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AN ANALYSIS FOR THE MAGNETIZATION MODE FOR HIGH DENSITY MAGNETIC RECORDING

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ABSTRACT

By the analysis of the self-consistent magnetization and the direct observation of the remanent magnetization of a real tape, the authors discussed the obstacles which are, and will be, encountered in attaining a higher recording densities with the present magnetic recording system, which uses mainly a longitudinal magnetization mode. Then the properties of the three magnetization modes (longitudinal, circular, and perpendicular) are compared. The mode transformation is also discussed. Finally a new perpendicular magnetic recording system is proposed for high density recording. And some results of fundamental experiments are presented. The system uses the perpendicular magnetization mode which is basically free from the demagnetization in very high densities. Its realization mainly owes to the development of a perpendicular anisotropy film and perpendicular magnetic heads.

I. INTRODUCTION

To realize a high density recording in the present magnetic recording system, it is especially needed to make the recording medium thin and highly coercive. It has recently been clarified that, in high density recording, demagnetization in the medium not only decreases the remanent magnetization, but also rotates magnetization vector to establish a circular magnetization mode, resulting in a significant decrease of reproduced signals.[1] It is understood that the merit of using a thin film is to prevent the circular magnetization from establishing. In the recent magnetic disks, the recording medium has been reduced in thickness, at a high pace, to such a point that a Co-system metal film of the thickness less than 500A is experimented (a linear density of around 20,000 BPI is aimed at). The necessity of such an extremely thin medium, and at the same time, of high coercivity (600-1,000 Oer) may also be deduced by the analysis of demagnetization mechanism of a longitudinal magnetization in high density recording process.[2] If a future system for high density recording is pursued in the same manner, the following obstacles will be unavoidably encountered, and practical limits will be reached:

(i) The recording density limit due to domain walls of a saw-tooth structure appearing at the magnetization transition region in thin films.[3]
(ii) The drop of S/N brought about by the decrease of remanent magnetization per bit for a thinner film and the deterioration of uniformity of the film.
(iii) The magnetic saturation of recording heads accompanied by the use of highly coercive films.

The obstacles all stem from the property of the longitudinal magnetization mode recorded by a ring-type head, that is, the demagnetizing field in the mode increases and approaches to the maximum value of $4\pi M$, as the recording density increases. Therefore, a desirable magnetic recording system in future should be one in which the demagnetizing field basically approaches to zero in higher recording densities. By predicting future advances in magnetic recording based on these viewpoints, the authors have arrived at the conclusion that, adding to the present longitudinal magnetization mode, other magnetization modes should be utilized, such as one whose magnetization is perpendicular to the medium surface or a circular magnetization mode lying on the perpendicular plane. Recently the authors have experimentally ascertained the feasibility of a new magnetization mode usable in high density magnetic recording.

In this paper some results of the direct observation of remanent magnetization of real tape is first presented by employing a Bitter method. Then the properties of the magnetization modes are discussed, and a new perpendicular magnetic recording system for high density recording is proposed.

II. REMANENT MAGNETIZATION IN HIGH DENSITY RECORDING

2.1. Vector Magnetization Distribution in Medium Cross Section

The recording field for a ring-type head is a vector field whose equi-field strength points lie on a semi-circle with center at the middle point of the head gap. Hence the magnetic recording process for the ring-type head should be analyzed in terms of the vector fields and magnetization. But the difficulties in theoretical treatment have forced the recording and reproducing processes to be mostly interpreted in terms of a scalar magnetization.

Recently, however, it has been pointed out that the reproduced voltage in high density recording is strongly affected by the vectorial property of the magnetization on the medium,[1,4] and that the recording and reproducing processes must be analized based on a true self-consistent magnetization ("true" in a sense not of a scalar quantity).

To obtain vector magnetization distribution in the medium, the following methods have been reported:

(i) Scaled-up model experiments for a head and tape system.[5,6]
(ii) Iterative calculation of vector magnetization.[7,8]

In these methods, magnetization distribution is indirectly obtained and a large number of experiments or calculations are necessary to obtain magnetization distribution for short wavelength recording where recording demagnetization is severe.

