Perpendicular Magnetic Recording Media with Glass Substrate

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1. Introduction

Hard disk drives (HDDs), not limited to applications in external recording devices for use with personal computers, are recently being used increasingly in commercial electronics (CE) applications such as recording devices for car navigation systems, game devices and other information appliances. The HDDs installed in such CE devices are required to be compact in size, and mainly use 2.5-inch and 1.8-inch size magnetic recording media with glass substrates.

Furthermore, owing to recent developments of digitized information, larger and larger quantities of data are being handled, and HDDs that are more compact yet have larger capacity are being requested of the HDD market.

Responding to the market needs for more compact size and larger capacity, in 1999 Fuji Electric began developing perpendicular magnetic recording media that used a perpendicular recording method(1) instead of the longitudinal recording method that had been in use previously, and pioneered the development of CoPtCr-SiO_2 granular perpendicular magnetic recording media(2), the mainstream perpendicular magnetic recording media currently on the market. Fuji Electric is presently advancing development toward higher recording densities by optimizing the manufacturing process, materials and layer structure of the CoPtCr-SiO_2 granular perpendicular magnetic recording media.

This paper describes Fuji Electric's efforts toward achieving higher recording density in the development of CoPtCr-SiO_2 granular perpendicular magnetic recording media, and also introduces the latest read-write evaluation technology which is indispensible for furthering the efficient development of perpendicular magnetic recording media.

2. Challenges in Realizing Higher Recording Density of CoPtCr-SiO_2 Perpendicular Magnetic Recording Media

In perpendicular magnetic recording media, the simultaneous realization of high thermal stability and low media noise is essential for realizing higher recording density. Namely, the challenge for realizing higher recording density is to reduce the recording bit volume V while increasing the aniaxial magnetic anisotropy constant K_u so that the magnetic energy, expressed as the product K_uV of the K_u value and the recording bit V, is maintained.

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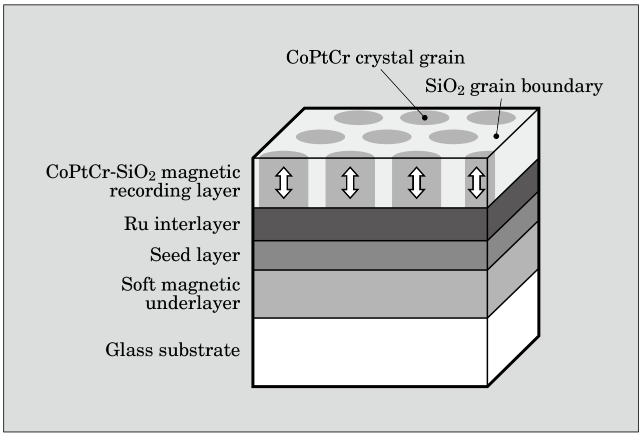
3. Efforts Toward Achieving Higher Recording Density in Perpendicular Magnetic Recording Media

3.1 Layer structure of CoPtCr-SiO_2 glass perpendicular magnetic recording media

CoPtCr-SiO_2 glass perpendicular magnetic recording media, as shown in Fig. 1, has a layer structure in which the characteristic soft magnetic underlayer of the perpendicular magnetic recording media is formed on a glass substrate, and formed above the underlayer are a seed layer and an interlayer for the purpose of controlling the grain size and crystalline orientation of the recording layer. Then, the CoPtCr-SiO_2 granular perpendicular magnetic recording layer, after having been formed, is covered by sequentially laminated overcoat layers of carbon, and finally the surface is coated with a lubricative layer.

Fig.1 Layer structure of CoPtCr- SiO_2 perpendicular magnetic recording media with glass substrate



3.2 Design of the composition of the CoPtCr-SiO_2 magnetic recording layer for higher recording density

(1) SiO_2 content and reduced media noise

In order to overcome the challenges encountered in realizing higher recording density in CoPtCr-SiO_2 perpendicular magnetic recording layer media, we examined the composition of the CoPtCr-SiO_2 granular perpendicular magnetic recording layer. With CoPtCr-SiO_2 perpendicular magnetic recording media, the media characteristics change significantly according to the percent composition of elements Pt and Cr and of SiO_2 with respect to Co in the magnetic recording layer, and therefore, the compositional design of the magnetic recording layer is a critical factor for achieving higher recording density. Consequently, we examined the effect of each of the above elements upon the media characteristics, and determined design guidelines for the magnetic recording layer composition.

