Chapter 1 Introduction

1-1 Motivation

As the progress of information technology, the importance and demand of data storage device is increasing similarly. With the rapid growth of data, the high-capacity optical storage systems are the tendency of development. So the disk develops form CD to DVD to become a high-capacity one. For the optical storage systems, the optical pick-up head is one of the key components and has great influence on the performance of the optical storage systems.

The schematic of a conventional optical pick-up head is shown in Figure 1-1. The pick-up head is composed of a laser diode, a grating plate, a polarizing beam splitter, a collimator, a mirror, an objective and photodiodes. The working principle of the pick-up head is that the laser beam from the laser diode passes through the grating plates to produce two secondary beams to maintain the correct tracking of the spot. Then, the beam passes the polarizing beam splitter and is converted into a parallel beam by the collimator. Passing through the quarter wave plate, the beam becomes circularly polarized, and is focused onto the surface of the dick by the objective lens. The reflected beam becomes orthogonally linearly polarized with respect to the source beam after passing through the quarter wave plate and is reflected by the PBS into the detectors.

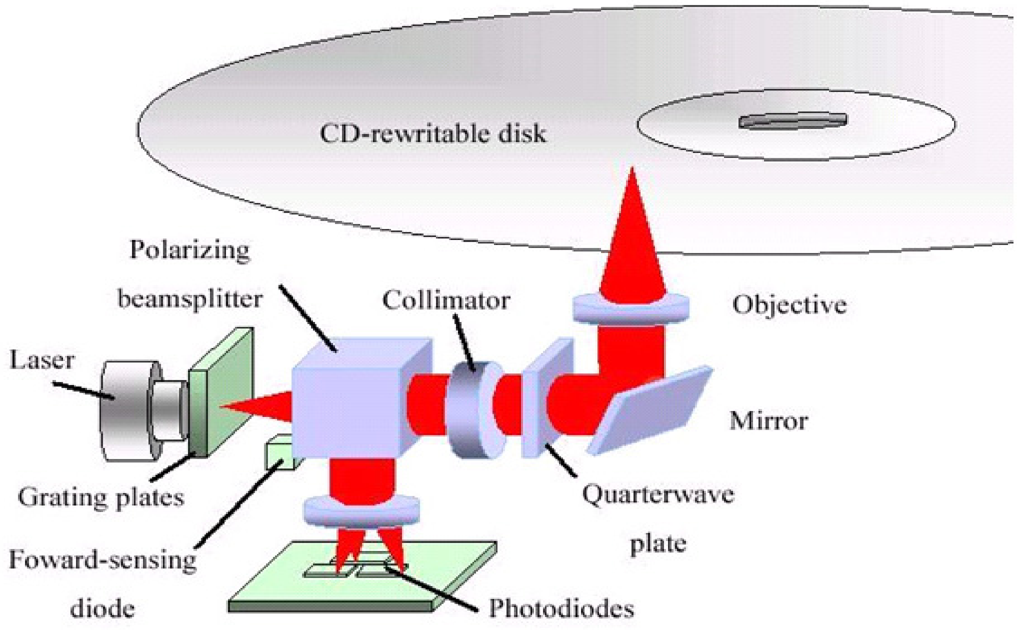


Figure 1-1: Conventional optical pick-up head

Compared with the conventional head, the miniaturized devices have the characteristics of shorter response time and less power consumption. In the trend of miniaturization, the Micro Electro Mechanical System (MEMS) is a good candidate since it is a technology employing semiconductor fabrication process to miniature electro-mechanical devices. In addition, MEMS devices can be combined with the signal processing circuits on the same chip to reduce the noise and signal distortion.

Figure 1-2 is a single-chip optical-disk pick-up head developed by M.C. Wu et al. [1]. The pickup head consists of a semiconductor laser source (hybrid integrated with the help of three-dimensional alignment plates), three micro-Fresnel lenses, a beam splitter, and two 45° reflective mirrors. All optical components are built monolithically on the silicon substrate.

