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Setsuo Yamamoto
Yoshihisa Nakamura
Shun-ichi Iwasaki

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EXTREMELY HIGH BIT DENSITY RECORDING WITH SINGLE-POLE PERPENDICULAR HEAD

Setsuo YAMAMOTO, Yoshihisa NAKAMURA and Shun-ichi IWASAKI
Res. Inst. of Elec. Commun. of Tohoku University, Sendai, JAPAN

Abstract *- Since perpendicular magnetic recording is free from recording demagnetization, high-density recording up to the intrinsic limit of a recording medium is possible. This prediction was verified experimentally in a flexible disk system using a single-pole head and a Co-Cr/Ni-Fe double-layer medium. We could record and reproduce signals up to 680kFRPI. The recording bit length at the highest density was of the order of the Co-Cr columnar diameter.*

INTRODUCTION

Perpendicular magnetic recording is essentially free from the severe recording demagnetization which is encountered at high densities in longitudinal recording. We have predicted that the ultimate recording density in perpendicular recording is limited by the intrinsic resolution of the recording medium[1].

Recently it was reported that the signals were recorded and reproduced up to 350kFRPI by using a Co-Cr single-layer medium and a ring head[2,3,4]. However, from the view point of the magnetic field distribution of the recording head, the single-pole head which generates a purely perpendicular magnetic field is preferable to the ring head in realizing the sharp magnetization transitions in the medium. In fact, Fujiwara and Yamamori showed that recording up to 400kFRPI was performed in the experiments of analog signal recording by pulse width modulation technique in the combination of a single-pole head and a Co-Cr/Ni-Fe double-layer medium[5]. We also succeeded in reproduction of the signals at 250kFRPI[6]. For achieving higher bit density recording in this system, the improvement of the sensitivity and resolution of the reproducing single-pole head is indispensable.

This paper describes the results of our experimental pursuit of extremely high-density recording in the perpendicular flexible disk system.

REQUIREMENTS FOR HIGH BIT DENSITY RECORDING

In perpendicular magnetic recording, the bit density response curve reflects the reproducing characteristics of the system directly, because the width of magnetization transition is much narrower than the main pole thickness of the reproducing head.

The null points of the reproduced voltage in the bit-density response curves are caused when the magnetic flux through the head coil becomes zero at the density where the length of two oppositely magnetized regions is equal to the thickness of the main pole. Therefore, in order to extend the first band in the bit-density response curve, it is necessary to reduce the main pole thickness.

On the other hand, even for a given reproducing head, the envelope which connects the maxima of the reproduced voltage in the bit-density response curve is changeable depending on the magnetic field distribution of the reproducing head (i.e. head sensitivity function), including the effect of the magnetic coupling between the main pole and the medium[6]. As the magnetic field distribution of the reproducing head becomes narrow, the envelope in the bit-density response curve becomes flat to higher density. This phenomenon occurs for small thickness and large saturation magnetization of Co-Cr layer and for small head-to-medium spacing. This is because the magnetic coupling between the main pole and the medium is enhanced, and the reproducing resolution of the single-pole head is improved in such cases.

Therefore, in order to reproduce the signals at high densities, the following requirements must be satisfied:

(a) Use of a single-pole head with a thin main pole film and with the structure which induces a strong magnetic interaction between the head and the medium.
(b) Use of a medium with a relatively thin Co-Cr layer and a thick Ni-Fe backlayer; because the reproducing resolution of the single-pole head is improved by reducing the distance between the main pole and the backlayer of the medium.
(c) Achievement of small head-to-medium spacing in order to decrease the spacing loss.

EXPERIMENT

In the experiments, the above-described requirements for high density recording were fulfilled in the following manner.

Single-Pole Head

The one-sided access type single-pole head was newly developed. The basic structure is shown schematically in Fig.1. The head consists of the auxiliary part (A) with the coil winding and the main pole part (B). The auxiliary pole (2 x 2 x 5 mm in size) is made of ferrite with #-shaped grooves on the top. The central core of the auxiliary pole is inserted with the coil. The main pole part is constructed of a soft magnetic Co-Zr-Nb film on a glass substrate. The inductance of the head itself was 6μH. The curvature of the main pole tip was 40mm, and the distance between the main pole tip and the auxiliary pole was 50μm. The thickness of the main pole film was chosen to be about 0.4μm to maintain the soft magnetic properties.

