Thermally Assisted Magnetic Recording

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Thermally assisted magnetic recording can solve fundamental problems concerning thermal fluctuation and write capability in magnetic recording, and it is regarded as the key technology for achieving densities exceeding 1 Tbit/in^2. This technology is classified into optical dominant recording and magnetic dominant recording. This paper describes these two methods and the differences between them. A theoretical estimation in optical dominant recording suggests that thermally assisted magnetic recording enables 10 times the density compared with conventional magnetic recording. Magnetic dominant recording was conducted on longitudinal synthetic ferrimagnetic recording media to prove its fundamental effectiveness. The signal-to-noise ratio and overwritability of thermally assisted magnetic recording without thermal erasure were assured. A newly proposed optical head with a butted grating structure provides good optical characteristics as the heating element for optical dominant recording, and its fabrication process is compatible with the process for the conventional magnetic head. This paper also describes the results of experimental thermally assisted magnetic recording and the fundamental design of a heating element that uses near field optics.

1. Introduction

The recording density of today's commercial magnetic disks is about 130 Gbit/in^2, which approximately corresponds to 80 GB per 2.5-inch disk. The annual growth rate of areal density was 100% in the 1990s, but it has slowed down since 2002. To increase the density, the magnetic grain size must be reduced to assure a sufficiently high signal to noise ratio (SNR). However, a drastic increase in density will not be achieved because of the thermal fluctuation problem. Thermal fluctuation is a phenomenon by which the recorded magnetic domains relax due to thermal decay over time, and it is more pronounced as the size of magnetic grains decreases.[1)] To overcome the thermal fluctuation problem, we must greatly increase the coercivity or magnetic anisotropy constant of the media. The stability factor defined as $K_u V / k_B T$ must be larger than 60 to ensure 10 years of storage (K_u: magnetic anisotropy constant, V: magnetic grain volume, k_B: Boltzmann constant, T: temperature).

The write magnetic field, on the other hand, becomes insufficient if the media have a coercivity that exceeds 10 kOe [1 Oe = (1000/4π) A/m] due to the fundamental limitations of ring-shaped write heads. Perpendicular recording has partly replaced longitudinal recording these days. However, the fundamental thermal fluctuation problem remains. A write field exceeding 17 kOe is not expected, even if the single-pole-trimmed (SPT) write head is perfectly designed and the SPT head is combined with perpendicular media that have a soft magnetic underlayer. Therefore, the density of conventional perpendicular recording can never reach 1 Tbit/in^2.

Thermally assisted magnetic recording solves these fundamental problems. This technology was originally proposed by Katayama[2)] and Saga[3)] separately in 1999 as a derivative technology of magneto-optical (MO) recording. Thermally assisted magnetic recording can be positioned as a fusion technology of magnetic recording and optical recording. This type of recording is referred to differently, for example, as heat (or optically) assisted magnetic recording or hybrid recording.

In this paper, we review the necessity and advantage of thermally assisted magnetic recording technology to achieve an areal recording density of 1 Tbit/in^2. We also report on read/write experiments of thermally assisted magnetic recording on longitudinal, synthetic ferrimagnetic media (SFM). A multilayer optical head called a butted grating is introduced as the heating element. This element has the advantage that the same planar batch process can be used to make the magnetic-recording coil and the readback head.

2. Thermally assisted magnetic recording

2.1 Necessity

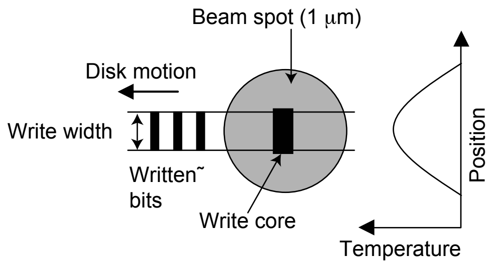
Areal density is proportional to the switching field H_0 of the media, and H_0 is proportional to the magnetic anisotropy constant K_u.[4)] The magnetic field of the present head has already reached the theoretical limit because the write pole material has an ultimate magnetic flux density B_s of 2.4 T. The write field in perpendicular recording is roughly twice that in longitudinal recording. However, a write field larger than 17 kOe is impossible even for perpendicular recording that combines an SPT head and a soft magnetic underlayer.

