Near Field MO Recording System

Sookyung Kim, Jin-Moo Park, Hewon Jeong, Jin-Yong Kim, Jin-Hong Kim*, and Nohyu Kim**

Digital Media Research Lab., LG Electronics

*Devices and Materials Lab., LG *Elite*

**Korea University of Technology and Education

In order to realize a practical storage with higher capacity, near field MO recording has been studied by designing an OFH stable and reliable against contamination. We analyzed an opto-mechanical system including the swing arm, suspension, slider, and developed an OPU adopting the OFH technology with an embedded thin film MO coil, and investigated the properties of lubricants for near field media. A high-frequency ultrasonic cleaning technique is applied and examined for the optical flying slider of the near field recording system to investigate the removal performance of the ultrasonic cleaning method for the sub-micron contaminants produced on the head.

Key words: near-field recording (NFR), magneto-optical (MO) recording, optical flying head (OFH), optical pickup unit (OPU), slider, suspension, solid immersion lens (SIL), swing arm, MO media, MO coil, magnetic field modulation (MFM), contamination, thermal problem, ramp load/unload, ultrasonic cleaning

1. Introduction

The optical flying head (OFH) with low flying height has been an essential technology to achieve high density in the first surface MO recording. Recently the OFH incorporated with high NA optics is being actively researched as an effective method to build a precise optical pickup unit (OPU) for ultrahigh density system including the near field recording (NFR).¹⁻³⁾ However, since the slider has to accommodate optical components for transmitting laser light from the laser diode to disk or from the disk to photodiode, its construction is much more complicated compared with the slider of the hard disk drives (HDD). Moreover, reliability in the head-media interface at very small gap has been regarded as one of most critical issues because of the lens contamination and head crash combined with thermal radiation from the disk in the NFR.

For manufacturing a small slider, a magnetic coil for the near field MO recording has been made by thin film technology embedded in the slider. Recently thin film technology made it possible to increase the frequency response of the coil enough to utilize magnetic field modulation (MFM) recording. In order to enhance data transfer rate in MFM, extensive effort has been made to lower the inductance of the MO coil^{4,5)}, consequently optimum design of the turns and area of the MO coil should be studied for practical slider assembly.

Since contaminants on the SIL and the disk surface make errors or even malfunction probable, it is highly required that the contamination should be reduced

especially for the function of removable disk media. Therefore, in the media design for the NFR, the surface of the disk should be treated for least contamination. The tribological problems have been introduced also in the optical system as in the hard disk drive, in which the role of lubricant films are very important with the viewpoint of contamination and thermal stability. In the NFR, sub-micron contaminants as small as the flying height of the slider may produce a severe damage on device performance and reliability.⁶⁾

The cleaning of the sub-micron particles becomes more difficult because the dominant adhesion force between the head and the contaminants, Van Der Waals force, increases very much as the particle size decreases.^{7,8)} Therefore it is indispensable to remove the sub-micron contaminants during the manufacturing process as well as the drive operation. Recently developed high-frequency ultrasonic (megasonic) cleaning technique is considered as one of the powerful methods to remove sub-micron particles less than 100 nm without surface erosion and many remarkable results have been reported.^{9,10)}

In order to realize a practical storage with higher capacity, we propose an OFH precisely equipped with high NA lenses and a thin film MO coil, and discuss designing issues for the OFH development against contamination or thermal problem. In order to secure both flying stability and reliability, we also studied a thin film MO coil structure with more efficiency for magnetic field intensity with wide bandwidth in the near field MFM MO system. In addition, the head cleaning mechanism is investigated not only to remove sub-micron contaminants but also to prevent the re-adhesion of the particles during the drive operation. The megasonic technique was applied and its performance tested for the cleaning of the flying head of NFR drive.