To reduce media noise in CoPtCr-SiO_2 perpendicular magnetic recording media, it is important to improve the magnetic isolation among magnetic crystal grains while reducing the size of those magnetic crystal grains. In the control of magnetic crystal grain size, individual crystal grains of the magnetic recording layer must be grown epitaxially on the interlayer crystal grains in a 1:1 correspondence. Accordingly, in order to reduce the crystal size in the magnetic recording layer, the crystal size of the interlayer must also be reduced.

On the other hand, magnetic isolation among the magnetic crystal grains is thought to be dependent upon the amount of SiO_2 (grain boundary width) segregated to the grain boundary that surrounds the magnetic crystal grains. In other words, by increasing the amount of SiO_2 content, the grain boundary becomes thicker and as a result, isolation among the magnetic crystal grains is improved and a reduction in media noise can be expected.

Figure 2 shows cross-sectional TEM (transmission electron microscope) images of the interlayer of CoPtCr-SiO_2 perpendicular magnetic recording media and of the CoPtCr-SiO_2 perpendicular magnetic recording layer when the amount of CoPtCr-SiO_2 content is changed. Also, Fig. 3 shows a schematic drawing of the change in crystal grain size and of the layer structure of the magnetic recording layer in CoPtCr-SiO_2 perpendicular magnetic recording media as obtained from cross-sectional TEM images. The crystal grain size shown in the drawing is the sum of the boundary width and the actual magnetic crystal grain size. In the composition range of 0 to 11 at% SiO_2 content, the crystal grain size, including the grain boundary width, remains nearly unchanged, but as the amount of SiO_2 content increases, the actual magnetic crystal grain size, which does not include the grain boundary width, decreases steadily, and the grain boundary width increases proportionally. This region corresponds to the range extending from points (a) to (b) in the schematic drawing of Fig. 3.

Fig.2 Cross-sectional TEM images of CoPtCr-SiO_2 perpendicular magnetic recording layers

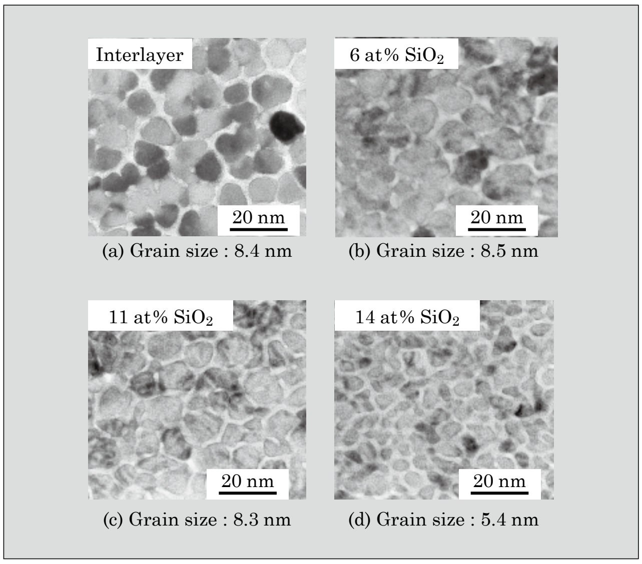
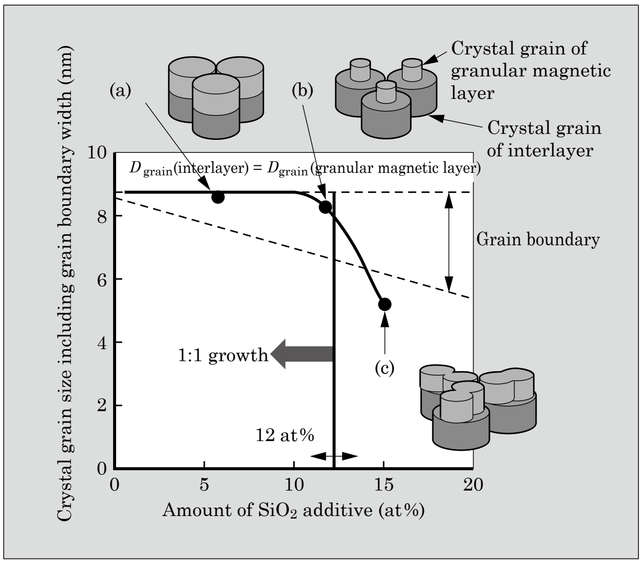


