Review

Perpendicular magnetic recording —Its development and realization—

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(Contributed by Shun-ichi IWASAKI, M.J.A.)

Abstract: The principle of conventional magnetic recording is that magnetic fields are applied parallel to the plane of the magnetic medium. As described in this paper, the invention and development of a new method of placing the magnetized information perpendicular to the plane of the magnetic recording medium is presented. The yield in the mass production of high-density hard disk drives (HDDs) for perpendicular recording is much higher than that of HDDs for conventional recording. Consequently, it is estimated that as many as 75% of the 500 million HDDs to be shipped this year will use this technology.

Keywords: perpendicular magnetic recording, high density recording, hard disk drive

1. Introduction

In May 2005, Toshiba (Japan) announced the shipment of a new music player with an installed hard disk drive, which for the first time in the world, used perpendicular magnetic recording. It was in 1977 that I first presented perpendicular magnetic recording at the International Magnetic Conference in Los Angeles. Therefore, it took all of 28 years until that technology first appeared in the marketplace.

Soon after, in January 2006, a perpendicular disk for computers was introduced into the market by Seagate Technology (U.S.A.), followed by Hitachi Global Storage Technologies (Hitachi GST, Japan) in May 2006, then by Fujitsu (Japan) in December 2006. Those front-running teams that had put the product into the market, Toshiba and Hitachi, were led by researchers who had been involved with the Iwasaki Laboratory of the Research Institute of Electrical Communication, Tohoku University.

The defect rate of perpendicular hard disks in mass production is much lower than that of the conventional horizontal type. Therefore, it is said that more than 70% of the 500 million hard disks that are scheduled to ship this year will use perpendicular magnetic recording technology. That ratio and related shipping volumes are increasing further and are expected eventually to replace longitudinal recording entirely in coming years. Taken together, this reflects that we are in the midst of technology innovation from a horizontal type to the perpendicular type, as far as hard disks are concerned. Seeing such a situation that products using the technology are now in mass production and placed widely in the marketplace, I finally feel proud satisfaction at being the inventor of such a widely used product.

Looking back at my research work of the past, I remember that I started working on magnetic recording in the 1950s under the direction of Prof. Kenzo Nagai. I focused the first efforts of my magnetic recording research, during 1952–1975, on analysis of basic recording process. The result of this research can be summarized in the following two works:

1) Development of metal particulate magnetic tape in 1958[1)]
2) Establishment of a recording theory based on self-consistent magnetization in 1968[2)]

During that work, it became clear to me that the increase of recording density was most important for research on magnetic recording. The

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invention of metal tape described above and the establishment of the theory of high-density magnetic recording were both achievements along that path of development. Moreover, I had noticed by 1975 that magnetization perpendicular to the plane of the recording medium was an extremely effective means to improve the recording density.[3),4)] These speculations and four discoveries are shown as major milestones in the early research on perpendicular magnetic recording that guided the beginning of perpendicular magnetic recording, as the following.

I. Perpendicular magnetization in longitudinal magnetic tape (1974)
II. Co-Cr alloy film with uniaxial perpendicular magnetic anisotropy (1975)
III. Effect of a double layer in perpendicular/longitudinal composite media (1978)
IV. Complementarity between perpendicular and longitudinal recording (1979)

Since that time, I have been working continuously on development of the magnetic head, specifically examining the basic structure of the recording medium and the evaluation of new characteristics of write/read processes. The principal policy of the research and development of perpendicular magnetic recording that I have conducted was that it was always open and therefore constantly advanced through the collaboration of many industries and universities at the Committee 144 on Magnetic Recording (established originally in August 1976) organized by the Japan Society for the Promotion of Science.

To date, the research has been conducted through research committee meetings held over 190 times (held every other month) and from eight international conferences on perpendicular magnetic recording. The collaboration of industries and academies, which is now proceeding widely in many fields, was already carried out at that time. This formation of a research organization took the key role in creating the perpendicular disk drive industry, as described later, which is a major innovation originating from Japan. I am very proud that I was able to organize such significant collaboration among industries and universities.

As described above, research work on this subject has been conducted in such a wide-open fashion and for an extremely long period. However, regarding the perpendicular disks that are on the market nowadays, nothing of its fundamental structure has changed from its original invention, such as its recording material, which is made from a cobalt and chromium alloy. The mode of combining a two-layer thin film recording medium with the single-pole type recording head also remains fundamentally unchanged, all of which means that it is tacitly understood that what is being done now is to continue to achieve the objective set forth in that invention merely by forming its structure more precisely than ever before.

That we worked from a definite guideline of development from the beginning of the research and development work must be underscored as a salient feature of this research. There can be no doubt about it.

Within the main context described below. Therefore, I would like to offer an explanation from the inventor's perspective of the ideas arising at the initial stage of the research work in addition to the process of how they have come to be realized.

2. Physics of conventional magnetic recording

Figure 1 depicts the principle of conventional magnetic recording that was used before perpendicular magnetic recording. The ring-shaped magnetic core has a narrow gap of less than 1 μm. A pair of magnetic poles, N and S, appears at edges of the

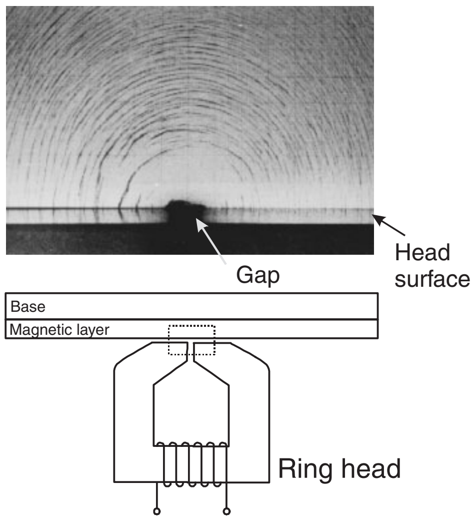

Fig. 1. Fundamental scheme of longitudinal magnetic recording with a ring-shaped head. Magnetic force lines of the ring head in the enlarged model experiment are shown.

gap when electric current flows in the wire coil around the magnetic core. The figure shows that such magnetic 'dipole' yields an arc shape of the magnetic field around the gap.

That figure portrays an enlarged model of a large ring head with iron powder around it at the top. Most iron powder in the vicinity of the gap was attracted to the pole pieces, reflecting that the strongest magnetic field exists there. Therefore, if a tape passes in front of the gap, the magnetic layer of the tape is magnetized, causing small magnets to be created within it; it is remanent as an actual recording. During the read process, when the recorded magnets retained in the magnetic layer of the tape pass in front of the gap, a voltage is generated as a result of magnetic induction effect at the head's wire coil. This principle has been used for the past century, achieving the increase of recording density supported by reduction of the recording magnet size.

Next, I would like to explain how a signal (magnet) is produced and retained on a tape or disk medium. Figure 2 shows an observation made over a cross-section of a magnetic tape.[4)] This is designated as a Bitter pattern, as visualized by attracting iron particles in a colloid solution to magnetic poles at the cutting cross-sectional surface of a recorded track center along the tape's longitudinal direction. Figure 2(a) depicts a low-density recording. Examination of the magnetic poles to which the iron powder is attracted, and also the magnetic field in the space surrounding them, reveals that the magnet is created and is remanent in the magnetic layer in the parallel direction (horizontal direction) to the tape, just as shown in the schematic model. The magnets, placed side by side, are aligned in alternate directions. Consequently, the magnetic flux lines are spread over a wide area outside the tape. During the readback process, a magnetic head detects such a magnetic field, inducing a readback voltage. In a low-density condition, or when both N and S poles of the magnets are separately located, the longitudinal recorded magnets are retained.

