Polymer based microlens by thermal reflow technique

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Polymer Based Microlens By Thermal Reflow Technique

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Abstract

Application of photonics is lagging behind IC because of two main drawbacks: size and manufacturing (particularly assembly) difficulties. MEMS technology allows to shrink the size of bulky optical components and to process optical components in batch with precise location, opening new opportunities for application. However, the traditional materials used for MEMS fabrication (Si and derived compounds) can not provide high quality optical components. I think that much better results could be obtained by using polymers which have already proved successful in terms of optical property and ease of fabrication. One such fabrication technique to make microlens using polymer is thermal reflow. The technique was first described by Popovic et al in 1988. It uses standard photolithographic process to create photoresist cylinders of desired dimension (based on the required focal length). These cylinders are then reflowed (melted) at an optimum temperature and time; such that the surface tension then pulls these cylinders into a hemispherical shape. The simplicity of the process and potential for large scale replication has attracted a lot of attention by various sectors of industry and research. However, a detailed study to precisely relate optical parameters (focal length, spherical aberration) with simple process parameters (dimension, temperature, reflow media, substrate, etc) is vital to get the desired profile of microlenses. I, thus studied various parameters governing the profile of microlenses for thermal reflow process. I also developed a mathematical model based on Young-Laplace equation to predict the profile formation, which aided to develop better insight about the process. In addition, I also used process modification to obtain other important categories of microoptical components,

such as micro mirrors (both converging and diverging; diverging microlens; micromould; cylindrical microlens). I have also devised a micro fabrication process on a silicon wafer to produce the lenses (using polymer reflow) with variable diameter and identical focal length. Etching of the silicon wafer has helped us producing a sheath to insert the optical fiber and mount the lenses on the optical fiber for endoscopic applications.

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List of Symbols

Symbol	Description
R_c	Radius of curvature of microlens
R_{cN}	Normalized radius of curvature of the microlens
$f, f_{opt}, f_{ti}, f_{lm}$	Focal length
n	Refractive index of microlens material (photoresist)
D_{cyl}	Diameter of microcylinder
D_{lens}	Diameter of microlens
D	When $D_{cyl} = D_{lens} = D$
r	Radius of the microlens ($r = D/2$)
r_N	Normalized base radius
h	Height of the microlens/ microlens sag
t	Thickness of the photoresist cylinder
NA	Numerical aperture
π	Pi
γ	Surface tension of photoresist
g	Acceleration due to gravity
ρ	Density of photoresist
ρ_a	Density of air
θ	Contact Angle
V_{cyl}	Volume of microcylinder
V_{lens}	Volume of microlens
$p(x)$	Microlens profile
x	Normalised radial position
a_0, a_2, a_4	Polynomial coefficients
E_{cyl}	Surface energy of microcylinder
E_{lens}	Surface energy of microlens
G_{cyl}	Gravitational energy of microcylinder
G_{lens}	Gravitational energy of microlens

Chapter 1: Introduction

1.1 Introduction

Miniaturization of optical components and their integration with the existing MEMS (micro-electro-mechanical system) devices has emerged as a new discipline in the last 2 decades, and is progressively making its way towards commercialization in a number of fields. It offers significant potential for achieving the micro-opto-electro-mechanical system (MOEMS) functionality necessary to meet the performance needs of a number of emerging applications, such as, imaging, sensing, communications, and control. Realization of these applications requires the development of a set of microoptical components and processes suitable for integration with MEMS devices and support microelectronics. The resulting MEMS “optical toolbox” will provide the standard building blocks with which photonic functions can be achieved within MOEMS. However, the traditional materials used for MEMS fabrication (Si and derived compounds) can not provide high quality optical components. I think that much better results can be obtained by using polymers, which have shown promising results for the fabrication of converging lenses, creating a whole new field of polymer based miniaturised optical systems as polymer-opto-electro-mechanical systems or POEMS.

I thus want to study the miniaturization of the traditional optical elements (mainly converging or plano-convex microlenses) using a batch process based on

polymers and lithography. As an application, I want to build a system aligned at fabrication that can be used in endoscopic application.

1.2 Micromachining Technologies

Micromachining or MEMS refers to the fabrication of devices with at least one of their dimensions in the micrometer range. Most of the MEMS devices and systems involve some form of lithography-based-microfabrication, which is borrowed from existing silicon based microelectronics industry [1, 2]. In the beginning, the emphasis was more on using silicon as a structural material with UV lithography as a base process. However, as the application of micromachining became wider, emphasis shifted to a wide-angled view of micromanufacturing methods, such as, surface micromachining; micromoulding; electroplating; and LIGA processes. The innovation in micromanufacturing methods thus in turn lead to more innovative applications. Consequently creating a never-ending cycle of process and application.

The idea of miniaturization, with its inherent advantages, was first introduced by Professor Richard Feynman in his famous presentation “*There's Plenty of Room at the Bottom*”, at the California Institute of Technology in the year 1959. He tried to explain some of the possibilities of miniaturization, including his famous question “*Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?*” [3]. Then onwards there have been many new inventions on the front of technologies, processes and applications.

1.2.1 Micromachining Technologies for Microoptical Applications

Microoptical components are basic building block of a MOEM system. Broadly, these components can be divided between waveguide optics and free space optics. In case of waveguide optics, light is confined by a lateral variation of refractive index. The propagation medium is generally homogeneous in the longitudinal direction. Lateral dimension may vary from few micrometers to one millimeter depending on single mode or multimode behavior of the waveguide (Figure 1.1).

Figure 1.1 SEM picture of a 4.5-μm-high and 5-μm-wide single-mode SU-8 waveguide [4]

In contrast, lateral confinement of light wave is not used in free space optics. Instead, light waves are guided by a series of discrete micro optical elements, such as, microlenses, beam splitters, micromirrors, microprisms, etc. Propagation medium is homogeneous in the lateral direction (Figure 1.2).

Figure 1.2 Free space optics [5]

1.2.2 Polymer as a Material for Micromachining

Polymer materials provide certain important advantages for MEMS and MOEMS applications including non brittle behavior compared with silicon and other semiconductor materials; potentially lower cost of preparation and processing [6]; low temperature processing and enhanced biocompatibility [7]; new methods of processing including molding, embossing, imprinting and thermal reflow [8]. However, one of the limitation which is associated with polymer is their instability and degradation in long run. This is a non issue, atleast for applications where polymer based micro components are used in conditioned environment or are used as disposable components. Moreover, there are also new developments in polymer technology in which degradation processes find helpful applications.

Figure 1.3 Breakdown of micromachined materials for MEMS fabrication (366 MEMS companies) [10]

Nevertheless, these components have shown good thermal and chemical stability as can be seen from the variety of polymer materials that have been used for

MEMS, including photodefinable polyimide (e.g., Kapton), non-photodefinable polyimide, photoresist, SU-8 resist, silicone elastomer (e.g., polydimethylsiloxane, or PDMS), liquid crystal polymer, biodegradable polymer, Parylene, Teflon and wax [9]. Today, polymer represents about 12% of micromachined materials for MEMS manufacturing in more than 366 MEMS companies in the world (Figure 1.3).

1.2.3 Introduction to Thermal Reflow

It can be understood that polymer processing offers new possibilities for making structures which were not possible or very complicated with conventional materials and processes. One such technique which can be used to reshape a predefined structure is thermal reflow of polymers (photoresist). The process is simple and provides a way to generate spherical/aspherical profiles, which can be modified to obtain various microoptical components (Figure 1.4).

Figure 1.4 Thermal reflow technique

Due to the flexibility of lithographic processing, it is possible not only to fabricate individual microoptical elements but also to integrate whole microoptical systems. Arrays consisting of a large number of densely packed microlenses can be

fabricated by this method at no additional cost as compared to a single microlens. The numerous advantages of fabrication of the microoptical components by this method thus warrant an understanding of the process and possible investigation to obtain optimal processing conditions for fabrication.

1.3 Objective of the project

I want to study the thermal reflow technique, which is based on polymers and lithography and utilise it to obtain a range of microlenses (and other derived microoptical components), and show that it is possible to fabricate a complete aligned system. Our main concern will be to control the profile through various means.

To show the viability of the technology, I propose to fabricate a set of microlenses which can be assembled on top of an optical fiber. The challenge will be to develop compatible process and tools to control the profile, which will govern the quality of these microlenses.

Specifically my work will include following points:

1. Study of the various design parameters for the thermal reflow technique and determine optimum reflow conditions
2. Modeling of microlens profile made by thermal reflow technique
3. To investigate the possible use of polymers for the fabrication of other micro optical components (e.g. micromirrors, diverging microlenses, micromoulds) using thermal reflow as the basic technique

4. Investigations of optical properties of polymers
5. To design and optimize various characterization tools for a range of microlenses measurements
6. To design and fabricate a set of polymer microlens on top of an optical fiber using the thermal reflow process

1.4 Organization of the report

Chapter 2 is mainly divided into two parts. In the first part, various refractive microlens fabrication techniques are reviewed with emphasis on thermal reflow technique, as this technique was used to produce microlenses. This review helps the reader to put the technique of thermal reflow in perspective with the other important techniques for producing refractive microlenses. In the second part, an overview of microlens applications is being discussed, which shows the scope of these micro structures. An investigation on the prevalent techniques to mount a microlens on an optical fiber, as a part of microlens application, is also done. This study does the ground work for chapter 6, where I show detailed design, fabrication and characterization of microlens (made by thermal reflow) on optical fiber tip, for an application in endoscopy.

Chapter 3 introduces the modeling problem for thermal reflow and explores the various modeling techniques found in literature to predict the profiles of microlens produced by thermal reflow of photoresist cylinders. It also discusses the approach to model the microlens profile based on Young-Laplace equation.

Chapter 4 discusses the experimental details of thermally reflowed microlenses. The aim of the experiments is to achieve the optimum conditions to get the desired profile and to study the effect of various reflow parameters on the profile formation, with an eye on to control the profile using these parameters. Thermal reflow technique is mostly used to fabricate convex microlenses. However, with certain modification other optical components like diverging microlens, micromirror, etc can be obtained. I will present these modifications and the detailed fabrication techniques to obtain the above mentioned microoptical components

Chapter 5 explores various characterization techniques to study and measure two important categories of microlens parameter: viz. Geometrical properties (microlens profile; radius of curvature; and contact angle); and Optical properties (focal length; refractive index; and absorption properties).

Chapter 6 discusses the fabrication details of microlens formed on an optical fiber. I have devised a microfabrication process on a silicon wafer to produce microlenses with variable diameter and identical focal length, while etching the silicon wafer has helped in producing a sheath to insert the optical fiber and mount the lenses on the optical fiber

Chapter 7 concludes the work and discusses the future implications.

Chapter 2: Literature Review

This chapter 2 is mainly divided into two parts. In the first part, various refractive microlens fabrication techniques are reviewed with an emphasis on thermal reflow technique as this technique was used to produce microlenses. This review helps the reader to put the technique of thermal reflow in perspective with other important techniques for producing refractive microlenses.

In the second part, an overview of microlens application is being discussed, which shows the scope of these micro structures. An investigation on the prevalent techniques to mount a microlens on an optical fiber, as a part of microlens application, is also done. This study does the ground work for chapter 6, where I show detailed design, fabrication and characterization of microlens (made by thermal reflow) on optical fiber tip, for an application in endoscopy.

2.1 Introduction to Microlens

2.1.1 Background

Making lenses has been an area of interest since long. By the mid of 17th Century, people like Robert Hooke had already produced their own lenses by melting Venetian glass rods ends [11]. However it was not until the advent of fiber optics that brought with itself the trend of miniaturization. The important fabrication techniques, nevertheless, were still based on classical way of grinding and polishing. More recently, the development of IC fabrication techniques and its adaptation in the field of optics, has lead to the shrinkage of optical components.

The use of these techniques helped to generate optical components in the micrometer range. These fabrication techniques give a large flexibility in the design of microoptical components, and support a possible integration for optoelectronic devices.

2.1.2 Classification of Microlens

Microlens is one of the most important elements in the field of microoptics. Based on the refraction or diffraction phenomena at the optical interface, it can be classified as refractive microlens or diffractive microlens. Classification of microlens is shown in Figure 2.1. In refractive microlens, the light is manipulated by analog phase element of considerable thickness in relation with the optical wavelength. In diffractive microlens light is diffracted at the periodic microstructure of the element.

Figure 2.1 Classification of microlenses

Fabrication techniques for diffractive microlens have a good control over process parameters, and produce microlenses with good reproducibility and uniformity,

which is a difficult task in refractive microlens production. However, from a system point of view, refractive microlens offers several advantages such as: reduced wavelength sensitivity as compared to diffractive microlens (a necessity for broadband applications), possibility of realizing large numerical aperture, and high light efficiency.

Graded Index microlenses are a different type of refractive microlens. Rather than being refracted at the surface profile, in GRIN lenses, the light is deflected by a refractive index gradient within the surface. In general, the aberration characteristics of GRIN microlenses are superior to conventional refractive microlenses. However, the major drawback with these kinds of lenses lies in the difficulty in fabrication. The precise formation of pre-specified graded index profile requires a very complex technology [12]. Based on the terminology of GRIN lenses, I defined refractive microlens with a varying surface profile as Graded Thickness Microlenses. The idea seems appropriate since grading of thickness is the most prominent feature here, and the reason for the functionality of these lenses. It also helps to draw an analogy with GRIN lenses.

Both the diffractive microlenses and the graded index microlens have particular benefits, and can be used for certain type of application. However, as a best compromise between simple manufacturing techniques, high speed, low cost and good quality of microlenses produced, gives graded thickness microlenses an edge over other kind of microlens.

2.2 Refractive (Graded Thickness) Microlens Fabrication

Techniques

In this section I review a few contemporary methods for the production of microlenses [13]. These fabrication techniques found in literature can be grouped in three broad categories, based on the underlying phenomena responsible for the microlens fabrication. Figure 2.2 shows various available techniques for the fabrication of graded thickness microlens.

Figure 2.2 Summary of techniques to fabricate refractive (graded thickness) microlenses

3-D patterning/ direct writing techniques use different approaches to physically remove certain part of material to generate surface profiles. For instance, grey

scale lithography uses a mask with a continuous intensity distribution to create surface profile by differential exposure to different areas of photoresist.

Fabrication technique based on volume expansion basically initiates a local volume change by some kind of exposure. This causes the localized swelling of the material, and hence formation of surface profile, which is governed by the minimization of surface energy.

Techniques based on surface energy minimization principle utilize the energy interactions between the material-substrate-environment to produce surface profile. These techniques do not involve the volume expansion, and hence are categorized under different section. However, the process is complicated because of dynamics of physiochemical mechanism involved and has to be optimized in most of the cases.

The brief discussion of the various techniques shown in Figure 2.2 is given below:

2.2.1 Grey-scale Mask (Greystone) Lithography

Grey-scale mask are being used to provide three-dimensional surface-relief refractive micro-lens with a single UV exposure. A very high resolution grey-scale mask can be written using a process based on a glass substrate which is sensitive to high energy beams or High-energy beam-sensitive (HEBS). During fabrication, a thin sol-gel film is first spin coated onto a substrate; the photosensitive sol-gel film is then exposed and patterned by a HEBS grey-scale

mask. Different optical density values on the mask will determine different UV intensities that the sol-gel film will be exposed. For negative-tone sol-gel material, after development the areas of highest exposure are preserved because of cross linking, and those with the lowest exposure will be dissolved in the developer.

Figure 2.3 Schematic diagram of micro-lens fabrication using HEBS grey-scale mask [14]

Figure 2.3 shows the steps to fabricate microlens using grey-scale masks. It requires a single-step fabrication of surface-relief structures without involving etching steps and does not limit the profile to spherical surface. For 3-D continuous-phase-level structures, the technique using sol-gel material and the HEBS grey-scale mask has a high potential for low-cost production of optical-quality silica micro-optical elements without tedious alignment and complicated etching processes.

2.2.2 MEMSNAS

The French and Japanese researchers of this fabrication technique coined the process as MEMSNAS: **M**icro-loading **E**ffect for **M**icro-machining of 3D

Structures with Nearly Arbitrary Shape. The process exploits the micro-loading effect which is usually an unwanted phenomenon that leads to different depths during the etching process. The etch depths depend greatly on the opening areas exposed to the etchant.

Figure 2.4 Fabrication sequence for MEMSNAS [15]

A mask consisting of an array of open circles with different diameters (Figure 2.4) was used to create different exposed area sizes. An array of uniformly distributed holes of different depths was etched. The first stage of smoothing process towards a continuous three-dimensional profile was achieved when under etching of the holes creates overlapping of the holes' edges. Further smoothing is accomplished through etching without the presence of the etching mask. The second stage of

etching is done under isotropic conditions. Both first and second etchings were performed by RIE using SF_6 .

2.2.3 Laser Ablation

One of the ways to produce microlens using direct writing technique was shown by Kris et al. [16]. Their technique was based on laser ablation. Here they used a simple circular aperture for the excimer beam and a high precision translation stage carrying the PMMA substrate, which was able to make circular movements (Figure 2.5).

Figure 2.5 A setup of laser ablation for producing microlens

The pulse energy and the pulse frequency (number of pulses per second) remained constant during the process. While the excimer laser was firing pulses, the translation stage made subsequent circular movements with different radii and speeds. The relationship between ablation parameters and eventual lens profile can be estimated. Due to the nature of the process, the fabrication of the

microstructure can take place in a very late stage of a heterogeneous assembly and makes it an attractive technique for fabricating micro-optical components on opto-electronic assemblies in comparison to other techniques.

2.2.4 Photosensitive Glass

There are a range of glass types which have been termed photosensitive. It was found that when these glasses are exposed to UV radiation followed by heating, their colour varies. This is due to the absorption of small metal colloids such as silver, copper or gold.

Figure 2. 6 Schematic representation of force developed by the densified phase produced by exposure and thermal treatment [17]

When these colloids reach a sufficient size they can act as nuclei for the growth of a crystalline microphase in the originally homogenous glass. If the fraction of this photo induced phase is high enough and the density of these regions is greater than the original homogenous glass, then a pattern is formed, as shown in Figure 2.6. Using an appropriate mask it is possible to produce lenses using this method. The exposed regions are denser than the non-exposed regions and as the glass is

heated above its softening temperature the non exposed glass is squeezed to form spherical lenses.

2.2.5 Optically Induced Volume Change

It has been found that when certain optical recording materials are exposed to light the resulting recording processes produce a volume change. This property has been used to produce microlenses in a number of different materials, including photopolymers and Dichromated Gelatin. The material is exposed to either UV, or visible light (for the case of dye sensitized photopolymers). The setup configuration is as shown in Figure 2.7.

Figure 2.7 Optical configurations to fabricate microlenses and micromirrors [20]

The resulting surface modulation is determined by the exposure profile. This method has been used by Reyna et al. [18], Lee et al. [19] using photopolymers and by Calixto et al. in Dichromated Gelatin [20]. The basic principle is similar to the one discussed above, but the range of material used is more and not limited to glass alone.

2.2.6 Proton Beam Ionization

Proton beam ionization method can be used to produce both concave and convex lens arrays in polymethyl methacrylate (PMMA) substrates. The PMMA substrate is irradiated by a proton beam through a circular aperture.

