Microwave-assisted Magnetic Recording Technology for HDDs Achieving Higher Recording Density

The capability of hard disk drives (HDDs) to store and provide access to large volumes of digital data with an appropriate latency time at low cost is resulting in increasing demand for HDDs with higher recording density for use as information storage devices supporting the development of high-level machine learning and artificial intelligence (AI) technologies. However, incremental improvements in conventional methods for achieving higher density that depend on downsizing of the magnetic heads and miniaturization of the bit size on the recording media are close to reaching a limit.

As a solution to this situation, the Toshiba Group has been engaged in the development of microwave-assisted magnetic recording (MAMR) technology and has achieved the technological breakthrough of increasing the density of HDDs by using a head with a spin torque oscillator (STO) to enhance the recording performance. We have now developed an extremely compact STO and a large-scale simulation technology for MAMR. We have conducted demonstration tests of prototype HDDs using the newly developed MAMR technologies, and confirmed that the MAMR HDD achieves higher recording performance compared with conventional HDDs.

1. Introduction

With the spread of smartphones, various sensors, cloud computing, and other digital innovations, the volume of digital data generated has been growing at an exponential rate. In the coming years, fifth-generation (5G) mobile wireless networks and self-driving cars will come into commercial use, spurring further growth in the volume of digital data generated. In addition, industry is working on the development of machine learning and other artificial intelligence (AI) technologies using such digital data. HDDs that provide access to a huge amount of digital data with reasonable latency at low cost are essential as an enabler for these technologies. The HDD industry is therefore under pressure to further increase the recording density of HDDs.

Conventionally, the recording density has been increased mainly by scaling the size of read and write head elements as well as the size of the magnetic grains of recording media. In recent years, however, the attempt to increase the recording density through scaling has been approaching the physical limit. As the main magnetic pole of write heads becomes progressively smaller, it is also becoming difficult to generate a magnetic field sufficient to write a medium. In addition, the shrinking media grains are becoming increasingly susceptible to thermal agitation, i.e., instability of the write magnetization due to thermal energy of the ambient temperature. To enhance immunity to thermal agitation, it is necessary to increase the anisotropy energy (K_u) of media grains. However, an increase in K_u generally causes an increase in magnetic coercivity, a measure of the magnetic field required for writing. The limitation of increasing the recording density of HDDs is characterized by the competing requirements of scaling, thermal stability, and writability, which are known as the magnetic recording trilemma.

To overcome this trilemma, the Toshiba Group is developing MAMR technology, one of the energy-assisted recording technologies. This report compares MAMR with heat-assisted magnetic recording (HAMR), describes the principle of MAMR operation, and provides the results of read/write tests of prototype MAMR HDDs.

2. Energy-assisted magnetic recording technologies

There are two major types of energy-assisted magnetic recording technologies: MAMR and HAMR. MAMR uses an STO to generate a microwave field. The application of a microwave field to a recording medium helps to reduce the magnetic field necessary to reverse the magnetization of bit cells and thereby enhance writability. In contrast, HAMR uses near-field light to locally heat the magnetic grains of a recording medium to a temperature close to the Curie point[*1] in order to reduce the coercivity of the medium and enhance its writability.
It is estimated that MAMR could reduce the magnetic field necessary for magnetization reversal by roughly one-third[(1)] whereas HAMR could theoretically reduce the necessary recording magnetic field almost to zero by heating a recording medium to the Curie point. However, the cobalt-chromium-platinum (Co-Cr-Pt) alloy used for the current recording media has a Curie point higher than 500°C depending on its composition, making it difficult to use HAMR. It is therefore necessary to develop a new material for HAMR recording media. In addition, heating a recording medium to high temperature might degrade the characteristics of the top media protection and lubricant layers. In consideration of the characteristics of MAMR and HAMR, we are aiming to achieve practical applications of MAMR technology.

3. Principle of MAMR operation

MAMR applies microwave and magnetic fields to a recording medium to generate ferromagnetic resonance (FMR), i.e., the magnetic interaction with the magnetization of a recording medium, inducing a substantial precession of its magnetization. As a result, MAMR makes it possible to reverse the magnetization of the recording medium with a lower magnetic field than in the case of the conventional magnetic recording. Therefore, MAMR write heads require an additional device to generate a microwave field while MAMR media need to interact with a microwave field properly.

