one may choose from a great variety of means, some possibilities are:

a. Vary the composition.

b. Vary the particle size.

c. Vary the shape distribution.

d. Vary the oxidation and reduction cycles and temperatures.

One problem with the metallic particles is that they tend to be pyrophoric and ignite spontaneously when exposed to air. This can be eliminated by avoiding exposure to an oxidizing atmosphere, or allowing controlled oxidation of the outside surface of the particles, which of course would tend to decrease somewhat their remanence. A simple calculation shows that using metallic particles one should be able to make recording surfaces with a remanence of 3000 - 5000 gauss, considerably higher than that of the oxides.

Of the three sets of particles discussed above, the Fe-Co metallic powders offer by far the greatest latitude in the variation of magnetic properties. Therefore, if the magnetic characteristics of optimally designed recording media are prescribed, and if they can be physically attained, they most certainly can be realized in the Fe-Co of Fe-Co-Ni metallic particle system (while this is not necessarily true for CrO_2 and γ-Fe_2O_3 particles).

METALLIC FILMS

Metallic recording surfaces have been made in a number of ways.[7] Their magnetic properties can be easily varied over the entire physically realizable range. In addition, they can be made to any thickness, even down to 0.1 micron or lower. By contrast, particulate media are probably limited to a minimum controllable thickness of about 1 micron with present coating techniques. Therefore, metallic films offer the greatest possible flexibility in the variation of parameters, and allow for the ultimate recording optimization not only from the point of view of the magnetic properties but of the thickness as well. The direction to this optimization is clearly indicated by relationships (2) and (3).

CONCLUSIONS

A very significant improvement in signal amplitude and resolution is offered by increasing the coercivity and the remanence and decreasing the thickness of digital recording surfaces used for high density storage. The greatest flexibility in particulate coatings is offered by ferromagnetic metallic particles, which, however, are limited to a minimum thickness of about 1 micron. The ultimate recording optimization can probably be achieved in thin metallic surfaces, where both the magnetic properties and the thickness can be produced to any desirable value.

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