Figure 2.8 Fabrication of PMMA lens by proton beam ionization

It can either be developed to remove the irradiated PMMA or exposed to a styrene monomer vapour to form a convex lens. This method has been examined by Kufner et al. [21]. First the PMMA substrate is irradiated using proton beam using a metal mask with circular opening. The PMMA is exposed to an atmosphere of monomer vapor, so that monomer diffuses and swells the irradiated regions. The process can be speeded up by additional UV illumination. The whole process is being depicted in Figure 2.8.

2.2.7 UV Curable Resins and Ink-Jet Fabrication

Microlens arrays have been produced using UV curable resins and optical adhesives. The technique involves the controlled application of liquid drops of the UV curable material onto a substrate. The droplets are drawn into a spherical

shape by the action of surface tension. These droplets are then irradiated with UV to cure them and turn them into solid microlenses.

Figure 2.9 Schematic drawing of inkjet apparatus

The controlled application of the resin can be achieved using computer controlled syringes, as done by Keyworth et al. [22], and also more recently using an Ink-Jet fabrication process by Ishii et al. [23, 24, 25]. A schematic drawing of inkjet apparatus is shown in Figure 2.9.

2.2.8 Hydrophobic Effect

A method has been developed to produce lens arrays by application of a patterned hydrophobic layer onto a substrate. When the substrate is dipped into hydrophilic monomer melt, the monomer forms droplets on the regions where no hydrophobic layer has been applied as shown in Figure 2.10.

Figure 2.10 Process flow for hydrophobic patterning [26]

Exposure of these droplets to UV light polymerizes the monomer and the lenses are formed. This method was examined by Hartmann et al. [26].

2.2.9 Hot Embossing

The hot embossing technique can be used to produce patterns in substrates. With the use of appropriate molds, lens arrays can be produced. The required mold is placed on top of the substrate and both are then placed on a heating plate as shown in Figure 2.11.

Figure 2.11 Experimental setup of micro hot embossing process [27]

The substrate is then heated to above its glass transition temperature. The soft substrate then takes the form of the mold that it is in contact with. The use of the method to produce microlens arrays was shown by Shens et al. [27].

2.2.10 Multi-Step Patterning and Mass Transport

In 1989 Liao et al demonstrated the first mass-transported microlens in GaP. They used GaP substrate to form six-step cylindrical mesa structure with an overall diameter of 120 μm , which was formed by repeated application of photolithography and bromine-methanol etching (Figure 2.12).

Figure 2.12 Multi-step patterning and mass transport

Mass transport was carried out in PH_4 and H_2 flow at approximately 1000 $^{\circ}\text{C}$. Complete smoothing of the size step mesa structure was observed after 81 hours of mass transport, and microlenses were formed [28]. GaP is transparent to wavelengths as short as 0.55 μm because of large energy band gap of 2.26 eV. This makes it a suitable material for making microlens for all GaAs based lasers.

2.3 Microlens by Thermal Reflow

Thermal reflow of polymer is an effective way to fabricate refractive microlenses. The technique is considered to be one of the least complicated techniques for

fabricating micro-optical elements. The technique, which is also a mass transport technique, was first described by Popovic et al in 1988. It uses single standard photolithographic process to create photoresist cylinders of desired dimension [29].

Figure 2.13 Making microlenses by melting photoresist

These cylinders are then reflowed (melted) at an optimum temperature and for an optimum time; such that the surface tension then pulls these cylinders into a hemispherical shape (Figure 2.13). In 1990 Daly et al fabricated a variety of microlenses with diameter ranging from few microns to three-fourth of a

millimeter [30]. If gravitational effects are presumed to be negligible, which for very small lenses will generally be the case, and assuming ideal conditions, one would expect the shape of these microlenses to be well approximated to a spherical surface. These spherical shapes then act as microlenses.

Figure 2.14 Microlens profiles

As it can be seen in Figure 2.14 (a, c) profile before the thermal reflow is flat, which is nothing but polymer based micro cylinders. After thermal treatment these cylinders are being converted to a hemispherical profile, which acts as microlens as shown in Figure 2.13 (b, d). Based on the applications these polymer microlenses can be directly used or can act as a mask to transfer the spherical profile to a glass substrate by plasma etching [31].

A similar method to produce arrays of micro-lenses using a sol-gel glass replication technology is demonstrated by Sayah et al [32]. The fabrication process involves two main steps. The first step is the transfer of a microstructure to a PDMS master. The second step is the spin coating with sol-gel material on the sacrificial PDMS master. The sol-gel structure is dried under vacuum and peeled away from the PDMS master. Subsequently, it is subjected to further heat treatments at higher temperatures, leading to a curved membrane structure, which act as microlenses.

2.4 Comparison of Techniques

To evaluate the feasibility of a fabrication technique for a certain application, various parameters need to be taken into account. In an effort to categorize the parameters of interest for selecting a fabricating technique, I distinguished parameters like profile quality; focal length and numerical aperture; profile control; and material processibility. A summary is shown in Table 2.1.

The data presented in the table is gives an idea about the strengths and limitations of the techniques. It does not attempt to limit the scope of a particular technique.

Table 2.1: Comparison of microlens fabrication techniques (f=focal length; NA=numerical aperture; D=diameter of lens; R_c =radius of curvature; h=microlens height)

Technique	Profile Quality	f; NA; D; R_c ; h	Profile Control	Material Processibility	Reference
Grey scale Mask	Poor Lateral Resolution ($\sim 8 \mu\text{m}$)	D = $50 \mu\text{m}$ / h = $1 \mu\text{m}$	Arbitrary Shapes	Sol-Gel/Photoresist	[14]
MEMNAS	Good Surface Roughness (25 nm)	D = $750 \mu\text{m}$ / h = $10 \mu\text{m}$	Arbitrary Shapes	Silicon	[15]
Laser Ablation	Poor Lateral Resolution ($> 1 \mu\text{m}$)	D = $460 \mu\text{m}$ / $R_c = 280 \mu\text{m}$	Arbitrary Shapes	Photoresist /PMMA	[16]
Photosensitive Glass	RMS deviation from perfect spherical shape = $0.2\text{-}0.4$ wavelength	f = $400\text{-}800 \mu\text{m}$ / NA = $0.11\text{-}0.19$	Spherical Shapes	Photo-sensitive Glass	[17]
Optically Induced	-	f = $4\text{-}15 \text{ mm}$ / D = $100\text{-}500 \mu\text{m}$	Spherical Shapes	Photopolymers/ Dichromated Gelatin	[18, 19,20]
Proton Beam Ionization	-	f = $50\text{-}1000 \mu\text{m}$ / NA = $0.2\text{-}1.0$	Spherical Shapes	PMMA	[21]
Ink Jet	Spherical Aberration at D $> 600 \mu\text{m}$	f = $50\text{-}150 \mu\text{m}$ / NA = $0.5\text{-}0.7$	Spherical/Aspherical	Photoresist/ UV curable adhesive	[22,23 ,24,25]
Hydrophobic Effect	Spherical shape deviation = $\pm 5 \text{ nm}$	D = $2\text{-}500 \mu\text{m}$ / NA = 0.362	Spherical Shapes	Monomer	[26]
Hot Embossing	-	D = $100\text{-}200 \mu\text{m}$ / $R_c = 60\text{-}280 \mu\text{m}$	Spherical Shapes	Polymer	[27]
Mass Transport	Good profile quality	f = $200 \mu\text{m}$ / NA = 0.325	Spherical Shapes	Gallium Phosphide	[28]
Thermal Reflow	-	D = $65\text{-}750 \mu\text{m}$ / NA = $0.3\text{-}0.6$	Spherical/Aspherical	Photoresist	[29,30]
Sol-Gel	-	D = $50\text{-}25 \mu\text{m}$ / f = $100\text{-}1000 \mu\text{m}$	Spherical Shapes	Sol-Gel	[32]

2.5 Microlens Application

Since its inception, the application of microlens has changed a lot. In this section I discuss few important applications of microlenses in the recent years (last 15 years to be precise). However the list is not exhaustive, but is an attempt to show the diversity of application of microlens.

2.5.1 Increasing Fill Factor for CMOS and CCD arrays

In response to increasing demands for low cost and small size camera (e.g. handphone cameras, etc), several solid state image sensor categories (CCD, CMOS) have been developed. The array consists of pixels each of which contains a photoreceptive part and electronic circuitry.

Figure 2.15 Microlens array to improve the efficiency of CMOS/CCD array

However, the electronic circuitry is typically shielded from the illuminating radiation by metalised photoshields, reducing the effective aperture of the pixels. By placing a microlens array on top of a CMOS or CCD sensor, the light can be concentrated into the photo-active detector area (Figure 2.15). An image sensor based on the similar principle was first proposed by Isihara et. al. [33].

2.5.2 Integral Photography

In integral photography, an array of micro lenses is used to encode several views of an object. Recording is made on a photographic plate or an image sensor, which is positioned in the focal plane of microlens array. To replay the three-dimensional image the light paths are reversed and the lens array generates light beams that intersect and form the 'integral' image.

Figure 2.16 Optical system for orthoscopic imaging of three-dimensional objects [34]

An optical system for reproducing three-dimensional images using the principle of integral photography was proposed by Davies and McCormick [35, 36, 37]. The key components are multiple arrays of lenses which relay, invert and encode a range of views of the object. As it can be understood the microlens arrays is being developed for a camera.

Figure 2.17 Image created using integral photography technique (by David Roberts, Leap Technologies- Wikipedia Search)

The camera uses two-dimensional arrays of plano-spherical lenses throughout. It can be used for directly recording the images that replay with full parallax and orthoscopic perspective. Figure 2.16 shows the configuration of an optical system to record an image based on the principle of integral photography. An image recorded by integral photography is shown in Figure 2.17

2.5.3 Lithography

Microlens array imaging system in connection with a contactless photolithographic technique is known as microlens lithography. This new technique is aimed at devices that require only moderate resolution, such as flat panel displays, micromechanics, or multichip module manufacturing. The goal is to create an erect 1:1 image of a large lithographic mask on a photosensitive layer.

Figure 2.18 Microlens array system for erect imaging at unit magnification [38]

The system described is a multiple-aperture system consisting of a stack of four microlens arrays forming an array of micro-objectives. A scheme of two adjacent micro objectives is shown in Figure 2.18. Two microlens arrays L1 and L2 are used for imaging. Two arrays FL1 and FL2 are combined to serve as a field lens array. A demagnification of the intermediate image is introduced to avoid crosstalk between adjacent micro objective channels. Each point in the object plane is simultaneously transported by different micro-objectives. The partial images overlap coincidentally in the final image to provide a single, complete image of the object.

2.5.4 Confocal Microscopy

Confocal microscopy has become an effective tool for three dimensional (3-D) imaging of biological as well as other objects (e.g., integrated circuits). Earlier the object was scanned by only a single point at a time, so it took a lot of time to get a surface profile of the whole object. One way to obtain multiple light spots on the surface under test is by the use of microlens array.

To enhance the efficiency of the optical channel, use of microlens array that has the same pitch and is centered on the pinhole axis works pretty well. Figure 2.19 shows the schematic of the experimental setup for confocal microscopy.

Figure 2.19 Schematic of the confocal microscope setup [39]

An important objective for the detection method would be the production of such an aligned pinhole-microlens array to perform confocal microscopy over wide surface with a much reduced scanning time.

2.5.5 Microlenslet-Array-Based Magnifier

The design of many optical imaging systems requires extremely compact and lightweight magnifying systems, for example, the magnification of miniature organic light-emitting diode displays in head-mounted projection displays

(HMPDs), which does not have stringent resolution requirements in the magnification process. A compact solution would be extremely beneficial for such an application because it would allow for improved design, increased field of view, and overall higher performance. Optical magnification systems based on microlenslet arrays could provide a useful solution for such applications.

Figure 2.20 Optical layout of 1: M imaging with a stack of two dissimilar microlens arrays

[40]

There are numerous possible configurations that can be used to create an optical 1: M magnifying system with a stack of two dissimilar microlenslet arrays. The general case for a stack of two microlenslet arrays is illustrated in Figure 2.20.

2.5.6 Optical Interconnection

A considerable effort is devoted to the design and production of optical means of connection, such as the individual elements of an array of light sources to the elements of an array of detectors. The ultimate aim is to produce data transmission systems which take advantage of the lack of interaction between light waves in

free space, and operate at higher data rates than are possible with conventional electronics. The basic requirement for such interconnection is an array of optical systems to collect light emitted by an array of sources, directs it to the appropriate element on the detector array and brings it to a focus on the active area.

In 1992 Hutley et al used a focal pairs of lenses in which the second lens was laterally displaced with respect to the first (Figure 2.21).

Figure 2.21 Afocal pair of lenses to steer a beam of light

The principle of operation was that the light from a distant source will be brought to focus by the first lens and re-collimated by the second. If the optical axes of the two lenses are coincident, and if the light is incident parallel to the common axis, the direction of the outgoing bundle of rays will be unchanged. If, however, the second lens is displaced sideways the output beam will be deviated by an angle which depends upon the magnitude of the displacement and the focal length of the lens.

An arrangement for interconnection based on the above principle is shown in Figure 2.22. Light is directed from a regular array of sources by means of a pair of lens. The lenses on the first array are regularly spaced to match the source array.

Figure 2.22 Pair of lens arrays as a spatially variant interconnection

Those on the second array are each displaced from the regular grid by the distance which is necessary to deflect the beam towards the appropriate detector. If the source array is in a suitable form such as surface emitting laser diodes or single mode optical fibers, it may be possible to dispense with the first lens array and place the sources at the focal plane. On the other hand it may be that the first array is still necessary in order to match the numerical aperture of the sources to that of the optical system which follows [41].

2.5.7 Shack-Hartmann Wavefront Sensor

The Shack-Hartmann wavefront sensor is a simple and elegant means for measuring the shape of a wavefront. The technique has found application in a wide variety of fields, from improving images of the vast cosmos to the more

down to earth measurements of the aberrations of the eye. It has become widespread throughout the world with hundreds of millions of astronomical images benefiting from the process to millions of corrective surgeries that will be performed in upcoming years to enhance vision.

Figure 2.23 Working principle for Shack-Hartmann wave sensor

The principle of operation is that when a plane wave front impinges on a microlens array, regular arrays of point are formed in a focal plane as shown in the Figure 2.23. If the wavefront is not plane, each microlens is illuminated by a wave front incident at a different angle. Hence the focal point of each lens is moved (d) from the central position as show in the figure. The movement of the focal point can be detected with a CCD array or a detector array and hence the overall shape of the wavefront can be determined [42, 43, 44, 45].

2.5.8 Miniaturized Chemical Detection System

Chemical microchips and miniaturized total analytical systems (μ TAS) cover a wide range of disciplines, such as analytical and organic chemistry, biochemistry, electronics, microengineering, solid state physics, laser physics and micro-optics.

Figure 2.24 Miniaturized chemical detection system [46]

Usually, a complex arrangement of lasers, detectors, filters, optics and high-precision mechanical stages is required for illumination and optical detection. Microlens arrays offer a large potential to reduce the size and to simplify the architecture of analytical systems. Figures 2.24 (a) and 2.24 (b) show schemes of a μ TAS using microlens arrays for parallel illumination and detection of microcapillaries.

2.5.9 Beam Shaping

Light-emitting diodes (LEDs) have large number of applications because of their numerous advantages such as low production costs, long lifetime, high efficiency, and flexibility in the design. This is mainly due to LED application as signal light and therefore the emitter chip and the shape of the epoxy dome are designed to

radiate with a maximum radiation power and an application dependent divergence angle.

Figure 2.25 LED beam-shaping system with microlens array [47]

This implies that for uniform illumination tasks, the LED beam is not well adapted and must pass a supplementary optical system that additionally shapes the beam, e.g. microlens array. An arrangement for beam shaping of LEDs with microlens array is shown in Figure 2.25.

2.5.10 Variable Focal Length Microlens

Variable focal length microlenses have attracted attention because of their usefulness as an alternative to mechanical focusing in miniaturized optical systems. Lenses having variable focal length eliminate the use of mechanical parts which greatly reduces the size of the optical assemblies, as well as focus can be achieved with high precision. Furthermore, it also provides an alternative to track a moving object or guide an optical channel. These kind of tunable lenses have been created by dynamic alteration of the refractive index or profile of microlens.

Figure 2.26 Device structure of LC microlens [48]

In 1996 Masuda et al. have demonstrated a liquid crystal microlens using a nematic liquid crystal (LC). The idea was to control the focal length through electrical means. To achieve that a hole-patterned electrode structure, where a spatial distribution of refractive index is induced by an axially symmetric non-uniform field, was used.

The gradient refractive index profile of the lenses, and hence their focal lengths, were continuously varied by altering the electric field in the hole pattern, as shown in Figure 2.26. Using hole pattern electrode on both the substrate gives a good control on the focusing as the disclination lines are suppressed. One of the disadvantages with these kinds of lenses is that the variation in focal length depends on the birefringence of the material and thus the lenses can only be used

with one orientation of linearly polarized light. This definitely restricts the application scope of such lenses.

Another approach to achieve a variable focal length lens is through controlling the lens profile with a variable parameter such as voltage or pressure.

Figure 2.27 Schematic representation of liquid lens [49]

The principle of operation of such liquid lenses can be understood from Figure 2.27. A cell contains two non-miscible liquids, one is insulating and non-polar 1, and the other is a conducting water solution 2. The liquids are transparent with different index of refraction, but with the same density, such that gravity does not deform the liquid-liquid interface, which remains spherical whatever the orientation of the cell is. The insulating liquid has the shape of a drop in contact with a thin insulating window (in gray). The window's surface is hydrophobic, so that the insulating liquid will sit on it. A transparent electrode is deposited on the external side of the window, which is known as the counter-electrode. Application of a voltage between the counter-electrode and the conducting liquid favors the wettability of the surface by this same liquid. This deforms the interface from

shape A to shape B and thus changes the focal length. Here electrowetting has been used effectively by Berge et al. to construct variable focus lenses by controlling the contact angle of a liquid drop with the application of voltage [49]. Furthermore Moran et al. have shown that variable focus lenses can also be realized making use of the lensing effect induced by controlled deformation of a liquid interface with application of pressure [50].

2.6 Microlenses on Optical Fiber Tip

Microlens assembly is needed for the general cases of beam collimation in microoptoelectro-mechanical systems (MOEMS) or specialized cases of lens on optical fiber tip. For most of the general cases the lenses must be set up normal to beams travelling parallel to the substrate. Fabrication of such arrangement involves in-plane patterning of a surface micromachined structure, and out-of-plane rotation and fixing. Such kind of microlens assembly can be performed either using an external manipulator, or using a microengine such as a linear vibromotor. Lens on a fiber tip on the other hands represent an emerging technology in fiber optics. A lens fabricated directly on the tip of a fiber could offer several benefits. It completely eliminates the need for alignment between the lens and the fiber, making a miniature and alignment-free optical design possible. Coupling light from a laser diode into a single-mode fiber with high efficiency and stability, for instance, can be achieved with these kinds of fiber lenses. Fiber lenses are very useful in optical fiber communications, as they make the design of optical components more compact. The use of fiber lenses can also be beneficial

in optical recording and fiber sensing, for which miniaturized fiber probes are highly desirable [51].

Few such techniques are discussed below:

2.6.1 Out-of-Plane Microlens Assembly

Surface tension can be used for self-assembly which can allow the formation of out-of-plane photoresist microlens arrays on silicon frames (Figure 2.28). A process for fabrication of refractive collimating microlens arrays based on the similar principle was demonstrated Syms [52].