The author and his co-workers have recently reported a new experimental method, by which a vector magnetization distribution is directly observed in the cross section of the actual magnetic tape using Bitter patterns.[1,9] In the method, magnetic colloids of Fe_3O_4 or MnZn ferrite powder (100-200 A in size) are dropped upon the cross section of the recorded tape, cut along the longitudinal direction in the middle of the track. By attaching an additional Mylar film on the surface of the magnetic medium, a simultaneous observation is possible for the flux in the cross section and for the external flux. Although the Bitter pattern obtained by the method is not adequate to measure quantitatively the intensity of magnetization, it is highly effective in understanding the macroscopic features of a vector magnetization in the actural tape.

Figure 1 shows examples of the Bitter patterns obtained for γ-Fe_2O_3 tape and their recording conditions are as follows.

(a) No-bias recording at the maximum reproduced voltage at λ=12μm.
(b) AC-bias recording with the optimum bias current at a signal current slightly exceeding one that gives the maximum reproduced voltage at λ=30μm. And
(c) NRZ recording with twelve consecutive flux reverals (bit interval being 4.75μm), at a saturation current for the first and last bits.

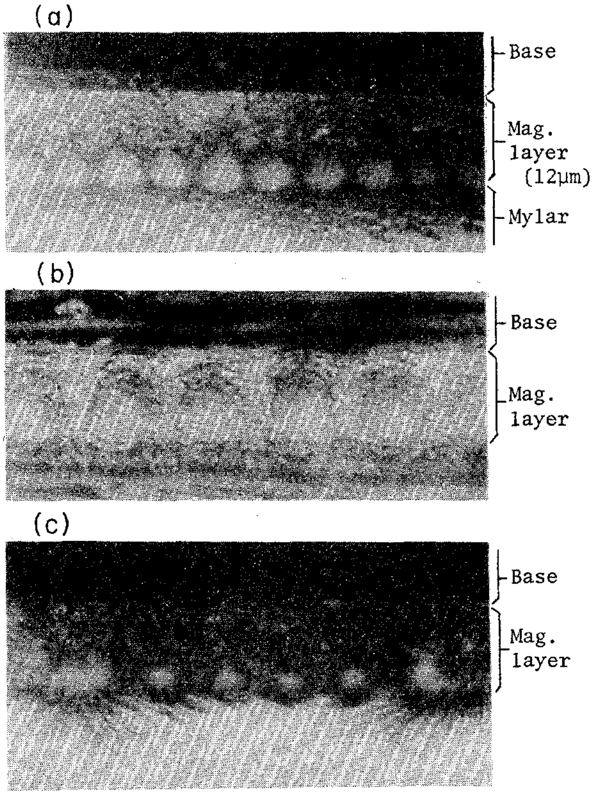

Fig.1 Bitter patterns of (a) no bias, (b) AC bias and (c) NRZ recording (12 bits).

In the Bitter method, the colloidal magnetic particles are adsorbed on the tape cross section by the forces due to the surface charge, σ, and volume charge, ρ, (=-div M). The adsorption is summarized as follows.[9]

(i) The colloidal particles are selectively adsorbed to the area where σ or ρ exists in the medium. The attractive force is given by $\kappa H_z(\partial H_z/\partial_z)$, where the z axis is a normal to the cross section, H_z the normal component of a magnetic field produced by σ and ρ, and κ the constant determined by the volume and permeability of the colloidal particles.

(ii) The calculation shows that the Bitter pattern of the cross section is symmetric for the internal and external of the medium when σ exists alone, but asymmetric when ρ coexists with σ. Therefore the asymmetric pattern corresponds to the state that the medium is vectorially magnetized.

(iii) No distinct Bitter pattern is observable when the complete circular magnetization mode is established in the recording medium (corresponding to a dip point[1,7]), since the mode is divergence free.

Based on the above statements, the Bitter patterns in Fig.1 may be interpreted as follows.