On the other hand, with high-density recording, when we try to shorten magnets to pack them closely, we found that the magnets' shape was altered to an eddy-like shape, as shown in (b). I had clarified this fact based on my research that was completed around 1975. The magnets start

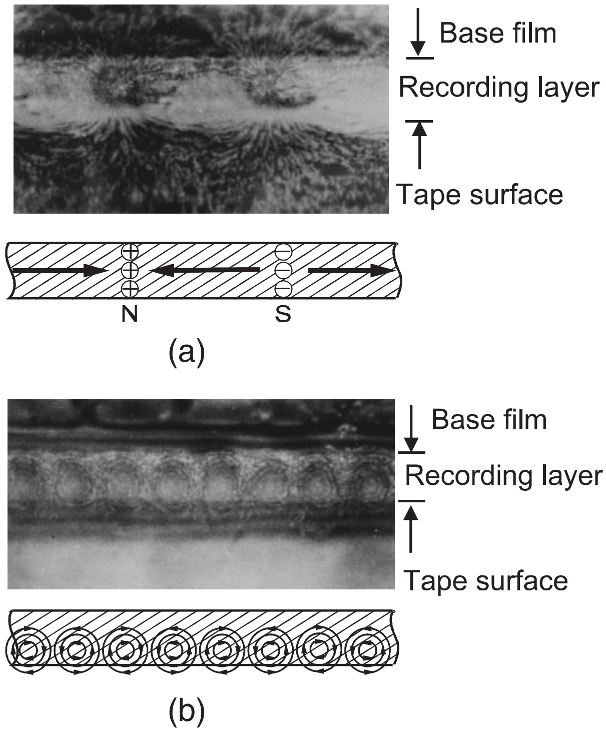

Fig. 2. Bitter pattern images of recorded magnetization at the cross-sectional surface of the magnetic tape: (a) Long wavelength, (b) Short wavelength.

changing into a spiral shape because of the repulsion force (demagnetization field) exerted between neighboring head-on magnets that face each other. As a result, the magnets were increasingly enclosed inside the tape. Thereby, the magnetic flux that was spread outside of the tape decreased; for that reason, the induced voltage for readback head is decreased. Overall, the density of the available highest density signals (shortest magnets) was approaching its upper limit for use. Before this mechanism for the magnetic rotation was clarified, it was understood that the magnetic field strength aligned in the horizontal direction, as shown in (a) in the figure, was weakened; for that reason, the density was approaching its upper limit for use.

Today, we have the means to calculate the magnetic state of the magnetic layer theoretically in a 'self-consistent' manner. Figure 3 portrays a high-density recording calculation example. Each small arrow shown in the figure indicates the direction and the strength of the recorded magnets. In high-density recording, each magnet starts rotating as

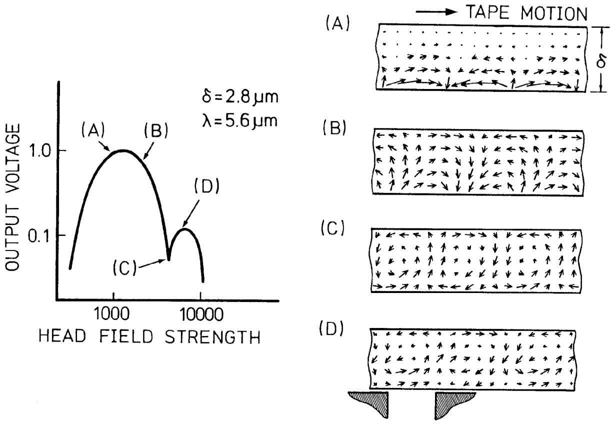

Fig. 3. Recorded magnetization distribution observed using a self-consistent computer simulation (δ, magnetic layer thickness in the tape; λ, recording wavelength).

the magnetic layer is gradually magnetized more strongly and more deeply. The highest playback voltage recognized by the magnetic head can be achieved when every magnet is aligned horizontally, as shown in (A) in the right hand of the figure. We then noticed that the playback voltage became very low when the magnets rotated and closed, as in the state shown in (C).

To achieve high-density recording, therefore, the phenomenon of how the magnets that are created and retained on the medium would rotate was found to be something very fundamental.

Proceeding with the description of the research work as presented above, the behavior of every magnetic recording medium used at that time is as listed in Table 1. In the table, "metal tape" made from alloy powder of iron and cobalt is included, which we developed to accomplish high-density recording.

Based on the results thus obtained, to attain high-density recording with a ring head, the most effective and certain means is to make the magnetic layer of the recording medium thinner and to increase the magnetic energy product (i.e., product of residual magnetization and coercive force) much further. Thereby, the magnetization state of (A) in Fig. 3 is realized. The metal particle tape concept arose based on such a longitudinal magnet.

However, this direction of medium development to achieve high-density recording was looking down the road to the zero thickness of the magnetic layer (consequently, the output voltage is null), which is the same direction in the past that had been taken to make the vacuum tube smaller. Consequently, I anticipated that we would eventually reach a structural limit. That limit loomed as a persistent and perplexing problem that burdened researchers and associated staff members working on magnetic recording at that time.

3. Beginning of perpendicular magnetic recording[3)]

The idea of perpendicular magnetic recording came to my mind first and foremost when I considered the possibility of using the perpendicular component of the magnetization directly for high-density magnetic recording because it always appeared in the pursuit of high-density recording, as described above. In the following, I will describe the early experiment that made me think of that idea (See Fig. 4).

In the experiment, high-density saturation recording was performed using a 12-bit pulse-train digital signal on a magnetic tape. In terms of the readback signals from this experiment, the first and the last readback pulses had large amplitudes, as shown in the waveform at the top of the photograph in Fig. 4. In contrast, the amplitudes of pulses in between, arising from the signals, were small or almost zero. Before this experiment, the reason for the disappearance of pulses was inferred to be that no (horizontal) magnets remained in between.

Table 1 Trend of magnetic recording medium

	γ-Fe_2O_3	Co-γ-Fe_2O_3	CrO_2	Metal particles (FeCo)	Thin film (Co)
Energy product (MGOe)	0.3	0.9	0.8	3.5	6
Film thickness (μm)	12	5	5	2.5	0.1
Linear density (bit/mm)	400	1000	1200	2900	3000
Year	1947	1974	1978	1978	1979

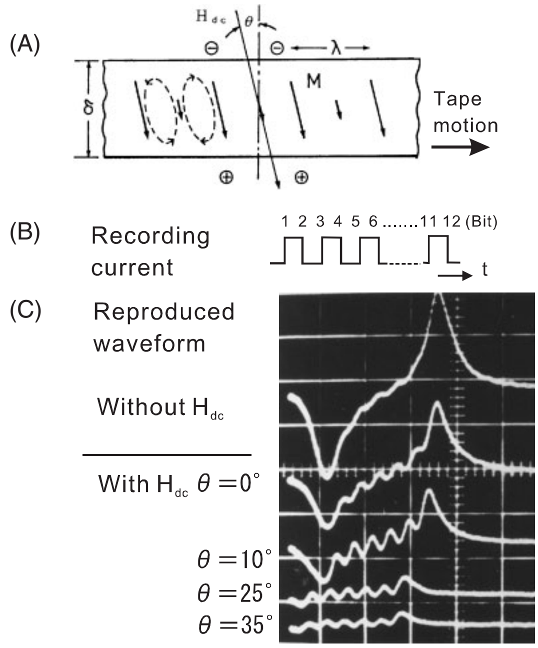

Fig. 4. Magnetization mode transformation by application of a dc magnetic field. (A) Method of mode transformation, (B) Recorded current, (C) Playback waveform variation by application of the dc field (M, magnetization for recording; H_{dc}, applied direct current magnetic field; and θ, angle of H_{dc} from the recording medium plane).

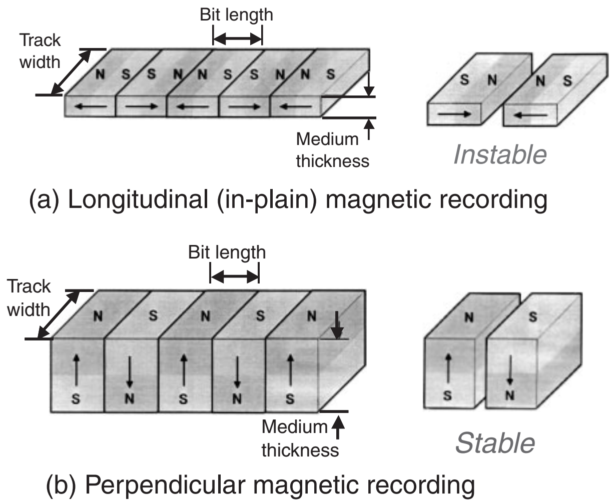

Fig. 5. Longitudinal (in-plane) and perpendicular magnetic recording mode.