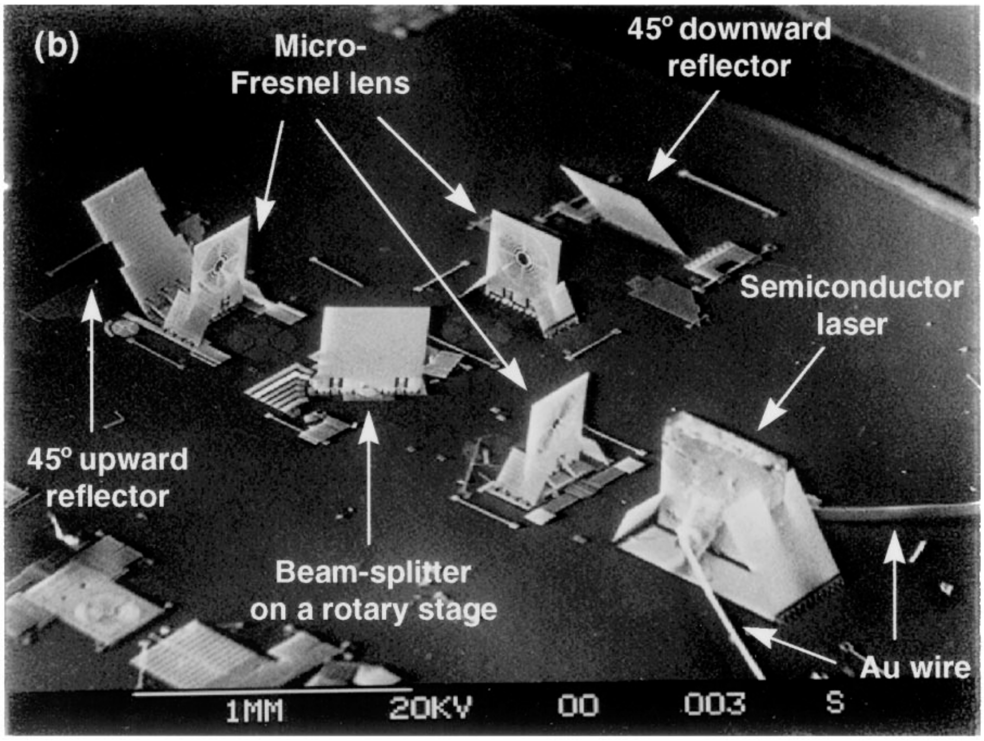


Figure 1-2: Scanning electron micrograph of the free-space integrated optical disk pickup head [1].

The MEMS based pick-up head of this research is composed of a laser diode, a coupling and beam shaping lens, a grating plate, a beam splitter, a focusing lens, focusing actuators, and photo detectors, as shown in Figure 1-3. This optical system is similarly to the conventional one in Figure 1-1. All the optical elements are prealigned during the design stage, which differ from the manual alignment in conventional pick-up head fabrication process.

In this thesis, the objective lens is used for focusing in the system. For a DVD pick-up head specification, the numerical aperture is designed as 0.65.

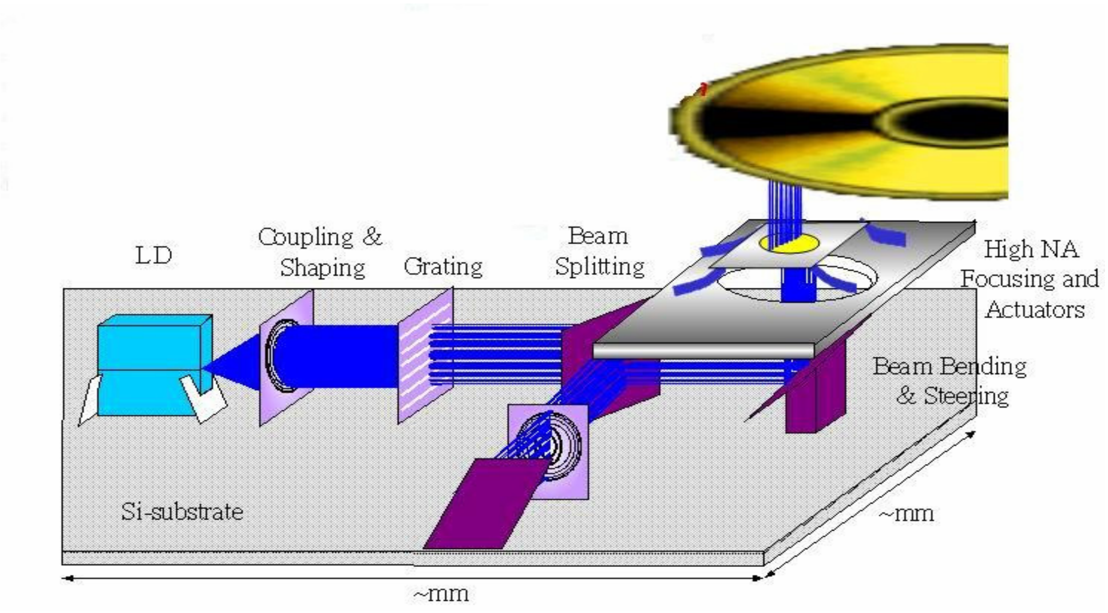


Figure 1-3: MEMS based optical pick-up head.

1-2 Micro Lens

There are three kinds of focusing microlenses. One is the refractive type, one is the reflective type, and another common focusing microoptical element is the diffractive type, as shown in Figure 1-4 [2]. The refractive and diffractive microlens will be discussed in this thesis.

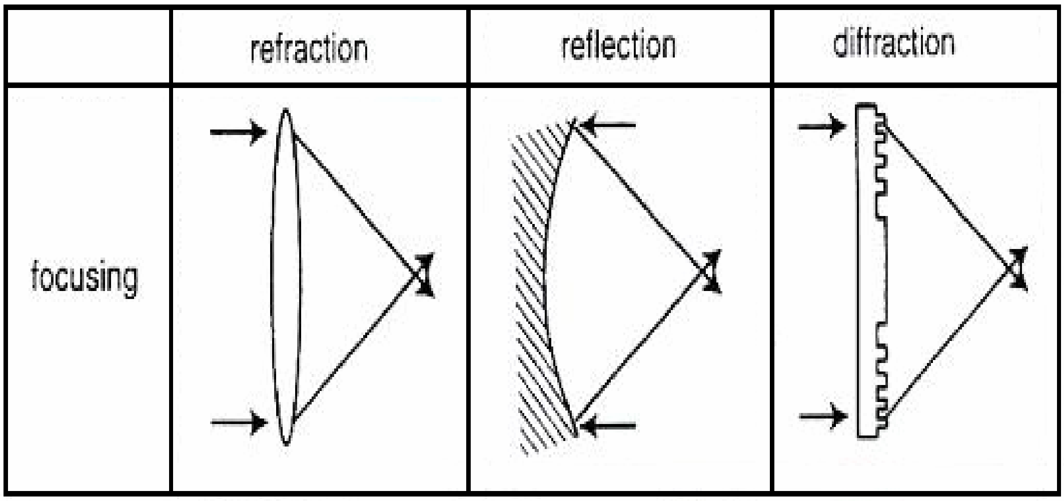


Figure 1-4: Different types of Microlenses [2]

1-2-1 Refractive Microlenses

A large variety of fabrication techniques have been applied to the fabrication of refractive optical elements (ROEs). Due to the analog nature of most fabrication techniques used for ROEs, their fabrication is often more difficult compared to the fabrication of diffractive optics. However, the fabrication of a planar refractive microlens array on semiconductor and dielectric substrates has been demonstrated using photoresist/polyimide reflow techniques.

