Chapter 2
Principle and Design

2.1 Basic Near-Field Recording (NFR) Principle

In general, the diameter of the spot size only focused by an objective lens in far field recording can be approximately expressed as:

$$D_{spot} \cong \frac{\lambda}{2(NA)} \tag{1}$$

$$NA = \sin\theta \tag{2}$$

In this equation, λ is the wavelength of the light source, NA is the numerical aperture of the lens, and θ is the maximum angle of rays in the focused light beam. So that the light source becomes a small spot to write and read data on the media, as shown in Fig. 2-1.

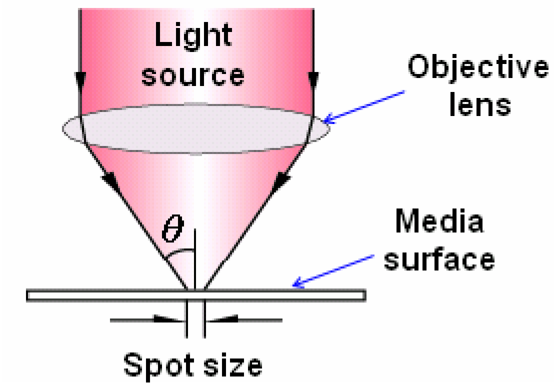
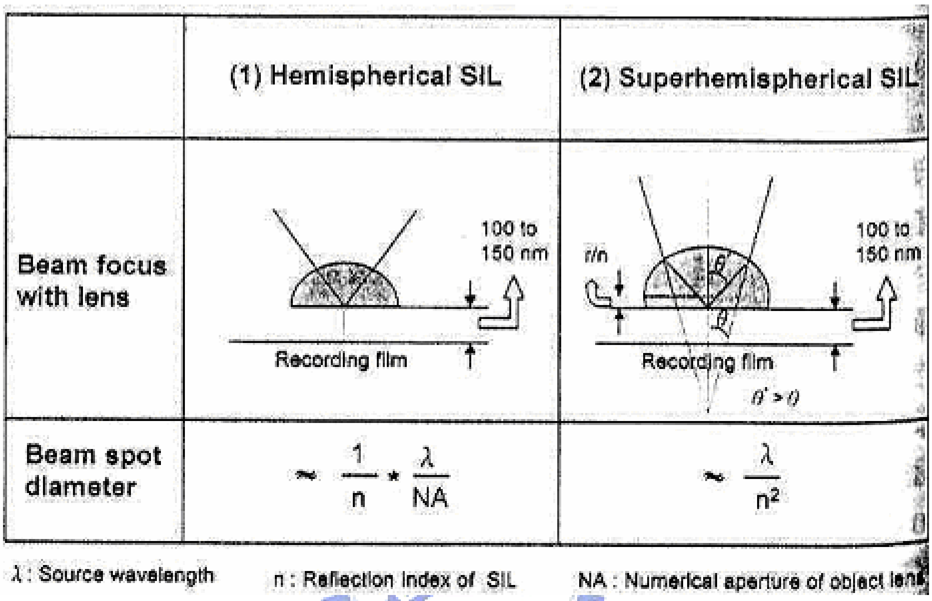


Fig.2-1 Illustration of a lens to focus the incident light

From equation (1), the spot size can be reduced by using an incident light with short wavelength or an objective lens with large numerical aperture. Generally the wavelength used in commercial optical data storage devices is from 630nm to 780nm, and the numerical aperture of the lens in air is less than one. Owing to the diffraction limit in far-field recording, the spot size is hard to be shrunk further. For this reason, there were many investigations toward near-field recording technology.

In near-field recording, the SIL/SSIL and aperture are the key components to reduce spot size for higher recording density.