To achieve 1 Tbit/in^2, there is an evident conflict between the write magnetic field and the coercivity of the media. K_u must be increased by one order of magnitude while maintaining a stability factor larger than 60. K_u can be increased by one order if we use FePt media instead of conventional perpendicular CoCrPt granular media. However, the switching field of FePt can be as high as 50 kOe, but its write field never exceeds 17 kOe.

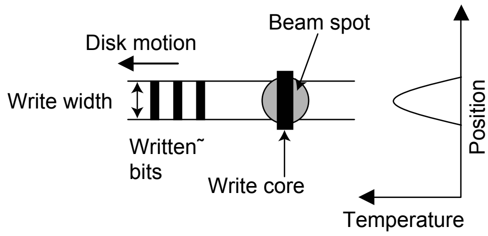
Thermally assisted magnetic recording enables us to avoid this conflict in the following way. We use media with a very high K_u and write data at high temperature with reduced coercivity. The written bits rapidly freeze during the cooling process, and the bits are stable at room temperature.

2.2 Recording method

Thermally assisted magnetic recording can be roughly divided into two methods (**Figure 1**). One method uses a beam spot size much larger than the track width. In this method, the write width is determined by the write core width. The other method uses an extremely small beam spot — as small as 50 nm — and the beam spot determines the write width. Near field optics is required to obtain the small beam spot because ordinary optics cannot produce an optical beam



(a) Magnetic dominant



(b) Optical dominant

Figure 1
Two types of methods: (a) magnetic dominant and (b) optical dominant.

smaller than the diffraction limit. In this paper, we call the first method magnetic dominant recording and the second method optical dominant recording.

Figure 2 illustrates the relationship between coercivity and temperature. The coercivity is much larger than the maximum write field at room temperature. It decreases as the temperature rises and becomes zero at the Curie temperature T_c. In magnetic dominant recording, the write temperature T_w is the temperature at which the coercivity becomes slightly smaller than the maximum write field. In optical dominant recording, the write temperature is just below the Curie temperature. The write field is relatively small because the coercivity decreases just below T_c. This method is basically similar to MO recording. Magnetic dominant recording is positioned as the method to prove the effectiveness of thermally assisted magnetic recording, and detailed experimental results of magnetic dominant recording on longitudinal media are described in Section 3. Optical dominant recording is necessary to achieve a density of 1 Tbit/in^2.

2.3 Increase in areal density

In this section, we describe the increase in areal density that can be gained by using thermally assisted magnetic recording. Lyberatos estimated the areal density for optical dominant recording when the write temperature T_w is close to the Curie temperature T_c,[5)] whereas Ruigrok[6)] treated a case where T_w is much lower than T_c. They dealt with FePt perpendicular media with a T_c of 690 K and calculated the temperature dependence of H_k and M_s for FePt by using the mean-field theory. They created two models — the mean field model and the critical volume model — and derived Equation (1) as a final expression when the cooling time is very short. In this equation, AD_{HAMR} and AD_{CON} represent the areal density of heat assisted magnetic recording (same as in thermally assisted recording) and conventional recording, respectively.

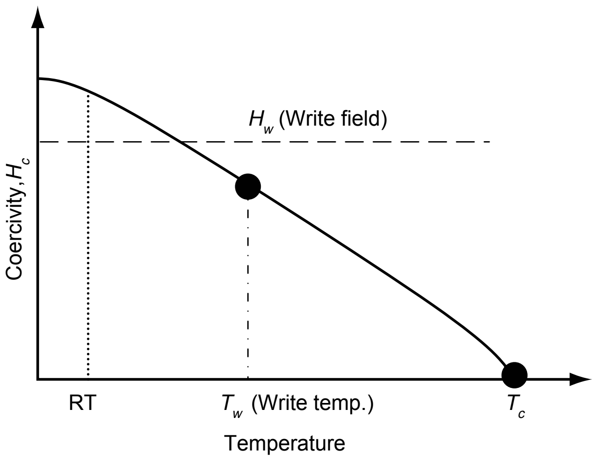


Figure 2
Relationship between coercivity and temperature.

