Investigation of transport phenomena in nano-scale head disk interface

Myo, Kyaw Sett

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**NANYANG
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**INVESTIGATION OF TRANSPORT PHENOMENA
IN NANO-SCALE HEAD DISK INTERFACE**

MYO KYAW SETT

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2017

INVESTIGATION OF TRANSPORT PHENOMENA IN NANO-SCALE HEAD DISK INTERFACE

MYO KYAW SETT

School of Mechanical and Aerospace Engineering

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Abstract

Heat-assisted magnetic recording (HAMR) is one of the potential magnetic recording technologies to achieve higher recording capacity and reduce the cost of data storage in hard drives. However, there are many mechanical challenges and difficulties in physical understanding to realize the HAMR for industrial application with stability and reliability. In the HAMR system, a laser beam or other heating sources will be used to heat up the recording medium to reduce the disk media coercivity below the magnetic field applied by a conventional recording head. The heated region in the medium is rapidly cooled to the ambient temperature after the writing process is completed. The head-disk interface (HDI) spacing between the read/write head and the disk is in nanoscale, and it keeps reducing for achieving higher density recording. The involvement of understanding the heat transfer process in the HAMR nano-scale interface becomes important in further developments of this technology.

This thesis presents a study to investigate transport phenomena in the head-disk interface of the HAMR system, including the air bearing, the heat generation and the heat transfer at the interface.

Firstly, the slider air bearing that supports a slider floating above a disk is modeled and studied using the Reynolds' equations based model. The direct Monte Carlo simulation (DSMC) method is then introduced to apply in the HAMR air bearing study, taking into account of thermal effect. The DSMC simulation results of the slider bearing characteristics are obtained with various slider postures and utilized for verifying those from the traditional continuum-based model. This is a pioneer research work in applying the DSMC method to solve HAMR air bearing problems. It is found that the presence of

localized laser heating process could increase the air bearing pressure acted to the slider surface and affect the slider flying behaviors.

Secondly, the heat generation resulted from the laser delivery system, which is supposed to be designed inside an integrated HAMR slider body, could cause the slider's temperature rise and thermal protrusion. This heat transfer process is examined by the finite element method using the ANSYS software in modeling and analyzing the thermal distribution of a HAMR slider. The numerical results predict that the heat dissipations in optical components of an integrated HAMR slider could lead to the contact between the flying head and disk, consequently causing the HAMR hard drive failure.

Thirdly, the HAMR recording disk is designed as the multi-layered format in order to achieve the desired temperature in a recording media layer while the data is being written or stored at the respective frequency. The heat transfer process in the disk is studied with the energy transformation models to obtain the disk surface temperature with a localized hot spot. The laser beam will also heat the air in the head disk interface region and its effect on the slider air bearing could influence the drive's reliability. This is due to the high disk-surface temperature at the localized laser-heating region, which could create the variation of gas properties and affect the surrounding components in the interface. As the interface region is nanoscale, the heat transfer in this region involves the thermal radiation between a slider and a disk. Therefore, a new heat transfer model is developed, which takes into account of the radiation effect associated with the slider temperature and its surface profile. By applying this new heat transfer model, more accurate slider temperature and protrusion profiles could be predicted under the slider flying condition in the HAMR system. Consequently, by comprehending thermal conditions and their effects in HAMR HDI, it could help in designing a proper air

bearing surface (ABS) and enhancing the reliability of HDI to contribute in thriving for the HAMR technology as a next generation hard drive technology.

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Chapter 1: Introduction

1.1: Evolution of Hard Disk Drives

Information storage in a hard disk drive (HDD) introduced in 1956 is one of the vital technologies for the information society. International Business Machines (IBM) introduced the first magnetic hard disk in the 305 RAMAC (Random Access Method of Accounting and Control) for data storage in 1956. The total capacity of 305 RAMAC drive was only 5 Megabytes (MB) and the areal density was 2000 bits/in² (100 bits/in and 20 tracks/in). Its magnetic read and write head was supported above the disk surface by an external pressurized hydrostatic air bearing, at a spacing of approximately 20 μm . In 1962, IBM introduced the 1301 series disk drive and it has a self-acting hydrodynamic air bearing for the slider flying above the surface of the disk (IBM, 2011). Later in 1973, a hydrodynamic air bearing technology was applied in the slider-disk interface of “Winchester” disk drive. This self-acting, hydrodynamic air bearing design continues serving as the basis of today’s HDD head disk interface (HDI). The magnetic HDD has become the well-known digital storage device due to its inexpensive, highly-reliable, quickly-accessible and high-density data storage system in this information era.

The hard disk drive (HDD) which is one of the most common used information storage devices has evolved possessing higher recording density, smaller size and lower price nowadays in order to satisfy the increasing demand for the digital data storage. In magnetic recording systems of HDD, the recording (read/write) head hovers over the surface of the rotating data disk for reading and writing data on the tracks. A HDD consists of mainly electrical and mechanical components assembled and enclosed in a

rectangular casing. One of two main assemblies inside HDD involves a spindle motor and a disk. The other assembly contains an actuator arm, a suspension, a gimbal/flexure, and a slider carrying with a read/write head for data transfer. This assembly is linked to a voice coil motor (VCM) for the recording head positioning over the specific data track. Figure 1.1 shows the components in a hard disk drive system.

1.2: Structure of a Hard Disk Drive

The components of a hard disk include the drive-spindle, disk, actuator arm, suspension, slider, and read or write head. The spindle holds the platters which are used for data storage. During operation, the platters are operated at a speed of 5400 to 10000 rpm (revolutions per minute) via a motor connected to the spindle. The read/write head is mounted beneath the slider and it is used to access the data on the disk. A suspension is an elastic beam-like element that holds the air bearing sliders and positions the read/write head closely to the disk without causing a head crash. This suspension is attached to an actuator arm, which is moved by the VCM across the disk when the read/write head is accessing the data on the disk. The VCM is controlled by a servo controller.

The main hard disk drive components and their respective functions are discussed in the following sections.

Figure 1.1 Hard disk assembly with component descriptions

1.2.1: The Disk (Platter)

The platter is the storage medium within the hard disk drive and it is manufactured using a non-magnetic material, commonly Glass or Aluminium, with a thin layer of coating of magnetic material on its surface. This magnetic layer is divided into various small micro-size regions which are also known as zones, tracks, and bits as shown in Figure 1.2a and 1.2b. Sectors are parts of each track which have defined the magnetic marking and sequential ID number. The track is a set of magnetic bits on the disk, divided into 512-byte sectors (1 byte is equivalent to 8 bits). The areal density of a disk is calculated from the product of tracks per inch (TPI) and bits per inch (BPI).

Figure 1.2 (a) Tracks per inch; Bits per inch and (b) Tracks on a disk platter and the platter assembly (Tandon, Rao, and Agrawal, 2006)

The disk (media) platter structure is a multi-layered one which is made of different materials to achieve the stability of data storage. Both the slider surface and the magnetic layer of the disk are covered by the diamond-like-carbon (DLC) overcoat to protect the surfaces from wear. The DLC overcoat layer is covered with a thin lubricant layer which is applied to the disk surface by dipping the disk in a lubricant reservoir. The magnetic layer is located under the DLC layer with a soft ‘underlayer’ beneath. The sublayer and the substrate layers are placed at the base of a recording media respectively as shown in Figure 1.3. The disk substrate is generally made of glass or aluminum. The magnetic layer and the carbon overcoat are deposited by sputtering or chemical vapor deposition.

A nearly uniform spacing between the slider and the disk requires maintaining during the disk drive operation. This spacing is called the ‘flying height’. The magnetic spacing (head-media spacing (HMS)) as shown in Figure 1.3, comprises of flying height (FH), head and disk protective carbon overcoats, and disk lubricant. The areal density growth is enabled by the continuous reduction of HMS and the current HDDs have the HMS on

the order of 10 nm to achieve an areal density of 500 gigabits per square inch (Gb/in²). The HMS involves a 5 nm flying height, the head and disk overcoats at 2 nm each and about 1 nm of disk lubricant film for the current HDDs (Marchon et al., 2013). The significant flying heights can be varied from head to head due to manufacturing tolerances in the disk drives. Furthermore, the FH modulation could occur at the particular disk radial position due to the disk waviness at low head disk interface clearance (Su et al., 2011).

Figure 1.3 Schematic view of head/disk interface

1.2.2: Read and Write Head

The read/write head reads and records data on the magnetic layer placed inside the platter. It includes a magneto-resistive read element and an inductive write element as shown in Figure 1.4. The magneto-resistive read element reads data by detecting the magnetic field generated from the magnetic medium on the disk platter and generates a voltage which is then processed as information. An inductive write element inside the slider records data on the magnetic medium by switching the directions of the tiny magnets bits of the storage disk. A binary system is used to record data in which

arranging two similar poles to meet each other is defined as 1 while opposite poles to meet each other is defined as 0.

Figure 1.4 Read/Write head with the disk (Devasahayam, 2005)

1.2.3: Air Bearing Surface (ABS) and Slider

A precisely designed and fabricated patterned surface, known as the air bearing surface (ABS), on the bottom surface of the slider generates the nano-scale air bearing in between the slider and disk surfaces during the operation as in Figure 1.5a and 1.5b. Various ABS designs in the market are manufactured to cater to varied needs and demands. Flying height is measured from ABS to the surface of the disk. Pitch is defined as the rotation angle about the slider's Y-axis (length wise) where a positive value indicates that the trailing edge is closer to the disk. Roll is defined as the rotation angle about the slider's X-axis (width wise) where a positive value indicates that the inner leading edge is close to the disk.

During the hard disk operation, the slider is flying above the disk and several forces acting on the slider can be identified. These forces are the suspension force from the suspension that pushes the slider downward, air pressure from the air bearing that lifts up or drags down the slider and the intermolecular forces in between the air bearing surface and disks surface if the slider is flying at ultra-low spacing. The balance of the resultant forces results in the final flying height. In low flying height range of the high areal density recording systems, the short range attractive forces, such as intermolecular, electrostatic and meniscus forces become important and they could cause instability of the head-disk interface.

Figure 1.5 (a) Slider Front View and (b) Slider Side View

1.3: Head Disk Interface (HDI) Technology

The read and write element is placed inside a slider body which is hovering above the disk platter as mentioned in the previous section. The disk rotation brings air under the slider that creates the pressure and provides the lifting force that causes the head to float above the disk. This lifting force is known as the ‘air bearing force’. One of the main parameters in HDI is the spacing between the head and recording medium; the flying height. The slider surface and the magnetic recording layer are covered by diamond-like-carbon (DLC) overcoats to keep both surfaces from the wear and the lubricant layer is

placed on top of the DLC layer of a disk to prevent any potential slider-disk contact. The magnetic spacing is defined as the distance between the bottom surface of the read/write element and the top surface of the magnetic disk layer. The magnetic spacing requires being reduced further in order to achieve better magnetic signal when higher density magnetic recordings take place and small form factor of HDD is required.

The areal density had been growing at an average compounded rate of about 44 % per annum for the past 50 years due to several critical technology milestones, among them are the thin-film head, thin-film media, Magnetoresistive (MR) head, Giant MR head, Tunneling MR head, load-unload scheme, Thermal Fly-Height Control (TFC) slider and etc. As of June 2015, the current HDD areal density; 1.2 terabits per square inch (Tbit/in²) has been demonstrated. Figure 1.6 shows the areal density growth trend in HDD storage capacity estimated by N. Zhou et al. (2014). Concurrently, the head to disk spacing of hard disk drives has been decreased by a factor of 2000 for higher density magnetic recording.

Figure 1.6 Projected areal density in the following years. CAGR, compound annual growth rates; SMR, shingled magnetic recording; BPM, bit patterned media recording which is another technology for reaching high aerial density (N. Zhou et al., 2014)

Figure 1.7 Historical variations of HMS versus areal density from (Marchon and Olson, 2009). The yellow star is an extrapolation to 4 Tb/in² (Marchon et al., 2013)

With the support of hydrodynamic air bearing in HDI, the slider is designed to fly over the spinning disk at a stable flying height. The head-disk interface (HDI) spacing has been decreased to as low as 1.5-2 nm achieving ultra-high magnetic recording density in the recent HDDs Wood (2009). The magnetic recording media is protected with a carbon overcoat and a lubricant film that has a thickness of approximately 1-2 nm in current hard drives. In order to achieve high recording density such as 1 Tbit/ in², the slider requires flying above the disk (the magnetic spacing between the head and disk) at 6.5nm (Wood, 2000). It is estimated that the head-media spacing (HMS) will be necessary to cross 7 nm mark to achieve the terabit per square inch density point (Marchon and Olson, 2009, Wood, 2009). However, the storage signal error rate will be unavoidable in such higher areal density recordings. Alternative recording technologies are being explored to increase the areal density beyond these limits. Among these technologies, the heat assisted magnetic recording (HAMR) is one of the promising approaches with considerable risks and significant engineering challenges.

1.4: Future Storage Technology: Heat-Assisted Magnetic Recording (HAMR)

Among recent computer storage devices, the magnetic recording device is still involving as the main role to store video, music records, photos and office data files and etc. in massive range. Therefore, the demand for high capacity hard disk drives keeps on increasing. In order to scale the areal density in magnetic recording, media signal-to-noise ratio (SNR), thermal stability and writability must be still in the balance. The current perpendicular recording, thin-film media and recording heads and giant magnetoresistive readers have enabled data storage density to 500 Gbits/in² approximately before reaching to the superpara-magnetic limit over which the magnetic energy in a single bit could not be maintained while storing data and this results in the loss of data (Bertram and Williams, 2000). In order to improve the signal-to-noise ratio (SNR) for the high-density recording, the media grain size reduction is necessary with high anisotropy grains to maintain the thermal stability at higher densities (Rottmayer et al., 2006).

The new recording technologies are required to overcome the superpara-magnetic limit and the heat-assisted magnetic recording (HAMR) is one of the prospective high-density recording technologies in current hard disk industry (Kryder et al., 2008, Matsumoto, 2006) while maintaining the proper balance between the media SNR, thermal stability, and writability. It requires heating a spot on the recording media with a laser beam. In order to perform this process, the slider body needs to be optimized and integrated with the near-field optical system inside for the precise heating and recording. By heating the media to its Curie temperature with a laser beam or any other means, the magnetic anisotropy and saturation magnetization are reduced continuously to nearly zero.

Consequently, the media coercivity drops below the magnetic field applied by the conventional write head with this effect in HAMR (Rottmayer et al., 2006). The heated region is then rapidly cooled to the ambient temperature when the head field is applied and the head magnetic field is larger than the local demagnetization fields of media grains in the track. Therefore, the magnetization of the media grains will be oriented in the direction of the applied head field (Inoue et al., 2006). Figure 1.8 shows the relation of writing temperature and media coercivity in the HAMR writing process.

Moreover, the HAMR recording head paired and integrated with the light delivery and the focusing optics must be able to fly at low head-to-media spacing ($<10\text{nm}$) and deliver a high magnetic field at the heating spot position (Kryder et al., 2008). A slider constructed and combined with the light delivery system and recording head components is called an ‘integrated HAMR slider’. The media requires heating above Curie temperature (about 700K) to reduce its coercivity during writing in this recording (Seigler et al., 2008). The optic transducer system will be located inside the slider for the heating process (Figure 1.9). Therefore, it will cause the temperature rise on the slider body while largely dissipating through the suspension and air bearing surface. The thermal energy generated could also affect the slider’s air bearing and its flying behaviors.

Figure 1.8 Diagram showing the HAMR writing process (Kryder et al., 2008)

Figure 1.9 Heat assisted magnetic recording system (Shiroishi et al., 2009)

1.5: Objectives and Scope of Work

The objective of this dissertation is to propose and describe the air bearing behavior with the effects of heat transport process in the HAMR system components and head disk interface. Knowing the potential challenges and issues of implementing the new high-density HAMR system in hard drive industry, a careful study of heat transport phenomena with appropriate numerical methods is necessary to enhance the understanding and solution accuracies of HAMR HDI problems. However, developing a whole numerical simulation model for the entire HAMR HDI system is unfeasible because of very complicated coupled-field mechanisms involved in the nano-scale interface. Therefore, the heat transfer processes in the HAMR slider body, interface region, and HAMR media are divided and modeled separately in the numerical simulation studies. And then, the results obtained from one study will be used as an input for another study to achieve more realistic outcomes. The heat transfer study and

analysis are carried out starting from the components of a flying HAMR integrated slider to the HAMR multi-layered disk through the interface region.

The finite element model of a HAMR slider body with the magnetic recording and optical delivery components inside is developed for studying heat transfer in the HAMR slider. Using this FEM model, the slider temperature and structural deformation are simulated in ANSYS software. Based on the laser beam intensity profile emitted from the HAMR slider, the temperature distribution of a multi-layered disk surface is computed and applied for the study of thermal effect in the interface region. A new heat transfer model is proposed to consider the thermal conduction and radiation effects in the nano-scale HAMR interface. With this new model, the effects of HAMR optical delivery components and media hot spot on the HAMR slider's flying performances are investigated and analyzed. Then, the particle-based DSMC method is used to validate all the findings of the bearing pressure against the slider surface with those from the continuum-based models in very high Knudsen number flow regime.

The main objectives of the dissertation are:

- to employ the direct simulation Monte Carlo (DSMC) method to study the air bearing characteristics in the nano-scale head-disk interface of a HAMR system.
- to study the effect of heat dissipation of the optical delivery and magnetic recording components on the slider temperature and thermal protrusion with the finite element model of an integrated HAMR slider.
- to examine the slider flying behavior variation in the steady state due to thermal effects from the HAMR optical delivery components in a HAMR system.

- to study the heat energy transformation process from a laser beam emitted from the slider to the multi-layered HAMR media structure and predict the thermal distribution on the media surface.
- to develop a new heat transfer model which could predict the thermal conduction and radiation in the nano-scale head disk interface more accurately.

It is believed that the proposed heat transfer model and present works could provide deeper understanding and contribution in developing a method for forecasting thermal effects on the reliability of HAMR system.

1.6: Layout of Thesis

This report contains six chapters including this chapter. The layout is as followed:

Chapter 1 introduces the background of hard disk drives and heat assisted magnetic recording (HAMR) technologies. The working principles of hard disk components such as recording head, disk, and flying slider are briefly described. The existing and future head disk interface technologies for high magnetic recording density system are also reviewed and analyzed. The potential issue and heat related problems of the HAMR system are discussed and the motivation of the present study is defined in this chapter.

The detailed literature reviews on the existing air bearing and heat transfer models are presented in Chapter 2. Understanding the heat transport process in the nanometer head disk interface is critical in predicting slider and media surface temperatures to achieve better system reliability. A high-temperature slider and a hot spot on the media could cause the variations in slider's flying behavior and this could further affect the reliability of the HAMR head disk interface. These HAMR effects are currently studied with the

traditional numerical methods which are applied to the current HDD technology using thermal flying height control (TFC) sliders. Those models are reviewed and discussed for the HAMR application. The potential designs and features of an integrated slider, a disk and the interface of HAMR system are also reviewed.

Chapter 3 introduces the direct Monte Carlo simulation (DSMC) method and uses it in solving the slider's air bearing problems of a simplified HAMR system. The small rectangular section with slider, disk surfaces and HAMR interface setup is developed in the DSMC simulation. The slider's bearing pressure against the slider's surface is studied with the presence of the hot spot on the disk. Effects of slider's postures, pitches and gap spacing on the slider's bearing pressure and force are presented.

In Chapter 4, the development of the HAMR slider finite element model and the analysis of head components' thermal distributions using ANSYS are discussed. The power dissipations with different power stages are applied in the optical delivery components for studying thermal effects on the slider's flying performance.

Investigation of thermal energy distribution in a HAMR multi-layered disk is presented in Chapter 5. The temperature distribution of a hot spot on the media is calculated to understand thermal effect in the HAMR interface. The back heating from a media hot spot could influence in temperature rise and the structural deformation of slider air bearing surface. The heat transfer model simulating HAMR interface is improved with the inclusion of thermal radiation from a hot spot due to the nano-scale gap between the slider and disk surfaces.

The last Chapter 6 provides a summary of the present work and the future work on the heat transfer model to study the thermal effects in the HAMR head disk interface.

Chapter 2: Literature Review

The current magnetic recording technology in hard disk data storage is based on the perpendicular magnetic recording. This technology is limited for high recording density like 1 Tbit/in² and beyond due to the requirement of very small magnetic grain size inside the recording medium and its stability at room temperature. The recording medium grain volume must be reduced to achieve higher areal density while maintaining good signal-noise ratio. As the result of reducing average medium grain size, thermal instability in magnetic domain of such medium could lead to the data loss. This medium will reduce the ambient temperature stability factor which is defined as the ratio of the stored magnetic energy; $K_u V$ (K_u is uniaxial magneto-crystalline anisotropy and V is the magnetic switching volume) and the thermal energy; $k_B T$ (k_B is Boltzmann constant and T is the recording temperature). The stability factor should be larger than 70 ($K_u V / k_B T \geq 70$) in order to prevent data loss and remain stable for 10 years (Thiele et al., 2002). The reduction of grain size in higher areal density recording can be compensated by bringing up the magneto-crystalline anisotropy value (K_u) of the medium. Consequently, the coercivity (H_C) of the recording media increases with K_u . This ultrahigh coercivity of the medium is much larger than the maximum recording head field provided by the conventional write head. To solve the problem, the coercivity of the media grains should be temporarily lowered by heating the medium above the Curie temperature (T_c) so that the writing process could be done by the standard write head field during the heating time. Therefore, the recording material requires a heating assistance to enable being switched by the fields from the conventional recording heads.

In the heat assisted magnetic recording (HAMR) technology, a laser beam is normally used to heat the recording medium as that in the magneto-optic (MO) recording. However, after the data is written by the head, HAMR medium requires being cooled

quickly back to the room temperature for restoring grain anisotropy and achieving thermal stability of high areal density medium, unlike MO recording system. As HAMR system targets for very high areal density recording, the recording medium will consist of very small magnetic grains and need a localized heating spot to avoid demagnetizing the neighboring tracks during the writing process. The properly confined heating spot on the medium is directly proportional to the bit aspect ratio (BAR: the ratio of track width and bit length) and inversely to the areal recording density (AD). The track width (TW) for 1 Tbit/in² recording areal density (AD) is defined as $TW = [BAR/AD]^{1/2}$ and it is 50.8 nm if the bit aspect ratio is set as 4 (McDaniel, Challener, and Sendur, 2003). Beyond 1 Tbit/in² recording density, the media track size to be heated is as small as 161 nm² of the area for 4 Tbit/in² (Greaves, Kanai, and Muraoka, 2013). Therefore, main challenges of developing a HAMR integrated head which includes both the optical delivery and magnetic recording systems are the ways of delivering the laser beam with a very small diameter spot and enough power heating on the recording media layer while writing data as shown in Figure 2.1.

There are also some major heat transfer problems due to the requirement of laser heating such as the heat loss during the energy transfer from the laser source (diode) to the transducer via waveguide, the coupling loss from the waveguide to the transducer and thermal effects of high temperature HAMR head disk interface (HDI) on the flying head performance. The reliability of HAMR HDI could be compromised due to these heat transfer problems. On the other hand, in order to transfer the laser power efficiently to heat the medium, the transducer located inside the head should be held in close proximity to the medium by coupling evanescent waves at the distance between the transducer and medium less than 10 nm before they deteriorate (Seigler et al., 2008). As for achieving higher recording areal densities beyond 1 Tbit/in², the distance between

the head and disk will be few nanometers and the evanescent waves could not diminish easily in the interface.