Figure 2.28 Microlens on a frame

The lens mount is formed in the bonded layer of a bonded silicon-on-insulator wafer, and rotated out of plane by the surface tension obtained by melting rectangular pads of thick photoresist. The lenses are formed by melting circular pads of the same resist. Correct alignment of the mount normal to the substrate is achieved by sequential self-assembly of a supporting frame.

2.6.2 Exposing Negative Photoresist at the Fiber Tip

Cohen et al. made microlens on fiber tip using the arrangement shown in Figure 2.29. The optical fiber was coated with negative photoresist by dipping or dropping.

Figure 2.29 Arrangement for exposing negative resist to form lens on fiber tip [53]

The region to be transformed into the microlens was exposed to UV light. The developed photoresist was hardened by postmarking which leads to crosslinking in the immediate vicinity of the fiber core. The unexposed photoresist is removed after development. Curved lens profiles were obtained because the exposing light intensity has a nearly Gaussian profile and also because the photoresist flows slightly at the post baking temperature.

2.6.3 Heating of Fiber Tip

There are varieties of methods such as propane-oxygen gas torch, electric arc or laser as a heat source to melt the fiber tip to form lens [54]. However, laser technique offers several clear advantages over the other techniques. The most

important being the precise control of heat affected zone. This follows from the inherent controllability of the output power of the laser and its delivery to the end of the fiber.

Figure 2.30 Schematic of optical setup for the laser system [55]

A setup was developed by Paek et al. (Figure 2.30) to form a spherical lens at the optical fiber end using a CO₂ laser. A beam splitter was used to transmit 30% of the laser power from a 6-W beam. A 0.5-cm diameter beam of 1.8 W of net power was focused on a fiber end with a germanium lens (F.L. = 1.78 cm). To refine initial settings a microscope was used to view the process.

2.7 Revisiting Microlens Applications

Application of microlens has attracted a lot of attentions from various sectors of industry and research. The range of uses for both individual and arrays of microlens is exceptionally diverse. Some applications which were proposed years

ago could be realized now; others have been specifically developed in response to the availability of the process. As the quality of the lenses goes up and the price of replication comes down, the range of application will grow even more dramatically. All the applications discussed here can be broadly divided in three categories, of Beam shaping (Intensity distribution of a single beam or generation of an array of beam); Interconnection (connection or steering of arrays of optical channels operating in parallel); and Imaging (formation of a macro image from array of beamlets). Table 2.2 summaries all the applications presented here.

Table 2.2: A summary of microlens application

Category	Application	Type of System	Reference
Beam Shaping	Shack-Hartmann Wavefront Sensor	Microlens Array	[42, 43, 44, 45]
	Beam Shaping	Microlens Array	[47]
	Variable Focal Length Microlenses	Individual Lens	[48,49,50]
Interconnection	Increasing Fill Factor of CMOS/CCD arrays	Microlens Array	[33]
	Optical Interconnection	Microlens Array	[41]
	Miniaturized Chemical Detection System	Microlens Array	[46]
Imaging	Lithography	Microlens Array	[38]
	Confocal Microscopy	Microlens Array	[39]
	Microlenslet-Array-Based Magnifier	Microlens Array	[40]
	Integral Photography	Microlens Array	[35, 36, 37]
	Microlens on Optical Fiber Tip	Individual Lens	[52,53,54,55]

Chapter 3: Modeling of Microlens Profile

Chapter 3 introduces the modeling problem for thermal reflow and explores the various modeling techniques found in literature to predict the profiles of microlens produced by thermal reflow of photoresist cylinders. It also discusses the approach to model the microlens profile based on Young-Laplace equation. The solution of the equation, which forms a second order non-linear Ordinary Differential Equation (ODE) is numerically obtained using MATLABTM.

3.1 Introduction

Photoresist reflow is one of the simplest techniques used today to fabricate microlenses. The technique uses standard photolithographic process to create micropillars, which are then thermally reflowed (melted) at an optimum temperature and time to transform them into microlens. However, it has been experimentally found that all the lens generated by reflow are not spherical in nature, but contain certain degree of asphericity. Moreover, for certain geometrical dimension of micropillar there occurs a dip at the centre during the thermal reflow. Figure 3.1(a, b) shows the difference of microlens profile with and without dip at the centre.

(a) Microlens (spherical/aspherical profile) (b) Microlens with dip at the centre

Figure 3.1 Cases for microlens profile

Due to the nature of dynamic physiochemical mechanism involved in the thermal reflow process, the problem is very complex, and till date no theory has satisfactorily explained the occurrence of dip. An ideal model would be the one that can accurately predict the formation of profile, as well as the occurrence of dip at the centre, based on the fundamental principles. Such a model would give a better understanding about the process, which would help in controlling the microlens profile. In the next section I shall investigate some models for predicting microlens profile.

3.2 A Review of Modeling Techniques

A number of techniques have been used to model the microlens profile obtained by thermal reflow, starting in 1994, when Sheridan et. al. proposed a model based on fourth order polynomial fit [56, 57, 58] to 2006, when Audran et. al. proposed a model based on Navier Stokes equation with a variable viscosity [59, 60]. During this period there were few more models which investigated the profile formation. The most prominent one being Curvature Correction Model by Abe

and Sheridan in 1999 [61, 62, 63], a model based on surface tension and gravity by Schilling et. al. in 2000 [64], and a model based on energy approach [12]. Before we discuss these models and propose our model, we take a look into a very simple model based on volumetric conservation and basic geometrical consideration that is used as a first guide to design the microlenses.

3.2.1 Geometrical Model

The simplest model to design microlens obtained by reflow is based on volumetric conservation and geometrical consideration [65, 12]. The model is based on the assumption that after the reflow of photoresist cylinder, the microlens formed has spherical profile, and the volume of photoresist is conserved i.e. volume of microcylinder (V_{cyl}) is same as volume of microlens (V_{lens}). The focal length of the resulting plano-convex microlens is determined by the radius of curvature (R_c) of resulting spherical-shaped profile (Figure 3.2)

$$f = \frac{R_c}{n-1} \quad (3.1)$$

where n is index of refraction for the lens material (photoresist).

Figure 3.2 Geometrical representation of reflow process

To obtain the radius of curvature (R_c) we consider the volume of microcylinder (before reflow)

$$V_{cyl} = \frac{\pi D_{cyl}^2 t}{4} \quad (3.2)$$

and the volume of the spherical microlens (after reflow)

$$V_{lens} = \frac{\pi h^2 (3R_c - h)}{3} \quad (3.3)$$

is same. Also, the model assumes that the diameter of the cylinder (D_{cyl}) does undergo any changes during the thermal reflow and is same as the diameter of the microlens (D_{lens}) i.e. $D_{cyl} = D_{lens} = D$. Height of the microlens (h) is related to the diameter of the microlens (D_{lens}) and the radius of curvature (R_c) by basic geometry of a spherical structure, and is given by

$$h = R_c - \left(R_c^2 - \frac{D_{lens}^2}{4}\right)^{\frac{1}{2}} \quad (3.4)$$

Conversely, the radius of curvature (R_c) of the microlens as

$$R_c = \frac{\frac{D_{lens}^2}{4} + h^2}{2h} \quad (3.5)$$

Alternatively, we can obtain the thickness of the photoresist (t) before melting to achieve a desired focal length (f)

$$t = \frac{h}{2} \left(\frac{4h^2}{3D^2} + 1 \right) \quad (3.6)$$

Using equations (1-6), it is possible to determine a combination of thicknesses and diameters for a specific focal length. Figures 3.3 and 3.4 show the dependence of radius of curvature (R_c), which is a measure of focal length (f), on the diameter (D) and thickness (t) of photoresist cylinders.

Figure 3.3 Radius of curvature as a function of lens/cylinder diameter

Figure 3.4 Radius of curvature as a function of cylinder thickness

We note that although the model is based on a 3D volume analysis, it is valid for 2D profiles as the lens has a circular symmetry. Moreover, the computation done

here will work well, with little change, for cylindrical lens which are obtained by the reflow of long strip of photoresist material. However, at the corner of the strip the behavior will change and thus the formula can only be used as a first guide to design lenses with long rectangular bases.

3.2.2 Models Based on Polynomials

Models based on polynomials are basically phenomenological models where the profiles are fitted based on a polynomial. This section examines three different heuristic approaches for a polynomial model [56, 57, 58], viz.

- Model A: The fourth-order polynomial based model
- Model B: Sum Model
- Model C: Product Model

Model A takes into account the inherent symmetry (symmetric about y- axis) of the lenses (for both spherical and cylindrical case). The profile is thus assumed to be an even function i.e. $p(x) = p(-x)$. The initial polynomial used can be written as

$$p(x) = \sum_{n=0}^2 a_{2n} x^{2n} = a_0 + a_2 x^2 + a_4 x^4 \quad (3.7)$$

For Model B (Sum Model), the polynomial is defined as:

$$p(x) = \sqrt{R_{cN}^2 - x^2} - \sqrt{R_{cN}^2 - r_N^2} + a_0 + a_2 x^2 + a_4 x^4 \quad (3.8)$$

Finally, Model C (Product Model) is defined as:

$$p(x) = \sqrt{R_{cN}^2 - x^2} - \sqrt{R_{cN}^2 - r_N^2} + \sqrt{R_{cN}^2 - x^2} (a_0 + a_2 x^2 + a_4 x^4) \quad (3.9)$$

Where

- a_0, a_2, a_4 are polynomial coefficients
- $p(x)$ is the microlens profile
- x is normalized radial position

- R_{cN} is normalized radius of curvature of the microlens
- $r_N = 1$, is the normalized base radius

These models can be solved with following boundary conditions:

- Area under the curve (equivalent to the initial volume of photoresist cylinder before reflow)
- Height at the edges is zero
- Critical/Contact Angle
- Central Height

Model A, B and C can be solved under boundary conditions mentioned to find the value of the coefficients, to obtain the profile. One disadvantage of Model A over Model B and Model C is that it doesn't have sphere/cylinder as the limiting case for the equation.

The three models have been shown to produce very similar profile. However, the experimental results show that the actual spherical aberrations are far lower than those predicted by all the models. Among the model shown, Model B appears to provide the analytic expression most suitable for the microlens profile. However, the problem with any model based on polynomials is that it does not explain profile formation or dip at the centre in terms of physical process.

3.2.3 Curvature Correction Model

Curvature Correction Model analyzes the microlens profile through generalization of Laplace Equation based on the curvature expansion for Surface Internal Energy. The model has an extra term of curvature to the usual surface tension and

volume, to predict the formation of dip [61, 62, 63]. This arrangement was based on intuition, and no real explanation is provided. Initially the derivation was made for cylindrical case (Single Dimension) only, to avoid the Gaussian curvature term. Later on when the model expanded the model for the spherical case, it became rather complicated. Thus polynomial approach was used to solve the model. The model also neglected the effect of gravity and doesn't work well with the strongly curved surfaces.

3.2.4 Surface Tension-Gravity Based Model

The model presents a finite-element method to calculate the 3D surface profiles of refractive microlens fabricated by photoresist-reflow technique [64]. The geometry of the microlens can be arbitrary. Surface tension and gravity are taken into account. The model is constructed based on the concept of generalized minimum-surface. The model basically studies the effect of the direction of gravity on the spot size of the microlens formed. Though the model claims to work for any arbitrary geometry, it does not discuss any spherical case, which happens to be the most practical case for microlens. Model also fails to predict the cases where dip occurs.

3.2.5 Navier Stokes Equation Model

The model is based on the Navier Stokes equation, and takes into account the evolution of resist viscosity with time and temperature [59, 60]. However, the variation in viscosity is arbitrary, and is based on the evolution of elastic modulus during the reflow. It also studies the dynamic formation of microlens profile of very small cylinder (diameter less than 5 μm), and discusses the contact angle

phenomena. The effect of gravity is not considered since it is negligible for such small dimensions. It also attempts to explain the formation of dip at the centre with the help of two opposing force of surface tension and cross linking.

3.2.6 Energy Model

For the photoresist cylinders on the substrate, the surface energy consists of the energy of the interfaces between photoresist-air (surface tension: γ) and photoresist-substrate (γ_s)

$$E_{cyl} = \gamma \left(\pi \frac{D_{cyl}^2}{4} + \pi D_{cyl} t \right) + \gamma_s \pi \frac{D_{cyl}^2}{4} \quad (3.10)$$

During melting of the resist, the mass transport takes place in order to find an energetically preferable shape. The surface energy of the photoresist cap formed during this melting process is calculated by means of

$$E_{lens} = \gamma \left(\pi \left(\frac{D_{lens}^2}{2} + h^2 \right) \right) + \gamma_s \pi \frac{D_{lens}^2}{4} \quad (3.11)$$

Here the possibility of a change of the contact area between the substrate and the photoresist is taken into account by assigning two different diameters D_{cyl} and D_{lens} to the different shapes. From Eqn. (3.10) and (3.11) we can calculate the difference in the surface energies (ΔE_S) of the two shapes of the photoresist. For the resulting shape of the microlens, the reduced surface energy is balanced by an increase in the gravitational energy (ΔE_G) of the photoresist cap. The gravitational energy (G_{cyl}) in the photoresist cylinder is

$$G_{cyl} = g \rho \pi \int_0^t \frac{D_{cyl}^2}{4} z dz = g \rho \pi \frac{D_{cyl}^2}{4} \frac{t^2}{2} \quad (3.12)$$

Here ρ denotes the density of the photoresist and g is the acceleration due to gravity. Due to the swelling of the photoresist cap the gravitational energy (G_{lens}) is increased to:

$$G_{lens} = g\rho \int_0^h V(z)dz = g\rho\pi\left(\frac{h^3 R_c}{6} + \frac{h^2 D_{lens}^2}{16}\right) \quad (3.13)$$

The energy balance taking into account the surface energies as well as the gravitational energies read

$$\Delta E_S + \Delta E_G = (E_{cyl} - E_{lens}) + (G_{cyl} - G_{lens}) = 0 \quad (3.14)$$

This theoretical approach helps us to understand the influence of the physical boundary conditions on the shape of the resulting photoresist microlenses. It is useful when investigating the influence of different substrates or processing temperatures. The shape of the microlenses depends on the ratio between the surface tension coefficients of the polymer-air and polymer-substrate interfaces. The surface energy of the substrate-photoresist interface varies for different materials. In particular, surface roughness, which increases the surface area, has an important influence on the energy balance. The processing temperature can also be expected to be a critical parameter, since it directly influences the surface tension [12].

3.3 Our Approach: Young-Laplace Equation

We think that the microlens profile can be predicted by our model which is based on the Young-Laplace equation. Since the model is based on fundamental principle we expect it to give a better understanding of the process involved. The model can be used as a tool to better understand the formation of experimental

profile, which in turn, could verify the relevance of the theoretical model in predicting the actual shape.

3.3.1 Basic Considerations for the Model

To apply Young-Laplace equation for the reflow process it must fulfill certain basic considerations [66, 67]. We assume that the photo resist becomes liquid during the reflow process with a fixed surface tension. The drop of liquid photoresist rests on a smooth surface of silicon substrate. The drop shape is axisymmetric and forms a uniform circle of radius r (Figure 3.5).

Figure 3.5 Axisymmetric sessile drop (liquid photoresist on silicon substrate) in air

The pressure drop ΔP across the photoresist-air surface is a function of gravitational potential and capillary pressure [68].

$$\Delta P = P - P_a = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right) = (\rho - \rho_a)gy + c \quad (3.15)$$

Where, R_1 and R_2 are two radii of curvature; ρ and ρ_a are density of photoresist (liquid) and density of air respectively; γ is surface tension; c is reference pressure; θ is contact angle; g is acceleration due to gravity.

Assuming that the axis of symmetry is identical to the y-axis of an orthogonal Cartesian coordinate system, then it is convenient to put one radius of curvature (R_1) in the plane of x-y coordinate. This radius is given by:

$$\frac{1}{R_1} = \frac{y''}{\sqrt{(1+y'^2)^3}} \quad (3.16)$$

where y' and y'' are first and second derivative of y with respect to x . The second radius of curvature (R_2) perpendicular to the x-y plane is given as:

$$\frac{1}{R_2} = \frac{y'}{x\sqrt{1+y'^2}} \quad (3.17)$$

At the apex point ($x=0, y=0$) both radii of curvatures has the same value i.e. $R_1 = R_2 = R_0$

Thus, $c = \frac{2\gamma}{R_0}$ where R_0 is the radius of curvature at the apex [69].

Combining equation (3.15), (3.16) and (3.17), we get

$$\frac{y''}{\sqrt{(1+y'^2)^3}} + \frac{y'}{x\sqrt{1+y'^2}} = \frac{(\rho - \rho_a)gy}{\gamma} + \frac{2}{R_0} \quad (3.18)$$

The above equation is a second order, non linear Ordinary Differential equation (ODE) in y .

The boundary conditions for the reflow process are quite different from the usual sessile drop analysis, where the area of contact between the drop and the substrate [68] adjust itself in accordance with the material contact angle. The same is not true with the reflow process, where the contact area between the substrate and photoresist (which is a measure of r) before and after the reflow remains the same, and is well justified experimentally. Thus, the profile generated is governed more by the geometrical proportions of the micro-pillar, than the material contact angle,

which is also well indicated by our experiments (See Chapter 5 for experimental verification).

The parameters ρ , ρ_a , γ , g , c and r have to be specified. Out of these parameters ρ and γ depend on the photoresist used for the fabrication. ρ_a depends on the medium surrounding the microlens during reflow. We reflowed microlens in air. R_0 is determined using “area under the curve A” (the shaded region in Figure 3.5, which is the measure of volume of microlens) as the boundary condition, which in turn depends on r and initial thickness t of the photoresist cylinders. Typical values for these parameters found in the literature [64] have been used, which are given in Table 2.1.

Table 3.1: Value of material constant

ρ	ρ_a	γ	g
1000 kg/m ³	1 kg/m ³	3.62 x 10 ⁻² N/m	9.81 m/s ²

3.3.2 Solution: Using MATLAB™

The ODE (equ. 3.18) is solved using MATLAB. Two approaches are available to solve the equation:

- Initial Value Problem
- Boundary Value Problem (Dirichlet, Neumann, Mixed)

Figure 3.6 Types of boundary conditions during the thermal reflow

First approach is simple and looks at the problem as an initial value problem, with initial condition of displacement and slope at the apex (Figure 3.6 (a)). Another approach is based on the non-linear shooting method which solves the ODE as a boundary value problem. Solving ODE using boundary conditions is more complicated than that of initial conditions. Initial value problems often have unique solutions, but boundary value problems could have none or more than one [70]. Also a boundary value problem is described based on the boundary conditions available (Figure 3.6 (b, c, d)).

A detailed Matlab code is given in the appendix for initial value boundary conditions.

3.4 Results and Discussion

Solution was done using the initial value approach because of its simple nature and unique solution. Setting initial condition at the apex, the Young-Laplace

model showed a good match with microlens in spherical shape (based on geometrical model). The profile works well for both high and low curvature microlens as shown in Figure 3.7 and 3.8. A comparison of contact angles based on geometrical model and Young-Laplace model shows a good match and proves the workability of the model (Table 3.2). It also verifies the variability of contact angle during the reflow process, which is well justified experimentally. A comparison of model profiles with experimental data will be discussed in chapter 5.