Fig.3 Schematic diagram of change in grain size and layer structure of CoPtCr-SiO_2 perpendicular magnetic recording layer



In this type of SiO_2 composition range, the crystal grain size of the interlayer and the crystal grain size of the magnetic recording layer (grain boundary width + magnetic crystal grain size) are approximately the same value, and as a result we can infer that the growth of one crystal grain in the magnetic recording layer on top of one crystal grain in the interlayer is implemented with a 1:1 correspondence. Moreover, from actual cross-sectional TEM images, clearly formed grain boundary structures and improved the segregation among crystal grains can be verified.

However, in the composition range where the SiO_2 content in the magnetic recording layer exceeds

12 at%, the crystal grain size in the magnetic recording layer decreases suddenly, and cross-sectional TEM images show deterioration in the degree of segregation of grains at several locations. Thus, in such a composition range where the SiO_2 content in the magnetic recording layer exceeds 12 at%, as can be seen in the schematic drawing of Fig. 3(c), multiple magnetic crystal grains having a small grain size and poor segregation are formed on top of a single crystal grain in the interlayer, and cross-sectional TEM images show the layer structure to be non-uniform. In other words, in compositions having a high concentration of SiO_2, the crystal size in the magnetic recording layer cannot be controlled by the crystal size of the interlayer. Namely, the optimal amount of SiO_2 to add to the magnetic recording layer depends on the crystal size in the interlayer, and the use of a magnetic recording layer composition containing this optimal amount of added SiO_2 enables a reduction in media noise.

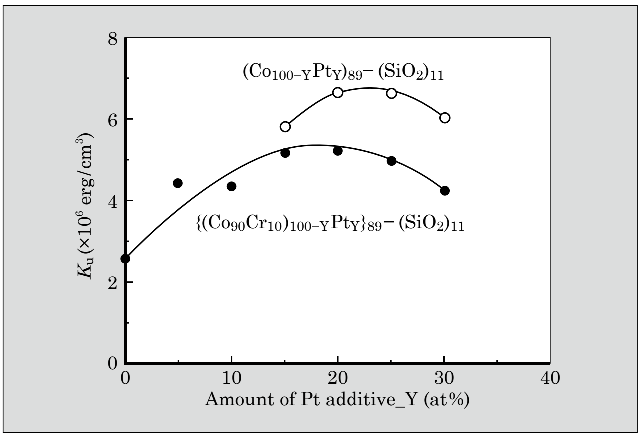
Given these findings, in order to achieve higher recording density in CoPtCr-SiO_2 perpendicular magnetic recording media, design guidelines for the magnetic recording layer composition increase the amount of SiO_2 added to the magnetic recording layer in order to decrease the actual magnetic grain size, which does not include the grain boundary width. Also, it is important to implement precise process control so as to maintain a 1:1 grain growth correspondence between the crystal grains in the magnetic recording layer and the refined and small-size crystal grains in the interlayer.

(2) Pt content and higher K_u value

A reduction in magnetic crystal grain size in order to realize higher recording density, however, leads to deterioration of the thermal stability. Accordingly, in order to increase the recording density of CoPtCr-SiO_2 perpendicular magnetic recording media, the K_u value must be increased to ensure the value of the thermal stability indicator of K_uV/kT (where V: volume of magnetic crystal, k: Boltzmann's constant, and T: absolute temperature). The K_u value of the perpendicular magnetic recording media depends largely on the amount of Pt added to the magnetic recording layer.