Figure 2.1 Simple Diagram of nano-scale HAMR head disk interface

Therefore, HAMR system involves new recording physics, new approaches to an integrated recording head with optic and magnetic components and new recording material which is covered with carbon overcoat and lubricant layers withstanding high temperature. HAMR system requires the development of the light delivery system, the thermomagnetic writer, a reliable head-disk interface and rapid cooling media to achieve efficient and reliable higher recording density. As HAMR recording system is a new challenge and promising technological approach for achieving high magnetic recording density, potential thermal, magnetic recording and mechanical issues, such as designing an integrated HAMR head which consists of magnetic and optic delivery systems, delivering a small hot spot on the medium, and developing a thermally stable small-grained disk and high temperature head-disk interface, need to be understood clearly. The integrated head, media, and head-disk interface of HAMR recording system will be discussed in details in the following sections.

2.1: HAMR Integrated Head, Media and Interface

2.1.1: Laser Delivery System and HAMR Integrated Slider

In a HAMR system, the energy source is used to heat up the recording medium locally near the Curie temperature to reduce the medium coercivity during the writing cycle for achieving higher recording density. It is important to address that the comprehensive mechanism of delivering a localized heating spot on the magnetic recording layer in HAMR system. The laser of the optical wavelength range can be delivered by low cost and high power industrial laser sources in current market. The laser heating approach is also appealing as it is based on non-contact heating to the magnetic grains in medium. The optical energy must be efficiently delivered from an optical energy source (laser diode) to the medium through an appropriate laser guide and a transducer that possesses with an aperture or an antenna to confine to a localized heating spot which requires being in a very small diameter size to avoid heating neighboring tracks. However, it is a challenging task to design the optical delivery system that can meet HAMR system requirements. Additionally, the integration of that delivery system with a magnetic recording head makes the task even more difficult. Basically, achieving a very small focused light spot to heat the magnetic grains is required in a HAMR system and a conventional lens could not do well enough for this job. The diffraction limit of a confined optical spot by the conventional lens can be defined as (Challener and Itagi, 2009):

$$D = \frac{0.5l}{n \sin\theta} \quad (2.1)$$

where D is the full-width spot diameter at the half maximum point (FWHM), l is the wavelength, n is the refractive index of the medium in which the light is focused, and θ

is the half angle of the cone of focused light. Eq. (2.1) gives the minimum full width at half maximum (FWHM) spot diameter created by a lens theoretically. For instance, using the conventional lens with the numerical aperture ($n \sin\theta$) of 0.85, the focused optical spot size is achieved approximately 240 nm at 405 nm of wavelength in Blu-Ray devices. This is about the smallest spot size for visible light when it focuses in air. However, this spot size is still very large comparing with the minimum requirement which is about 25 nm or lower for a hot spot size in a HAMR system. By using a solid immersion lens (SIL) which is proposed by Mansfield and Kino (1990), the spot size could be reduced by n times as the light is focused inside a transparent high-index material of SIL. The ' n ' term represents the refractive number of SIL. However, the spot size produced by SIL will still be larger than the desired 25 nm heating spot size. Practically, developing the objective lens of a transducer based on SIL is not possible because the maximum angle of the light rays (θ) incident on the SIL is limited. The theoretical FWHM spot diameter described in Eq. (2.1) cannot be realized in reality.

Figure 2.2 Diagram of sample solid immersion lens

In HAMR recording system, a new method is required in focusing light energy to provide a confined thermal spot which has a smaller diameter than its diffraction limit. One of design approaches of focusing the optical energy on the medium is to force the light passing through a sub-wavelength aperture (hole) but the efficiency of laser power transition is traded off. Betzig et al. (1992) applied a circular aperture to demonstrate

magneto-optic data storage recording. The laser transmission efficiency (Tm) (far field transmission) is defined as the ratio of the power at the area transmitted through the hole to the power at the area of a plane wave which is normally incident upon the hole and it describes as below (Challener et al., 2003):

$$Tm = \left(\frac{64\pi^2}{27} \right) \cdot \left(\frac{D_{hole}}{l} \right)^4 \quad (2.2)$$

where D_{hole} is the hole diameter and l is the wavelength of the light. However, this equation is valid for circular holes in the extremely thin ideal conductor. With the best metal film such as silver and gold in front of the recording medium, more power is delivered to the medium and the hot spot in the medium is larger. As shown in Eq. (2.2), the ratio of the diameter of a hole the laser passed through to the laser wavelength (constant value for the same laser source) will be reduced much with the smaller diameter hole affecting the transmission efficiency down at subwavelength dimension. The ‘near field’ heating method with this optic device could concentrate light energy into a spot smaller than the diffraction limit as the light energy couples evanescently into the HAMR recording medium when the lens surface is very close to the target surface. The effect of near field heating will decay with further distance between the near field transducer (NFT) and the medium. The gap distance must be much smaller than a wavelength in order to couple the power from NFT to medium efficiently. This will not be an issue as the recording head that needs to be collocated with the optical delivery system is supposed to be flying in few nanometers range above the medium in HAMR application.

All the components of the optical delivery field need to be carefully considered to obtain the true size hot spot in the media when analyzing transmission efficiency of a transducer with aperture (Challener et al., 2003, Challener et al., 2009). Otherwise, the

optical spot size from the non-complete optical delivery components may be underestimated than the true spot size. Challener et al. (2003) also showed that the simulated field intensity of light transmitted through an aperture with the recording film is much smaller than that without the film. Therefore, it was noted that the magnetic recording medium should be included in the simulation model for computing heat transfer process in HAMR interface. Another important part to be considered properly for designing the HAMR optical delivery system is the efficiency of the NFT. It is because power dissipated within the transducer and low efficiency of the thermal heat sinking of the transducer could lead to the components' temperature rise and affect the reliability of hard drives. The NFT coupling efficiency which is one of the near-field properties must be approximately 5% for meeting HAMR requirements with low production cost (Challener et al., 2009).

In order to evaluate the performance of various NFT designs, different figures of merit (FOMs) are applied in the previous literature reviews. These FOMs include far-field transmittance efficiency, peak field intensity in the neighboring medium, percent of dissipated power in the medium and temperature increment in the medium (Challener et al., 2006). Each measurement method has its own benefits and drawbacks. The far-field transmittance efficiency method could not reflect the near-field coupling efficiency of NFT and it is not useful for selecting a NFT in HAMR system. The second method; the ratio of the peak electric field amplitude in a NFT to the electric field amplitude of an incident plane wave is quite appropriate to be applied in HAMR study because it can relate the peak field intensity within the medium with the power dissipation (P_{dis}) within the medium as below:

$$P_{dis} = \frac{1}{2} Re(\sigma) |E|^2 \quad (2.3)$$

where $|E|^2$ is the field intensity in a lossy medium and σ is the complex optical conductivity of the lossy material.

The optical conductivity is directly related to the complex optical dielectric constant of the material. However, the field intensity integrated all over the volume of the medium requires being considered for calculating Eq. (2.3) and the outcomes can be different for different NFT designs. Moreover, the peak field intensity depends on the wavelength and polarization of the incident light beam and the shorter wavelength is desired as the field intensity is directly proportional with $1/l^2$ at the beam focus. Using Eq. (2.3), the dissipated powers inside NFT and medium are calculated based on the electrical field intensity within those components and the percentage of power dissipated within the medium is obtained to evaluate the performance of a NFT. Given that the thermal properties of the medium are known, the temperature profile in the medium could be computed using the power dissipated inside which is achieved beforehand. However, it is practically difficult to obtain the exact material properties of the HAMR media as it has also been under the experimenting and developing stages for a real product. In this dissertation, the resulted medium temperature distribution profile will be calculated based on the power dissipation inside the medium via the electric and magnetic field intensities received at the medium surface from an integrated HAMR head.

The near field enhancement mechanisms of a transducer are important for enlarging field intensity and a properly-designed near field transducer possesses one or more of these mechanisms. They include the localized surface plasmon resonance (LSPR), the lightning rod effect, and the dual-pole effect. There are many antenna and aperture based NFT designs available for delivering optical energy into the medium with the much

lower sub-diffraction limit spot size in HAMR interface. Challener and Itagi (2009) studied numerically several NFT performances in term of peak intensity, power dissipation into the medium, and the resulting spot size relating to the appropriate geometry which could be realized approximately in HAMR system and summarized as in Table 2.1. The presence of a recording medium is considered in their simulation cases to reflect the HAMR situation.

NFT design	λ_{res}	Peak $ E ^2$	P_{diss}	FWHM spot size (nm ²)
Circular aperture	650	0.07	0.14%	113×142
Rectangular aperture	650	0.80	0.92	43×25
Bow-tie aperture	725	1.38	1.7	59×56
C aperture	700	2.42	2.1	34×39
Triangle antenna	650	0.77	1.1	55×54
Beaked triangle	725	2.82	2.9	43×41
Bow-tie antenna	650	1.41	1.4	39×36
Canted bow tie	750	2.61	2.1	31×36

FWHM full width at half maximum

Table 2.1 Summary of near-field transducer (NFT) performance. The peak $|E|^2$ intensity is normalized by that of the incident beam (Challener and Itagi, 2009)

As from Table 2.1, C-aperture, beaked triangle, and canted bow tie NFTs could provide high peak field intensity and delivered power percentage to the medium with relatively small hot spot size. Among those NFT designs, a C-aperture NFT which is also called a ridge waveguide transducer has better potential to be fabricated and integrated with the magnetic recording head. The C-aperture transducer as shown in Figure 2.3 is typically applied for transporting microwaves. This type of NFT which is made of metal film and surrounded by dielectric material could obtain the field enhancement from the localized surface plasmons (LSP) excitation at the resonance wavelength with the appropriate size, shape, material of structure, and the surrounding medium. The ridge in the center

concentrates the field intensity due to its shape and it is called the lightning rod effect of C aperture transducer. Moreover, the ridge packs the field lines and enhances the field strength between the ridge and the opposite side causing the dual pole effect. This transducer occupies all the field enhancement mechanisms and it is modified to suit the use in HAMR application. Şendur, Peng, and Challener (2005) suggested that a low index dielectric layer in between the solid immersion lens (SIL) and the C aperture transducer could develop the total internal reflection at different index boundaries of layer materials to create evanescent waves.

Figure 2.3 The C aperture (ridge waveguide) transducer

Concerning to the nano-sized antenna based transducers, the canted bow tie and beaked triangle transducers could provide high peak field intensity with relatively small thermal spot size as shown in Table 2.1 (Challener and Itagi, 2009). According to the simulation results in Challener et al. (2006) paper, the flat bow tie could not confine the optical power in a region at the resonant frequency with the presence of medium unlike the one without the medium. Therefore, it showed that it is critical to include the medium in the laser heating models in order to reflect the similar conditions as those of the HAMR interface. Only by canting the bow tie antenna of NFT, the concentrated optical power is transferred to the medium in a small diameter spot and the coupling efficiency of optical

delivery is increased. The coupling efficiency is defined as the fraction of the total incident optical power that is absorbed in the heating region of the medium.

Figure 2.4 (a) Canted Bow-tie Transducer and (b) Beaked Triangle Transducer

The flat triangle antenna NFT also could not confine the peak field intensity within the medium but it rather spreads along the length of transducer instead of its tip. In order to achieve the confined optical field in the medium, it requires to be modified to have a small beak at the triangle tip. Both of the canted bow tie and beaked triangle transducers have the disadvantage in fabricating inside a HAMR recording head due to their atypical shapes and small dimension requirements. Apart from the aperture and antenna based NFTs, Tawa, Hasegawa, and Odajima (2007) designed NFT as a structure of stacked multilayers which have high and low diffraction gratings in order to generate a subwavelength optical spot. They experimentally demonstrated that a ‘butted-grating structured’ NFT could produce a subwavelength optical spot through using a scanning near-field optical microscope. However, their experiments and simulations are lack of the medium presence. Therefore, the resulted optical spot size might not represent to the real HAMR application.

The integrated HAMR head design and recording demonstration were reported by Seigler et al. (2008) from Seagate. In most of HAMR research works in the literature,

the HAMR integrated head design was based on a simplified version of the current perpendicular magnetic recording (PMR) head to integrate with an optical delivery system, as shown in Figure 2.5. There are many challenges for the HAMR head design and integration such as magnetic field delivery, optical delivery and combination of magnetic and optic field delivery compilation. Due to the limitations imposed by the HAMR recording, a few modifications require to be made on the current PMR head in term of magnetic field delivery as they could affect the performance of the head. These limitations as proposed by Seigler et al. (2008) include:

1. The magnetic pole needs to remain far from the waveguide (WG) core in order to reduce large optical losses in the WG. But at the same time, it also needs to be brought into close proximity to the WG to be collocated with the thermal spot in the media during the writing process. These two interests are conflicting with each other obviously.
2. The bit which is written requires passing through the peak of the thermal spot before reaching the front edge of the pole that creates the recording magnetic field.
3. The perpendicular recording in HAMR requires the WG core to be offset in the gap of the head.

As for the optical delivery system, the parabola shaped planar solid immersion mirror (PSIM) was developed for reflecting and focusing of the incident light striking on its edge. The PSIM includes the planar WG at the core for transporting light and the core was made of high-index refraction material such as tantala ($n \sim 2.25$). The core was sandwiched with two low refraction cladding layers made of alumina ($n \sim 1.67$). Seigler et al. (2008) highlighted that the PSIM requires being in very close proximity to the media surface for coupling with evanescent waves before they decay.

Figure 2.5 (a) Cross-sectional and (b) top down diagrams of a HAMR head that combines a PSIM with an input coupling grating and a magnetic recording ring head (Seigler et al., 2008)

Using the principle of an antenna transducer and the stacked film structure with the grating as a laser waveguide, Challener et al. (2009) applied a lollipop shaped NFT with a PSIM to focus the laser beam for heating the media as shown in Figure 2.6. They demonstrated the track writing using an integrated HAMR recording head which includes a PSIM based waveguide and a lollipop NFT located at the central focus of PSIM. The magnetic recording head components were fabricated together with the optical delivery system inside a HAMR head. The 35 μm diameter spot of the incident light beam is guided to strike at the grating of the waveguide and it couples with the planar waveguide body. Next, the incident field is confined at the peg through the circular disk of NFT and the optical energy is transported to the recording medium. The space between the NFT and the top medium surface is set as 7.5 nm. The laser light field is confined to a spot via those optical delivery components for heating the medium grains. In their paper, it demonstrated that the spot size is reduced to about the quarter of the incident wavelength. The material of NFT is set as gold because of its chemical inertness and high melting temperature. The electric fields are generated from the

oscillation of surface plasmons (SP) at the tip of lollipop NFT to couple the energy efficiently to the medium surface. This NFT also has the lightning rod effect due to a small tip of the lollipop shaped metal transducer. It enhances concentrating field lines on the recording media. At 870 nm of wavelength, the best coupling efficiency was achieved at 8%.

Figure 2.6 Diagram of the NFT and its position in the PSIM. A planar solid immersion mirror with a dual offset grating used to focus a waveguide mode onto the lollipop NFT (The disk moving direction is out of paper) (Challener et al., 2009)

In the research work of Challener et al. paper (2009), those optical delivery components are embedded in an integrated HAMR head together with magnetic recording components. The authors demonstrated recording a track width of 70 nm with an integrated head by heating the medium to generate $\Delta T=400\sim 500^{\circ}\text{C}$ in nanoseconds at the recording density as high as 375 Tbm^{-2} . They concluded that the laser beam could successfully heat the medium in a small spot size up to the medium Curie temperature which is about 700K. The authors also highlighted that thermal managements of the head, medium, and interface are still challenging for a real product due to the nature of high temperature operations. Especially to a tiny NFT in the integrated head, thermal

dissipation inside its structure and surrounding components could deform or melt it during long operations.

A gold plasmonic E-antenna transducer integrated into a HAMR recording head as another type of a HAMR head is proposed by Stipe et al. (2010) to improve the track width reduction and optical energy efficiency in the magnetic recording. The laser was delivered from a laser diode through the uniform rectangular shaped waveguide to the transducer. The waveguide was made of Ta_2O_5 at the core area and SiO_2 was used as the cladding material. A layer of SiO_2 was inserted in between a waveguide and NFT in order to enhance the surface plasmon effect similar to the research work of Şendur et al. (2005) mentioned above. The E-antenna NFT was based on the ridge waveguide design but it was assumed as an antenna transducer. It was modified and enhanced with finite gold boundaries optimizing for better efficiency. It consisted of a notch, a body and two wings which served as the charge reservoir and boundary conditions for surface plasmon excitation in the body as shown Figure 2.7. The body linked as the bridge for generating surface plasmons from the wings at a notch which has the ‘lightning rod’ effect to improve the near field transportation of optical energy.

Figure 2.7 (a) Cross section of uniform waveguide with the core and (b) Cross section of the E-antenna at the end of the waveguide (Stipe et al., 2010)

In HAMR head, a NFT component, which locates very close to the air-bearing surface (ABS) at the trailing edge region, converges the laser light into a small area spot on the medium and magnifies the field strength by exploiting a resonance effect containing surface plasmons (SPs). According to Challener et al. (2003), the HAMR head with a gold lollipop peg added at the focus of the PSIM absorbs the optical energy and the peg provides the lightning effect for field confinement. The NFT temperature rises up to several hundred degrees and its reliability becomes one of the main concerns in developing HAMR system. Moreover, due to the thermal dissipation to the surrounding, the thermal protrusion could happen inside the slider body. Some critical head components such as the writing and reading elements could also be affected by the internal thermal stress and distortion. As the resistance of the magnetic sensors is temperature dependent, the temperature increment in the head will induce the thermal noise to the readout signal.

In Seigler et al. (2008) paper, as the proposed integrated HAMR heads have a laser waveguide (WG) locating close to the adjacent magnetic write pole for the efficient HAMR recording, the laser absorption rates of the poles are about 10%-30% at from 50nm to 10nm of the distance between the core of the waveguide and the pole. With more than 200nm of the gap in between the magnetic pole and NFT, total laser power loss percentage due to the presence of pole at NFT could be insignificant. The NFT temperature increment is due to its design for being high efficiency and the amount of increment depends on the absorbed power, its size and the space between the transducer and the pole (Xu et al., 2011). A temperature increase of a NFT could cause the transducer detached from the waveguide and/or its structural deformation or protrusion. Comprehending the connection between the transducer temperature rise and its structural deformation is important for designing a reliable HAMR integrated head.

According to Xu et al. (2011), the bigger size of the transducer and smaller refractive index (n) of the transducer material are always desired for high efficiency and low absorption. The presence of media and its material could also affect the absorption and efficiency of laser energy transportation from an integrated head to the recording layer which locates inside the media. The details of media effect on thermal management of HAMR interface will be discussed in the next section.

2.1.2: HAMR Multilayer Recording Media and Its Localized Heating Spot

In HAMR system, the temperature field on the disk could be highly non-uniform around a heat spot caused by a laser beam. The grains in the media become superpara-magnetic and they are thermally unstable in their magnetic states while the magnetic grain size requires reducing to increase the storage density in a higher density recording method like HAMR system (Lu and Charap, 1994). The superpara-magnetic limit imposes a signal-to-noise ratio, thermal stability, and writability tradeoff which prevent to scale traditional magnetic recording technology to higher storage densities. The size at which the magnetic state of a grain is no longer thermally stable is called superpara-magnetic limit (Lu and Charap, 1994)

$$\frac{K_u V}{k_B T} > 70 \quad (2.4)$$

where K_u is the uniaxial anisotropy coefficient, V is the grain volume, k_B is Boltzmann's constant and T is the temperature. According to Eq. (2.4), thermal stability can be realized for small grains when K_u is large. Although the recording material with adequate K_u for Tb/in² recording density is identified (Weller et al., 2000), their coercivity at the room temperature is too large for switching by the conventional recording heads.

The high anisotropy materials can support grain sizes as small as few nanometers in diameter but the coercivity of those materials is larger than the magnetic field that can be generated by a conventional recording head. In HAMR system, using a localized heating source, the addition of heat is introduced to the medium to achieve a very high effective writing field gradient. This task should be operated without the additional involvement of modifying the magnetic recording head in HAMR system due to high manufacturing cost but it should be adding and integrating the optical delivery system within the slider which carries all components. The concept of heating the medium for higher recording density is realized in terms of the simple relation as below:

$$\frac{dH_{write}}{dx} = \frac{dH_k}{dT} \cdot \frac{dT}{dx} \quad (2.5)$$

where the first component on the right side is the slope of the medium's temperature dependent anisotropy field $H_k(T)$ just below the Curie temperature (T_C) and the second one is the gradient of the thermal profile in the medium at the freezing temperature (down or cross-track) (Kryder et al., 2008). The Curie temperature (T_C) is the critical temperature at which the medium magnetism and the anisotropy field vanish. Therefore, the magnetic anisotropy and saturation magnetization continuously drop to nearly zero when the magnetic material is heated to its Curie temperature (Kryder et al., 2008). HAMR writing process makes use of this effect to reduce coercivity below the applied magnetic field by heating the media. Once the head field is applied, the heated region in the medium is rapidly cooled to the ambient temperature as shown in Figure 1.8.

As a heat spot on HAMR medium requires high thermal gradient with the effective heat sink, the laser induced heating rates are estimated of order 10^{11} - 10^{12} K/s and the laser heating duration in one heating and cooling cycle in HAMR is as short as 1 ns (Kryder et al., 2008). Heating and cooling rate of the medium must occur within about 1 ns in

order to achieve the high data rates with a large thermal gradient and to ensure the recorded data are thermally stable during cooling to the ambient temperature. The heated region requires being rapidly cooled down to the ambient temperature while the magnetic field is applied during the writing process. The localized heating source causes surface thermal distortions and internal thermal stresses in the HAMR disk. The laser power requirement of heating the FePt medium above 750K which is its Curie temperature is about 0.5 mW (Thiele et al., 2002, Xu et al., 2011). However, the main difficulty is to know the local temperature in a small region of the disk caused by the laser heating. The thermal profile of the recording medium depends not only on the optical profile generated by a NFT but also on the materials and the structures of the recording medium. Xu et al. (2012b) reported that the thermal boundary resistance (BTR) which exists at all of the boundaries between two different materials and in-plane (lateral) thermal conductivity of a recording layer are the major factors in determining a thermal spot size on the medium. The thermal conductivities of the nanometer sized thin films in the multi-layered medium are much different from those of their bulk material. Disk temperature is highly non-uniform around the media hot spot. The previous simulation works (Wu, 2007, Wu and Talke, 2011, Zeng et al., 2012, W. Zhou et al., 2012) simply applied a heat flux imposed at the medium surface to study the thermal distribution on the disk induced by the laser heating in HAMR. Mansuripur, Connell, and Goodman (1982) have proposed and developed an optical absorption model of laser energy in a stationary multilayer structure for data storage on magneto-optic disk. Actually, the laser was regarded as an electromagnetic wave and the absorption rate of optical energy in the media can be derived from the Maxwell equations. Mansuripur and Connell (1983) improved this model to utilize in the moving media by superposing of the static solutions. Based on these absorption models, the unsteady energy conservation

equation is solved numerically after determining the absorptivity of the disk surface empirically with the time averaged Poynting Vector using the plane electromagnetic wave in Maxwell equation (G. Chen, 2005) in this dissertation. These optical absorption models were further used by Yu et al. (2013a) to investigate the heat transfer and lubricant depletion processes in multi-layered media structure of HAMR system which is shown in Figure 2.8. The multi-layered HAMR media structure is designed to fulfill high temperature gradient requirement and reduce the media temperature to the ambient temperature in nanoseconds. There are additional layers such as the heat sink layer and intermediate layers included in the HAMR media. It is critical to recognize the top surface temperature of HAMR media for studying the heat transfer process in the interface.

