Perpendicular Magnetic Recording

From Invention to Commercialization

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***Abstract*—Perpendicular Magnetic Recording (PMR) was invented in 1975 by Shunichi Iwasaki, a Professor of Tohoku University at that time, and his research group. The first paper to report successful experimental demonstration of high density recording by PMR was published in 1977 in the IEEE Transactions of Magnetics. After 28 years of intensive works, perpendicular magnetic recording was commercialized on hard disk drive (HDD) in 2005. It achieved great success used for all hard disk drives within a couple of years. In this paper, an innovation of PMR research and its engineering HDD integration processes from the invention to the commercialized products are reviewed.**

Keywords—perpendicular magnetic recording; head; medium; hard disk drive; Co-Cr; Co-Pt-Cr-O; double layered medium; single-pole-type head

I. INTRODUCTION

The amount of created information is rapidly growing due to the vast spread of ICT (Information and Communication Technology) along with the various Internet services. Data storage is therefore becoming an indispensable infrastructure of society. Magnetic recording contributes as the core technology to store the gigantically large information, such as hard disk drives and magnetic tapes in offices, homes, data centers, and everywhere. Nowadays all hard disk drives and even tape drives employ perpendicular magnetic recording that had taken over conventional longitudinal magnetic recording. By perpendicular magnetic recording the areal recording density on a recording medium of magnetic recording devices was dramatically increased so that information storage capacity can meet the demand for the large information.

The technology transition took place to establish the novel paradigm of perpendicular magnetic recording. Professor Dr. Shunichi Iwasaki and his research team in the Research Institute of Electrical Communication, Tohoku University, Sendai, Japan, was the inventor of perpendicular magnetic recording. The first paper that reported successful experimental demonstration of high density perpendicular magnetic recording was published by Shunichi Iwasaki and Yoshihisa Nakamura in 1977 [1]. The following paper on the improved structure of recording medium was established principle head and medium structure [2]. The first hard disk drive by perpendicular magnetic recording was shipped in 2005 [3]. It took all of 28 years until that technology first appeared in the marketplace. Very shortly after, front-running teams had put the product into the market in US, Japan, and worldwide. It was only several years that perpendicular magnetic recording totally replaced conventional longitudinal recording in all hard disk drives. To the significant technological transition many experts from wide areas of science and technology contributed, such as nano-magnetics technology, magnetic material, electrical engineering, signal processing, precision mechanics, tribology, and so on. Perpendicular magnetic recording is not merely technological invention but also a comprehensive evolution of science of magnetism, magnetic recording engineering, information science, and social science of big data era. [4]

In the second half of this paper, the foundation of the intrinsic design concept of stable perpendicular magnetic recording and the key material development results in research state are reviewed. The integration of the perpendicular magnetic recording into HDD system at the recording density up to 133 Gbit/in^2 was also studied. Through the HDD integration study for commercialization, the performance consideration for high density perpendicular magnetic recording and the impact to future small form factor design direction are discussed.

II. INVENTION OF PERPENDICULAR MAGNETIC RECORDING

A. Fundamental structure of perpendicular head and medium

In the first perpendicular magnetic recording paper published in 1977 [1], the first evidence of perpendicularly recorded magnetization was explicitly demonstrated by experiments. They employed a recording layer of cobalt-chromium (Co-Cr) perpendicular magnetic anisotropy film [5] and single-pole writing head [6]. Although there was a similar recording head proposal before the invention [7], no evidence on the existence of perpendicularly recorded magnetization in the recording layer was presented.

Essentially novel magnetic writing-head and recording medium, and new recording physics, were indispensable to establish perpendicular magnetic recording. In the first paper in 1977 [1], the fundamental structure of writing-head and recording layer with perpendicular magnetic anisotropy was presented to experimentally show the superior high density recording performance. Right after the first paper, the double-layered recording medium structure was presented [2], which achieved a strong writing field with the magnetic image effect with the soft-magnetic film of the double-layer structure. The novel recording physics of complementary principle on perpendicular recording was established in 1980 [8]. The fundamental recording scheme thus established and remains unchanged even today in the practical hard disk drive applications.