Table 3.2: Comparison of contact angles

Microlens Parameters	Contact Angle (θ) for Spherical Profile	Contact Angle (θ) for Young-Laplace Profile
$D = 530 \mu\text{m}$; $t = 20 \mu\text{m}$	17.0°	18.9°
$D = 275 \mu\text{m}$; $t = 25 \mu\text{m}$	38.5°	43.2°

Figure 3.7 Young-Laplace Profile for low aspect ratio lens ($t/D = 0.038$)

Figure 3.8 Young-Laplace Profile for high aspect ratio lens ($t/D = 0.090$)

We studied the effect of surface tension on the value of R_0 (radius of curvature of microlens at the apex), which is a measure of sphericity and focal length of the microlens (Table 3.3). The value of R_0 decreases with an increase in the value of γ (surface tension) while keeping the other parameters constant. This means a photoresist with higher value of surface tension will tend to form a high curvature profile.

Table 3.3: Effect of surface tension on R_0 [$D = 530 \mu\text{m}$; $t = 20 \mu\text{m}$]

γ	R_0
$2.00 \times 10^{-2} \text{ N/m}$	$819.5 \mu\text{m}$
$3.62 \times 10^{-2} \text{ N/m}$	$819 \mu\text{m}$
$5.00 \times 10^{-2} \text{ N/m}$	$818.5 \mu\text{m}$

We also studied the effect of the direction of gravity on R_0 . The value of R_0 decreases for a negative value of g (Table 3.4) while keeping the other parameters constant. Negative value of g signifies the hanging position of microlens during the reflow process. This suggests that microlens reflow at hanging position helps in the formation of more curved profile.

Table 3.4: Effect of gravity direction on R_0 [$D = 530 \mu\text{m}$; $t = 20 \mu\text{m}$]

$g \text{ (m/s}^2\text{)}$	$R_0 \text{ (}\mu\text{m)}$
9.81	819
-9.81	817.5

The variation in R_0 is small, but will dominate for the cases of big lenses, when gravity will have a stronger effect on the microlens profile. However, our model very well shows the formation of profile and effects of fabrication parameters (gravity, surface tension). To summarize, Young-Laplace model is reliable in predicting microlens profile and gives a better understanding of the profile formation with first principles. Our model also leaves scope for modification, which will be helpful for the prediction of dip, by introducing a variable surface tension of photoresist cylinder during the thermal reflow. This may be explained by the variable degree crosslinking of photoresist across the microlens height during the thermal reflow.

3.5 Comparisons of Models

A comparison of all the modeling techniques is summarized in Table 3.5.

Table 3.5: A comparison of models

Model	Principle	Advantage	Limitation	Reference
Geometrical	Volume Conservation based on spherical profile	Very Simple / First guide to design microlenses	Provides only dependence with geometry	[61, 62]
Polynomial	Fourth Order Polynomials	Better profile fitting	Only an analytic model	[52, 53, 54]
Curvature Correction	Curvature expansion for surface internal energy	Profile prediction and Dip occurrence	Addition of curvature term is intuitive	[57, 58, 59]
Surface Tension-Gravity	Generalized minimum-surface	Discusses influence of gravity / Spherical profile prediction	No dip explanation / Doesn't discuss contact angle	[60]
Navier-Stokes	Navier Stokes equation- with variable viscosity	Explains occurrence of dip with basic principles	Assumes contact angle to be constant which is not valid for all cases	[55, 56]
Energy	Energy balance for surface and gravitational energies	A simple approach based on first principles	Thorough mathematical description of process is needed	[12]
Young-Laplace	Based on Young-Laplace Equation	Good profile prediction / Based on first principles / Discusses contact angle variation	Not valid for dip occurrence, but could be incorporated in future	[Our Approach]

Chapter 4: Optimization and Applications of Thermal Reflow

In this chapter we will be discussing the experimental details of thermally reflowed microlenses. The aim of the experiments conducted is to achieve the optimum conditions to get the desired profile and to study the effect of various reflow parameters on the profile formation with an eye to control the profile using these parameters. This will constitute the first part of this chapter (Section 4.1 and 4.2)

Thermal reflow technique is mostly used to fabricate convex microlenses. However, with certain modification other optical components like diverging microlens, micromirror, etc can be obtained. We will present these modifications and the detailed fabrication techniques to obtain the above mentioned microoptical components in section 4.3.

4.1 Fabrication Procedure

Fabrication of microlens on a silicon substrate involves three standard process of wafer cleaning, photolithography (spin coating, exposure and development) and thermal reflow.

4.1.1 Preparation of Substrates

Prior to the commencement of the actual fabrication process, the silicon substrates have to be cleaned thoroughly. The cleaning process is a standard one and crucial

in obtaining the final product of the fabrication process, as any impurities or dirt on the substrate might affect the successful fabrication of microlens.

A point wise detail of the cleaning process is given below:

- Silicon wafers are first immersed in piranha solution ($\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$) for 20 minutes at a temperature of 120°C
- Wafers are rinsed in de-ionized (DI) water bath
- Wafers are dipped in hydrogen fluoride acid (HF) for 10 minutes to remove any oxide layer present on the wafer.
- The wafers are then removed from HF and rinsed with de-ionized water again
- The wafers are dried with an automated air dryer (spin dryer)
- The wafers are baked at 110°C for about 5 minutes on a hot plate to remove any moisture on the substrate.
- The wafers were then left aside to cool and were ready for fabrication purposes.

4.1.2 Photolithography Process

Photolithography is the key process in the fabrication of the micro-optical elements by reflow technique. The cleaned silicon wafer was used as the substrate to form photoresist (PR) cylinders. AZ9260, a positive photoresist was used for patterning micro cylinders. Following steps will detail the process:

- The cleaned substrate is coated with a layer of HMDS (or hexamethyldisilazane) to increase the adhesion between the photoresist and the substrate

- A layer of AZ9260 is spin coated onto the substrate. A single coating of the photoresist gave a maximum thickness of 10 μm
- Pre baking of coated layer is done on a hotplate for 4 minute at a temperature of 110°C.
- For thicker layer ($>10\mu\text{m}$) of photoresist, multiple coating was done, which is nothing but repetition of last 2 steps on the same wafer. A detailed description of multiple coating and its application in controlling the thickness of PR is discussed in chapter 6.
- Substrate with PR layer is then ready for the exposure. Time of exposure is dependent on the thickness of PR layer, as well as the intensity of UV light (9.3 mW/cm^2). The exposure time was optimized w.r.t thickness of PR (Table 4.1)
- The desired mask is used to pattern the PR layer. A mask containing circles of diameter ranging from 50 μm to 700 μm was already manufactured.
- After exposure the substrate is ready for development. AZ9260 developer is used. The development time again is dependent on the thickness of PR coated and was optimized was different thickness (Table 4.1)

Table 4.1: Optimization of exposure and development time for various thicknesses of photoresist (AZ9260)

Thickness of PR (μm)	Exposure Time (seconds)	Development Time (minutes)
10.5	50	1
21.4	85	1.5
29.7	140	3
39.6	240	9

4.1.3 Thermal Reflow (Melt)

Thermal reflow occurs when the PR cylinders are heated close to the glass transition temperature ($\sim 115^{\circ}\text{C}$) of the photoresist. The principle of reflow depends on surface tension acting on the liquefied resist, which forms the hemispherical lens shape.

4.2 Study of Reflow Parameters

4.2.1 Simulation of Temperature Gradient across Microlens

A hot-plate was used to thermally reflow the photoresist cylinders. Hot plate starts heating the photoresist cylinder from the bottom, which may produce a temperature gradient across the height of the microlens. However, the air around the microlens causes convection currents which tend to unify the temperature gradient. Moreover, the thickness of microlens is too small to produce any significant temperature difference across two extreme points (the base and the tip). To verify the hypothesis, a thermal analysis was simulated in AnsysTM.

Following parameters were used for the simulation:

Thermal Conductivity= 0.7 W/m K

Environment Temperature= 25°C ; Hot Plate Temperature = 116°C

Size of microlens; $D=200\text{ }\mu\text{m}$; $h=40\text{ }\mu\text{m}$

Convection Coefficient= $100\text{ W/m}^2\text{ K}$

A nodal solution for the temperature distribution of the microlens is shown in Figure 4.1. As can be seen the base of the microlens is at the same temperature as

that of hot plate. The temperature, however, decreases along the microlens tip. But, this decrease in temperature is too small to cause any uneven heat distribution during the thermal reflow. A detailed Ansys code is also given in the appendix.

Figure 4.1 Temperature gradient across microlens reflowed on a hot plate in air

From the analysis it can be safely concluded that the temperature of the hot plate is actually the thermal reflow temperature, and this temperature is same across the microlens height for all practical purposes.

4.2.2 Optimization of Reflow Temperature and Time

To study the effects of reflow temperature and time, photoresist cylinders were reflowed with diameters varying from 50 μm to 700 μm and thicknesses of 10-40 μm , on a hotplate. For optimization, I chose cylinders with an initial thickness (t) of 10 μm thick PR. The maximum diameter lens reflowed (to attain a

hemispherical profile) was found to be 200 μm . For all the cylinders above 200 μm diameter, the spherical profile did not form. Table 4.2 shows the value of microlens height (h) at various combinations of temperature and time. We notice that the maximum dome height achieved by a 200 μm diameter cylinder is 16.4 μm for the reflow conditions of 35 minutes at 115°C. If we consider a 150 μm diameter cylinder, the maximum dome height reached is 16 μm for 35 minutes at 115°C. Consider the case of reflow for 25 minutes at 115°C, the dome height for 150 μm diameter cylinder is bigger than that of 200 μm diameter cylinder. Apparently there is an optimum condition of reflow for a 150 μm diameter cylinder between these two conditions. We can conclude that for each diameter comes a new set of optimum condition of reflow, though the difference may not be quite significant.

Table 4.2: Optimization of reflow temperature and time ($t=10\mu\text{m}$): Hot plate heating

Time/Temperature	Microlens height (h in μm) for diameters:		
	150 μm	200 μm	300 μm
5 minutes at 110°C	Spherical profile not formed	Spherical profile not formed	Spherical profile not formed
5 minutes at 115°C	12.9	12.0	Spherical profile not formed
15 minutes at 115°C	13.15	12.0	Spherical profile not formed
25 minutes at 115°C	15.7	13.9	Spherical profile not formed
35 minutes at 115°C	16.0	16.4	Spherical profile not formed
5 minutes at 120°C	15.6	16.2	Spherical profile not formed

However, for all experiment conducted on varying diameter of lenses, reflow for 35 minutes at 115°C could be safely assumed to be an optimized reflow condition.

When the same set of lenses (50 μm to 700 μm) were reflowed in an oven to observe the effect of a uniform heating on the lens, we could only reflow upto a diameter of 150 μm (115° C for 35 minutes). Apparently, oven heating leads to higher evaporation of solvent, thus making the resist less mobile which hinders the mass transport during the reflow process.

4.2.3 Effect of Medium of Reflow

The medium of reflow was changed from air to liquid (oil) to observe the effect on the profile. I used a hotplate to heat the oil. However, there is a difference in temperature of the hot plate and the oil. If the lenses are reflowed under oil, care should be taken to measure the temperature of the oil, which in turn is the actual reflow temperature. Table 4.3 shows the difference in temperature of the hotplate and the oil.

Table 4.3: Reflow under oil (t=10 μm)

Hot plate temp (°C)	Oil temp (°C)	Time (minutes)	Maximum Diameter reflowed
140	117	35	150 μm
150	130	35	200 μm
203	176	30	250 μm
230	203	30	250 μm

However, we also notice see that the reflow temperature under oil is greater than that in air. We can also reflow a 250 μm diameter cylinder for most of the reflow conditions. However the reflow under oil makes the cleaning of the lens a bit difficult. We used various organic solvent such as IPA and ethanol, but none

really helped in the cleaning. Finally we resorted to cleaning with soap form, which gave satisfactory results.

4.2.4 Lateral Expansion of Photoresist during Thermal Reflow

To test the expansion properties of different sized and shaped aperture is important from the point of view of modeling, where a fixed diameter is used as a boundary condition. Moreover, a test structures with arbitrary shape can find applications in microlens with frame, as well as doughnut microlens for aberration correction. For the study, a mask made of arbitrary shaped aperture was designed. Reflow was tested for apertures with sharp corners (e.g. square triangle, etc) as well as smooth shaped apertures (e.g. circle, ellipse) and combination of both (Figure 4.2).

Figure 4.2 Structures with different apertures

It was noticed that the lateral dimensions of these structures do not change after reflow. Apparently, there is a strong adhesive force between the PR and the substrate which do not let the expansion or contraction of these structures. This observation is very important from the point of view of modeling where diameter of the cylinder (before reflow) is considered to be equal to the diameter of

microlens (after reflow). A detailed analysis for lateral expansion of photoresist during reflow is presented in chapter 5.

4.2.5 Summary

Based on the experiments we can conclude:

1. Temperature of the hotplate can be safely assumed to be the reflow temperature
2. An optimized temperature and time of 115° C and 35 minutes, respectively works well for reflow of a range of microcylinders
3. Apparently reflow on hotplate works better than reflow on oven
4. Changing media for reflow (from air to oil) have significant effect on the profile in a positive sense. However, we still persisted with reflow in air since cleaning of microlens posed a problem.
5. Lateral expansion of PR structures was insignificant which is important observation from modeling point of views

4.3 Fabrication of Micro Optical Component

The main area of interest was fabrication of converging microlenses due to their wide area of demand and application. However, during the project duration, I looked into various improvisation and modification in the basic polymer reflow technique to achieve other optical components (Figure 4.3). In this section we will discuss the modification to the basic techniques for the fabrication of other micro optical components.

Figure 4.3 Micro optical components

4.3.1 Convex Microlenses

Converging microlenses are the most important optical element of the microoptical components (Figure 4.4). The whole idea is to get an aberration free profile to form high quality convex microlenses. The applications and fabrication techniques discussed in chapter 2 was with regard to the convex microlenses.

Figure 4.4 An Array of convex microlens

4.3.2 Concave Microlenses

During the process of thermal reflow it has been experimentally found that all the lens produced by reflow are not spherical in nature and for certain geometrical dimension there occurs a dip at the centre. To create both converging and diverging profile on a single substrate, we fabricated micropillars (made of photoresist AZ9260) with same thickness, but varying diameters onto a silicon substrate (Refer section 3.1 for occurrence of dip). The whole fabrication is done in three simple steps of photolithography, viz. coating of photoresist on the substrate; exposure; and development, to get micropillars.

Figure 4.5 Simultaneous fabrication steps for concave and convex microlens

These micropillars were then reflowed at an optimized temperature and time. The whole process is depicted in Figure 4.5.

Each of the micropillars has different aspect ratio (thickness/diameter), and hence the nature of profiles generated is different as listed in the Table 4.4.

Table 4.4: Geometrical parameters suitable for the formation of
concave/convex profile

Diameter (D) μm	Initial thickness (t) μm	Aspect Ratio (t/D) μm	Dip	Profile
144	8.3	0.057	No	Convex
192	8.3	0.043	No	Convex
244	8.3	0.340	Yes	Concave
340	8.3	0.024	Yes	Neither
244	21.9	0.064	No	Convex

Figure 4.6 Profiles formed at different aspect ratio of cylinder t/D (curves 1, 2, 3: $t=8.3\mu\text{m}$,
curve 4: $t=21.9\mu\text{m}$)

It can be seen from Table 4.4 that for an initial thickness (t) of $8.3\mu\text{m}$ the profile is convex till diameter (D) is equal to $192\mu\text{m}$. As D is increased the profile changes its nature, and for $D = 244\mu\text{m}$, a concave profile is formed. However, as the thickness is increased, keeping the diameter same we again get a convex profile ($D = 244\mu\text{m}$, $t = 21.9\mu\text{m}$). Graphical representation of experimental

profiles at different aspect ratio is very well shown in Figure 4.6. Looking at graphs 2 and 3 in Figure 4.6, it can be concluded that the dip profile (or concave profile) can also be controlled with the geometrical dimension which can help to control the focal length. Cross-section

Figure 4.7 3D profile obtained using contact profilometer

Figure 4.7 (a, b) shows the 3 D experimental plot for both the cases of convex and concave profiles. These profiles were obtained using contact profilometry technique. However to use a dip profile as a diverging lens we need to use only the central part of the lens and thus would mask the outer ring (probably patterning a diaphragm on the wafer before the pillar formation) as shown in Figure 4.8.

Figure 4.8 Masking of dip profile to create diverging (concave) microlens

This peculiarity will reduce the density of lens in closely packed array, but that it is probably less an issue than for converging lens as diverging lenses are not used for light collection.

It has been shown that the formation of dip can be utilized to get a concave profile. Based on the aspect ratio, steps have devised to simultaneously create both concave and convex microlenses on a single substrate [71].

4.3.3 Cylindrical Microlenses

The fabrication of cylindrical microlenses is almost similar to the spherical microlens. The only difference is in the initial geometry of photoresist. For

Figure 4.9 Cylindrical microlens

spherical microlenses (concave or convex) the initial geometry is a cylinder. But the case of cylindrical microlens the initial geometry is either a cube or cuboid (Figure 4.9).

4.3.4 Micromirrors

Micromirrors are also formed by adding an extra step to the formation of microlens (concave, convex or cylindrical). Coating a good hemispherical profile

of a microlens with a good reflective metal like gold gives a diverging micromirror (Figure 4.10).

Figure 4.10 Micromirror

4.3.5 Micro Moulds

The fabrication of a micro mould for microlens array replication includes four basic processes, as shown in Figure 4.11.

Figure 4.11 Fabrication steps for micromoulds

Photolithography was used to form micro-cylinders (circular aperture) or cubes (square aperture) on a silicon substrate. Multiple layers of AZ9260 photoresist are coated to vary thickness (t) of the developed micro-cylinders/cubes. The thickness

was varied between 10 μm and 40 μm . Various diameters/side dimension (50 μm to 700 μm) and geometrical apertures (circle and square) were incorporated into the mask design. The pitch of the micro structures was also varied from 200 μm to 600 μm . Since very thick photoresist layers (~ 40 μm) were used, which is not normally the case in photolithography, design of experiment method was used to find out the optimal conditions for exposure and development time (Steps 1 and 2).

These structures were then reflowed (melted) at an optimum temperature and for an optimum time; such that the surface tension then pulls these structures into a spherical shape (Step 3).

The reflowed lenses were sputtered with the electroplating seed layer (Step 4; Figure 4.11) and finally, electroplated (Step 5). For sputtering, a Chromium/Gold layer was chosen to form a conductive seed layer over the non conducting PR lens and Si substrate as it presents an excellent conductivity and does not oxidize easily. Cr layer of 50 nm and Au layer of 200 nm were sputtered. Note that the combined thickness (250 nm) of the seed layer was still negligible when compared with the thickness of the lens. This ensured that the final copper mould is unaffected by the seed layer thickness.

To fabricate a electroplated structure we used copper as the mould material, as the mould will be later used for injection molding and need to be assembled with other forms obtained by traditional machining in copper. As such it is necessary to have a uniform layer of copper that is being electroplated over the microlens die

with a smooth surface finish. We found that three main parameters affected the uniformity of copper deposition, viz the rotation of the counter electrode, the current density and the seed layer area. These three parameters were optimized through a series of experiments [72].