When this head contacts with the double-layer medium in recording and reproducing operations, the eight ferrite projections on the auxiliary part couple with the backlayer of the medium magnetically to form the return path of the magnetic flux. Therefore the reproducing sensitivity of this head is about four times higher than that of the conventional single-pole head used in our laboratory, whose auxiliary pole is located on the other side of the medium with respect to the main pole.

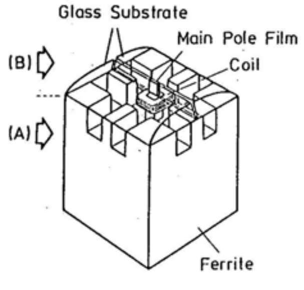


Fig.1 Structure of single-pole head.

Co-Cr/Ni-Fe Double-Layer Medium

The Co-Cr/Ni-Fe double-layer media were prepared by RF sputtering on polyimide substrate with thickness of 50μm. Thinner Co-Cr is preferable to improve the reproducing resolution of the single-pole head, because the small distance between the main pole and the backlayer induces strong magnetic coupling. However, the perpendicular magnetic anisotropy field decreases abruptly for thicknesses of Co-Cr layer less than 0.1μm. Therefore the thickness of the Co-Cr layer was chosen to be 0.1μm to maintain high perpendicular magnetic anisotropy. On the other hand, for the backlayer, the thick and soft magnetic Ni-Fe layer is desirable. The thickness was 0.5µm, and coercivity was less than 0.5Oe. The total thickness of the magnetic layer was 0.6µm, which is about ten times thicker than that of the thin-film medium for high-density longitudinal recording.

The geometric dimensions and magnetic parameters of the media are listed in Table 1.

Table 1 Geometric dimensions and magnetic properties of media.

Co-Cr/Ni-Fe Double-Layer Media
$\delta_{Co\text{-}Cr}$: 0.09-0.13µm
$Hc_{\perp}$: 380-980Oe
Ms : 360-420emu/cc
Hk : 2.3-6.5kOe
$\delta_{Ni\text{-}Fe}$: 0.5µm

Head-to-Medium Spacing

Fig.2 shows the correlation between head/medium spacing and D_{50}*, where D_{50}* is D_{50} on the envelope connecting the maxima of the reproduced voltage in the bit-density response curve. D_{50}* was introduced to estimate the extension of the bit-density response curve excluding the influence of the main-pole thickness loss of the reproducing head. As shown in the figure, a D_{50}* of 250kFRPI can be obtained at spacings less than 0.03µm.

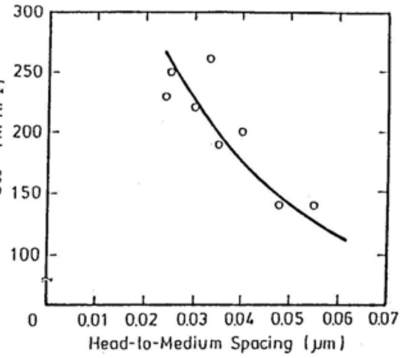
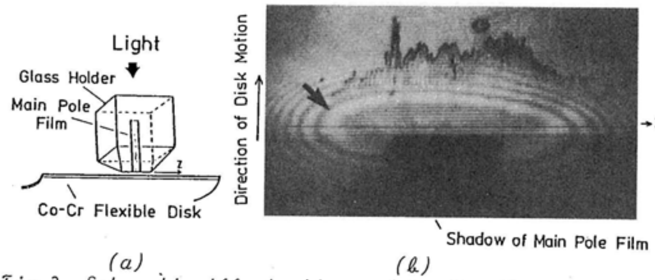