In order to realize the perpendicular magnetization, the recording layer must have a sufficiently strong perpendicular magnetic anisotropy to keep the perpendicular magnetization against the demagnetization field. Information writing into the Co-Cr recording media was carried out by the dominant perpendicular recording field generated by the single-pole head. Thus, the Co-Cr based perpendicular anisotropy media with the soft-magnetic underlayer and the single-pole head are imperative combination of perpendicular magnetic recording. Fig. 1 schematically shows a principle structure of the head and media in perpendicular hard disk drives in comparison with those of conventional longitudinal magnetic recording. It was almost the same as the firstly proposed structure except the read sensor was changed from inductive sensor to a highly sensitive magneto-resistive sensor. This basic head and media structure achieved great success used for all hard disk drives.

The most essential discovery in the invention was the Co-Cr recording medium that possesses perpendicular magnetic anisotropy, which is indispensable to form perpendicularly recorded magnetization in a medium. The Co-Cr film was firstly employed as a recording medium with perpendicular magnetic anisotropy. Because of the shape of recording layer demagnetization field acts to align the magnetization in in-plain direction, perpendicular magnetic anisotropy is therefore necessary to keep the perpendicular magnetization. Fig 2 shows hysteresis loops of Co-Cr films measured with vibrating sample

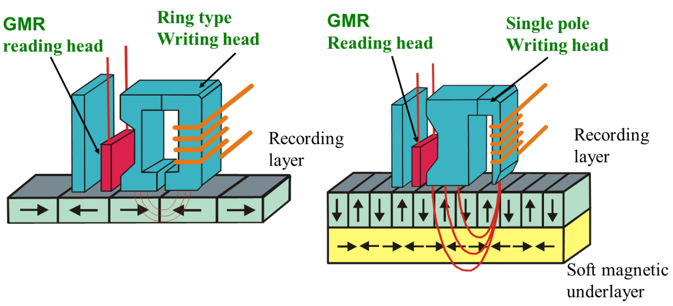

Fig. 1. Head and medium structure of longitudinal (left) and perpendicular (right) magnetic recording.

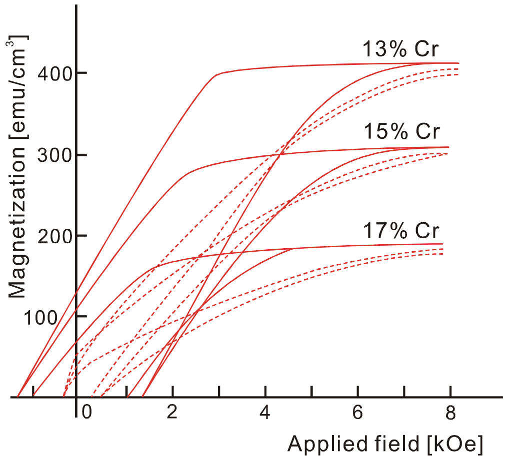

Fig. 2. Perpendicular (solid lines) and in-plane (broken lines) hysteresis curves of CoCr perpendicular recording media with various Cr contents.

magnetometer, or VSM. Because of the shape of the recording layer film, the loops are inclined by demagnetization field. The intrinsic hysteresis loops should be therefore sufficiently square, which means stable perpendicular magnetization in the recording layer.

The Co-Cr medium have a fine granular structure, which also was a significant advantage as a high density recording medium [5]. Such magnetic structure significantly reduces medium noise and attained high areal density recording. Even today the Co-Cr based material is employed with addition of platinum (Pt) in order to enhance magnetic anisotropy.