(A) Sinusoidal recording at short wavelength

It is estimated from Fig.1(a) that in short wavelengths ($\lambda/2<\delta$), σ and ρ coexist and the medium is vectorially magnetized. For no bias recording, the surface layer of the medium is assumed to be most strongly magnetized. Since the area where the colloidal particles are adsorbed corresponds to the magnetized area, it is seen from the figure that at the maximum reproduced voltage, the depth of magnetization, or the effective thickness of magnetized layer, δ_e, is given by

$$\delta_e \simeq \lambda/4.$$

This result agrees with Middleton's analysis for the optimum output in short wavelengths.[4]

The effect of AC bias field is, on the other hand, to improve the linearity between the signal field and remanent magnetization in the medium and to increase δ_e as well. This effect is clearly observed in Fig.1(b); the contour line of the Bitter pattern, which represents the thickness of an adsorbed particle layer, changes at a gradual interval and the medium is magnetized to almost full thickness.

It is also observed in the figure that an incomplete circular magnetization mode exists around the middle layer, and that a part of residual flux makes a closed path inside the medium. This part of the flux does not contribute to reproduced voltage, hence the generation of such a flux closure decreases the reproduced voltage. This is an interpretation of the recording demagnetization in short wavelengths. As reported, the formation of a complete circular mode brings about a "dip phenomena" in the reproduced voltage.[1]

(B) High density digital recording

It is observed in Fig.1(c) that, for NRZ high density recording of a train of a finite number of bits, vector magnetization appears near the medium surface for the middle bits.

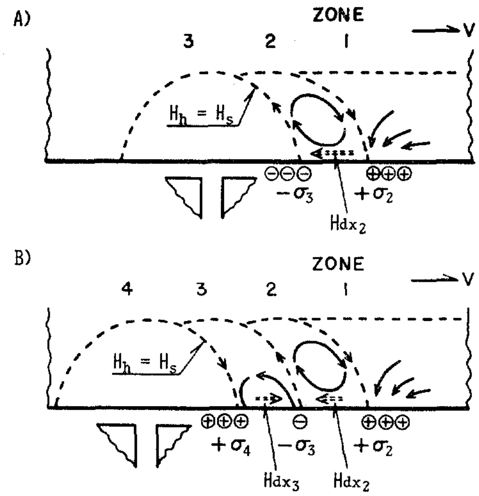

Fig.2 Recording process at the times of A) 2nd bit and B) 3rd bit are applied.

Figure 2 shows a model in the recording process for a train of a finite number of bits, based on the distribution of σ.[12] In the figure the broken lines represent the vector head field lines equal to the saturation field H_s of the medium. In Fig.A), the zone 1 is a saturated region, and the first bit reverses the magnetization in the zone 2 and produces a strong surface charge $+\sigma_2$. The subsequent reversal by the second bit causes another surface charge $-\sigma_3$ to appear in the zone 3. This demagnetizing field in the x direction is, as reported already,[1] the very origin to form a circular magnetization mode, as shown by the solid line in the zone 2. In Fig.B), the longitudinal component of the demagnetizing field Hdx_3 in the zone 3, produced by the third bit, is very weak (since σ_4 is same polarity with σ_2 and $\sigma_3 \ll \sigma_2$), leaving the magnetization structure open but shrinked. It is conslusively assumed that for the NRZ high density recording of a finite number of bits, complete and incomplete circular modes appear alternately, and decrease the surface magnetic charges for the middle bits.[10]

The flux closure observed in Fig.1(c) results from the fact that, for an even number of bits, the external field produced by the strong charges due to the first and last bits enhances the field of the same polarity for the middle bits.

In high density recording, it is safe to conclude that the decrease in the reproduced voltage, and hence the limit of recording density, is brought about mainly by the rotation of magnetization vectors and the decrease in the effective thickness of magnetized layer, as described above.

Possible techniques to prevent the rotation of magnetic vectors are to nullify the M_y component by making the medium thinner or to magnetize only the surface layer of the medium. But for these techniques, there is a practical limit imposed by S/N, as discussed in Section 1.

2.2. Transformation of Magnetization Mode

The rotation of magnetic vector, and hence the recording demagnetization, is obviously influenced by both the field of a ring-type head and the demagnetizing field related to the recorded wavelength λ and the medium thickness δ.[1] This means that a further decrease in the medium thickness causes the same phenomena to occur only at a shorter wavelength, with the difficulties in high density recording remaining unchanged.