$$\frac{AD_{HAMR}}{AD_{CON}} = \left[\frac{K_u(T_s)\left[1-\frac{H_d}{H_k}(T_s)\right]^2}{K_u(T_w)\left[1-\frac{H_d}{H_k}(T_w)\right]^2} \right]^{2/3} \qquad (1)$$

Here, H_d is the demagnetizing field and T_s is the storage temperature. Because the contribution of H_d/H_k is small, Equation (1) is simplified to Equation (2).

$$\frac{AD_{HAMR}}{AD_{CON}} = \left[\frac{K_u(T_s)}{K_u(T_w)} \right]^{2/3} \qquad (2)$$

Equation (2) gives almost the same results as those of Ruigrok, although a different approach was taken.

Figure 3 shows how Lyberatos plotted AD_{HAMR}/AD_{CON} as a function of write temperature for FePt using Equations (1) and (2). In Figure 3, the Ruigrok model indicates the plots obtained from Equation (2). No big difference is evident between the Ruigrok and Lyberatos models, and AD_{HAMR}/AD_{CON} is in the range of 2 to 3 when the write temperature is much lower than the Curie temperature.

Lyneratos also estimated the maximum value of AD_{HAMR}/AD_{CON} when the write temperature is close to the Curie temperature. **Figure 4** shows the results obtained by using Equation (2)

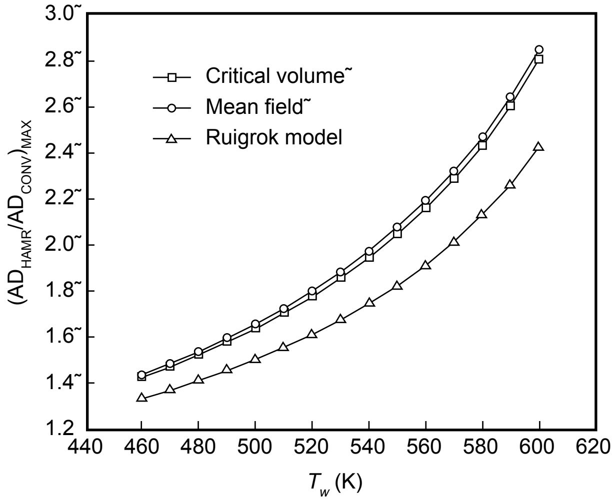


Figure 3
Ratio of areal density between HAMR and conventional recording as a function of write temperature.5)

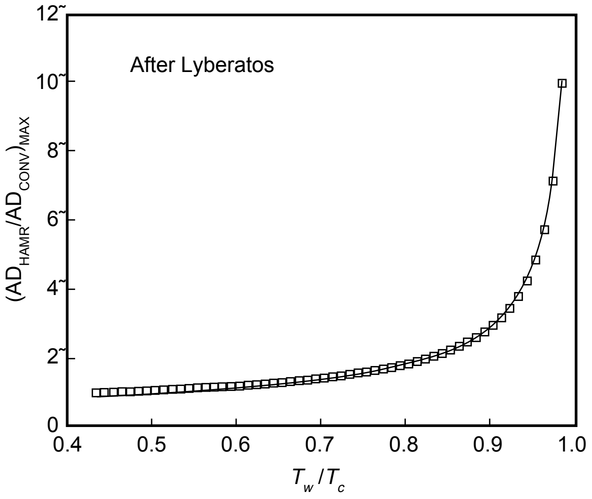


Figure 4
Ratio of areal density between HAMR and conventional recording as a function of write temperature.5)

and an approximate equation that well describes $K_u(T)$ for FePt. $(AD_{HAMR}/AD_{CON})_{MAX}$ increases drastically for $T_w/T_c > 0.95$ and reaches as high as 10. He concluded that the write field is sufficient because the coercivity decreases just below the Curie temperature, even when FePt has a switching field of 50 kOe.

