

Granular-type Perpendicular Magnetic Recording Media

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1. Introduction

Hard disk drives (HDDs) came into practical use in 1956, and recently their recording density has been increasing at rapid rates of 60 to 100 % annually, and is predicted to continue to increase at annual rates of 30 to 60 %. As a consequence of this remarkable growth, the method of longitudinal magnetic recording, which has been in use thus far, is finally approaching its limit in terms of recording density due to its tradeoff between low noise performance and thermal stability. The problem of thermal instability is a phenomenon in which the signal stability cannot be maintained due to an inversion of the recorded magnetism caused by thermal energy at room temperature. With longitudinal magnetic recording, thermal instability becomes larger as recording density increases.

The method of perpendicular magnetic recording was proposed by Iwasaki et al.⁽¹⁾ in 1975, and has characteristics which are completely opposite those of the longitudinal magnetic recording method. Namely, as recording density increases, this method of perpendicular magnetic recording becomes more effective at suppressing thermal instability. Because this method is in principle well suited for high density recording, in anticipation of its practical application, much research has been performed relating to magnetic recording media and magnetic heads.

In 1999, Fuji Electric began developing perpendicular magnetic recording media and investigated the major technical challenges of achieving a magnetic recording media that combines low noise performance, high thermal stability and overwrite capability, and also the practical application of an easier-to-manufacture soft magnetic underlayer for thick films. At present, solutions to these practical challenges are in sight, and Fuji Electric is now studying ways to achieve mass-production, which is expected to begin at the end of 2005 or the beginning of 2006.

This paper describes the status of Fuji Electric's development of perpendicular magnetic recording media including a perpendicular recording layer having a granular structure and an electroless plated soft magnetic underlayer having excellent manufacturability.

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2. Basic Layer Structure and Development Challenges of Perpendicular Magnetic Recording Media

The basic layer structure of perpendicular magnetic recording media is shown in Fig. 1. Perpendicular magnetic recording media is produced by fabricating a soft magnetic layer on a substrate of aluminum or glass, forming a perpendicular magnetic recording layer on top of the soft magnetic layer, and then forming a protective lubricating layer. Figure 1 has been simplified, but each layer actually consists of multiple layers, and actual perpendicular magnetic recording media is fabricated by complex production processes and has a more sophisticated layer structure. The practical application of this perpendicular magnetic recording media faces the two main technical challenges listed below:

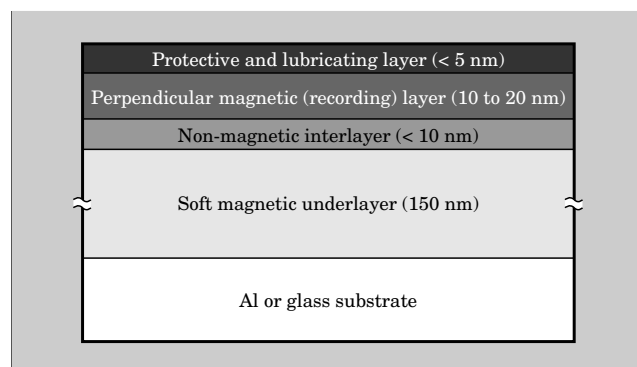
- (1) Technology for a soft magnetic layer that includes magnetic domain control

Development of a soft magnetic layer that is easy to manufacture, capable of extracting high precision performance from the magnetic head, and is unaffected by electromagnetic noise in the environment

- (2) Technology for a granular magnetic layer

Development of a magnetic layer having low noise, high thermal stability and good overwrite capability

Fig.1 Layer structure of perpendicular magnetic recording media



3. Development of a Soft Magnetic Underlayer

In order to achieve practical application of perpendicular magnetic recording media, development of a special layer structure known as a soft magnetic underlayer is necessary.

The perpendicular magnetic head generates a magnetic field while information bits are being written, and the purpose of the soft magnetic underlayer is to draw this magnetic field into the magnetic layer efficiently.⁽²⁾ Accordingly, a soft magnetic material having a high saturation flux density and fabricated to a film thickness of several hundred nanometers is required. The fabrication of such a film is considered to be extremely difficult with conventional sputtering techniques, both in terms of the manufacturability and production cost. Additionally, there is a need to suppress the spike noise. Spike noise is a large noise and is a serious problem caused by magnetic domain walls occurring within the soft magnetic layer.