	(1) Hemispherical SIL	(2) Superhemispherical SIL
Beam focus with lens		
Beam spot diameter	$\sim \frac{1}{n} * \frac{\lambda}{NA}$	$\sim \frac{\lambda}{n^2}$

λ : Source wavelength n : Reflection index of SIL NA : Numerical aperture of object len

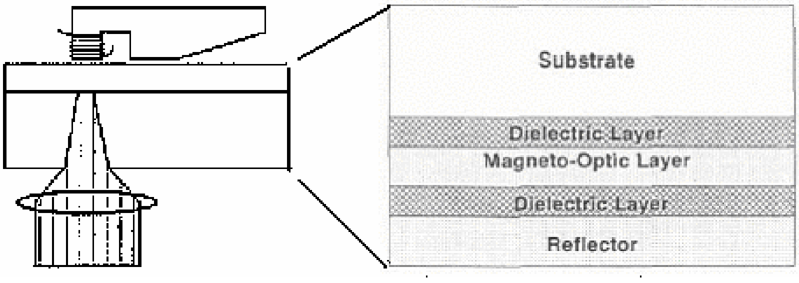
Fig.2-2 Principles of the SIL and SSIL (Tsai, 1998)

As shown in Fig.2-2, the principle of the SIL near-field optics is that by focusing light inside a high index of refraction lens, hence the wavelength is reduced by a factor of n, where n is the refractive index of the lens. The spot size is expected to improve by a factor of n too. So the recording density can be increased. Another near-field technique is to use the SSIL component. By using SSIL component, the focusing angle becomes larger, and the sinθ approaches to one. This makes the NA value closer to n. Then, the spot size can be shrunk “n^2” times comparing with the conventional spot size without the SIL or SSIL. Therefore, the recording density can be increased too.

The other method to reduce the spot size is using the sub-micro aperture. When the diameter of the aperture is smaller than the wavelength of the incident light, the spot size of the light passed through the aperture is unrestricted by the diffraction limit but decided by the aperture size. The smaller aperture size leads to a smaller spot size when the aperture is smaller than the wavelength of the incident light. Therefore, the recording density can be increased too.

2.2 MO Recording Theorem

The original MO recording technique was announced in 1958. At the outset, the MO recording is a far-field recording technique. Hence the SIL/SSIL or aperture is not applied. As shown in Fig.2-3(a), the basic theorem of MO recording is that when the magnetic layer of the disk was locally heated over a special temperature (Curie Temperature, about 300°C) by laser, and a magnetic field is applied by a coil simultaneously. The heating spot in the magnetic layer was magnetized by this extra magnetic field, and the magnetized molecules of the heating spot will be oriented to a specific direction. When the heating spot cool down, the arranged direction of the molecules was fixed. This phenomenon was called “Kerr Effect”. Then, the data can be identified by the different arranged direction of the molecules. The material of the recording disk is shown in Fig.2-3(b).



(a) (b)

Fig.2-3 (a) The basic theorem of MO recording (b) The material of recording disk

It is known that due to the diffraction limit, the recording density of the traditional MO technique can not be increased. Hence the near-field recording technology included the SIL/SSIL and aperture components were employed to increase the recording density in MO technique. The principle of data storage in near-field recording is accomplished by "Evanescent Coupling". From the equations developed by Scottish Physicist James Maxwell, any form of electromagnetic radiation enclosed within a boundary will produce waves outside that boundary that decay at exponential rate. If the object is close enough to that boundary (within a fraction of the wavelength), it will receive some of the evanescent radiation. In some cases, evanescent coupling can produce a very high quality effect, inducing more than 50% of the energy in the source of radiation to couple with the material in the near filed. The power would decay by the transmission distance. The power of light source in evanescent coupling performs is proportional to $e^{-i2\pi d/\lambda}$. The "d" is the gap between aperture and disk. If the "d" is too large, the diffraction effect will be increased in near-field recording. So the "gap" should be kept about λ/3 to λ/4. When the disk is rotating with a high speed and the air gap (flying height) between the pickup head and disk is very narrow, the airflow will be significant in that scale and a considerable force at the bottom of the pickup head due to the airflow will occur. This force will cause a tilting or rolling pickup head with an uncertain flying height. To gain an effective power, the gap must be precisely controlled beyond one third or half of the wavelength. The closer the gap is, the more difficult to control will be. Variation in the air gap will result in the uncertain performance in data storage. So the air-bearing structure is adopted to control the flying height in near-field recording.