Single-pole-type writing-head that generates dominant perpendicular recording field was another key device for perpendicular magnetic recording [6]. The single-pole head was originally developed for magnetic tape or flexible disk in early days. Fig. 3 is a schematic structure of the head for tape and flexible disk experiments. It consists of a main pole for writing and a relatively large energizing auxiliary pole with a winding that magnetizes the main pole located at another side of the recording medium. The separated pole structure was not practical for the hard disk drive application, an integrated structure of both poles was later employed. A thin-film

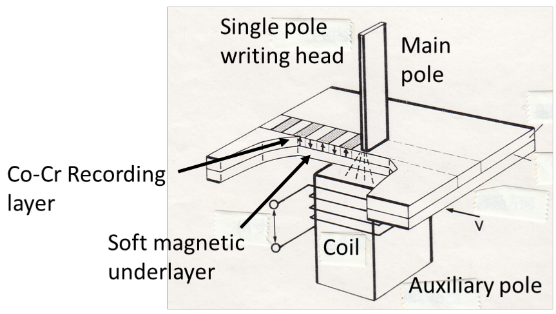

Fig. 3. Originally employed single-pole head for the experiments. Induced flux in the main pole with the auxiliary pole used for writing. In reading, induced main pole flux is detected by the auxiliary pole.

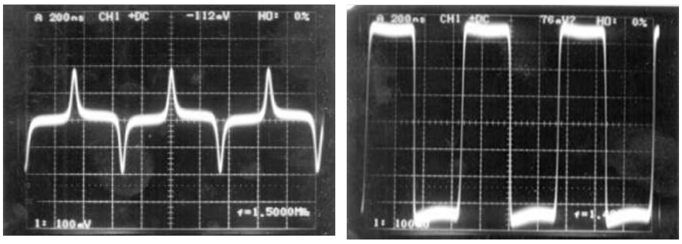

Fig. 4. Read-back waveforms of GMR head for longitudinal (left) and perpendicular (right) magnetization.

conductor surrounding the main pole energized the head to write magnetization.

Because the single-pole writing-head could be also used as the reading-head. Inductive sensors, or coil windings, originally used in the early experiments as reading sensors. The giant magneto-resistive reading-head later took over, because it is much more sensitive than the inductive sensors for high areal-density magnetization in hard disk drives. It was well adapted with reading channels developed for perpendicular magnetic recording. The single-pole head was eventually merged with giant magneto-resistive read-head (GMR head) to ensure a good reading sensitivity.

The read-out waveform of perpendicular recorded magnetization significantly differs from that of longitudinal magnetization. Fig. 4 shows the waveforms, in which the waveform of perpendicular magnetic recording is a sort of antiderivative of that of longitudinal magnetization. This fact meant that read channel must be re-designed to ensure reliable data detection, and therefore, previous LSI chip designed for longitudinal recording cannot be employed. Some new signal processing method were proposed for the unfamiliar waveform. New class of partial response maximum likelihood (PRML) detection was established [9].

Such improved technologies were unified to demonstrate as prototyping of hard disk drive [10]. The areal density at that time was 52.5 Gbit/inch^2, which overridden the cutting edge of longitudinal recording at that time.

III. HARD DISK DRIVE DEVELOPMENT

The invention and the extended research of the practical PMR had led the efforts towards the commercialization of a key storage device HDD. The PMR had been a strongly demanded to break the areal density limit of the longitudinal magnetic recording (LMR).

However, very difficult challenges to realize perpendicular magnetic recording system by using CoCr-based medium in early stage had been identified. Contact recording trial with low Ku (= 1.3 x 10^6 erg/cc) and low squareness (= Mr/Ms) Co-Cr-Ta perpendicular medium showed large signal decay at -3.1 %/decade indicating a severe issue of low density signal degradation with time [11]. Although high Ku (= 2.5 x 10^6 erg/cc) (Co/Pd)n multi-layer medium was introduced, signal stability and high SNR were not sufficiently achieved [12][13][14]. Finally issues of large write spacing loss and external field robustness based on previous low squareness perpendicular media experiments were reported in the reference [15].

A. *Concept of Stable Perpendicular Magnetic Recording*

A CoCr-based medium showed good recording performance at high recording density. However, signal stability at low recording density was insufficient due to thermal agitation. The experimental tests on a low squareness CoCr-based medium revealed severe readout waveform distortion in leading part of the isolated pulse due to the recording demagnetization phenomena by reversed head fields after transition formation. A lack of nucleation field Hn loses the supports to magnetization against disturbing fields and easily degrades the written magnetization resulting in waveform distortion or signal decay [16].

