PERPENDICULAR MAGNETIC RECORDING

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ABSTRACT

This paper describes the recent studies for the magnetic head, the medium and the recording properties on a new perpendicular magnetic recording system. The complemental features between the perpendicular and the longitudinal recording are discussed to establish an efficient magnetic recording system. Superior response in the amplitude and the peak shift characteristics for a digital signal proves that the perpendicular magnetization mode is basically free from the recording demagnetization in high densities and the maximum density has been limited merely by the resolution of the reproducing head. Significant improvement for the recording and the reproducing sensitivities of a perpendicular head has been made by using a composite anisotropy medium composed by double layers of Fe-Ni and Co-Cr thin films.

1. INTRODUCTION

The present magnetic recording system with a ring-type head fundamentally uses the longitudinal magnetization mode in the recording medium. To realize a high density recording in the system, it is especially needed to make the recording medium thin and highly coercive. In the recent magnetic disk used in computer memory, the recording medium has been reduced in thickness at a high pace, to such points that the coated γ-Fe_2O_3 film of thickness less than 1 μm is used and the Co-system metal film less than 0.05 μm is experimented. The necessity of such an extremely thin medium, and at the same time, of high coercivity may be deduced by the analysis of the demagnetization mechanism in the longitudinal recording process.[1,2,3] However, if a future system is pursued in the same manner, the practical limit will be reached as a result of the decrease in the remanent magnetic moment of a recorded signal.

From the above view point, we have recently proposed a new perpendicular recording system and confirmed that an extremely high density recording 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 magnetic recording are presented. The complemental features for the perpendicular and the longitudinal magnetization modes are also discussed to realize an efficient magnetic recording system.

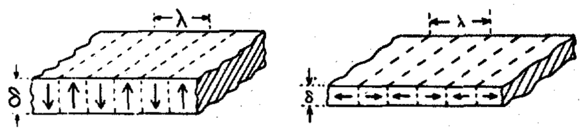
2. COMPLEMENTAL PROPERTIES OF THE MAGNETIZATION MODES

In Fig. 1 the complemental features in the magnetic recording using the perpendicular and the longitudinal magnetization modes are summarized.

The basic feature of the perpendicular magnetization is that the demagnetizing field H_d in the recording medium decreases to zero with shortening of the recorded wavelength λ.[3] Furthermore, for NRZI digital signals, the demagnetizing field H_d always approaches to zero at the center of the transition region of magnetization in the medium.[3] The fact leads to the conclusion theoretically that, in perpendicular magnetization mode, the ideal step change magnetization for the NRZI signal can be obtained. In practice, it is expected that the length of the magnetization transition region can be decreased to the value as the same order with the size of the grain or the crystalline structure of the medium. Therefore, perpendicular recording has the magnetization mode essentially suitable for the digital recording.

On the contrary, the longitudinal magnetization mode used at present has the feature that H_d increases and apporaches to the maximum value of $4\pi M$ with shortening λ.[3] The result corresponds to that, in digital recording, H_d reaches its maximum near the transition and does widen the transition region or increase the peak shift of the recorded pattern in the medium. Consequently, the magnetization distribution changes gradually near the transition region as has been shown by the iterative calculation.[2] Therefore, it is supposed that the longitudinal magnetization mode is suitable inherently for the recording of an analog signal. The magnetic properties desired in the perpendicular and the longitudinal recording are reflected from above-mentioned demagnetization mechanism in both magnetization modes. From the above view points, it is safe to conclude that the both magnetization modes have a complemental feature to establish an efficient magnetic recording system.

	a) Perp. Mode	b) Longi. Mode



	$\lambda \to 0$ $H_d \to 0$	$\lambda \to 0$ $H_d \to 4\pi M$
Head	Single pole-type	Dipole (ring)-type
Medium	Perp. Anisotropy Thick δ High Ms, High Hc	Longi. Anisotropy Thin δ Low Ms, High Hc
Signal	Digital (Sat.)	Analog (non-Sat.)
Rec. Method	Modulation (FM, PCM)	AC Bias Method
Erase	DC Field	AC Field

Fig. 1 Complemental features of perpendicular and longitudinal magnetization mode.

The similar interpretation can be given in the recording method for both magnetization modes. The AC bias method in the longitudinal recording has been established certainly on the fact that the recording due to the AC bias field alone is not possible, since severe recording demagnetization appears in the recording process.

