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# **FABRICATION OF MICROLENS IN POLYMERS WITH THERMAL REFLOW**

**Farhan Badar**

**Supervised by Dr. Mauricio Moreno Sereno, (UB)**

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# Fabrication of Microlens in Polymers with Thermal Reflow

**Farhan Badar**

UB – University of Barcelona, Martí i Franques 1  
Department of Electronics, Faculty of Physics  
08028 Barcelona, Spain

**E-mail:** [farhanbadar@hotmail.com](mailto:farhanbadar@hotmail.com)

**Abstract.** This study shows that it is possible to fabricate lenses with a very small diameter by depositing and melting the photoresist layer on a glass substrate. Thermal Reflow technique has been used to melt the top surface of lens and thus convex lenses have been developed in the form of spheres having diameter ranging from 50 - 175 $\mu\text{m}$  of thickness 10 $\mu\text{m}$  each. We present a study of melted microlens arrays and it concentrates on the production and measurement of microlens arrays. We explain the mechanism of fabricating microlens arrays and study their optical properties.

**Keywords:** Microlens, photoresist, thermal reflow, surface profile, measurement

## 1. Introduction

In this paper we review thermal reflow method of production of microlens. Photoresist reflow technique has been used to produce the microlens arrays. It is characterized as a low cost and one of the most popular methods to produce microlens.

Another lithography technique used to transfer patterns on the substrate known as Electron Beam Lithography (see figure 1a). The electron beam lithography uses a focused beam of electrons to form patterns on a substrate after going through several technological steps, in contrast with optical lithography which uses light for the same task (see figure 1c). In this type of lithography negative and positive photoresists are used just like optical lithography but these resists are sensitive to electron beam and are called as e-beam resists. In electron beam lithography, masks are not used to transfer patterns unlike optical lithography which uses photomasks to project the patterns. An electron gun is used to supply the electrons, an electron column shapes and focuses the electron beam and then a wafer is positioned under the electron beam for processing<sup>[1]</sup>.

A convex lens surface can also be achieved by a simple and easy process called proximity printing in which gap is made between mask and photoresist. Slice/s of plastic or glass having an aperture is used to insert between mask and photoresist to create a gap (see figure 1b & 1d). As the gap spacing increases between the mask and the photoresist, the aerial light intensity profile produced on the photoresist surface will strongly degrade due to diffraction effects<sup>[2]</sup>. Also, if the gap spacing is increased then the diameter of lens, focal length and radius of curvature will also increase but height of the lens and Numerical Aperture will decrease.

Microlenses are used in several different applications. They are used to couple light to optical fibers, as the laser beam size is larger than that of core diameter, they focuses the laser beam to a spot size smaller than the diameter of core so the light could completely couple with the fiber. Microlenses are also used to collect light and focus on the CCD/CMOS arrays that would have otherwise fallen on the non-sensitive areas of CCD arrays, so the light collecting efficiency of CCD arrays can be increased by using microlenses. Microlenses can also be used in digital projectors to focus the light on the active areas of LCD used to generate the image to be projected. This paper concentrates on describing the fabrication of microlens arrays by thermal reflow technique in detail, the properties of the photoresist are examined, the measurement of the surface profiles of the microlenses and PDMS replica of microlens are discussed.