Figure 2.8 Sample multi-layered HAMR disk structure (Yu et al., 2013a)

2.1.3: HAMR Nano-scale Head Disk Interface

In HAMR technology, the recording magnetic grains are heated close to the media Curie temperature within a few nanoseconds during the writing process, which reduces the coercivity of the media and allows writing data with the available head fields as shown in Figure 2.9. HAMR utilizes the thermal energy produced by a laser pulse shooting

down on the media from the trailing edge of flying slider head (Alex et al., 2001, Rausch et al., 2006, Saga et al., 1999). Then, the heated region can quickly cool down within sub nanoseconds after the laser is turned off, by using the proper design of media with a heat sink layer enabling data rates in the gigahertz range. Therefore, HAMR introduces some serious thermal issues to the head disk interface. Some major issues include the failure of the near-field transducer (NFT) due to high temperature, unstable slider flying performance by the slider thermal deformation, and lubricant depletion from the media caused by the rapid laser heating.

Figure 2.9 A HAMR head recording to a disk medium using a laser source to heat the medium locally in order to assist the recording process by temporarily lowering its resistance to magnetic (Pan and Bogy, 2009)

During the laser heating operation to the magnetic media layer in HAMR system, other than the magnetic layer, the air layer between the disk and head, the carbon overcoat, the lubricant and the slider body will also be affected due to the heat transfer from a laser source. Besides, the slider's air bearing characteristics will also be changed and consequently, influence on the reliability of a hard disk drive. The read/write transducer (the head) is located at the trailing edge of the slider which is flying above the rotating disk; the data is stored or read. The pressurized thin layer of air (air bearing layer) is developed above the disk surface and it keeps the head-disk separation to reduce the

friction and wear by maintaining a uniform distance between a slider and a disk. The flying slider provides the primary air bearing lubrication to the HDI. The air bearing designs locating at slider surfaces are shaped to compress the boundary layer of air under the slider, generating the adequate pressure to maintain stable flying and minimal variation of flying height at different radial positions on the disk.

Considering the ultra-low nanometer flying height, a localized hot spot on the media could cause the change in the head-disk interface region due to the local heating effect. The thermal variation in HDI could increase the slider body temperature and also affect the slider's flying characteristics consequently. The effects on the slider's temperature have been studied in previous publications and according to the results, the laser delivery system and localized hot spot on the media could cause the slider temperature increase distinctly (McDaniel, Challener, and Sendur, 2003, Peng et al., 2005, Xu et al., 2006). Peng et al. (2005) studied the mechanical and magnetic performance of the HAMR head due to the residual heat dissipated in a waveguide and an optical transducer. They concluded that the HAMR disk could be affected with severe thermal stress by laser heating and the head-disk contact could also happen due to the thermal distortions of a HAMR head with the heat source embedded in.

The fully integrated HAMR head design was introduced and demonstrated by Seigler et al. (2008) and their HAMR head design is shown in Figure 2.10. In their study, the waveguide is modeled as a parabolic-shaped three-layered structure including a planar solid immersion mirror (PSIM) core layer and top and bottom 'cladding' layers which are intended to insulate the heat dissipation to others. The incident laser is coupled into the waveguide and NFT to focus a laser spot on the medium. The similar HAMR optical system design is proposed and used by Challener et al. (2009) in their demonstration at an areal density of 0.242 Tb/in² recording. Using that particular head design in a thermal

flying height control (TFC) slider, Zheng et al. (2012) observed that the heat dissipation in a waveguide affects the thermal deformation and slider's flying characteristics based on a finite element model built by ANSYS. They also showed that the slider flying height change was followed by the thermal protrusion variation due to the heat dissipation into a waveguide. They suggested the importance of the positions of two heaters and their power ratio applied to achieve a stable and efficient recording process with a HAMR TFC slider.

Figure 2.10 Schematic model of HAMR-TFC slider and (b) diagram of HAMR optical system, including near field transducer (NFT) and wave guide (Zheng, Li, and Talke, 2012)

The magnetic head-disk spacing directly relates to the recording areal density and higher density recording requires lower spacing. This spacing includes: mean mechanical spacing (the flying height), slider overcoat thickness, disk overcoat thickness, lubricant thickness, and pole tip recession of a read/write transducer as shown in Figure 2.11. A molecularly thin layer of the perfluoropolyether (PFPE) lubricant is coated on the surface of the protective diamond-like-carbon (DLC) overcoating layer which prevents damaging a magnetic recording layer underneath. In current hard disk drive systems, the thickness of lubricant film is approximately 1-2 nm. The slider-disk (physical) spacing

should be less than 2 nm as the expected magnetic spacing is 6.5 nm to realize magnetic recording densities beyond 1 Tb/in² (Gupta and Bogy, 2005, Wood, 2009).

Figure 2.11 Head disk spacing components and definition of magnetic spacing and physical spacing

In a HAMR system, another issue of instability in HDI is caused by the lubricant depletion on the media surface. The lubricant on the disk is exposed to the laser heating while writing the data in HAMR and the interaction between the slider and disk could be affected due to the temperature change in the lubricant material. The heat and mass transfer of the lubricant on the media is directly related to the media temperature distribution around a localized heating region. There are many different slider and lubricant interaction mechanisms to cause the lubricant depletion in the conventional (non-HAMR) hard drives (Dai, Hendriks, and Marchon, 2004, Marchon et al., 2005, Novotny and Baldwinson, 1991, Wu, 2006) such as lubricant scission, mogul, and ripple formations. In HAMR, the mobile lubricant from ultra-thin lubricant films is depleted when these films are heated up to very high temperature by a laser beam to reduce the magnetic coercivity (Tagawa and Tani, 2011). Since the lubricant layer serves as a corrosion protection layer, the lubricant depletion may lead to the whole HDD system failure. It is important to maintain the thickness of a lubricant layer on the disk for enhancing the reliability of HDI. There are many research works done for the theoretical

and experimental studies of lubricant depletion caused by the laser heating in HAMR system (Tagawa, Andoh, and Tani, 2010, Tagawa and Tani, 2011, Tagawa, Tani, and Ueda, 2011, Wu, 2007, Wu and Talke, 2011).

Wu research works (Wu, 2007, Wu and Talke, 2011) developed a model to simulate the lubricant depletion under a scanning laser beam in a HAMR system combining the effects of evaporation, thermocapillary stress, thermoviscosity, and disk structure on the lubricant depletion. Recently, Zeng et al. (2012) also developed the simulation model for studying the lubricant depletion in HAMR including the effects of lubricant evaporation enthalpy, thermal induced surface tension, and initial lubricant film thickness. The improved evaporation model is proposed by W. Zhou et al. (2012) by relating with the experiment results obtained from Tagawa et al. research works (Tagawa, Andoh, and Tani, 2010, Tagawa and Tani, 2011, Tagawa, Tani, and Ueda, 2011). Ma et al. (Ma, Chen, and Liu, 2012, 2013, Ma et al., 2012) from Data Storage Institute (DSI) employed a self-developed HAMR tester with controlling the repeatability of laser heating temperature for studying the lubricant depletion process. In all the numerical studies of the lubricant depletion process mentioned above (Wu, 2007, Wu and Talke, 2011, Zeng et al., 2012, W. Zhou et al., 2012), the depletion in a single heating cycle is calculated. However, in the experiment, the lubricant depletion profiles are only measurable after multiple heating cycles. Therefore, the author and other researchers studied the lubricant depletion with an optical absorption model (Mansuripur and Connell, 1983, Mansuripur, Neville Connell, and Goodman, 1982) and included the effect of multiple heating cycles for better comparison with experimental results (Yu et al., 2013a).

After reviewing potential issues and existing research works in HAMR head disk interface, it is understood that accurate predictions on the heat transfer process during

the laser heating period are critical and useful for designing and building up a stable and reliable HAMR head disk interface. In the next section, the author will review and discuss the air bearing model, heat transfer model, and other numerical methods used for the simulations of the HAMR head disk interface.

2.2: Numerical methods for nano-scale head disk interface

2.2.1: Numerical methods for slider air bearing

The slider (head) and disk together with the gas layer in between form a slider air bearing in the head-disk interface (HDI) region. The traditional macroscopic hydrodynamic equations such as Navier-Stokes' and Reynolds' have been used to model the slider bearing with large gap spacing in the past (Lu and Charap, 1994). However, the current trend towards the nanometer level air bearing spacing is driving the limits of validity for these continuum equations (Sone, 2002). Therefore, as for the recent nano-scale HDI technology, the air bearing gas flow requires simulation methods that model the gas flow at the particle levels or adding approximate corrections to the continuum models. After Maxwell has discovered the 'velocity slip' effect near a moving wall (Burgdorfer, 1958), many slip correction models have been developed to apply the Reynolds' equation for Knudsen number (Kn) > 1 .

In nano-scale gas flow at the HDI region, the non-dimensional Knudsen number ($Kn = \lambda/h$), defined as the ratio of the molecular mean free path (MFP) of the gas, λ , ($\lambda \approx 65$ nm for air at the standard temperature and pressure (STP)), to a characteristic flow field dimension, h , indicates the flows are often rarefied. The characteristic flow field ' h ' is taken as the minimum or local flying height in calculating the Knudsen number in HDI.

Based on the Kn number in the flow field, there are four flow regimes are defined as (Gross, 1980, Szeri, 1998) :

$$Kn \leq 10^{-2} \quad \text{continuum flow,}$$

$$10^{-2} < Kn < 0.1 \quad \text{slip flow,}$$

$$0.1 \leq Kn < 10 \quad \text{transition flow,}$$

and

$$Kn \geq 10 \quad \text{molecular flow.}$$

Figure 2.12 shows these Knudsen number limits on the conventional mathematical formulations at high Kn flows. As Kn increases, the behavior of a gas flow near a solid bounding surface is dominated by the effect of gas molecule-surface interactions. The Reynolds number is typically very small at high Kn number. Due to the rarefaction effect caused by the high Knudsen number, the flow velocity at the surface starts to slip and the viscous shear stress is much reduced. In high Kn flows, the thermodynamically non-linear region extends from the surface and that region formed is known as Knudsen Layer (KL). The Navier-Stokes (NS) equations with the slip-velocity modification and temperature jump boundary condition can often adequately predict the flow field outside KL. However, they fail to grasp the flow behavior in KL region (Lockerby, Reese, and Gallis, 2005).

Figure 2.12 The Knudsen number limits on the mathematical models (Bird, 1994)

Many well-known models with modified slip velocities have been developed to predict the pressures in the head disk interface of HDD. In 1959, Burgdorfer (1958) introduced the Reynolds equation with the slip correction for $Kn < 1$. The second-order slip model is introduced by Hsia and Domoto (1983) and higher order models include the 1.5-order slip equation of Mitsuya (1993), Beskok's model (Beskok and Karniadakis, 1999), and the Boltzmann–Reynolds approach of Fukui and Kaneko (1995). In the Fukui and Kaneko method, the Poiseuille flow rate was calculated on the basis of a linearized Bhatnagar–Gross–Krook (BGK) model of the Boltzmann equation (Bhatnagar, Gross, and Krook, 1954). The Fukui and Kaneko model is sometimes referred as the molecular gas lubrication (MGL) model (Fukui and Kaneko, 1988) and it is used in Data Storage Institute (DSI) developed the air bearing solution software; ABSolution for predicting the distributions of bearing pressure and solving air bearing problems. The non-dimensional pressure governing equations with modified slip models are as below:

$$\frac{\partial}{\partial x} \left(QPH^3 \frac{\partial P}{\partial x} - \Lambda_x PH \right) + \frac{\partial}{\partial y} \left(QPH^3 \frac{\partial P}{\partial y} - \Lambda_y PH \right) = 0 \quad (2.6)$$

where P is the normalized air bearing pressure (p/p_0), H is the normalized gap spacing between the slider and disk (h/h_0), Λ_x and Λ_y is the bearing numbers along the slider's length ($\Lambda_x = \frac{6LU\mu_0}{p_0 h_0^2}$) and width directions ($\Lambda_y = \frac{6WV\mu_0}{p_0 h_0^2}$) respectively, μ_0 is the dynamic viscosity of air, L is the slider length, W is the slider width, U and V are the velocity components in the x and y directions respectively. p_0 and h_0 represent the standard atmospheric pressure and the initial flying height, respectively. Q is the Poiseuille flow factor and it has been modified in different slip models as following:

$$Q = 1 \quad \text{No slip model} \quad (2.7a)$$

$$Q = 1 + 6aKn/ph \quad \text{First-order slip model} \quad (2.7b)$$

$$Q = 1 + 6aKn/ph + 6(Kn/ph)^2 \quad \text{Second-order slip model} \quad (2.7c)$$

$$Q = 1 + 6aKn/ph + (8/3)(Kn/ph)^2 \quad \text{1.5-order slip model} \quad (2.7d)$$

$$Q = f(Kn/ph) \quad \text{Fukui-Kaneko's MGL model} \quad (2.7e)$$

where a is the surface accommodation factor. The Fukui-Kaneko model was validated and confirmed for applying in the range of Kn up to 6 which is formed for minimum spacing of 10 nm under the standard atmospheric pressure (Takeuchi et al., 1994). The particle-based simulation methods such as molecular dynamic (MD) method and the direct simulation Monte Carlo (DSMC) method could predict more accurate results for very high Kn number flows. MD simulation method would take very long for achieving air bearing results which are in the millisecond time frame. Another kinetic method; the DSMC method can predict more accurate results for very high Kn number gas flows

with much shorter computational time than that of MD method and the details are discussed in the following section.

2.2.2: The Direct Simulation Monte Carlo (DSMC) Method

The DSMC method was introduced and invented by Bird in the early 1970s (Bird, 1976, 1994). It is a particle based simulation method for rarefied gas flows and those with heat transfer problems in a microchannel. The DSMC method can be applied to very dilute gases even when the Kn number is larger than 10 (Bird, 1994). It is the popular particle method for the analysis of collisional flows which have intermolecular collisions significantly affecting the fluid behaviour. The DSMC method has also been employed as a simulation tool for predicting the slider bearing behaviour in HDI of the hard drive system (Alexander, Garcia, and Alder, 1994, W. Huang, Bogy, and Garcia, 1997, Liu and Eddie Ng, 2001).

In kinetic theory, the mean free path (MFP) (λ) is defined as the average distance traveled by gas molecules between two collisions at the equilibrium state, where there is no presence of boundary plates. In the KL region, the gas molecules collide with the bonding surfaces more frequently than the collisions of gas molecules-molecules and consequently, the gas MFP (λ) will be reduced due to the decrement of distance a gas molecule travelled before a collision happens in the flow. The kinetic methods such as directly solving the Boltzmann equation (Sone, 2002) or the direct simulation Monte Carlo (DSMC) method (Bird, 1994) can provide more accurate predictions of non-equilibrium flows.

The DSMC method makes no continuum assumption. It models the flows as its physical existence: a collection of discrete particles, each with a position, a velocity, and an internal energy, etc. Each particle in the simulation domain usually represents a large

number of molecules in the physical system having the same properties. In this sense, the DSMC method solves the Boltzmann equation using a representative random sample drawn from the actual velocity distribution. The computational domain of the flow field is divided into many cells as which each containing several sub-cells. Simulated particles are allocated according to the physical problems for simulating the flow in the interested domain.

Based on the Boltzmann equation, it separates the flow particle movement into two distinct stages such as the movement and collision stages in each simulation time step. This is the main approximation made in the DSMC method. The particles move and interact with the domain boundaries in the ‘movement’ stage. This method uses a stochastic algorithm inherently to calculate the intermolecular collision probabilities in each cell and scattering distributions conforming to the kinetic theory. Different collision models such as the variable hard sphere (VHS) and the variable soft sphere (VSS) models, can be applied to make the intermolecular collisions more realistic physically as real molecules. In the hard-sphere (HS) model, the assumption of collision is like the billiard ball collision and the cross section is: $\sigma = \pi d^2$ where d is the sphere diameter. Bird (1994) proposed a new model, which takes into account the decrease in cross-section as the relative velocity between molecules increases. The diameter of the sphere is allowed to vary according to

$$d = d_{ref}(c_{r,ref}/c_r)^v \quad (2.8)$$

with a simple inverse power law v , where c_r is the relative velocity between the molecules at the pre-collision condition and the subscript ‘ref’ denotes reference values. During the collision, the momentum is conserved such that

$$m_1 c_1 + m_2 c_2 = m_1 c_1^* + m_2 c_2^* = (m_1 + m_2) c_m \quad (2.9)$$

where m_1 and m_2 are the masses of the two molecules, c_m is the velocity of the center of mass of the pair of molecules, c_1 and c_2 are the pre-collision velocities of the two collision partners in a typical binary collision and c_1^* and c_2^* are the post-collision velocities. The energy conservation dictates that the magnitude of relative velocity $c_r = c_1 - c_2$ remains constant during the collision. The post-collision velocity can be described as

$$c_1^* = c_m + \frac{m_2}{m_1 + m_2} c_r^* \quad (2.10a)$$

$$c_2^* = c_m - \frac{m_1}{m_1 + m_2} c_r^* \quad (2.10b)$$

A new direction for the post-collision velocity vector is selected after the magnitude of the relative velocity has been known from the pre-collision velocities. In general, the direction will depend on the pre-impact velocities and differential cross-sections are used to select the in-plane angle by assuming that the post-collision scattering is anisotropic. In DSMC method, as for simplicity, the scattering is assumed as isotropic. By letting the two R_1 and R_2 are two random numbers,

$$\cos\theta = 2R_1 - 1 \quad (2.11a)$$

$$\phi = 2\pi R_2 \quad (2.11b)$$

where θ is the deflection angle of the relative velocity and ϕ is the angle between the collision plane and another reference plane which is parallel to the pre-collision velocity. Eq. (2.11a) is derived from $\theta = \pi - 2\theta_A$ where the angle θ_A is created by the interaction of a reduced mass particle with a fixed scattering center. This determination of the deflection angle θ is the key step in the analysis of the dynamics of a binary elastic collision. Then, the components of relative velocity at the post-collision condition are achieved by

$$c_r^* = |c_r|\cos\theta, c_r^* = |c_r|\sin\theta\cos\phi, c_r^* = |c_r|\sin\theta\sin\phi \quad (2.12)$$

Macroscopic quantities, such as flow speed, density, and temperature, are obtained by sampling the microscopic state of all particles in the computational domain. The algorithm of the DSMC simulation method consists of four primary processes such as moving the particles, indexing the particles in the domain, simulating collision and sampling the flow field properties.

In the simulation, a particle moves along its trajectory until it collides with another particle or a boundary. The time step used in the simulation should be small enough comparing with the mean collision time for better accuracy. Therefore, the requirement of setting an appropriate time step is important during the uncoupling of the movement and collision of particles. The intermolecular collision in DSMC method applied in this dissertation is set as a binary collision in which only two particles involve and the collision particle pair is selected by a probability method to reduce the computation time. Any particle that reaches a boundary is processed according to the appropriate boundary condition. There are two types of boundary conditions: thermal walls and fluxing reservoirs. The top and bottom thermal walls are set for modeling the surfaces of the slider (read/write head) and disk respectively in the simulation. When a particle strikes either of these walls, the particle velocity is reset according to a biased Maxwellian distribution.

The gas flow inlet and outlet boundaries are treated as infinite, equilibrium fluxing baths at standard temperature and pressure (STP). The flow velocities at these boundaries are programmed to maintain at the ambient pressure. Therefore, the particles in the simulation are easily reentering into the computation domain via the inlet from the outlet at higher velocities than the specified disk speed. Both of these boundaries settings are critical and they require to be modeled as connecting each other as a whole channel by

simulating the flow properties and conditions of entering or leaving particles to be similar statistically. Therefore, as for maintaining the ambient pressure at the inlet and outlet and reducing computation time, the periodic boundary conditions are applied at the entry and exit of a flow channel. This period boundary setting is suitable for the slider bearing simulation in the head disk interface according to the previous research work (Alexander, Garcia, and Alder, 1994). In order to simulate a steady problem, these processes are repeated until a steady flow is established at an adequate large time, and the final result is a time average of all values from the cells in domain after achieving the steady state.

In above sections, the existing and potential numerical methods for solving the slider air bearing problems of the conventional head disk interface have been discussed. The author will apply the numerical methods discussed above to solve the slider bearing problem of HAMR interface in this dissertation. Applying with the particle based DSMC method, the air bearing performance of HAMR system will be forecasted and the continuum based MGL model will be validated for the applicability in the HAMR problem. However, the involvement of high-temperature laser heating process in the HAMR interface impels the author exploring any potential improvement in developing the numerical heat transfer model of HAMR system. In next section, the current heat transfer model of the head disk interface with a thermal flying height control (TFC) slider will be discussed and the near field heat transfer computation method will be studied.

2.3: Heat Transfer Models in Nano-scale Head Disk Interface

Thermal flying-height control (TFC) sliders have been used in the recent commercial hard disk drives (HDDs) for achieving high magnetic recording capacity. This technology allows the read-write head which locates inside the slider lowering near to the media surface and it creates smaller space in between the head and disk during the recording or reading process. One or two heaters are included inside the slider body and located near to the reader or writer components or both for heating the surrounding slider material to expand. The heat transfer process occurs in the head disk interface and inside the slider body in the TFC technology. However, temperature increment is few tens of degrees at the air bearing surface and the heat flow is from a slider to a disk around the trailing edge region unlike the HAMR system, in which the temperature rise at the disk surface could be from 750 to 1000 K to create the Curie temperature at the magnetic recording layer underneath depending on the media material (Kryder et al., 2008). Therefore, the current numerical heat transfer model which is aimed for the conventional TFC head disk interface might not be suitable for HAMR application. In this section, the existing models will be reviewed first and the potential method for developing a new numerical model for the HAMR HDI heat transfer process will be discussed later.

2.3.1: Current Heat Transfer Model for TFC Head Disk Interface

In recent HDDs, the cost competitive high recording density is achieved with the ultra-low flying height of 5 nm using thermal fly-height control (TFC) technology (Kurita et al., 2005). With this technology, the large portion of the slider stays at relatively large flying height while the read/write elements operates with a narrow spacing for the

improvement in magnetic signal noise ratio. In the TFC technology, a resistive heater or two which is embedded around the read/write elements inside the head structure is electrically powered to protrude the slider trailing edge region during reading and writing processes. The current is applied through the heating element and the head disk spacing is reduced as the protrusion around the head components occurs due to the divergence of different thermal expansion coefficients inside the slider body. It is called the heater pole tip protrusion (H-PTP) as shown in Figure 2.13.