The lens pattern can also be transferred to the substrate by reactive ion etching (RIE) [3] or ion milling [4]. Figure 1-5 shows the schematic drawing of the out-of-plane refractive spherical lens [5]. Here, surface-micromachining processes are employed in the planar refractive microlens fabrication to create low-cost, high-quality out-of-plane refractive microlenses. And the focal length of refractive microlens is independent of the optical wavelength (except a weak dependence due to the dispersion of the lens material).

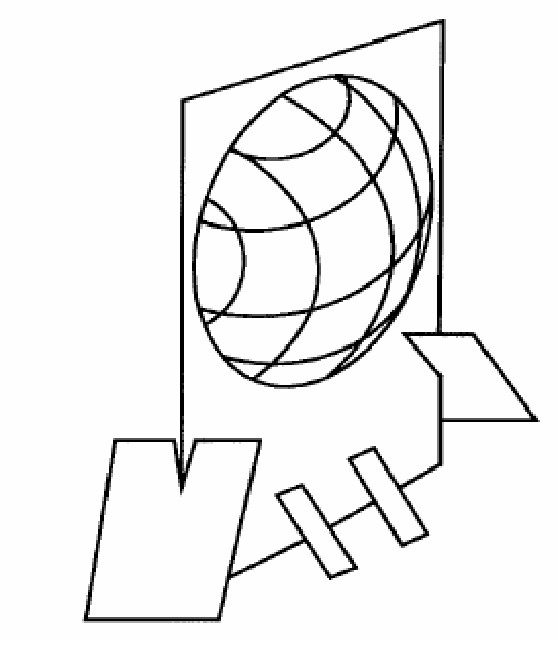


Figure 1-5: Schematic of an out-of-plane refractive microlens [2].

1-2-2 Diffractive Microlenses

Diffractive optics can be viewed as an approach to the fabrication of optical components optimized for the application of photolithography techniques. In refractive optical elements (ROEs), the light is manipulated by analog phase elements of considerable thickness (in relation to the optical wavelength). For optimized components, the solution is to lie in the periodic nature of the light wave $U(x)$. If a light wave is delayed by one wavelength (corresponding to a phase lag of $\varphi=2\pi$), no difference to the original wave can be found.

$$U(x, \varphi) = A_0(x)\, e^{i\varphi} = A_0(x)\, e^{i(\varphi+2\pi)} = U(x, \varphi+2\pi) \qquad (1\text{-}1)$$

Retardation occurs, for example, when the wave passes through a dielectric material. The insensitivity of the light wave to phase jumps of $N \cdot 2\pi$ (N=integer) allows one to reduce the thickness of an optical element without changing its effect on a monochromatic wave, as shown in Figure 1-6. In transmission the maximum thickness of the corresponding optical component can be reduced to $h_{max}=/(n-1)$, where n denotes the refractive index of the component material and λ is the wavelength of the incidence light.

Diffractive microlenses are very attractive for integration with free-space microoptical bench (FS-MOB) because:

1) the focal length can be precisely defined by photolithography system;

2) microlenses with a wide range of numerical apertures (F/0.3–F/5) can be defined;

3) microlenses with diameters as small as a few tens of micrometers can be made;

4) the thickness is on the order of an optical wavelength.

The thin construction is particularly suitable for the surface micromachining process because the thicknesses of the structural layers are only on the order of 1 μm.

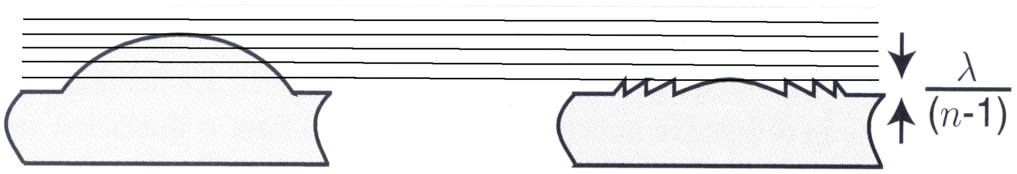


Figure 1-6: Blazing of a lens results in a reduced thickness [2].

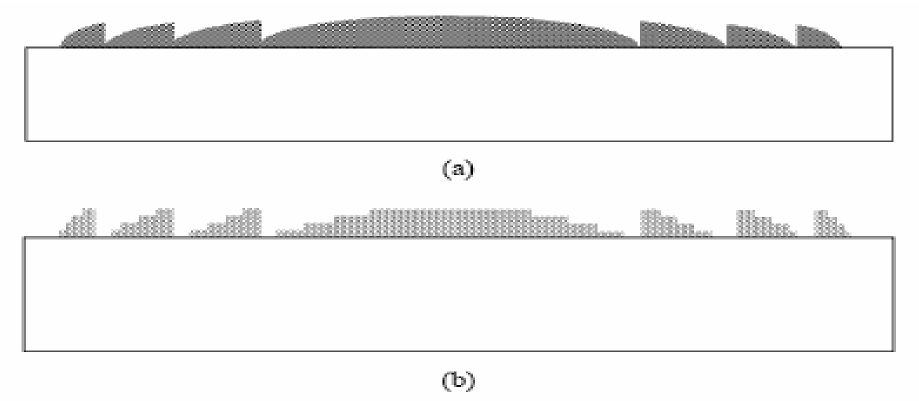


Figure 1-7: Schematic of (a) a continuous relief Fresnel zone plate,
(b) a multiple-step binary microlens.