However, based on the finding of 'circular magnetization' described above, the magnets were certainly there, with an eddy-like shape, as marked by the dotted line in the figure shown above. It is expected that the magnetic field rotation might be in the rightward direction and leftward direction for adjacent magnets.

I applied a dc magnetic field perpendicularly to the magnetic tape plane to find it. I did so because I expected that such an applied magnetic field (direct current) would strengthen the magnet portion that was aligned in the same direction as that of the spiral in the tape, and simultaneously weaken the neighboring portion, thereby imparting a magnetization distribution with strength and weakness appearing alternately, as shown by the short and long arrows in the figure. Then, removing the applied magnetic field, I thought perpendicular magnets of positive and negative magnetic poles would each appear as mutually adjacent, that they would appear side-by-side.

Results showed that the size of the signals in between was apparently restored like the second waveform shown on the photograph. When the magnetic field direction was tilted slightly. The signal amplitude apparently increased. This indicates that the high-density signals, which had been impossible to reach in the past, were detectable in this way by converting the magnetization to a perpendicular direction. I was extremely excited about this result. I again thought clearly about perpendicular magnetization.

To that time, what everybody else had been doing was the way in which we align magnets in the horizontal direction toward the tape plane—the 'longitudinal mode' shown schematically in Fig. 5(a). However, what I found is that another mode exists in which we can align magnets perpendicularly to the tape plane, as depicted in (b) of the figure. This is the 'perpendicular mode', or perpendicular magnetic recording.

Reviewing the characteristics that we have identified so far, we now know that in the longitudinal mode, the magnets aligned as adjacent are invariably repulsive. In other words, such a repulsive force is exerted in the direction in which each magnet (information) is going to spread. For that reason, there seems to exist a fundamental restriction to align magnets in high density and to use them for recording information. We have already described that this type of restriction would appear in the form of magnetization rotation.

In the perpendicular mode, in contrast, the adjacent magnets all exert an attractive force because magnetic poles with different signs are aligned alternately on the plane. In other words, the force is exerted in the direction in which all the magnets are put together. Therefore, it is readily understood that to align magnets or to store records in high density, the perpendicular mode would be far better from a perspective of compactness, i.e. overall density. In fact, the experimental result obtained for magnetization in the perpendicular direction, as described previously, does prove it.

In summary, I finally made up my mind to start research on perpendicular magnetic recording. That was in 1976. I fully expected that the research in that area would expand and change the existing mode of magnetic recording to a great extent. For that reason, I consulted with Dr. Seiji Kaya of the Japan Society for the Promotion of Science. From that time, the 144 Committee for Magnetic Recording was founded to promote it further.

4. Development of perpendicular magnetic recording technology[4)]

The first step I thought of was to change the magnetic head. One must change the magnetic field of the existing ring head by 90° and apply the magnetic field perpendicularly to the tape to make a magnet perpendicular to the tape plane. After numerous trials, we ultimately developed a magnetic head structured with its magnetic main pole made of a thin magnetized film placed on the magnetic layer side of the tape. On the other side was an auxiliary magnetic pole made of a thick magnetic material with a coil. Figure 6 portrays the head used for the enlarged model experiment.[5)] When the electric current is run in the wire coil wound over the auxiliary pole, magnetic flux is generated, which attracted into the main pole and focused strong field distribution appears in front of the main pole. Consequently, the magnetic field is applied perpendicularly to the tape surface. Figure 7 depicts an actual fabricated perpendicular head. On the left-hand-side is the auxiliary pole made of soft magnetic ferrite with a wire coil wound at its tip. The right-hand-side is the main pole made of the thin film of iron and nickel (of less than 1 μm thickness) surrounded by the non-magnetic ceramic material. The tape is intended to move through the gap separating the poles, which is approximately 100 μm wide. That was the first perpendicular head that we developed. Using that head, valuable data

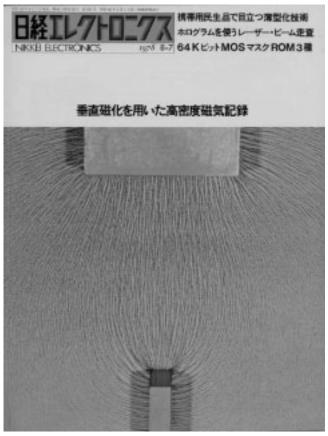

Fig. 6. Magnetic flux distribution of a perpendicular head in an enlarged model experiment. This photograph appeared on the cover of a magazine, Nikkei Electronics, of August 7, 1978,[5)] which reported perpendicular magnetic recording.

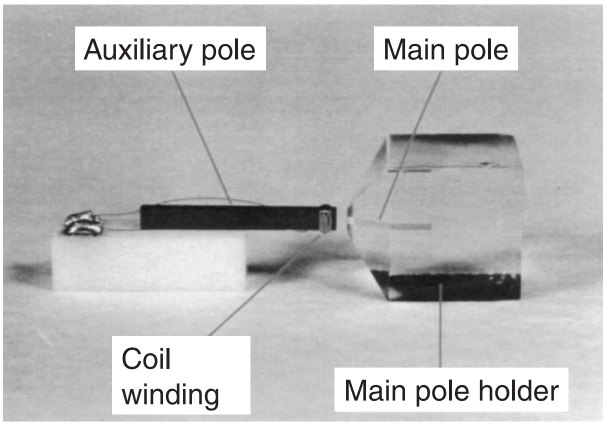

Fig. 7. Auxiliary-pole driven single-pole type head.

were obtained at the initial stage of our research work.

The next important development was the perpendicular recording medium. A medium material was required for which the magnetic surface poles of N and S were retained on the surface plane, which is designated as a perpendicular anisotropy film. We found in 1975 that a thin film made of cobalt (Co) and chromium (Cr) alloy was the most promising perpendicular medium material. Luckily enough, that material was available as a result of research work of magneto-optical recording, which was being conducted parallel in our laboratory at that time. This finding ultimately created the most

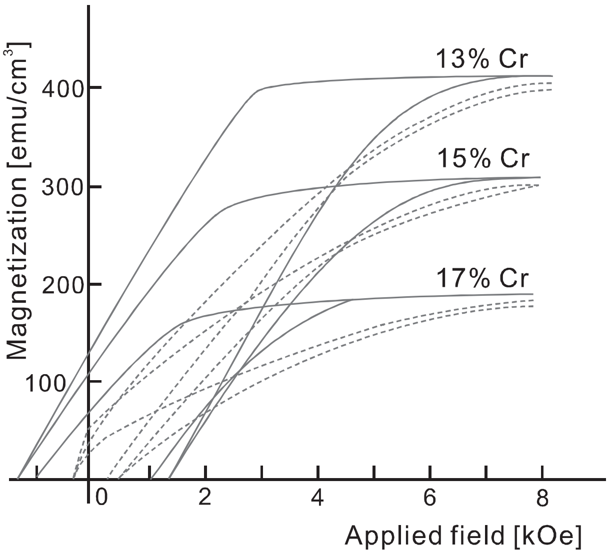

Fig. 8. Perpendicular (solid lines) and in-plane (broken lines) hysteresis curves of Co-Cr perpendicular recording media with various Cr contents.

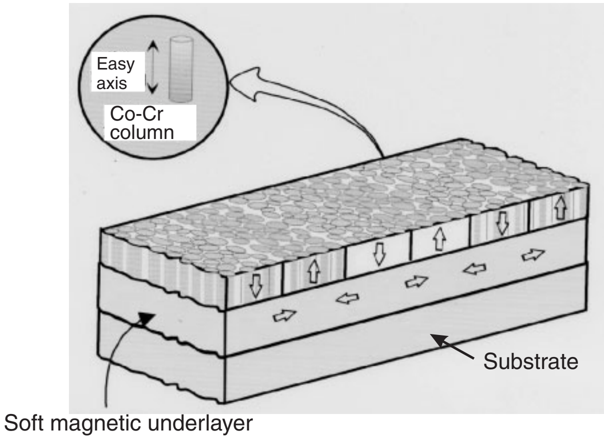

Fig. 9. Double-layered perpendicular magnetic recording medium.

effective means of accomplishing perpendicular magnetic recording.