Fig.2 D_{50} versus head/medium spacing.*

The head/medium spacing was measured by a two-beam interferometric technique[7,8]. For the actual head used in recording and reproducing, the light does not go through the auxiliary pole part of the head. Hence a transparent dummy head with the same curvature as that of the actual head was contacted to the recording disk, and light with center wavelength of 528nm and half-value width of 12nm was applied to the head as shown in Fig.3(a). Fig.3(b) shows an example of the light interference fringe pattern. The flexible disk rotates at a speed of 2m/s. The stagnation of the fluid lubricant can be seen down stream of the main pole. The central area of the fringe pattern is almost as dark as the surrounding fringes (shown by an arrow) where the phase difference of the two rays, one reflected by the main pole tip and the other by the surface of the medium, is just 180°. This shows very good head/medium contact. The minimum spacing calculated from the light intensity of the interference fringe pattern along the dark scanning line in the figure was about 0.02µm. For the static state of the medium, the value of the minimum spacing was almost same as that in the dynamic state.

In a contact recording system, the head-to-medium spacing is fundamentally caused by the surface roughness of the medium[9]. The surface roughness profile of the medium was measured by a stylus-tracing surface profilometer. In many cases, the short-wavelength irregularities were superimposed on the long-wavelength undulations in the profiles. When the head contacts with the medium, the short-wavelength irregularities have an influence on the spacing. By spectrum analysis using the maximum entropy method[10], it was found that a spacing less than 0.03µm is achievable using smooth media which possess these irregularities with an average amplitude of less than 50Å.



(a) (b)

Fig.3 Schematic illustration of head/medium configuration for measurement of spacing (a), and interference fringe pattern (b).

Measurement of Rec. & Rep. Characteristics

The measurements of recording and reproducing characteristics were performed in a 5.25-inch flexible disk system. The head/medium relative speed was chosen in the range from 0.8 to 2m/s. A fluid lubricant was used, and the spacing was kept less than 0.03µm.

At high densities, the measurement of the reproduced voltage with an oscilloscope becomes difficult because of the degradation of the signal to noise ratio. Hence, the spectrum analyzer was introduced to measure the amplitude of the fundamental component in the reproduced signal. The measured bit-density response curves by the two methods were fitted at the densities over 100kFRPI where the influences of the harmonics in the reproduced signal are negligible, and entire bit-density response curves up to several hundred kFRPI were obtained.

RECORDING AND REPRODUCING CHARACTERISTICS

High Density Recording Characteristics

Fig.4 shows the measured bit-density response curve. The geometrical dimensions and magnetic properties of the medium are listed in the figure. The reproduced voltage, normalized with respect to the track width (µm), turns of winding and head/medium relative speed (m/s) was 20nV$_{0\text{-}p}$ at low densities, because the high-sensitivity single-pole head was used. The ratio of the reproduced voltage at the second peak after the first null to the isolated pulse peak was over 70%, and D_{50}* exceeded 250kFRPI. A photograph of the reproduced pulse from an isolated magnetization transition is shown in Fig.5. Even for the thin main pole (about 0.4µm in thickness), the pulse shape is not triangular but trapezoidal as can be encountered for a thick main pole. This shows that the reproducing resolution of the single-pole head is very high.

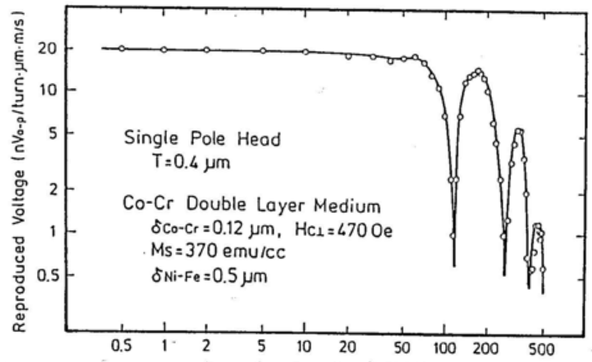


Fig.4 Bit-density response curve (I).

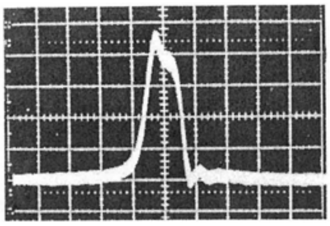


Fig.5 Reproduced pulse from isolated magnetization transition. X : 0.4μm/div.