There are two kinds of diffractive microlenses, one is the continuous kinoform lens, and another is the approximation of the kinoform lens. The continuous kinoform relief lens can be made by direct laser writing in photoresist or patterned by gray scale mask shown in Figure 1-7(a) [6]. The approximate kinoform lens can be made by multiple-step process of binary-optical design. The advantage of the multiple-step binary microlens is easy to fabricate. Figure 1-7 (b) is the schematic diagrams of a multiple-step binary microlens.

The binary Fresnel zone plate has alternating transmission and blocking zones. Though it is very easy to fabricate, however, its efficiency (diffraction efficiency into the first-order beam) is limited to 10%. The efficiency of a binary microlens with $M = 2^m$ step levels is

$$\eta = \left[\frac{sin(\pi/M)}{\pi/M} \right]^2 \tag{1-2}$$

The efficiency increases with the number of step levels at the expense of more complicated fabrication processes. For example, η= 41% for M=2, η= 81% for M=4, and η= 99% for M=16. Fabrication of binary microlenses on various substrates has already been demonstrated. Figure 1-8 [6] shows the SEM micrograph of a binary micro-Fresnel lens which is made by one binary mask step. And the laser-beam-direct-write Fresnel microlens with a radius of 106μm, numerical aperture of 0.21 is shown in Figure 1-9 [7].

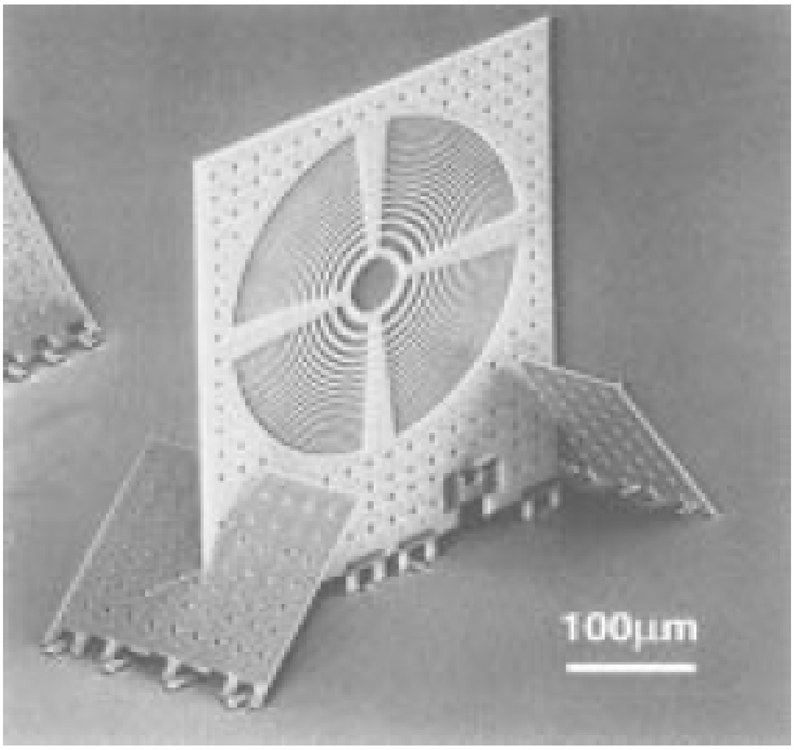


Figure 1-8: SEM of an out-of-plane binary Fresnel microlens

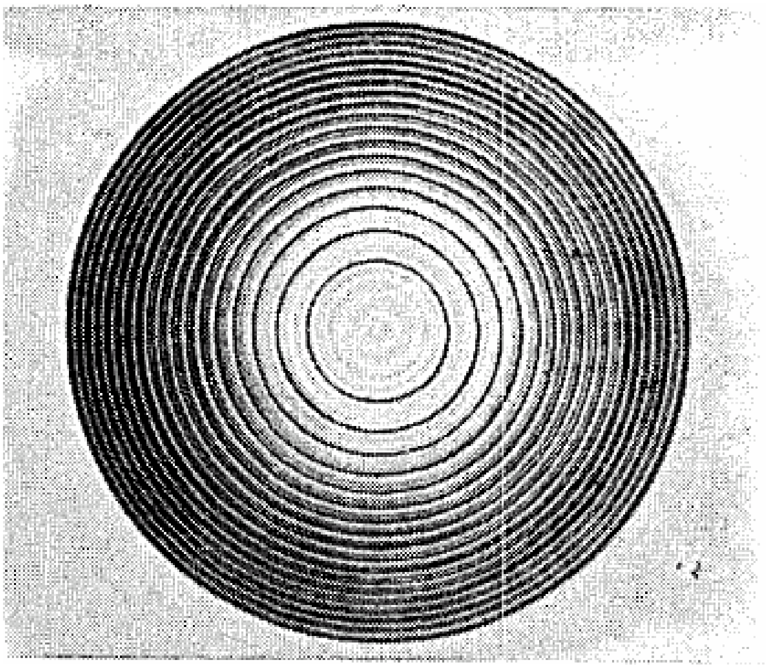


Figure 1-9: Laser-beam-direct-writing microlens, where the lens radius is 106μm with a N.A. of 0.21 [7].