Fuji Electric has previously developed process technology for sputtering a soft magnetic underlayer by inserting a pinning layer that actively performs magnetic domain control between the substrate and the soft magnetic layer, and by performing the necessary magnetic annealing to suppress spike noise. This process technology can be implemented inside a sputtering machine without adversely affecting manufacturability.

However, even when this processing method is employed, sputtering is required to fabricate a soft magnetic layer having a thickness of at least 100 nm and a multilayer that performs the magnetic domain control, and a technical breakthrough is needed in order to achieve the same manufacturability as with longitudinal magnetic media.

In addition to magnetic recording media, Fuji Electric also produces aluminum substrates plated with a non-magnetic nickel phosphorous (NiP) layer for use with recording media, and possesses advanced technology for fabricating electroless plated layers and polishing technology for achieving an ultra-smooth surface on the plated layer. Thus, for this soft magnetic underlayer which requires a thick film, Fuji Electric developed fabrication technology using an electroless plating technique having high manufacturability and surface smoothing technology, and successfully improved the prospects for practical application.

The soft magnetic plated layer achieves soft magnetic properties by using less phosphorous (P) additive than the non-magnetic NiP-plated layer conventionally used with aluminum substrates. This plated layer has a higher degree of hardness and can be made thinner than a conventional non-magnetic NiP layer. Moreover, the electroless plating process and polishing process we have developed use essentially the same production processes as in the conventional production

of aluminum substrates, thereby enabling the low cost production of a substrate having a high-performance soft magnetic underlayer.

Figure 2 shows an atomic force microscope (AFM) image of the surface of the NiP-plated soft magnetic underlayer we have developed. The surface roughness (R_a) of approximately 0.1 nm is smaller than the approximate 0.3 nm R_a of non-magnetic NiP-plated layers currently in use in commercial products, and this lower roughness is sufficiently low to support the lower flying heights of magnetic heads that will accompany the higher densities of recording media in the future.

Figure 3 (a) shows a mapped image of the noise generated from the NiP-plated soft magnetic underlayer we developed, as read from a magnetic head. For the sake of comparison, Fig. 3 (b) shows the noise generated from a 200 nm-thick Co amorphous soft magnetic underlayer produced by conventional sputtering techniques. The color shading in the figure corresponds to the magnitude of the noise. Magnetic domain control was not performed in either case.

In the soft magnetic underlayer produced by sputtering, there exist multiple regions in which a large amount of noise is generated. This is spike noise caused by magnetic domain walls that occur within the soft magnetic layer. On the other hand, in the NiP-

Fig.2 AFM image of the surface of NiP-plated soft magnetic underlayer

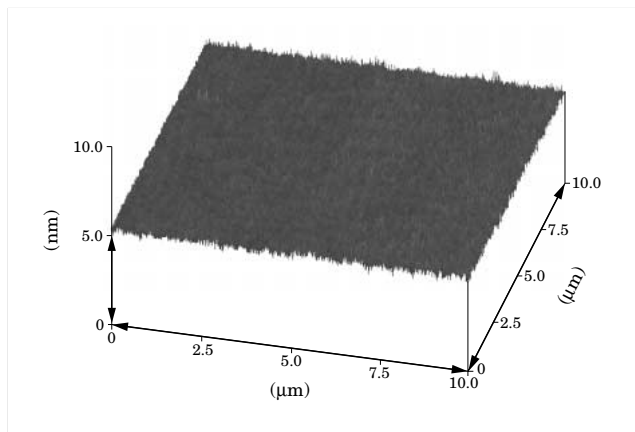
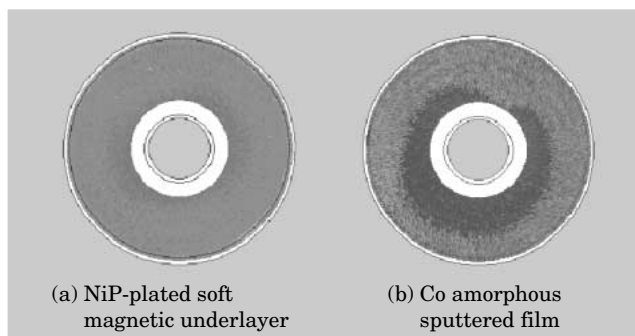