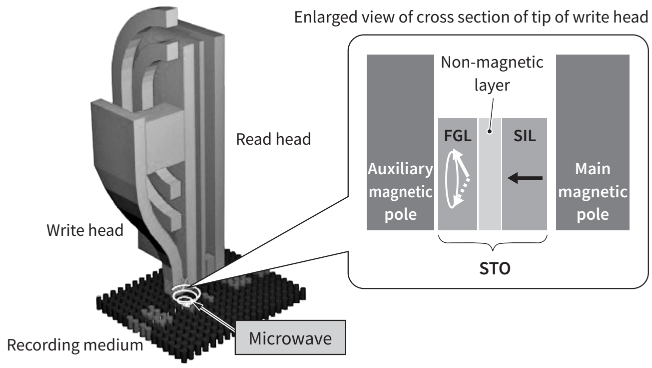


Figure 1. Structure of MAMR read and write heads
An STO lies between the main and auxiliary magnetic poles of tip of write head.

3.1 Write head for MAMR

An STO is added to the MAMR write head to efficiently generate a microwave field. The STO is placed in a gap between the main magnetic pole that generates a recording magnetic field and the auxiliary magnetic pole, as shown in **Figure 1**. The STO has a field generation layer (FGL) that generates a microwave field and a spin injection layer (SIL) that injects spin torque into the FGL. The magnetic FGL and SIL are separated by a conductive non-magnetic layer[(2)(3)]. During a write operation, the gap in the MAMR write head has a magnetic field that varies with the recording magnetic field. As a result, the FGL and the SIL are magnetized to the direction of the magnetic field within the gap. At this time, when DC (direct current) drive current is applied to the STO, the FGL induces a precessional motion of the magnetization because of the interaction between the SIL and the FGL via spin torque (which is hereinafter referred to as oscillation). The oscillation of the FGL magnetization generates a microwave field, causing both microwave and magnetic fields to be applied to the recording medium[(4)].

(*1) Transition temperature at which ferromagnetic materials exhibit paramagnetic behavior

3.2 Recording medium for MAMR

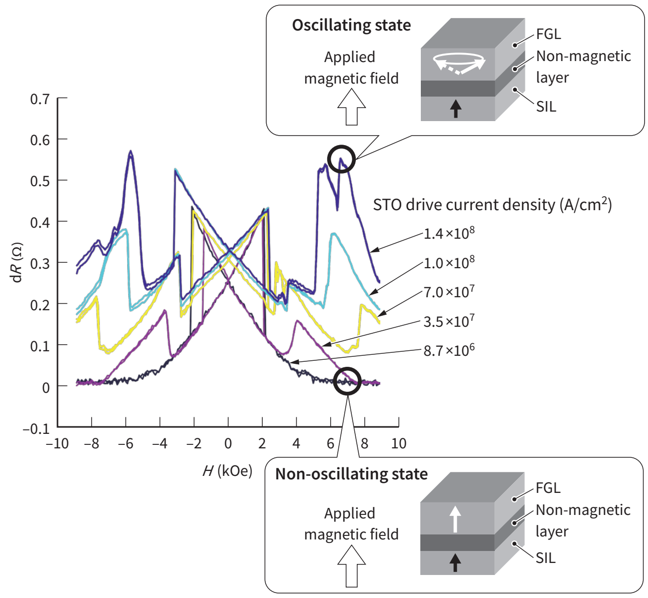
A recording medium for MAMR needs to efficiently generate ferromagnetic resonance with the magnetization of the media grains according to the microwave field emitted by the STO. Specifically, the anisotropy field (H_k) of the media grains must be adjusted so that it will satisfy the resonance conditions at the oscillating frequency of the microwave. However, an increase in H_k causes an increase in the magnetic coercivity of the recording medium. To avoid this, the MAMR medium has multiple recording layers with different H_k values in order to balance the energy-assist efficiency of the microwave and the magnetic coercivity of the recording medium.

4. Development of fundamental technologies for realization of MAMR

To realize MAMR, we have designed an STO and developed an MAMR simulation technology. The following subsections show the results of the read/write tests of MAMR read/write heads developed using this simulation technology.

4.1 STO technology

We have developed a prototype of an ultra-small STO that generates a microwave field. **Figure 2** shows the relationship between the rate of change in the STO resistance (dR) and the applied magnetic field (H). When a magnetic field equivalent to that in the head gap and an STO drive current were applied, dR increased with the oscillation of the FGL magnetization. The STO oscillated at 22 GHz. The dR curves were symmetrical about the zero point of H, indicating that the STO oscillates in a similar manner in both positive and negative recording magnetic fields. Consequently, we have realized an ultra-small STO with a satisfactory oscillation frequency and characteristics.



* Arrow indicates magnetization direction.