Similar to the HAMR system, the head disk interface of a TFC slider gain the external energy from the heat source and the unnecessary structural deformation of slider could affect the drive's reliability. There are two types of undesired protrusions occurred in the TFC head disk interface such as the environmental temperature induced pole tip protrusion (T-PTP) and writer induced pole tip protrusion (W-PTP) which is caused by a writer pole through Joule heating of the write current. Those deformations could cause the glitch in the nanometer spaced head disk interface and affect the slider's flying pattern. In the worst case, the slider could crash with the head-disk contact. Such problems caused by the heat flux from the external heat source towards the slider body were studied both numerically and experimentally in some previous works (Juang et al., 2008, H. Li, Liu, and Chong, 2005, Zhang and Bogoy, 1999, W. Zhou et al., 2009a, W. Zhou et al., 2008).

Figure 2.13 Schematic diagram of the slider attitude when the heater is turned on and off. The air bearing force compensates the part of protrusion by TFC heating (Juang et al., 2008)

Since the slider is floating above the disk during the operation, the cooling effect from the air flow beneath must also be considered in the heat flux calculation between the slider and disk. The heat conducted from the slider to the disk moves through the ABS and its effect represents as the function of both FH and air bearing pressure distribution acted on the ABS. It means that all thermal boundary conditions around a slider body could influence the structural deformation together with the selection of slider design and materials. The slider body emits the heat energy via the ABS to the surrounding interface region. Therefore, a coupled-field analysis method is required to study the temperature rise and thermal protrusion on the TFC slider body (W. Zhou et al., 2009b). The coupled-field model includes an air bearing model, a heat transfer model, and a thermal-structural finite element (FE) model to investigate the slider's flying performance and thermal influence on the slider.

The Navier-Stokes (N-S) equation and energy equation are still usable with the discontinuous boundary conditions applied in solving the air bearing problems by previous researchers (Burgdorfer, 1958, Fukui and Kaneko, 1988). The viscosity of the

air (μ) is assumed uniform in the air bearing and the z-direction velocity component (w) is approximated to zero. Therefore, the pressure in z-direction remains constant. As for the air bearing problem, the assumptions were made that the magnitudes of $\left|\partial/\partial x\right|$ and $\left|\partial/\partial y\right|$ much smaller than that of $\left|\partial/\partial z\right|$ and the velocity w is approximated to zero (Zhang and Bogy, 1999). The thermal conductivity is constant for the air bearing application. The viscous dissipation term in the energy equation could be negligible when the temperature difference between the slider and disk surface is larger than zero.

By assuming the air properties in the interface are constant approximately, the N-S equation and the energy equation are decoupled and solved separately for the temperature distribution in the interface. With the assumption of the velocity slip condition and temperature jump condition at the boundaries of the air bearing, the boundary conditions for x- and y-directional velocities and temperatures can be obtained. After that, the velocities; u and v are solved with those boundary conditions. The velocities results are substituted in the energy equation for finding the temperature distribution in the air bearing. Then the heat transfer flux from the air bearing to the slider can be calculated as below (Zhang and Bogy, 1999):

$$q = q_{conduction} + q_{viscous} = k \frac{T_s - T_d}{h + 2b\lambda} + \frac{h^3}{24\mu} \left[\left(\frac{\partial p}{\partial x} \right)^2 + \mu \left(\frac{\partial p}{\partial y} \right)^2 \right] + \frac{\mu U^2 h}{2(h + 2a\lambda)^2} - \frac{Uh^3}{6(h + 2b\lambda)(h + 2a\lambda)} \frac{\partial p}{\partial x} \quad (2.13)$$

where k is the thermal conductivity, T_s and T_d are the temperatures of the slider and the disk respectively, U is the linear disk velocity, μ is the viscosity of the air, h is the slider-disk spacing, λ is the mean free path of air, p is the air bearing pressure, $a = (2\sigma_M)/\sigma_M$, $b = 2(2 - \sigma_T)\gamma/\sigma_T(\gamma + 1)Pr$, σ_M is the momentum accommodation

coefficient, σ_T is the thermal accommodation coefficient, γ is the ratio of the specific heats (c_p/c_v), and Pr is the Prandtl number.

The heat transfer equation shown in Eq. (2.13) consists of the heat conduction term $q_{conduction} = k \frac{T_s - T_d}{h + 2b\lambda}$ and the heat dissipation terms which involve the rest terms in RHS of Eq. (2.13). These dissipation terms come from the Couette flow, Poiseuille flow, and the combination effect of both flows (Zhang and Bogoy, 1999). The viscous dissipation term in Eq. (2.13) is one or two orders smaller than the heat conduction term and it is ignored in solving the heat transfer problems with TFC sliders (Juang and Bogoy, 2007). Therefore, it can express the heat transfer between a slider and a disk as follow:

$$q = k \frac{T_s(x, y) - T_d}{h(x, y) + 2b\lambda(x, y)} \quad (2.14)$$

where x and y are the coordinates of the slider, λ is the mean free path of air at local pressure p .

The localized mean free path is calculated by assuming the air molecular as a hard sphere (HS) and is defined as $\lambda(x, y) = \lambda_0 p_0 / p(x, y)$ where λ_0 is the mean free path of air at atmospheric pressure p_0 . The mean free path is the average distance travelled by a molecule between collision events in the molecular gas dynamic computation. This parameter is based on the molecular model and the HS model is used commonly for simplicity. However, it is not practical in air bearing solution, as the effective cross section of a molecule is not constant during the collision. The cross section varies with the translation energy and it depends on the coefficient of viscosity with temperature. W. Zhou et al. (2008) proposed the new heat transfer model with the variable hard sphere (VHS) and variable soft sphere (VSS) models to reflect the realistic temperature dependent viscosity relation. The improved localized mean free path calculated with

temperature effects is shown as:

$$\lambda(x, y) = \lambda_0 \zeta \left(\frac{T}{T_0} \right)^{\omega+0.5} \frac{p_0}{p} \quad (2.15)$$

where ζ is a factor to show a generalized mean free path for HS, VHS and VSS models and ω is the temperature exponent of the viscosity. The ζ value is 1 for HS model while it decreases to 0.8244 and 0.625 for VSS and VHS models, respectively. The temperature exponent of viscosity ω also varies with molecule models. It is 0.5 for the HS model and 1 for VHS molecules. As for most of the gases, it is set as 0.7 (W. Zhou et al., 2008).

Juang and Bogy (2007) and W. Zhou et al. (2009b) studied the air bearing issues with thermal effects with a TFC slider. They created three-dimensional finite element (FE) model of an entire TFC slider with complete heating element and recording head components. Next, they applied the thermal-structural coupled-analysis which includes the air bearing model, the heat transfer model, and the FE slider model. The steady solution of air bearing model is based on the generalized Reynolds equation with modified slip velocity; called the molecular gas lubrication (MGL) model developed by Fukui and Kaneko (1988). The bearing force is calculated through numerous iteration processes by finding the balancing steady-state flying attitude which includes the flying height, pitch angle, and roll angle. In that way, the pressure distribution acted on the ABS is solved first using Eq. (2.6).

The heat energy transportation process from a slider to disk will be affected by the air bearing cooling and it depends on the flying attitude (D. Chen, Liu, and Bogy, 2009). Therefore, after solving for the steady flying attitude, the heat flux across HDI is achieved by solving Eq. (2.14). The resulted heat flux is applied as the thermal boundary

condition in the thermal-structural analysis of the FE slider model in ANSYS software. The heat transfer at non-ABS surfaces of a slider is dominated by the heat convection and its convection coefficient is set as 100 W/m²K in numerous previous works. The finite element model (FEM) analysis predicts the temperature and protrusion distribution of the entire slider. These temperature and structural deformation profiles are then applied back in the air bearing modeling for finding the steady flying attitude. These steps are iterated few times until the variation percentage of maximum protrusion and FH between the current and previous iterations is below 1% (W. Zhou et al., 2009b).

Besides the heat transfer model shown in Eq. (2.14), L. Li et al. (2015) and Zheng et al., (2010) also developed other heat transfer models for the heat transfer in the narrow air bearing interface with a TFC slider. But their approaches in developing the near field heat transfer model were varied. In Zheng et al. (2010) work, the heat flux between the head and the disk was calculated by appending the Stefan-Boltzmann equation as a radiation term to the heat transfer model in Eq. (2.14). A factor ‘C’ was added in front of the radiation term and the value of C was estimated from Shen, Narayanaswamy, and Chen, (2009) experiment data. This is the first-order approach to investigate the near field effects on the heat transfer in HDI. L. Li et al. (2015) approach for the near field heat transfer was based on the modified Planck blackbody radiation distribution while considering the near-field evanescent wave between two infinite, homogeneous bodies separated by a small gap. The near field radiative heat flux model is as shown below:

$$q_{nfr} = \frac{1}{\pi^2} \int_0^\infty d\omega [\Theta(\omega, T_1) - \Theta(\omega, T_2)] \int_0^\infty s(\omega, \beta) d\beta \quad (2.16)$$

where $\Theta(\omega, T) = \frac{\hbar\omega}{\exp(\hbar\omega/k_B T) - 1}$ is the mean energy of a Planck oscillator at frequency ω and temperature T and $\hbar$ is the Planck constant divided by 2π . The integral of $s(\omega, \beta)$ over β is a weight function that modifies the Planck blackbody radiation distribution. By

assuming that the disk is made of a single aluminium layer and the slider is made of a dielectric material; Al_2O_3 , the dielectric function was applied to solve the $s(\omega, \beta)$ function by defining as the contributions from propagating and evanescent waves (L. Li, Zheng, and Talke, 2015).

The above discussed techniques and methods were developed by several researchers to obtain the equilibrium solutions of slider temperature rise, peak air pressure point, and protrusion rate in the interface region of a TFC magnetic recording system. The situation of HAMR head disk interface is fundamentally similar to that of the TFC application but much more complicated as high temperature heat sources are involved. Due to the co-location of the laser delivery system and magnetic poles inside one slider body, the thermal dissipation event is unavoidable and the study of its effects on the slider temperature and deformation is critical to understand the complete picture of the heat transfer process in HAMR head disk interface. In next section, previous studies on the HAMR heat transfer problems and their impacts on the air bearing will be reviewed and discussed.

2.3.2: Heat Transfer in HAMR Interface and Near Field Heat Transfer

In an integrated HAMR head, thermal energy could be generated from some heat sources such as the laser delivery system, TFC heater, and media hot spot. These thermal effects could cause a hard drive failed due to the head disk contact in the interface. There are few experimental and numerical studies published on the heat transfer problems for a HAMR slider (Bechtel and Boggy, 2011, Schreck et al., 2014, Xu et al., 2011, Xu et al., 2012a, Xu et al., 2012b, Zheng, Li, and Talke, 2012). However, the complete numerical study of thermal effects triggered by these external heat sources on the HAMR slider's flying performances has not been reported yet.

In a HAMR system, a laser diode (LD) is normally used to generate a laser power to a NFT through a waveguide. In HAMR sliders designed in Rausch et al. (2006) and Stipe et al. (2010) papers, a laser diode is placed outside the slider and delivers the laser energy into a waveguide by fibre or free space coupling. Xu et al. (2011) studied the heat effect caused by a LD mounted on a slider and observed that the heat conducted to a waveguide through the slider body caused the slider temperature rise. The heat distribution from a LD to a slider is uniform and the area surface affected is large (Schreck et al., 2014). However, the overall slider deformation due to a LD is not significant with the assumption of placing a LD outside of a slider body. Its deformation can be compensated with the TFC method (Xu et al., 2012a). In this dissertation, the effect of laser diode power dissipation will not be considered in the numerical model as the author assumes the LD location is separated from a slider.

There is another factor affecting the slider temperature originated from a localized hot spot on the disk (media). The hot spot on the media surface induces the slider temperature through the back heating process. Huang et al. (2012) found that the temperature rise is about 3% to 6% of recording layer's Curie temperature. They calculated the temperature distribution on the media surface initially and it was applied in the conduction heat transfer model to investigate the slider temperature increments. Their results might be underestimated since only the heat conduction was considered without considering near-field thermal radiation effects.

During the writing process in a HAMR system, the laser heating requires turning on while the head is writing on the data sector, but it turns off to avoid heating a servo sector as the quality of servo patterns could decline with high temperature. Therefore, a pulsed laser power profile is usually used to control the laser on and off situation over

data and servo zones. Xu et al. (2012a) numerically studied the pulsed laser power effect and they reported that the NFT temperature response is as rapid as 2 μ s while the thermal protrusion response is slower at 2-3 ms with the constant laser power. The response time of the transducer protrusion is due to the slow heat diffusion speed of a NFT and its surrounding materials; the dielectric. The protrusion response time is almost the same as that of a TFC slider. However, with the continuous pulsed laser power applying to a NFT, the protrusion keeps increasing up to the maximum protrusion within 3 ms while the temperature change follows the laser pulse pattern. Since the average duration of disk rotation cycle is in the range of 4-11 ms with respect to the rotating speed of 5400 and 7200 rpm for 2.5-inch hard drives, the protrusion by the NFT heat dissipation attains its steady state level before completing a revolution even with the pulsed laser power input.

Schreck et al. (2014) experiment and simulation results confirmed these findings. The experiment setup for measuring the ABS surface protrusion due to the NFT power dissipation was based on atom force microscopy (AFM) technique detecting the defection of a cantilever to capture a simultaneous topography imaging, similar to that used by D. Li et al. (2013). However, they measured the NFT protrusion of a nonflying head. Their results stated that the NFT temperature rise is localized in a small region and the affected slider deformation is sharp comparing with the bulge shaped protrusion caused by a TFC system. The sharp protrusion by a NFT is difficult to be compensated by TFC heating and D. Li et al. (2013) estimated that the protrusion could be reduced by 15% due to the cooling effect of a flying slider in the actual head disk interface. As the NFT protrusion size, shape, and distribution depend on the material properties of the head, slider, and optical delivery components, the protrusion results from the simulation and experiment could vary in HAMR system. According to Schreck et al. (2014)

simulation results, the protrusion in dynamic response clearly reaches to 90% of the steady state value within 80 μ s. The rest of slider structure temperature response time by the laser heating is about 1 s as shown in Figure 2.14.

By the previous reviews on the NFT protrusion during the laser heating, it confirms that the laser delivery efficiency caused the conversion of laser energy to heat energy along the way of the delivery stage. The estimated power absorptions and losses in different laser delivery components are presented in the head disk interface as shown in Figure 2.15 (Dahl and Bogoy, 2014). The coupling losses and power loss to the nearby write pole occur while the laser is travelling along a waveguide. The power loss from a waveguide to a write pole could affect the writing quality and the offset gap should be designed properly (Seigler et al., 2008). The heat dissipation in a NFT is assumed about 1% to 2% of the incoming power to the NFT and it could be about 2 mW. This amount of power can cause a small NFT volume increasing its temperature sharp while focusing the incident laser into a hot spot on the media. Consequently, the NFT would deform and trigger its efficiency drop which affects the magnetic recording quality and reliability.

Figure 2.14 The most prominent protrusions known to the TFC and HAMR systems against time (Schreck et al., 2014)

Figure 2.15 Schematic diagram of heat flow in HAMR head disk interface and the estimated power budget and losses from a laser diode to a magnet recording bit in HAMR system (Dahl and Bogy, 2014)

Next, there are some research studies for developing more accurate heat transfer model with near field radiation considered. Budaev and Bogy (2014) proposed a mathematical model to the near-field heat radiation problem across the nano-scale vacuum gap using the Planck's laws of thermal radiation with a steady heat flux. They found that the heat transfer coefficient between two half-spaces distanced by a nano-scale vacuum gap is much larger than that computed by the blackbody radiation. This finding is as same as the experiment and simulation results using two polar dielectric surfaces from Shen et al. (2009) and Narayanaswamy et al. (2009) publications. Their experiment results showed that the heat transfer between dielectric surfaces at nanometer gaps exceeds by three orders of magnitude than Planck's blackbody radiation law's prediction as shown in Figure 2.16. Mulet et al. (2002) also confirmed that the radiative heat transfer between two semi-infinite bodies at nanometer distances increases several orders of magnitude. As discussed earlier, L. Li et al. (2015) solved the heat transfer problem with TFC

sliders considering the thermal conduction and near-field radiation. Their radiation model was based on the assumption of two semi-infinite bodies separated by the gap with evanescent waves. They concluded that the near-field radiation effect in the head disk interface (HDI) region is significant to be included in the numerical heat transfer model of HDI.

Figure 2.16 Comparison of normalized near field heat transfer coefficients obtained by using sphere-plate setup and Planck's blackbody radiation's prediction versus the gap for a 100 μm (blue circles) and a 50 μm (violet triangles) diameter sphere (Shen, Narayanaswamy, and Chen, 2009)

2.4: Summary

In this chapter, the author reviewed the current works in developing and designing the HAMR head, media, and head-disk interface. The main challenges and major problems in this area were analysed and discussed. The author also reviewed some numerical methods used in simulating the slider's head-disk interface, including DSMC, MGL and

coupled-field analyses for a TFC and HAMR slider. Finally, some heat transfer models used to calculate heat flux across the head-disk interface were reviewed. These reviews remind that understanding all thermal and structural variations inside a slider, on the disk surface and in the interface are critical and essential as the slider air bearing response depends on the whole air bearing surface (ABS) profile and temperature distribution. The steady-state elevated temperature and protrusion due to the side effects of laser heating on the slider body are important to consider in the overall head disk interface design in the view of mechanical and magnetic recording. In the next chapters, the following works will be performed to study the heat transportation in the nano-scale head disk interface. First, the DSMC method will be applied to investigate thermal effects on the HAMR head-disk interface. Then, the author will develop a finite element model of an integrated HAMR slider with the realistic head and optical components to study the thermal distribution and geometrical transformation. Once the slider surface deformation data are obtained by solving thermal-structural analysis in ANSYS software, it will be applied to the air bearing simulation MGL model to study the flying performance of a HAMR TFC slider. Using the electro-magnetic wave equation, the surface temperature of the multi-layered HAMR media will be determined via the energy transportation method of laser heating. Finally, the backing heating effect in HAMR HDI will be studied by adopting a new heat transfer model which considers both the thermal conduction and near-field radiation and compare with other reference papers for validation.

Chapter 3: Study of Thermal Effect on HAMR Air Bearing using DSMC method

In this chapter, a proper simulation structure model was developed with the direct simulation Monte Carlo (DSMC) method to predict the slider bearing performance of HAMR head disk interface (HDI). As for the higher areal density recording, the head media spacing requires reducing to few nanometers and the air flow in between the head and media becomes very rarefied. The rarefaction is represented by Knudsen number which is the ratio of the molecular mean free path of gas inside to the minimum spacing in HDI. The flow is reckoned as a ‘transition flow’ or even ‘free molecule flow’ in the head-disk interface of a current hard drive.

Figure 3.1 Schematic diagram of HAMR head media interface

Previously, there was a DSMC simulation study relating with the slider posture effect (Alexander, Garcia, and Alder, 1994, Liu and Eddie Ng, 2001) on the air bearing characteristics of conventional head disk interface. As in HAMR system, the slider needs to be optimized and integrated with the optical heating system inside for the

precise heating and magnetic data recording. The HAMR recording head paired with the light delivery system and the focusing optics must be able to fly at low head-to-media spacing (<10 nm) and deliver high field at hot spot position (Kryder et al., 2008). Therefore, the study of HAMR head-disk interface requires considering the heat transfer effects while solving air bearing problems. The conventional Reynolds equation with a slip correction does not include any thermal term by simply assuming that the air bearing is isothermal in the interface. It could make the Reynolds equation with modified slip model which is the current air bearing model not suitable for solving HAMR air bearing case directly. Hence, the DSMC method is proposed for solving air bearing problems in the HAMR interface with. The DSMC method has been widely utilized for modeling the gaseous flows under rarefied flow condition as it could attain the physical features of the flow. It is a promising numerical simulation tool to understand the air bearing characteristics in HAMR application.

3.1: DSMC Method and Code Validation

As mentioned in Section 2.2.2, the DSMC method is a particle based simulation applying with a statistical algorithm for modelling the rarefied gas flow. The DSMC method is a promising tool for the micro-flow simulations and it was validated for computing the flow of high Knudsen number in the air bearing interface (Alexander, Garcia, and Alder, 1994). There is no assumption on the continuum flow and separate the flow particle movement into two stages such as the movement and collision stages in each simulation time step. The macroscopic properties of air flow in the interface are derived statistically from the physical particle properties of the microscopic flow field in DSMC simulations. In this section, the author would apply the DSMC method and

validate its applicability in solving conventional slider bearing problems. In DSMC simulation setups of this dissertation, the slider air bearing problem was simplified as a two-dimensional, micro-channel flow with a stationary, slightly inclined surface (slider) above a horizontal plane (disk) moving in the x-direction with the tangential velocity U_b as shown in Figure 3.2, which is also quite similar to the setup used in some previous works (Alexander, Garcia, and Alder, 1994, Liu and Eddie Ng, 2001). The constant ambient temperature of $T_0 = 273$ K and a pressure of $P_0 = 1$ atm were maintained at inflow and outflow boundaries by adaptively adjusting the appropriate molecular velocity of particles at the boundaries. Both slider and disk surfaces were assumed as fully accommodated ones and the collision model used the variable hard sphere (VHS) particles. Argon gas was used in all simulation case studies because it is a simple monoatomic molecule gas with zero internal degrees of freedom. Besides, since the argon gas has the similar mean free path and potential energy as those of the air, the bearing characteristics in the argon gas should be close to that in the air. Therefore, many previous works (W. Huang, Boggy, and Garcia, 1997, Liu and Eddie Ng, 2001) regarded the argon gas as a good candidate to replace the air and used it in their DSMC simulations.

Figure 3.2 The slider and disk layout in the DSMC bearing interface model

As for validating the DSMC simulation code, the results from Liu and Eddie Ng (2001) were used to compare the outcomes of simulation tests using the current DSMC code. The channel length (L) was set as 5 μm and the minimum channel height (H_o) was 50 nm with three different disk moving velocities of $U_b=25, 50, 90\text{m/s}$. The comparison in Figure 3.3a shows that the DSMC outcomes from Liu and Eddie Ng (2001) and the current study agreed well with each other. In another validation tests, various pitch angles (α) from 0.004 to 0.016 rad were placed with $U_b=25\text{ m/s}$. The comparison of pressure distributions on the slider surface is shown in Figure 3.3b and it illustrated that they were also in good agreement. Furthermore, the generalized lubrication equation solution of Fukui and Kaneko (1988) using $\alpha = 0.01\text{ rad}$ was included for better evaluation and it also agreed with the DSMC result.

Figure 3.3 (a) Comparison of the pressure distributions at various disk speeds (U_b) between the DSMC results of the code used in this paper and those of the referred paper (Liu and Eddie Ng, 2001). The other parameter settings are: $H_o = 50\text{ nm}$ and $\alpha = 0.01$ radians.

Figure 3.3 (b) Comparison of pressure distributions on the slider surface from the present DSMC code, Liu and Eddie Ng (2001) and the generalized lubrication equation solution of Fukui and Kaneko (1988). The other parameter settings are: $H_o = 50$ nm and $U_b = 25$ m/s.