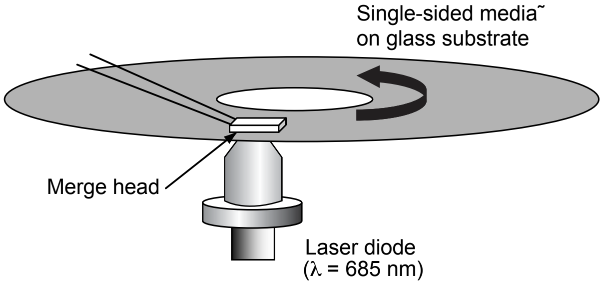


Figure 5
Schematic view of read/write system.

3. Read/write experiments on longitudinal media

3.1 Read/write system

Dynamic measurements were conducted using a conventional spin stand equipped with an optical head used for a commercial MO drive (**Figure 5**). The magnetic head was a commercial one used for a 40 GB/platter commercial drive. The write core width was 0.25 μm, and the read core width was 0.17 μm. The DC laser beam was irradiated during writing through the glass substrate. The beam spot size on the media was 1.1 μm with a wavelength of 685 nm.

3.2 Recording media

The longitudinal media used for the R/W experiment were SFM. SFM are composed of a thin bottom layer (CoCr alloy) and a thick top layer (CoCrPtB alloy), and these two layers are ferrimagnetically exchange coupled through a thin Ru layer.7) With this structure, we can obtain a high K_u and thicker film media, ensuring a large stability factor even for small grain sizes.

Three kinds of media (SFM-L, -H, and -X) were deposited by sputtering on glass substrates with a 2.5-inch diameter (conventional commercial 2.5-inch disks have a capacity of 40 GB/platter and a density of 70 Gbit/in^2). The magnetic properties of the three media used for the read/write experiments are shown in **Table 1** together with those of commercial 40 GB/platter media. The coercivity H_c and anisotropy constant K_u in the three media are larger than in the 40 GB/platter commercial media. SFM-X have a particularly small $M_r\delta$ (*Mr*: remnant magnetization, δ : film thickness). A small $M_r\delta$ leads to a narrower transition width for the written bit, as described later.

Dynamic coercivity $H_{c,dynamic}$ must be taken into account instead of static coercivity when data is written at high frequency. Dynamic coercivity is as follows.[8)]

$$H_{c,dynamic} = H_0 \left\{ 1 - \left[\left(\frac{k_B T}{K_u V} \right) \ln \left(\frac{f_0 t}{\ln 2} \right) \right]^{2/3} \right\} \qquad (3)$$

Here, H_0 is the switching field of the media, f_0 is the thermal attempt frequency, and t is time in seconds. The logarithmic function originates from the exponential nature of thermal decay.

Figure 6 shows the dynamic coercivity as a function of the time during which the magnetic field is applied during writing. These results were obtained by using Equation (3) and the conditions of K_uV/k_BT = 80 and T = 300 K. Although the saturation magnetization M_s is not directly included in Equation (3), it has a relation with H_0 that is roughly expressed as K_u/M_s. At room temperature, the coercivity measured by a vibrating sample magnetometer (VSM) is about 4 kOe. The coercivity at high-frequency writing is roughly twice that measured by VSM. When the temperature is moderately raised to 400 K, the dynamic coercivity changes only slightly. When media with a 20% lower K_u are used, the dynamic coercivity decreases significantly.

Table 1
Magnetic properties of experimental media and 40 GB/platter commercial media.

˜	40 GB/platter˜	SFM-X˜	SFM-L˜	SFM-H˜
$M_r\delta$ (memu/cm^2)˜	0.29˜	0.19˜	0.30˜	0.37˜
M_s (emu/cm^3)˜˜˜			270˜	330˜
H_c (Oe) 1 kOe/s˜	4700˜	5430˜	4600˜	6000˜
H_c at 0 K (Oe) ˜˜		12 000˜	10 200˜	9600

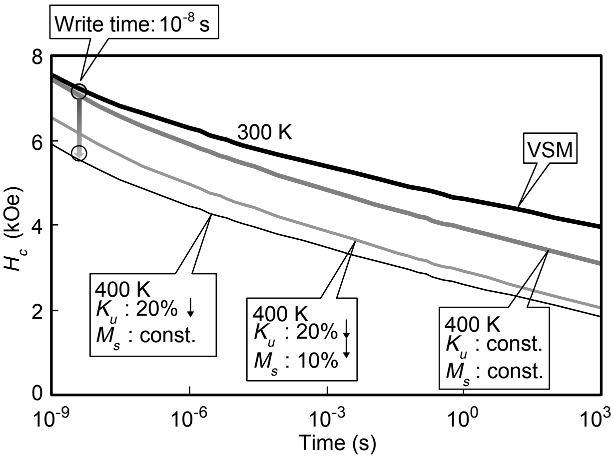


Figure 6
Dynamic coercivity as a function of switching time.