1-3 Microlens Fabrication

In this section, the fabrication processes of the microlens are discussed.

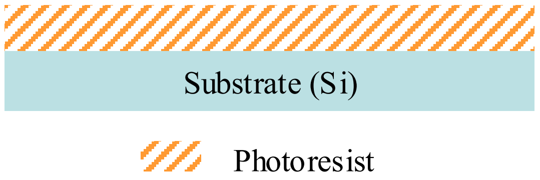
1-3-1 Reflow Method

The reflow prosess is used to fabricate microlens by melting the photoresist as shown in Figure 1-10. This process can only fabricate the refractive type microlens.

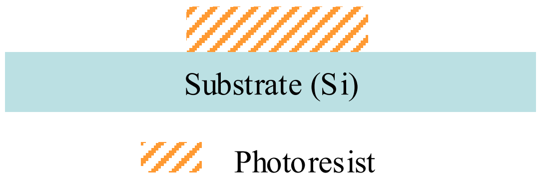
The structure is heated to temperatures above the glass temperature of the photoresist. Due to the surface tension, the shape of the photoresist changes to minimize the surface energy. The focal length f of the microlens is determined by the radius of curvature r_C of the spherical profile:

$$f = \frac{r_C}{n-1}, \tag{1-3}$$

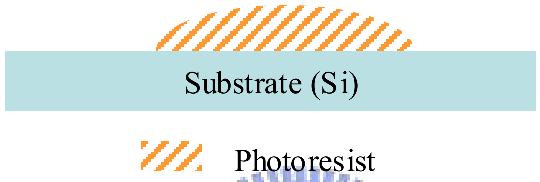
where n is the index of refraction. Although the reflow process is easy to fabricate, the focal length is hard to control.



1. Coat the photoresist on silicon substrate.



2. Define the pattern of the lens.

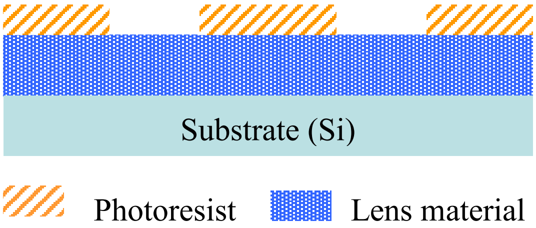


3. Reflow: photoresist melting.

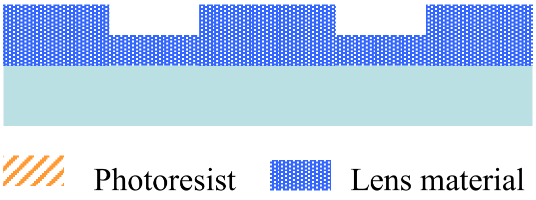
Figure 1-10: Reflow process for refractive microlens.

1-3-2 Binary Method

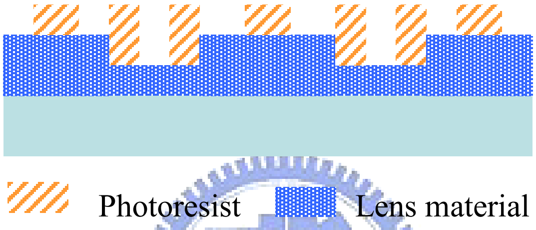
The binary method is used to generate multilevel profiles. For a n level steps it takes $\log_2 n$ masks. The four level fabrication steps are shown in Figure 1-11. In a good approximation of the microlens, the levels should be as many as possible. The precision of the alignment is the key point of this method when the number of levels increases. So the complexity and the alignment are the shortcomings of the binary process.



1. Deposit the lens material, coat and pattern the photoresist.



2. Etch the lens material by RIE.



3. Coat and pattern the photoresist again.

4. Etch the lens material by RIE again.

Figure 1-11: Fabrication process of the binary method.

1-3-3 Gray Scale Technology

To solve the issues in the reflow and binary process, the gray-scale technology has been proposed. This technology uses a sub-micrometer resolution and locally modulates the intensity of ultraviolet light on the mask. Different intensity on the mask will change the photoresist depths respectively. The advantage of this method is that only one mask for a three-dimensional pattern is required and the fabrication process is simpler than the binary mask. Several gray-scale technologies with different mask fabrication process are described following.

First is the halftone mask schematically shown in Figure 1-12 [8], and a three levels profile shown in Figure 1-13 [9]. Different square patterns in the halftone mask cause different gray levels. If the resolution of the photolithography system is smaller than the pattern, the pattern on the mask will be completely transferred to the photoresist. The basic concept of this method is that the resolution of the photolithography system must be larger than the minimum size of the pattern on the mask. Therefore, the shape of the pattern can not be recognized by photolithography system. For a reliable process, the photolithography stepper should be used. A three gray levels pattern in AZ4620 shows in Figure 1-14[9].

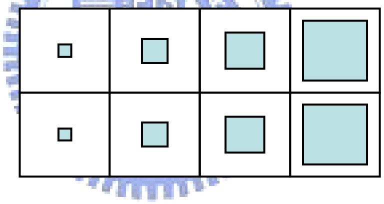


Figure 1-12: The schematic of the halftone mask.