## Electron beam lithography

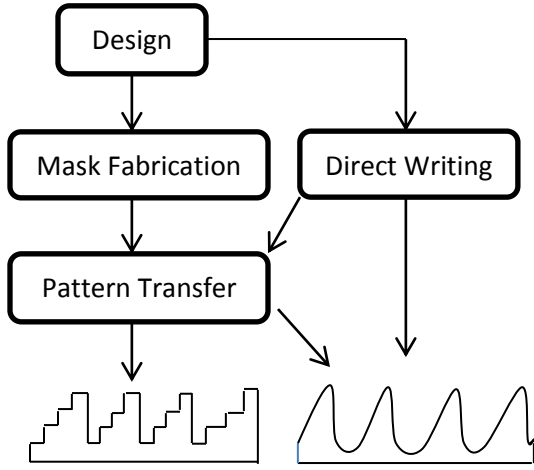


Figure 1a

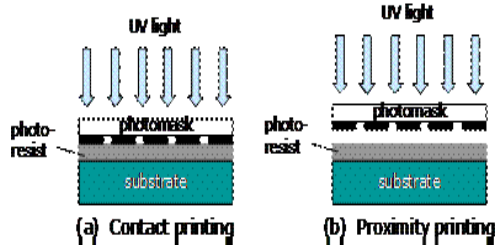


Figure 1d

## Proximity Printing

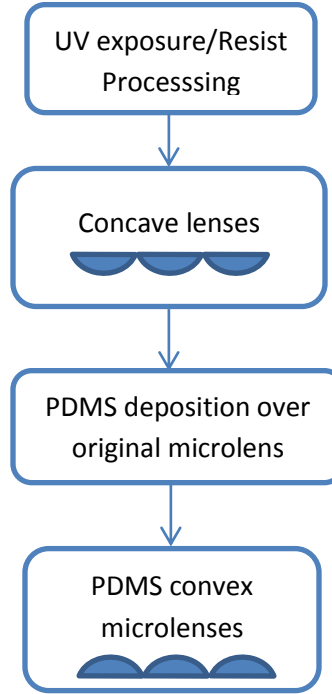


Figure 1b

## Optical lithography (Multilevel Optics)

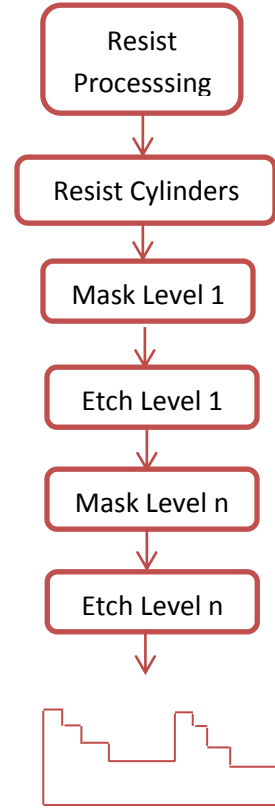


Figure 1c

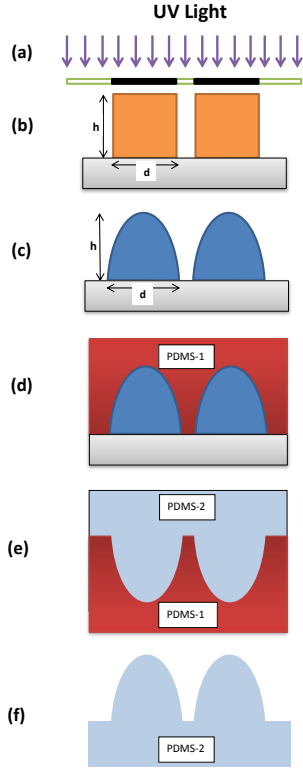
Figure 1: The possible steps involved in Electron beam lithography (figure 1a), Proximity printing (figure 1b) and Optical lithography (figure 1c) with the output of each technique is also shown in this figure. In figure 1d, (a) and (b) show the pictorial representation of contact and proximity printing respectively. In (b) a gap is maintained between photoresist layer and the mask while in (a) there is no gap.

## 2. Thermal reflow technique and microlens fabrication

### 2.1 Optical lithography

Substrate is coated with a chemical called as photoresist. In this study AZ9260 photoresist from MicroChemicals® has been used and figure 2 gives the complete description of the process. Spin coating is used to apply the liquid on a substrate, it ensures uniformity of thickness. Photoresist is exposed by a stepper/aligner - a machine that focuses, aligns, and moves the mask exposing select portions of the substrate to short wavelength of light (figure 2a) <sup>[3]</sup>. Transparent portions of the photoresist layer are washed away by the developer solution.