The thermal stabilities of the three media are shown in **Figure 7**. These were measured using a Superconducting Quantum Interference Device (SQUID) magnetometer. The vertical axis shows signal decay, and the horizontal axis shows the applied magnetic field H_d during the SQUID measurement. Both the SFM-L and SFM-H have better thermal stability than the 40 GB/platter commercial media because of their larger K_u.

3.3 Dynamic recording[9)]

Figure 8 shows the dependence of the track average amplitude (TAA) on the head position in the cross-track direction at a laser power PL of 5 mW. The TAA was measured at each write head

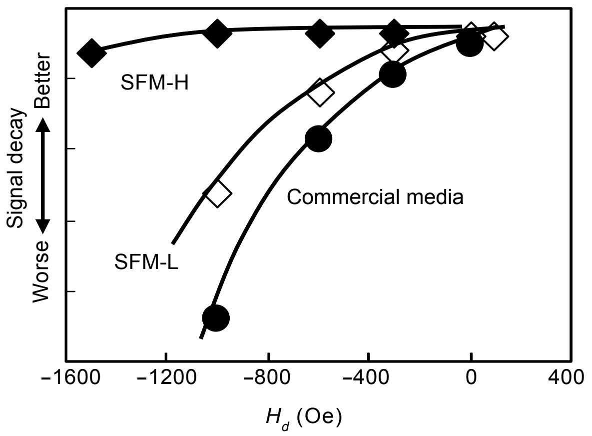


Figure 7
Dependence of signal decay on applied magnetic field during SQUID measurement.

position by moving the head to within +/– 2 μm of the center of the optical beam spot. The thermal profile half-width is about 1 μm. Although the optical beam spot is four times wider than the write core, the write width is roughly 0.25 μm and is therefore about the same as the width of the write core.

The overwrite properties of the SFM-L and SFM-H are shown in **Figure 9**. The vertical axis shows a residual signal amplitude of 87 kFCI (kFCI: kilo flux changes per inch) after overwriting at 700 kFCI. The overwritability was drastically improved by elevating the laser power PL for both media, which reflects the thermal assistance effect. In particular, an overwrite of less than –30 dB, which is the criterion for practical use, was obtained with a wide range of write currents.

Figure 10 (a) shows the effect of thermal erasure for the SFM-L when the laser is operated once. The normalized track average amplitude does not change at laser powers up to 5 mW. The

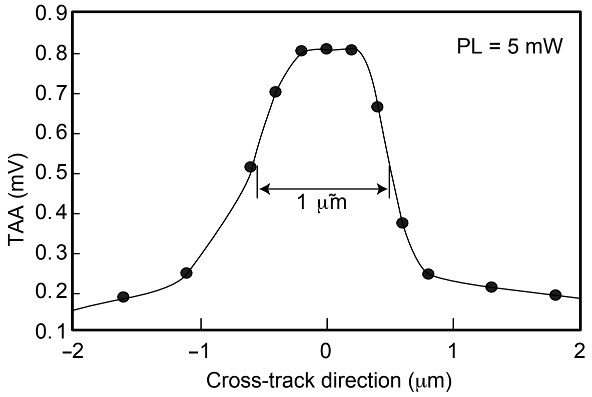
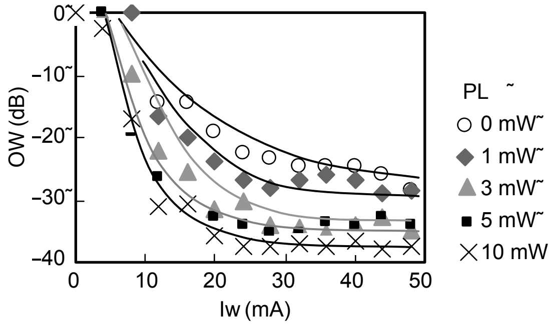
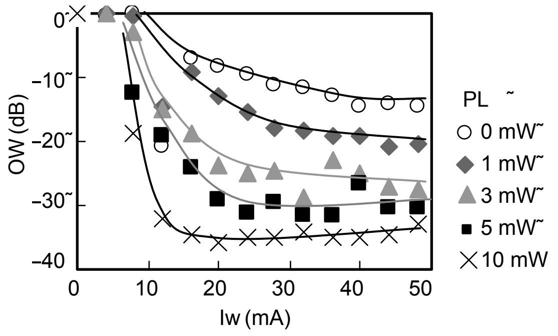