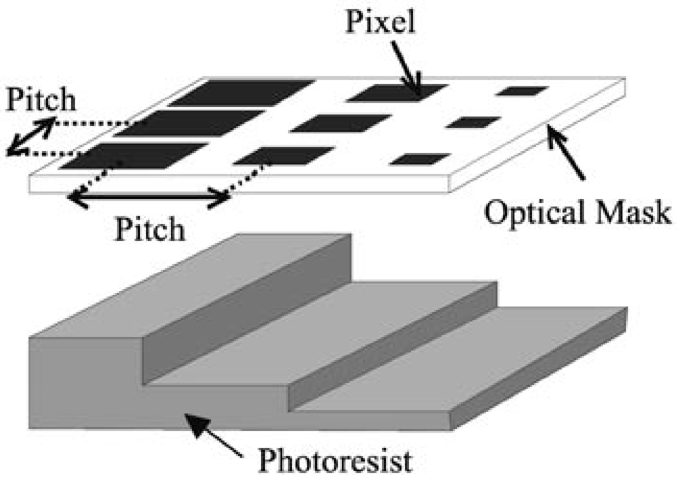


Figure 1-13: Example of a three-level gray-scale mask pattern and the resulting photoresist structure [9].

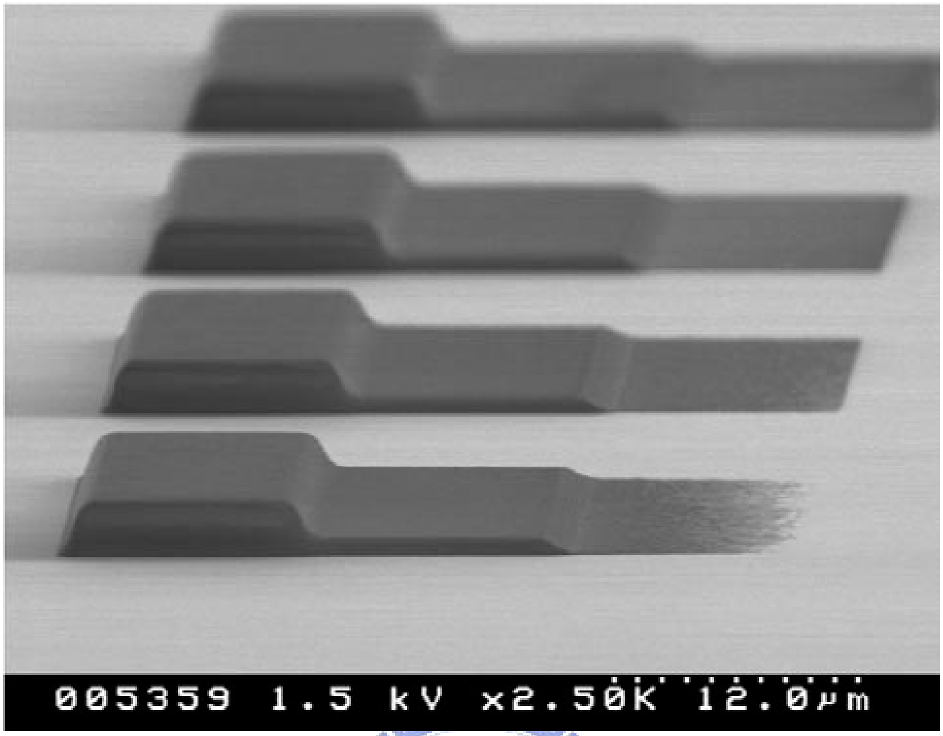
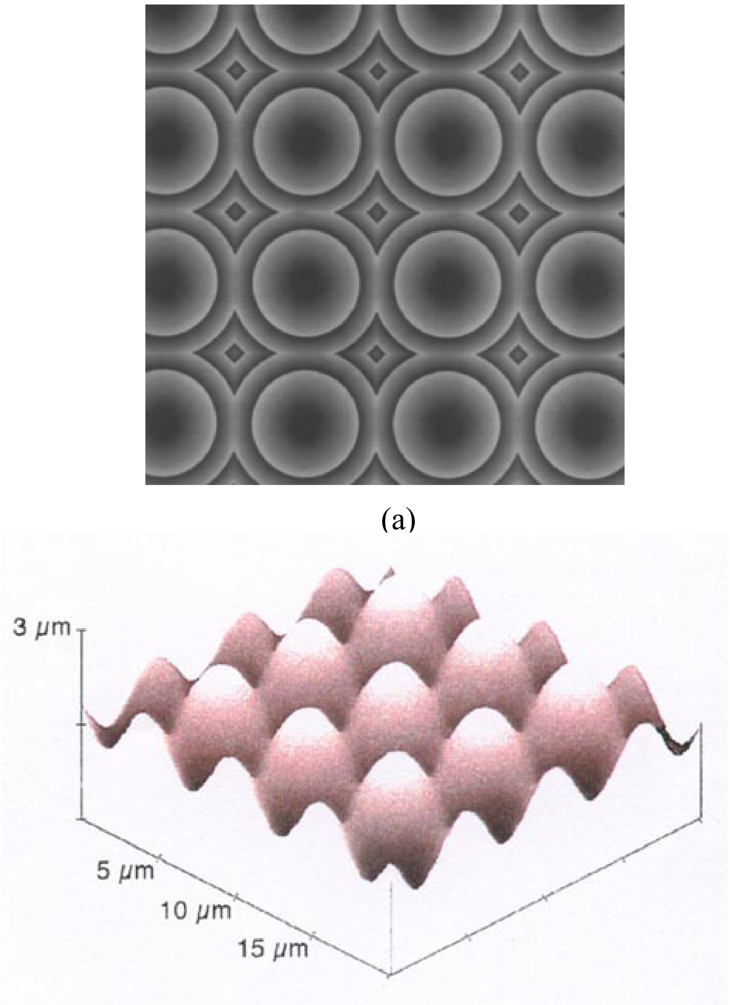


Figure 1-14: Three gray levels patterned in AZ 4620 photoresist resulting from a similar mask pattern in Figure 1-13 [9].