It was observed that the rotation of the jig (wafer holder) was the most important parameter in obtaining a uniform layer of copper. To control the electroplated surface we reduced the seed layer area by covering the wafer with transparency films during the sputtering process. Finally, during our experiments we used the following parameters: current = 0.5 A; sputtered area = 37 cm²; current density = 1.45 A/dm²; rotation of jig = 20 revolution/minutes. The copper layer was electroplated until a uniform thickness of ~1.5 mm was obtained.

After electroplating, the removal of copper mould from the silicon substrate was carried out by etching Si in KOH solution (wet etching). The remaining PR lenses inside the mould were then removed by dipping the Cu mould in acetone (Step 6).

Figure 4.12 shows the SEM picture of the copper mould.

Figure 4.12 SEM pictures of copper mould

The molding technique with PDMS was employed to replicate lenses from the copper micro-lens mould [73]. Lens replication is performed to verify the functionality of the copper mould as a mass replication technique. Replication included both circular and square lens shapes.

The PDMS was mixed 10:1 with the curing agent and poured over the mold before it was left to cure at room temperature for 2 days. The slow curing ensured that very few bubble were trapped in the PDMS layer. However peeling of the PDMS after curing was a little tricky. A slight distortion was observed in certain cases despite the flexibility of the material and some PDMS was left onto the mould. Figure 4.13 shows replicated lens as observed under SEM.

Figure 4.13 PDMS microlens replicated from Cu mould

Clearly an anti-adhesive layer needs to be deposited on the mould surface as it is customary in most molding process. However we did not try to optimize this replication process as the final process will be using very different polymer. Still the replication was good enough to allow checking the geometry of the replicated lenses. Diameter and pitch measurements were done using an optical microscope

and the replication accuracy (about 1%) was found to be within measurement error, establishing the good quality of our complete process [65].

4.3.6 Summary

Thermal reflow is a very simple technique, basically used to make convex microlens. A simple modification or additions of some steps during the fabrication can help us to obtain other microoptical components. The idea behind the fabrication of all these components was to depict the technique of thermal as a versatile technique for fabrication of a range of microoptical components.

Chapter 5: Microlens Characterization

Microlens characterization is needed to optimize the process parameters of the fabrication technique, and also to satisfy the requirement for a specific application. The characterization of microlens (or even bigger lens) can be split into two groups: optical characterization and geometrical characterization. Optical characterization accommodates the point of view of end user and the applications for which it is needed. It requires the accurate measurement of parameters, like, focal length, depth of focus, aberrations, wavefront profile, efficiency and point spread function. On the other hand geometrical characterization mostly entertains the need of manufacturer, where a quick and reliable technique is needed to measure the profile of microlens, which helps in optimizing the fabrication parameters. Moreover, geometrical characterization can also provide good estimates of radius of curvature (a measure of focal length) and spherical aberration of the microlens. It also provides profile data for verification of model with experimental profile.

In principle the measurement of microlenses is no different from conventional large lenses. However, their small size does create problems using the standard equipments. Since there is no single technique which can comprehensively measure all the parameters over a range of microlens, there is a need to standardize, modify or improvise available techniques [74].

5.1 Geometrical Characterization

Geometrical characterization involves the accurate measurement of microlens profile for an estimation of radius of curvature (R_c), sag (h) and contact angle (θ).

Figure 5.1 Depiction of geometrical parameters

Also measurement of parameters like diameter (D) and thickness (t) of micro cylinder (before reflow) are very important. A complete profile is the best way to generate the information about a microlens. Various geometrical parameters are depicted in Figure 5.1.

Also measurement of parameters like diameter (D) and thickness (t) of micro cylinder (before reflow) are very important for the profile optimization, since the profile of microlens after the reflow is dependent on the initial geometry of photoresist micro cylinders. A complete profile is the best way to generate the information about a microlens, though measurement of individual parameters is quick and comes in handy to make initial guess of the profile generated.

As we discussed earlier a single technique is not available to measure the variety of parameters with accuracy, we resorted a series of technique to geometrically characterize the microlens produced (Figure 5.2).

Figure 5.2 Geometrical characterization techniques

5.1.1 Optical Microscopy

Microscope is a standard way to acquire projected image of an object. Microscopes with vertical orientation are very common, and can be used to observe the top view of a microlens. Once calibrated with a standard scale, they can provide an accurate value of microlens diameter (D) (Figure 5.3).

Figure 5.3 Vertical configuration of microscope and top measurement (D , t , h) of microlens

This value of diameter (D) then can be used for comparison of D values obtained by other techniques. In addition to D , a vertical configuration of microscope can also estimate a relatively accurate value of microlens height (h). The idea is to first being in focus the microlens base (or substrate) and then the tip of the lens. The vertical distance moved by the microscope will then give the value of microlens height (h). However, the accuracy of h may not be good for thinner microlens because of backlash and play in focusing column. Ultimately the accuracy is limited also by the depth of focus of the objective, which for large magnification (X100) is at best about $1\text{ }\mu\text{m}$.

Figure 5.4 Horizontal configuration of microscope and side measurement (D , t , h , R_c) of microlens

A horizontal configuration of microscope can also be used, which provides the side-projected-image of the microlens. Through this configuration an estimate of the values of h , t , θ and R_c can be made. Normally microlens height is very small in comparison with its diameter. Thus, an accurate value of h , t , θ and R_c is

difficult to obtain with right accuracy for the cases of thin microlens. Though the technique works well for thicker microlens (Figure 5.4).

Even though D , h , t , θ and R_c of microlens can all be approximated using these two techniques, the microscope is better for the estimation of D before and after the reflow. Table 5.1 summarizes the advantages and limitation of the technique from the point of view of microlens measurement.

Table 5.1: Optical microscopy for microlens measurements: Advantages and Limitation

Advantages	Limitation
Best way to measure lateral dimensions (D)	Gives only projected profile
Can measure h , t , θ and R_c with horizontal configuration of microscope	Do not work well for shallow profiles contact angle (θ) measurement
Non contact method	Can not measure 3D profile

5.1.2 Contact Profilometry

Contact Profilometry is a useful technique to measure 2D and 3D (using multiple 2D scans) profiles of microlens. The principle is based on a sensitive detection stylus which scans the microlens surface along a line (single or multiple scan). The accuracy of measurement is limited by the shape and the size of the stylus tip. The size of the stylus determines the ultimate lateral resolution, to about 50 nm or below, which is probably not an issue for microlens measurement. However, the shape of the tip, on the other hand, has significant influence on the accuracy of measurement for steep microlenses. The stylus tip may prove to be too wide to

reach down to the microlens edge leading to a wrong profile as shown in Figure 5.5.

Figure 5.5 Cases for contact profilometry

Especially, when the profile has continuously changing slope the estimation is very difficult. Hence, the contact angle (θ) value as well as the diameter (D) is not accurate for the cases of steep (non vertical) microlens profiles. However, the profiles generated for shallow lenses are accurate and the technique can be used confidently for microlenses below certain threshold value of slope (standard tip have an angle of 40° - 50°).

Another issue with contact profilometry is that there is always a possibility of sample damage, which occur as the diamond tip of the stylus traverse the soft photoresist surface. We note that it is not an issue for the measurement of the cylindrical profile, as the thermal reflow treatment will “heal” the eventual scratches of the stylus. More problems occur during a single scanning of the microlens or for the measurement of h ; the stylus may miss the apex, leading to an inaccurate value of lens height. Nevertheless, multiple scan of the microlens,

although slow, gives an accurate value of h . Also, measurement of thickness (t) of the photoresist (micro cylinder) before thermal reflow is very accurate. Table 5.2 gives an overview of the advantages and limitations of the technique.

Table 5.2: Contact profilometry microlens measurements: Advantages and Limitation

Advantages	Limitation
Good way to estimate t and h	Contact with specimen may damage it
Generate accurate 2D and 3D profiles for shallow lens	Inaccurate for steep profiles
D of photoresist cylinders can be estimated accurately	Slow (multiple scanning)

5.1.3 Scanning Electron Microscope (SEM)

Scanning electron microscope (SEM) is one of the ways to obtain an accurate value of contact angle (θ) and 2D projected profile. With SEM, value for contact angle is not limited to thick lens, as was the case with optical microscope (horizontal configuration). However, SEM is not capable of providing any information about the surface profile since the image captured is a projected image, which is very important to estimate the nature of microlens and the optimization of fabrication parameters. But, it can very accurately measure the values of h and D , which may be an overkill when we already have simpler techniques of measuring h (contact profilometry) and D (optical microscopy).

A simple way to find out θ and 2D projected profile (h and D) is shown in Figure 5.6. A microlens to be imaged through SEM needs to be made conductive by coating a layer of metal. With right positioning of the microlens in SEM chamber,

an image can be captured. The edges of the images can be extracted with image processing software like ImageJ. This image can then be exported to MATALAB for further processing and display.

Figure 5.6 Data acquisition from SEM image

One of the downside of using SEM is that it is a destructive technique since the photoresist (dielectric) microlens has to be coated with a conductive layer, which forbids their further use. Table 5.3 summarizes the advantages and limitations of the technique.

Table 5.3: Scanning electron microscope (SEM) microlens measurements: Advantages and Limitation

Advantages	Limitation
Good way to estimate θ	Gives only projected profile
Can accurately estimate values D and h	Maybe overkill in view of availability of simpler and cheaper techniques
Works well for all profile (shallow and steep)	Destructive technique

5.1.4 White Light Confocal Microscopy

White light confocal microscopy is a non contact method that can measure 3D profiles of steeping structures by producing sharp, blur-free images of a specimen at various depths. The basic principle is that light emitted from a point light source is imaged into the object focal plane of the microscope objective. The reflected light from the specimen, at regular depths, is detected by a photo diode behind a pinhole. Images are then taken point-by-point and reconstructed with a computer.

Figure 5.7 Profile acquired using white light confocal profilometry

A three-dimensional (3D) reconstruction of a volume of microlens becomes possible by assembling a series of thin slices taken along the vertical axis. The

minimum distance between the two slices will decide the vertical resolution of the technique, which is limited to the numerical aperture of the objective used (DOF). As understood the system depends on the detection of reflected light, which only works if the angle of reflection of the beam is small. If the slope of the microlens is larger than a critical value (linked to the numerical aperture of the imaging objective), the amount of light reflected back is too small for good data acquisition, as can be seen at the edges of the microlens in Figure 5.7.

Figure 5.8 Contact angle measurement by white light confocal profilometry

Using a higher numerical aperture (NA) objective (large magnification) can improve on the number of data points, but that leads to smaller field of view, making it difficult to acquire the complete profile. Figure 5.8 shows that contact angle can be measured using a higher magnification objective, but the field of view is smaller. Table 5.4 depicts the advantages and limitation of the technique from microlens measurement perspective.

Table 5.4: White light confocal profilometry microlens measurements: Advantages and Limitation

Advantages	Limitation
Non contact technique to generate 2-D and 3-D Profiles (h , D)	Data acquisition is not good on large slope
Contact angle (θ) can be measured by using high NA objective	Shallow lenses of large diameters cannot be adequately analyzed (trade off between vertical resolution and field of view)

5.1.5 Fluorescence Confocal Microscopy

As we have seen conventional confocal microscope can measure high aspect ratio structures, but at the edges the amount of light reflected back to the photo detector becomes negligible and hence there is a loss of data. The data acquisition at the edges of microlens can be improved by increasing the number of photons arriving at the detector by coating microlens with a layer of some fluorescence material or fluorophore. As the fluorescence signal will be emitted in all direction we not limited by the specular reflection on the sample surface as in normal microscopy. Based on the similar principle, we have developed a workable recipe for measurement of steep microlens.

Figure 5.9 Sample preparation for fluorescence confocal profilometry

The choice of fluorophore is one of the most important aspects of fluorescence confocal microscopy. The fluorophore should tag the correct part of the specimen. It must be sensitive enough for the given excitation wavelength. The surface of the microlens was made to fluoresce by coating it with a layer of Rhodamine 6G⁺ solution dissolved in MeltMountTM ++ (Figure 5.9).

For the sample preparation, a small amount of the Meltmount (quarter of the stick) was transferred to a beaker holding an equal quantity of the Rhodamine 6G solution previously prepared (0.3 gm/l). This beaker was then kept in an oven overnight at a temperature of 90°C. The dye dissolved well to form a homogenous solution. However, the Meltmount-Rhodamine solution solidified as soon as it was brought outside the oven or in touch with the cold lens surface. To obtain a layer of this Meltmount-Rhodamine solution on the lens surface, we needed a liquid which dissolved Meltmount at room temperature and did not dissolve/chemically react with the AZ9260 photoresist of the microlenses. Toluene was found to fit the criterion. A small drop of an almost saturated solution of Rhodamine6G-Meltmount solution in toluene was prepared and put on the lens surface. Toluene, being volatile at room temperature, evaporated leaving a layer of Meltmount with the Rhodamine on the lens surface. The most suitable ratio of Rhodamine 6G in Meltmount (to get sufficient fluorescence from the sample) was found to be 7.628×10^{-5} (weight/weight) (<http://www.cargille.com/meltmount.shtml>).

Multiple lenses were examined and the three-dimensional surface topography as well as parameters like radius and height was calculated with the help of

ImageProTM. The samples thus prepared were observed with a laser scanning confocal microscope. The wavelength of the laser source used was 514 nm. 25 optical sections were taken between the perceived (from the reflected light image) top and bottom of the lens, wherein each frame was averaged 6 times (Figure 5.10).

Figure 5.10 Sequence of 25 optical sections of microlens at various heights

The step size varied in accordance with the height of the lens used. The fluorescent images thus obtained were analyzed. The approach was successful and gave very accurate readings for the diameter and height of various lenses. Using the count size option in ImagePro, these images were measured for their area, which was then used to calculate the radius. From the data file generated by the confocal microscope, we know the distance between individual frames, which fix the vertical resolution. This was used to calculate the distance of each frame from the lowermost frame (that is, the one with the largest radius). A plot with diameter and height then gives microlens profile (Figure 5.11).

Figure 5.11 Steep profile measurement by fluorescence confocal profilometry (Half profile)

Profile measurement by reconstruct fluorescence confocal microscopy technique is an accurate non-contact topography method that can be applied for the measurement of steep microlenses with good data acquisition at the edges of microlens. However, there are certain limitations to the technique which are listed along with its advantages in the Table 5.5.

Table 5.5: Fluorescence confocal microscopy microlens measurements: Advantages and Limitation

Advantages	Limitation
Non contact technique to generate 2-D and 3-D Profiles (h , D , θ)	Shallow lenses of large diameters cannot be adequately analyzed (trade off between vertical resolution and field of view)
Better data acquisition at the edges of microlens (even with large slope)	Sample preparation is time consuming and the technique is not completely non-destructive

5.2 Results: Geometrical Characterization

Having explored the various characterization techniques from the perspective of microlens measurement, we discuss our characterization results and their implications for the microlens, which were carried out by the techniques discussed above.

5.2.1 Study of Lateral Expansion of Photoresist

Checking the lateral expansion of photoresist during the reflow process is needed for a better understanding of the process. The information is also required during the mathematical modeling of reflow technique, which was one of the concern. I measured the diameter of the micro cylinder (before reflow) and diameter of

Figure 5.12 Microlens diameter (D) comparison before and after reflow by optical microscope measurements with error in measurement

microlens (after reflow) using an optical microscope. We estimated the measurement error by measuring each sample for 5 times. The variation in diameter was observed to fall within $\pm 1 \mu\text{m}$. Using this variation in measurement of diameters ($\pm 1 \mu\text{m}$), we calculated the percentage difference in diameters (before and after reflow) over the diameter of micro cylinder (before reflow), along with new error values. This result is depicted in Figure 5.12. As can be seen the percentage variation in diameter for more than 90% of values falls within $\pm 2\%$. From this analysis it is apparent that the adhesion between the photoresist and the substrate is very strong and it doesn't allow any lateral movement of the resist during the thermal reflow. This means that the diameter before reflow is same as diameter after reflow. The result is significant, especially during the modeling of the process, where non variant nature of diameter can be used as a boundary condition.

5.2.2 Measurement of t and h

Accurate measurement of t and h plays a significant role during the process optimization. Once the value of D is fixed (which is decided during the mask design), it is t that determines the profile formation and can be controlled by the manufacturer. Similarly, it is h along with D , that determines the radius of curvature and hence the focal length of the microlens formed after reflow. Thus, an accurate estimate of h is needed to estimate the value of R_c . Both the t and h were measured using contact profilometry technique. The vertical resolution of

Figure 5.13 Microlens height (h) measured at different values of using D using contact profilometry [$t=27.5 \mu\text{m}$]

stylus was 100 nm, and error in measurement was also less than 100 nm. Hence, the values of h were recorded with no significant error as shown in Figure 5.13.

5.2.3 Measurement of Contact Angle

Understanding the variation in contact angle (θ) of microlens w.r.t microlens diameter (D) for optimization of process is needed for the generation of aberration free microlens profile. We used SEM image to estimate θ for a range D . To estimate error, we used multiple measurements (5 times) on a sample to check the accuracy, and a found a deviation of 2° in the two extreme readings. While this variation can be estimated, the amount of error incurred during the image processing (ImageJ) and curve fitting (MATLAB) is difficult to estimate.

Assuming an error of 2° we plotted variation in θ with change in D of the microlens (Figure 5.14).

Figure 5.14 Experimental plot for diameter vs. contact angle using SEM ($t=21.4 \mu\text{m}$)

A theoretical value of contact angle based on the spherical profile is also plotted with the experimental data. As can be seen, the deviation in contact angle from theoretical value (a measure of sphericity of microlens) increases after certain value of diameter ($D > 400 \mu\text{m}$). This means that a deviation in spherical shape of microlens occurs, which can be used as a way to control profile shapes for aberration free microlens. Moreover, variation in contact w.r.t microlens diameter for a constant thickness of photoresist cylinder was the basic hypothesis used during the microlens profile modeling (Chapter 3).

5.2.4 Estimation of R_c

Another important parameter of a microlens is its radius of curvature (R_c). As told earlier, an accurate estimate of focal length (F_l) (based on R_c) can be made using the geometrical measurements of microlens. There is an indirect way to find out R_c of the microlens using the value of h and D measured from contact profilometer and optical microscope, respectively. Here we assume that the profile formed is spherical in nature and the radius of curvature can be estimated by the values h and D .

A theoretical value of h can also be calculated to estimate theoretical value of radius of R_c and focal length using the relation $R_c = [h^2 + (D/2)^2] / 2h$, as a means of comparison.

Figure 5.15 Radius of curvature based on spherical profile by contact profilometer measurements [$t = 27.5 \mu\text{m}$]

As already assumed the error in measuring h is too small to affect the value of R_c , the error estimate of R_c is dependent on the accuracy of D , which was estimated using the error analysis, and is shown in Figure 5.15. From the graph, the value of R_c for a range of D were estimated, and these values can be used as first guide to design microlens. While this is true, this plot is also indicative that for diameters (D) larger than 400 μm microlens profiles deviate from the ideal spherical profile (for $t=27.5 \mu\text{m}$).

5.2.5 Verification of Modeling of Microlens Profile

The experimental profiles obtained are compared with Young-Laplace model and a spherical fit (equivalent to geometrical model).

An experimental profile along with Young-Laplace model is plotted in Figure 5.16 to illustrate how these profiles compare with each other.

Figure 5.16 Profile comparison: Model vs. Experimental

It is to be noted that Young-Laplace model spans only half of the microlens profile as its initial condition is set at apex and evaluated towards the right edge of base. As can be seen Young-Laplace model is in good agreement with the actual profile. Difference of profile is shown in Figure 5.17 to quantify the deviation between experimental profile and model profile. A maximum variation of $1.5 \mu\text{m}$ can be seen at coordinate $D = 100 \mu\text{m}$, which will also include measurement error.