On the contrary, as for the recording process, it is expected that the wavelength response of the perpendicular recording extends markedly in high density region including the wavelength of the AC bias frequency.[3] In perpendicular recording, therefore, the

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application of the modulation techniques (FM, PCM etc.) becomes more effective than AC bias method used in the longitudinal recording. It is expected similarly that the erasing by DC field is preferable than AC field, if the perpendicular-type erasing head is used.

3. PERPENDICULAR MAGNETIC HEAD

Magnetic heads for perpendicular recording must be able to produce a field whose perpendicular component has an intensive but sharp distribution. The head shown in Fig. 2 is a perpendicular type head, proposed by the author et al in 1976.[3,4] The main pole (A) of a permalloy thin film supported by glass (C) contacts perpendicularly with the recording medium to record signals. The other pole, an auxiliary pole (B), 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). 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 EMF.

To investigate the magnetic field distribution around the main pole, a model head was constructed in which the main pole thickness T_m was scaled up to about 10^4 times as much as the practical head.[4]

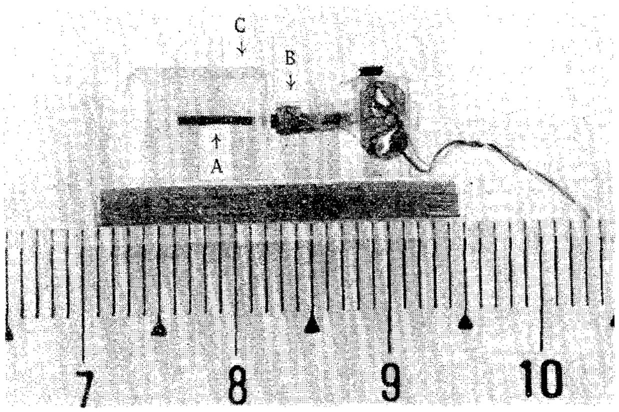

Fig.2 Side view of perpendicular magnetic head (A: Main pole, B: Auxiliary pole and Winding C: Glass holder).

Figure 3 shows the result obtained by the model experiment. The original of the co-ordinate is at the center of the top surface of the main pole. The solid and broken lines represent respectively the perpendicular component H_y and the longitudinal component H_x which are all normalized by the perpendicular field strength at the origin. The perpendicular field H_y around the main pole is consisted by the following two terms.[3] The first term is the 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 field produced by the main pole, which is magnetized by the auxiliary pole field. Consequently, it is expected that the perpendicular field distribution becomes sharp with increasing the permeability of the main pole. The fact was ascertained by the model experiment.[4]

In the perpendicular recording head, however, the interaction between the surface charges of the head and the recording medium cannot be ignored. When the recording medium approaches closely to the main pole, the magnetic field produced by the magnetized medium superposes to the demagnetizing field with opposite polarity in the main pole. Then, the decrease in the demagnetizing field results in the increase in the main pole field.[4]

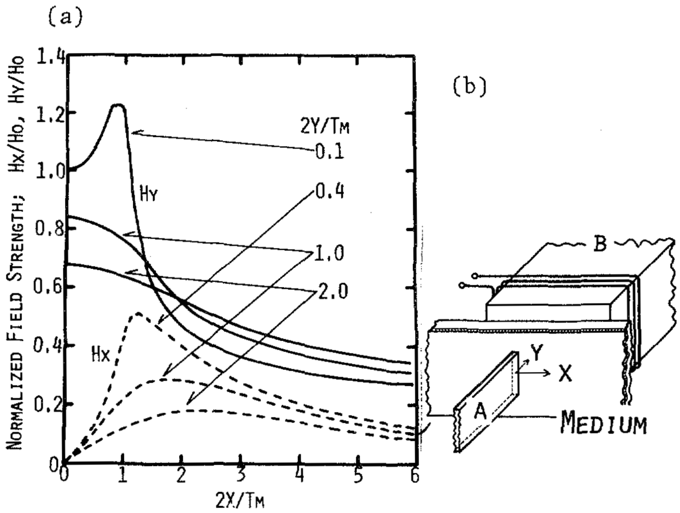

Fig. 3 Magnetic field distrubutions around the main pole (Thickness: Tm) and head construction (over view) (b).