2.3 Concept Design

According to the available researches, various near-field pick-up head structures were demonstrated recently. In near-field recording technique, the SIL/SSIL and aperture components are adopted to shrink the spot size for high recording density. As shown in Fig.2-4, it is known that combining the SIL and aperture together can obtain better resolution and performance. Hence the SIL and aperture will be combined together in this research.

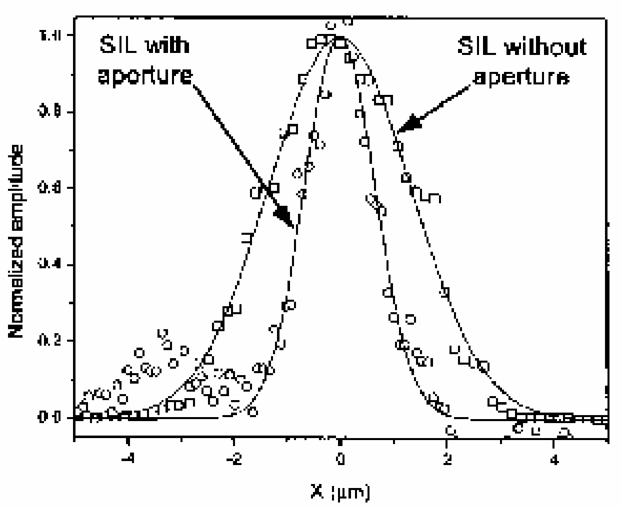


Fig.2-4 Intensity distribution of the laser beam with and without the sub-micro aperture (Fletcher et al., 2000)

As shown in Fig.2-5, the research here presented a new MO pick-up head structure combining the microcoil, the SIL, and the sub-micro aperture for near-field recording. In this MO pick-up head structure, the laser beam is guided into the SIL by a fiber that has a fiberlens in front-end of the fiber instead of the traditional objective lens. Then the incident light is focused by the SIL again. The final spot size is decided by a sub-micro aperture. By the Evanescent Coupling effect, this final laser spot transfers the partial laser energy to magnetic layer. The partial laser heats the magnetic layer over the "Curie Temperature" (i.e. the glass transition temperature). Furthermore, a magnetic field is applied by microcoil (about 200~300Oe) simultaneously. The heating spot in the magnetic layer is magnetized by this extra magnetic field. Owing to the "Kerr Effect", the data can be written and read on the magnetic layer. The fabrication process of this MO pick-up head is based on surface micromachining (MEMS technology) and electroplating technology. The detailed fabrication process will be described in chapter 3.