The stream-wise locations of forces with three different pitch angles (α) were compared for validation purpose as shown in Figure 3.4 and they were also comparable. Here the stream-wise location of the bearing force acted on the slider surface is defined as:

$$X_c = \frac{\sum_{i=1}^n (P_i - P_0) X_i}{\sum_{i=1}^n (P_i - P_0)} \quad (3.1)$$

where n is the cell number along the x-direction, X_i is the individual cell position in the x-direction, P_i is the localized pressure and P_0 is the atmospheric pressure. From Figure 3.4, it was obs

Figure 3.4 Comparison of stream-wise locations of the slider bearing forces from the present DSMC code and those of Liu and Eddie Ng (2001)

To validate the current DSMC code, further comparisons between DSMC results with those based on the traditional Fukui and Kaneko's MGL equation (1988) are performed. In the air bearing study of conventional hard disk drives, Fukui and Kaneko's MGL equation is broadly used in the air bearing simulation code including ABSolution software, a DSI's self-developed commercial software widely used by several industrial companies. Figure 3.5 compares the air bearing pressure profiles on the slider surfaces resulting from DSMC code and ABSolution software at various minimum channel heights H_o and disk velocities U_b . Again, good agreements are observed for those comparisons. Furthermore, Reynolds equations with modified slip models are applied as shown in Eqs. (2.6) and (2.7) for predicting air pressure profiles in the interface region. Those modified models which have varying Poiseuille flow factors (Q) and are also included in ABSolution software are listed as i) 1st order slip model, ii) 1.5-order slip model, iii) 2nd order slip model, and iv) Fukui-Kaneko's MGL (FK) model. With the small gap spacing of 2 nm (H_o) and the disk velocity (U_b) of 30 m/s, the pressure distribution results obtained from those slip models and the current DSMC code were

compared in order to observe the validation of those models in the high Knudsen number flow as in Figure 3.6. It was found that the outcome of FK model was still comparable with that from the DSMC method contrasting other slip models.

Figure 3.5 Comparison of the air bearing pressure profiles on the slider surface resulting from current DSMC code and from ABSolution software (W. Zhou et al., 2009b)

Figure 3.6 Comparison of the air bearing pressure profiles on the slider surface resulting from current DSMC code and from the continuum equations. The parameter settings are $H_i = 20 \text{ nm}$, $H_o = 2 \text{ nm}$ and $U_b = 30 \text{ m/s}$.

In the MGL equation, the air bearing was assumed isothermal. However, the HAMR technology introduces considerable thermal concerns in modeling the slider air bearing mechanism. Fukui and Kaneko (1995) presented a form of the MGL equation including a thermal creep flow for large temperature differences between the boundary wall and the ambient characteristic temperature. W. Zhou et al. (2009a) derived the heat transfer model for arbitrary Knudsen numbers flows working together with ABSolution code (MGL model) to study the air bearing characteristics of TFC sliders. Bechtel and Bogy (2011) also developed a generalized lubrication equation with the thermal creep consideration to study the flying performances in HAMR due to the air temperature variation and they observed that the thermal creep flow is negligible compared to the Poiseuille and Couette flows. However, thermal effects of the optical heating source on the HAMR slider bearing were still required investigating and verifying the findings obtained from the previous publications. There is no publication of research work on the air bearing effect in HAMR HDI using the DSMC method found until this chapter is being written.

3.2: DSMC Simulation Model Development

The air bearing force and flying height prediction in HAMR HDI are very important for designing and optimizing in the slider air bearing design of HAMR system. In this section, the particle-based direct simulation Monte Carlo (DSMC) method was utilized to study the air bearing characteristics in HAMR HDI. The slider air-bearing problem was simplified as a two-dimensional, micro-channel flow with a stationary, slightly inclined surface (slider) above a horizontal surface (disk), which was moving in the x-

direction with the tangential velocity (U_b). This simplification was reasonable because the channel width was extremely larger than the channel height and the flow changed in that direction was negligible. The two-dimensional model geometry used in the simulations is shown in Figure 3.2.

To facilitate the simple computation, the argon gas which has the number density of $2.6883 \times 10^{25} \text{ m}^{-3}$, the mean free path (λ) of 62 nm and the viscosity-temperature exponent of 0.81 under ambient temperature ($T_0 = 273\text{K}$) and pressure ($P_0 = 1 \text{ atm}$), was used in all cases. Both surfaces were still fully accommodated and set as diffuse reflection models. The simulation also assumes variable hard sphere (VHS) particles with the reference diameter of argon $d = 4.17 \times 10^{-10} \text{ m}$ (Bird, 1976).

The maximum spacing (flow inlet) was denoted by H_i and the minimum spacing (flow outlet) was denoted by H_o . At the inflow and outflow boundaries of the interface, a constant ambient temperature of $T_0 = 273 \text{ K}$ and a pressure of $P_0 = 1 \text{ atm}$ were placed. The appropriate molecular velocities of particles at the boundaries were adaptively adjusted to maintain the ambient temperature and pressure. The time step was set smaller than the mean-free time which represents the mean time between succeeding collisions of particles. In the following DSMC case studies in this dissertation, the average time step was about $3 \times 10^{-12} \text{ s}$. It was much smaller than the mean time between successful collisions of particles as the mean free path of argon gas was two orders larger than the effective diameter of argon at the atmospheric pressure, about $3.6 \times 10^{-10} \text{ m}$. The channel length (L) was set as 5, 30 and 100 μm , respectively. The shorter channel length case requires less computation resources and time compared with the longer one such as 1 mm of channel length, even though the outcomes for the latter one are closer to the reality.

In DSMC simulations, it is also assumed that the thermal distribution shape of a hot spot on the disk is in the positive half-sine waveform for HAMR application as shown in Figure 3.7. The far field laser intensity distribution is usually expressed as a Gaussian function. However, for the near field laser heating like the HAMR heating process, the temperature distribution of a hot spot on the media might not follow the Gaussian function. It was not certain which function could best describe the temperature distribution of the hot spot in HAMR system. The sine function instead of a Gaussian function was assumed for temperature distribution simply because this function was more easily implemented into the wall boundary in DSMC simulations. No matter which kind of function was used in the simulation models, it was believed that the results could not be significantly different because the heated spot was too small in diameter ($\sim 50\text{nm}$) comparing with the flow length.

Figure 3.7 Temperature distribution profile with a hot spot on the disk

The DSMC physical simulation space was segregated into 1100×20 sampling cells averagely for all simulation cases. Ten sub-cells were involved for each cell both in x

and y directions. The cell size in the x-direction was about 4 nm with the average sampling cell setting. Therefore, the mean free path to cell size ratio was adequate even for the simulation case applying with the ideal air which has about 48.6 nm of the stream mean free path. The average number of molecules in the whole simulation domain of all cases was about 1.5 million roughly. The number of molecules per cell was arranged to contain more than 60 which was much more than a sufficient number of molecules per cell (>20). In all DSMC cases, the inlet and outlet mean flow velocities were predicted and modified in line with the conservation of flux of molecules passing through the boundaries at each time step for maintaining the constant ambient pressure at boundaries. The treatments of boundary conditions of the inlet and outlet in DSMC simulations were similar to those applied by Liu and Ng (2001).

After validating the current DSMC code in the previous section, it was utilized to study the heat effects caused by a hot spot on the disk or high temperature slider body itself at various pitch angles. The slider body temperature (T_s) was assumed to be uniform across the surface of the air bearing slider. Figure 3.7 shows the temperature distribution profile of a 0.05 μm hot spot in the 5 μm long channel. This thermal profile was placed in the DSMC model of HAMR HDI system and a numbers of case studies were carried out to analyze the air bearing problem with different slider postures in HAMR system. These DSMC method outcomes and analysis are presented in the next section.

3.3: Results and Discussions

In the following simulation tests, the minimum channel height (H_o) was varied from 1 to 50 nm and the pitching angle (α) was fixed at 0.01 rad as for reflecting extremely low head-disk spacing in today's hard disk drives. However, the flow channel length (L) was

fixed at 5 μm for minimizing computational resources and it was much shorter than the real slider length which is about 1 mm. Other channels such as 30 and 100 μm in length were also used for studying the flow length effect and their results were compared as in Figure 3.8. The pressures and bearing force acted on the slider surface are calculated in DSMC method by the following equations:

$$p = \frac{\eta}{s\Delta t} \sum (m\xi_z - m\xi'_z) \quad (3.2)$$

$$W = \int_s (p - p_o) dS \quad (3.3)$$

where ξ_z and ξ'_z are the velocity components of incoming and outgoing molecules, p and p_o are the air bearing pressure and ambient pressure respectively, η is the molecular ratio of real number of molecules to simulation molecules and S is the small area of the slider surface.

The pressure distribution profiles on the slider surface were plotted against the normalised flow channel length for all channels as shown in Figure 3.8. The pressure value in each channel was normalized by its respective peak value for better comparison. Regardless of the channel length, the pressure bump acted on the slider surface was observed around the location of the hot spot. It was worth to note that the effect of hot spot became more significantly when the location of hot spot was close to the air bearing pressure peak. In the 5 μm (L) long channel, the hot spot was located 0.5 μm away from the outlet edge and it caused the higher pressure bump than its peak pressure as the hot spot location was close to the edge. In the longer L channels, the further the locations of hot spots moved away from pressure peaks, the lower pressure bumps caused by hot spots happened and the pressure bumps were about 50% of their respective pressure peaks. Therefore, the hot spot effect on the air bearing could be reduced by proper slider design to make the (laser) heat source away from the air bearing peak pressure position.

Figure 3.8 Comparison of normalized slider bearing pressure profiles for channel lengths (L) of 5, 30 and 100 μm with a hot spot size of 0.1, 0.5 and 1.5 μm respectively locating at 10% of its channel length from the outflow edge. The other parameter settings are $U_b = 50 \text{ m/s}$ and $H_o = 5 \text{ nm}$.

3.3.1: Effect of Media Hot Spot Sizes

In order to achieve high density recording in the HAMR application, the diameter of a spot area heated by the light source for reading and writing should be less than 50 nm by the prospective near field optical system (Knight, 1998). As in the initial part of the simulation studies, the spot sizes of 50 nm or larger diameters were applied to understand how different hot spot sizes could affect the air bearing behaviours. After realizing that the hot spot effect could clearly be noticed in the pressure distribution profile in any flow channel length, there would be no more run with a 100 μm long channel in this study since the simulation took too long to complete. The hot spot sizes of 0.025, 0.05 and 0.1 μm were positioned with their centres at 0.5 μm away from the outlet edge in 5 μm long channel. As for 30 μm long channel, the 0.5 and 1 μm spot sizes were set and their centres located at 2.5 μm away from the outlet edge. Figure 3.9

shows the comparison of pressure profiles with various hot spot sizes against the normalised length. The peak value of the pressure bump was about 6.5 atmosphere pressure (atm) with 0.025 μm spot, while it increased to about 7.4 atm with 0.1 μm spot. This might be because the surrounding air molecules in the interface gained more energy from a hot spot and they exerted stronger pressure on the slider surface. The slider bearing force, which was obtained by integrating the bearing pressure on the slider surface, is shown in the insert plot of Figure 3.9 against the normalised length. The force increments in percentages due to spot sizes of 0.025, 0.05 and 0.1 μm were about 1%, 2.5%, and 4.5%, respectively, as compared with the force for the case without a hot spot. As a result, it was deduced that the hot spot size more than 0.05 μm could cause the change in air bearing behaviour in $L = 5 \mu\text{m}$ channel.

Figure 3.9 Comparison of air bearing pressure profiles on the slider surface due to different hot spot sizes in channel length (L) of 5 μm . The other parameter settings are $U_b = 30 \text{ m/s}$ and $H_o = 5 \text{ nm}$. Insert: The plot of air bearing forces.

As for a 30 μm long channel, the simulation studies were done with the hot spots of 0.5 and 1 μm only because the smaller hot spot size requires much longer computing time to complete. The plot of bearing pressure distributions shown in Figure 3.10 also illustrated the proportional increment of bearing pressure and force with the presence of a hot spot, which was similar with the increment in the 5 μm long channel case. The increasing forces in percentages were found to be about 3% and 6.4%, respectively, for 0.5 and 1 μm hot spots. By extrapolating the bearing force shown in the insert plot of Figure 3.10, it was estimated that the hot spot size of around 0.05 μm could cause less than 1% increment on the slider air bearing force. Therefore, for a real head-disk interface, a 50 nm hot spot could not influence much on the air bearing characteristics but its location should be away from the bearing pressure peak.

Figure 3.10 Comparison of air bearing pressure profiles on the slider surface due to different hot spot sizes in channel length (L) of 30 μm . The other parameter settings are $U_b = 50 \text{ m/s}$ and $H_o = 10 \text{ nm}$. Insert: The plot of air bearing forces.

3.3.2: Effect of Pitch Angles

With the fixed H_o , the growing pitch angles allowed more molecules coming into the interface region. As the result, more molecule collisions happened and the velocities of molecules increased to build up higher pressures acted on the slider surface. The resulted pressure profiles increased with the slider pitch angles as shown in the main diagram of Figure 3.11. It was observed that a hot spot on the disk caused the slider bearing pressure and force to increase with its size at the particular pitch angle. However, the hot spot size which is less than $0.05\ \mu\text{m}$ did not affect the air bearing substantially according to the simulation results of the author's previous published results (Myo et al., 2011).

In this sector, the tests were conducted by varying the pitch angle (α) from 0.004 to 0.016 rad with the $0.05\ \mu\text{m}$ hot spot located on the disk. The hot spot center was situated $0.45\ \mu\text{m}$ away from the flow exit in all tests. As in the main diagram of Figure 3.11, since the overall bearing pressure increased with a larger pitch angle, the amount of pressure hump due to a hot spot was elevated even with the fixed hot spot size. Consequently, it triggered increasing the bearing force acted on the slider surface.

Figure 3.11 Comparison of air bearing pressure profiles on the slider surface with a 0.05 μm heated spot on the disk for different pitching angles and (insert) the comparison of bearing forces at different pitch angles with a 0.05 μm heated spot and without a heated spot.

It was also found that the base area of pressure hump around a heated spot location is wider in small pitch angle than that in the large one. This might be due to the narrower spacing between the slider and disk at a lower pitch, which caused the impact widely from a heated spot to its surrounding. In insert chart of Figure 3.11, it was observed that the increasing pitch angle enlarged the air bearing force nearly in a linear way and the existence of a hot spot increased the total bearing force at each posture position. Furthermore, the larger pitch angle caused higher bearing force on the slider with the same size of a hot spot. Hence, the results suggested that the slider posture affected the air bearing performance with a heated spot which is 0.05 μm or larger size in HAMR application.

Figure 3.12a shows the variation of normalized total bearing force acted on a slider with a hot spot size for different pitch angles. Here it was defined as a normalized force value so that the effect of pitch angle on the total force could be evaluated more clearly. It was found that the variation of normalized bearing force with a heated spot for a larger pitch angle was higher than that for a smaller one, which means that pitch angle effect became more and more important as its value increased. This was because the amount of pressure hump produced by a heated spot, as shown in Figure 3.11, increased with a pitch angle. Therefore, at larger pitch angles, the slider bearing force could be more sensitive to the variation of heated spot size. The bearing force increments of about 10%, 9% and 7% with the pitch angles of 0.016, 0.01 and 0.004 rad respectively using the heated spot size of 0.15 μm while comparing the case without a heat spot.

The stream-wise locations of bearing forces on the slider surface, as shown in Figure 3.12b, moved closer to the slider trailing edge as compared with those for larger H_o (50nm) case. They shifted further towards the trailing edge of the slider when a localized heated spot size that is larger than $0.05\mu\text{m}$, was involved in the interface.

Figure 3.12 The variations of (a) total bearing force acted on the slider surface and (b) positions of resultant force with a heated spot for different pitch angles. The normalized total force represents the respective total force with a heated spot divided by the total force without a heated spot.

3.3.3: Effect of Head Disk Spacings

Next, as the head disk spacing keeps reducing further more for higher density recording in HAMR application; it is useful to study the effect of smaller gap spacing on the air

bearing behaviour. In order to study the spacing effect, the minimum channel height (H_o) decreased from 5 nm to 1 nm with a fixed pitch angle (α) at 0.01 rad. The results are shown in Figure 3.13. It was found that the bearing pressure increased significantly and its peak position moved away from a pressure bump caused by a heated spot when the minimum spacing H_o decreased. From the inset chart of Figure 3.13, the results showed that the bearing force also increases proportionally as H_o was reduced.

Figure 3.13 Comparison of air bearing pressure profiles on the slider surface with a $0.05\mu\text{m}$ heated spot on the disk for different minimum channel heights (H_o) with a fixed pitch angle (α) of 0.01 rad and (insert) comparison of bearing forces at different minimum channel heights with a $0.05\mu\text{m}$ heated spot.

3.3.4: Effect of Slider Body Temperatures

Finally, the effect of slider body temperature on the air bearing was studied with the DSMC method. It was assumed that the temperature on the slider surface was higher than the ambient one and it was uniform across the slider surface. Such high temperature on the slider body may be caused by the heat dissipation in the HAMR optical delivery

system, electrical heater, writer or other components. Figure 3.14 shows that both bearing pressure and force increased gradually as slider body temperature (T_s) changed from 0°C to 100°C at $\alpha = 0.004$ rad. This is because the thermal energy released from the slider body entered the interface and affected the bearing pressure and force. In other words, the surrounding gas molecules in the interface gained more energy from the thermal transfer process of a hot spot or slider body and exerted stronger pressure on the slider surface when the gas molecules struck on it. As a result, the bearing force, which is derived from the pressure distribution on the slider surface, increased as the temperature of a hot spot or a slider body rose up. Based on the simulation results with other pitch angles, it was also observed that the total bearing force increments caused by higher slider temperature were quite uniform at any slider pitch angle as shown in Figure 3.15. This suggested that the heat energy from the slider surface ensured similar effects on the bearing pressure and force regardless of the pitch angle of the slider.

Figure 3.14 Comparison of air bearing pressure profiles on the slider surface with varied slider body temperatures for a fixed pitch angle (α) of 0.004 rad

Figure 3.15 Comparison of total bearing forces acted on the slider surface with different slider temperatures and slider pitch angles

Figure 3.16a shows the variation of the normalized total force acted on the slider with high slider body temperature for different pitch angles. Here a normalized force value was also set to evaluate pitch angle effect at various slider body temperatures. The results show that the normalized bearing force gradient increased with the falling pitch angle, which means that the pitch angle effect became less important at its higher values. This was because the total bearing force increment with slider temperature was almost the same at each pitch angle, but the absolute total force value at $T_s = 0^\circ\text{C}$ raised with each higher pitch angle, as shown in Figure 3.16a. Therefore, the normalized force value, which represents the relative change of bearing force at various slider temperatures, turned out smaller as pitch angle increased, which meant that the air bearing total force was insensitive to the variation of slider temperature at higher pitch angles. Using with $T_s = 100^\circ\text{C}$ and the pitch angle of 0.004 rad, the bearing force increases by 18% comparing with $T_s = 0^\circ\text{C}$ and the same pitch angle. About 14% and 10% of force increments happen with pitch angles of 0.01 rad and 0.016 rad respectively using $T_s = 100^\circ\text{C}$ slider.

Figure 3.16b shows the relation of the pitch angle with the slider stream-wise location of force. It was realized that the stream-wise location of bearing force shifted towards the slider leading edge with higher slider temperatures. The effect of slider temperature on the location shift inclined to be opposite to that of the heated spot.

Figure 3.16 Variations of (a) total bearing force acted on the slider surface and (b) positions of resultant force with varied slider temperatures for different pitch angles. The normalized total force represents the respective total force divided by the total force resulted from the test with $T_s=0^{\circ}\text{C}$

3.4: Conclusions

Based on the above investigations and analysis, it pointed out that the DSMC method is a useful tool to investigate the slider bearing pressure change in a HAMR system due to a hot spot on the disk or slider body temperature variations. The outcomes claim that a heated spot sized around 50 nm (in diameter) on the disk could not contribute much to increasing the slider bearing pressure and force. Keeping the hot spot position away from the air pressure peak is more critical to reduce its effects on slider bearing characteristics. Higher slider body temperature caused by the heat dissipation in HAMR optical components or writer could increase the bearing pressure and force in HAMR application. The force increment is more significant in a shorter channel and it could affect the slider bearing performance to some extent. The variations of bearing pressure will cause the alterations in slider flying behaviour and the reliability of a hard drive system could be compromised. As for studies of slider's posture effects, it was found that both the air bearing pressure and total bearing force increased with the slider pitch angle and the stream-wise location of bearing force shifts closer to the trailing edge with the growing pitch angle. The pressure and force increments caused by a hot spot on the media with a larger pitch angle were higher than those with a lower pitch angle. The slider bearing force tended to be more sensitive to the variations of hot spot sizes at a larger pitch angle. Using with the high pitch angle at 0.016 rad and the spot size of 0.15 μm , the bearing force increases by about 10% based on the case without a hot spot at the same angle. With a low pitch angle, the effect of a hot spot was small on the air bearing characteristics but the slider body temperature effect became larger. The slider bearing force was more sensitive to the variation of slider body temperature at a smaller pitch angle. The bearing force could also rise by 18% applying with a $T_s = 100^\circ\text{C}$ slider and a pitch angle of 0.004 rad comparing with $T_s = 0^\circ\text{C}$ slider at the same pitch angle. The

stream-wise location of bearing force moved to the trailing edge with a larger heated spot while it led to the opposite direction as the temperature on the slider body increased up. According to the numerical results obtained in this study, it was concluded that the slider posture effects on the air bearing should also be carefully considered in the head disk interface of a HAMR system.

Chapter 4: Thermal Distribution and its Effects in HAMR Slider Head

In HAMR application, the fundamental problem of creating a sub-wavelength thermal (optical) spot on the disk have been solved by a two-stage light delivery system that consists of a waveguide to funnel laser light down to a near-field transducer (NFT) placed at the end of the waveguide. The purposes of a NFT are to magnify the field strength using surface plasmons (SP) and to concentrate the field at the air bearing surface in an area which is smaller than the largest dimension of the NFT. Then, the NFT will couple the thermal energy into the magnetic recording layer of a HAMR disk over the desired area.

Figure 4.1 Sample HAMR integrated recording head schematic from Stipe et al. (2010) publication

Initially, the optical-only HAMR head with an external coil and a separate read head were utilized to demonstrate and test a light delivery system heating the media. In later time, Seagate built and published HAMR integrated heads with the parabolic waveguide called a planar solid immersion mirror (PSIM) and the Lollipop NFT in the write gap (Challener et al., 2009). However, the details related to a laser source used in their

demonstrations were not mentioned. Moreover, it was reported that the optical efficiency was seriously affected by absorption losses in the writer component and the reliability of the head life was shortened due to the heat transfer problem in HAMR integrated heads (Challener et al., 2009, Rottmayer et al., 2006). Some other hard disk companies such as HGST and Headway, proposed their HAMR integrated heads (Stipe et al., 2010) but their research works are still mainly on the optimized head designs with the optical delivery system for better reliability and efficiency. The design development of reliable and cost-effective HAMR integrated head is one of the main challenges for realizing mass production of standard HAMR system. However, understanding the heat transfer process of the light delivery system in the slider body and predicting thermal distortions of head components are also very important for enhancing an integrated HAMR head design. Likewise, studying the heat transfer process in the multiple-layered HAMR media and thermal distribution on the media surface could advance the numerical heat transfer study of HAMR system as the high temperature media surface of a multiple-layered HAMR media directly relates to the variations of slider surface temperature.