Figure 4 shows the dependency of the K_u value according to the amount of Pt content in CoPtCr-SiO_2 perpendicular magnetic recording media and in CoPt-SiO_2 perpendicular magnetic recording media, which does not have any Cr content. In the magnetic recording layer of the perpendicular magnetic recording media that was studied, the Cr content was fixed at 10 at% and the amount of SiO_2 additive was fixed at 11.2 at%. Regardless of whether Cr was added to the magnetic recording layer, the K_u value reached a gradual maximum when the amount of Pt additive was in the vicinity of 15 to 25 at%. Since media noise is large for the CoPt-SiO_2 alloy by itself, Cr is added and has the effect of reducing media noise, but even with a magnetic recording layer composition in which the Cr content is 10 at%, the K_u value of 5.3×10^6 erg/cm^3 is large. In compositions having a high Pt content, the lower K_u value is believed to be attributed to the formation of a fcc (face-centered cubic lattice) phase in the crystal grain.

Fig.4 Change in K_u value according to amount of Pt additive in CoPtCr-SiO_2 perpendicular magnetic recording media



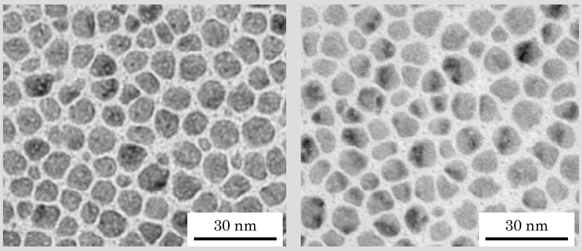
Thus, the K_u value of CoPt-SiO_2 perpendicular magnetic recording media can be controlled to a suitable value by the amount of Pt additive. However, increasing the amount of Pt in order to raise the K_u value leads to an increase in media noise. Therefore, when adding an amount of Pt to the magnetic recording layer, so that the desired media characteristics can be obtained for the required recording density, it is important that the magnetic recording layer composition be designed in consideration of and in balance with the percent of Co content.

4. Improved Media Characteristics by Optimizing the CoPt-SiO_2 Magnetic Recording Layer Composition

The example below describes the case in which, based on the abovementioned design guidelines for the magnetic recording layer, the CoPtCr-SiO_2 granular perpendicular magnetic layer composition was optimized for the material and crystal grain size of the existing interlayer in order to improve the media characteristics and realize a higher recording density.

Figure 5 shows cross-sectional TEM images of the magnetic recording layers in media that uses a magnetic recording layer having a conventional composition and in the CoPt-SiO_2 perpendicular magnetic recording media that uses a new magnetic recording layer developed by optimizing the magnetic recording layer composition. Except for the change in magnetic recording layer composition, both types of perpendicular recording media were fabricated with the same sputtering conditions. Both types of media exhibited the same total grain size of approximately 8.3 nm, which is the sum of the actual magnetic crystal grain size plus the grain boundary width. Because these values are approximately the same as the crystal grain

Fig.5 Cross-sectional TEM images of CoPtCr-SiO_2 perpendicular magnetic recording layers



Crystal grain size not including grain boundary width : 6.5 nm
Grain boundary width : 1.7 nm

(a) Conventional magnetic recording layer composition

Crystal grain size not including grain boundary width : 6.1 nm
Grain boundary width : 2.2 nm

(b) New magnetic recording layer composition

size of the interlayer, the individual crystal grains in the magnetic recording layer are assumed to grow in a 1:1 correspondence with the crystal grains of the interlayer. Moreover, although the total grain sizes were approximately the same, the magnetic crystal grain size and grain boundary width were 6.1 nm and 2.2 nm, respectively, in the new composition media and were 6.5 nm and 1.7 nm, respectively, in the convention composition media, indicating that the grain boundary width increased and the magnetic grain size was refined as a result of the optimization of the composition. These findings suggest that the initial objective of improving magnetic isolation among magnetic crystal grains and enhancing media characteristic can be attained. Therefore, we compared media characteristics of these types of perpendicular magnetic recording media.

Table 1 shows the values of coercivity H_c and signal-to-noise ratio (SNR) for these perpendicular magnetic recording media having different recording layer compositions. The H_c value for media having a conventional composition was of 8.2 kOe, while the H_c value for the new composition media was 9.3 kOe, thereby verifying an approximate 1 kOe increase in the H_c value. Moreover, a comparison of the SNR value also revealed an improvement of approximately 0.4 dB in the SNR value of the new composition media.