Fig.6 shows bit-density response curve for another medium. In figure, the plots indicated by open circles and triangles were measured with the oscilloscope and the spectrum analyzer, respectively. The reproduced signal was observed with the oscilloscope up to the fourth band. The reproduced voltage at 450kFRPI was about 3mV$_{o-p}$ at a head/medium relative speed of 0.8m/s and a reproducing amplifier gain of 60dB.

With the spectrum analyzer, the reproduced signals were observed at higher densities. Fig.7 shows the frequency spectrum of the reproduced signal at 620kFRPI which gives the fifth peak in the bit-density response curve. The carrier to noise ratio was 14dB at a head/medium speed of 0.8m/s, an IF band width of 10kHz in the spectrum analyzer and a track width of 100μm. In this way, the reproduced signal was confirmed up to 680kFRPI.

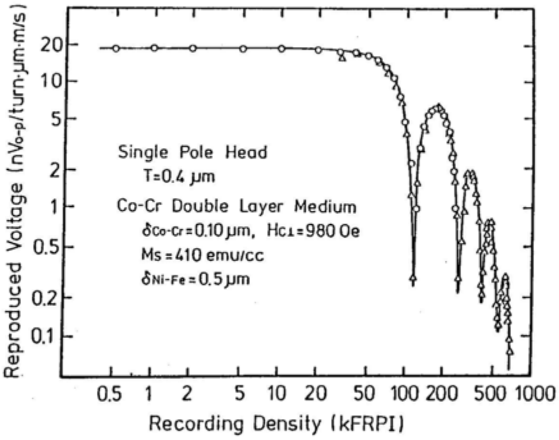


Fig.6 Bit-density response curve (II).

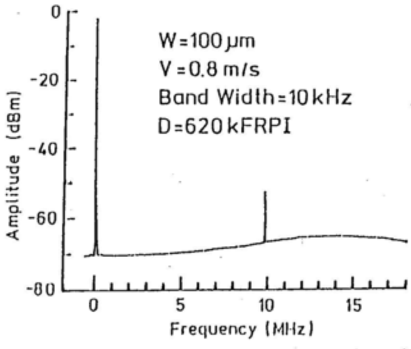


Fig.7 Frequency spectrum of reproduced signal at 620kFRPI.

Recording Resolution of Medium

The major advantage of perpendicular magnetic recording over longitudinal recording is the fact that even for thick media, (0.6μm in thickness), extremely high density recording is achieved. It can be surmised that the magnetization state at high densities is close to the intrinsic limit of the Co-Cr layer.

From the observation of the cross-sectional Lorentz image of a Co-Cr layer, it was found that the magnetic domain width is in the same order as the diameter of the Co-Cr columnar particles[11]. This result suggests that one columnar particle corresponds to one magnetic domain. It was also found that the columnar particle diameter grows with increasing film thickness.

For the Co-Cr layer used in our experiments, the average diameter of the Co-Cr columnar particles is about 210Å. The bit length at 680kFRPI, 370Å, is thus about twice the columnar diameter. Adding the consideration that the recorded magnetization transition width averaged over the track width should be wider than the columnar diameter, we can conclude that the signals were recorded in the medium at the high density to the intrinsic limit of the medium, and were reproduced in this experiment.

CONCLUSIONS

The feasibility of high-density perpendicular recording was investigated in the flexible disk system with single-pole head and Co-Cr/Ni-Fe double layer medium.

In order to improve the reproducing sensitivity and resolution, the geometrical dimensions and magnetic properties of the head and medium were optimized, and head-to-medium spacings less than 0.03μm were achieved. As a result, we could detect signals up to 680kFRPI by using a medium with a total magnetic layer thickness of 0.6μm. The bit length at the highest density was of the order of the Co-Cr columnar diameter.

The prediction that perpendicular recording enables high-density recording up to the intrinsic limit of the recording medium is thus now confirmed experimentally.

However, the application of such high densities to a practical recording system depends on the achievement of the stable head-to-medium spacing of less than 0.03μm with maintaining the durability of the head and the medium.

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