Figure 8
Dependence of TAA on write head position in cross-track direction at laser power PL of 5 mW.

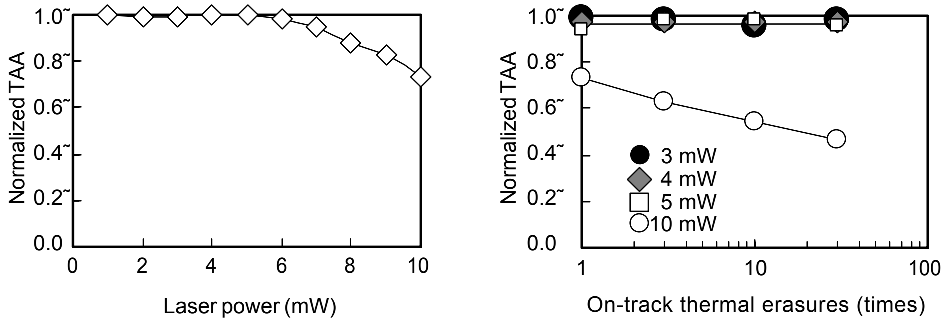


(a) SFM-L



(b) SFM-H

Figure 9
Dependence of overwrite property OW on write current Iw of (a) SFM-L and (b) SMF-H for each PL.



(a)

(b)

Figure 10
TAA of SFM-L for (a) single laser irradiations and (b) multiple irradiations.

laser power needed to obtain an overwrite of less than –30 dB is about 3 mW. Therefore, the power margin is large enough to prevent thermal erasure. **Figure 10 (b)** shows how TAA changes over multiple erasures. The figure shows that on-track thermal erasure only occurs at powers of 5 mW and above, which is sufficiently higher than the 3 mW needed to obtain an overwrite of less than –30 dB.

Figure 11 shows the change in SNR ($\Delta S/Nm$) of the SFM-L and SFM-H for various write currents Iw compared to the SNR of commercial media recorded at an Iw of 40 mA. With thermal assistance, the SNRs of both media were greatly improved compared with the SNRs without thermal assistance. The SNR of the SFM-L at 3 mW recording was equivalent to that of the 40 GB/platter commercial media without thermal assistance. Both the SFM-L and SFM-H exhibit a good SNR over a wide range of write currents.

PW_{50} is a criterion for recording resolution and is defined as the half width when an isolated pulse signal is reproduced. PW_{50} is empirically known to be roughly proportional to $M_r\delta/H_c$, which relates to the transition width of the recorded bits. The dependence of PW_{50} on laser power is shown in **Figure 12** for the SFM-L, SFM-H, SFM-X, and 40 GB/platter commercial media. Compared with the 40 GB/platter commercial media, the SFM-H and SFM-X have the same value, and the SFM-L have a smaller value without thermal assistance. PW_{50} increases drastically at laser powers above 5 mW for the SFM-L, which have a rather low coercivity. The transition width of recorded bits increases due to the decrease in coercivity caused by the excessive temperature rise. SFM-X show a minimum PW_{50} at 3 mW, and their value is better than that of 40 GB/platter commercial media. This reflects the fact that SFM-X have a particularly small $M_r\delta/H_c$, as shown in Table 1.

From the results given in this section, we conclude that both the SNR and overwrite without thermal erasure are assured in thermally assisted magnetic recording. Thus, the effectiveness of thermally assisted magnetic recording has been proven.