These findings clearly demonstrate that by optimizing the magnetic recording layer composition so as to closely match the interlayer material and crystal grain size, the media characteristics can be improved significantly. These findings are the results of improved magnetic isolation due to the increased grain boundary width which has been verified by cross-sectional TEM images. Applying these techniques, 2.5-inch media having a 160 GB capacity and a recording density of 250 Gbits/in^2 was commercialized in 2007.

However, in order to achieve next-generation 2.5-inch media with 250 GB capacities and recording densities of 400 Gbits/in^2 and above, further refinement of the interlayer's crystal grain size, which determines the magnetic crystal grain size, and optimization of

Table 1 H_c and SNR values of CoPtCr-SiO_2 perpendicular magnetic recording media

	Coercivity	Signal to noise ratio
	H_C (kOe)	SNR (dB)
Conventional magnetic recording layer composition	8.2	14.3
New magnetic recording layer composition	9.3	14.7

the sputtering process and magnetic recording layer composition to refine the magnetic crystal grains and improve magnetic isolation are necessary, and such development is ongoing.

5. Evaluation Techniques for Perpendicular Magnetic Recording Media

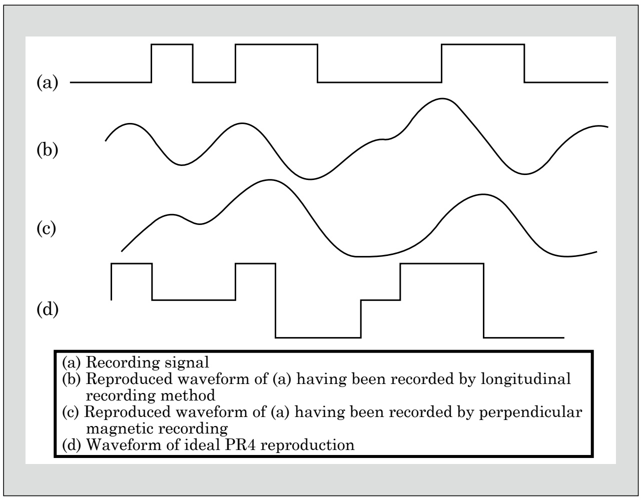
5.1 Evaluation of perpendicular magnetic recording media characteristics

Important factors for realizing higher recording densities in present-day HDDs include the establishment of perpendicular magnetic recording, and the advancement of technology for a media recording layer that simultaneously achieves both refinement and thermal stability, advancement of magnetic head technology for switching the magnetic field abruptly, reduction in spacing loss due to FOD (flying on demand) technology, and signal reconstruction techniques based on PRML (partial response maximum likelihood). Based on empirical knowledge acquired from the era of longitudinal recording, media characteristics had formerly been evaluated by examining the widely-known SNR value and analog signals such as overwrite, but because the signal processing carried out within an actual HDD was not considered, this type of media evaluation was inadequate as a technique for realizing higher recording densities. Here, as a representative evaluation indicator for magnetic recording media, an evaluation technique is introduced that identifies inherent problems in the widely used MF (middle frequency)–SNR and rectifies those problems.

5.2 Differences with conventional media from the perspective of record and reproduction

PR4 is a PRML method that is widely used in the reproduction signal processing of present-day HDDs. The PR4 method subtracts from an input signal string a string that has been shifted by two bits, and then outputs the result, and is based on a design philosophy of actively utilizing the mutual interference from signals of adjacent bits and obtaining the sign inversion of adjacent bits, i.e., a differential waveform. Essentially, this method was designed to make full use of the characteristics of longitudinal magnetic recording media in which magnetic flux leakage outside the media occurs at magnetic transition locations only, but with the popularization of perpendicular magnetic recording, this signal processing method continues to be used

Fig.6 Examples of reproduced signal waveforms of a recorded signal



even today.