A created fundamental concept was that the high nucleation field was a must to realize stable perpendicular recording mechanism to sufficiently resist thermal agitation. The recording tests on a newly developed high squareness CoPtCrO perpendicular medium successfully showed the suppressed recording demagnetization as shown in Fig. 5 [16][17]. The high perpendicular magnetic anisotropy CoPtCrO medium with exchange coupling among magnetic grains aligned the magnetization perpendicular to plane in recording process to finish up the stable written magnetization. The suppression of the recording demagnetization in writing process on high Hn medium is a key factor to realize stable perpendicular magnetic recording.

The developed CoPtCrO/Ru media showed high squareness of 0.98 and Hn of 2 kOe at 300 K temperature as shown in Fig. 6 [18]. A new sputtering process in high pressure Ar and oxygen mixed gas atmosphere was established to realize granular CoPtO medium with oxygen-rich amorphous grain boundaries. The mixed gas concentration controlled the physical isolation and the exchange coupling among magnetic grains. Cr addition and Ru underlayer were effectively enhanced both of the high nucleation and the isolated fine grain structures [17][18]. The new sputtering process with oxygen was totally different from the conventional CoCr sputtering process which basically avoids oxygen.

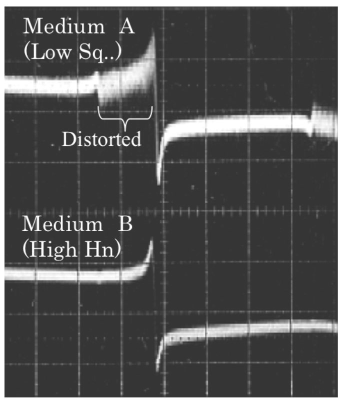

Fig. 5. Isolated pulse waveform of low squareness perpendicular medium A and high Hn perpendicular medium B. Medium A showed severe distortion in leading part of the pulse [16].

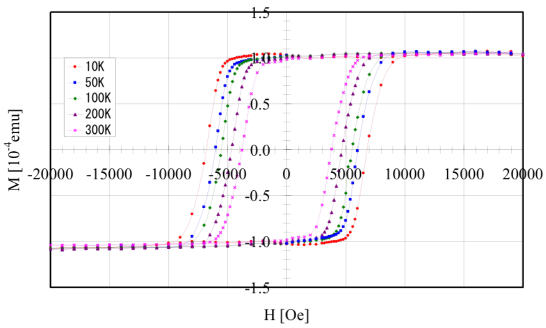

Fig. 6. Hysteresis loop of high Hn CoPtCrO/Ru perpendicular anisotropy media [18]

Fig. 7. Photograph of 1.8" perpendicular magnetic recording HDDs. 40 GB single-platter model (MK4007GAL, 5 mm height; left) and 80 GB two-platter model (MK8007GAH, 8 mm height; right).

B. HDD Integration Challenges of Perpendicular Megnetic Recording

The transition from longitudinal recording to perpendicular recording is the first major recording scheme evolution in the history of the hard disk drive industry. Such big transition could potentially bring up a number of problems. In order to minimize any unexpected or hidden issues, intensive integration study of the perpendicular recording hard disk drive system was conducted in Toshiba.

Perpendicular magnetic recording head and medium operate with strong mutual coupling in both writing and reading. Therefore, the head and medium integration is the key focus to maximize the performance. Toshiba built many prototype drives and tested from the early stage to study the integrated performance and the environmental robustness as working drives [19][20][21].

The first commercial perpendicular magnetic recording HDD was 1.8" 40 GB/platter drives at the areal density of 133 Gbit/in^2 [3] by Toshiba. Fig. 7 shows the photograph of the 1.8" perpendicular magnetic recording HDD products of 40 GB model (single platter, 5 mm height) and 80 GB model (two platters, 8 mm height). The bit error rate (BER) of the drive was 3 x 10^{-6} or $\log_{10}$(Raw BER) of -5.52 at 989 kBPI.