Figure 2. Relationship between STO resistance and applied magnetic field

dR increases with the magnetization of the FGL.

4.2 MAMR simulation technology

We have also developed a large-scale MAMR simulation technology capable of performing an integrated analysis of a sequence of MAMR processes, including the application of a recording magnetic field, the oscillation of an STO, the response of magnetic grains in recording media, and the formation of magnetic domains. Since this simulation is compute-intensive, it runs on a graphics processing unit (GPU) that is typically used for machine learning and other AI-based systems.

First, we calculated the oscillation characteristics and microwave emissions of the STO using a simplified MAMR write head model. The simulation results showed that the STO oscillated at 21 GHz and that a microwave field was localized in the vicinity of the STO. This means that the STO has oscillation characteristics suitable for MAMR. Next, we simulated the write process of recording media using a magnetic field generated by the STO and the write head. The simulation results showed that the application of a 20 GHz microwave field increased the signal-to-noise ratio (SNR) of the write head by up to 7 dB (**Figure 3**). This indicates that MAMR is feasible and can provide a higher recording density than conventional magnetic recording methods.

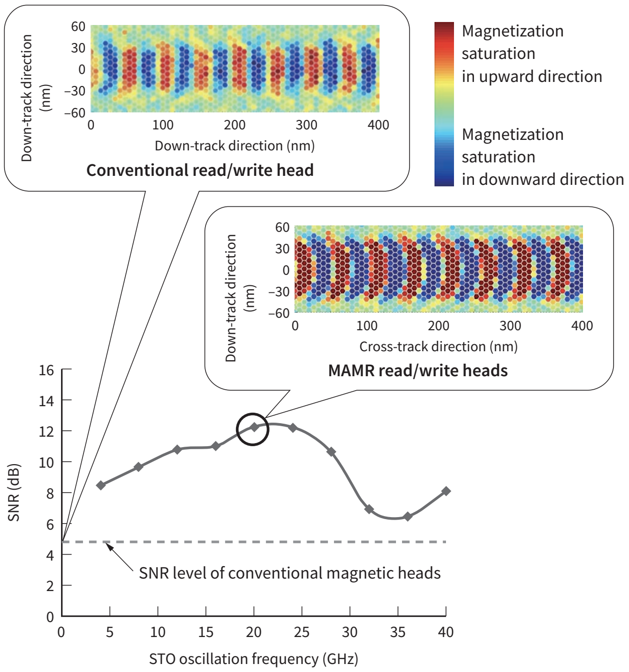


Figure 3. Results of simulations of SNR of conventional and MAMR read and write heads

The application of a microwave field provides MAMR read/write heads increase the SNR by up to 7dB.

4.3 Verification of MAMR technology using MAMR read/write heads and media

To verify MAMR technology, we have fabricated prototypes of MAMR read/write heads with an STO designed using the above MAMR simulation technology. A measurement of the STO showed that it oscillated stably at 23 GHz. Next, we examined the recording characteristics of the MAMR media. **Figure 4** shows the changes in overwrite performance over a range of write current (I_w). It indicates that, when the STO is on, MAMR provides a roughly 10 dB higher overwrite performance than a conventional magnetic recording method without an STO. As is the case with the result obtained from a recording simulation described in Section 4.2, this result indicates that the microwave field emitted by an STO helps to achieve good write performance, demonstrating the feasibility of MAMR[5][6]. As a result of the foregoing, MAMR is considered to be a promising next-generation high-density HDD recording technology capable of overcoming the trilemma associated with high-K_u recording media.

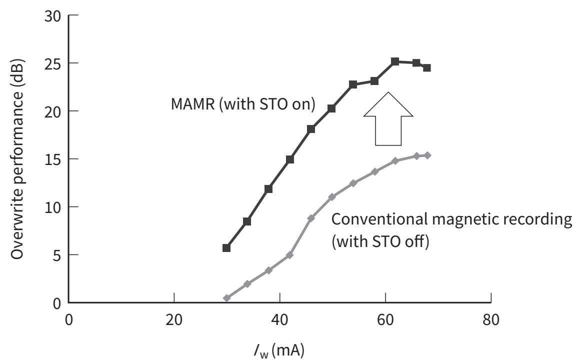


Figure 4. Results of evaluation of overwrite performance of MAMR read and write heads

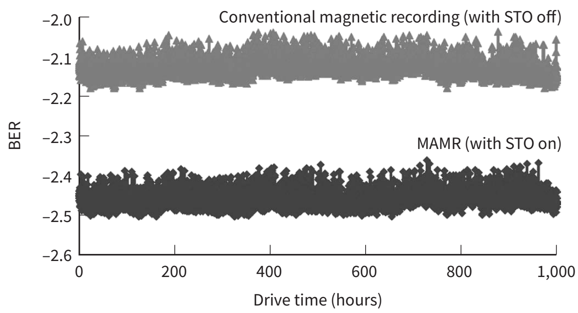
When the STO is driven at appropriate I_w, MAMR provides a roughly 10 dB higher overwrite performance.