Figure 4 shows the measured distributions of the perpendicular field component in the layer of $y/T_m=0.05$ between the main pole and the medium. The recording medium in the model consists of the pieces of Alnico 5 magnets which are arranged so as to have the easy axis of magnetization in the perpendicular direction of the medium. In this experiment, the spacing between the main pole and the recording medium is 1 mm, the thickness of the medium is 15 mm, and T_m=10 mm. The solid and broken lines in the figure represent the magnetic field distributions normalized by the field strength at the origin in the presence and the absence of the medium, respectively. In the presence of the medium, the magnetic field strength considerably increases and the field distribution becomes very sharp. The result represents also the fact that an intensive and a sharp distribution of the perpendicular magnetization has been realized in the medium. Therefore, the perpendicular head efficiently acts in the very high density region

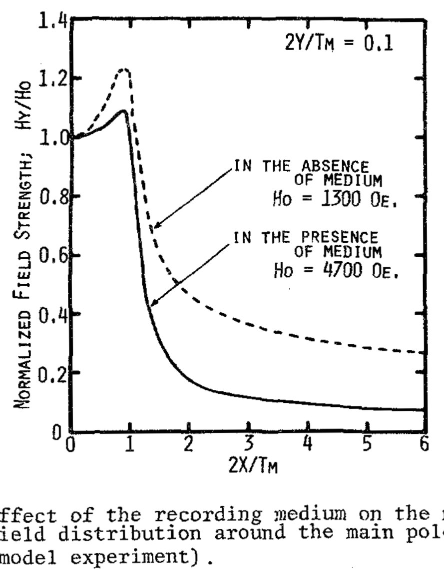

Fig. 4 Effect of the recording medium on the magnetic field distribution around the main pole (model experiment).

and an almost demagnetization-free recording becomes possible.

As has been shown in the figures, the SPT head has a feature that it can produce the perpendicular magnetic field with sharp distribution function over a large range of intensity. 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. 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 beneath the coil.[2]

4. PERPENDICULAR RECORDING MEDIUM

4.1 Uniaxial perpendicular anisotropy medium

For the perpendicular recording medium, the magnetic properties shown in Fig.1, are necessary to obtain a high output voltage and a high recording resolution. Furthermore, the mechanical and the chemical stability of the medium and the mass productivity are also desired. Taking into account these properties, we have prepared the Co-Cr perpendicular anisotropy film.[3,6] Cobalt has a large magneto-crystalline uniaxial anisotropy energy, hence it can be used to develop the perpendicular anisotropy film. The films must have the anisotropy field H_k surpassing the maximum demagnetizing field $4\pi Ms$. Therefore, it is effective to add other metals to reduce Ms, keeping the c-axis oriented perpendicular to the film surface. We have chosen chromium as an additional metal, because the Co-Cr alloy has a relatively stable hcp phase at a lower content of Cr, and at the same time, the saturation magnetization is expected to decrease when the small amount of Cr is added. To prepare the film of Co-Cr alloy, Co and Cr are co-deposited by an RF sputtering on the Polyimide film. RF sputtering was made in the Ar gas atmosphere of 0.01 Torr after the back ground pressure reaches below 2×10^{-7} Torr.[6] The most influential factor on the magnetic properties was found to be Cr content of the film. The saturation magnetization Ms of the film almost linearly decreases with increasing the Cr content.

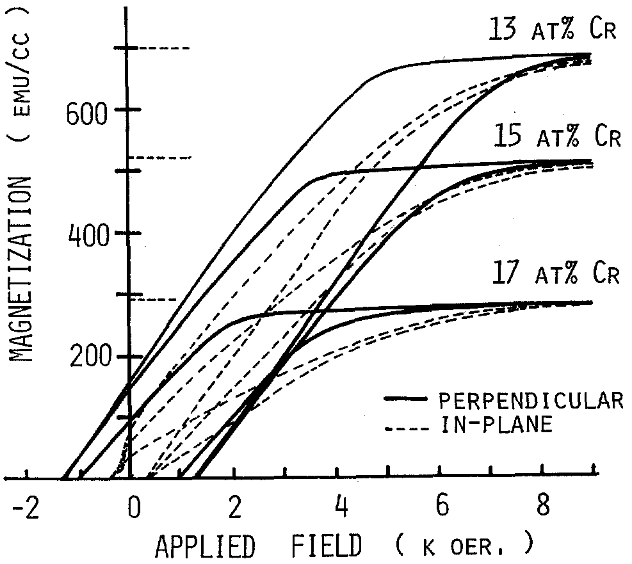

Fig. 5 M-H loops of Co-Cr sputtered films measured by disk samples of 5 mm in diameter (single layer).