This magnetic film was produced using the sputtering method in a vacuum chamber to deposit the atoms of Co and Cr on a heat-resistant plastic substrate. Typical magnetization characteristics of prepared samples at that time are presented in Fig. 8. This perpendicular anisotropy film was discovered from a question we posed about the extremely narrow in-plane hysteresis loop, which was observed when Cr atoms were added to the Co film.[6)]

Based on this method, fine columnar grains grow to be closely packed perpendicularly to the substrate surface. Because the columnar grains have a crystalline structure to be magnetized in the normal direction, the recording layer made of this material was able to support perpendicular magnetization to the film plane. This Co-Cr alloy system is thought to be the most appropriate material to use for perpendicular magnetic recording even now; its development with some other additive materials such as platinum (Pt) or silicon oxide (SiO_2) is proceeding.

Looking back at how the perpendicular anisotropy magnetic film was found, the major factors were the following.

- The research scope had been expanded to the area of optical (heat) laser recording using a thin film of cobalt.
- New research on magnetic recording based on perpendicular magnetization had begun.
- Radio-frequency (RF) sputtering method, which produces the columnar grain structure perpendicular to the film plane, was used for the first time.

I am convinced that we would not have found the Co-Cr perpendicular anisotropy film if any one of the above three factors had been absent. This is the reason why I stated earlier that we were lucky.

Furthermore, when this Co-Cr perpendicular anisotropy film was made into a double-layered structure with an in-plane magnetization film attached behind, as shown in Fig. 9, both write and readback sensitivities were increased dramatically by 10 times over those of a single-layered film. The read/write testing further showed that the SN ratio was sufficiently good. By the time we had reached this stage, I was certainly confident that this research on perpendicular magnetic recording was going to be successful.[7)]

Using the magnetic head and perpendicular medium described above, a prototype of a perpendicular magnetic recording disk system was built up for the first time in association with a single-pole magnetic head and a double-layered perpendicular medium combined (See Fig. 10).

The pole of the single-pole head is visible in the middle of the photograph in the figure. The magnetic disk used here was the same flexible disk as that widely used for personal computers, word

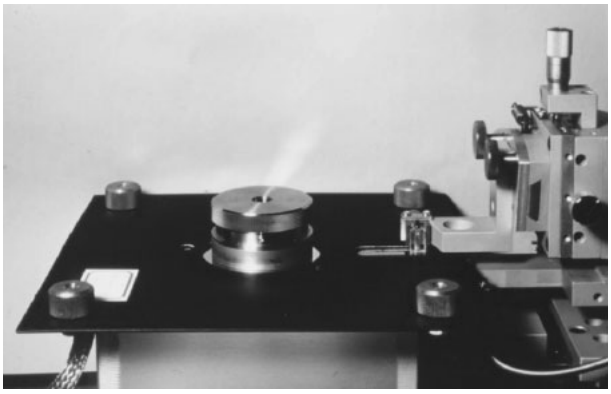

Fig. 10. Perpendicular flexible disk drive with a Co-Cr/Ni-Fe double layered recording medium and a single pole head. The auxiliary magnetic pole was located on the rear side of the disk.

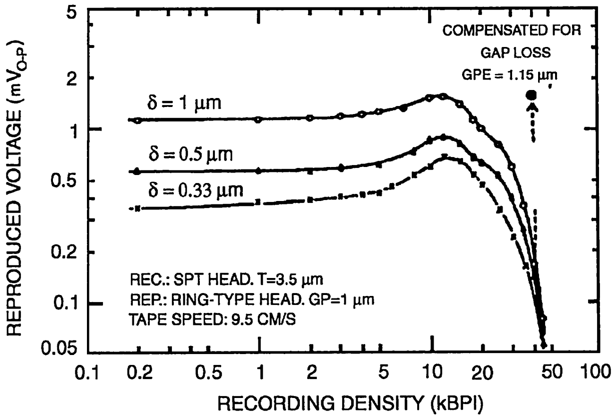

Fig. 11. Reproduced voltage versus linear bit density characteristics for perpendicular magnetic recording with various recording layer thickness, δ.

processors and other applications. The disk has a similar structure in some respects to that of a music LP record; the main-pole of the head corresponds to the needle of a record player. In the record player, we know that the sound is reproduced by the vibration of the needle from the rotating record disk. Similarly, for the case of the perpendicular disk, the induced magnetic flux at the main-pole by the magnetized perpendicular medium was transmitted to the auxiliary magnetic pole in the opposite side of the disk, generating a voltage in the coil wire wound around the auxiliary pole. This very first perpendicular disk drive produced valuable data during the first few years of research work; the data greatly contributed to clarify fundamental characteristics of perpendicular magnetic recording. In summary, the data proved that perpendicular magnetic recording is appropriate for high-density digital information recording.

I first reported on perpendicular magnetic recording at the First Topical Symposium of the Magnetics Society of Japan (May 1977)[8),9)] and at the 1977 Intermag Conference (Los Angeles, CA, June 1977).[4)] The paper was about recording with a single-pole head on a strip of Co-Cr tape and reproduction with a conventional ring head. Figure 11 shows that the paper described a flat response up to 100 kFRPI, even for the thickest medium when the gap loss was compensated. Incidentally, the maximum linear recording density of an IBM 3370 hard disk drive at the time was only 10 kFRPI.

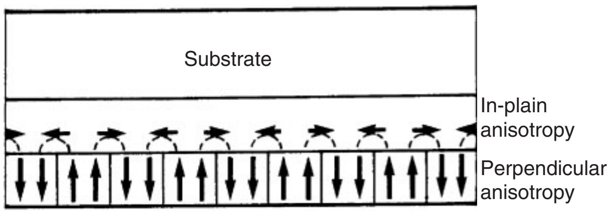

Fig. 12. Flux flow in a double-layered perpendicular magnetic recording medium. Horseshoe-shaped bits are formed with the perpendicular and in-plane anisotropy films.

After these experiments, I once more inferred that two possibilities would become particularly important in the future of perpendicular magnetic recording.

1) High density should be attainable with a thicker recording medium.
2) Horseshoe-shaped bits with less demagnetization might be obtainable at a remanent magnetization comprising perpendicular and in-plane components, as presented in Fig. 12.[10)] (In the double-layered medium, however, it was a concern that a magnetically soft underlayer might limit the recording resolution.)

The problem at the time, however, was that perpendicular magnetization was only barely reproducible with a high-sensitivity ring head because of the lack of the read sensitivity of single-pole type heads. In fact, this problem was pointed out by one of my friends, Dr. Dennis Speliotis, at the 1978 Intermag Conference in Firenze, Italy. On the return trip from the conference, I reconsidered the "Reciprocity Law" in magnetic recording. The law defines the proportional linear relation between the recording and reproducing sensitivities with negligible interactions between the head and the medium. A typical interaction is that corresponding to the occurrence of the circular mode in longitudinal magnetic recording. In perpendicular magnetic recording, on the other hand, no fundamental change in the magnetization is expected, irrespective of the recording current and density, because of the attractive (magnetizing) force between adjacent recorded bits. Immediately before my departure to the conference in Firenze, it had been found that saturation recording was obtainable with a much smaller recording current in a double-layered medium than that in a single-layer perpendicular recording medium. On my way home from the conference, stopping in Paris, the idea occurred to me that the reproducing sensitivity would also be increased in proportion to that in the recording of a single-pole head. Cherishing this new idea, I found the return from Paris to Sendai to be a long trip. Subsequent experiments on a double layered medium confirmed that the increase in the output was proportional to that in the recording sensitivity. The first result is presented in Fig. 13. This phenomenon was explainable later as the concentration of the magnetic flux in the main pole of the head.[10] The relation turned out to be extendable to higher recording densities, as presented in Fig. 14 with reproduced waveforms indicating a single-peaked pulse resembling that of a conventional recording.[7]

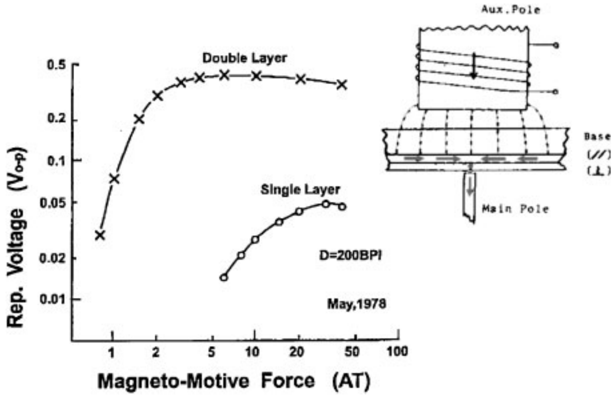

Fig. 13. The first data of recording magneto-motive force versus reproduced output characteristics of a double-layered perpendicular medium and a single-pole head in comparison to a single layer perpendicular medium (May 19, 1978).

