Magnetic Recording Technology  
(Ultimate Solutions for Future Density Growth)

Hisashi TAKANO*

磁気記録技術（記録密度の極限）

高野 公史*

*Research, HGST Inc. (1 Kirihara-cho, Fujisawa-shi, Kanagawa 252-0888)
*HGST研究所（〒252-0888 神奈川県藤沢市柳原町1）

Introduction

The phenomenal increase in the storage capacity of magnetic hard disk drives (HDD) in recent decades has been fueled not only by clever improvements in the engineering of tiny devices but also by discovery, and advances in understanding of fundamental physical phenomena associated with magnetism at the nanometer length scales.\(^1\) Hard drive capacity (see Fig. 1) is governed largely by the number of bits which can be packed in a given unit area, Areal Density (AD), on the recording media. Over the past 55 years, the units of this core metric have increased from kb/in\(^2\), to Mb/in\(^2\), to Gb/in\(^2\), and recently to Tb/in\(^2\). The nontrivial task of making the early inductive transducers smaller had enabled Compound Annual Growth Rates (CAGR) of about 40% in the first 35 years. Subsequent increases in AD were largely due to fundamental changes in the three main magnetic components of the hard drive: the recording media, the write element of the transducer, and the read element of the transducer.\(^2\) These three components interact and govern an important characteristic of information storage and retrieval in the HDD, namely the magnetic signal to noise ratio (SNR). Improvements in non-magnetic component technologies, such as signal processing, spindle bearings, active transducer-to-media spacing control, servo mechanical control, and variable bit aspect ratio along the radial direction have also been crucial to AD growth. The award of the Nobel Prize in Physics to Albert Fert and Peter Grünberg in 2007 for the discovery of Giant Magnetoresistance (GMR) indicates the importance of fundamental research to the HDD industry. GMR was incorporated into transducers for magnetic recording in the late 1990s and followed the use of ordinary Anisotropic Magnetoresistance (AMR) introduced earlier in that decade. The implementation of Tunneling Magnetoresistance (TuMR) in 2005–2006 has proven even more effective in increasing readback amplitude.\(^3\) The growth in CAGR from 40 to 60 to 100% which began in the mid 1990s and spanned the following several years was only partly due to these advances in the transducer read element (Fig. 2). Significant improvements in the write element, and even more importantly in the recording
media, were essential in facilitating this unprecedented shrinkage in bit size. Typically, the limiting factor in magnetic SNR is the noise from the media component. The introduction of new technology into the recording system has occasionally resulted in large, although temporary, gains in CAGR. Over the past five years innovations such as the use of perpendicular recording have allowed for continued growth in AD although at more moderate and historic rates of 40–50%. Maintaining AD growth will continue to rely on the discovery and successful implementation of new concepts to improve magnetic sensors and storage media.

2. Perpendicular Recording

By changing sputtering conditions and substrates, the crystallographic c-axis, and hence easy magnetic axis, of Co-based thin films can be changed from in-plane to out-of-plane. There are four principal benefits which result from aligning bit magnetic moments perpendicular to the film plane compared to the longitudinal configuration (Fig. 3). The biggest advantage comes from the fact that the write field vector should be mainly directed perpendicular to the media plane. This is in contrast to longitudinal recording where the desirable large parallel component is achieved by having a gap between pole pieces with the field ‘fringing’ out into the media, as in Fig. 3. The field strength inside the write gap is about twice as large as the fringe fields in the media some 15 nm away. In perpendicular recording, the media is effectively in the write gap so that much larger fields are possible. This is achieved by adding a magnetically soft layer below the hard recording layer in the media. The disk then becomes part of the write element, as illustrated in Fig. 3. A large write field allows for smaller media grains and thus smaller bits to maintain SNR and thermal stability. In addition to this substantial benefit, the magnetostatic field arising from neighboring bits in longitudinal recording tends to destabilize the transition. The opposite is true in perpendicular recording. This can be easily understood by playing with a pair of bar magnets. At higher frequencies of the recorded pattern the larger magnetostatic contribution to the energy barrier in perpendicular recording allows for smaller grains or anisotropy. A final benefit from perpendicular recording is due to the fact that the stray field emanating from transitions is larger than in longitudinal recording. This can easily be calculated using a bar-magnetic model. This implies a larger reader response and larger change in voltage from the read element giving a larger electronic contribution to overall SNR. In the absence of the transition to this new technology, AD growth rates would probably have fallen well below the historical 40–50% enjoyed in recent years (Fig. 2).