2. Overview of OPU for the near field MO recording

A near field MO recording system adopting the OFH is shown in Fig. 1. The OFH that is incorporated with both a thin film MFM coil, which has 1.1 effective NA combined with the SIL and objective lens of 0.6 NA. It flies at a height of approximately 60nm from the disk surface at 2 m/s. In this system, a laser beam from the laser diode (LD) is delivered to a small mirror located at the end of a swing arm, shifting its direction to the small objective lens of the slider connected to the swing arm through the suspension. Three-dimensional view of the OPU is shown in Fig. 2, in which the OFH is connected to the swing arm through the suspension.

Fig. 1. A schematic of conceptual NFR storage system

The OFH is important for the construction of a SIL-based NFR system with small disk-media gap size and high data transfer rate. The flying head is very similar to the slider of a HDD, but it has an optical unit on the upper side to transmit light from the laser diode to disk or from the disk to photodiode. Therefore, the OFH should have both mechanical and optical performance to yield a near-field optical signal of high S/N under stable flying height during the read/write motion. Generally, both objective lens (OL) and SIL have to be made with relatively large size in manufacturing processes such as glass molding and machining. Therefore, the OFH should be effectively designed to enable loading of heavy optical components onto the sliders without flying instability during various seek motions.

The OPU based on the 650 nm LD has tolerance specifications as listed in Table I. Acceptable tolerance within 0.03λ wavefront error seems very tight, but it can be compensated and relaxed by adjusting the collimator lens. The numerical aperture (NA) of the OL and effective NA based on the refractive index of SIL are 0.6 and 1.11, respectively. The entrance pupil diameter is $\Phi 1.60$ mm and the effective focal length is 1.30 mm. Because the working distance of the OL is only 0.666 mm, the radius of hemispherical SIL is limited to 0.500 mm. In the case of a two-element NFR lens system, it is desirable that the aberration caused by improper positioning of a hemispherical SIL due to assembly errors (off-center and tilt with respect to optical axis) is small.

Fig. 2. A 3-dimensional view of the OPU structure developed for the NFR

Fig. 3. Cross-sectional view of the OFH

3. The OFH and slider design

Recently, the OFH has been widely researched, since it has merits of low gap size of head/disk, fast data transfer rate for near-field recording. In spite of that, it remains impractical in use because it requires small and light optical units, precise fabrication process, low thermal damage, prevention of contamination, and so forth. In our NFR drive, the OFH consists of focusing objective lens with 2.2 mm of diameter and hemispherical SIL with 1.0 mm of diameter and is integrated in the flying slider as shown in Fig. 3.

The area of the slider facing to the disk is 2.8 mm x 3.8 mm, and its thickness is 0.5 mm for the working distance of the objective lens. A super-hemispherical lens is incorporated in the through-hole of the slider and the bottom of the lens is bonded onto a glass plate in the role of optical window. The through-holes are machined on slider substrate bar, and ball lenses are inserted inside it. Then the bottom of the bar is polished to make hemispherical lenses, and, in the next step, the air bearing surface (ABS) is patterned on the bottom surface by the process of ion milling. The suspension is designed to load 3-4 gram force onto the slider, and has an integrated gimbal and load arm.

Fig. 4 shows the ABS of the slider, which consists of taper, rails, and negative pressure regions. Its shape is similar to ordinary sliders but it is different in that it generates more floating pressure despite of low velocity and more negative pressure for higher air bearing stiffness. From the geometric center of view, the rail region is mostly near the leading edge of the slider. The objective lens occupies two thirds of the upper slider, so we design the suspension to put load upon the slider near the region

Table I. Tolerance specifications of the OPU

Error sources	Acceptable errors ($< 0.03\lambda$)	Collimator compensation	Collimator horizontal shift
OL thickness	$< 0.6 \mu\text{m}$	$< 40 \mu\text{m}$	$-1 \text{ mm} <$
SIL thickness	$< 0.2 \mu\text{m}$	$< 11 \mu\text{m}$	$-0.85 \text{ mm} <$
Adhesive thickness	$< 0.15 \mu\text{m}$	$0 \sim 12.5 \mu\text{m}$	$-0.8 \sim 0.2 \text{ mm}$
OL tilt	1.1°	1.6°	$-0.013 \text{ mm} <$
SIL tilt	2.4°	2.8°	$-0.006 \text{ mm} <$
OL-SIL Decenter(L)	$21 \mu\text{m}$	$25 \mu\text{m}$	$< 0.052 \text{ mm}$
Defocus(X)	$0.35 \mu\text{m}$	$20 \mu\text{m}$	$-0.8 \text{ mm} <$

Fig. 4. Perspective view of the air bearing surface

of the leading edge.