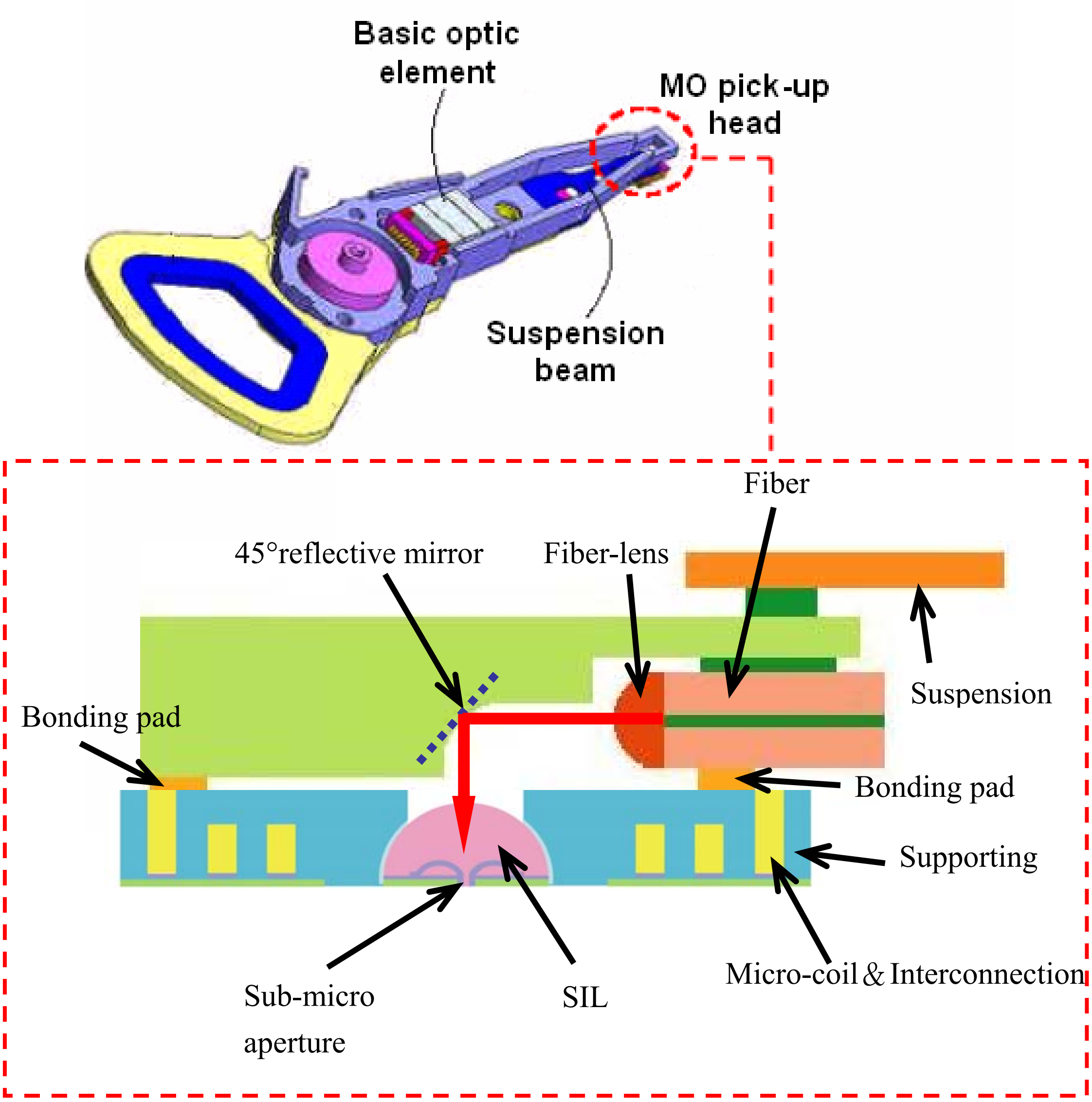
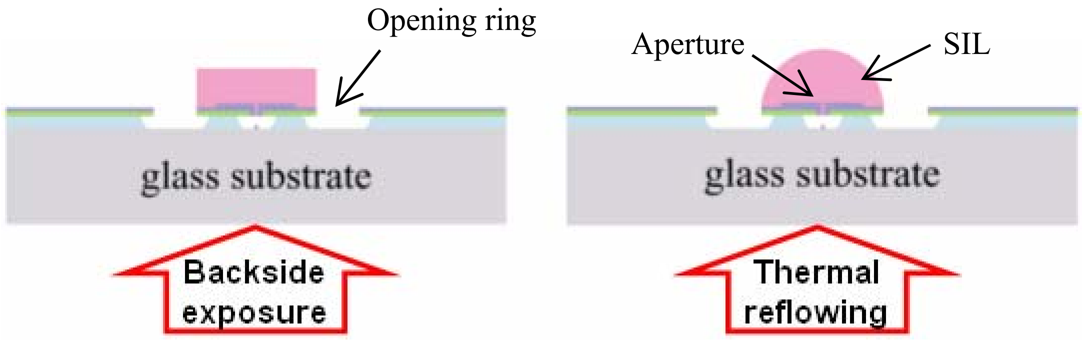


Fig.2-5 Integrated MO pick-up head structure

In this MO pick-up head, the key step in fabrication process is the self-alignment that used glass substrate to align precisely between the SIL and aperture by backside exposure. The following section will describe the self-alignment concept.