Figure 5 shows the M-H loops of the films of different Cr contents, measured parallel(//) and perpendicular(⊥) to the film surface. The measurements were made for disk samples (5mmϕ) of a 0.8 μm-thick film. In the figure, no compensation for demagnetization is made for the perpendicular M-H loops. Therefore, it is supposed that an intrinsic M-H loop(⊥), after compensated for the demagnetization, has a rectangular shape with an almost infinite slope. On the contrary, the M-H loop(//) has a very small hysteresis loss. From the result, it is safe to conclude that the Co-Cr film has an easy axis of magnetization in the normal to the film plane and a hard axis lying in the film plane. The micro-structure of the crystallines of the film was investigated by the transmission electron microscopy as shown by Fig.6.[6]

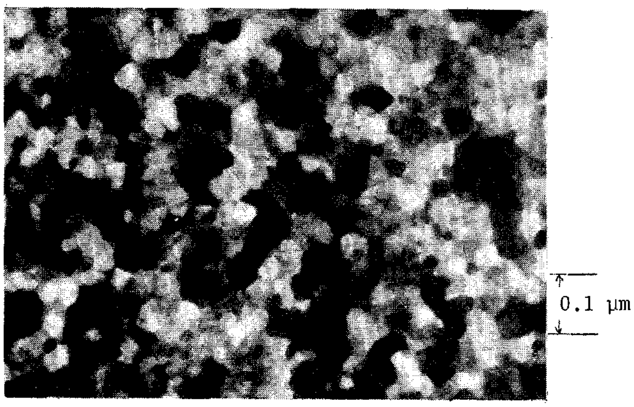

Fig. 6 Transmission image by electron microscopy of Co-Cr film of 0. 34 μm in thickness.

The Co-Cr film has a columnar structure composed of closed packed fine grain, which glow perpendicularly from the surface of the Polyimide film. The column diameter was estimated from the SEM image to be about 0.1 μm for the film of thickness 1.0 μm. The fact agrees very well with the result of transmission electron microscopy. The columnar structure is closely related to the c-axis orientation of hcp structure of the Co-Cr, which is the origin of the perpendicular anisotropy. It was ascertained that, from the X-ray analysis, the Co-Cr film was found to have an exact hcp structure, and no σ phase nor bcc phase of Cr was observed. The lattice constant C is 4.055 Å for the film of 20 at.% Cr, which is slightly smaller than the lattice constant of bulk Co (4.069 Å). As described above, the Co-Cr sputtered film shows some suitable properties for the perpendicular magnetic recording medium, such as the perpendicular anisotropy, the fine grain structure, and the rectangular M-H loop.

4.2 Composite anisotropy medium

The sputtering technique, on the other hand, is applicable to realize the composite anisotropy recording medium,[7] which includes the Co-Cr perpendicular anisotropy film. A composite anisotropy recording medium (double layer) has been developed with the aims of the decrease of the magnetic reluctance of the air gap, and of the increase of the recording sensitivity of the perpendicular head.[7]

Figure 7 shows the effect of the composite anisotropy medium for the flow of the flux in the recording process.[7] M(//) and M(⊥) in the figure represent the thin films of the Fe-Ni and Co-Cr alloys which are deposited successively by an RF Sputtering on the Polyimide film. Since the Fe-Ni film has an easy axis of magnetization in the film plane, a horizontal magnetic path is made for the flux induced by an auxiliary pole. This is in effect equivalent to reducing the magnetic reluctance of the air gap or to increasing the recording sensitivity of the perpendicular head. It is also expected that, from the reciprocity theorem, the reproducing sensitivity of the perpendicular head can be improved by using such recording medium.