Flying height of the slider is designed to be 100 nm and the minimal height of the slider is 40 nm, and pitch angle is 90 μ rad at a linear velocity of 1.94 m/s. If the surface of the disk is so rough that the slider motion will go into fluctuation or crash, the signal disturbance will be induced. For that reason, the dynamic properties, such as air bearing stiffness, of the slider should be estimated and improved as well.

Fig. 5 shows the flying height of the slider and air bearing stiffness calculated by flying simulation. When the load of the flying slider is varied with range of 1-6 gram force, the height of the lens center is from 200 nm to 60 nm, the minimal height of the rail is from 90 nm to 20 nm, and the air bearing stiffness is from 200 kN/m to 1300 kN/m. Using these value, we determine 3-4 gram force of the load, 100 nm of the head-gap and 600 kN/m of air bearing stiffness.

4. Slider dynamics and loading and unloading ramp model

In the NFR drive, the laser beam from the LD is delivered to a small mirror located at the end of a swing arm, shifting its direction to the small objective lens of the slider connecting the swing arm through the suspension. Therefore the coupled dynamic motions of the optomechanical system including the swing-arm, mirror suspension and slider should be analyzed so that the beam spot is finally positioned to a target point of the optical disk.

The theoretical analysis and experiment on the optimal

Fig. 5. Flying height and air bearing stiffness of the slider with respect to preload

Fig. 6. Vertical motion of the slider during load

design of the OFH system and seeking algorithms should be considered to reduce manufacturing and alignment errors within an allowable limit. In this paper, a ramp loading mechanism for reliability of the OFH during load/unload operation is investigated. The OFH with suspension assembly is modeled and the flying slider dynamics during transient motion is simulated. The motion of the slider is modeled as three degrees of freedom system by the following governing equations^{11,12)} (Zeng and Bogy, 1999)

$$m \frac{d^2 z}{dt^2} = -F_{sz} + F_{cz} \iint_A (p - p_a) dA \quad (1)$$

$$I_\theta \frac{d^2 \theta}{dt^2} = -M_{s\theta} + M_{c\theta} + \iint_A (p - p_a)(x_0 - x) dA \quad (2)$$

$$I_\beta \frac{d^2 \beta}{dt^2} = -M_{s\beta} + M_{c\beta} + \iint_A (p - p_a)(y_0 - y) dA \quad (3)$$

Here, z , θ and β are the vertical displacement at the slider's center, pitch and roll; m , I_θ , I_β are the mass and moments of inertia of the slider, F_{sz} is the suspension force in the Z-direction, $M_{s\theta}$ and $M_{s\beta}$ are suspension moments in the pitch and roll directions, p_a is ambient pressure, p is the pressure governed by the generalized Reynolds equations, F_{cz} is the contact force and $M_{c\theta}$ and $M_{c\beta}$ are the contact moments.

The suspension is modeled as a spring-damper system with stiffness and damping in the Z, pitch and roll directions. The design objectives for loading/unloading (L/U/L) ramp are to prevent the slider from impacting the disk during load and to minimize the lift-off forces during unload. During load, the slider hits the disks for some initial conditions, such as negative pitch. During unload, the suction forces generated by sub-ambient cavities and/or the effects of skew angle result in suspension oscillation and a long unload process.