Fig.3 Spike noise observed at NiP-plated soft magnetic underlayer



plated soft magnetic underlayer we developed, it can be seen that spike noise is not generated despite the fact that no special magnetic domain control was implemented.

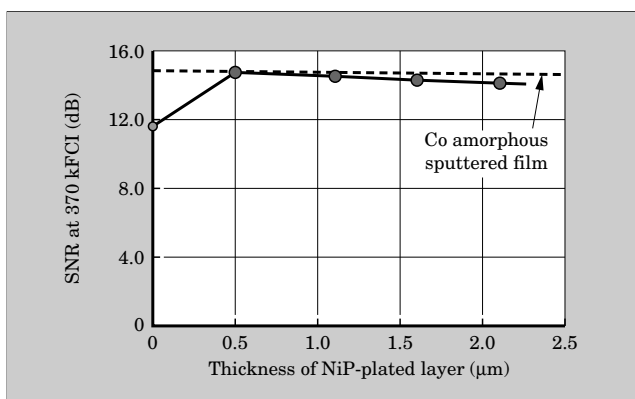
Figure 4 shows the signal-to-noise-ratio (SNR) dependency on thickness of the plated layer at a linear recording density of 370 kFCI (flux changes/inch) in perpendicular magnetic recording media produced using an aluminum substrate attached to an NiP-plated soft magnetic underlayer. The dotted line in the figure shows the SNR values of perpendicular magnetic recording media similarly produced on top of a 200 nm-thick Co alloy amorphous soft magnetic underlayer fabricated by sputtering.

The SNR values of the perpendicular magnetic recording media on an NiP-plated soft magnetic underlayer are essentially the same as those of the media on a sputtered soft magnetic underlayer. Moreover, a comparison between the overwrite performance of the media confirms that the media which uses the newly developed NiP-plated soft magnetic underlayer realizes almost same recording performance as the media that uses the conventional sputtered soft magnetic underlayer.

Fuji Electric is also developing technology for fabricating a plated soft magnetic underlayer on a glass substrate. This was previously considered difficult to achieve, but by developing a new glass substrate preprocessing technique, it is becoming apparent that sufficient adhesive force and manufacturability can be achieved simultaneously.

The use of aluminum and glass substrates to which this plated soft magnetic underlayer is attached will eliminate the need for the sputtered fabrication of thick soft magnetic underlayers. It is extremely advantageous that perpendicular magnetic recording media can be manufactured using the sputtering equipment of conventional longitudinal magnetic recording media and this is considered to be a large factor in approaching the practical application of perpendicular magnetic recording media.