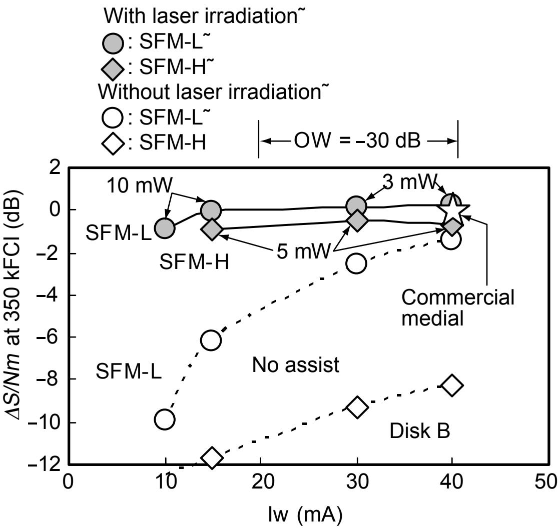


Figure 11
Dependence of relative SNR on write current. Dashed lines show $\Delta S/Nm$ when writing without laser irradiation. Star (☆) shows $\Delta S/Nm$ of 40 GB/platter commercial media.

4. Heating element for writer

The laser spot size must be extremely focused to achieve optical dominant recording. Therefore, we need to develop a heating element that emits near-field light. The requirements for the heating element are as follows: a) the beam spot size

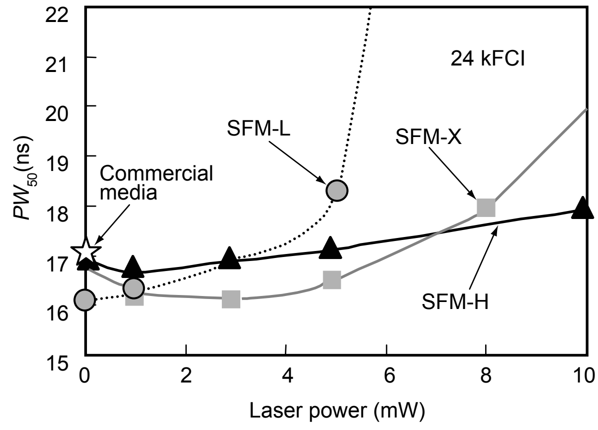


Figure 12
Dependence of PW_{50} on laser power. Star (☆) shows PW_{50} of 40 GB/platter commercial media.

must be smaller than 50 nm; b) the optical efficiency must be as high as about 2% to heat the media to the required temperature; c) because of the magnetic spacing (i.e., the relatively large distance between the head and magnetic film), the attenuation length of the near-field light must be greater than 10 nm; and d) integration of the heating element with the magnetic head must be possible. Concerning requirement d), the fabrication process must be compatible with the process for the magnetic head, and precise positioning between the beam spot and write pole must also be assured.

For the near-field-light heating element, ridge waveguide,[10),11)] bow-tie antenna,[12),13)] zone plate grating,[14)] and SMASH head[15)] versions have been proposed. However, the write fields of these proposals will be limited to about 100 Oe because they are combined with a coil without a magnetic core.

We have proposed the butted grating structure for the heating element,[16)] which was designed by the software Poynting,[17)] which analyzes electromagnetic waves using the Finite Difference Time Domain (FDTD) method. This structure is suitable for thermally assisted magnetic recording because the process used to fabricate it is compatible with the process for the current magnetic head. This means that the head, which must integrate the heating element and read/write elements, can be fabricated on an AlTiC substrate using a planer process. Consequently, a strong magnetic field is available.