Fig. 6 shows the flying attitudes of the proposed slider model during load as a design example. Here, the slider mass is 0.037 g. The ramp profile is designed to have the vertical velocity of 10 mm/s during load. The preload of

the suspension is 3 gf. The total loading time is about 0.02 sec. Since the slider mass including a lens is larger than that in HDD, the loading motion of the slider approaches the flying height after several oscillations. Further numerical simulation using this L/UL model has also demonstrated the stable unloading motion of the slider. Parameter studies show that the slider motion during load/unload is very sensitive to the initial conditions in the pitch direction and loading/unloading velocity. Using this model, we determine the optimized parameters to meet design requirements and show stable and robust performances.

5. Thin film MFM MO coil

A magnetic coil for the near field MO recording has been made by thin film technology and embedded in the slider. Recently thin film technology made it possible to increase the frequency response of the coil enough to utilize magnetic field modulation (MFM) recording. In order to enhance data transfer rate in MFM, extensive effort has been made to lower the inductance of the MO coil.^{4,5)} However, there is an unavoidable trade-off problem in the coil design for the near-field MO recording. That is to say, it is advantageous to decrease the number of turns and the area of the MO coil for wideband frequency characteristics, while it is advantageous to increase the number of turns and the area of the MO coil for magnetic field intensity. Therefore, the optimum value of the turns and area of the MO coil must be determined.

In our design, required magnetic field intensity and bandwidth of the coil is 200-300 Oe at 30 μm from the center of the coil and 30-40 MHz, respectively. Therefore, if possible, with keeping the minimum magnetic field intensity, the number of turns and the area of the coil should be minimized to decrease the inductance of the coil. The MO coil can be assumed to be the collection of current loops which are located in the same plane with a different diameters. Therefore, the magnetic field of the MO coil can be calculated with following equation^{13,14)}

$$H_z = \sum \frac{IR_n^2}{2(R_n^2 + z_n^2)^{3/2}} \quad (4)$$

Table II. Coil specifications for recording.

Turn	24 turns
Current	200 mA
Field Intensity	200~300 Oe
Inductance	90 nH
Resistance	11 Ω
Inner diameter	80 μm
Outer diameter	380 μm
Bandwidth	30~40 MHz

where H_z is the Z component of the magnetic field of total current loop, R_n is the radius of each loops and z_n is the distance from the loop center of each loops.

Using Eq. 4, we determined the maximum number of turns, and R_n 's to keep the necessary magnetic field intensity. Table II shows the specification of the designed coil. The coil was made by the electro-plating technology and attached to the recess region of the slider. The center of the coil is etched with a diameter of 80 μm for the mesa of the objective lens, which removes the interference between the coil and the laser path of the objective lens. The distance of the bottom surface of the slider and the recording surface of the disk is controlled through a thinning process of the coil substrate by ion milling.

6. MO Media

Since temperature at the NFR disk surface is increased by the irradiation of the laser beam, the thermal behavior of the lubricants was examined, and the results of three types of lubricant films are shown in Fig. 7. Three lubricants of Z-dol, Z-dol TX, and AM-3001 have the same repeating monomers of ethylene oxide ($-\text{CH}_2\text{CH}_2\text{OH}$) and methylene oxide ($-\text{CH}_2\text{OH}$), but their end-groups are different. The end-groups determine the thermal and tribological behavior and are $-\text{CH}_2\text{OH}$, $-\text{CH}_2(\text{OCH}_2\text{CH}_2)_p\text{OH}$, and $-\text{CH}_2\text{OCH}_2\text{C}_6\text{H}_5\text{O}_2$ for Z-dol, Z-dol TX, and AM-3001 respectively. Lubricant films were prepared on Si wafer and the thermal stability of them was measured using Thermo Gravimetric Analyzer (TGA).

Figure 7 shows the dependence of weight loss after 4 hours annealing as a function of temperature. Z-dol shows the highest loss of weight among the materials, it loses about 40 % of weight at 200 $^\circ\text{C}$. However, only 7 % of weight loss is seen for AM-3001. At 150 $^\circ\text{C}$, nearly no loss is observed for AM-3001, but some weight loss can be seen for Z-dol TX and Z-dol. Z-dol shows the highest loss of weight at high temperature, Z-dol TX is intermediate, and AM-3001 showed the least loss.