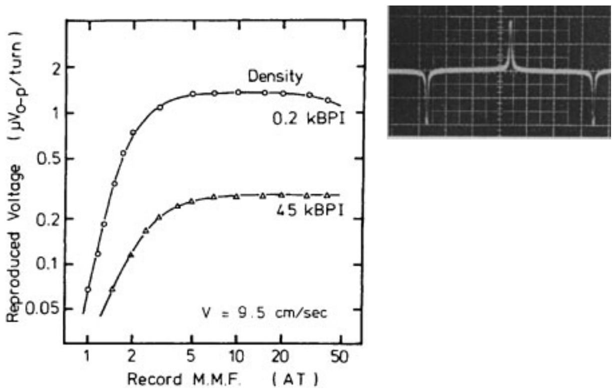

Fig. 14. Saturation characteristics for a double-layered medium showing no reproduced amplitude reduction at high densities (45 kBPI), even for excess recording magneto-motive forces (M.M.F.). The waveform is for a 200 BPI signal, being the same mono-pulse as that in longitudinal recording.

5. Pathway to realization of perpendicular magnetic recording

5.1 Decision of the principal recording method. Considering the evolution to the novel perpendicular magnetic recording, I particularly examined the complementary relation to conventional longitudinal recording, which is the complementary nature between the two recording modes.[10),11] It is an important implication from the fundamental relation that the force exerted between the recorded bits (magnets) is repulsive in longitudinal magnetization, in contrast, it is attractive in perpendicular magnetization. Regarding these two methods as to which one to use, the relation in Fig. 15 can be derived with respect to the magnetic head, recording medium, signals, and recording method. This complementarity relation[10] described above was a principal guiding principle to carry out research to continue, without fail, the practical development of a magnetic head, medium, methods, and so on.

There had been a long discussion related to whether this concept should be expressed as "complementary" or "dual". The term of "dual" means having two aspects, and "complementary" means combining them to form the whole. Two different systems are required for longitudinal and perpendicular magnetic recoding, with appropriate heads and media for each that have entirely different

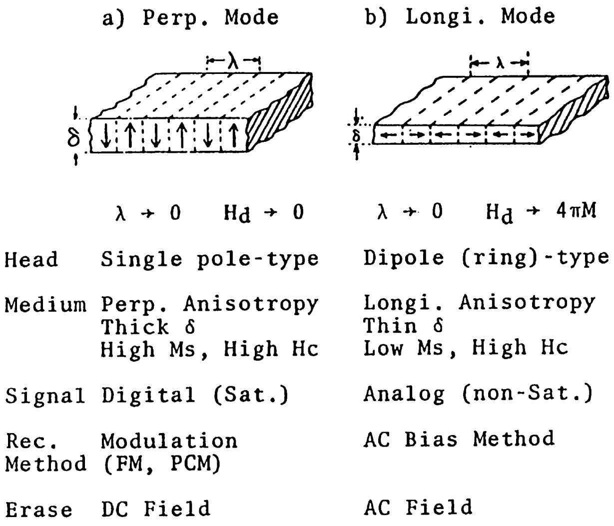

Fig. 15. Complementary relation between perpendicular type recording and longitudinal recording.[10)]

characteristics. Therefore, for this principle, the term of complementary is more appropriate to express their nature.

Based on such a complementary nature, we can consider how the smallest bit can be determined for both recording modes. To reduce the bit size in longitudinal recording, it would be necessary to minimize the factor of $Br\delta/H_c$ by reducing the thickness of δ and increasing the coercive force of H_c. The recording density of the recording medium is determined by the relation of the $Br\delta/H_c$. Therefore, it is very structure-oriented. For the perpendicular magnetic recording, in contrast, because its resolution depends entirely on the playback head resolution, the smallest bit on the recording layer can be formed as small as the size of fine grains of the magnetic film. Perpendicular magnetic recording can be said to be more material-oriented.[12)] Figure 16 shows the mutual relation of the two.

In perpendicular magnetic recording, because the bit magnetization is aligned in an anti-parallel way, the recording bits are mutually attracted with respect to the magnetic force, which allows them to be packed densely to produce a highly dense configuration. In similar fashion, because the head and medium are also mutually attractive, the writing head field distribution becomes steeper and more focused as the medium approaches the head. For that reason, a narrow track recording is

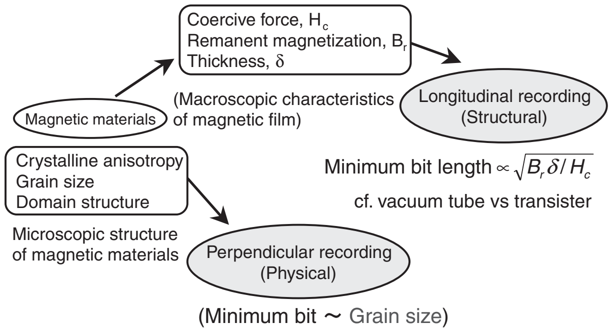

Fig. 16. Conceptual explanation of how the recording upper limit is determined.[12)]

readily realized. It can attain a high linear recording density and can simultaneously accommodate even a narrow track recording. Therefore, the areal recording density is more easily increased using perpendicular recording than using longitudinal recording.[13)]

In August 1979, Dr. Seiji Kaya happened to visit my laboratory with my ex-supervisor, Dr. Kenzo Nagai. They viewed an experiment of perpendicular magnetic recording. At that time, Mr. Taizo Yokoyama took up perpendicular magnetic recording in his cartoon section of the Asahi Newspaper, during the school entrance examination season. He drew a satirical cartoon showing that it would be very nice for the students who were taking examinations if their memory capacity were increased to a great extent. At that time in the past, we saw that science and technology were giving hopes and dreams to society. I was very impressed with his high level of sensitivity: I remember it to this day.

Furthermore, in 1984, my friend, Mr. Clark Johnson, who used to be the president of the IEEE Magnetics Society, testified in the Senate, the upper house of the U.S. Congress. In his address, he said that, "In Japan very many research accomplishments are being published only in Japanese language journals. The Western countries are isolated from such valuable studies. America started translating Soviet journals of the Physics Society when the Soviet Union had launched Sputnik (the first artificial satellite was launched in 1957). Similarly, America should translate the scientific journals of Japan." That is one of the things that I am very proud of. At that time, Japan was designated as "Japan as number one," even as it was simultaneously criticized for merely following basic studies that other countries were pioneering. On the other hand, we produced such an atmosphere in which it was said that "America is isolated from important information of Japan because Americans cannot read Japanese, so it is both unavoidable and very important that we start translating the scientific journals of Japan." We were also very proud of fostering that mode of thinking.

In America, at around 1982, several venture companies of perpendicular recording had been founded. In a similar fashion, from around 1985, American universities started supporting magnetic recording research centers one after another. I believe that happened because of the impact of our 144 Committee on Magnetic Recording in Japan Society for the Promotion of Science (JSPS), which was described above in section 3. Subsequently, IBM proposed a new read head using the Magneto-Resistive (MR) effect, which produced a separate stream from perpendicular recording in the roadmap, however even during that time, our Committee continued steadily with its activities to promote perpendicular recording; now we have had meetings more than 190 times.

Counting the number of papers on perpendicular magnetic recording published in IEEE Transactions on Magnetics, Fig. 17 shows a very deep valley during the mid-1990s in terms of its growth because an American manufacturer, IBM, proposed to use a high-sensitivity read head employing MR effect instead of the existing inductive head. A strong international trend supported by the majority came to follow IBM to continue using conventional longitudinal recording. Looking back now, I think it was really a "Death Valley." During that period, we were trying to recover from that valley, and had international conferences related to perpendicular recording as many as seven times to fill that gap in activity in the area.