Second is the High Energy Beam Sensitive (HEBS) mask [10]. The principle of the mask is to project the electron beam to the high energy beam sensitive glass, and control the energy of the electron beam to form the gray-scale levels. The base glass composition consists of silica, metal oxides, halides and photo inhibitors [11]. Typically TiO_2, Nb_2O_5 or Y_2O_3 are used as photo inhibitors. The photo inhibitors are used to dope the silver ion containing complex crystals, silver-alkali-halide. These $(AgX)_m$ $(MX)_n$ complex crystals are the beam sensitive material that will be changed by electron beam, and the HEBS glass will have different gray-levels with different illuminated energy. Because the HEBS mask is made by electron beam, the resolution of it will be much higher than others. Figure 1-15 shows a gray-scale HEBS pattern on the mask and polymer.



(a)

(b)

Figure 1-15: Diffractive microlens array (a) on HEBS mask (b) on polymer [11].

Finally is the Focused Ion Beam (FIB) mask proposed in this thesis, which is described in the following. FIB systems have been produced commercially for approximately ten years, primarily for large semiconductor manufacturers. The applications of FIB system are mainly in the area of microelectronics fabrication, such as direct maskless, resistless patterned implantation, ion milling, ion induced surface reactions for etching or deposition, lithography, microanalysis; and microscopy [12]. FIB etching of resist/Ni multilayer films has been demonstrated [13]. Figure 1-16 shows a fused silica microtube, and Figure 1-17 shows the six facet cutting tool for ultraprecision machining by FIB system [14].

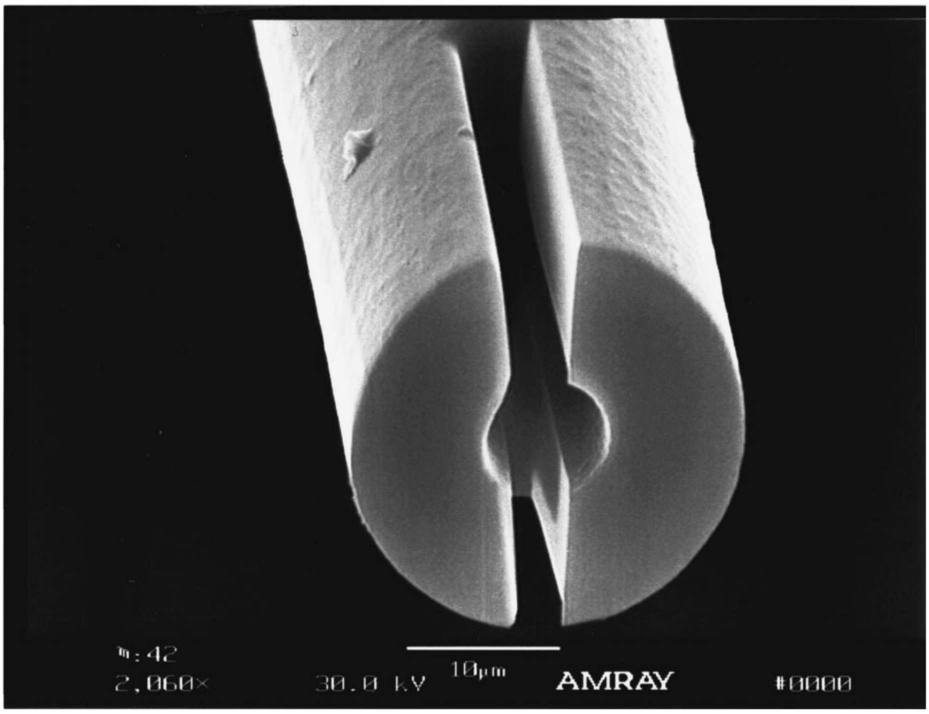


Figure 1-16: Nominal 30 μm diameter fused silica microtube by FIB milling [14].