Figure 8 shows the cross-sectional view of the composite anisotropy medium which was observed by using the scanning electron microscopy.[7] The specimen was prepared by ripping after dissolving the Polyimide base in hydraziné hydrate. Even for the double layer medium, it is observed that the Co-Cr layer has a columnar structure, which grow perpendicularly from the surface of the Fe-Ni layer. On the other hand, the Fe-Ni layer exhibits no micro-structure suggesting homogeneity in the layer. Therefore, the Co-Cr layer behaves as a perpendicularly magnetizable medium and the Fe-Ni layer acts as a highly permeable back layer to improve the recording sensitivity.

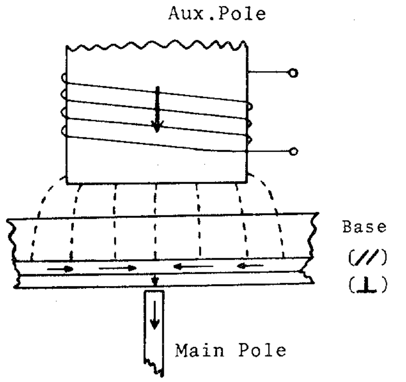

Fig. 7 Flow of flux in double layer medium at recording process.

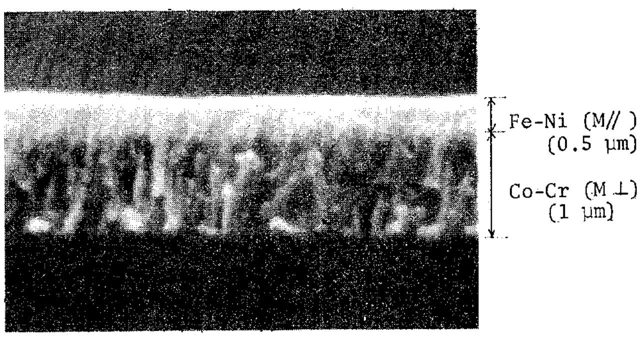

Fig. 8 Cross section of a composite anisotropy recording medium (Polyimide base is excluded by dissolving in hydragine hydrate.).

5. PERPENDICULAR RECORDING CHARACTERISTICS

It was proved experimentally that the fundamental properties of the perpendicular magnetic recording are;[3,9,10]

(i) The reproduced voltage increases significantly in high densities, and the gap-loss compensated result predicts that the remanent magnetization in the recording medium is not demagnetized even in high densities.[3,9]

(ii) If all the thickness of the medium is magnetized in the perpendicular direction, a high density recording is possible even for a thick medium.[3,9]

(iii) The reproduced voltage increases with increasing the coercive force Hc(⊥) and the saturation magnetization Ms of the perpendicular anisotropy medium, but the wavelength response curve scarcely depends on the values of Hc(⊥) and Ms.[10]

The effects of δ, Ms and Hc of the medium in perpendicular recording characteristics are quite contrasted with ordinary longitudinal recording.

The experiment is focusing presently on the investigations for the practical limiting factor of the maximum density of perpendicular recording and for the possibility of the reproduction by the perpendicular head.

5.1 Reproduction by ring-type head

To investigate the limiting factor of the maximum density of the perpendicular recording, the reproduction was made with a high resolution ring-type head having the narrow gap length (Gpe = 0.67 µm). The recording was made with the perpendicular head having the main pole of a Fe-Ni electro-deposited film of 1 µm thick and the auxiliary pole of Mn-Zn ferrite of 0.7 mm thick. As for the recording media, the short sample of the tape and the flexible disk made by composite anisotropy medium (double layer) and the uniaxial perpendicular anisotropy medium (single layer) were used. Both the Co-Cr and Fe-Ni layers of the composite anisotropy medium are 0.5 µm in thickness, and the Co-Cr single layer medium is 1 µm in thickness. The coercivity and the saturation magnetization of Co-Cr layer in both media are about 1200 ∿ 1300 Oe. and 600 emu/cc, respectively.