5. Evaluation of a prototype HDD with MAMR read/write heads and media

We are working on the development of 3.5-inch nearline HDDs incorporating MAMR read/write heads and media. We have added a power supply for STO drive to the head amplifiers for the read/write heads and fitted nine platters and 18 MAMR read/write heads into the prototype 3.5-inch HDD. Many HDDs were used for evaluation. **Figure 5** compares the changes in the bit error rate (BER) of the MAMR and conventional HDDs over time. The MAMR media were made of materials similar to those used for conventional recording media. Figure 5 presents the results obtained at a recording density close to the maximum recording density of the existing HDDs. It shows that MAMR with an STO provides a significant reduction in the BER.

Generally, an STO with higher drive current generates a microwave field with higher intensity and thus provides higher energy-assist for MAMR, resulting in a greater reduction in the BER. However, excessive current could degrade reliability because of Joule heating and electromigration within the STO. In the example shown in Figure 5, the BER of MAMR remains unchanged for up to1,000 hours of write operations without any STO degradation, the possibility of which had been a concern. From this evaluation, we have also obtained information about adequate STO drive conditions.

We will continue to develop MAMR read/write heads that provide even higher reliability and optimize the STO drive conditions in order to realize high-capacity MAMR HDDs with performance and service life equivalent to those of conventional HDDs.



* BER is shown in common logarithm scale.

Figure 5. Results of long-term reliability tests of prototype MAMR HDDs

MAMR provides a reduction in BER and operates stably for up to 1000 hours.

6. Conclusion

We evaluated the feasibility of MAMR since we considered it to be a promising energy-assisted magnetic recording technology that would solve the trilemma associated with the increasing recording density of HDDs. We have developed an integrated large-scale MAMR simulation technology incorporating the operation of an ultra-small STO, a source of a microwave field, so as to demonstrate the feasibility of MAMR. Based on the evaluation results, we have manufactured MAMR read/write heads with an ultra-small STO and performed read/write tests on magnetic media. It was confirmed that MAMR provides an increase in overwrite performance and a reduction in the BER. As a result, it has been confirmed that MAMR is a promising magnetic recording technology that will solve the magnetic recording trilemma. At present, we are working toward commercialization of 3.5-inch nearline HDDs incorporating MAMR read/write heads and media.

To further increase the recording density, it is necessary to reduce the size and increase the K_u of magnetic grains on recording media. Recently, the HDD industry has been considering the use of iron-platinum (Fe-Pt) ordered alloy that provides K_u several times to several tens of times higher than the currently used Co-Cr-Pt alloy[7].

We will continue to endeavor to realize MAMR and develop new magnetic recording materials to increase the recording density of HDDs.

References

(1) Zhu, J. G. et al. 2018. “Microwave Assisted Magnetic Recording.” IEEE Trans. Magn. **44**(1): 125–131.

(2) Shiroishi, Y. et al. 2019. “Future Options for HDD Storage.” IEEE Trans. Magn. **45**(10): 3816–3822.

(3) Xi, H. et al. 2004. “Microwave generation by a direct current spin-polarized current in nanoscale square magnets.” Appl. Phys. Lett. **84**(24): 4977–4979.

(4) Narita, N. et al. 2014. “Analysis of Effective Field Gradient in Microwave-Assisted Magnetic Recording.” IEEE Trans. Magn. **50**(11): 3203004.

(5) Yamada, K. et al. 2013. "STO Oscillation and Its AC Field in MAMR Heads." Digests of The 24th Magnetic Recording Conference TMRC 2013, Tokyo, 2013-08, IEEE. 2013, Session E-E1: 64–65.

(6) Takeo, A. 2014. "MAMR - R/W Performance Improvement by Mag-Flip STO Assist." 2014 IEEE International Magnetics Conference (INTERMAG 2014). Dresden, Germany, 2014-05, IEEE. 2014, Session AD-02.

(7) Weller, D. et al. 2000. “High *K*u materials approach to 100 Gbits/in2.” IEEE Trans. Magn. **36**(1): 10–15.