The TFC sliders are designed to be used in HAMR application for obtaining the dynamic flying-height control and minimizing the laser induced thermal effect on the spacing variations. This kind of TFC HAMR slider includes the heater and laser delivery system. The local temperature at the magnetic media can reach to beyond 900 K during the write cycles (Zheng, Li, and Talke, 2012). The only main purpose of heating the media with the laser light in HAMR system is for the facilitation of magnetization without any mechanical damage to the disk or effect in the head-disk clearance. However, due to the residual heat in the waveguide and optical transducer which causes the unexpected thermal deformation on the slider, the slider flying and magnetic

performances could be affected greatly. Therefore, it is necessary to develop some numerical methods to study those issues.

The objective of studies in this chapter is to find out the thermal effects from an optical transducer (NFT) locating near the air bearing surface on the surrounding recording components and flying performance of a HAMR TFC slider. The slider flying performances will be computed with the MGL model in ABSolution software after obtaining the thermal distribution and protrusion profiles from the finite element analysis model in ANSYS.

4.1: Numerical Method

An iterative solution is required to obtain the accurate predictions of the thermal protrusion and temperature distribution on the HAMR slider body. This is because the thermal protrusion of the slider will change the pressure and heat flux distributions across the ABS, and these changes will inversely affect the thermal protrusion. A detailed iteration process between the self-developed air bearing simulation called ABSolution and ANSYS software is similar to that in W. Zhou et al. (2009b) work. The work flow chart of couple field analysis is shown in Figure 4.2. Firstly, the laser heating spot condition such as the temperature distribution profile of a hot spot on the disk requires being known in order to integrate with the HAMR head disk interface simulation model. The numerical heat transfer model of the multiple-layered HAMR model will be based on the optical absorption model of laser energy in the multiple-layered magneto-optic disk created by Mansuripur et al. (1982) works.

Figure 4.2 Flow chart of couple field analysis for the study of HAMR HDI heat transfer process

After obtaining the thermal distribution profile of the disk surface, it is utilized in the molecular gas lubrication (MGL) model for solving slider bearing problems together with the slider surface thermal and structural profiles which are achieved from ANSYS software. As for the first step, thermal and structural profiles are assumed at the ambient temperature and as an uniform flat surface respectively. The MGL model predicts the air bearing pressure and force acted on the slider surface with the resulted static slider flying height. While the air bearing characteristics are computed with the MGL model, the heat transfer coefficient values at the air bearing surface boundaries could be achieved and imported into the finite element model of slider body structure in ANSYS software. With the finite element thermal and structural model and analysis in ANSYS, the temperature and structural deformation distributions due to high temperature HAMR

components could be calculated and the results are to be applied in the MGL model again for iteration process. The iteration process will end until the stable slider flying height is achieved in the simulation. The following sections will discuss the development procedures of numerical models for a multiple-layered HAMR media and an integrated HAMR slider structures.

4.2: Numerical Model Developments

4.2.1: Development of Multiple-layered HAMR Media Model

First, it is assumed that the heating laser provides a stream of electro-magnetic power through the near-field optical device located inside a HAMR head. When the laser stream reaches to the surface of the recording medium, part of the incident power is reflected back and the rest is transmitted into the medium. As only parts of power are transmitted inside the medium, some are transformed into the thermal energy in the medium. Therefore, it is necessary to study how the laser electro-magnetic power is propagating into the medium and what its thermal energy along the depth of medium (z-direction) could distribute.

Figure 4.3 shows the reflection and refraction of the electromagnetic field (laser power) at the media surface. This study is based on the single layered structure and it is used as the initial stage for performing thermal analysis in multiple-layered disk structure of HAMR media. However, based on the knowledge gained from the single-layered structure, the study would extend to power distribution in the multiple-layered disk structure and it is possible to analyse the thermal distribution in each layer more accurately.

Figure 4.3 Reflection and refraction of an electromagnetic field at an interface

The laser power density function $P(x,y,z,t)$ in the media can be expressed as:

$$P(x, y, z, t) = P_{xyt}(x, y, t)P_z(z) = P_{xy}(x, y)P_z(z)P_t(t) \quad (4.1)$$

$$\iint_{-\infty}^{\infty} P_{xy}(x, y) dx dy = 1$$

$$P_z(z = 0) = 1$$

where $P_{xy}(x, y)$ and $P_z(z)$ are the power density in the unit area of the x-y plane and the power density change in z-direction respectively when the total incident laser power is a unit. Before the laser power reaches to the medium surface (before zero in z-direction shown in Figure 4.4), the power propagating function $P_z(z = 0) = 1$ is a unit. $P_t(t)$ is the time variation of the incident laser power value. In Eq. (4.1), the power density on the x-y plane $P_{xy}(x, y)$, along the z-direction $P_z(z)$ and the time variation $P_t(t)$ are independent and can be treated separately.

Figure 4.4 Typical Structure of HAMR media (Yu et al., 2013a)

Because the author assumes that the laser power distribution only varies along the depth of media in this study, the calculation of laser power density variation in the z -direction ($P_z(z)$) will be carried out. As the laser power is assumed as the stream of electro-magnetic power, the time averaged Poynting Vector using the plane electromagnetic wave in Maxwell equation is applied as follow (G. Chen, 2005):

$$P_z(z) = \text{Re}\left[\frac{1}{2}E(z) \times H^*(z)\right] \quad (4.2)$$

where $E(z)$ and $H(z)$ are the electric and magnetic field components (complex) of the laser electro-magnetic wave, and $H^*(z)$ is the conjugate of $H(z)$. The laser electro-magnetic wave in the media is described as a plane wave. It is because (1) the laser is a plane electro-magnetic wave within the focus length, (2) the media layer must be within the focus length of the incident laser beam during laser beam shining on the media and (3) almost all the power transformation happens in the media layer. Therefore, the following assumptions are based on the plane wave description.

The $H(z)$ and $E(z)$ of laser electro-magnetic wave in its propagating process can be described by Maxwell's equations. As for the k^{th} layer in the media, $H(z)$ and $E(z)$ of a

plane electro-magnetic wave meet these criteria (G. Chen, 2005, Mansuripur, Neville Connell, and Goodman, 1982):

$$\left[\frac{d^2}{dz^2} + \left(\frac{z\pi n^{(k)}}{\lambda} \right)^2 \right] E_k(z) = 0 \quad (4.3)$$

$$\frac{d}{dz} E_k(z) + i \frac{2\pi}{\lambda} H_k(z) = 0 \quad (4.4)$$

The general solutions of Eq. (4.3) and (4.4) are:

$$E_k(z) = \alpha^{(k)} \left\{ \exp \left[-i \frac{2\pi n^{(k)}}{\lambda} z^{(k)} \right] + \beta^{(k)} \exp \left[i \frac{2\pi n^{(k)}}{\lambda} z^{(k)} \right] \right\} \quad (4.5)$$

$$H_k(z) = n^{(k)} \alpha^{(k)} \left\{ \exp \left[-i \frac{2\pi n^{(k)}}{\lambda} z^{(k)} \right] - \beta^{(k)} \exp \left[i \frac{2\pi n^{(k)}}{\lambda} z^{(k)} \right] \right\} \quad (4.6)$$

where $\alpha^{(k)}$ and $\beta^{(k)}$ are the parameters related to the incident and the reflected components in the k^{th} layer. The $n^{(k)}$ and $z^{(k)}$ are the complex refractive index and the relative z -position in the k^{th} layer (thickness) respectively:

$$n^{(k)} = n_r^{(k)} + i n_{im}^{(k)} \quad (4.7)$$

$$z^{(k)} = z - \sum_{j=k+1}^N \delta_j \quad (4.8)$$

where δ_j is the thickness of the k^{th} layer ($k = 1, 2, \dots, N=n+1$). The total number of layers is n . The $(n+1)^{\text{th}}$ layer denotes the disk surface (air) and its thickness is zero. The first layer starts from the substrate glass layer.

Before Eqs. (4.2), (4.5) and (4.6) are applied to calculate the power transformation in the media, two parameters $\alpha^{(k)}$ and $\beta^{(k)}$ of laser power propagation must be calculated first. The $\beta^{(k)}$ can be determined by the continuity requirement of both the $H(z)$ and $K(z)$ on the boundary of two neighbouring layers (G. Chen, 2005, Mansuripur, Neville Connell, and Goodman, 1982):

$$\beta^{(k)} = \frac{\frac{n^{(k)} - n^{(k-1)}}{n^{(k)} + n^{(k-1)}} + \beta^{(k-1)}}{1 + \frac{n^{(k)} - n^{(k-1)}}{n^{(k)} + n^{(k-1)}} \beta^{(k-1)}} \exp(-i \frac{4\pi n^{(k)}}{\lambda} \delta_k) \quad (4.9)$$

To meet the continuity requirement, the $\alpha^{(k)}$ must be:

$$\alpha^{(k)} = \frac{\exp\left(-i \frac{2\pi n^{(k+1)}}{\lambda} \delta_{k+1}\right) + \beta^{(k+1)} \exp\left(i \frac{2\pi n^{(k+1)}}{\lambda} \delta_{k+1}\right)}{1 + \beta^{(k)}} \alpha^{(k+1)} \quad (4.10)$$

As the reflected light from the bottom surface of the medium, ($\beta^{(1)} = \beta^{(substrate)}$) is assumed as zero. The $\beta^{(k)}$ can be calculated recursively starting from that of 2nd layer onwards. After $\beta^{(k)}$ is calculated, the $\alpha^{(k)}$ in each layer can be calculated recursively from that of 6th layer (DLC layer). $P_z(z=0) = P_z(\text{air}) = |\alpha^{(k)}|^2/2$ and $P_z(z=0) = 1$ so that it becomes $\alpha_{air} = \alpha_7 = \sqrt{2}$.

By substituting Eqs. (4.1) ,(4.5) and (4.6) into Eq. (4.2), the power density function in the kth layer is obtained as below (G. Chen, 2005, Mansuripur, Neville Connell, and Goodman, 1982):

$$\begin{aligned} P_z^{(k)}(z) &= \text{Re} \left[\frac{1}{2} E^{(k)}(z) \times H^{*(k)}(z) \right] \\ &= \frac{1}{2} |\alpha^{(k)}|^2 \left\{ n_r^{(k)} \alpha^{(k)} \left(\exp\left(\frac{4\pi n_{im}^{(k)}}{\lambda} z^{(k)}\right) - |\beta^{(k)}|^2 \exp\left(-\frac{4\pi n_{im}^{(k)}}{\lambda} z^{(k)}\right) \right) \right. \\ &\quad \left. + 2n_{im}^{(k)} |\beta^{(k)}| \sin\left[\frac{4\pi n_r^{(k)}}{\lambda} z^{(k)} + \phi(\beta^{(k)})\right] \right\} \end{aligned} \quad (4.11)$$

After the energy flow rate of individual layer in the media is calculated by using Eq. (4.11), the heat generating rate within unit volume can be computed for the certain depth of the media layer as follow:

$$Q(z) = -\frac{d}{dz}P_z(z) \quad (4.12)$$

The local temperature in the media layers can be calculated from the general heat conduction equation (Wu, 2007, Yu et al., 2013a, Zeng et al., 2012):

$$\rho C \frac{\partial}{\partial t} T(x, y, z, t) = K \left(\frac{\partial^2}{\partial^2 x} + \frac{\partial^2}{\partial^2 y} + \frac{\partial^2}{\partial^2 z} \right) T(x, y, z, t) + \frac{\partial}{\partial z} P(x, y, z, t) \quad (4.13)$$

where ρ and C are the material density and the specific heat, respectively, K is thermal conductivity coefficient and t is time.

After the numerical model of the multiple-layered media is created, the same quad layered structure data is used in the Mansuripur et al. (1982) paper for verification purpose. Figure 4.5 shows the structure of quad layered media used in the study. Table II in Figure 4.5 listed thermal and optical properties of each layer. After comparing the average flow rate of optical energy through the media along z-direction from the reference paper (Mansuripur, Neville Connell, and Goodman, 1982) and the current numerical calculation, it is found that they agree well with each other as shown in Figure 4.6. Therefore, this energy distribution numerical model can be used for studying the power distribution in HAMR multi-layered media.

Layer	Thickness Z (Å)	Refractive index n	Specific heat C (J/cm ³ /deg)	Heat conductivity K (J/cm/deg/ sec)
1. Substrate (PMMA)	∞	1.46	1.7	0.002
2. Reflector (aluminum)	320	1.2–6.9i	2.7	2.4
3. Intermediate layer (glass)	720	1.5	2.0	0.015
4. Magnetic Film (MnBi)	120	3.1–3.5i	2.6	0.16
5. Overcoat (glass)	1000	1.5	2.0	0.015

Figure 4.5 Structure of quadrilayer magneto-optical disk and the layers' properties
(Mansuripur, Neville Connell, and Goodman, 1982)

As for HAMR multiple-layered media, the media structure and properties values were formatted as described in Figure 4.7 and Table 4.1, respectively. The optical properties of layers mentioned in this study are obtained from Black Ph.D. thesis (2010) and the refractive index database webpage (Polyanskiy, 2016). It was observed that the results at boundaries of each layer and those at its adjacent layers were the same due to the assumption of continuities of electric and magnetic fluxes across the boundaries while the numerical equations were solved. These results could be used for calculating the heat transfer in the desired layer especially the recording media. The power density distribution along the z-axis in HAMR multiple-layer media is shown in Figure 4.8.

Figure 4.6 The comparison of the average flow rate of optical energy flow through the media along z-direction with those from the reference paper (Mansuripur, Neville Connell, and Goodman, 1982) and the calculation from the present model

No.	Layer Description	Thickness (nm)	n-ki	Wavelength (nm)
1	Glass Substrate (Si)	Infinite	1.511	785
2	Ta	3	1.137-3.409i	785
3	CrRu	60	3.2117-5.568i	785
4	TiN	10	0.862-3.665i	785
5	Recording Media(FePt)	12	2.831-1.745i	785
6	DLC	4	2.235-0.374i	785

Table 4.1 Measured Index of Refraction for assorted materials of HAMR media (Black, 2010, Polyanskiy, 2016)

According to the results in Figure 4.8, the power propagation process initiated from the top of DLC layer (from the top surface of the medium structure) which had 4 nm of thickness was at about 40% of the input laser power. The normalized energy flow rate across the DLC layer gradually decreased from 40% to 38.5% almost in a linear manner. However, the gradient of energy flow rate through the media recording layer was steeper from 38.5% to 20% with a non-linear behaviour. It suggested that the optical energy loss in the recording layer (FePt) is larger and the optical energy is transformed into the heat energy inside the layer. This energy transformation is desirable for HAMR recording system because the magnetic grains in the recording media layer are designed to be heated up for achieving higher recording density. After the laser passed through the interlayer (TiN) layer which is below the recording layer, the energy flow rate dropped to 16.7%. The heat sink layer (CrRu) had 60 nm of thickness and it was placed in the HAMR disk for fast response of heating and cooling during the recording process. The gradient of energy flow rate in this layer was very steep and the flow rate reached to zero after passing the heat sink layer. Therefore, the layers below the heat sink layer could not receive any optical energy from the laser beam and no temperature increment in

these layers will be occurred due to the laser heating. This is one of the essential features of HAMR multiple-layered disk.

Figure 4.7 Co-ordinate system and HAMR recording medium structure

This optical energy flow rate was used to calculate the temperature distribution on the top of HAMR media with Eq. (4.13). The resulted hot spot temperature distribution followed the Gaussian distribution. The peak temperature was set at 673 K and the diameters of spot sizes which are based on full width at half maximum (FWHM), were arranged as about 48 and 72 nm, respectively. The hot spot temperature distribution profile applied in the following case studies was as shown in Figure 4.9. This thermal profile is applied to assemble as a hot spot on the disk to study its back heating effect on the slider temperature rise and deformation in the next chapter.

Figure 4.8 Laser power density distributions in the multiple-layered media

Figure 4.9 Temperature distribution of a localized media hot spot

4.2.2: Development of Finite Element HAMR Slider Model in ANSYS

The head components of a slider include the upper and lower poles, write coil, upper shield, lower shield, the heater and the rectangular-shaped near-field transducer (NFT). A schematic model of a Femto-sized HAMR TFC slider and its components at the deposited edge of the slider applied for case studies in this section are shown in Figure

4.10. The structure of NFT was modelled as an E-shape one and its property was set as gold. The waveguide core material was assembled as tantalum pentoxide (Ta_2O_5) and the core was separated from NFT by a 36 nm-thick SiO_2 layer. The waveguide core and NFT were sandwiched by the waveguide cladding layer which was made of glass. The HAMR head design was mainly based on the one in Stipe et al. (2010) paper. The commercial ANSYS software was used to carry out finite element analysis (FEA) simulation on the thermal protrusions caused by the heat dissipations of the NFT and waveguide. ANSYS is an excellent FEM analysis tool for studying a nanometer-level thermal protrusion of a millimeter-sized slider body. A three-dimensional finite element (FE) model of a Femto form-factor ($0.85 \times 0.7 \times 0.23 \text{ mm}^3$) slider design was built for the numerical studies and analysis of HAMR slider head. In most parts of the slider, the hexahedral (brick) elements were applied and the tetrahedral (four-triangular faces) elements were used only for the geometry which did not allow the use of the former one. For thermal boundary conditions of the slider, heat transfer coefficient was set as a constant of $100 \text{ W/m}^2 \text{ K}$ at non-ABS surfaces of the slider and the heat transfer coefficient at the ABS surface was calculated by applying the heat transfer model adopted by W. Zhou et al. (2008) and Huang et al. (2012).

Figure 4.10 Schematic of components in a femto-sized HAMR TFC slider with the blow up view of its trailing edge part

In the thermal-structural model, element SOLID70 which is an 8-node element with a single degree of freedom was primarily used. The development of meshing took a huge proportion of work and it was often most tedious. All volumes of the slider structure components were divided into smaller sweepable volumes in order to fully make use of hexahedral elements such as SOLID70. Finer meshes were assigned in critical regions such as writing pole, coil, heater and NFT while coarse meshes were applied for less important parts. The complexity of the photoresist and coil geometries required the tetrahedral option of SOLID90 element instead of the hexahedral SOLID70 element. Providing that the components with the SOLID70 elements were meshed first, the usage of SOLID90 enabled to create the transitional pyramid elements at the interface between SOLID70 and SOLID90 as shown in Figure 4.11. These transitional pyramid elements allowed converting the 20-node degenerate tetrahedral SOLID90 element into a 10-node

non-degenerate SOLID87 one. Consequently, it reduced the number of nodes and the computation time.

Figure 4.11 SOLID90 and SOLID70 element models in ANSYS software

The numerical simulation involves the coupling (interaction) between the thermal load and structural displacement and it is known as a thermal-structural coupled-field analysis. In this work, the sequentially coupled physics analysis was employed to simulate the thermal-structural effect of the slider. The solution involves two steps: the first step is to solve the thermal loads, and the next one is to convert the temperatures from the thermal analysis to body force loads for structural analysis. During the structural analysis, SOLID70, SOLID90, and SOLID87 were converted into SOLID45, SOLID95, and SOLID92 which are the elements for structural analysis respectively. The thermal boundary condition is to set heat transfer coefficient as $1.0 \times 10^5 \text{ W/m}^2\text{K}$ on the ABS initially and $100 \text{ W/m}^2\text{K}$, which is 3 or 4 orders of magnitude smaller than ABS boundary condition, on the other surfaces such as side and top surfaces (Juang, 2014). Next, the thermal convection coefficient at ABS is obtained from the output of MGL model in ABSolution; DSI-developed air bearing solution software and input into this

FEM model for better representation of a practical case. Thermal boundary conditions of other surfaces left unchanged as the initial ones.

Table 4.2 lists material mechanical parameters applied in the finite element analysis model and those were obtained from previous publications (AZoM, 2010, Kurita et al., 2006). The mechanical properties of gold were based on the bulk value. The final meshed slider structure is shown in Figure 4.13 and it showed that the trailing deposited edge of the slider was meshed much denser than other slider parts. This is to ensure better accuracies in simulating the thermal effects on the head components and to optimize the computational time.

Figure 4.12 (a) The bottom view (ABS view) of femto-sized HAMR slider structure with (b)pole, writing coil and heater and (c)NFT, cladding layer and waveguide designs

Figure 4.13 (a) Femto slider structure and (b) Slider mesh in ANSYS

Parts	Material	Young's Modulus (GPa)	Poisson's Ratio	CTE x 10 ⁻⁶ (/K)	Thermal Conductivity (W/m K)
Substrate	AlTiC	390	0.22	7.1	20.0
Basecoat	Alumina	410	0.25	7.1	1.0
Overcoat	Alumina	410	0.25	7.1	1.0
Shields	NiFe	200	0.30	12.8	35.0
Poles	NiFe	200	0.30	12.8	35.0
Heater	NiFe	200	0.30	12.8	35.0
Writer coil	Cu	130	0.34	15.4	403.0
Isolation layer	Polymer				
0 (°C)		3.80	0.35	22.0	0.5
50		3.70		30.0	
75		3.58		48.0	
100		3.42		52.0	
125		3.26		51.0	
NFT ⁺	Au	79	0.42	14.2	310.0

Ref: M. Kurita, T. Shiramatsu, K. Miyake, et al, *Microsyst Technol* **12**, 369, 2006.
+ <http://www.azom.com/article.aspx?ArticleID=5147>

Table 4.2 Mechanical properties of materials used in the analysis model (AZoM, 2010, Kurita et al., 2006)

As mentioned above, a coupled-field analysis method, which includes an air bearing model, a heat transfer model, and an ANSYS thermal-structural finite element (FE) model was required to investigate the flying and thermal performances of a HAMR slider at various surface temperatures and air bearing surface profiles. An iterative solution with ANSYS model and numerical air bearing (MGL) model was applied to obtain the thermal protrusion and temperature distribution on the HAMR slider body.

The reason was that the thermal protrusion of the slider could change the pressure and heat transfer coefficients distributions across the ABS, and these changes would inversely affect the thermal protrusion. Once the thermal protrusion of the slider was determined, the respective FH of the slider could be achieved from the air bearing (MGL) model of the DSI-developed ABSolution software which was employed for computing the slider's flying performance. The heat transfer model applied in calculating the heat flux across the HDI in the couple-field analysis was based on an expression derived by Zhang et al. (1999). The heat flux between the slider and the disk could be described as,

$$q(x, y) = -k \frac{T_s(x, y) - T_d(x, y)}{h(x, y) + 2b\lambda(x, y)} \quad (4.14)$$

where x and y are the coordinates of the slider, T_s and T_d are the temperatures of the slider and the disk, respectively, k is the thermal conductivity of air, h is the slider-disk spacing, λ is the mean free path of air, $b = 2(2 - \sigma_T)\gamma/\sigma_T(\gamma + 1)Pr$, σ_T is the thermal accommodation coefficient, γ is the ratio of the specific heat, and Pr is the Prandtl number. During the case studies, it was observed that the resulted heat fluxes of different cases are ranged from about 5×10^7 to 2×10^8 W/m². The numerical studies of thermal energy transportation and its effects on slider bearing characteristics were performed with the numerical HAMR media model and an iterative solution between MGL and finite element models of the integrated slider discussed above. A detailed discussion of the outcomes and analysis of thermal effects on the HAMR slider and bearing performance with the back heating effect were presented in the next section.