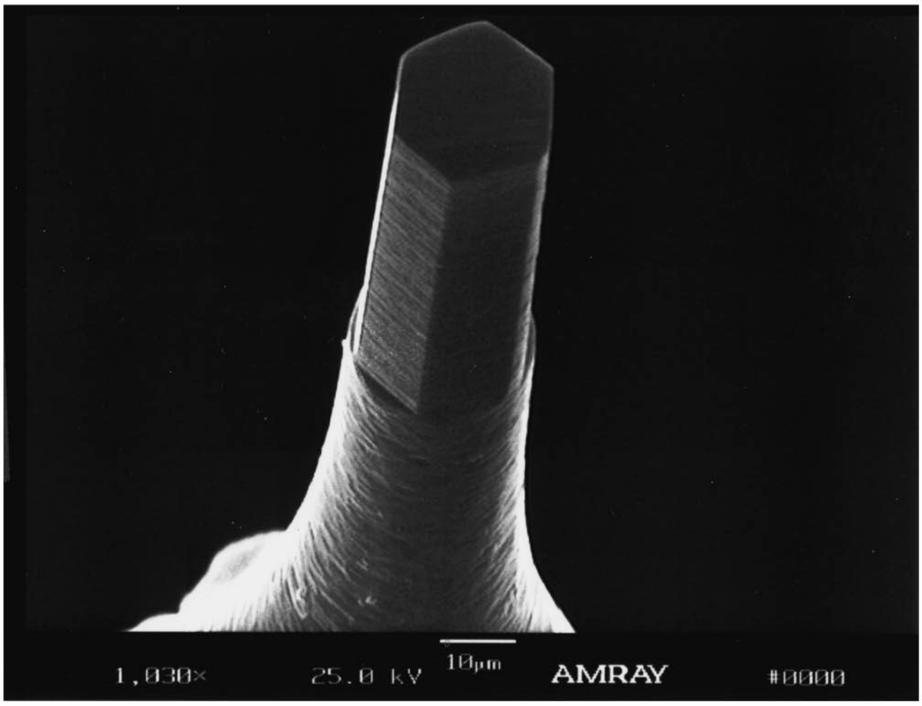


Figure 1-17: SEM of a six facet cutting tool for ultraprecision machining [14].

FIB systems use a finely focused beam of gallium ions that can be operated at low beam currents for imaging or high beam currents for site specific sputtering or milling. Basically, FIB is a system that ionizes the gallium and utilizes electrical field to speed up the ions, and then focus the high energy Ga^+ to desired spots by electrostatic field. The FIB system uses a Ga^+ ion beam to raster over the surface of a sample in a similar way as the electron beam in a scanning electron microscope. A FIB system is composed with several devices, such as ion column, vacuum system, control system, operation interface, and auxiliary gas supply (various for different applications). The specifications and features of the FIB system used in this thesis are listed below [16].

- 7 FEI (986, 800 and 200) systems
- 5 nm resolution at 5 pA
- Deep sub-micron milling, copper line open
- Metal deposition for tungsten or platinum, and silicon oxide deposition
- Halogen gas assisted etching
- Navigation with high accuracy laser interferometer stage

The FIB system are used to mill the silicon nitride on a silicon wafer to generate the gray-scale level as the mask. Due to the high resolution, 5nm at 5pA and deep sub-micro milling, the gray-scale mask can be done well. The detail mask design and fabrication process will be proposed in Chapter 2 and 3. A typical FIB schematic is shown in Figure 1-18.

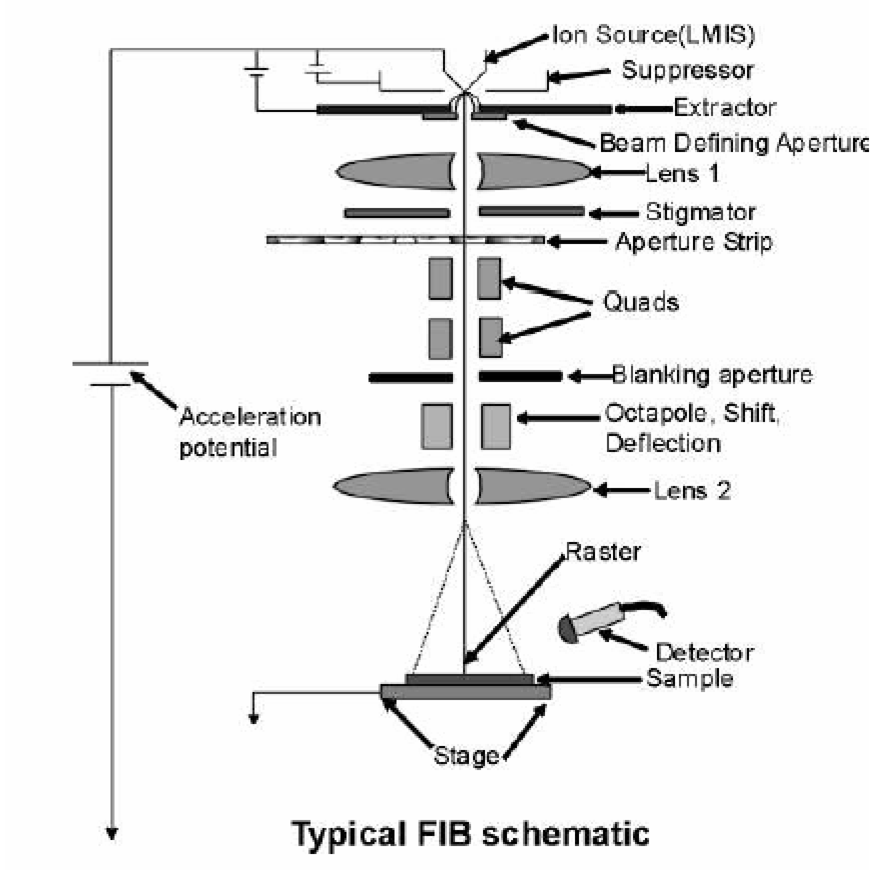


Figure 1-18: Typical FIB schematic [15].

1-4 Thesis Overview

The objectives of this thesis are:

(a) Fabricate the microlens by the gray-scale technology.

(b) Use FIB to write patterns in the silicon nitride films to form the mask.

The fundamental principles of the microlens are described in detail in Chapter 2. The fabrication process, experiment results is described in Chapter 3. The measurement results and issues are described in Chapter 4. Conclusion and future work are discussed in Chapter 5.