Figure 9 shows the reproduced voltage vs. recording magneto-motive force characteristics for tape sample in all 1's NRZ recording at the densities of 0.2 kBPI and 45 kBPI. The amplitude of the reproduced voltage represents the value divided by the number of turn in winding of the ring head. The solid and the dotted lines are the results of the double and the single layer media, respectively. The recording sensitivity in the composite anisotropy medium becomes about 10 times larger in comparison with the single layer medium and reaches at almost the same order as the ordinary ring-type recording head. The fact means that, in the double layer medium, the bottom layer film (Fe-Ni film) acts to decrease the magnetic reluctance of the perpendicular head as has been shown in Fig.7. Furthermore, the amplitude of the reproduced voltages for both media scarcely drop after the saturation even in high density region. The result correspond to establish a stable horse-shoe type remanent magnetization in the double layer medium.[3,7]

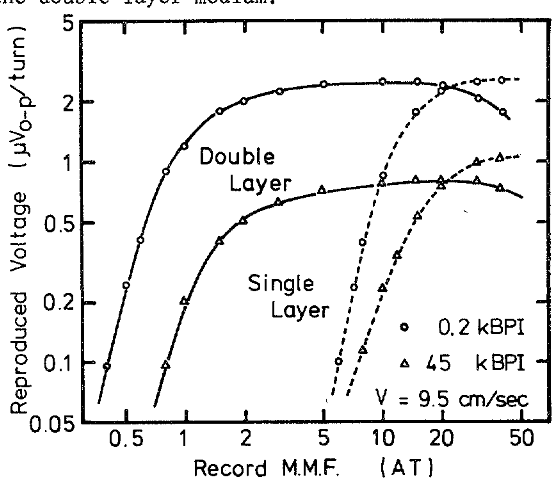

Fig. 9 Reproduced voltage vs. recording magneto-motive force characteristics [Record: perpendicular head, Reproduction: ring head].

Figure 10 shows the reproduced voltage (per turn) vs. bit density characteristics measured for the double layer (solid line A) and the single layer (dotted line B) media in the saturation recording of all 1's NRZ signals. In both curves, the null point and the second peak in the amplitude of the reproduced voltage appear at about 75 kBPI and 100 kBPI, respectively. The wavelength of the null point corresponds to the effective gap length (Gpe = 0.67 µm) of the ring-type reproducing head. The result shown in Fig.9 and 10 indicate that, in perpendicular recording, any severe recording demagnetization does not take place, and the maximum density has been limited merely by the resolution of the reproducing head.

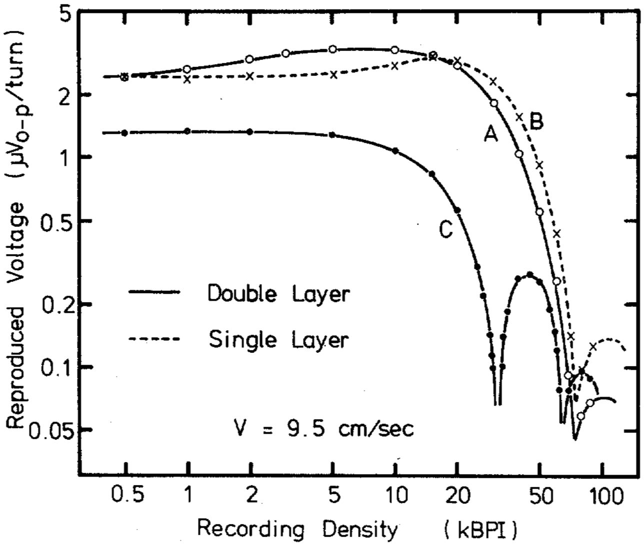

Fig. 10 Reproduced voltage vs. bit density characteristics [Record: perpendicular head, Reproduction: ring head (A, B) perpendicular head (C)].

The fact is also ascertained in the peak shift characteristics shown in Fig.11. The peak shift of the double layer medium was measured for a 2-bits pattern in NRZI. To investigate the peak shift characteristics the output pulses of a ring-type reproducing head were once differentiated and the increment of the distance between two pulses was measured.[8] The peak shift was found to be very small in quantity even for a double layer medium and it mostly depends on a reproducing head gap. It has also been proved that the peak shift scarcely depends on recording conditions such as recording current amplitude, the main pole thickness and the recording medium thickness.[8] The results lead to the conclusion that the superposition principle is applicable in determining the waveform of a finite number of digital signals.

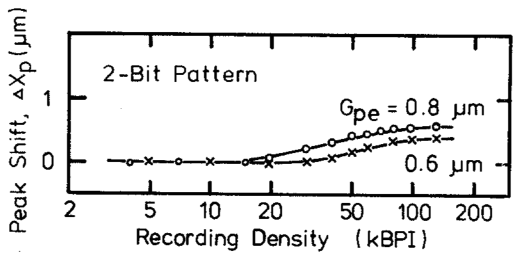

Fig. 11 Peak shift vs. bit density characteristics measured by 2-bits NRZ signal (double layer medium).