For a future high density recording system, therefore, it is worth-while to investigate a detection technique of such a circular mode. The author et al. have found that the following transformation of magnetization is very effective.[1,10]

Figure 3 shows the transformation method: Applying a static field H_{dc} to the medium, on which a circular magnetization mode (broken line) has been recorded, at an angle slightly tilted from the normal plane, the magnetization can be transformed to an almost unidirectional perpendicular magnetization as shown by solid lines and can be reproduced by a ring-type head.

Figure 4 shows the result after the mode transformation technique is applied to the NRZ recording of a finite number of bits. Figure 4(a) is the reproduced waveform obtained at the same recording conditions as that for Fig.1(c), showing the significant decrease of the reproduced voltage for the middle bits which are in the circular magnetization mode. Figures 4(b)-(d) illustrate the recovery of the reproduced voltage for the middle bits by the mode transformation. These figures also show the decrease in the amplitude for the first and last pulses and in the interval between them. Figure 5 shows the peak shift improved by the mode transformation.[10]

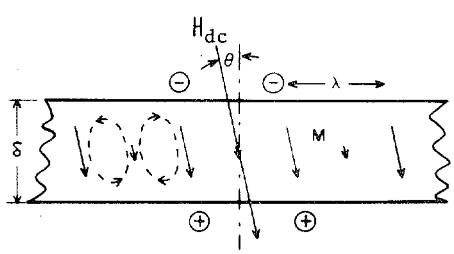

Fig.3 Method of mode transformation.

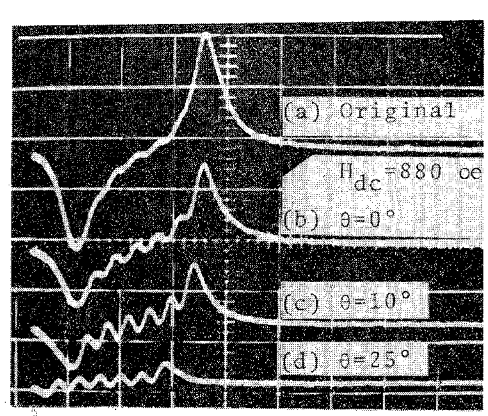

Fig.4 Effect of magnetization mode transformation. (bit length 4.75μm)

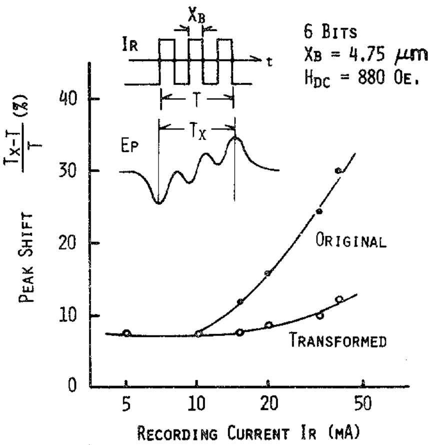

Fig.5 Change of peak shift after H_{dc} was applied.

By the mode transformation technique, the equalization of the pulse amplitude and the minimization of the peak shift are possible. The two effects are very important for high density recording.

The reproduced voltage for the middle pulses recovers most significantly at around $\theta \approx 10°$. The fact is believed to be based on the spacial gradient of the equifield lines (vector) near the trailing edge of the ring-type head.

The results of Figs.4 and 5 are very important in two points: First, it proposes one of the detection methods of the circular magnetization mode, and secondly, it shows that, even for an oriented γ-Fe_2O_3 tape, a perpendicular magnetization can effectively exist in high density recording.

III. REMANENT MAGNETIZATION MODES USABLE MAGNETIC RECORDING

It follows from the discussion in the previous section that, adding to the conventional longitudinal mode, the utilization of the perpendicular and circular modes can not be ignored especially in high density recording.

In Fig.6 the features of these fundamental remanent magnetization modes are summarized.

(a) is for the longitudinal mode, mostly used at present, featuring that the demagnetizing field, H_d, increases and approaches to the maximum value of $4\pi M$ with shortening recorded wavelength λ. Therefore the medium must be thin and have a high coercivity, but as mentioned in Sec.2, H_d always constitutes an obstacle in attaining higher density.