Our heating element with the butted grating is shown in **Figure 13**. In the figure, the X-Y plane is parallel to the surface of the media, the X-axis corresponds to the circumferential direction, and the Y-axis corresponds to the radial direction. The arrow-shaped polyhedron is a multi-layer grating of Al/diamond/Al/SiO_2/Al/diamond/Al. The 400 nm light is incident from the upper left, and the near-field light is emitted from the lower right. The basic idea of the butted grating is to butt a one-period high-transmission-efficiency grating (Al/SiO_2) in the central part of the structure with very low-transmission-efficiency Al/diamond gratings that have a small number of periods at either side for increasing the optical transmission efficiency. As a result, a high optical transmission of the nano beam is achieved through the SiO_2, which is 30 nm in the X-direction. Furthermore, as the light, which is polarized in the X-direction, propagates in the minus Z-direction, it becomes narrow in the Y-direction due to the interference of multiple reflections from the sidewall. The calculated beam spot size is 45 nm

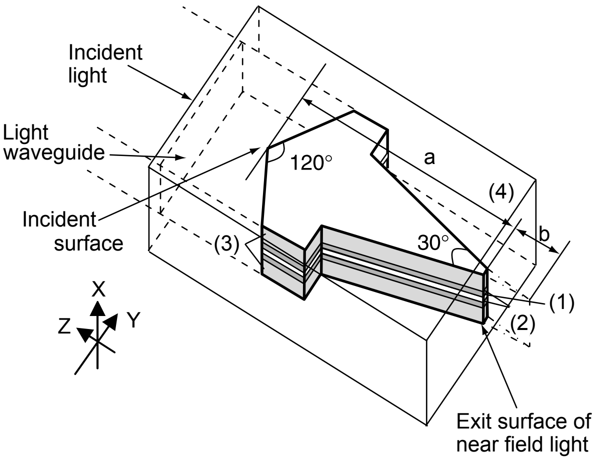


Figure 13
Heating element with multi-layer butted grating of SiO_2 (1), Al (2), and diamond (3), Al (4).

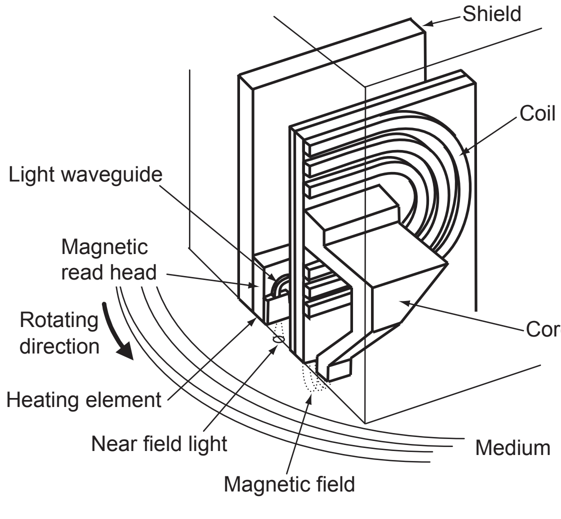


Figure 14
Conventional integrated head with butted grating heating element.

in the X-direction and 60 nm in the Y-direction. The Z-direction tolerance is 15 ± 5 nm, indicating that the attenuation length is large enough compared with the magnetic spacing. The optical efficiency is 1.6%, which is lower than that required, but this will be improved by optimizing the structure's design.

The butted grating heating element can be formed by sputtering and etching, and it has good affinity with the conventional magnetic head. **Figure 14** shows a conventional magnetic head that integrates a heating element and butted grating.

5. Conclusion

In this paper, we emphasized that thermally assisted magnetic recording is the key technology for overcoming the thermal fluctuation and write capability issues in magnetic recording and described its features. A theoretical estimation suggests that thermally assisted magnetic recording enables 10 times the density compared with conventional magnetic recording.

The following experimental and calculation results were reported. Firstly, magnetic dominant recording conducted on a longitudinal SFM shows that both the SNR and overwritability without thermal erasure are assured. Secondly, our butted grating optical head is the prime candidate for the heating element because its fabrication process is compatible with that of a conventional magnetic head.

Our research is now in the phase of proving the effectiveness of thermally assisted magnetic recording, and we have to determine whether the technology can be used in a real drive in terms of system margin and cost. Besides the heating element, there are many other challenges to be overcome, for example, how to integrate the heating element with the magnetic head, thermal issues about the integrated head and the media, and the characterization of media with the very large anisotropy constant of FePt.

The growth rate of areal density for both longitudinal and perpendicular recording has slowed down since 2002, and a big breakthrough is now strongly needed. We believe that thermally assisted magnetic recording is the only way to achieve 1 Tbit/in^2.

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