Figure 5.17 Deviation between model profile and experimental data

The experimental profiles obtained were also compared with spherical fit (equivalent to geometrical mode). An experimental profile with spherical fit, along with the deviation is plotted for both the cases of profile with dip and without dip. Figure 5.18 shows that the microlens is also in good agreement with the spherical fit for the profile without dip.

Figure 5.18 Spherical fit to experimental data: Without dip

This is further confirmed by the error plot in Figure 5.19, where we see that for most of the surface of the lens the error is less than 500 nm.

Figure 5.19 Error plot indicating the deviation of the measured profile with the fitted hemispherical profile: Without dip

Figure 5.20 Spherical fit to experimental data: With dip

However, similar conclusion is not true for the cases where dip occurs, as can be seen in Figures 5.20 and 5.21. The amount of error has increased to more than 3 μm , clearly showing that the microlenses are not spherical.

Figure 5.21 Error plot indicating the deviation of the measured profile with the fitted hemispherical profile: With dip

However, closely observing the error plots (Figure 5.19 and Figure 5.21) between the experimental data and the spherical fit, we can clearly see a difference in error for the two extreme points. This difference is seemingly inherent in the stylus measurement, and does not depend on model (both geometrical and Young-Laplace). This error once accounted will further reduce the deviation between experimental profile and model profile.

5.3 Comparison of Techniques

All the five techniques explored were used to measure microlens profile and other parameters (D , t , h , θ , R_c). Few techniques suited a certain parameters based on the accuracy, ease of measurement, nature of technique (destructive or non destructive). A summary of suitability of techniques is given in Table 5.6. An arbitrary indicator of the feasibility of a technique, based on our experience of microlens characterization, is devised. “+” represents the suitability of technique, “+ + +” being the most suitable; $\times$ represents the unsuitability of the technique.

Value of D was mostly measured by the vertical configuration of the optical microscope, which suited it the most. t and h were mostly measured by contact profilometry. Value of θ was measured using an SEM. For shallow lenses profile measurement contact profilometry was used, while steep lenses profile were measured using fluorescence confocal microscopy. A validation of h can be done by white light confocal microscopy, while estimate of D , h , R_c and θ can be made using vertical configuration of microscope for the thick lenses.

Table 5.6: Comparison of geometrical characterization techniques

Technique/ Parameter	Optical Microscope (Vertical Configuration)	Optical Microscope (Horizontal Configuration)	Contact Profilometry	SEM	White Light Confocal Microscopy	Fluorescence Confocal Microscopy
Profile	2 D Projected	2 D Projected	2D/3D	2D Projected	2D/3D	2D/3D
Lens Type	All	Thick	Shallow	All	Steep	Steep
D	+++	++	++	++	++	++
H	+	++	+++	++	+++	++
T	+	++	+++	×	×	×
θ	×	+++	++	+++	++	++
R_c	×	++	++	++	+	++

5.4 Material Characterization

Based on the applications, polymer microlenses can be directly used or can act as a mask to transfer the spherical profile to a glass substrate. For the application when these photoresist microlens are directly used, two important optical properties of photoresist (viz. refractive index and transmission spectra) are required to be studied to find out the suitability of photoresist as a structural material for microlens.

5.4.1 Refractive Index of Microlens

Prism Coupling System (Metricon 2010) was used to measure the refractive index of photoresist (AZ9260). A layer of thickness $\sim 12 \mu\text{m}$ was spin coated on glass slides. These glass slides were baked at different temperature and time (Table 5.7). The idea was to simulate the optimized condition of reflow (115°C for 35 minute).

Table 5.7: Study of refractive index (Wavelength of light: 633 nm)

Sample	PR layer baked at Temperature ($^\circ\text{C}$)	Baking Time(minutes)	Refractive Index
A	115	10	1.6212
B	115	20	1.6243
C	115	35	1.6255
D	115	40	1.6241
E	110	4	1.6132
F	110	20	1.6192

At the optimal condition of reflow (115°C for 35 minute), the value of refractive index was found to be 1.6255.

5.4.2 Transmission of Light Spectrum

The objective of this experiment was to study the changes in the transmission of the light spectrum after the reflow temperature (115°C for 35 minutes) is reached. We used the UV spectrophotometer to measure the transmission spectrum for both before and after reflow conditions. Two similar glass slide were coated with different thicknesses of the AZ9260 photoresist. The difference is thickness of PR was measure and was found to be $17 \mu\text{m}$. Both of these glass slides were then cut into two halves. One of the set of slide was heated at the temperature of 115°C for 35 minutes; transmission was measured and data was plotted. For the second set of glass slide, the transmission was measure and plotted at without baking. Figure

5.22 shows the graph for percentage transmission at various wavelength of light, for both cases.

Figure 5.22 Percentage transmission of light (spectrum) before and after heating of resist for 17 μm thick resist (without Fresnel loss)

We can notice that transmittivity of the photoresist remains almost zero (for both of the cases) till 320 nanometer of wavelength. The transmission starts increasing after that and reaches the maximum value 90% (approx) at 800 nanometer of wavelength. However between these two values, the transmission is different for both of the cases. From this study we can safely deduce that the microlens produced by thermal reflow of photoresist have good transmission value ($>80\%$) for wavelengths greater than 600 nm. At this wavelength a lens about 40 μm diameter will roughly absorb about 40% of light that is a lens of about 2 dB, which in general acceptable.

5.5 Focal Length Characterization

Focal length is the most important criterion from the point of view of end user. . However, it is difficult to measure focal length accurately and easily at the same time for microlenses. In this section we will discuss three different techniques to estimate the focal length of the microlens.

5.5.1 Focal Length Estimation Using Theoretical Model

This is an indirect technique to find out the value of focal lengths. Here we assume that the profile formed is spherical in nature and the radius of curvature can be estimated by the value h and D . A theoretical value of h is used to find out the theoretical value of radius of R_c . Experimental value of h was measured using a contact profiler. Based on the value of respective value of h and D , theoretical as well as experimental focal length based on spherical profile can be calculated.

Table 5.8: Experimental value of diameter (D) and sag (h) for t=21.4 μm

Diameter (before reflow) μm	Diameter (after reflow) μm	After reflow sag (h) μm
40	43	27.9
54	53	30.1
74	74	34.1
95	96	36.0
114	114	37.3
146	147	38.8
195	196	40.1
244	245	40.7
291	290	41.4
340	341	41.0
392	390	41.0
441	438	40.7
490	490	40.7
591	590	39.7
687	690	38.1

The equations which related sag (h), diameter (D), radius of curvature (R_c), and refractive index (n) to focal length (f) are discussed in chapter 3 (Equation 3.1 to 3.6). Table 5.8 shows the experimental value of h w.r.t. D . A plot for focal lengths is shown in Figure 5.23.

Figure 5.23 Focal length based on spherical profile

These values of focal length are calculated for refractive index (n) of 1.62, as measured in section 5.4.1. Focal lengths shown here are good indicator, and were used to optimize the fabrication process.

5.5.2 Microscopic Technique: Object at Finite Distance

We propose a simple technique to measure focal length of a microlens that can be used in any lab and is based on imaging using a simple microscope. Actually when we observe a microlens under a microscope, the microlens becomes part of the optical system and will change the way the image of the microscope is formed.

In our case we place a simple aperture in the illumination path of the microscope and we try to find its image by varying the focus of the microscope. Actually it turns out that for different focus position we observe multiple focused images of the aperture. By using the position of the image it is possible to retrieve the focal length the microlens. In our system, the estimation of the focal length of the microlens is simply based on the measurement of the image position for an object placed at a finite distance from the microlens. However, in the fabrication of microlenses on wafer surface, it is not easy to access both side of the lens as the substrate is often opaque and reflecting. In seeking a simple way to make this measurement, we decided to use a reflecting refractive microscope, a tool commonly found in most laboratories, and take the measurement from one side of the lens.

Fig 5.24 Close up of microscope setup

A ray diagram is used to explain and illustrate the images formed from the plano-convex lens on a reflective silicon surface. This arrangement presents itself a way to measure the focal length of microlens. Using this combination of microlens on mirror, we studied the image formation by means of Mitutoyo FS60 microscope (Figure 5.24).

We briefly describe the steps:

1. Place an object between the lamp and the objective.
2. Bring the microscope objective (include all the component except the stage) to configuration **I** (Figure 5.25). Let k be the distance between the objective and objective plane.
3. Place the mirror (without lens) on the objective plane. Move the setup by distance a for image to be formed (Case II).
4. Bring the combination of microlens on mirror on the objective plane. Move by distance b in opposite directive to form the image again (Case III).
5. Using geometrical optics it is easy to deduce that $a-b$ acts as the image distance (v) and $a+b$ acts as the object distance (u). Using thick lens correction, $v = a-b-h$; and $u = -(a+b-h)$. Value of u is negative because the object is virtual (sign convention).
6. Using object distance and image distance, the focal length of the microlens can be found. However, this focal length (f) is half the focal length of the plano convex lens. A plano convex lens on top of a mirror acts a double convex lens because of the 2 times refraction at the curved surface: one,

when the light enters from air to lens; two, when the same light after being reflected from the mirror is again passed through the lens (Figure 5.26).

Figure 5.25 Focal length measurement using a microscope: Schematic

Figure 5.26 Refraction at curved surfaces

The image formed at the mirror (silicon substrate) for case II and a de-magnified image through microlens (case III) is shown in figure 5.27.

Figure 5.27 Images through mirror and microlens

Value of a depends on objective magnification and object position. We used an objective of 20X magnification and fixed the object position. Once these two parameters were fixed, the value of a was constant for all the microlens, and was

Table 5.9: Parameters for focal length measurement using microscope (Objective: 20X)

Microlens Diameter (μm)	Sag (h) (μm)	a (μm)	b (μm)	$v=a-b-h$ (μm)	$u=- (a+b+h)$ (μm)	$f=uv/u+v$ (μm)	$2f$ (μm)
196	40.1	585	462	82.9	-1087.1	89.7	179.4
245	40.7	585	418	126.3	-1043.7	143.6	287.3
290	41.4	585	374	169.6	-1000.4	204.2	408.4
341	41.0	585	331	213	-957	273.9	547.9
390	41.0	585	285	259	-911	361.8	723.7
438	40.7	585	242	302.3	-867.7	463.9	927.8
490	40.7	585	200	344.3	-825.7	590.5	1181.0
590	39.7	585	135	410.3	-759.7	892.1	1784.2
690	38.1	585	90	456.9	-713.1	1271.7	2543.4

found to be 585 μm . Value of b decreases with an increase in the microlens diameter. Values of all the parameters are shown in Table 5.9. Sag (h) and diameter (D) were measured using a profilometer and microscope, as discussed earlier. A plot of microlens diameter and focal length is shown in Figure 5.28. The trend is very similar to the one obtained by spherical model.

Figure 5.28 Focal length by microscope: Object at finite distance

5.5.3 Measurement of Focal Length with Object at Infinity

A more direct measurement of microlens focal length would be to use an object placed at infinity: in that case the distance between the microlens apex and the image plane directly equals the focal length. The measurement requires a well aligned and precise setup. The layout of the designed setup is shown in Figure 5.29. A brief description of the components used and their specification is given below:

1. LASER Source: The laser source used was a HeNe Laser (Wavelength 633 nm). Laser light is often chosen for focal length measurement due to its coherent nature. This means that the emitted light waves are in phase with one another and

are nearly parallel; they are able to travel a considerable distance without spreading as compared to a bright light source example lamp.

2. Microlens (With Stage): Microlens holder with a stage was used to ensure rays of laser light is parallel to the principle axis of the microlens for precise measurements and to avoid any unnecessary refraction of beams.

Figure 5.29 Layout of experimental setup for focal length measurement

3. Imaging Setup (Imaging Lens and CCD Camera): An imaging lens was used to bring the image closer to the CCD camera because of the order of focal length for microlens would be in micrometer regime. Different microscope objective (such as 5X to 20X) were used depending on the diameter of microlens tested. The CCD camera was used to observe and capture image of laser spot focussed by the microlens.

4. Piezo Actuator: The actuator was used to move the imaging setup for very precise focussing of the laser spot. The actuator used could move up to a very precise step of 100 nanometer.

Figure 5.30 Experimental setup for focal length measurement

An experimental setup for the focal length measurement is shown in Figure 5.30.

A ray diagram showing the focal length measurement is using the above setup is shown in Figure 5.31. Parallel beams of light after being refracted by the microlens is focused at the focal point. The distance between the microlens apex (or tip) and the focal point gives the back focal length of the microlens.

Figure 5.31 Ray diagram for focal length measurement

Microlens images at two different cross section are shown in Figure 5.32. The first image shows the microlens edge. Second image shows the focused laser spot by microlens

(a) Microlens edge

(b) Microlens focal point

Figure 5.32 Microlens images at different sections

Table 5.10: Focal length comparison [Refractive index (n) = 1.62]

Diameter of microlens (D) in μm	Optical Focal Length (f_{opt}) in μm	Focal Length derived from R_c ($f = R_c / n - 1$) in μm	Percentage Difference ($f_{opt} - f$) / f_{opt} X 100
674	2121	1980	6.6
579	1409	1386	1.6
474	938	924	1.5
424	709	753	-6.2
377	557	600	-7.7
324	468	453	3.2
275	339	341	-0.6
225	250	247	1.2
178	182	173	4.9
125	122	104	14.7
98	89	79	11.2
78	65	63	3.0
43	37	39	-5.4

Table 5.10 compares the focal length measured by the experimental setup (f_{opt}) and the theoretical focal length (f) based on the spherical profile, along with the percentage difference.

A graphical plot for the focal length for various microlens diameters is shown in Figure 5.33.

Figure 5.33 Optical focal length measured using experimental setup

Chapter 6: Microlens on Optical Fiber

6.1 Introduction

Bio-Imaging fibers are integral part of medical endoscopic systems, as it offers potential imaging and sensing applications. Imaging fiber bundles and integrated fiber lens forms the imaging fiber conduit. However, current imaging fiber lenses are based on integrated GRIN rod lenses, which pose distortion problems in the image. Also, illumination and imaging channels has to be separate. A new generation of imaging fibers with custom made multiple lenses configuration can subdue such limitations by enhancing the illumination areas as well as acceptance cone for imaging. To that effect we propose to use microlens fabricated using polymer reflow. For a biomedical application we need to terminate a 600 μm diameter imaging fiber with a group of lenses of different diameters - but with similar focal length. We have devised a microfabrication process on a silicon wafer to produce the lens with variable diameter and identical focal length, while etching the silicon wafer has helped us producing a sheath to insert the optical fiber and mount the lenses on the optical fiber [75].

6.2 Requirements and Design

The application requires a combination of lenses with same/different focal lengths and/or surface areas on tip of an optical fiber. Out of these combination, certain lenses (smaller) will act as illumination channel to lighten up the object, whose image will then be captured by the central (big) lens which will feed the

information to the imaging channel. This information will then be processed and utilized for the biomedical application. For this particular case illumination lenses will have short focal lengths in comparison with that of imaging lens (as shown in the Figure 6.1). In other case, the illuminating lenses are of same focal length but different surface area (diameter). This particular requirement then add one more step to the process. We will discuss both of these cases in the fabrication detail. Since silicon is used as a substrate, a transparent layer of another material was needed which would support the lenses after the removal of silicon. This layer will also act as a connecting platform between the optical fiber and the lenses.

Figure 6.1 Lenses on fiber for illumination & imaging

6.3 Modeling of Lenses for the Design

The microlens elements were modeled as thin paraxial lenses. The design parameters of microlenses were based on ray tracing. It involved the volumetric equivalence and geometrical considerations.

Using equations (section 3.2.1), it is possible to determine a combination of thicknesses and diameters for a specific focal length. The dependence of focal length on these two parameters gives us latitude to design a permutation of microlenses for a comparable focal length but with different thicknesses and diameters. A plot based on the above model is shown (Figure 6.2). We assumed index of refraction (n) for the photoresist (AZ 9260) = 1.62.

Figure 6.2 Equal focal length for combination of D and t

As, our application required a set of microlenses on top of a 600 μm diameter optical fiber. We considered two cases:

Case 1: Small lenses (illumination lenses) have shorter focal lengths in comparison with that of imaging lens (big central lens).

Case 2: Both small and the central (big) lenses have the same focal length.

As we can see from the plot (Figure 6.2) the focal length could be increased either by increasing the diameter or by decreasing the thickness. For the first case, we need short focal lengths illumination lenses (smaller diameter) and large focal length imaging lens (bigger surface area, thus bigger diameter). For the second case we used a thicker central (big) lens to decrease its focal length so as to match it with the thinner and smaller outer lenses.

6.4 Mask Design

The whole fabrication involved the use of 3 masks:

Mask 1: This mask was designed for making an entrance hole for the insertion of optical fiber. The insertion hole has the diameter of 600 μm which coincided with the diameter of the fiber.

Figure 6.3 Mask 1

The design also incorporated a bridge between the substrate and the lens frame to hold the frame onto the substrate, so as to prevent it falling during the etching step. The mask was designed as a dark field clear feature mask. This mask was used on the back side of the double side polished wafer (Figure 6.3).

Mask 2: Mask 2 consists of square patterns to generate a square shaped hole (the depth of which depends on the thickness of the SU8 layer). This is used on the top side of the wafer, in alignment with the back side circular opening for the fiber. This mask provides the differential thicknesses of AZ9260 PR layer for central big

lens and outer smaller lenses. The mask was designed as a dark feature clear field mask, since a negative photoresist (i.e. SU8) was being patterned (Figure 6.4).

Figure 6.4 Mask 2

Mask 3: This mask was designed for the photolithography of the micro cylinder (both central big lens and outer small lenses), which were to reflow to make microlenses. The mask was used in alignment with the square shaped holes on the mask 2. It was a dark feature clear field mask (Figure 6.5).

Figure 6.5 Mask 3

Figure 6.6 shows the superimposed design of the three masks.

Figure 6.6 Arrangement of cells on the mask

6.5 Fabrication Details

To obtain different initial polymer thickness, as required for the case 2, we used a pedestal under the lower lens pillar as presented in Figure 6.7.

Figure 6.7 Top view & cross-sectional view of the device

The diameter of central (bigger) lens D , and the diameters of outer (smaller) lenses could be varied as long as they add up to give 600 μm (which is the diameter of the fiber), with sufficient gap between each lens. Based on the diameters (D and d) and the focal length required we chose the thickness of PR for the lenses. Figure 6.8 depicts the notation for various dimensions used in mask design. D_f is the diameter of the fiber (which is equal to 600 μm for the case shown). D_h and a represents the size of square hole and distances between the lenses.

