71. *Magnetic Recording by Perpendicular Magnetization Mode*

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1. Introduction. To realize a high density recording in the present longitudinal magnetic recording system using a ring type magnetic head, it is especially needed to make the recording medium thin and highly coercive. In the recent magnetic disks used in a computer memory, 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 $0.05\ \mu\text{m}$ is experimented. The necessity of such an extremely thin medium, and at the same time, of high coercivity may also be deduced by the analysis of demagnetization mechanism in recording process.¹⁾ However, if a future system is pursued in the same manner, the practical limits will be reached as a result of decrease in remanent magnetic moment of a recorded signal.

From above viewpoint, we have recently proposed a new perpendicular recording system, and confirmed that an extremely high recording density of 100,000 bits/inch can be realized by using a new type magnetic head and recording medium. In this paper the basic concept and the properties of a new perpendicular recording system are presented.

2. Remanent magnetization in recording medium. 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 of medium by a ring-type head should be analyzed in terms of the vector fields and magnetization.^{2),3)} The analysis has not been accomplished because of the difficulty in treating the vector quantities in nonlinear magnetization.

The author has recently found that a vector magnetization can be directly observed in the cross section of the actual magnetic tape using Bitter patterns.⁴⁾ In the method, magnetic colloids of Fe_3O_4 or or MnZn ferrite powder (100–200 Å in size) are dropped upon the cross section of the recorded tape, cut along the longitudinal direction in the middle of the track. Fig. 1 shows example of the Bitter pattern obtained for $\gamma\text{-Fe}_2\text{O}_3$ tape recorded by ac biased sinusoidal signal at $\lambda=30\ \mu\text{m}$. (λ : recorded wavelength). In the Bitter method, the col-

Fig. 1. Bitter pattern in cross section.

Fig. 2 (left). Method of mode transformation.

Fig. 3 (right). Effect of mode transformation.

loidal magnetic particles are adsorbed on the tape cross section by the forces due to the surface charge, σ and volume charge, ρ ($= -\text{div } M$) of recorded signal. It is estimated from Fig. 1 that in short wavelengths, σ and ρ coexist and the medium is vectorially magnetized.⁵⁾ It is also observed that a part of residual flux makes a closed path around the middle layer of the medium. This part of the flux does not contribute to reproduced voltage, hence the generation of such a flux closure (we named a circular mode) decreases the reproduced voltage.

The origin of the circular mode is obviously influenced by both the field of a ring-type head and the demagnetizing field.⁴⁾ For a future high density recording system, therefore, it is worth-while to investigate a detection technique of such a circular mode. The author has found that the following transformation of magnetization is very effective.⁴⁾ Fig. 2 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 a perpendicular magnetization as shown by solid lines and can be reproduced

Fig. 4. Properties of magnetization mode.

by a conventional ring-type head. Fig. 3 shows the result after a static field H_{dc} is applied to digital recording of 12 bits signal. Fig. 3(a) is the reproduced voltage for the middle bits which are in the circular magnetization mode. Figs. 3, (b)–(d) illustrate the recovery of the reproduced voltage for the middle bits by the mode transformation. The result of Fig. 3 is very important in two points: First, it proposes one of the detection methods of the circular magnetization mode, and secondly, it shows that, a perpendicular magnetization can effectively exist in high density recording.

3. Perpendicular recording system. 1) *Properties of perpendicular magnetization mode.* It follows from the discussion in the previous section that, adding to the conventional longitudinal mode, the utilization of the perpendicular mode can not be ignored in high density recording. In Fig. 4 the features of both fundamental remanent magnetization modes are summarized.⁵⁾ (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.^{1), 3)} (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 significant improvement can be expected for the S/N of reproduced voltage by increasing remanent magnetic moment per unit signal. But some developments must be made; such as recording medium with magnetic easy axis perpendicular to the medium plane (K_1) and magnetic heads that produce highly pure perpendicular field.

The problem is, therefore, how to realize magnetic heads and medium which make such magnetization possible.

2) *Magnetic head and medium for perpendicular recording.* Perpendicular magnetic head must be able to produce a field whose

Fig. 5 (left). Structure and line of force in perpendicular head (model).
 Fig. 6 (right). Hysteresis loops of Co-Cr films.

perpendicular component has an intensive but sharp distribution. In the evolution of magnetic heads, a perpendicular head of a symmetric dipole 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.^{5),6)} The head of Fig. 5, proposed by the authors, is a perpendicular type head which has an asymmetric structure with the main pole of a magnetic thin film in contact with the recording medium to record signals. An auxiliary pole with the winding, is very large in size compared with the main pole, and positioned on the other side to the recording medium at a sufficient distance. In this structure, the perpendicular field H_y near the main pole is approximately given by Eq. 1, choosing the origin of the coordinates at the center of the main pole surface.⁵⁾

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

where t is the thickness and M magnetization of the main pole. The first term, h , in Eq. 1 is the field at the place of the main pole, which is produced by an auxiliary pole; the second term is the field produced by the main pole, which is magnetized by h .

The head has a feature that it can produce H_y with the sharp distribution function, given by Eq. 1, over a large range of intensity.⁷⁾

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 recording medium must have different properties from those of the bubble materials; a strong adhesion of the magnetic layer to the base material, a high

Fig. 7 (left). Reproduced voltage vs. bit density characteristics.

Fig. 8 (right). Bitter pattern at surface (1 $\mu\text{m}/\text{div}$).

producibility, especially in mass production, and M_s as high as possible. Taking into account these properties, we have prepared Co-Cr perpendicular anisotropy films by a RF sputtering.^(6),8) Co has a large magneto-crystalline 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

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

where K_u is a magneto-crystalline 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.

Fig. 6 shows M-H loops of the Co-Cr sputtered film measured parallel ($\cdots$) and perpendicular ($—$) to the film surface. No compensation for demagnetization is made to the perpendicular M-H loop. The result shows that the film has an easy axis perpendicular to the film surface.

3) *Perpendicular recording characteristics.* Fig. 7 shows the reproduced voltage vs. recording density characteristics in digital recording with the thickness of Co-Cr films as a parameter. The recording was made on a Co-Cr film by the main pole (about 3.5 μm in thickness) which is contact with the film. The reproduction was made with a ring-type head with narrow gap length ($Gp=1 \mu\text{m}$). The dotted line in the figure shows the predicted output increase after the gap loss in reproducing process is compensated.

From Fig. 7, the following facts may be deduced: (1) The reproduced voltage increases in high densities, and the gap-loss compensated result predicts that the remanent magnetization is not

demagnetized even in high densities.

(2) If all the thickness of the recording medium is magnetized in the perpendicular direction, a high density recording is possible even for a thick medium. These results are the fundamental properties of the perpendicular recording and never acquired by the present longitudinal recording.

Fig. 8 shows the recorded signal at the density of 100,000 bits/inch observed by Bitter method. Since direct observation is difficult at a very high density, the Bitter pattern was made by applying a perpendicular field H_{dc} to the film after recording. Although the spacing of stripes obtained by the method is two times as large as the actually recorded signal,⁸⁾ we can confirm that the high density recording of 100,000 bits/inch is possible on a relatively thick medium. (The present density used in computer disk file is 6,300 bits/inch.)

4. Conclusion. As for perpendicular type magnetic heads, a few analyses have been reported so far⁹⁾ but no one has yet succeeded in the experiment of high density recording with the heads. The authors have carried out the fundamental experiment by combining 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 density recording. The perpendicular recording has the magnetization mode that can increase essentially the remanent magnetic moment of signals in high density recording, and is believed to give an important break-through in improving the present magnetic recordings technique.

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