2.4 Self-Alignment Concept

In order to obtain a better performance, the SIL/SSIL and aperture is combined together in MO pick-up head structure. But owing to the aperture size is very narrow in near-field recording technique (about 300~600nm). Therefore, the alignment range between the aperture and the SIL/SSIL will become very small. It means that the alignment between the aperture and the SIL/SSIL is very difficult. If the alignment step has a “shift”, the performance will be lost or failed. For this reason, the research here brings up a new idea that the SIL and aperture can be aligned precisely by backside exposure step on glass substrate to fabricate MO pick-up head. This idea is called “Self-Alignment”. The self-alignment mechanism is shown in Fig.2-6(a). First, the initial aperture is made by lift-off process. Then, the sacrificial layer is etched by chemical solution to form the opening ring. The light source can pass through this opening ring for backside exposure. After, the initial aperture is shrunk by deposition technique until the scale arrives in sub-micro order. The columnar photoresist pattern is defined by backside exposure step on glass substrate for self-alignment. Finally, the columnar photoresist pattern is heated to temperature above the glass transition temperature (Tg). By thermal reflowing mechanism, the SIL structure can be obtained, as shown in Fig.2-6(b). By using the self-alignment technique, the SIL and aperture can be aligned precisely. Hence the misalignment problem between the SIL and aperture can be overcome. Furthermore, this fabrication process is a batch process.



(a) (b)

Fig.2-6 (a) The Self-Alignment mechanism (b) The thermal reflowing mechanism

2.5 Designs of Individual Parts

The dimensions and materials of the devices combined in the MO pick-up head will be discussed in next section. The different sizes of the devices will be designed.

2.5.1 Sub-Micro Aperture

The sub-micro aperture below the SIL can limit the spot size further. Here, the initial aperture is formed into a pedestal layer by lift-off process. The amorphous silicon is deposited by sputtering as the material of pedestal layer. Then, the initial aperture is sputtered the metal layer for shrinkage aperture. Therefore, a sub-micro aperture can be obtain after shrinkage initial aperture step, as shown in Fig.2-7(a) and Fig.2-7(b). Total components including the SIL, aperture, and microcoil in MO near-field pick-up head are fabricated above this pedestal layer. However, the design parameters of aperture are dependent on the thickness of the pedestal layer, initial aperture size, and the thickness of the shrinkage aperture (i.e. the thickness of the deposited metal layer).