Figure 6.8 Notation for design parameters

Table 6.1: Microlens design parameter

Cell	D_h (μm)	a (μm)	d (μm)	D (μm)
1	290	75	75	200
2	280	70	110	200
3	260	50	100	200
4	260	60	80	200
5	260	60	90	200
6	260	50	70	200
7	280	45	75	220
8	280	60	90	220
9	300	80	100	200
10	-	-	100	250
11	-	-	80	250
12	-	-	90	250

For example, if $D = 200 \mu\text{m}$ and the focal length required is $500 \mu\text{m}$, the thickness of PR for the central lens will act as a constraint, which will be fixed at $\sim 8 \mu\text{m}$ (see Figure 6.2). Now the focal length of the illumination lens will determine its diameter, since both lenses will have the same thickness (first case) i.e. if we need the a focal length of $200 \mu\text{m}$, the diameter (d) will be fixed at $120 \mu\text{m}$. For the second case where we need the comparable focal lengths for both type of lenses, we have plenty of combinations for the small lenses to reach the same focal length of $500 \mu\text{m}$. For example, $d = 150 \mu\text{m}$; $t_1 = 5 \mu\text{m}$ or $d = 100 \mu\text{m}$; $t_1 = 2.5 \mu\text{m}$, etc. However, there are limitations based on the fabrication methodology as well as the reflow process (insufficient surface energy) which limit the choice. A completer list of design parameters are shown in Table 6.1.

Double polished silicon wafer was used as the substrate for the fabrication. The wafer was coated with $10 \mu\text{m}$ layer of SU8-10. All the intermediate procedures were followed as per MicroChem Data Sheet for SU8-10 [appendix]. This layer was exposed without any mask. After exposure it was post baked but not developed. The wafer was bonded with another wafer (support wafer) using a thin coating of AZ9260 PR on the side of SU8 coating (front side). A support wafer is desirable during the through hole etching (DRIE) to prevent any breakage of the main wafer due the flow of gases. Back side was then used for DRIE etching of the wafer to make it compatible for fiber inclusion. A small link to latch each cell on the wafer was left to prevent it from falling during the process. The front side of the wafer was then again coated (t_2) and patterned with SU8 layer (Figure 6.7). This step provided a platform for coating a layer of AZ9260 PR, giving different thicknesses of AZ9260 PR at the centre (T) and at the circumference (t_1). Some

samples with uniform thicknesses throughout were also included to obtain variable focal lengths for illumination and imaging lenses. This layer of was AZ9260 was coated, patterned and reflowed at optimum temperature and time to make the lenses. Backside etching of the wafer, to facilitate the inclusion of the fiber, was performed before the fabrication of the lenses to avoid any heat treatment during the DRIE, which could damage the lenses.

Stepwise explanation of the process as shown in the Figure 6.9 is given below:

1. Base layer of SU8 was spin coated on cleaned double sided polished silicon wafer.
2. A layer of AZ9260 was coated on top SU8 layer, which facilitated the bonding of support wafer.
3. Backside etching of main substrate is done using anisotropic DRIE etching. Mask 1 is used. The support wafer is then removed carefully so as to avoid any damage to the SU8 layer
4. A second layer of SU8 is coated and patterned. Mask 2 is used.
5. A layer of AZ9260 is coated over the patterned layer of SU8. This layer acts as the structural material for microlens fabrication.
6. AZ9260 layer is patterned using mask 3.
7. The patterned microcylinders are then reflowed at optimum temperature and time to get microlenses.

For case 1, step 4 is not required since the initial thickness for both illumination and imaging lens is same (i.e. $t_2 = 0$ and $t_1 = T$) which makes the process simpler and reduces the number of mask from 3 to 2. However, for

case 2, there are intermediate steps between 4 and 5 (Figure 6.10). These additional steps include a second spin coating or a plasma etching or both to make the surface of PR uniform throughout.

Figure 6.9 Flow chart for fabrication

Figure 6.10 Substeps to achieve step 5

6.6 Results and Discussion

The parameters (D , d , t_2 , t_1) were varied to try different combinations of lens diameters and thicknesses, which in turn affected the focal lengths of lenses combinations. For the central lens (imaging lens) the diameter was varied from 200 μm to 250 μm . The diameters of the outer (illuminating) lenses were also altered from 70 μm to 110 μm .

6.6.1 Base Layer

The base layer of SU8 acts as a transparent seat for PR microlens. The transparent layer of SU8 is required because it is an interface between the fiber and the lenses. SU8 is also a negative photoresist and once exposed it doesn't get affected by further exposure or development. It also becomes very robust once crosslinked,

and hence gives good overall sturdiness to the device. The thickness of SU8 base layer was chosen to be 10 μm , and could be varied based on the requirement.

6.6.2 Wafer Bonding

Before processing the wafer for DRIE process, it was bonded with another wafer. Since the DRIE was through-hole, a support wafer was needed to strengthen the main wafer so as to avoid any breakage due to gas inflow. However the bonding used was a temporary one, so that wafers could be easily removed without affecting the SU8 layer beneath. Two different ways were tried to bond the wafers:

1. A layer of AZ9260 PR was coated on the support wafer and was manually adhered to the main wafer. This set of wafers was then heated at 110°C for 10 minutes to achieve the bonding. However the removal of wafers was a bit tricky in this case. Acetone was used to dissolve the AZ9260 PR layer. But keeping the wafers in acetone for longer period affected the SU8 layer underneath. An optimum time was required such that acetone can dissolve AZ layer without affecting the SU8.
2. Vacuum grease was used to stick the wafers together. The removal was easy too. However the removal (cleaning) of the grease after the process was a problem. To decrease the area of wafer in contact with the grease, only 4 small drops of grease were used to bond the wafers. This decreased the cleaning of grease though not completely eliminated it.

Both these approaches worked well for the bonding of wafers.

6.6.3 Formation of Silicon Frame

Through-wafer etching was achieved using Alcatel DRIE machine. The wafer thickness of 425 μm was etched with standard parameters. However the etching rate was first determined by etching the wafer for 10 minutes and measuring the depth of etch. Based on the etching rate determined and total thickness of the wafer, etching time was calculated (Figure 6.11).

Figure 6.11 Etching at the corners

Etching rate at the centre was found to be larger than at the corners. This differential etching rate was apparently due to the difference in etching area. The

(a) Wide View

(b) Close view

Figure 6.12 Silicon frame after DRIE etching

etching area was far greater at the centre than that at the corners. Therefore etching of the corners was considered the deciding factor to gauge the completion of through-etching process. A connecting link was provided, which could be seen in the Figure 6.12 (b). This feature was implemented during the design phase to avoid dropping of the structure during DRIE process. The etching has to be inspected throughout the DRIE process since a prolonged etching might affect the SU8 layer beneath. Though the selectivity between silicon and PR is quite high (approx 1:150), yet over etching was intentionally avoided to minimize the interaction of gases with the SU8 surface.

6.6.4 Wafer Removal

As mentioned earlier, another challenge was to remove the bonded wafers after DRIE (the support wafer and the main wafer). Since AZ9260 PR was used to bond the two wafers (which also included SU8 layer in between), acetone was used for the removal but for an optimum time; such that it dissolved AZ PR but did not affect SU8. Prolongated use of acetone dipping could affect the SU8 layer which is the base used for making lenses. Wafers bonded with vacuum grease were removed manually, without the application of any solvent

6.6.5 Differential Coating

The depth of the central square (t_2) which is responsible for differential thicknesses for the central and outer lens was varied from 0 to 34 μm . When $t_2 = 0$, step 4 no longer exists which in turn makes the fabrication simpler. Thickness of AZ9260 layer (t_1) was also varied to compensate for the depth using multiple

coatings. Profilometer was used to measure the depth of the square holes patterned on the SU8 layer.

Figure 6.13 Square hole

A typical square hole patterned on SU8 layer is shown in Figure 6.13. One of the concerns was to get sharp edges so as to define the square hole distinctly. Following the SU8 data sheet from Microchem, to develop the resist, helped a lot in avoiding indistinct edges.

Table 6.2: Multiple coating

Depth of square hole t_2 (μm)	Differential thickness of AZ9260 coated (μm)			Thickness t_1 (μm)	Deduction-Resultant thickness with hole T (μm)
	Coating 1	Coating 2	Coating 3		
4.6	3.9	2.4	1.4	18	23
9.1	6.3	2.4	1.5	27	36
15.5	12.1	4.2	1.7	33	48
34.6	23.9	6.1	3.5	43	77

Single coating of AZ9260 was not sufficient to get an even layer throughout.

Multiple coating helped achieved an even layer. This technique presents a simple way to obtain different values of thicknesses across the wafer with a single mask. A range of difference in thickness ($T-tI$) can be obtained based on the depth of the square hole (Table 6.2). Figure 6.14 depicts the technique of multiple coating. A square hole of depth $9.1\text{ }\mu\text{m}$ is coated with PR (coating 1). This leads in a decrease in differential height. Third coating finally reduces the differential height to $1.5\text{ }\mu\text{m}$. Due the multiple coating the overall thickness of PR may sometime exceeds the required thickness. Reactive ion etching (RIE) can reduce the overall thickness of the PR, keeping the difference constant. This way a range of values, to design the microlens, can be obtained.

Figure 6.14 An experimental plot for differential coating

Table 6.3 shows the values of various parameters used to etch AZ9260. Since the substrate is made of SU8 (a photoresist), we observed some etching on the SU8 substrate also.

Table 6.3: RIE Parameters (O_2 : 9 sccm; CF_4 :1 sccm; Power: 200-220 W; Pressure: 88 mTorr)

Time	Thickness (SU8)	Thickness (AZ9260)
0	51.3 μm	23.3 μm
40 minute	48.5 μm	16.9 μm

The etching rate for AZ9260 was far greater than that of SU8. However, etching of SU8 is not significant for the process since a thicker layer of SU8 will nullify the effect.

6.6.6 AZ Patterning over the SU8 layer

A layer of AZ9260cp was coated on the SU8 substrate (both with square holes and without it). This layer was then exposed and developed in the standard AZ9260 developer.

Figure 6.15 PR cylinders without square hole (case 1)

Figure 6.15 shows the microscopic picture of microcylinders array for case 1. A profile of such is shown in Figure 6.16. The thickness of central big cylinder as well the outer small cylinders.

Figure 6.16 Profile of PR cylinders (case 1)

For case 2, the micro-cylinders were fabricated with differential thickness, as shown in Figure 6.17. The overall thickness of the central big cylinder is more than that of outer small cylinders, as seen in Figure 6.18.

Figure 6.17 PR cylinders with square hole (case 2)

The increment in thickness is directly proportional to the depth of the square hole.

Figure 6.18 Profile of PR cylinders (case 2)

Figure 6.19 shows the photoresist cylinders on top SU8 layer, along with the outer silicon frame. These cylinders are yet to be transformed into microlenses by the reflow process.

Figure 6.19 Full view after PR patterning (before reflow)

6.6.7 Thermal Reflow

Reflow temperature was studied and optimized at 115° C for 30 min. (refer chapter 4). The process was carried out on a hotplate (rather than oven) which apparently helped in achieving a more spherical profile.

Microscopic picture for the cases are shown in Figures 6.20 and 6.21.

Figure 6.20 Microlens without square hole (case 1)

Figure 6.21 Microlens with square hole (case 2)

A complete image of microlens along with the silicon frame is shown in Figure 6.22

Figure 6.22 Microlens with silicon frame

6.6.8 Measurement of Microlens Profile

Lens profiles were measured using the profilometer to estimate the curvature and hence the focal length of microlens for both the cases. Figures 6.23, 6.24, 6.25 and 6.26 show the microscopic view of lenses on top of SU8 layer, along with their profiles which were measured using profilometer. A square hole could be clearly seen in the microscopic image (Figure 6.27). A careful inspection of the profile will also reveal the same. Here, the difference in the height of the tip of lenses is not only due to the difference in the original thickness, but also due to the reflow process. It has been found that bigger diameter lenses will attain bigger dome height or sag (h). This could be verified with the Figure 6.24. Here, the original thickness before reflow was the same, but after reflow the central lens (bigger lens) resulted in higher dome height (h).

Figure 6.23 Microscopic image of microlens (case 1)

Figure 6.24 Profile of microlens (case 1)

Figure 6.25 Microscopic image of microlens (case 2)

Figure 6.26 Profile of microlens (case 2)

Figure 6.27 A 3-D experimental plot for microlens on square hole

Looking at the Table 6.4 we notice that it is possible to decrease the difference in focal lengths between the two lenses significantly. A further refinement in the thickness of the layers would allow to decrease this difference further or to increase it if needed.

Table 6.4: Various parameters of microlens profile (μm) ($n=1.62$)

	Case	D	t	h	R_c	$f = R_c/n-1$	$f_{Im}-f_{Ii}$
1	Illumination lens (I_i)	104	29	34	56	91	109
	Imaging lens (I_m)	193	29	46	124	200	
2	Illumination lens	104	29	34	56	91	84
	Imaging lens	193	38	58	109	175	

6.6.9 Microlens on Optical Fiber: Packaging

The square silicon frame supporting the lenses provides a 600 μm hole for the insertion of the fiber (Figure 6.28).

Figure 6.28 Silicon frame and fiber

Finally the optical fiber has been directly inserted into the slot provide by the silicon frame. Thus it could come in direct contact with the transparent SU8 layer. Another possible way is to directly attach it with the SU8 layer, removing the silicon frame altogether. Figure 6.29 shows the lenses along with the optical fiber inserted in the slot on the silicon frame.

Figure 6.29 Lens on optical fiber

6.6.10 Microlens on Optical Fiber: Optical Characterization

The setup used for focal length measurement (discussed in chapter 5) was modified for lens-on-fiber testing. The imaging fiber bundle used in endoscopy has maximum transmission for wavelength between 600 nm to 700 nm, as shown in Figure 6.30. Our microlens too were designed for maximum transmission wavelength (>600 nm) as discussed in chapter 5.

Figure 6.30 Light transmission through fiber bundle at wavelengths (a) 500 nm (b) 600 nm (c) 700nm (d) 800nm

Laser light source (wavelength 633 nm) was coupled to the fiber bundle and microlens-on-fiber focusing was tested as shown in Figure 6.31.

Figure 6.31 Images of microlens coupled with fiber bundle at different cross section (a) SU8 layer holding microlenses (b) Focal spot for illumination lens (c) Focal spot for imaging lens

6.7 Conclusion

A set of microlens with different surface areas and focal lengths have been fabricated on tip of a 600 μm diameter optical fiber for biomedical application. A single step process to get differential thicknesses of lenses to achieve the constant focal lengths (for variable diameter) has been demonstrated. The base layer of SU8 was used to give a transparent platform to fabricate microlens combination. This layer also acted as an intermediate layer between the lenses and optical fiber.

Chapter 7: Conclusion and Future Work

7.1 Conclusion

Fabrication of micro optical elements by thermal reflow of polymer is gaining recognition as a mainstream process. A multiple approach was used in this project to comprehensively study the main aspect of thermal reflow and use it to obtain polymer based microlens for MOEMS application. Point wise conclusion is given below:

- Modeling of thermal reflow based on Young-Laplace Equation
- Optimization of reflow parameters to obtain good quality microlens
- Study of characterization techniques to test a range of microlens
- Modification of thermal reflow technique to obtain diverging microlens, micromirror, and micro mould.
- Development of a simple technique of differential coating to control the focal length of microlens produced by thermal reflow
- Application of microlens obtain by thermal reflow for fiber imaging in endoscopy

7.2 Future Work

The future work may include:

- Incorporation of the crosslinking of polymers as a parameter to predict the formation dip in the Young Laplace model
- To integrate various optical elements on a substrate for free space optics

References

1. M. J. Madou, "Fundamentals of Microfabrication: The Science of Miniaturization", *CRC Press*
2. K. E. Petersen, "Silicon as a Mechanical Material", *Proceedings of the IEEE*, Vol. 70, No. 5, May 1982
3. R. P. Feynman, "There's Plenty of Room at the Bottom", *Journal of Microelectromechanical systems*, Vol. 1, No. 1, pp 60-66
4. M. Nordström, D. A. Zauner, A. Boisen and Jörg Hübner, "Single-Mode Waveguides With SU-8 Polymer Core and Cladding for MOEMS Applications", *Journal of Lightwave Technology*, Vol. 25, No. 5, 1284-1289
5. M. C. Wu, L. Y. Lin, K. S. J. Pister and S. S. Lee, "Micromachined free-space integrated micro-optics", *Sensors and Actuators A: Physical*, Volume 50 1995, Pages 127-134
6. W. Sutomo, X. Wang, D. Bullen, S. K. Braden and C. Liu, "Development of an end-point detector for parylene deposition process", *Journal of Microelectromechanical Systems (JMEMS)* 2003, 12, 64-70
7. X. Wang, J. Engel, J. Chen, and C. Liu, "4th Advanced Technology Workshop on Packaging of MEMS and Related Micro Integrated Nano Systems, International Microelectronics And Packaging Society Symposium (IMAPS 2002)": Denver, CO, 2002
8. M. Khoo and C. Liu, "Micro magnetic silicone elastomer membrane actuator", *Sensors and Actuators A: Physical* 2001, 89, 259-266
9. C. Liu, J. Chen, J. Engel, J. Zou, X. Wang, Z. Fan, K. Ryu, K. Shaikh and D. Bullen, "Polymer micromachining and applications in sensors, microfluidics and nanotechnology", *Available in Polymer Reprints*, Vol. 44, No. 2
10. G. Andrieux, J-C. Eloy, E. Mounier, "Technologies and market trends for polymer MEMS in microfluidics and lab-on-chip", *Proceedings of SPIE* Vol. 5718, pp 60-64
11. R. Hooke, "Micrographia", *the Royal Society of London*, 1665
12. S. Sinzinger and J. Jahns, "Microoptics", *WILEY-VCH GmbH & Co. KGaA* 2003

References

13. T. Feidhlim, O'Neill and John T. Sheridan, "Photoresist reflow method of microlens production Part I: Background and experiments", *Optik* 113, No. 9 (2002) 391–404
14. X. C. Yuan, W. X. Yu, N. Q. Ngo and W. C. Cheong, "Cost-effective fabrication of micro-lenses on hybrid sol-gel glass with a high-energy beam-sensitive gray-scale mask", *Optics Express* 10 (2002), 303–308
15. T. Bourouina, T. Masuzawa, and H. Fujita, "The MEMSNAS Process: Microloading Effect for Micromachining 3-D Structures of Nearly All Shapes", *Journal of microelectromechanical*, Vol .3, No. 2, April 2004
16. K. Naessens, P. V. D. en R. Baets, "Microlens fabrication in PMMA with scanning excimer laser ablation techniques", *Proceeding Symposiums IEEE/LEOS Benelux Chapter, 2000, Delft, The Netherlands*
17. N. F. Borrelli, D. L. Morse, R. H. Bellman and W. L. Morgan, "Photolytic technique for producing microlenses in photosensitive glass", *Appl. Opt.* 24 (1985) 2520–2525
18. A. Reyna, D. Quiroga and S. Calixto, "Dynamical optical microelements on dye sensitised gels", *Appl. Opt.* 39 (2000) 3948–3954
19. H. J. Lee and K. S. Park, "Self-developed formation of relief optical microlens by dry photopolymer", *Mol. Cryst. Liq. Cryst.* 349 (2000) 19–22.
20. S. Calixto and M. S. Scholl, "Relief optical microelements fabricated with dichromated gelatin", *Appl. Opt.* 36 (1997) 2101–2106
21. M. Kufner and S. Kufner, "Fabrication of monolithic integrated fiber-lens connector arrays by deep proton irradiation", *Microsystem Technol.* 2 (1996) 114–118
22. B. P. Keyworth, D. J. Corazza, J. N. McMullin and L. Mabbott, "Single-step fabrication of refractive microlens arrays", *Appl. Opt.* 36 (1998) 2198–2202
23. Y. Ishii, S. Koike, Y. Arai and Y. Ando, "Ink-jet fabrication of polymer microlens for optical-I/O chip packaging", *Jpn. J. Appl. Phys.* 39, Part 1 (2000) 1490–1493
24. W. R. Cox, C. Guan and D. J. Hayes, "Microjet Printing of Micro-optical Interconnects and Sensors", *SPIE Phot. West Proc.*, 3852 (2000), p-400
25. W. R. Cox, D. J. Hayes, T. Chen, H. J. Trost, M. E. Grove, R. F. Hoenigman and D. L. MacFarlane, "Low cost optical interconnects by microjet printing", *IMAPS International Journal of Microcircuits & Electronic Packaging* 20 (2) 1997, 89 – 95