The different thermal behavior seems to be attributed to not only the molecular weight but also the change of conformation due to the different end-groups. The molecular weight of Z-dol, Z-dol TX, and AM-3001 are 2000, 2200, and 3200, respectively. On the other hand,

Fig. 7. Weight loss of three lubricants after 4-hour annealing as a function of the temperature.

Fig. 8. Ultrasonic cleaning setup

AM-3001 contains lots of strong bonds such as C-F and O-H than relatively weak C-O bond, which make the AM-3001 strong at high temperature. The dissociation energy of C-F and O-H is more than 470 kJ/mol, and that of C-O is 360 kJ/mol.

7. Megasonic cleaning mechanism

The cleaning of small particles becomes more difficult when the particle size decreases because the dominant adhesion force, Van Der Waals force, increases very much as the particle size decreases.^{7,8)} The megasonic technique was applied and tested for the cleaning of the flying head of NFR drive. 1 MHz ultrasound with maximum 100 Watt was used to remove the artificial PSL (Poly Styrene Latex) particles and alumina particles of 100 and 500 nm deposited on the surface of the slider by the atomizer.

The ultrasonic cleaning equipment used in the experiment is composed of three parts as shown in Fig. 8. To investigate the cleaning efficiency of the ultrasound quantitatively, two kinds of artificial contaminant particles with known size are deposited on a very clean SIL which is prepared in class-1000 clean room. Alumina and characteristics for the metallic contaminants and non-metallic contaminants typically are found in optical disk drives and hard disk drives such as Polycarbonate and fluorocarbon (Teflon).

The shape of PSL is a sphere with very regular sizes in diameter (200 nm and 500 nm) and the alumina particles has a uniform distribution over the range from 400 nm to 1500 nm with a mean diameter of 1000 nm. The deposition of the artificial contaminants on the SIL surface is conducted by spraying a mixed solution of ethanol and the particles on the surface in the state of aerosol. The ethanol attached on the surface with the particles is volatilized quickly and the particles deposited without any mark on the surface. The amount of the contaminants over the unit area, which is a density of the contaminants, is controlled by the time duration of spraying.

After the deposition of the particles, PSL and alumina, a number of ultrasonic cleaning test are

Fig. 9. Ultrasonic cleaning results for PSL at 10W
(a) before cleaning, (b) after cleaning

performed at the different operation conditions depending on the power level of the ultrasound and the cleaning time. The power of the ultrasound applied on the SIL varies from 10 to 70 W and the time of cleaning from 5 seconds up to 10 minutes at each level of ultrasonic power. Figure 9 describes the cleaning efficiency for PSL after a certain amount of time elapses at 10 W. In the test, approximately 50 % of particles are removed after the first 30 seconds, and 70 % and 90 % removal efficiency are obtained after 2 minutes and 5 minutes respectively. With the higher level of ultrasonic energy, the more powerful cleaning performance is observed.

In the case of 70 W of the ultrasonic power, a good cleaning over 50 % of cleaning efficiency is achieved even in a couple of seconds. Even in the lower level of ultrasonic power, the cleaning performance is excellent and fast enough to be able to be used for the cleaning method of the NFR head. It is clear from the figure that a very good cleaning performance and effectiveness can be achieved for sub-micron contaminant particles of the head of NFR drive system by using the megasonic technique.

8. Conclusion

In order to realize a practical storage system with higher capacity, near field MO recording was studied by designing a stable and reliable OFH against contamination or thermal problems. We developed an OFH precisely equipped with high NA lenses and a thin film MO coil,

load/unload ramp and media for the near field MO recording. Design considerations were introduced for a stable and reliable OFH against contamination. A high-frequency ultrasonic cleaning technique was applied and examined for the head of NFR drive to investigate the removal performance of the ultrasonic cleaning method for the sub-micron contaminants produced on the head.

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