Figure 6 shows (a), the recording signal waveform, and the results of signal processing to generate (c), a reproduced waveform of signal recorded by perpendicular magnetic recording, and (d), a reproduction waveform using the PR4 method. In the case of the PR4 method, in order to obtain the final PR4 output waveform from the relation between the actual recording signal and the reproduction signal, PR4 equalization is implemented using a FIR (finite impulse response) filter provided after the reproduction signal sampling. Specifically, in order to obtain the PR4 equalization signal y_n from the reproduction signal string $\{x_n\}$, equation (1) is computed with the FIR being expressed as a numerical sequence $\{a_n\}$.

$$y_n = \Sigma a_{n-k} x_k \quad \cdots\cdots (1)$$

A numerical sequence $\{a_k\}$ (FIR filter) is selected so that the waveform approaches the ideal PR4 waveform during this process. As shown in Figs. 6(a) and (b), with longitudinal magnetic recording, the record signal waveform and the reproduction signal waveform have a differential relationship, and the abovementioned FIR filter provides only compensation processing, but with perpendicular magnetic recording, the FIR filter is actually responsible for the differential processing.

Another significant difference with longitudinal magnetic recording media is the dependency on the SUL. The SUL not only facilitates recording by absorbing magnetic fields from the head during recording, but also has the effect of amplifying the signal during reproduction as a result of the polarization that occurs due to the recording magnetization. This polarization differs according to the magnetization switching distance and also according to the media structure. For example, the polarization increases for media having a shorter distance between the recording layer and SUL, and polarization also increases as the magnetization switching distance becomes longer, and since only low recording density signal intensities are amplified, the resolution appears to decrease. The FIR filter provided in a perpendicular magnetic recording HDD also implements restoration processing in consideration of the inter-symbol interference due to the SUL polarization.

5.3 Problems with the MF-SNR

MF-SNR, a typical evaluation index for magnetic recording media, is the ratio of recording signal intensity for 2-bit recording and reproducing to the noise intensity obtained by integrating the spectrum up to the 1-bit inversion frequency. This index is closely correlated to the error rate and has been highly regarded ever since the era of longitudinal magnetic recording. As described above, the MF-SNR used with perpendicular magnetic recording is different than the signal processing implemented with an actual HDD, and therefore the correlation with the error rate may be questioned.

With longitudinal magnetic recording, the waveform of a reproduction signal, i.e., the magnetic field that reaches the magnetic head from the media, closely resembles the signal of a waveform reproduced by the PR4-method, but differs significantly from that of perpendicular magnetic recording, and accordingly, the waveform of the signal to be evaluated, after having passed through a filter, differs from the waveform of a directly measurable signal prior to passing through the filter. Moreover, the reproduction signal waveform of perpendicular magnetic recording media is influenced by the media's structural factors, such as the SUL and interlayer thickness, and the FIR filters will be different if these factors are different. Accordingly, when evaluating perpendicular magnetic recording media, it is desirable to estimate a suitable FIR filter for each media, and then to evaluate the signal quality after the signal has passed through the filter.

5.4 Method of SNR evaluation by FIR filter transmission signal processing

A method of evaluating the SNR according to a signal that has passed through a filter, and the effectiveness of this method, are described below. First, the frequency dependence (linear recording density dependence) of the reproduction signal intensity is measured and the impulse response is computed, and then an inverse transformation applied to obtain an equalization filter. A filter obtained thusly is converted to the frequency domain by applying a Fourier transform, and is then multiplied by the reproduction signal power spectrum obtained from a spectrum analyzer, and the spectrum of the signal after having passed through the filter is obtained. The series of signal processing steps are shown in Fig. 7.

For an MF signal that has been recorded onto Fuji Electric's perpendicular magnetic recording media, Fig. 8 shows the noise spectrum of a reproduction signal as obtained by a spectrum analyzer and the noise spectrum after multiplication with a PR4 equalization