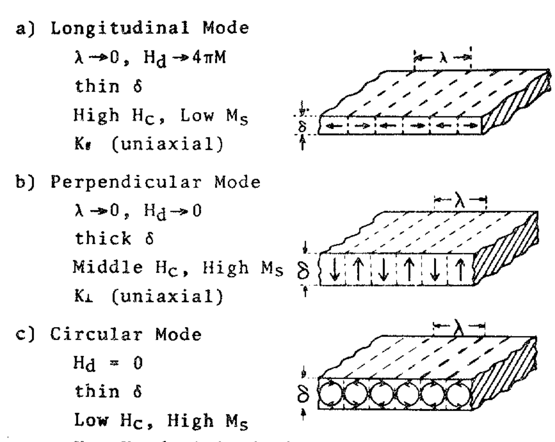

Fig.6 Features of fundamental magnetization modes.

(b) is for the perpendicular mode, whose basic feature is that H_d decreases to zero with shortening λ. Fundamentally, therefore, a thinner medium is not necessary for high density recording, and a significant improvement can be expected for the S/N of reproduced voltage by increasing remanent magnetic moment per bit (remanent magnetization × volume of magnetized region/bit). But some developments, which may greatly change the conventional magnetic recording system, must be made; such as recording medium with magnetic easy axis perpendicular to the medium plane ($K\perp$) and magnetic heads that produce highly pure perpendicular field.

(c) is for the circular mode, which has the greatest feature that H_d is basically zero. This fact is extremely attractive, since magnetic recording will be free from demagnetization, which is unavoidable at present; hence as in magnetic cores, the maximum remanent magnetization and little inter-bit interaction will be realized. To this end, however, recording medium and reproducing technique must be fundamentally altered. The mode is noteworthy from the viewpoint of increasing volume density in future.

The common advantage for (b) and (c) lies in the fact that H_d does not constitute an obstacle in attaining high density recording.

Incidentally a horseshoe-type magnetization mode, which has long been used as a permanent magnet, is usable in high density recording. The mode is understood to lie between (a) and (b). But the magnetization mode in the direction of the track width is excluded from the discussion, since it will contradict the future trend of increasing track density.

IV. PERPENDICULAR MAGNETIC RECORDING SYSTEM

4.1. Fundamental Features of Perpendicular Recording

Between (b) and (c) of Fig.6, the most realizable system at present will be the former. The authors have investigated how to realize it. The following is its outline.

It is demagnetization that determines a recording wavelength at which the perpendicular component, M_y, of the remanent magnetization in the medium surpasses the longitudinal component, M_x. If the medium is sinusoidally magnetized, uniformely through the thickness and over an infinit track width, the static demagnetizing factors $N_{\parallel}$ and $N_{\perp}$, for the longitudinal and perpendicular magnetization, respectively, are given by,[11]

$$N_{\parallel}=4\pi\{1-(\lambda/2\pi\delta)(1-e^{-2\pi\delta/\lambda})\}$$
$$N_{\perp}=4\pi-N_{\parallel} \tag{1}$$

where λ is recorded wavelength. If $\lambda/\delta<4$, then $N_{\parallel}>N_{\perp}$, hence the perpendicular recording being advantageous. The dynamic demagnetization[7] will give much longer crossover wavelength. In digital recording, the difference of the demagnetizing field is more noticeable between the perpendicular and longitudinal magnetization mode. Assuming an isolated transition of the perpendicular magnetization, M_r in magnitude, the perpendicular demagnetizing field in the medium is given by Eq.2, in the coordinate system shown in the insert of Fig.7.

$$H_y=4M_r\{\tan^{-1}\frac{x}{y-\delta/2}-\tan^{-1}\frac{x}{y+\delta/2}\} \tag{2}$$

The result is depicted in Fig.7 by solid lines. In this case, H_d approaches to zero near the transition, hence it does not widen the transition region, nor increase peak shift, as in the longitudinal mode. Furthermore, the interaction between adjacent bits acts so as to decrease H_d, as the bit interval becomes shorter.

This fact means that, compared with the longitudinal mode, the perpendicular mode has magnetization structure essensially suitable for high density recording.