Fig.4 Change of SNR vs. thickness of NiP-plated layer



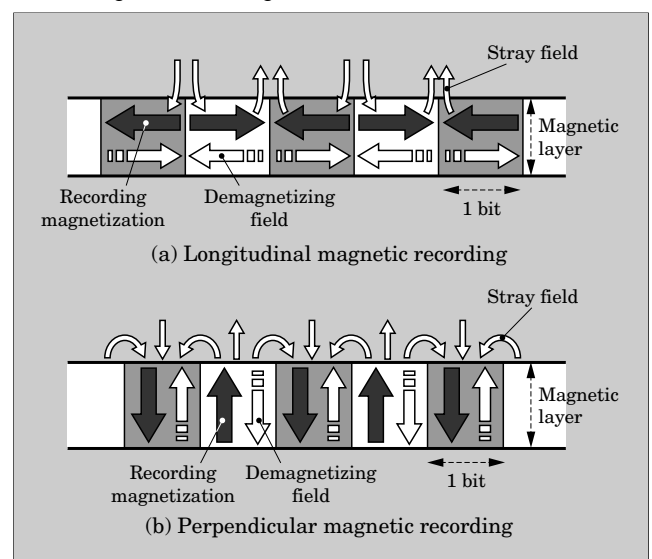
4. Granular Magnetic Layer Technology

4.1 Problems and challenges associated with conventional media

Figure 5 (a) schematically shows the longitudinal magnetic recording method and Fig. 5 (b) schematically shows the perpendicular magnetic recording method. In the case of longitudinal magnetic recording method media that magnetically records information bits in a direction parallel to the plane of the media, as the recording density increases, a demagnetization field increases in a direction that counteracts the recorded magnetization corresponding to the information bits, and thus the recorded information bits become unstable. If the trend toward higher densities progresses and the recorded bits become smaller in size, the corresponding magnetic energy of the magnetic grain will decrease and recorded bit information will gradually be erased by the thermal energy at room temperature. This is the so-called “thermal stability” problem. The longitudinal magnetic recording method is presently achieving recording densities of 60 to 100 Gbits/in², and its practical limit will probably be reached at densities of 160 to 200 Gbits/in².

On the other hand, because the perpendicular magnetic recording method records bit information in a direction perpendicular to the plane of the media, it is unlikely that a demagnetization field would cause a thermal stability problem as in the case of the longitudinal magnetic recording method. Because the magnetization tends to become more stable as the recording density is increased, and thus the recorded magnetization is better able to withstand a demagnetization field, the method of perpendicular magnetic recording is, in principle, well suited for high density magnetic recording.

Fig.5 Schematic diagram of longitudinal and perpendicular magnetic recording



In general, to achieve lower noise performance of magnetic recording media, regardless of whether longitudinal or perpendicular recording methods are used, it is necessary to make the grains that constitute the media as small and uniform in size as possible and to magnetically isolate them from one another. If the grain size is made even smaller in order to achieve lower noise performance, the magnetic energy of the grains will decrease in accordance with the decreased cubic volume of each grain and this will result in deterioration of the thermal stability. Therefore, it is important that a material having a large value of magnetocrystalline anisotropy (K_u) is utilized.

With longitudinal magnetic recording media, by sputtering a CoCrPt alloy onto a heated underlayer, the Cr atoms, which are less soluble to Co, segregate to the grain boundary, thereby achieving a small size and magnetic isolation of the grains, and because the main entity becomes the CoPt alloy which has a large intragranular K_u value, thermal stability is maintained.

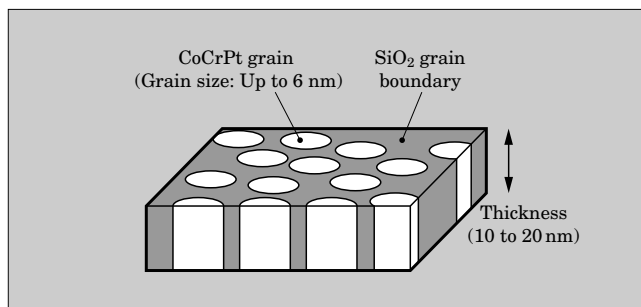
On the other hand, if heated film deposition using a CoCrPt alloy is similarly performed with perpendicular magnetic recording media, the Cr will be less likely to segregate to the grain boundary and the grain size will become larger than in the case of longitudinal magnetic recording media. Moreover, because the Cr is less likely to segregate at the grain boundary, the intragranular K_u values in grains containing residual Cr are lower than expected, and the simultaneous realization of low noise performance and high thermal stability is difficult to achieve. Because the axis of easy magnetization, the c-axis in a hexagonal close-packed (hcp) structure is oriented in a direction perpendicular to the film surface in the case of perpendicular magnetic recording media, the conjectured cause of this phenomenon is believed to be due to the orientation of the hcp (002) surface, having the lowest surface energy and whose grain size are likely to become coarse during thin film deposition. Consequently, a magnetic layer having low noise and high thermal stability must newly be developed for use with the perpendicular magnetic recording media.