3. Energy Assisted Magnetic Recording

While perpendicular magnetic recording has been firmly established as the vehicle for mainstream mass produced disk drives, the trilemma is looming again. The requirement for smaller grain size in the media for good SNR, yet adequate thermal stability, is driving up the anisotropy of the media to the point where the recording process becomes marginal. Beyond perpendicular magnetic recording, there are much more ambitious proposals being explored. Two of them can be classified under Energy Assisted Magnetic Recording (EAMR). In addition to a magnetic field from the write pole, an additional source of energy assists in the recording process. The first EAMR technology that is being explored in the HDD industry is Heat Assisted Magnetic Recording (HAMR) for application beyond 1 Tb/in.\(^2\), as illustrated in Fig. 4. Due to the very small grain sizes, the medium anisotropy field \(H_K\) is expected to be on the order of 50kOe. The reversal of the grain magnetization is facilitated through the application of heat. The temperature of the media is raised from ambient to about its Curie temperature. As the media cools the write field

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**Fig. 2** Growth in areal density. Large increases in the late 1990s were due to the advent of high moment writer materials, reader MR/GMR technology and improved media magnetics.

**Fig. 3** Longitudinal and perpendicular magnetic recording
is applied to freeze in the magnetization in the desired orientation. Delivery of the heat will take place through a laser system whereby the laser spot is focused down to just below the track width. The final shape of the light spot is obtained though the use of a near field transducer. At the end of the transducer an evanescent wave is produced which couples into the media and creates heat. A second energy assisted recording technology is Microwave Assisted Magnetic Recording (MAMR), as illustrated in Fig. 5. The basic principle of MAMR is to add a microwave frequency ‘assist’ field with some preferred orientation and polarization relative to the normal static write field. The magnetization of a grain can then be reversed with a static write field that normally would be too small to cause reversal. Initial micromagnetic simulations show promising results albeit for relatively large magnitude of the oscillating field. Modeling also suggests significant sensitivity to the oscillation frequency that requires optimization to individual grain properties. Delivery of the oscillating field is envisioned with the aid of a spin torque driven microwave oscillator located in close proximity of the write pole. This microwave oscillator would have a track width similar to the write pole and only locally deliver the microwave field. This eliminates the so-called write pole skew issue during recording while the write head is not tangential to the disc, and consequently would eliminate the need for a field-constricting trapezoidal shape of the write pole.

4. Outlook

In order to achieve the approximate 40% compound areal density growth rate that the HDD industry has delivered over the past 50 years, several key technology innovations have been employed. Many of the innovations in the last decade have been aided by fundamental materials science breakthroughs in head and media technology such as GMR and TuMR read head materials and AFC coupled longitudinal and granular oxide perpendicular media. The most recent enabling technology, perpendicular magnetic recording, has allowed a rapid increase in areal density from 130 to 520 Gb/in² in under four years. As perpendicular recording technology moves up the “S” curve of maturity, the industry is focused on the next set of innovations that will continue to spark future areal density growth up to 5 Tb/in² and above (Fig. 6). The continuing technical challenge in increasing HDD areal density is to achieve a balance among the signal-to-noise ratio and thermal stability of small grain media and the ability of the head to write the media. The industry is working diligently on several potential enabling technologies such as Shingled Write, Energy Assisted Recording and BPM to continue areal density growth. Another challenge for the industry is to balance these increasingly more complex technologies while continuing to maintain the low cost per GByte needed to support unit growth. Understanding and exploration of the large variety of fundamental physical phenomena involved in current, proposed and future technologies can only serve to enhance the possibilities for finding solutions to these challenges.

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References

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著者紹介

高野公之（たかの ひさし）
Hisashi Takano is vice president of research for HGST, a Western Digital Company, headquartered in San Jose, California. In this role, Mr. Takano has responsibility for developing key technologies which are necessary for the future growth of hard disk drives, such as capacity improvement and performance and reliability enhancement. Mr. Takano received his B.S. and M.S. degrees in electronic engineering from Tohoku University, Sendai, Japan in 1983 and 1985, respectively.