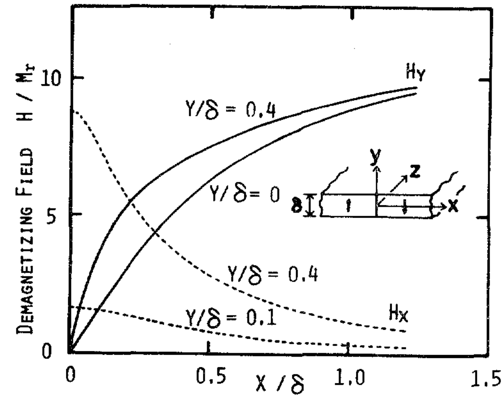

Fig.7 Demagnetizing field by an isolated transition of M_y.

4.2. Magnetic Heads for Perpendicular Recording

Magnetic heads for perpendicular recording must be able to produce a field whose perpendicular component has an intensive but sharp distribution. In the evolution of magnetic heads, a perpendicular head, one as shown in Fig.8(a) or one in a single pole-type, was once considered in 1920's. With this type of head, however, it is very hard to produce a field precisely in the perpendicular direction by adjusting the axes and magnetic properties of both poles. Furthermore, the fact should be noted that in those years, a magnetic film did not exist which could be magnetized perpendicularly to the film plane. From these reasons, the head of type (a) is imagined to be abandoned only with the conception.

On the other hand, for the head of type (b), which appeared in almost same years, the idea of using a longitudinal magnetization mode was introduced. Comparing with the type (a), the head of type (b) is imagined to have produced far large output voltage for a long wavelength signal. At the same time, the conception led to the invention of a ring-type head (c) in 1935.

The head of type (d), proposed by the authors, is a perpendicular type head, which has an asymmetric structure compared with the type (a), with the main pole of a magnetic thin film in contact with the recording medium to record signals. The other pole, an auxiliary pole, is very large in size compared with the main pole, and positioned on the other side of the recording medium at a sufficient distance. In this structure, the perpendicular field, similar to that of the single pole-type head, can always be applied to the medium, with no factor to tilt the field from the normal of the medium. Hence the head is called a single pole-type head (abbr. a SPT head).

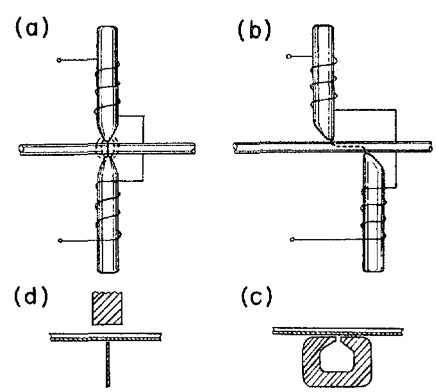

Fig.8 Evolution of magnetic heads (a,b,c) and perpendicular head(d).

For the SPT head, if the auxiliary pole is energized by a winding around it, the main pole is magnetized from its pole tip, therefore the recording is possible by a relatively small MMF.[11]

The perpendicular field near the main pole is approximately given by Eq.3, choosing the origin of the coordinates at the center of the main pole surface.

$$H_y = h + 2M\left\{\tan^{-1}\frac{x-t/2}{y} - \tan^{-1}\frac{x+t/2}{y}\right\} \qquad (3a)$$

$$M = \kappa h \qquad (3b)$$

where t is the effective thickness and κ the susceptibility of the main pole, and the thickness of the auxiliary pole is assumed to be infinite. The first term, h, in Eq.3a is the weak perpendicular field at the place of the main pole, which is produced by the auxiliary pole and almost constant in the x direction; the second term is the strong field produced by the main pole, which is magnetized by h.

The SPT head has a feature that it can produce H_y with the same distribution function, given by Eq.3a, over a large range of intensity. If the main pole is directly energized by winding a coil around it, a strong field cannot be produced, since magnetic saturation occurs at the thin film yoke beneath the coil.[11] The head also has a practical merit that the wear of the main pole does not influence the field distribution and that the auxiliary pole can be placed apart from the recording medium.