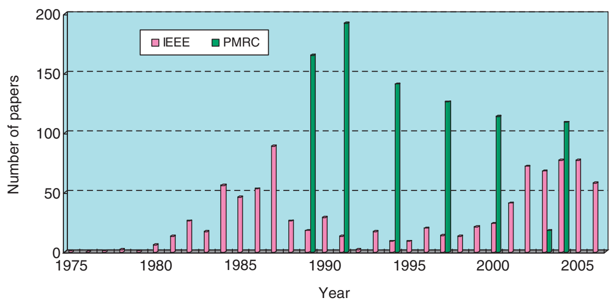

Fig. 17. Year-by-year trend of the number of papers related to perpendicular magnetic recording for journals of the IEEE Magnetics Society, and for the Perpendicular Magnetic Recording Conference (PMRC).

As part of the activities of the 144 Committee during that time, we proposed a new type of write head and experimented with it at the RIEC, Tohoku University, and the Akita Research Institute of Advanced Technology. We achieved an improved error rate at high densities to a much greater degree than longitudinal recording, but it was insufficient to change the prevailing trend.

However, at that time, one American scientist insisted that there was a physical density limit of conventional longitudinal recording (or, in-plane magnetization recording). As the medium becomes extremely thin, demagnetization of the recorded magnetization takes place because of thermal fluctuation. Consequently, the recorded magnetic information disappears over time. This destructive phenomenon is physically unavoidable when using longitudinal recording because the medium thickness must be thinner in order to increase the areal density. The product of the magnetic anisotropy constant K_u (K_u is proportional to $M_s H_k$, where M_s is saturation magnetization, and H_k is an anisotropy field) and the magnetic grain volume V is the factor determining the thermal stability of recorded magnetization. This value decreases for longitudinal recording in high density because of the very thin medium. Consequently, the remanent magnetization becomes increasingly and extremely unstable because of heat.

In contrast, for perpendicular magnetic recording, a thick medium can be used in high-density recording, and the M_s of a medium can be large. Having time along the horizontal axis, as presented in Fig. 18, it is readily apparent that demagnetization caused by random thermal fluctuation is very much suppressed in perpendicular magnetic recording.[14)] The long argument between longitudinal and perpendicular recording was settled at last. It can be said that it was a moment at which the true value of perpendicular magnetic recording was recognized for the first time widely and to a great degree. For this very reason, the strong impetus for development of perpendicular recording resumed.

5.2 Emerging from "Death Valley". Figure 19 portrays the prototype of a 2.5 inch hard

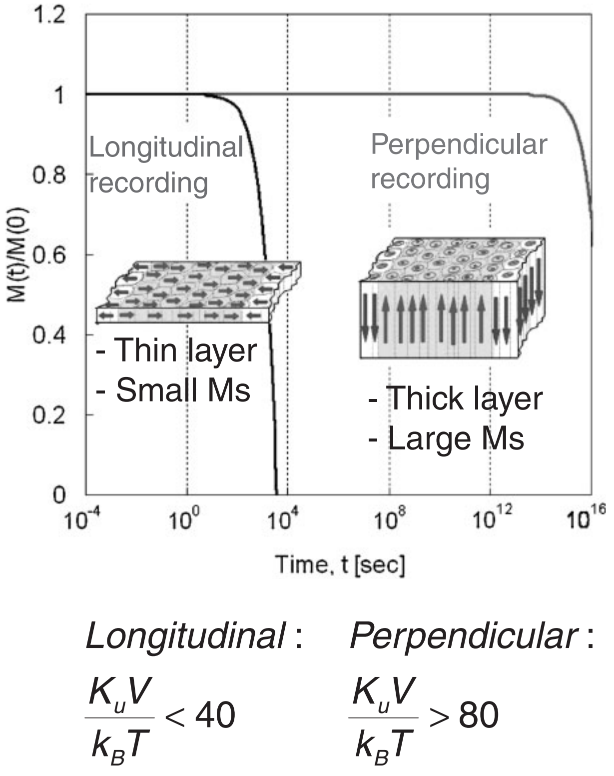

Fig. 18. Stability of perpendicular type recording bits in the phenomena of thermal magnetization decay. (M_s, saturated magnetization; K_u, energy of magnetic anisotropy; V, volume of particles; k_B, Boltzmann constant; and T, absolute temperature.)

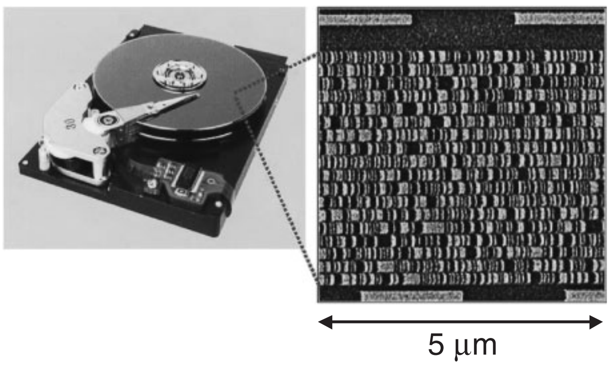

Fig. 19. Prototyping of a hard disk drive using perpendicular magnetic recording (52.5 Gb/in^2) and its recording bit image on the disk, by Hitachi Ltd.[15]

disk drive that Hitachi produced in 2000.[15] Its areal recording density is 52.5 Gigabits per square inch. Our original head, as described above, had an auxiliary pole at the opposite side of the medium, but they put the auxiliary pole at the same side of the main pole to combine them. It was necessary to have them on the same side as a mass-production product. The track width of a single-pole head is 150–200 nm. In order that individual written tracks do not mutually overlap, the main pole of the write head has a wedge-like cross-sectional view whose rear end is larger. The head has a very precise structure into which a Giant Magneto-Resistive (GMR) read head was merged. This product was first produced by Mr. Hisashi Takano and his team, who graduated from the master's course of my laboratory in 1985.

Regarding the double-layered medium described previously, exchange interaction affects between the perpendicular recording layer and the soft magnetic underlayer, the so-called SUL, which works as a flux path, disturbs the good characteristics of the recording layer. A thin Ruthenium (Ru) interlayer at the interface avoids this disturbance. Well-oriented uniform grain structure was therefore realized, which contributed to increase the attainable areal density. Step by step, the perpendicular medium was improved to approach my ideal performance, as presented in Fig. 16.

The perpendicular medium presented in Fig. 20 was fabricated by Mr. Yoichiro Tanaka and his group at Toshiba.[16] He also graduated from the master's course of my laboratory. Its hysteresis loop has good squareness; its grain structure is very good. A good film structure, in which grains consist of cobalt, chromium, and platinum in hexagonal-close-pack crystalline, realized good separation using non-magnetic amorphous materials.

In actual disk drives, characteristics like those presented in Fig. 21 have become available.[17] The figure shows how recorded magnetization changes according to the thermal fluctuation as the recording density is increased. With longitudinal recording, recording bits become increasingly unstable as the recording density is increased, in contrast, in perpendicular magnetic recording, the recorded magnetization becomes more stable at high densities. This is a typical difference derived from inherent essential natures of the two recording modes. As a consequence, it can be concluded that perpendicular recording is fundamentally appropriate for high-density recording. In perpendicular magnetic recording, the head and disk strongly interact with each other, which brings stability against ambient circumstance such as temperature

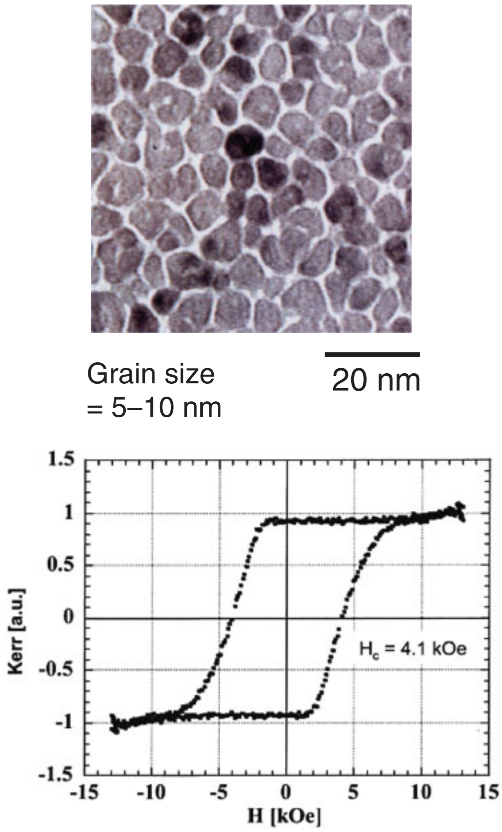

Fig. 20. Plan view of a CoPtCrO/Ru perpendicular magnetic medium using transmission electron microscopy (TEM) (upper) and its Kerr hysteresis curve (lower) by Toshiba.[16)]