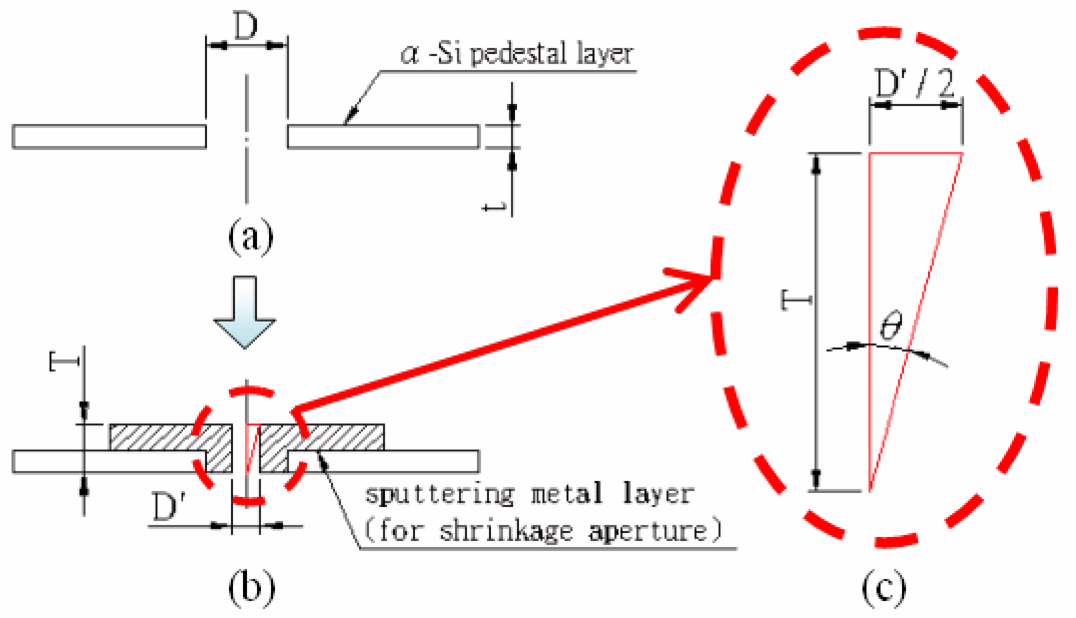


Fig.2-7 (a) Initial aperture size defined into a pedestal layer (b) Aperture size after shrinking with metal deposited (c) The basic geometrical for aperture design

The aperture design is shown in Fig.2-7. The t is the thickness of pedestal layer, D is the initial aperture size, T is the total thickness that included the thickness of pedestal layer and the deposited metal layer, D' is the final aperture size, and the θ is the maximum angle of rays in the focused light beam. As shown in Fig.2-7(c), according to the basic geometrical theorem, the θ can be calculated by the following equation:

$$\theta = \tan^{-1}\left(\frac{D'}{2T}\right) \tag{3}$$

Besides, the numerical aperture of the lens (NA) can be approximately expressed as:

$$NA = \sin\theta \tag{4}$$

From above equation (3) and (4), the θ and NA that is desired in the aperture design can be obtained. For example, a initial aperture size 2μm (D) is made inside the pedestal layer by photoresist lift-off process. The thickness of the pedestal layer (t) is 250nm. Then, a metal layer is sputtered above the pedestal layer to shrink the aperture size until sub-micro scale. The final aperture size (D') and the total thickness (T) are

500nm and 1000nm, respectively. According to the equation (3) and (4), the maximum angle of rays in the focused light beam (θ) is about 14°, and the numerical aperture of the lens (NA) is calculated about 0.24 in this case. The design parameters of aperture are listed in Tab.2-1.

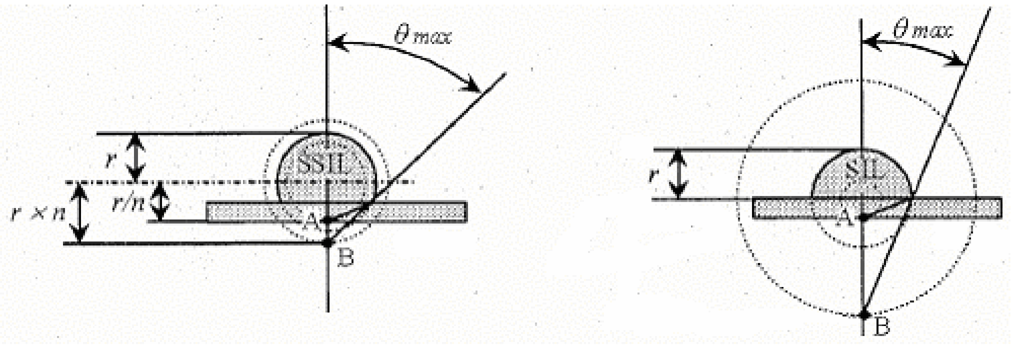
Tab.2-1 The design parameters of aperture