4.3. Perpendicular Anisotropy Film

As for the films which have an easy axis of magnetization perpendicular to the film surface, many materials have recently been reported for use in magnetic bubble devices. The films for magnetic recording must have different properties from those of the bubble materials; a strong adhesion of the magnetic layer to the base material, a high producibility, especially in mass production, and M_s as high as possible and H_c high enough to support high magnetization (especially needed at low densities). Taking into account these properties, the author et al. have prepared Co-Cr perpendicular anisotropy films.[12]

Co has a large manetocrystalline anisotropy energy, hence it may be used to develop perpendicular anisotropy films. To develop the films in a relatively thin thickness, the anisotropy field H_k must satisfy the relation

$$H_k > 4\pi M_s, \quad \text{or } K_u > 2\pi M_s^2 \qquad (4)$$

where K_u is a magnetocrystalline anisotropy constant. Therefore, it is effective to add Cr to Co so as to reduce M_s, keeping the C-axis oriented perpendicular to the film surface.[11]

To prepare the films, a RF sputtering was employed, which is superior to other methods in the reproducibility and adhesion of the film. A Polyimide film was used as base materials.

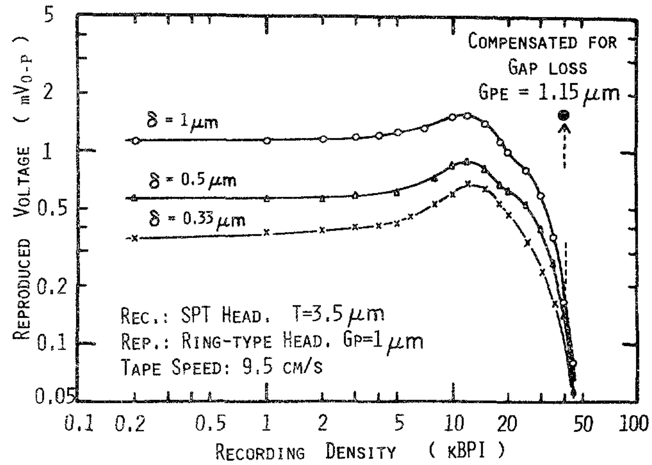

Fig.11 Reproduced voltage vs. bit density characteristics. (cf. Output voltage of a γ-Fe_2O_3 tape (thickness-12μm) is 2V at 200 BPI by use of ring-type record head.)

M_s of Co-Cr sputtered films decreases lineary with increasing content of Cr, almost in accordance with the tendency of bulk. The X-ray diffraction pattern shows only a (002) line of a h.c.p. structure, assuring the *C-plane is parallel to the film plane.* It has been also ascertained that Co and Cr are deposited in the state of solid solution. Fig.9 shows M-H loops of the Co-Cr sputtered film measured parallel(//) and perpendicular ($\perp$) to the film surface. No compensation for demagnetization is made to the perpendicular M-H loop. The results shows that the film has an easy axis perpendicular to the film surface. The films which have M_s=200-300 Gauss are generally suitable for use in the perpendicular magnetic recording.

4.4. Recording Characteristics

Figure 10 is a Bitter pattern which shows a transition sturcture in the perpendicular recording. The stand-still recording was made on a Co-Cr film by the main pole (about 3.5μm in thickness) which is in contact with the film and magnetized by the auxiliary pole exitation. In this case, colloidal particles are adsorbed to the point where the field gradient, due to surface charges on the Co-Cr film, is maximum. In the Bitter pattern, no zig-zag wall structure[3] is observed around the transition region, and a very narrow transition width can be realized.

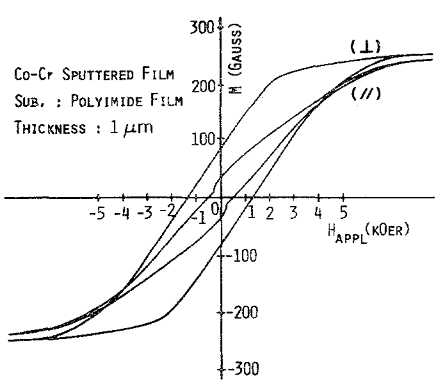

Fig.9 Hysteresis loops of Co-Cr film.

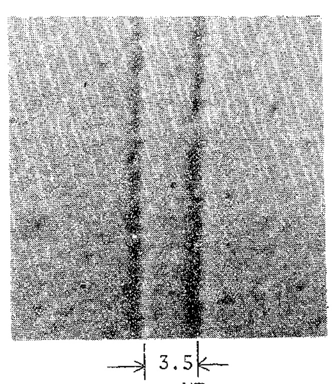

Fig.10 Bitter pattern of stand-still recording.