C. Fundamental Features pf Perpendicular Magnetic Recording

The study of perpendicular magnetic recording integration into HDDs revealed the fundamental behavior and features. Thermal stability is one of the most important feature as data storage devise. Fig. 8 shows the recording density dependence of signal thermal decay rate which is defined as averaged signal amplitude loss in dB for every tenfold time period in unit "dB/decade". The observed signal decay rate was as small as -0.055 dB/decade at low linear density of 10 kBPI. In contrast with longitudinal magnetic recording for which thermal decay rate becomes larger as linear density increases [22], perpendicular recording behaves to approach nearly zero as the linear density increases up to 460 kBPI. The natural property of the dipole magnetization pair enhances the thermal stability in the high density region and is the most important significance of the perpendicular recording. The thermal decay rate can be controlled with the medium nucleation field Hn to provide ample performance margin even at low recording density. The raw BER hardly showed degradation with time from 1 second to 200k seconds, longer than 5 decades of time. The concept of the high squareness and high Hn perpendicular medium magnetics based on the CoPtCrO material [18] was found to be valid.

A significant finding was that the BER of perpendicular magnetic recording on high Hn medium was less sensitive to flying height (corresponds to head-media spacing) than that of longitudinal magnetic recording [20]. Perpendicular magnetic recording showed about 30% less flying height sensitivity than longitudinal recording as shown in Fig. 9. Air pressure sensitivity in write process was found almost half of that in read process for perpendicular magnetic recording.

In order to expand operational temperature range, the write performance at low temperature is very important because the write performance could be easily degraded due to temperature dependent anisotropy of recording layer. In comparing to BER

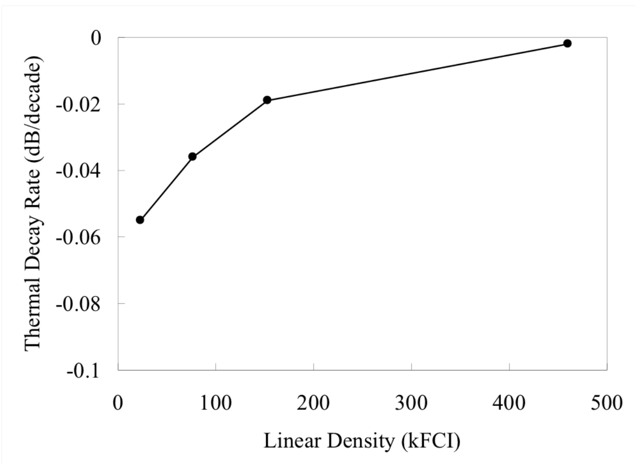

Fig. 8. Recording density dependence of signal thermal decay rate at 65 degree C temperature

of longitudinal recording which degraded by 1.3 at -20 degree C in synchronizing with overwrite degradation at low temperature due to the increased switching energy of the recording layer, perpendicular recording showed BER (logarithmic) degradation by only 0.5 at -20 degree C. Perpendicular recording keeps higher degree of margin in the write performance than longitudinal system in cold environment [20].

The investigated key features in perpendicular recording integration are reviewed in comparison with those of longitudinal recording. Table I shows the original findings of the complementary relationship [8] and the features of thermal stability, spacing sensitivity, low temperature performance and others revealed in drive integration [18][20][21][23]. As suggested in Table I, perpendicular recording and longitudinal recording have a complementary relationship in various performance based on the difference of the interaction between magnets as recorded bits. The complementary relationship between perpendicular and longitudinal recording becomes the fundamental guiding for future high density recording research.

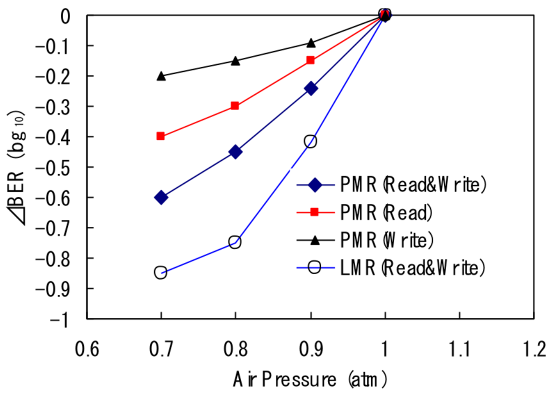

Fig. 9. BER change as a function of air pressure for perpendicular magnetic recording (PMR) at 133 Gbit/in^2 and longitudinal magnetic recording (LMR) at 83 Gbit/in^2. 0.1 atm air pressure reduction corresponds to about 1 nm flying height reduction. [21]