5.2 Reproduction by perpendicular head

From a practical point of view, the reproduction of the signals by the perpendicular head, which is similar with the recording head, is very important. As has been shown in Fig.9, the recording sensitivity of the perpendicular has been improved significantly by using the composite anisotropy medium. The result means also that, from the reciprocity theorem, the amplitude of the reproduced voltage of a perpendicular head can be increased by using the comosite anisotropy medium.[7]

Figure 12 is the reproduced voltage (per turn) vs. recording magneto-motive force measured by using the perpendicular head for both record and reproduction. The perpendicular head is the same as the recording head used in Fig.9 and the detection of the signal was made with a coil wound around the auxiliary pole. The amplitude of the reproduced voltage by the perpendicular head has been reached about a half of the ring head reproduction, as has been obtained by a comparison of Fig.9 and Fig.12. The curve C in Fig.10 represents the reproduced voltage of the perpendicular head (per turn) vs. bit density characteristics in the saturation recording of all 1'NRZ signals. The first and the second null points are observed at the densities of 32 kBPI (wavelength 1.6 μm) and 65 kBPI (wavelength 0.8 μm), respectively. The phenomenon depends on the thickness loss of the main pole in the perpendicular head, which is correspond to the gap loss of the ring head. Therefore, these null points can be shifted to higher density region by using a thinner main pole.

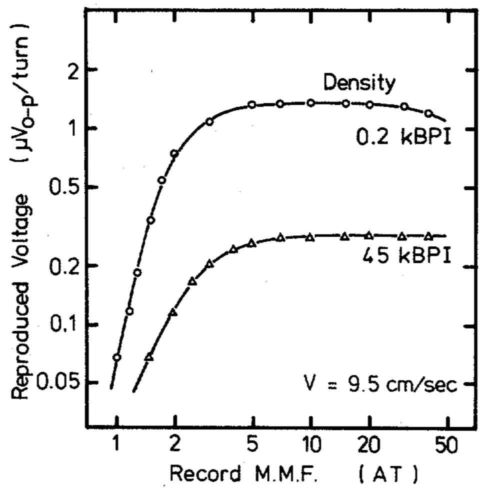

Fig. 12 Reproduced voltage vs. recording magneto-motive characteristics [Record, Reproduction: perpendicular head].

(a)

(b)

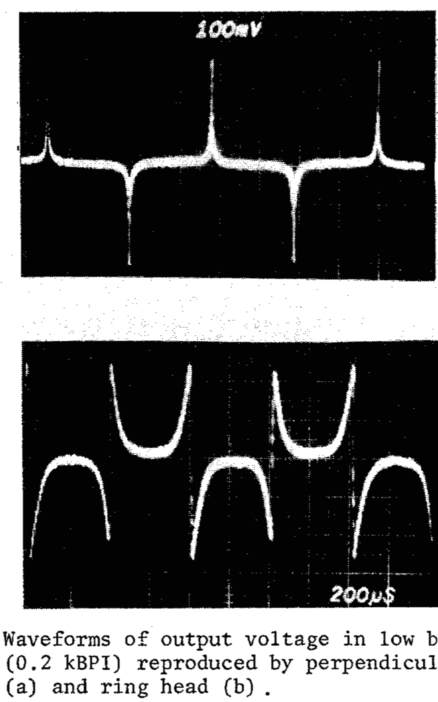

Fig. 13 Waveforms of output voltage in low bit density (0.2 kBPI) reproduced by perpendicular head (a) and ring head (b).

Figure 13 a) shows the reproduced wavefrom by the perpendicular head at low density (0.2 kBPI). The waveform is quite different with the ring head reproduction shown in Fig.13 b) and the results are interpreted by using the reproducing head field functions (Hy, Hx) and the perpendicular remanent magnetization in the medium.