4.2 Granular magnetic layers for higher recording densities

Prior to developing perpendicular magnetic recording media, Fuji Electric leveraged its experience in developing low-temperature-deposition capable, granular-type longitudinal magnetic recording media by developing a magnetic layer for use in granular-type perpendicular magnetic recording media that simultaneously achieves small granular size, decreased intergranular magnetic interactions and a high perpendicular orientation.^{(3), (4)}

In the granular magnetic layer we developed, CoCrPt-SiO₂ with an additive of SiO₂ or other oxide is used as the grain isolation material. Figure 6 shows a

Fig.6 Schematic diagram of granular magnetic layer



schematic diagram of this magnetic layer. Because the non-metal of SiO₂ is added, SiO₂ easily precipitates out at the grain boundary even without heating the substrate at the time of film deposition, and this has the advantage of increasing the degree of isolation among grains at room temperature and maintaining a large intragranular K_u value.

However, because the substrate is not heated, it is difficult to control the growth of grains in the granular magnetic layer. Consequently, it is important to control the microstructure of an intermediate layer provided underneath the magnetic layer. Specifically, by controlling the unheated film deposition conditions of a ruthenium (Ru) intermediate layer, this method decreases the variations in Ru crystallinity and grain size, thereby improving the crystallinity and grain size uniformity of the granular magnetic layer. The results of various studies have revealed that in order to grow a single magnetic grain on top of a single grain in the Ru intermediate layer, it is important to control the initial growth layer of the magnetic layer by controlling the size of grains in the Ru intermediate layer or by controlling the surface condition of the Ru intermediate layer. Based on this knowledge, we were able to control the desired microstructure by implementing extremely high level and precise control of the film deposition conditions.

As a corporate participant in the “Development of High Density and Small Size Hard Disk Drives” [IT program (RR2002) of MEXT] collaborative research project for which the Research Institute of Electrical Communication at Tohoku University plays a central role, Fuji Electric is conducting research into higher density granular magnetic layers.

This collaborative research has already confirmed that the CuCrPt alloy magnetic layer formed on the Ru intermediate layer has an extremely large K_u value of 9×10^6 erg/cm³ or above, and even when SiO₂ is added to this Co alloy magnetic layer to give it a granular structure, the intragranular K_u value is maintained at an extremely large value. This finding suggests that it will be possible to realize perpendicular magnetic recording media that maintains high thermal stability even if the grain size in the magnetic layer is reduced beyond its present size. Based on the results of this study, we believe that it is possible to realize perpen-

dicular magnetic recording media having a high areal density of 200 Gbits/in² or more by optimizing the composition of the existing granular magnetic layer to increase the K_u value, suitably controlling the microstructure of the Ru intermediate layer to obtain uniform magnetic grains, and advancing miniaturization and magnetic isolation.

4.3 Improvement of the overwrite performance

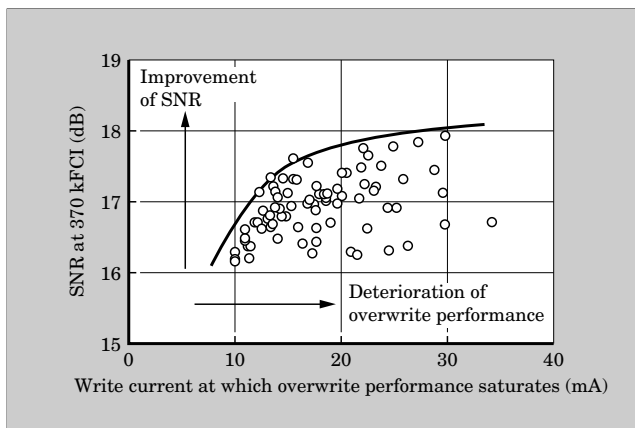
In the case where miniaturization and magnetic isolation of the grains in the magnetic layer are advanced in order to achieve lower noise performance and the intragranular K_u value is increased in order to maintain high thermal stability as described above, there is concern that coercivity (H_c) of the magnetic layer will increase, resulting in a deterioration of the overwrite performance. On the other hand, in order to support the higher track densities that accompany high density media, the track width of the magnetic head's writing element must be made narrower. This narrowing of the track width causes the magnetic field generated by the magnetic head to decrease. Consequently, improving the overwrite performance of the media will become increasingly important in the future.