When the irradiated/exposed regions are soluble by the UV light and developer removes the soluble portion, a positive image of the mask is produced in the resist actually known as positive photoresist. In case of negative photoresist, the dark portion of resist becomes soluble and transparent portion remains insoluble. When we put the sample in developer solution the soluble portion washes away (figure 2b).



**Figure 2:** (a). UV light exposing on the resist through the mask. (b). Unexposed regions (orange) become cylindrical lenses due to surface tension while exposed regions are washed away during development. (c). perfect spherical lenses (blue) obtained after Thermal Reflow. (d). Replication of microlens by depositing PDMS (red) over microlenses. (e). Second replication by depositing PDMS (sky blue) over first replica (red) to obtain convex microlenses. (f). PDMS Convex lenses.

## 2.2 Photoresist melting

Thermal reflow technique is to apply appropriate elevated temperature to polymers for certain time. Each polymer has a glass transition temperature  $T_g$ . As the applied temperature approaches the  $T_g$ , the polymer has significantly reduced viscosity and is able to reflow such that smoother surface can be achieved by the surface tension (figure 2c). The degree of polymer's fluidity can be controlled by the applied temperature, which determines the reflow rate and the degree of roughness reduction can be controlled by the reflow time<sup>[4]</sup>. In our case, the effective temperature for AZ9260 photoresist to reflow is 150°C. Other values of effective temperature and reflow time have also been used in different researches<sup>[4]</sup> <sup>[5]</sup> but we have achieved perfect results by setting reflow temperature at 150°C with a reflow time of 45 minutes. Several experiments have been conducted with different reflow times in order to see the surface profile of microlenses.

## 2.3 Optical considerations

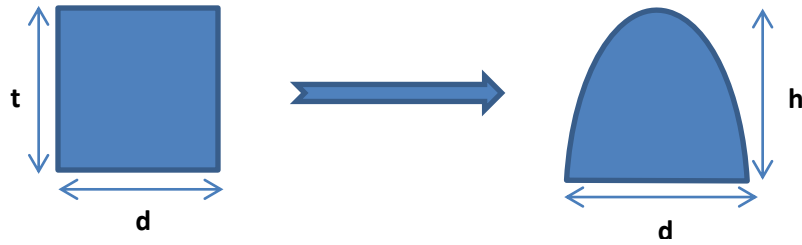
The volume of the lens doesn't change when it is melted and becomes in a spherical shape from a square shape<sup>[6]</sup>. The volume of a spherical lens before melting is shown in Figure 3 and is given by

$$V_b = \pi r^2 t$$

where

The resist thickness required for the spherical lens is denoted by " $t$ " and is given by

$$t = h/6(3 + (h^2/r^2))$$



**Figure 3: Transformation of cylindrical lens to spherical**

It is necessary to calculate the basic optical properties of a lens that are its diameter ( $d=2r$ ), numerical aperture (NA), focal length ( $f$ ), refractive index ( $n$ ), height ( $h$ ) and radius of curvature (ROC). In our experiments, single spherical surface lenses have been obtained on a substrate. Focal length and the radius of curvature are given by

$$f = ROC/(n-1)$$

$$ROC = (r^2/2h) + ((k+1)/2)h$$

where:  $k$ = conic constant=0 (for a spherical lens)  
 $r$ =radius of the lens

height of the lens is given by

$$h = ROC - (ROC^2 - r^2)^{1/2}$$

The volume of the spherical lens after melting is given by

$$V_a = (1/3). \pi h^2. ((3ROC)-h)$$

### 3. Photolithography process

#### 3.1 Substrate cleaning

The patterns are usually obtained on glass and Si substrate. We have done experiments on glass that is cheaper but silicon can also be used. The substrate needs to be clean properly in order to get the fine contact between the glass and photoresist layer. Substrate is washed with acetone, ethanol, methanol and isopropanol that are used as cleaning agents to ensure the dirt free surface.