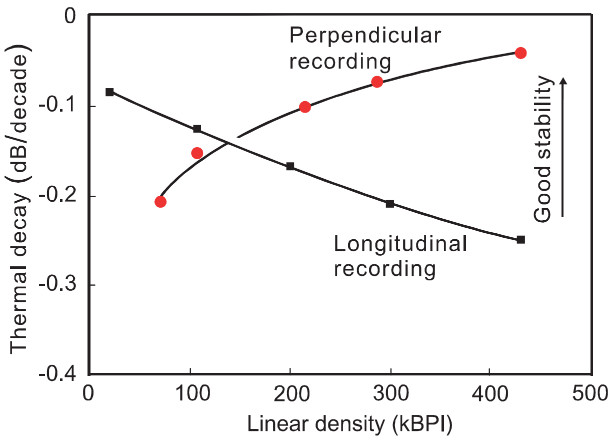

Fig. 21. Thermal stability of recording bits of a hard disk drive, indicating that the higher the density of perpendicular magnet recording, the less the decrease the stability becomes, thereby showing sufficient stability, by Toshiba.[17)]

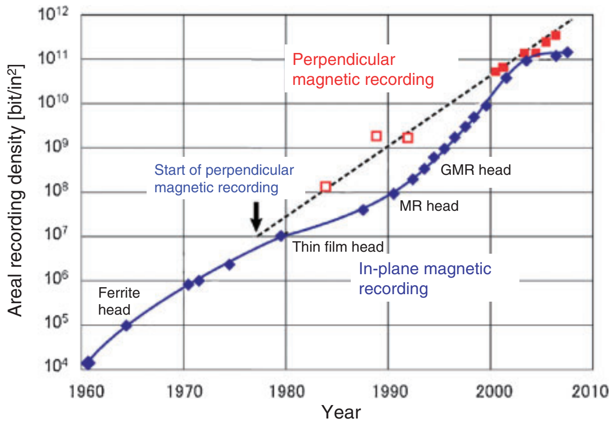

Fig. 22. Yearly growth of areal recording densities of HDD with longitudinal and perpendicular magnetic recording. (□, 50 kBPI × 2.5 kTPI in 1984, 250 kBPI × 7.1 kTPI in 1989, trial product of FDD at Tohoku Univ. and Fujitsu trial HDD product of 2 Gbits/in^2 in 1992; ■, Hitachi and Toshiba—HDD products and prototype; ◆, longitudinal magnetic recording)

and air pressure, which in turn affects spacing of the head and medium.

According to the achievements described above, recently the mass media have come to report perpendicular magnetic recording frequently as an accomplishment. An article of the Asahi Newspaper in May 2005 reported that a storage capacity of as much as 10 times was achievable. Interestingly, or somewhat strangely, this 10 times' capacity had been a standard assessment many times in the past. Although we have actually surpassed that number of 10 times, it seems that, at every opportunity, "10 times more density" is still bandied about as a catch-phrase. People seem to like that expression very much. Now we have a 1.8-inch disk with 80 Gigabytes and even more. What a difference we have now, knowing that a 5 Megabyte capacity disk called RAMAC (the first hard disk drive developed by IBM in 1956) became available with 50 disk-plates, each with 24-inch diameter.

In Fig. 22, the horizontal axis shows the time by year: longitudinal magnetic recording is seen to grow, since IBM introduced the MR read head and even a Giant Magneto-Resistive (GMR) head. However, we learned that such longitudinal recording would reach its areal density limit at approximately 100 Gbits/inch^2.

The breakthrough that transcended this areal density limitation was perpendicular magnetic recording. The dotted line in the figure marks the density trend of perpendicular magnetic recording.

It extends the trend more than 100 Gbit/inch^2 with a linear development, possibly entering into the terabit density domain. The fact that the trend of perpendicular recording shows a linear line throughout the entire period from the experimental age to the actual mass-production age proves that the combination of the principle and its associated devices to achieve high-density recording was correct.

I discussed complementarity earlier. Examining various aspects of both recording modes, longitudinal and perpendicular, their salient characteristics are symmetrically opposite. In the read process, because the medium must be very thin in longitudinal recording, the signal output was extremely small. This is the reason why a highly sensitive MR head was required. I knew that such an approach would be practically limited, so I repeatedly advised not to adhere to that approach, and instead moving on to perpendicular recording; I am afraid nobody listened. That is life in this world.

Signal processing for readback signals has been changed. That is simply a matter of course because longitudinal recording was fundamentally appropriate for analog signals. Therefore, standing on the concept of 'complementarity', which means the accomplishment of a total world by adding perpendicular recording to the conventional longitudinal recording world, is important. This is not a concept of 'duality' or a dual entity.

5.3 Trend prospects. Looking at magnetic recording as three development eras, piano wire recording (length), a tape recording as a recorder (in-plane), and perpendicular recording, as depicted in Fig. 23, it is readily apparent that each era has a length of 40 years.[18] To myself, I have emphasized the significance of this 40 year period. I remember I had made efforts according to this '40 year law'. A magnetic tape was invented in 1935: an invention in Germany. Then in America, video tape recording and computer disks became available, and further development was made. From now on, regarding perpendicular recording, much further development will be made to realize ultra-small and large-capacity hard disk drives or highly functional mobile equipment, et cetera. Today we have heard a lot about ubiquitous computing. Perpendicular magnetic recording will serve as a crucial tool to open such new technology, and usher in the new civil society to come.

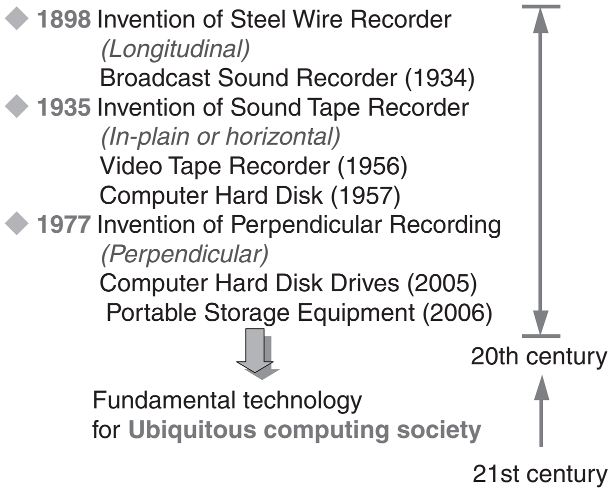

Fig. 23. Principal history of magnetic recording.

The following are what I have asserted as the 40-year cycle. Examining the electrical devices, for example, a new and fundamental evolution has occurred every 40 years such that we had triodes (1903), transistors (1949), and Large Scale Integrated circuitry (LSI) (1980s). Looking at communication technologies, wireless communication experiments by Marconi (1901), microwave communications (1940s), and optical communications (1980s) each happened at a 40-year interval because a new technology can mature with the period of 40 years; a new generation of researchers grows up along with the developed technology. It is true that after 40 years have passed, there is nothing left to be continuously investigated or developed. As far as magnetic recording, it was just about time for longitudinal recording to end and fundamental evolution should be carried out, I believe.[19]

Looking at this trend of development of magnetic recording, I cannot stop considering what technology evolution will take place in 2020, which will be the end of the 40 years from the start of perpendicular recording, for which I feel many discussions are required. It might be recording at an atomic level. Or, because quantum communication is under consideration, it would be no surprise if such a thing as quantum memory were to come to exist in terms of recording. The day might yet come when such technologies will be put to practical use.