To validate the couple-field analysis method, the results from the current numerical models are compared with those from Huang et al. (2012). In their paper, they studied the media back heating effect on the slider temperature rise using the HAMR media without a heat sink layer and the HAMR slider finite element analysis (FEA) model.

They used two types of HAMR sliders such as the one with the near-field transducer (NFT) and the one without the NFT. They concluded that slider temperature rise due to the media hot spot back heating is about 3% to 6% of recording layer's Curie temperature using the HAMR head with a metallic NFT. Slider temperature rise due to media back heating depends mainly on the NFT and its surrounding materials. However, they didn't describe any detail of HAMR slider design and materials used in the head/optical components in the paper. Therefore, it was not possible to set exactly the same FE model as theirs. However, based on the HAMR slider design described in Stipe et al. (2010) paper, the comparisons could still be made between the current results and those of Huang et al. (2012) paper for model validation. The comparison results are shown in Figure 4.14. It is observed that two sets of results are comparable with small hot spot sizes less than (100 nm) but the current model predicts higher temperature rise with larger spot sizes.

Figure 4.14 The comparison of slider temperature rise vs hot spot size (FWHM) between current FE model and that from L. Huang et al. (2012) simulation work

4.3: Results and Discussions

In all simulation case studies, the heater is powered at 40 mW. Different ranges of energy power settings are allocated on the waveguide and NFT to study their thermal effects caused by heat dissipation in these components. The result in Figure 4.15 showed the slider thermal deformation profile due to the heat dissipation in the NFT and waveguide when the heater power was set as 40 mW. Two protrusion peaks were clearly observed at the trailing edge of the slider and they were caused by the heater and NFT/waveguide heat losses, respectively. It was also observed that the highest temperature occurred around NFT region and the slider body deformed significantly due to heat dissipation in the optical delivery system components. Therefore, it is necessary to study the slider flying behaviour change caused by this deformation in HAMR interface.

Figure 4.15 Thermal protrusion profile as shown in ANSYS with powers applied to NFT, waveguide and the heater.

4.3.1: Effect of NFT Power Loss

To differentiate the FH change caused by the heat loss in NFT from that caused by dissipation in the waveguide, firstly different energy loss values were assigned to the NFT only with the heater power on. Sharp temperature increments resulted from different NFT power losses at the localized NFT region as shown in Figure. 4.16a. Temperature increment was up to as much as 800 K for 4 mW of NFT power dissipation inside the slider body. The growing peak temperature trend was almost in a linear manner with the power dissipation amount at NFT component.

(a)

(b)

Figure 4.16 Comparison of (a) temperature distribution profiles along the center line of the slider with various NFT power loss settings and (b) peak temperature increments against power losses at NFT component

Thermal deformation results were plotted in Figure 4.17. It was observed that thermal protrusion increment was about 1 nm at 1 mW of NFT heat loss and its profile appeared in the pointed shape with a narrower width. This was because the NFT component was assembled in the middle of cladding layers which are made of low thermal conductivity material; SiO₂. When the NFT power loss was adjusted at 2.0 mW and above, thermal protrusion around the NFT region grew significantly with the rising temperatures. NFT temperature developed up to about 1000 K with the power of 4.0 mW assigned to the NFT. Such high temperature was more than the melting point of gold material which constructs a NFT component. Therefore, it was necessary for the practice to reduce the power loss at NFT as much as possible for those undesired slider deformation problems. The solution method could be to enlarge NFT volume or design an additional heat sink layer for reducing temperature rise. Next, the slider flying height (FH) performance related with the power dissipations in NFT were studied and the FH changes with different NFT power loss settings were shown in Figure 4.18. It was discovered that with higher heat dissipation in the NFT, FH drop rate at the writer location became obviously steeper than that at the reader location. FH change at NFT location followed up with the similar gradient of FH drop at writer region but it was closer to the disk due to the protruded deformation around the optical component region. At 4.0 mW of NFT power loss, the FH at NFT, writer and reader positions are around 0.88, 1.15 and 1.8 nm, respectively. The FH drop at NFT position is about 2 nm with 4 mW of NFT power dissipation from the case of no NFT power loss.

Figure 4.17 Comparison of thermal protrusion profiles along the center line of the slider with various NFT power loss settings

Figure 4.18 Slider's flying height changes near the locations of NFT, writer and reader with various NFT power loss settings.

4.3.2: Effect of Waveguide Power Loss

Afterward, varied energy powers were assigned to the waveguide only to study the effects of heat dissipations in the waveguide. According to the deformation outcomes shown in Figure 4.19b, higher power dissipation in waveguide caused wider structural deformation around writer position than that affected by the NFT power loss. The protrusion increment was also almost in a linear manner and around 0.75 nm of protrusion was produced with every additional 6 mW dissipation power to the waveguide. The protrusion peak increased with waveguide power loss and it became about same or higher levels than another protrusion peak resulted from the heater. Therefore, thermal dissipation from a waveguide could also influence the slider's flying performance largely. After that, temperatures of writer pole at different waveguide power losses were observed and the pole temperature is higher than waveguide's at each power setting. The trend of its peak temperature also rose like the waveguide component's temperature trend as shown in Figure 4.20. The FH changes at the reader, writer and NFT positions with different waveguide power settings were calculated by using ABSolution software and compared in Figure 4.21. FH became smaller with higher power loss in the waveguide. The FH drops at the writer and NFT positions were steeper with rising power dissipations to waveguide. Critically, with high power loss at 30 mW in the waveguide, the contact between the slider and disk could happen around the writer location. The combination effect of heat dissipations in NFT and waveguide should definitely influence more in the head disk interface. Therefore, it was concluded that higher heat energy loss in optical delivery components might lead severe slider/disk contact and affect the slider flying stability.

(a)

(b)

Figure 4.19 Comparison of (a) temperature profile and (b) thermal protrusion profiles along the center line of slider with various waveguide power loss settings

Figure 4.20 Comparison of peak temperature points at waveguide and writer pole along the center line of slider with various waveguide power loss settings

Figure 4.21 The respective FH changes near the locations of NFT, writer and reader with various waveguide power loss settings.

4.3.3: Effect of Media Back Heating

As for the study of back heating effect, it was assumed that no power loss occurred in optical components of an integrated HAMR slider. Heater power was also turned off in the simulation studies. The heat transfer process between the slider and disk surfaces was predicted using Eq. (4.14). These settings ensured that temperature rise and slider protrusion caused by the back heating effect were observed more clearly. The gap spacing between the slider trailing edge and the disk is fixed at 2 nm as shown in Figure 4.9, which means that the spacing between NFT component and disk is about 4 nm. The peak Curie temperature of recording media is set as 673 K or 400° C. The hot spot center was designed intentionally to be located under the NFT position. Two different diameters of heat spots (FWHM) such as 48 and 72 nm were adopted in case studies. The initial slider body temperature was set as 300 K; the room temperature.

The resulting slider temperatures in both down-track (x-direction) and cross-track (y-direction) are shown in Figure 4.22. Maximum temperature rises were 1.5 K and 9 K for 48 and 72 nm of spot sizes respectively. The down-track temperature distribution was asymmetric across the waveguide and NFT region because thermal properties of optical components were different on the slider air bearing surface. Applying with the larger heat spot, the wider area or almost all area of optical components were exposed to high temperatures and it caused higher temperature rise with 72 nm of spot size. Consequently, thermal protrusion increased up to 0.09 nm with the back heating from a heat spot, which is about 8 times larger than that with 48 nm of heat spot size, as shown in Figure 4.23. Although this protrusion value was relatively small, it could become significant when the slider's FH dropped to below 1 nm. From Figure 4.23a, it was observed that the protrusion profile was not smooth due to varying thermal expansion coefficients (TEC) of head components in the region affected by back heating. The peak

protrusion in down-track direction occurred around the NFT component which is made of gold and has higher TEC value. This deduction was supported by observing the thermal protrusion profile in cross-track direction. Two shallow dips at the sides of protrusion profiles (in the x-direction) were caused by very low TEC of cladding material (SiO_2).

Figure 4.22 The comparison of slider temperature distributions due to the media back heating in (a) x-direction (down track) and (b) y-direction (cross track) using different heat spot sizes

Figure 4.23 The comparison of slider thermal protrusion profiles due to the media back heating in (a) x-direction (down track) and (b) y-direction (cross track) using different heat spot sizes

4.4: Conclusions

In this chapter, numerical studies of thermal effects of optical components on the slider flying behaviour in the HAMR head disk interface were carried out using ANSYS finite element (FE) analysis coupled with ABSolution software. An enhanced coupled-field iterative method was developed to understand the heat energy transportation process in the nano-scale head disk interface and structural deformation of the HAMR slider body

with more reasonable HAMR media model. Different power settings were assigned in the NFT and waveguide and the results showed that higher heat dissipation in a NFT alone could affect the slider's FH due to the additional thermal protrusion induced around the writer. The FH drop at the NFT location is about 2 nm when the NFT power dissipation becomes 4 mW from nothing. Moreover, the temperature of a gold NFT could reach more than its melting temperature with this kind of power loss. The heat dissipation in a waveguide could also influence on FH drop. Further slider thermal protrusion of 0.75 nm is resulted with every 6 mW of waveguide dissipation increment. 30 mW or larger waveguide heat dissipation may cause the flying slider contacting with the disk and the drive reliability could be affected seriously. Therefore, it is very important to improve the efficiency of laser optical delivery system for less heat dissipation occurred in its components.

Slider temperature and thermal protrusion increased due to the back heating process of a media heat spot were also studied. The results showed that the thermal protrusion increased up to 0.09 nm with the back heating from a heat spot with 72 nm of heat spot size. Therefore, the backing heating could be another significant factor for inferior thermal influence on slider's flying characteristic. In this chapter, a simple heat conduction model as shown in Eq. (4.14) was adopted for studying the hot spot back heating without considering the thermal radiation effect. In next chapter, this heat transfer model will be further improved by including a thermal radiation term inside and this new model will be used together with ANSYS FE model of a HAMR TFC slider and an optical absorption model to study the hot spot back heating effect at the HAMR head-disk interface in details.

Chapter 5: Near Field Heat Transfer Model of Head Disk Interface

5.1: Introduction

In HAMR system, the media requires being heated to the Curie temperature (~ 700 K) by the laser beam shooting from the trailing edge of the air bearing slider for recording data on it. Figure 5.1 shows the schematic diagram of the media hot spot back heating process at the HAMR head-disk interface while the laser is heating the media for recording the data. The desired high Curie temperature at the recording layer increases the surface temperature of recording media which is required to have smaller area of a single bit for achieving higher density recording. However, the reverted heat energy from a media hot spot causes undesired slider temperature rise by the near-field thermal conduction and radiation at the head-disk interface (Zheng, Li, and Talke, 2012).

Figure 5.1 Schematic diagram of the back heating from a media hot spot in HAMR head disk interface

Previous research studies have been conducted for thermal effects on a HAMR head-disk interface. For example, Yu et al. (Yu et al., 2013a, Yu et al., 2013b) numerically

studied the lubricant depletion caused by the laser heating on the media of a HAMR system. Zheng et al. (2012) investigated the effect of heat dissipation in a waveguide on the thermal deformation and slider's flying characteristics based on a finite element (FE) model built by ANSYS software. They concluded that the heat dissipated in the waveguide which is one of optical delivery components generates an undesired thermal protrusion with a small radius at the read/write element region. Huang et al. (2012) studied the slider temperature rise due to the media hot spot back heating. They found that head temperature increases linearly with higher media temperature and larger spot size. Near-field radiation effect of a media hot spot on the slider temperature rise was not considered in their research, though.

An integrated HAMR slider consists of magnetic recording components and optical laser delivery components. The air bearing surface (ABS) of a HAMR slider is protected with the carbon-overcoat layer which is dielectric as in the same way as the disk surface is. Theory estimated that the near field radiation between dielectric surfaces is beyond the Planck's blackbody radiation limit when the characteristic length scales are comparable to the wavelength of thermal radiation (Mulet et al., 2002, Narayanaswamy et al., 2009). Zheng et al. (2010) enhanced the heat transfer model by adding radiation heat flux generated from Stefan-Boltzmann equation and using the scale factor to account for the effect of near-field radiation in the small gap spacing of thermal flying height control (TFC) system. However, the experimental study and theoretical analysis conducted by Narayanaswamy et al. (2009) revealed that the near field radiation effect in the nano-scale gap of two objects could cause the heat transfer coefficient increased as the inverse of the square of its gap spacing. Furthermore, Shen et al. (2009) demonstrated experimentally that the radiative heat transfer at up to 30 nm of the gap between two flat surfaces could exceed by 3 orders more than the amount predicted by Planck's

blackbody radiation law. Therefore, it is necessary to develop a more realistic radiation model based on the previous experimental data for studying back heating effect of the hot spot.

In this chapter, a series of numerical simulations were executed to gain an insightful knowledge on the heating effect of a media hot spot on the temperature and protrusion distributions of a HAMR TFC slider. The chapter will be organized as follows. First, the numerical models which mainly consist of a FE model of the entire slider with magnetic and optical structures, an optical absorption model will be introduced for generating the temperature profile of a hot spot and a heat transfer model for predicting the thermal conduction and radiation at the HAMR head-disk interface. Next, the effects of hot spot size, shape, and gap spacing will be investigated under the conditions with or without thermal radiation considered. Finally, the results will be summarized and the improvement approaches for the reliability of HAMR head-disk interface will be advised at the last section.

5.2: Developments of Numerical Models

5.2.1: FE Model of HAMR TFC Slider

The same HAMR TFC slider design of Chapter 4 is used in the case studies of this chapter. A detailed schematic model of a Femto-sized HAMR TFC slider ($0.85\text{mm} \times 0.7\text{mm} \times 0.23\text{mm}$) with its magnetic and optical head components embedded at the trailing edge of the slider was shown in Figure 4.10. The head components of a TFC slider consist of the upper, lower pole, write coil, upper shield, lower shield, the heater, cladding layer, near field transducer (NFT), and waveguide. The structure of NFT was modelled as an E-shape one and its property is set as gold. The HAMR head design was

mainly based on the one designed by Stipe et al. (2010). A FE model of this HAMR TFC slider was developed using the commercial ANSYS software. The temperature distributions and thermal protrusion profiles were obtained by performing the thermal-structural coupled field FE analyses using ANSYS like W. Zhou et al. (2009b) work. In structural analysis, constraints were added to the top surface of the slider. For the thermal boundary conditions of the slider, the author set the heat transfer coefficient as a constant of $100 \text{ W/m}^2 \text{ K}$ at non-ABS surfaces of the slider. The heat transfer coefficient at the ABS surface was calculated by applying the new proposed heat transfer model which considers the thermal radiation effect at nano-scale head disk interface.

An iterative solution is required to obtain the thermal protrusion and temperature distribution on the slider body. A detailed introduction of iteration process between the air bearing simulation model and finite element model of ANSYS software was discussed in Section 4.2.2 of Chapter 4. However, it is necessary to highlight here that the volume of NFT is about 4 orders of magnitude smaller than that of the entire slider and thus the meshes at the NFT and slider trailing edge region are much denser the rest of the slider as shown in Figure 5.2. The unstructured triangle meshes at the air bearing surface nearer to the disk is also designed to be denser comparing with the area far away from the disk as shown in the air bearing pressure distribution result of Figure 5.3. Therefore, the mesh arrangement of the slider in simulations could improve computational efficiency with better accuracy.

Figure 5.2 Air bearing design applied in simulation studies and localized mesh distribution near trailing edge.

Figure 5.3 Slider air bearing pressure distribution with triangular mesh pattern displayed in (a) isometric view and (b) top view.

In the iterative method, the slider temperature is assumed as uniform distribution for the very first iteration and the air bearing calculation is performed to obtain the convection distribution at ABS. The air bearing solver is designed to provide two sets of convection data such as the overall heat flux based on the coarse mesh and the localized convection distribution around the NFT component as shown in Figure 5.4. The node and heat convection data transferring algorithm is developed to convert the heat flux value at each node in ABSolution to corresponding one on the mesh of FE slider model. The

temperature difference between the slider and disk at each node is used in heat flux calculation. This approach is different from the thermal data transfer process from the air bearing model to the ANSYS FE slider model during iteration unlike in Chapter 4. It is because when the power dissipations inside the slider and back heating processes are considered together in simulation models to represent a real HAMR scenario in this chapter, the heat flux flow directions are different over the entire slider surface. In Chapter 4, the media back heating process alone without power dissipation was investigated. Through the thermal-structural analysis on the slider model with certain parameter settings in ANSYS, the thermal and structural distribution profiles of ABS are achieved and then imported into the air bearing model for next iteration. In such way, the iteration of coupled field analysis is carried out until the variation percentage of maximum protrusion and FH between the current and previous iterations is below 1%.

Figure 5.4 Overall convection coefficient distributions with the localized convection coefficient distribution over the slider surface resulted from the numerical air bearing model in ABSolution

5.2.2: Optical Absorption Model

In a HAMR system, a laser beam with wave length λ_0 and power P_W is shot from the integrated head onto the rotating disk surface for heating up the recording magnetic grains during the writing process. The laser power penetrating into the media for heating could be represented with an optical absorption model governed by Maxwell equations related with the electric E and magnetic H field intensity (G. Chen, 2005, Mansuripur, Neville Connell, and Goodman, 1982, Yu, Zhou, and Yu, 2015, Yu et al., 2013a). After the electric and magnetic field intensities were determined with the optical model, the rate of the energy transported into each layer of the media can be obtained by the Poynting vector theorem, which can be written as (Yu, Zhou, and Yu, 2015, Yu et al., 2013a)

$$\begin{aligned}
 S_k(z) &= \text{Re} \left[\frac{1}{2} E_k(z) H_k^*(z) \right] \\
 &= \frac{1}{2c_0\zeta} |A_k|^2 \left[N r_k \left(e^{-\frac{4\pi N e_k}{\lambda_0} \left(z - \sum_{j=k+1}^{n+1} \delta_j \right)} - |B_k|^2 e^{+\frac{4\pi N e_k}{\lambda_0} \left(z - \sum_{j=k+1}^{n+1} \delta_j \right)} \right) \right. \\
 &\quad \left. - 2N e_k |B_k| \sin \left(\frac{4\pi N r_k}{\lambda_0} \left(z - \sum_{j=k+1}^{n+1} \delta_j \right) + \Phi(B_k) \right) \right]
 \end{aligned} \tag{5.1}$$

where $E_k(z)$ and $H_k(z)$ are the electric and magnetic field components in the k^{th} layer of disk structure (the layers are numbered from the bottom to the top), N_k is the complex refractive index ($N_k = N r_k - iN e_k$), c_0 is the speed of light in vacuum, ζ is the magnetic permeability, δ_k is the k^{th} thickness layer, the coefficients A_k and B_k denote the light amplitude and the reflection in the k^{th} layer, respectively.

If the laser intensity distribution on the disk surface can be expressed by the Gaussian function, the heat generation rate along the disk thickness direction can then be written as (Yu, Zhou, and Yu, 2015, Yu et al., 2013a)

$$\dot{Q}_k = -\frac{P_W}{\pi r^2} \frac{dS_k}{dz} e^{-\frac{(x-x_0)^2+(y-y_0)^2}{r^2}} \quad (5.2)$$

where x_0 and y_0 are the spatial coordinates for the centre of the laser beam, and r is the e^{-1} radius of the Gaussian beam. In this study, x_0 and y_0 are fixed at the middle of E-shaped NFT component tip. The unsteady heat conservation equation in the Cartesian frame can then be written as,

$$\frac{\partial T}{\partial t} = \alpha_k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\dot{Q}_k}{\rho_k C_{pk}} \quad (5.3)$$

where t is time, T is the temperature, α_k , ρ_k , C_{pk} are the thermal diffusivity, the density, and the specific heat capacity of the k^{th} layer medium, and x , y , z are the spatial coordinates. This energy equation was solved numerically to obtain the temperature distribution of hot spot on the disk surface induced by the laser beam. At the surface of disk, the air flow at the head-disk interface convects the heat away. The corresponding boundary condition used in the present study is:

$$\alpha_1 \rho_1 C_{p1} \frac{\partial T}{\partial z} = h_f T \quad (5.4)$$

where h_f is the convective heat transfer coefficient and the subscript 1 denotes the surface layer.

A finite volume method (FVM) with second order accuracy in both time and space was used to solve the governing equation for energy. After the energy equation has been solved numerically, the temperature distribution on the disk top surface was obtained. This thermal profile was applied to assemble as a hot spot on the disk in the HAMR slider FE model to study the back heating effect of a media spot on the slider temperature and protrusion rise due to thermal conduction and radiation heat transfer. Since the previous studies have confirmed the validation of present models by comparing with the results obtained by the commercial software ANSYS in Chapter 4,

validation studies will not be performed again in this chapter. In the next section, a new heat transfer model is introduced for calculating the heat flux across the HAMR head-disk interface.

5.2.3: New Heat Transfer Model with Thermal Radiation

In a HAMR system, the temperature of a hot spot on the disk surface is non-uniform and it could affect the slider body temperature due to nano-scale heat transfer between the read/write element and the disk. Currently, most of the previous works used an expression derived by Zhang and Bogoy (1999) and W. Zhou et al (2008) to solve the heat transfer problem in a thin head-disk interface. In their works, they assumed the continuum equations such as the Navier-Stokes (NS) equation and energy equation were still usable in solving air bearing problems. The slip condition was applied for the velocity and the jump condition was for solving the temperature at the boundaries of the air bearing. The heat conduction was the main factor in the heat transfer process of the head disk interface. They derived an expression for the heat flux between the slider and the disk as,

$$q(x, y) = -k \frac{T_s(x, y) - T_d(x, y)}{h(x, y) + 2b\lambda(x, y)} \quad (5.5)$$

where x and y are the coordinates of the slider, T_s and T_d are the temperatures of the slider and the disk, respectively, k is the thermal conductivity of air, h is the slider-disk spacing, λ is the mean free path of air ($\lambda = \lambda_0 P_0 / P$), $b = 2(2 - \sigma_T)\gamma / \sigma_T(\gamma + 1)Pr$, σ_T is the thermal accommodation coefficient, γ is the ratio of the specific heat, and Pr is the Prandtl number.

This model is widely used for solving the conductive heat flux between the slider and the disk. However, for HAMR interface as shown in Figure 5.1, the temperature

difference between the slider and disk is certainly large and the heat flux due to the radiation could not be ignored any longer like the thermal flying height control (TFC) slider case. Zheng et al. (2010) enhanced the heat transfer model for HAMR sliders at low flying height by adding Stefan-Boltzmann equation in their research. The total heat flux due to the conduction and radiation could be described as,

$$q(x, y) = -k \frac{T_s(x, y) - T_d(x, y)}{h(x, y) + 2b\lambda(x, y)} + C\varepsilon\sigma(T_s^4 - T_d^4) \quad (5.6)$$

where ε is the emissivity of a black body, σ is the Stefan-Boltzmann constant, which is $5.6704 \times 10^{-8} \text{ kg/(s}^3 \cdot \text{K}^4)$, and C is the scale factor for the effect of near-field radiation in the nano-scale interface which depends on the gap spacing between slider and disk. However, the value of scale factor C is quite difficult to be defined with accuracy in reality.