References

26. D. M. Hartmann, O. Kibar and S. C. Esener, "Characterization of a polymer microlens fabricated by use of the hydrophobic effect", *Opt. Lett.* 25 (2000) 975–977
27. X. J. Shen, L.W. Pan and L. Lin, "Microplastic embossing process: experimental and theoretical characterizations", *Sensors and Actuators A* 3323 (2002) 1–6
28. Z. L. Liao, V. Diadiuk, J. N. Walpole, D. E. Mull, "Gallium Phosphidemicrolenses by mass transport", *Applied Physics Letters* 55(2), (1989) 97-99
29. Z. D. Popovic, R. A. Sprague and Connell G A N, "Technique for monolithic fabrication of microlens arrays", *Appl. Opt.* 27 (1988)1281–4
30. D. Daly, R. F. Stevens, M. C. Hutley and N. Davies, "The manufacture of microlenses by melting photoresist", *Meas. Sci. Technol.* 1 (1990) 759–766
31. E. M. Strzelecka, G. D. Robinson, L. A. Coldren and E. L. Hu, "Fabrication of refractive micro-lenses in semiconductors by mask shape transfer in reactive ion etching", *Microelectronic Engineering* 35(1997), 385-388
32. Sayah, V. K. Parashar and M. A. M. Gijs, "Micro-Replication of Optical Lenses in Glass Using a Novel Sol Gel Technology", *Micro electro mechanical systems, 15th IEEE international conference 2002*, 516 – 519
33. Y. Ishihara, K. Tanigaki, "A high photosensitive IL-CCD image sensor with monolithic resin lens array", *Electron Devices Meeting, International Volume 29*(1983), 497 – 500
34. R. F. Stevens and T. G. Harvey, "Lens arrays for a three-dimensional imaging system", *J. Opt. A: Pure Appl. Opt.* 4 (2002) S17–S21
35. N. Davies, M. McCormick and L. Yang L, "Three-dimensional imaging system: a new development", *J. Appl. Opt.* 27 (1988) 4520–.
36. R. F. Stevens and N. Davies, "Lens arrays and photography", *J. Photogr. Sci.* 39 199–208
37. N. Davies, M. McCormick and M. Brewin, "Design and analysis of an image transfer system using microlens arrays", *Opt. Eng.* 33 (1994) 3624–33
38. R. Volkel, H. P. Herzig, P. Nussbaum, R. Dandliker, "Microlens array imaging system for photolithography", *Opt. Eng.* 35 (1996) 3323–3330
39. M. Eisner, N. Lindlein and J. Schwider, "Confocal microscopy with a refractive microlens-pinhole array", *Opt. Lett.* 23 (1998), 748–749

References

40. V. Shaoulov, R. Martins and J. P. Rolland, "Compact microlenslet-array-based magnifier", *Opt. Lett.* 29 (2004), 709-711
41. M. C. Hutley, P. Savander and M. Schrader, "The use of microlenses for making spatially variant optical interconnections", *Pure Appl. Opt.* 1 (1992) 337-346
42. J. Hartmann, "Objektivuntersuchungen", *Zt. Instrumentenk.*, Vol.24, No.1, 1904
43. R. Shack, B. Platt, "Production and use of a lenticular Hartmann screen", *Journal of the Optical Society of America*, Vol.61, No.5, p.656
44. J. Schwiegerling and D. R. Neal, "Historical development of the Shack-Hartmann Wavefront Sensor", *Internet Source*
45. D. Daly, "Microlens Array", *CRC* 2000
46. P. Nussbaum, R. Volkel, H. P. Herzig, M. Eisner and S. Haselbeck, "Design, fabrication and testing of microlens arrays for sensors and Microsystems", *Pure Appl. Opt.* 6 (1997), 617-636
47. A. Buttner, U. D. Zeitner, "Wave optical analysis of light-emitting diode beam shaping using microlens arrays ", *Opt. Eng.* 41(10), 2002, 2393-2401
48. S. Masuda, T. Nose and S. Sato, "Dependence of optical properties on the device and material parameters in liquid crystal microlenses", *Jpn. J. Appl. Phys.* 34 (1995) 4668
49. B. Bergea and J. Peseux, "Variable focal lens controlled by an external voltage: An application of electrowetting", *Eur. Phys. J. E* 3(2000), 159-163
50. P. Moran, S. Dharmatilleke, A. H. Khaw, K. W. Tan, M. L. Chan and I Rodriguez, "Fluidic lenses with variable focal length", *Applied Physics Letters* 88, (2006) 041120
51. E. Li, "Characterization of a fiber lens", *Opt. Lett.* 31(2006), 169-171
52. R. R. A. Syms, "Refractive collimating microlens arrays by surface tension self-assembly", *IEEE Photonics Tech. Letters*, Vol. 12 (Nov. 2000), No. 11
53. L. G. Cohen and M. V. Schneider, "Microlenses for coupling junction lasers to optical fibers", *Appl. Opt.* 13(1974), 89-94
54. A. Vaidya and J. A. Harrington, "Sculpted optical silica fiber tips for use in Nd: YAG contact tip laser surgery: part 1-fabrication techniques", *Optical Engineering* 31(1992), 1404-1409

References

55. U. C. Paek and A. L. Weaver, "Formation of a spherical lens at optical fiber ends with a CO₂ laser", *Appl. Opt.* 14 (1975), 294
56. J. T. Sheridan, N. Schwider, S. Streibl, M. Haselbeck, M. Eisner and H. O. Falkenstorfer, "Modeling and measurement of melted microlens shapes", *Optik*, 97, No.4, 1994
57. F. T. O'Neill and J. T. Sheridan, "Photoresist reflow method of microlens production Part II: Analytic models", *Optik*, 113, No.4, 2002
58. F. T. O'Neill, J. T. Sheridan and S. Abe, "Melted Microlenses: Fabrication, Performance and Modeling", *Proc. of SPIE* 4876, 274, 2003
59. S. Audran et al., "Study of dynamical formation and shape of microlens formed by the reflow method", *Proc. of SPIE* 6153, 61534D, 2006
60. S. Audran et al., "Study of mechanisms involved in photoresist microlens formation", *J. Micro. Eng.* 86 (2006), 1087-1090
61. S. Abe and J. T. Sheridan, "Curvature correction model of droplet profiles", *Physics Letters, Section A: General, Atomic and Solid State Physics*, 253 (5-6), pp. 317-321
62. F. T. O'Neill and J. T. Sheridan, "Melted (reflow) microlens array formation", *Proc. of SPIE* 5183, 172, 2003
63. F. T. O'Neill et al., "Photoresist reflow method of microlens production: Modeling and fabrication techniques", *Proc. of SPIE* 5456, 197, 2004
64. A. Schilling, R. Merz, C. Ossmann and H. P. Herzig, "Surface profiles of reflow microlenses under the influence of surface tension and gravity", *Opt. Eng.*, 39, No. 8, 2171-2176, (2000)
65. Y. N. Goh, M. Ashraf and F. Chollet, "Design Fabrication and characterization of copper micro mould for microlens array using electroplating", presented at Asia-Pacific Conference of Transducers and Micro-Nano Technology (APCOT 2006), Singapore
66. H. Y. Erbil, "Surface Chemistry of Solid and Liquid Interfaces", Blackwell Publishing
67. H-J Butt, K. Grafts and M. Kappl, "Physics and Chemistry of Interfaces", WILEY VCH

References

68. J. S. Allen, "An analytical solution for determination of small contact angles from sessile drops of arbitrary size", *Journal of Colloid and Interface Science*, 261 (2003) 481-489
69. A. W. Adamson, "Physical Chemistry of Surfaces", Wiley, New York
70. A. Stanoyevitch, "Introduction to numerical ordinary and partial differential equations using MATLAB", Wiley-Interscience, 2005
71. M. Ashraf, F. Chollet, "Simultaneous fabrication of concave and convex microlenses using thermal reflow", *ICMAT (MEMS Technology and Devices) 2007, Singapore*
72. C. H. Seah, S. Mridha and L. H. Chan, "Growth morphology of electroplated copper: effect of seed material and current density", *IEEE (1998) IITC 98- 159*
73. F. Chollet, C. H. Low, S. K. Lee and C. Yang, "Fabrication of concave and convex optical elements with polymer for free-space micro-optical bench", *Comp. Eng .Science (IJCES) Vol. 4 No. 3 433-446*
74. M. Ashraf, C. Gupta, F. Chollet, S. V. Springham and R. Rawat, "Geometrical characterization of refractive microlens made by thermal reflow of photoresist cylinders", *ICMAT (MEMS Technology and Devices) 2007, Singapore*
75. M. Ashraf, F. Chollet, M. Matham, and C. Yang , "Polymer microlens with independent control of radius and focal length for an imaging fiber", *Proceedings of the SPIE, Volume 6037, pp. 66-76 (2006)*

List of Publications

1. **M. Ashraf**, F. Chollet, M. Matham, and C. Yang , “Polymer microlens with independent control of radius and focal length for an imaging fiber”, *Proceedings of the SPIE, Volume 6037*, pp. 66-76 (2006)
2. Y. N. Goh, **M. Ashraf** and F. Chollet, “Design Fabrication and characterization of copper micro mould for microlens array using electroplating”, presented at *Asia-Pacific Conference of Transducers and Micro-Nano Technology (APCOT 2006)*, Singapore
3. **M. Ashraf**, F. Chollet, “Simultaneous fabrication of concave and convex microlenses using thermal reflow”, *ICMAT (MEMS Technology and Devices) 2007*, Singapore
4. **M. Ashraf**, C. Gupta, F. Chollet, S. V. Springham and R. Rawat, “Geometrical characterization of refractive microlens made by thermal reflow of photoresist cylinders”, *ICMAT (MEMS Technology and Devices) 2007*, Singapore
5. **M. Ashraf**, A. Sreenath and F. Chollet, “Fabrication of inexpensive metallic mould for nanoimprinting using colloidal monolayer as a nanomask”, *Proceedings of the SPIE, Volume 6415*, pp. 64151F (2007)
6. **M. Ashraf**, A. Sreenath and F. Chollet, “Low-cost mould for nano-imprinting uses monolayer of self-organized nanospheres”, *SPIE NEWSLETTERS* <http://spie.org/x14253.xml>
7. X. Ting, **M. Ashraf**, P. Dixit, N. Lin, J. Miao and F. Chollet, “Regular nanopitched carbon nanotube array using nanosphere lithography for electronics applications”, *ICMAT (Nanodevices And Nanofabrication) 2007*, Singapore. To be published in a special issue of the *Journal of Nanoscience and Nanotechnology*
8. **M. Ashraf**, F. Chollet, M. Matham, and C. Yang , “Fabrication of polymer-based-reflowed microlenses on optical fiber with independent control of focal length for endoscopic applications”, presented at *International Conference on Advanced Materials (ICAM) 2007*, Bangalore, India
9. **M. Ashraf** and F. Chollet, “Investigations of thermal reflow of photoresist to produce a variety of microoptical components”, *abstract accepted at Advanced Fabrication Technologies for Micro/Nano-Optics & Photonics, Photonic West (MOEMS-MEMS 2008)*
10. F. Chollet and **M. Ashraf**, “Simultaneous measurement of focal length and index of refraction of microlens using a compound microscope”, submitted to *Journal of Micromechanics and Microengineering*

List of Publications

11. **M. Ashraf**, C. Gupta, F. Chollet, S. V. Springham and R. Rawat, "Geometrical characterization techniques for microlens made by thermal reflow of photoresist cylinder" submitted to *International Journal of Optomechatronics* 2008
12. Prediction of profile for photoresist reflowed microlens based on Young-Laplace equation, *manuscript in preparation*
13. A review of refractive microlens fabrication techniques, *manuscript in preparation*

Appendix

MATLAB CODES

```
% solve.m
% SOLVING YOUNG-LAPLACE EQUATION FOR MICROLENS PROFILE AND COMPARING
THE
% PLOT WITH EXPERIMENTAL PROFILE

close all          % Close all windows before running the codes
clear all          % Clear all data before running the codes
clc                % Clear any data in command windows
format short g     % Format to represent data

% REAL CODE STARTS NOW
global Ro RR        % Ro(in SI units)= RR(in micron)
for RR=500:1:700;   % "for" loop to optimization
    Ro=RR*1e-6;     % Ro(radius of curvature at apex)
    r=232.5 ;       % Experimental radius in micron
    initial = [0;0]; % Initial Condition (slope-displacement at
APEX)
    tspan=[1e-10 r*1e-6]; % Span ( From Apex to one end of the profile)

% SOLVING 2nd ORDER ODE (YOUNG-LAPLACE EQUATION) AS DEFINED IN FILE
F.m
[X,Y] = ode45('F',tspan,initial); % MATLAB ODE45 solver with its
input
X=1e6*X;           % X coordinate in micron
Y(:,1)=1e6*Y(:,1); % Y(:,1)=displacement;Y(:,2)=slope
a=size(Y);         % Length of Y
b=a(1:1);          % No. of rows in Y
theta=180*atan(Y(b,2))/pi; % Contact Angle
H=Y(b)-Y(1);       % Sag Height

% LOADING EXPERIMENTAL DATA
load D_400_t20.m;   % Loading experimental data
XX=D_400_t20;       % Assigning a name to exp. data

% ALIGNMENT OF EXP. DATA WITH Y-L DATA (APEX AT THE ORIGIN)
l=max(XX(:,1))-min(XX(:,1)); % Range for x coordinate (exp. dia)
m=max(XX(:,2))-min(XX(:,2)); % Range for y coordinate (exp. sag)
k=size(XX);           % Size of the exp. data
xx = XX(:,1) - (max(XX(:,1)) - 0.5*1)*ones(k(1),1) ;
yy = XX(:,2) - (max(XX(:,2)) + 0)*ones(k(1),1);

%AREA UNDER CURVES (MEASURE OF VOLUME)
At= abs(trapz(xx,yy)); % Area under experimental profile
Ayl=abs(2*trapz(X,Y(:,1))); % Two times area under Y-L profile
delta=abs(At-Ayl); % Difference in areas
per=(delta/At)*100; % Percentage deviation

%LOOP FOR ITERATION OF AREAS
    if per < 1 % If percentage deviation is less
                % than 1 then break out of loop
        break
    end
end % Otherwise increment RR by 1

%-----
```

Appendix

```

%PLOTS FOR EXPERIMENTAL VS YOUNG-LAPLACE
figure(1)
plot(X,-Y(:,1),'*',xx,yy,'o')      % Plot profiles
grid                                % Show Grid
xlabel('Diameter (\mu m)')
ylabel('Height (\mu m)')
title(' EXPERIMENTAL DATA VS YOUNG-LAPLACE PROFILE ')

%FITTING SPHERICAL PROFILE TO EXPERIMENTAL DATA
[xc,yc,R,aa]=circfit(xx,yy);
thetal = linspace(0,pi,100);
x3 = R*cos(thetal) + xc;
y3 = R*sin(thetal) + yc;
figure(2)
plot(x3,y3,xx,yy,'o')              % Plot profiles
grid                                % Show Grid
xlabel('Diameter (\mu m)')
ylabel('Height (\mu m)')
title(' SPHERICAL FIT TO EXPERIMENTAL DATA')

%FINDING DEVIATION IN SPHERICAL PROFILE AND EXPERIMENTAL DATA
k=xx.^2 + aa(1)*xx + aa(3);
l=sqrt(yc^2 - k);
m1=yc+l;
m2=yc-l;
figure(3)
plot(xx,m1-yy)                     % Plot profiles
grid                                % Show Grid
xlabel('Diameter (\mu m)')
ylabel('Height (\mu m)')
title(' DEVIATION IN SPHERICAL PROFILE AND EXPERIMENTAL DATA')

%FITTING SPHERICAL PROFILE TO YOUNG-LAPLACE DATA
[xc1,yc1,R1,aaa]=circfit(X,-Y(:,1));
theta2 = linspace(0,pi,100);
x4 = R1*cos(theta2) + xc1;
y4 = R1*sin(theta2) + yc1;
figure(4)
plot(x4,y4,X,-Y(:,1),'*')          % Plot profiles
grid                                % Show Grid
xlabel('Diameter (\mu m)')
ylabel('Height (\mu m)')
title(' SPHERICAL FIT TO YOUNG-LAPLACE DATA')

%FINDING DEVIATION IN SPHERICAL PROFILE AND YOUNG-LAPLACE
k1=X.^2 + aaa(1)*X + aaa(3);
l1=sqrt(yc1^2 - k1);
mm1=yc1+l1;
mm2=yc1-l1;
figure(5)
plot(X,mm1+Y(:,1))                  % Plot profiles
grid                                % Show Grid
xlabel('Diameter (\mu m)')
ylabel('Height (\mu m)')
title(' DEVIATION IN SPHERICAL PROFILE AND YOUNG-LAPLACE PROFILE')
%

%PLOTS FOR EXPERIMENTAL Vs YOUNG-LAPLACE Vs SPHERICAL PROFILE
figure(6)
plot(X,-Y(:,1),'*',xx,yy,'o',x3,y3) % Plot profiles

```

Appendix

```

grid                                     % Show Grid
xlabel('Diameter (\mu m)')
ylabel('Height (\mu m)')
title(' EXPERIMENTAL Vs YOUNG-LAPLACE Vs SPHERICAL PROFILE ')

```

ANSYS CODE

```

/NOPR ! Suppress printing of UNDO process
/PMACRO ! Echo following commands to log
FINISH ! Make sure we are at BEGIN level
/CLEAR,NOSTART ! Clear model since no SAVE found
! WE SUGGEST YOU REMOVE THIS LINE AND THE FOLLOWING STARTUP LINES
/input,start110,ans,'d:\appl_sw\Ansys Inc\v110\ANSYS\apdl',,,,,,,,,,1
!*
/FILNAME,microlens,0
/PREP7
!*
ET,1,PLANE55
!*
TOFFST,273
!*
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,1,,0.7
CYL4,0,0,145e-6,180,0,0
BLC4,-145e-6,0,290e-6,105e-6
FLST,3,2,5,ORDE,2
FITEM,3,1
FITEM,3,-2
ASBA, 1,P51X
FLST,2,1,5,ORDE,1
FITEM,2,5
AESIZE,P51X,10e-6,
MSHKEY,0
CM,_Y,AREA
ASEL,,, 5
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
FINISH
/SOL
!*
ANTYPE,0
FLST,2,1,4,ORDE,1
FITEM,2,13
!*
/GO

```

Appendix

```
DL,P51X, ,TEMP,116,1
FLST,2,1,4,ORDE,1
FITEM,2,12
/GO
!*
SFL,P51X,CONV,500, ,25,
/STATUS,SOLU
SOLVE
FINISH
/POST1
!*
/EFACET,1
PLNSOL, TEMP,, 0
FINISH
```