I found some data to be very interesting, as presented in Fig. 24. These are quantities of information storage capacities obtained through the

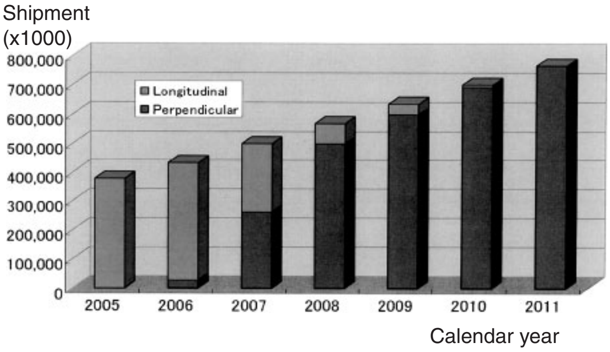

Fig. 24. Yearly change and projection of shipment ratio between perpendicular and longitudinal HDDs.

web pages of U.C. Berkeley. Results show that the amount of magnetically recorded information is overwhelmingly greater than that using other technologies. Mass-production of hard disk drives that supported this large capacity available is remarkable, 250 million shipped units in 2003 and 360 million in 2005. Although we have no precise data available now, the number of shipments might be over 400 million or 500 million in 2006 or 2007.

Talking to people of Hitachi GST, Fujitsu, Hitachi, and Toshiba, they say that about 75% of hard disk drive shipments will be of perpendicular products. In 2010, probably all such products requiring memory will have adopted perpendicular recording drives. In this way, such large companies as Toshiba, Hitachi, Fujitsu, and Seagate Technology are all concentrating on producing perpendicular disk drives.

I have been given commemorative plaques marking first FDD products from Mr. Atsutoshi Nishida, the President of Toshiba, Mr. Hiroaki Nakanishi, CEO of Hitachi GST, and Mr. Ichiro Komura, Vice President of Fujitsu, and Mr. William D. Watkins, the CEO of Seagate Technology LLC, as expressions of gratitude to me as an inventor, for supporting production of perpendicular hard disk drives. Figure 25 is a photograph of those given to me on display at the gallery of Tohoku Institute of Technology. I am considering that such commemoration signifies the extent of collaboration that occurred among industries and universities on this research and development work.

This is the end of the main text presenting what I would like to describe. Up to this point, we should recognize that this is not just a useful technical device that brings ubiquitous applications: a much more important concept of research was accomplished. Figures 26 and 27 present the concept of strategic scientific research that I proposed when I was a member of the Science Council of Japan based on the research work I experienced:[20] it should not be merely a linear model starting from basic research followed by its application; then by development of products; rather it should be a cyclical model of creation, development, and integration. The integration is the correct mode of integrating the idea with society, which is the most important aspect of all. Knowing that this is a culture that can encompass all of those things, all models are mutually well

Fig. 25. Commemorative gifts from HDD companies displayed at the gallery of the Tohoku Institute of Technology. Photos are with Mr. A. Nishida (President, Toshiba), Mr. H. Nakanishi (Chair, Hitachi GST), Mr. I. Komura (Vice President, Fujitsu), and Mr. W. Watkins (President, Seagate Technology) from the left.

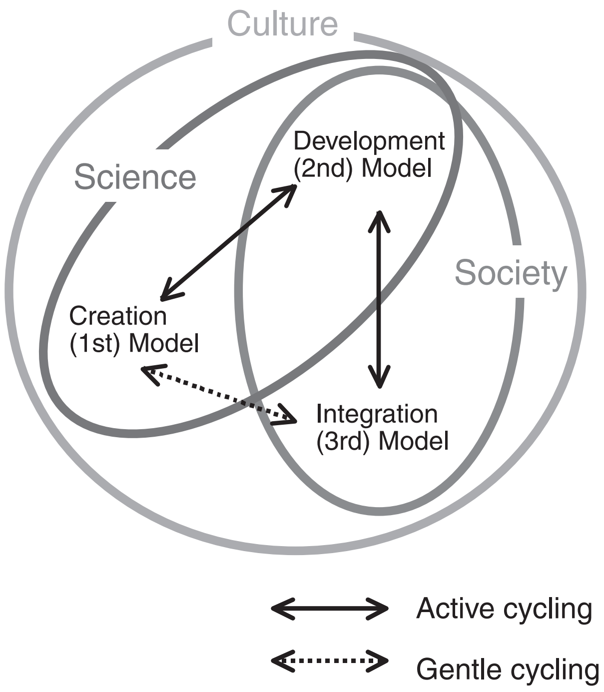

Fig. 26. Mutual relation between research models.

1st model – Creation Model Research
Proposal of hypothesis and verification
Original, Unconventional, Recognize/Discover
Non Competitive

2nd model – Development Model Research
Standardize and Popularize
Precise, Objective, Design/Make
Competitive

3rd model – Integration Model Research
Integration with teh real world
New recognition, Social, Humanity, Ethical
Cooperative

Fig. 27. New classification of research work.

balanced. That is something I believe desirable to strive for as an advanced country.

The creation model stage of the cyclical model referred to herein must be noncompetitive. As far as perpendicular magnetic recording was concerned, because nobody was working on it in the beginning, so no competition occurred. For that reason, we had a difficult time. Competition in the industry is very keen, as described previously, if it comes to a development model stage. Through that competition, I am hoping that good products that can be well utilized by society will be produced and put on the market. Lastly, I would like to say that I am considering the relationship of science and technology within our society at large, now that I have reached the objective of my own research work.

6. Conclusion

In August 2006, I attended a conference on perpendicular magnetic recording sponsored by IEEE that was held at Carnegie Mellon University in the eastern USA. During the banquet, I was officially commended for my invention of perpendicular magnetic recording and the achievement I made, which ultimately led to the developments to follow for a long period of time. I received a standing ovation at that time. During the applause, I remembered what one responsible person of a venture company was saying at the beginning of the 1980s, "Japan produces in the most efficient way the cars and semiconductors that were invented in America; then exports them back to America. Similarly, we would like to produce the products of perpendicular magnetic recording and export them to Japan. That is a true give-and-take relationship, is it not?"

Now that not only Seagate Technology, but also other American hard disk drive companies are moving toward production of perpendicular type recording, I truly feel that I have taken part in the "give" portion of that idea of give-and-take.

As a research worker, I am very happy with the fact that the idea that was first developed 30 years ago in one room of the Research Institute of Electrical Communication at Tohoku University is now rooted throughout the modern world. It is really stepping into the "integration to society," which I have been posing as one of my mottoes.

I was able to achieve my objective of my research work through cooperation on the part of many people for such a long time, and also by the good luck that has come along with that diligent effort. I hereby express my deep gratitude for everything that I have received from so many. Lastly, I received valuable cooperation in writing this document from Prof. Hiroaki Muraoka of the Research Institute of Electrical Communication, Tohoku University.

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Profile

Shun-ichi Iwasaki was born in 1926 and received a BS and Ph.D. degrees from Tohoku University in EE and basic research on magnetic recording in 1949 and 1957, respectively. From 1952 to 1989, he has been engaged in the basic and applied research of magnetics and material sciences as associate professor (1957), full professor (1964), and director of the Research Institute of Electrical Communication (1986) in the Tohoku University. From 1991 to 2000, he was a member of the Science Council of Japan and he was elected as a member of the Japan Academy in 2003.

He moved to Tohoku Institute of Technology in 1989 as a president and the chief director, president emeritus since 2008. His outstanding works are 1) invention of metal particulate magnetic tape in 1958, 2) establishment of self-consistent magnetic recording theory in 1968, and 3) invention of perpendicular magnetic recording in 1977, as the work is depicted in this paper briefly. By his research activities, he was awarded the Technical Achievement Award of the Computer Society (1988), the Cledo Brunetti Award (1989), and the life Fellow of the IEEE (1997). He was also awarded the prizes of Medal of Japan Academy and a Person of Cultural Merit of Japan in 1987. He also received other 19 prizes from other institutes of technologies and science foundations in Japan. He is an honorary member of the Institute of Electrical Engineers, the Institute of Electronics, Information and Communication Engineers, the Acoustical Society of Japan, the Magnetics Society of Japan, and the Institute of Image Information and Television Engineers of Japan.