TABLE I
Complementary relationship and performance-related features in HDD integration between perpendicular recording and longitudinal recording

	Perpendicular	Longitudinal
Original findings of complementary relationship [8]		
	$\lambda \rightarrow 0$, $Hd \rightarrow 0$	$\lambda \rightarrow 0$, $Hd \rightarrow 4\pi M$
Head	Single pole-type	Dipole (Ring)-type
Medium	Perp. Anisotropy	Longi. Anisotropy
	Thick d	Thin d
	High Ms, High Hc	Low Ms, High Hc
Signal	Digital (Sat.)	Analog (non-Sat.)
Rec. Method	(FM, PCM)	AC Bias Method
Erase	DC Field	AC Field
Performance-related features in HDD integration		
Media	High squareness	Low squareness
	(Uni-axial orientation)	(Pseudo-2D random ori.)
	With soft underlayer	Recording layer only
Thermal	Good at high density	Good at low density
Stability	- Controlled by Hn	
Write Process	Medium in write flux path	Medium outside of path
	- Efficient writing	
	- High frequency writing	
	- Wide temperature range	
	Low spacing sensitivity	High spacing sensitivity
	- Relaxed spacing	- Narrow spacing required
	Sharp transition	
	Narrow erase band	
	- High TPI servo writing	
Read Process	High output	Low output
	- High SNR	
	- Good tracking servo	
	- Relaxed head sensitivity	- High head sensitivity required
	Narrow reading	Wide reading
Signal	With DC component	Without DC component
Channel	Positive coefficient PRML	Negative coefficient PRML

IV. Conclusions

In 1977, 40 years ago, the first paper on perpendicular magnetic recording was published by Shunichi Iwasaki and his research team in Research Institute of Electrical Communication, Tohoku University. The innovation on the Co-Cr perpendicular recording medium, single-pole writing head, and complementary recording physics were firstly established to achieve the perpendicularly recorded magnetization against demagnetizing field. The research team experimentally proved high density perpendicular recording was achieved.

The intrinsic and practical design concept of stable PMR was established in 2001 through the research to realize a creative high-squareness granular perpendicular recording medium. The high nucleation field of perpendicular magnetic medium supports the very stable magnetization against disturbance fields in recording processes. Thereafter, the high-squareness granular perpendicular medium structure with oxide-based grain boundaries became the industry standard in commercialization. Toshiba successfully developed the world's first 1.8" 40 GB/platter HDD product featuring the PMR technology at the highest recording density of 133 Gbit/in2 as a commercial HDD in 2005. The integration study showed that the thermal stability, low temperature performance and spacing robustness in writing process were great advantages of the PMR HDDs. PMR and LMR have a complementary relationship in various performance based on the difference of the interaction between magnets as recorded bits. This was a complete guiding principle to make the research and development efforts successful.

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REFERENCES

[1] Shunichi Iwasaki, Yoshihisa Nakamura, "An Analysis of the Magnetization Mode for High Density Magnetic Recording," IEEE Trans. Magn., MAG-13, 1272-1277, 1977.

[2] Shunichi Iwasaki, Yoshihisa Nakamura, Kazuhiro Ouchi, "Perpendicular Magnetic Recording with a Composite Anisotropy Film," IEEE Trans. Magn., MAG-15, 6, 1456-1458, 1979.

[3] Available: http://www.toshiba.co.jp/about/press/2004_12/pr1401.htm

[4] Shunichi Iwasaki, "Perpendicular Magnetic recording -Its development and realization-", Proc. Jpn. Acad., Ser. B, 85, 37-53, (2009).

[5] Shunichi Iwasaki, Kazuhiro Ouchi, "Co-Cr Recording films with perpendicular magnetic anisotropy," IEEE Trans. Magn., MAG-14, 5, 849-851, 1978.