Fig.7 Signal processing steps with perpendicular magnetic recording

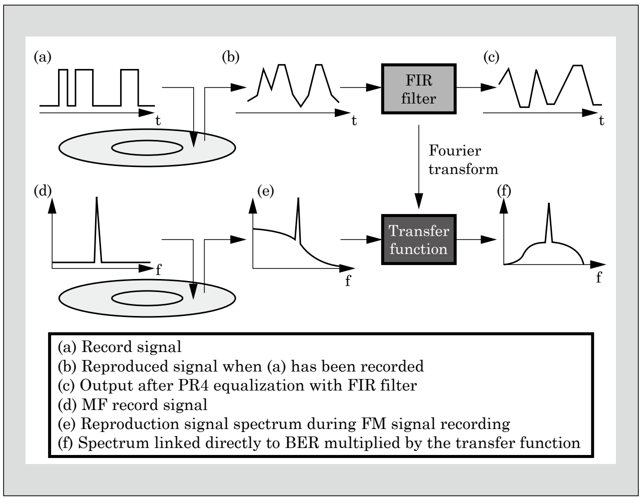


Fig.8 Noise spectrum after multiplication by PR4-equalized filter

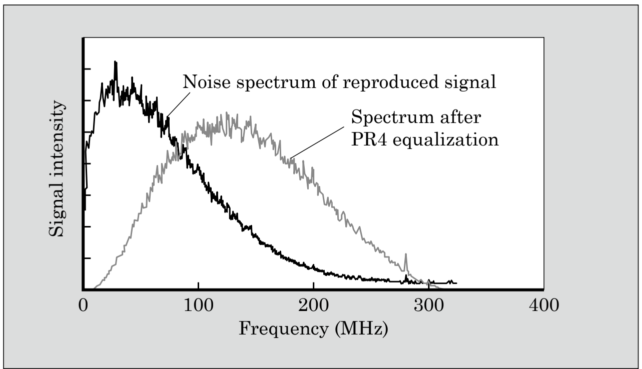
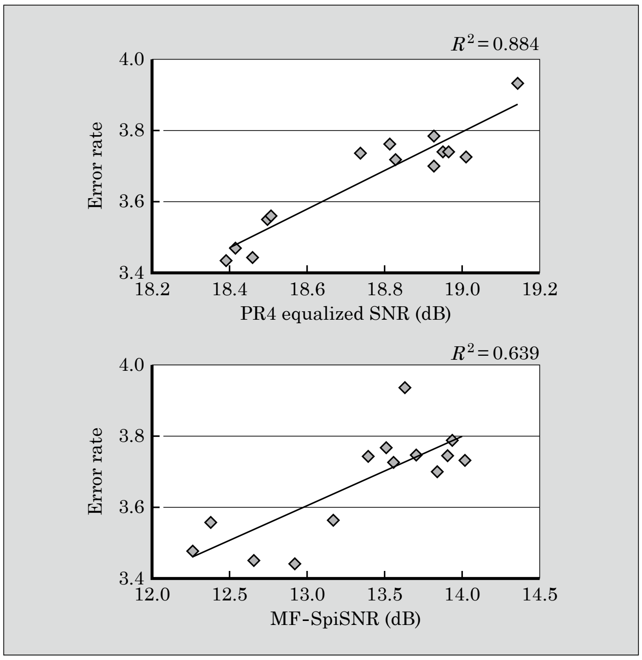


Fig.9 Relationship between each SNR and measured error rate



filter. The noise intensity of the reproduction signal itself is concentrated in the low frequency region, but there is no effect on the SNR after PR4 equalization, and noise increases in the MF vicinity, and therefore the reduction of noise in the MF vicinity is important.

Figure 9 compares ordinary MF-SNR and PR4 equalized SNR values evaluated for various types of perpendicular magnetic recording media having different structures or compositions with actually measured error rate values. Using the SNR evaluation method described herein and only the additional hardware of a spectrum analyzer, dramatic improvements in the error rate which expresses the digital reproduction quality and the response thereto were observed.

6. Postscript

In order to respond in a timely manner to market requests for larger capacity HDDs, Fuji Electric is promoting close cooperation with external parties while advancing the development of higher recording density in perpendicular magnetic recording media. However, for the realization of recording densities greater than 1 Tbits/in^2, there is a limit to the extent that improvements can be made to the existing perpendicular magnetic recording media structure, and some sort of technical breakthrough is needed. In the future, technical development will shift its focus toward next-generation technologies such as discrete track media and thermal assist media, and Fuji Electric intends to establish these technologies at an early stage.

References

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