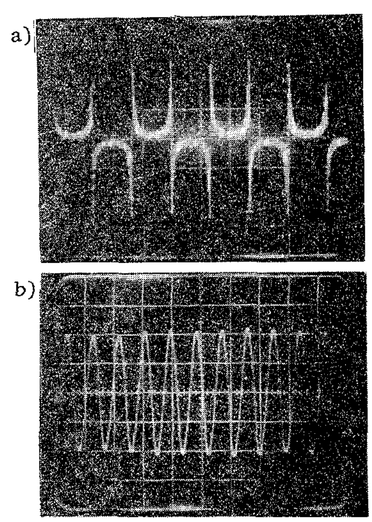

Fig.12 Reproduced waveform for signals of a) 200 BPI and b) 30,000 BPI.

Figure 11 shows the reproduced voltage vs. recording density characteristics in digital recording with the thickness of Co-Cr films as a parameter. The recording condition is same as in Fig.10 except that the film is moving. In the figure the Maximum recording density more than 30,000 BPI (D_{50}) is realized in a relatively thick film. In the experiment, the reproduction was made with a ring-type head (G_p=1μm). The point marked by the symbol ◎ in the figure shows the predicted output increase after the gap loss is compensated for G_{pe}=1.15μm. In Fig.12 reproduced waveforms are shown for low (200 BPI) and high density recording (30,000 BPI)(G_p=0.5μm). The reproduced waveform in low density is quite different from the conventional one, but it is readily interpreted by reciprocity theorem using the head field function for a ring-type head.[11]

The following facts may be deduced from the experimental result shown in Fig.11.

(i) The reproduced voltage increases significantly in high densities, and the gap-loss compensated result predicts that the remanent magnetization is not demagnetized even in high densities. It will increase theoretically.

(ii) If all the thickness of the film is magnetized in the perpendicular direction, a high density recording is possible even for a thick film. This fact means that the effects of M, H_c and δ of the film on recording density obey the principle of the perpendicular mode as shown in Fig.6(b).

These results are the fundamental preperties of the perpendicular recording and never acquired by the longitudinal recording.

The advantage of the perpendicular recording in high densities may also be understood by the comparison of a remanent magnetic moment $\mathcal{M}$. As for the recording by a ring-type head, for example, Fig.1(a) represents the recording density of about 5,000 BPI and its remanent magnetic moment $\mathcal{M}(\approx H_c \cdot \delta_e \cdot \lambda/2)$ for γ-Fe_2O_3 tape per unit track width (1cm) is about 3×10^{-5}emu/bit. If the recording at 20,000 BPI is done on a metallic film (H_c=1,000 Oer, δ=500 A), $\mathcal{M}$ reduces to about 6×10^{-7}emu/bit, assuming the longitudinal magnetization as shown in Fig.6(a). If the same density is, on the contrary, recorded in the perpendicular magnetization as shown in Fig.6(b), using a 1μm-thick Co-Cr film, $\mathcal{M}$ can be increased up to about 3×10^{-5}emu/bit. Such an increase in remanent magnetic moment will be effective in increasing recording density and reducing noises.

V. CONCLUSION

Analyzing the self-consistent magnetization of the recording medium, this paper describes that the present recording system with a ring-type head is not the best system in attaining a high storage density. Then, the perpendicular recording system is proposed, in which the demagnetization effect is essentially small in high densities. As for perpendicular type magnetic heads, a few analyses have been reported so far,[14,15] but no one has yet succeeded in the experiment of high density recording with the heads. The suthors have carried out the fundamental experiment by conbining perpendicular anisotropy films with magnetic heads which produce the perpendicular field, and ascertained that the perpendicular recording system exhibits a strikingly superior response in high densities.

The perpendicular recording has the magnetization mode that can increase essentially the remanent magnetic moment of signals in high densities, and is believed to give an important break-through in improving the present magnetic recording technique. The fact that, in the perpendicular recording, the restriction of demagnetization on recording densities is exceptionally small will influence greatly the development of recording medium and recording theory as well. And a number of magnetic heads in practical structure will be considered. They are important themes in magnetic recording to be studied from now on.

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