[6] Shunichi Iwasaki, Yoshihisa Nakamura, "The Magnetic Field Distribution of a Perpendicular Recording Head," IEEE Trans. Magn., MAG-14, 5, 436-438, 1978.

[7] A. S. Hoagland, "High-Resolution Magnetic Recording Structures," IBM J. 2, 2, 91-104, Apr. 1958.

[8] Shunichi Iwasaki, "Perpendicular Magnetic Recording," IEEE Trans. Magn., MAG-15, 1, 71-76, 1980.

[9] Yoshihiro Okamoto, Hisashi Osawa, Hidetoshi Saito, Hiroaki Muraoka, Yoshihisa Nakamura, "Performance of PRML systems in Perpendicular Magntic Recording Channel with Jitter-like Noise," J. Magn. Magn. Mat, 235, 259-264, 2001.

[10] Hisashi Takano, Yasutaka Nishida, Atsuko Kuroda, Hideki Sawaguchi, Yuzuru Hosoe, Takashi Kawabe, Hajime Aoi, Hiroaki Muraoka, Yoshihisa Nakamura, Kazuhiro Ouchi, "Realization of 52.5 Gb/in2 Perpendicular Recording," J. Magn. Magn. Mat., 235, 241-244, 2001.

[11] H. Hamilton, R. Anderson, K. Goodson, "Contact perpendicular recording on rigid media", IEEE Trans. Magn., Vol. MAG-27, no. 6, pp. 4921-4926, 1991

[12] W. Cain, A. Payne, M. Baldwinson, R. Hempstead, "Challenges in the practical implementation of perpendicular magnetic recording", IEEE Trans. Magn., vol. MAG-32, no. 1, pp. 97-102, 1996

[13] H. Hamilton, "Status report: Perpendicular contact recording on rigid media", JMSJ, vol. 18, Supplement, no. S1, pp. 171-178, 1994

[14] B. Larsson, K. Ho, S. Sun, "PRML recording performance of multilayer Pt/Co alloy media", JMSJ, vol. 21, Supplement, no. S2, pp. 135-139, 1997

[15] D. Thompson, "The role of perpendicular recording in the future of rigid disk storage", JMSJ, vol. 21, Supplement, no. S2, pp. 9-15, 1997

[16] A. Takeo, S. Oikawa, T. Hikosaka, Y. Tanaka, "A new design to suppress recording demagnetization for perpendicular recording", IEEE Trans. Magn., vol. 36, no. 5, pp. 2378-2380, Sep. 2000

[17] S. Oikawa, T. Akihiko, T. Hikosaka, Y. Tanaka, "High performance CoPtCrO single layered perpendicular media with no recording demagnetization", IEEE Trans. Magn., vol. 36, no. 5, pp. 2393-2395, Sep. 2000

[18] Y. Tanaka, T. Hikosaka, "Perpendicular recording with high squareness CoPtCrO media," *J. Magn. Magn. Mater*., 235, pp.253-258, 2001

[19] Y. Tanaka, N. Nakamura, and K. Watanabe, "Current development status and future prospects of magnetic recording and optical disc technology," *Toshiba Review*, Vol. 57, No. 7, pp. 2-7, 2002

[20] Y. Tanaka, "Recording performance and system integration of perpendicular magnetic recording," *J. Magn. Magn. Mater*., 287, pp.468-474, 2005

[21] Y. Tanaka, "Fundamental features of perpendicular magnetic recording and design consideration for future portable HDD integration", IEEE Trans. Magn., vol. 41, no. 10, pp. 2834-2838, Oct. 2005

[22] Y. Hosoe, I. Tamai, K. Tanahashi, Y. Takahashi, T. Yamamoto, T.Kanbe, Y. Yajima, "Experimental study of thermal decay in high-density magnetic recording media," *IEEE Trans. Magn*., vol. 33, no. 5, pp.3028-3030, Sep. 1997

[23] Y. Tanaka, "Integration of perpendicular recording to HDD," *Proc. IEICE Tohoku Section Symposium on Advanced Technology*, pp.27-34, 2002 (in Japanese)