In the present study, the radiative heat flux is not calculated by the blackbody radiation law as the previous research works showed that the radiative heat transfer coefficient in a nanometer ranged gap depends on the gap distance between two plates (Narayanaswamy et al., 2009, Shen, Narayanaswamy, and Chen, 2009). In their papers, the radiative heat transfer coefficient between two glass surfaces followed an asymptotic relation given by $\alpha \approx B/h^2$ against the distance, where B is constant and h is gap distance. They concluded that this proximity theory gave a correct order of magnitude in the experimental range and was in reasonable agreement with the experimental result. Based on their experimental data, i.e., the near field heat transfer coefficient value of two glass plates is about $2230 \text{ W/m}^2 \text{ K}$ at 30 nm gap, the value of constant B was determined as 2.007×10^{-12} . Since both slider and disk surfaces are covered with the same layer of carbon overcoat, which may result in strong resonant excitation, it is reasonable to assume that the proximity theory between two glass surfaces could be extended as an empirical

formula for radiative heat transfer between the slider and disk surfaces. In such a case, the total heat flux between the slider and disk surfaces can be written as,

$$q_{total} = -k \frac{T_s(x, y) - T_d(x, y)}{h(x, y) + 2b\lambda(x, y)} - B \frac{T_s(x, y) - T_d(x, y)}{h^2(x, y)} \quad (5.7)$$

As for this heat transfer model, it is worth to note that its radiation term is based on experimental data with temperature difference ΔT between two surfaces at 1 K only. For the HAMR head-disk interface, ΔT between the NFT and the media is normally larger than 200 K. In such a case, parameter B should not be a constant anymore and may increase with ΔT . Currently, it is difficult to get the relation between B and ΔT due to lack of experimental data.

Budaev and Bogoy (2014) proposed a method to solve the near-field heat radiation problem across the nano-scale vacuum gap using the Planck's laws of thermal radiation with a steady heat flux. They found that the heat transfer coefficient between two half-spaces distanced by a nano-scale vacuum gap is much larger than that computed by blackbody radiation. This finding is similar to the experiment result using two polar dielectric surfaces by Shen et al. (2009). L. Li et al. (2015) solved the heat transfer problem with TFC sliders considering thermal conduction and near-field radiation. Their radiation model was based on the assumption of two semi-infinite bodies separated by the gap with evanescent waves. They concluded that near-field radiation effect in the head disk interface (HDI) region is significant to be included in the numerical heat transfer model of HDI. In the following section, the comparisons between the proposed heat transfer model and Li's one will be made for near field radiation studies.

5.3: Results and Discussions

5.3.1: Effect of Laser Spot Size

As for high density magnetic recording system like the HAMR case, the spot size of heating the media track is supposed to cover as small as 161 nm^2 of the area for 4 Tbit/in^2 (Greaves, Kanai, and Muraoka, 2013). The laser beam requires heating up the media to Curie temperature (about $600\sim 700\text{K}$) in nanoseconds during the writing process. The temperature profile of media hot spot on the surface applied in case studies is obtained from the optical absorption model derived from Maxwell equations as described in section 5.2.2 and it approximately follows the Gaussian distribution shape, as shown in Figure 5.5. The peak temperature was set at 973 K and the diameters of spot sizes which are based on full width at half maximum (FWHM), were set as 24.2 nm , 48.3 nm and 72.5 nm , respectively. The centre of hot spot location was designed to be under the cross mark of E-shaped NFT component in the simulation studies as shown in Figure 4.10.

Figure 5.5 Gaussian's distribution shape of media hot spot: (a) Isometric view; (b) top view. The small squares represent element nodes built by ANSYS.

The gap spacing between the slider and disk surface is fixed at 0.5 nm in this study. Initially, only the heat conduction effect was included in the heat transfer model without considering the radiation effect. As shown in the temperature results of Figure 5.6a, larger diameters of hot spots caused higher slider temperature increments on the surface of optical delivery components. The temperature increment rate from using a 48.3 nm spot to a 72.5 nm spot was higher than the increment rate using a 24.2 nm spot to a 48.3 nm spot due to the coverage region from the back heating effect. Consequently, the slider protrusion as shown in Figure 5.6b followed the similar tendency as the trend of temperature distribution. It was also found that the protrusion profile was not smooth due to varying thermal expansion coefficients (TEC) of head components affected by back heating. The peak protrusion occurred around the NFT component which is made of gold and had higher TEC value. Two shallow dips at the sides of protrusion profiles were caused by very low TEC of cladding material (SiO_2).

(a)

(b)

Figure 5.6 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider with various hot spot sizes.

Thermal radiation effect is not considered.

Next, thermal radiation process was incorporated in the new heat transfer model and it was employed to calculate more accurate heat flux values between the slider and disk

surfaces of the HAMR interface. Applying with the heat flux with radiation effect, the temperature and protrusion distributions around the optical delivery components which are located near the slider trailing edge were simulated by ANSYS software. It was observed that magnitudes of both temperature and deformation increase significantly due to the radiation effect at each spot size as in Figure 5.7. The radiation effect could as well be seen more clearly in Figure 5.8a and 5.8b which compared the peak temperature and protrusion at different hot spot sizes using 0.5 nm of gap spacing. Without thermal radiation, the peak temperature is raised by 4 K, 7 K and 12 K for 24.2, 48.3 and 72.5 nm of spot sizes, respectively. However, when the thermal radiation process was involved, the temperature increased to 7 K, 14 K, and 24 K at respective spot sizes. As a result, the peak thermal protrusion increased from about 0.025 nm, 0.049 nm, and 0.094 nm to 0.048 nm, 0.095 nm and 0.181 nm, respectively, at different spot sizes due to the thermal radiation effect. Compared with the gap spacing at 0.5 nm, these protrusion values were obviously not minor. Therefore, the thermal radiation effect should be considered carefully in such a small gap of HAMR head disk interface.

(a)

Figure 5.7 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider with various diameters of hot spot. Thermal radiation effect is considered.

(b)

Figure 5.8 Comparison of (a) peak slider temperature and (b) maximum thermal protrusion at different diameters of hot spots. The gap spacing is fixed at 0.5 nm.

5.3.2: Effect of Gap Spacing

While the head-disk spacing is continuing to decrease for achieving higher recording density, it is useful to analyze the effect of gap spacing change on the hot spot backing heating. In the simulations, the media hot spot size was fixed at 72.5 nm and set the gap spacing as 0.5, 1 and 2 nm, respectively. Initially, only the heat conduction effect was involved in the simulation studies. As shown in Figure 5.9a, the peak temperature increased from 306.8 K to 313.7 K when the gap spacing was reduced from 2 nm to 1 nm. However, the temperature fell by 1 K once the gap spacing is changed from 1 nm to 0.5 nm. This is because the conductive heat flux was mainly determined by the gap spacing and mean free path which is related to the air bearing pressure ($\lambda = \lambda_0 P_0 / P$) in Eq. (5.5). At 0.5 nm of gap spacing, the air bearing pressure near the hot spot area was found lower than that at 1 nm of gap spacing due to the occurrence of contact between the slider and disk. Therefore, the heat flux and temperature rise at 0.5 nm gap are slightly smaller than those at 1 nm gap. From Figure 5.9b, the results illustrated that thermal protrusions followed the similar trend of temperature increment with reducing

gap spacing. The maximum thermal protrusion was about 0.05 nm at gap spacing of 2 nm and it increased to about 0.094 and 0.101 nm at gap spacing of 0.5 and 1 nm, respectively.

(a)

(b)

Figure 5.9 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider at various gap spacing. Thermal radiation is not considered here.

Subsequently, new thermal transfer model with the radiation effect was applied to study the back heating effect on the slider with varied gap spacings. The overall temperature and protrusion profiles as shown in Figure 5.10 displayed similar shapes with those using conduction model only. However, the radiation heat transfer caused a significant rise in the magnitudes of both temperature and structural deformation as the gap spacing between the optical components and the disk was lowered. For example, as the gap spacing decreases from 2 to 0.5 nm, the slider temperature rise jumped from 7 K to 24 K respectively when thermal radiation effect was included in the numerical model. Consequently, thermal protrusion increased from 0.061 nm to 0.181 nm at the same gap spacing range.

To see radiation effect more clearly, the author compared the peak temperature and protrusion for the cases with and without radiation effect. The results were displayed in Figure 5.11. It is obviously observed that the radiation at very small gap spacing could have more significant effect. This is because the thermal radiation is inversely proportional to the square of the gap spacing. The smaller the gap spacing, more significant the contribution from thermal radiation could be. It is observed that thermal transfer at 0.5 nm is noticeably more than that at 1 nm and it validates that at very low gap spacing, the radiation effect increases exponentially, especially at the trailing edge where the minimum gap spacing is located as shown in Figure 5.12.

(a)

(b)

Figure 5.10 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider at various gap spacing with thermal radiation considered.

(a)

(b)

Figure 5.11 Comparison of (a) peak slider temperature and (b) maximum thermal protrusion at different gap spacing. The hot spot size is fixed at 72 nm.

Figure 5.12 Comparison of heat transfer coefficient along the center line of the slider at various gap spacing with thermal radiation considered.

The numerical results presented here are based on a new thermal radiation model which is derived from Shen et al. (2009). It is necessary to compare with another theoretical radiation model derived from L. Li et al. (2015) to study the radiation effect at nano-scale gap spacing. As shown in Figure 5.13, the increments of temperature and protrusion due to the back heating are varying with different radiation models. The results based on L. Li et al. (2015) work show much higher temperature and protrusion increments than those from current studies. At 1 and 2 nm of gap spacing, temperature increments are about 90 K and 30 K respectively due to the hot spot back heating alone. However, these data seem much higher than experimental results from Huang et al. (2012), which predicted the slider's temperature rise by ~13 K using a similar hot spot size on the disk media. This suggests that a more accurate thermal radiation model may still be required at the gap spacing below 2 nm, which should be carefully considered in the future.

(a)

(b)

Figure 5.13 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider at 1 nm and 2 nm gap spacings with thermal radiation using two different radiation models.

5.3.3: Effect of Laser Spot Profile

Studying thermal distribution of a HAMR media hot spot still continue for the progress of HAMR development and the exact distribution profile of hot spot on the disk is not certain yet. Therefore, Gaussian's temperature distribution profile was usually assumed for a media hot spot in most of the previous related studies. In the current study, the assumption of temperature distribution profile of a media hot spot followed in a pulse, a trapezoidal or a Gaussian's shape to observe the hot spot shape effect on back heating. Figure 5.14 illustrated these three types of temperature distribution profiles applied for a media hot spot on the disk. The width of a trapezoidal top part was set as 72.5nm, which is the same as the pulse width. As for Gaussian distribution profile, its FWHM was also fixed as 72.5nm for better comparison. The peak temperatures for those media hot spots were all set as 973K. The peak temperatures for those media hot spots were all set as 973K.

Figure 5.14 Different types of temperature distribution profiles applied for a media hot spot

First of all, only the heat conductive flux was applied in the simulation to study the media hot spot back heating effect. From the results shown in Figure 5.15a, it was observed that temperature increment with trapezoidal distribution was highest at 13.6K

and the Gaussian distribution hot spot produced 12.7K of temperature rise. The lowest temperature increment at 1.2K was caused by the pulse distribution profile. It was because the heating area for pulse shape was much smaller than that for the trapezoidal and Gaussian distribution. Therefore, the total energy transferred from the disk to the slider by back heating was insufficient to cause larger temperature increment on the slider body. The results in Figure 5.15b showed that the slider protrusions caused by back heating with different distribution profiles were 0.007, 0.094, and 0.108 nm for the pulse, Gaussian and trapezoidal distributions, respectively.

(a)

(b)

Figure 5.15 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider using different hot spot distribution shape without thermal radiation considered.

When the radiation effect was considered in the simulation, the resulted slider temperature and thermal protrusion enlarged regardless of the profile shape. However, the magnitudes of slider temperature and deformation increments were different with varying hot spot profile shapes. The increments of temperature and thermal protrusion caused by the trapezoidal distribution profile were the largest at 34 K and 0.24 nm, respectively. This amount of slider protrusion occupied 48% of gap spacing (0.5nm) between slider and media surfaces. Using the Gaussian distribution profile, the temperature rise occurred by 24 K with 0.181 nm of peak protrusion. The influence of slider temperature and protrusion increments caused by the pulse distribution profile was the least comparing with the other two profiles as shown in Figure 5.16.

(b)

Figure 5.16 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider using different hot spot distribution shape with thermal radiation considered.

5.3.4: Back Heating Effect with NFT Power Dissipation

In a HAMR system, when the laser beam passes through the optical components of the slider, such as the waveguide and NFT to shine on the disk for heating the magnetic grains on the disk, some of its power could dissipate to heat energy inside the NFT. As the result, the temperature of NFT which is the main component for focusing a laser beam goes up tremendously and it also deforms in shape. The effects on the slider temperature and deformation due to the power dissipations in the NFT had already been presented in Chapter 4. In this section, the author will further study back heating effects with considering power dissipation in the NFT to reflect the real conditions in HAMR system. In the simulations, the power dissipation in the NFT was set at 2 mW with 0.5 nm of gap spacing between the slider and disk surfaces. The FWHM of a hot spot was fixed as 72.5 nm and its distribution followed Gaussian's.

Three different scenarios were considered here, i.e. 1) only power dissipation in the NFT was included without considering back heating effect; 2) back heating effect was considered, but its thermal radiation effect was not considered; 3) both back heating thermal conduction and radiation effects were considered in the simulation. Figure 5.17a and 5.17b showed the comparisons of slider temperature and protrusion among three different scenarios. The back heating from a hot spot caused higher temperature and protrusion increments when the power dissipation in the NFT was considered in the simulation model. Temperature rises by 55 K and 0.27 nm was protruded when the back heating process (with radiation effect) was included in the simulation. However, around the NFT region, the temperature rise and protrusion increment for scenarios 2 and 3 were found to be almost the same, which means that thermal radiation effect might not be significant when power dissipation in the NFT considered. It was because the additional heat inflow caused by the thermal radiation inside the hot spot could be offset by heat outflow outside the hot spot area. Therefore, the total heat flux from the disk to the slider was quite similar for the cases 2 and 3. Based on the results of these case studies, it concluded that the backing heating from a hot spot should be carefully considered in simulating heat transfer across the head-disk interface of a HAMR slider.

(a)

(b)

Figure 5.17 Comparison of (a) surface temperature distribution and (b) thermal protrusion profiles along the center line of the slider among three different scenarios. The power dissipation in the NFT is set at 2 mW.

5.4: Conclusion

In this chapter, the author numerically studied back heating effect of media hot spot on a TFC slider with HAMR optical components. The simulation models consisted of a FE model using commercial software ANSYS, an optical absorption model for the temperature profile of a media hot spot and a heat transfer model which considers both thermal conduction and radiation effects. The numerical results showed that as the media hot spot size increases or gap spacing decreases, the temperature and protrusion increments near the HAMR NFT region become larger due to the conductive heat transfer across the head-disk interface. If thermal radiation effect is further considered, this increment will be more significant. It was worthy to note that about 0.181 nm of thermal protrusion happened using a 72.5 nm of the hot spot at very small gap spacing of 0.5 nm. This protrusion amount is quite comparable with the current head-disk spacing, which is usually 1 nm and below. Moreover, the trapezoidal distribution profile of a media hot spot with radiation effect could even cause larger thermal protrusion up to 0.24 nm which is about 48% of 0.5 nm gap spacing. In the case with NFT heat dissipation and back heating processes, the slider temperature could rise by 55 K and 0.27 nm of protrusion comparing with those from the case without back heating effect while the NFT dissipation power is set at 2 mW with 0.5 nm spacing. Therefore, the back heating effect from a media hot spot must be considered carefully for improving the reliability of HAMR head-disk interface because it could create high impact on the slider temperature and protrusion increment, especially with the thermal radiation effect.

Chapter 6: Conclusions and Future Work

6.1: Conclusions

Heat assisted magnetic recording (HAMR) technology is a very promising high density recording technology even though many challenges and issues are to overcome for making it in the real hard drive product. This technology is still currently in the research and development stage for mass production. The experimental data of HAMR interface is very limited due to the unavailability of a HAMR slider and media for the research purpose, technical complexity, and high setup cost. Thermal and structural stages of a HAMR slider head, a media, and the nanometer spaced interface are scarcely measurable at the moment. Therefore, developing accurate and efficient numerical models of nano-scale HAMR interface is essential for researching and designing reliable HAMR hard drives. In this dissertation, modeling of an integrated HAMR head, development of the heat transfer mechanism on a multi-layered HAMR media, development of the new heat transfer model in nano-scale head disk interface and investigation of all the possible thermal effects on slider's flying behaviors due to the laser heating in the nano-scale HAMR interface were addressed and included in the simulation studies. The main conclusions from the present study are obtained as below:

- 1) The kinetic theory-based DSMC method is proposed in predicting the bearing pressure acted on the slider surface with a localized media hot spot in the nano-scale HAMR head disk interface. This work of solving HAMR slider bearing problems with the DSMC method is one of the alternate approaches in realizing thermal challenges of the HAMR interface. The DSMC method was verified by comparing its results with those based on the continuum-based bearing models. The good agreement is achieved

with Fukui-Kaneko's MGL (FK) model. The pressure bump is created on the slider bearing pressure profile due to a localized media hot spot. However, the hot spot diameter of 50 nm or less could only cause lower than 1% of air bearing force increment. The combination of higher pitch angle at 0.016 rad and spot size of 0.15 μm increases by about 10% of the bearing force comparing with the case without a hot spot at the same angle. With a high temperature ($T_s=100^\circ\text{C}$) slider and the pitch angle of 0.004 rad, the bearing force could also rise by 18% based on the normal slider ($T_s=0^\circ\text{C}$) at the same pitch angle. Making use of the particle-based DSMC method in solving HAMR air-bearing problems was established and one paper was published in the study of slider posture effects on the slider bearing performance.

2) A coupled-field analysis method including an ANSYS finite element model, a molecular gas lubrication model, and a heat transfer model in the interface was developed for numerical simulation studies for the HAMR system. A probable integrated HAMR head design is modeled into the FE model with ANSYS software in this dissertation. The power dissipation in NFT component alone contributes the sharp localized protrusion and consequently, the FH drops happen. The FH drop at NFT location is about 2 nm when the NFT power dissipation becomes 4 mW from 0 mW with a high local temperature of 800 K which is about the gold melting point. The heat dissipation in a waveguide could also influence on the FH drop. Slider thermal protrusion of 0.75 nm is resulted additionally with every 6 mW of waveguide dissipation increment. Critically, with 30 mW or larger waveguide heat dissipation, the slider trailing edge region contacts with the disk and the HDI reliability is affected seriously according to the simulation results.

3) The optical energy distribution pattern in the multi-layered HAMR media is modelled and computed with the time averaged Poynting Vector using the plane

electromagnetic wave in Maxwell equation to estimate the media top surface temperature without using the traditional heat flux model. Through the energy flow rate distribution along the media thickness, the media surface temperature increment due to a localised laser beam was included in the coupled-field analysis model for studying the back heating effect from a localized hot spot. The conventional heat transfer model in the nano-scale head disk interface is based on the heat conduction model for TFC application. A localized hot spot on the disk surface contributes thermal energy back to a slider body and the surrounding head disk interface. Computing with the conventional model, the ‘media back heating’ effect is studied and the simulation results show additional temperature rise and slider protrusion caused by this process. The thermal protrusion increased up to 0.09 nm with the back heating from a heat spot with 72 nm of heat spot size and it could be significant for low slider flying height below 1 nm.

4) As the high temperature localized heating on the media surface is involved in the narrow HAMR interface, a new heat transfer model with the near-field thermal radiation process was proposed. The thermal radiation model which is added into the new heat transfer model was derived from the experimental results of Shen et al. (2009). The new heat transfer predicts 0.181 nm of thermal protrusion resulted using a 72 nm of hot spot at very small gap spacing of 0.5 nm. Different temperature distribution shapes of a localized hot spot are applied in the back heating process and the trapezoidal shaped profile causes highest thermal protrusion at 0.24 nm. In order to simulate all the possible thermal contributions considered in HAMR heat transfer models, the case studies with the NFT power dissipation and back heating are carried out to comprehend thermal effects in realistic HAMR HDI condition. Temperature rises by 55 K and 0.27 nm of protrusion increment are resulted when the back heating process is included in the

numerical model. This kind of numerical modelling setup is one of the first complete HAMR simulation arrangements to study thermal effects in HAMR HDI.

Understanding the temperature change and distortion in a HAMR head is essential for designing reliable HAMR heads and sliders. Hence, in this dissertation, more comprehensive simulation model workflow was proposed and developed to investigate the heat transfer process and slider's flying attitude in the high temperature nano-scale HAMR HDI region. These proposed numerical models would facilitate as prediction tools for designing and developing a more efficient and reliable HAMR system for the next generation hard disk drive.

6.2: Future Work

This dissertation has reported the heat transportation phenomena in the nano-scale head disk interface region with numerical studies. Since the real HAMR slider head design is not available yet outside the industrial corporations, the experiments for studying the slider's flying patterns with a HARM system are not possible and should be included in the future work. Currently, accurate numerical models and analysis are the necessary tools for research purposes in the HAMR head and interface.

- 1) The head disk interface setup in the particle-based simulation method; the DSMC method can be simulated with the air gas mixture as the interface medium in the head disk interface. By using the gas properties of real air molecules in the DSMC setup, more accurate air flow properties in the interface region can be predicted in solving the air bearing problem of a flying HAMR slider. Subsequently, those simulation results could be applied for verifying numerical models used for HAMR system simulations.

- 2) Based on the steady state results of flying HAMR slider performance with the improved numerical heat transfer model, the dynamic simulation platform can be developed in the future for realizing the dynamic slider flying behaviours in a HAMR system.
- 3) In order to investigate steady state thermal radiation coefficient between the slider and disk surfaces in the nano-scale head disk interface experimentally, the experiment test platform could be equipped with a dielectric sphere (as a slider) and a dielectric flat substrate (as a disk) placing in few nanometers distance because of parallelism difficulty. However, the exact experiment setup to simulate an actual head disk interface will be very difficult due to the issues of achieving high speed airflow in between two surfaces and different test geometries. Applying with the radiation heat transfer coefficient data, the proposed numerical heat transfer models can be enhanced by applying in nano-scale HAMR interface.

Publications Arising from The Thesis

1. Myo, K. S., Zhou, W., Huang, X., Yu, S., & Hua, W. (2012). Slider Posture Effects on Air Bearing in a Heat-Assisted Magnetic Recording System. *Advances in Tribology*, 1-6, (169207).
2. Myo, K. S., Zhou, W., Huang, X., & Yu, S. (2015). Numerical investigation of thermal effects on a HAMR head-disk interface. *Microsystem Technologies*, 21(12), 2641-2647.
3. Myo, K. S., Zhou, W., Huang, X., & Yu, P. (2016). Back Heating Effect of Media Hot Spot at Nanoscale Head-Disk Interface, *Microsystem Technologies*, Published online on 20 August 2016 (DOI 10.1007/s00542-016-3107-9), 1-11.

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