Figure 14 shows the flexible disk-type recording medium used in the experiment. The flexible disk is 20 cm in diameter and the double layer medium was deposited successively on both side of 50 μm-thick Polyimide base. Mechanical curling in the disk can be excluded by the method. No interference between the recording media deposited on the top and the bottom surfaces of the disk was observed in both record and reproduction by a perpendicular magnetic head. The fact may be interpreted by a strong interaction between the main pole and the surface layer of the medium having the uniaxial perpendicular anisotropy.

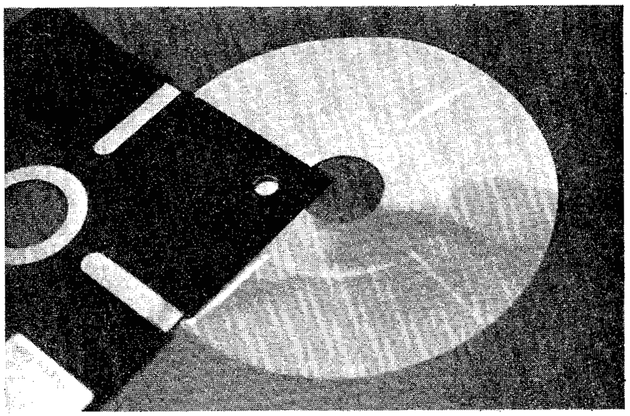

Fig. 14 Flexible disk type recording medium (Contact recording is made on the rotating disk by perpendicular head.).

6. CONCLUSION

In this paper the recent studies for the perpendicular magnetic recording are summarized. We have carried out the experiment by combining perpendicular anisotropy medium with magnetic head which produces the perpendicular magnetizing field and ascertained that the perpendicular recording has the magnetization mode essentially suitable for a high density digital recording. Significant improvement has been made on the amplitude and the peak shift of the reproduced voltage vs. bit density characteristics in digital recording. The result depends mostly on the fact that, in perpendicular recording, any severe recording demagnetization does not take place even in high density region as compared with the longitudinal recording.

Furthermore, the reproduction with a perpendicular head has been realized by using the composite anisotropy medium. Although the composite anisotropy medium includes the soft magnetic material of Fe-Ni layer, neither deterioration of the frequency response nor the peak shift was observed. From the result, it is safe to conclude that the practical system using the perpendicular head in reproduction as well as in recording has been realized.

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REFERENCES

(1) S. IWASAKI and K. TAKEMURA; "An Analysis for the Circular Magnetization Mode in Short Wave Length Recording," IEEE Trans. Magn., vol. MAG-11, no. 5 (1975)

(2) D. SPELIOTIS and C.S. CHI; "Computer-Based Modeling of the Digital Magnetic Recording Channel," IEEE Trans. Magn., vol. MAG-14, no. 5 (1978)

(3) S. IWASAKI and Y. NAKAMURA; "An Analysis for the Magnetization Mode for High Density Magnetic Recording," IEEE Trans. Magn., vol. MAG-13, no. 5 (1977)

(4) S. IWASAKI and Y. NAKAMURA; "The Magnetic Field Distribution of a Perpendicular Recording Head," IEEE Trans. Magn., vol. MAG-14, no. 5 (1978)

(5) S. IWASAKI; "High Density Magnetic Recording using Perpendicular Magnetization Mode," Jour. Inst. Television Engineers of Japan, vol. 32, no. 5 (1978) (in Japanese)

(6) S. IWASAKI and K. Ouchi; "Co-Cr Recording Films with Perpendicular Magnetic Anisotropy," IEEE Trans. Magn., vol. MAG-14, no. 5 (1978)

(7) S. IWASAKI, Y. NAKAMURA and K. OUCHI; "Perpendicular Magnetic Recording with a Composite Anisotropy Medium," To be published as Intermag Conference paper (1979) IE-8

(8) S. IWASAKI and T. SUZUKI; "Peak Shift in Perpendicular Magnetic Recording," IECE Tech. Group Meeting of Magn. Rec., Japan, paper MR 78-24 Dec. (1978) (in Japanese)

(9) S. IWASAKI; "Magnetic Recording by Perpendicular Magnetization Mode," Proc. of the Japan Academy, vol. 54, ser B, no. 7 (1978)

(10) S. IWASAKI, Y. NAKAMURA and H. MURAOKA; "Recording Density of Perpendicular Magnetization Mode," Joint Convention, Elec. Comm. Eng. of Japan. paper 237 (1979) (in Japanese)