	***D* (μm)**	***D'* (nm)**	***t* (nm)**	***T* (nm)**	***θ***	***NA***
Case1	4	500	150	1900	~7.5°	~0.13
Case2	2	500	250	1000	~14°	~0.24
Case3	1	500	250	500	~27°	~0.45
Case3	1	500	150	400	~32°	~0.53

It can find a phenomenon from above table. A smaller initial aperture size (D) and the thickness of pedestal layer (t) can be obtained a larger incident light angle (θ) and the numerical aperture (N.A.). Hence the spot size will be shrunk very large. However this fabrication process used backside exposure on glass substrate for self-alignment. If the thickness of pedestal layer was too small, the backside exposure could be fail. Conversely, if the thickness of pedestal layer was too large, it will cause a worse performance in near-field recording. Besides, the total thickness (T) and the final aperture size (D') should match the NA of the incident light to ensure that the incident light can be focused into the sub-micro aperture.

2.5.2 The Solid Immersion Lens (SIL)

The principle of the SIL/SSIL has been explained in the 2.1 section. The standard SIL/SSIL structure is shown in Fig.2-8.



(a) (b)

Fig.2-8 Standard structure (a) SSIL (b) SIL

The SIL is made by thermal reflowing process. Here, the photoresist AZ-4620 is chosen as the material of the SIL for the easy fabrication process. The total thickness of the SIL structure will be designed about 30μm due to the output transmission efficiency, as shown in Fig.2-9. I_o means the input intensity while the I_f means the output intensity. The design parameters of the SIL structure are shown in Fig.2-10.

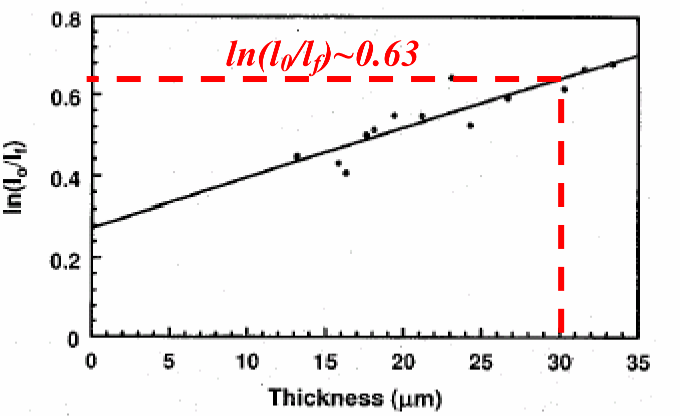


Fig.2-9 Absorption versus thickness of the AZ-4620 (King et al., 1996)