As a result of advancing the control of the microstructure and magnetic layer composition in order to decrease noise while maintaining high thermal stability in the granular magnetic layer we developed, the larger H_c value caused the overwrite performance to become insufficient in the case of a narrow track head, and consequently the record and playback performance deteriorated.

Figure 7 shows a graph of the SNR at the write current at which overwrite performance saturates, indicating the overwrite capability of the media at a linear recording density of 370 kFCI in granular magnetic layer media produced under various conditions. From the graph, it can be seen that the overwrite capability of media deteriorates as the SNR value increases.

In order to overcome this tradeoff and to realize

Fig.7 Relationship between SNR and overwrite performance



good write capability and SNR characteristics simultaneously in the media, we attempted to improve the composition of the granular magnetic layer and the film deposition process. In other words, in order to enhance the overwrite performance while maintaining low noise characteristics without changing the grain size and grain boundary structure of the magnetic layer, and instead of changing the controlled microstructure and surface conditions of the Ru intermediate layer, it is important to improve the composition of the granular magnetic layer and the film deposition process.

Table 1 lists the overwrite performance and SNR values for media A having improved write capability and conventional media B, which were evaluated using heads of different track widths. Here, media A has an H_c value of 5.3 kOe and media B has an H_c value of 6.6 kOe. In the case where measurement was made with a magnetic head having a wide track width of 0.3 μm and generating a large magnetic field, the overwrite performance of approximately 40 dB was sufficient for both types of media and the SNR was essentially the same in both cases. On the other hand, when the measurement was performed with a magnetic head having a narrow track width of 0.2 μm which is compatible with high density media, in contrast to the extremely poor overwrite performance of less than 30 dB and the low SNR of media B, media A exhibited a dramatic improvement with a relatively good overwrite performance of 36 dB and an SNR of 1.5 dB greater than that of media B. Accordingly, by improving the write capability without changing the microstructure of the magnetic layer, it is possible to realize media that provides sufficient overwrite performance and exhibits a large SNR even with a narrow-track-width head.

A spin-stand tester was used to measure the potential of the high density perpendicular magnetic recording media we developed, and those results are shown in Table 2. Because the spin-stand tester cannot be expected to have a precise tracking servo as in the HDD, measurement was performed with the on-track mode. Specifically, the byte error rate (BER) is measured while varying the linear recording density, the linear recording density is obtained at the time

Table 1 Recording performance of improved media

	Overwrite performance (dB) 379 kFCI overwritten by 50 kFCI	SNR (dB) 370 kFCI
Improved media A+ Wide-track head	39.2	15.05
Conventional media B+ Wide-track head	40.0	14.75
Improved media A+ Narrow-track head	36.4	21.25
Conventional media B+ Narrow-track head	29.9	19.68

Table 2 Recording density achieved

	Linear recording density (BER = 10^{-5})	Gbits/in ² (BAR = 1 : 5)
May 2002	727	106
September 2002	793	126
July 2003	867	150
February 2004	900	162

when BER = 10^{-5} and then the obtained value is multiplied by the bit aspect ratio (BAR) of the linear recording density to track density which is set at 1 : 5 to compute the areal recording density. Here, the thickness of the carbon protective film in the perpendicular magnetic recording media ranges from 3.5 to 4.5 nm and this is 2.5 nm thicker than the design specification. The measured results reflect this correspondingly large spacing loss, but according to the results of a recent evaluation, the areal recording density of 162 Gbits/in² has been realized.

5. Conclusion

In order to realize the ubiquitously networked society of the 21st century comfortably, the existence of low cost cache memory capable of rapidly processing large quantities of intermediate information clusters is essential. The device exhibiting the best balance

among the requirements for large capacity, high speed and low cost is the HDD. If practical application of a palm-sized, large capacity, perpendicular magnetic recording HDD is achieved, it is thought that the market for HDD memory applications will expand endlessly.

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