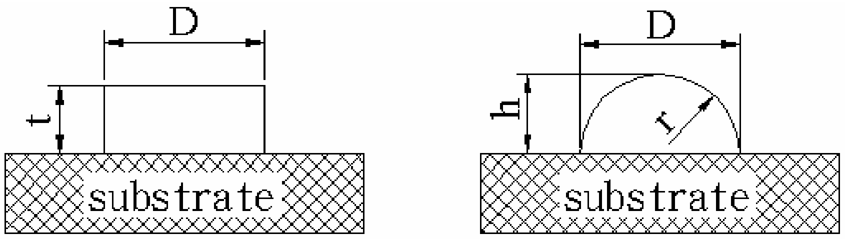


Fig.2-10 The parameters of the fabricated SIL structure

D: the diameter of the patterned photoresist

t: the thickness of the photoresist before reflow process

h: the height of the lens after reflow process

r: the radius of microlens curvature of the lens after reflow process

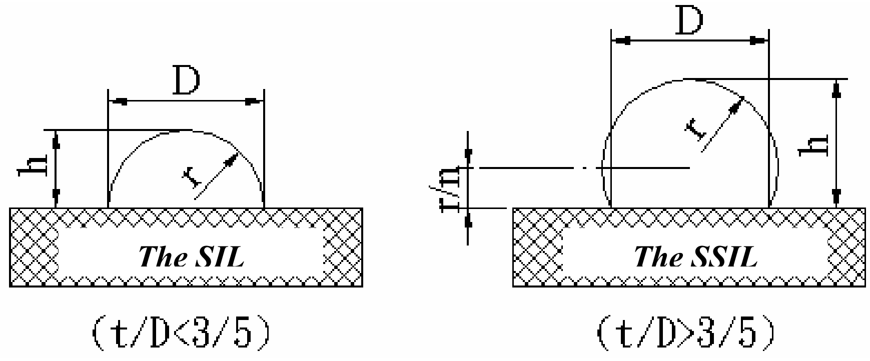
For the SIL structure, there are several issues that should be taken into consideration:

1. The beam intensity after passing through the photoresist (I_f) is determined by the intensity of the incident light (I_0). Because the absorption of the SIL material (AZ-4620) is proportional to its thickness, the total thickness of the overall SIL is designed about 30 μm to make sure the optical transmission through the SIL higher than 53% efficiency after the calculation according to Fig.2-9. So the equation (5) can be written as following:

$$h \le 30\mu m \qquad (5)$$

2. In 2001, Lin et al. presented an innovative process to fabricate microlens array. The microlens fabrication result shows that the reflowed shape can be controlled by the diameter (D) and thickness (t) of the photoreist cylinder. According to the experimental result, the critical aspect ratio (t /D) to become a super-hemisphere is 3/5.

Namely, when the aspect ratio of the patterned photoresist is larger than 3/5, the reflowed shape will be a SSIL structure. Oppositely, if the aspect ratio of the patterned photoresist is less than 3/5, the reflowed shape will become a SIL structure, as shown in Fig.2-11.



(a) (b)

Fig.2-11 The aspect ratio of the patterned photoresist is (a) Small than 3/5 for the SIL structure (b) Large than 3/5 for the SSIL structure

3. Here, it assumes that the photoresist volume does not change during the fabrication process. Before melting, the photoresist volume is calculated from the volume of the cylinder:

$$V_{cyl} = \pi\left(\frac{D}{2}\right)^2 \times t \tag{6}$$

The volume of the spherical photoresist lens after melting, as shown in Fig.2-12, the volume can be calculated as following:

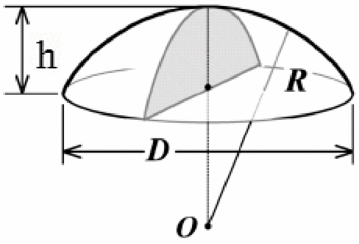


Fig.2-12 The profile of photoresist pattern after thermal reflowing process

$$V_{lens} = \pi\int_{r-h}^{r}(r^2 - y^2)dy = \pi h^2\frac{(3r-h)}{3} \tag{7}$$

4. The r can be calculated from the volume of the photoresist droplet. Here, by basic geometrical considerations, the radius of microlens curvature of the lens can be calculated as following:

$$r = \left(h^2 + \frac{D^2}{4}\right)/2h \tag{8}$$

By using equation (6)-(8), the relation between the thickness of the photoresist cylinder and the height of the microlens after reflowing process is calculated as equation (9):

$$t = \frac{h}{6}\left(3 + 4\frac{h^2}{D^2}\right) \tag{9}$$

5. Finally, the focal length f of the resulting microlens is determined by the radius of the microlens curvature r as following equation:

$$f = \frac{r}{n-1} \tag{10}$$

"n" is the refractive index of the microlens material. From above description, the design parameters of SIL are listed in Tab.2-2.

Tab.2-2 The design parameters of SIL

		t (μm)	***D (μm)***	***t / D***	***h (μm)***	***r (μm)***	***T.E. (%)***
For SIL (t /D<3/5)	*Case1*	20	60	1/3	30.00	30.00	53.3
	Case2	20	70	2/7	31.50	35.19	50.7

(The T.E. means the transmission efficiency.)