#### 3.2 Spin coating

Substrate is coated with a layer of a chemical called as photoresist. The standard spin profile that is used for AZ9260 is 2000 – 4000 rpm for 30 seconds to achieve a thickness of 10  $\mu\text{m}$ . Multiple coatings help in achieving more thick films and require thick resists such as AZ9260. From figure 4, the thickness of the resist decreases as the spin speed increases and vice versa. In this study, 10 $\mu\text{m}$  resist thickness was achieved by setting the spinner at 2000rpm and tested at different reflow temperatures.

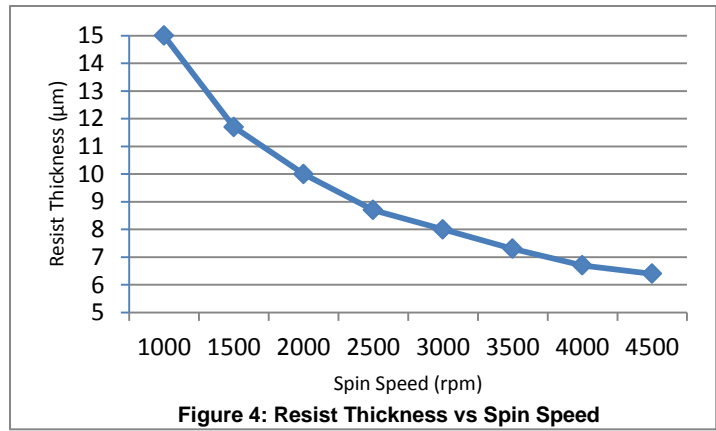


Figure 4: Resist Thickness vs Spin Speed

#### 3.3 Soft bake

After the coating of photoresist on a substrate it is placed on a hot plate for soft baking. Typically this will be between 90 – 100°C for 20 – 30 minutes. The photoresist layer is soft and a slightly hard surface is required for the perfect results. So the purpose of the softbake is to semi-harden the photoresist.

#### 3.4 Ultraviolet exposure

The substrate is exposed to UV light on an aligner after the process of soft baking. The exposure time is set according to the particular type of photoresist and the wattage of the bulb being used because some photoresist requires less exposure time and some requires more. In our experiments, samples were exposed for 2 minutes as the exposure time of 2, 2.5 or 3 minutes is recommended for AZ9260 resist by the manufacturer.

### 3.5 Development

Developer solution is a chemical being used to remove the dissolved photoresist. It is selected according to the type of photoresist being used. The substrate is then immersed in the developer with the help of tweezers for the specified development time, in our case it was 2 minutes approximately. Once all the dissolved photoresist is removed from the substrate and the desired pattern is achieved the substrate is then washed with water to stop the developing process.

## 4. PDMS microlens

PDMS (Polydimethylsiloxane) is a silicon based polymer and it is highly used in microfluidics. In this work PDMS has been used for replication of microlens.

- PDMS pre-polymer and curing agent (Sylgard 184, Dow Corning, NC, USA) are mixed at a 10:1 ratio. The PDMS mixture must be degassed for 30 minutes under vacuum prior to pouring onto the microlens master.
- In our work, replicas of the original lenses have been obtained by depositing PDMS over substrate containing arrays of microlenses and after curing at 90°C for 20 minutes the PDMS layer is peeled off the substrate, resulting in concave microlenses appeared on the PDMS (“red” in figure 2d).
- Silanization of the concave PDMS surface is necessary to avoid the sticking of new PDMS layer on it.
- By again depositing a new PDMS layer over the first replica, arrays of convex microlenses can be produced (see Figure 2e).

In the silanization process:

- The sample is rinsed with water and subsequently dried with air.
- The sample is placed within a vacuum chamber, aside from this, place a drop of Trichloro (1H, 1H, 2H, 2H perfluorooctyl) silane on a small piece of glass.
- After 30min in a vacuum, the sample is placed in an oven for 60min at 80°C.

Convex microlenses can be obtained by two ways after when we are done with thermal reflow. With the help of electron beam lithography we can obtain an array of hard microlens but the cost is significantly higher as compare to array obtained through depositing PDMS over the original microlens array.

## 5. Confocal microscopy

In our experiments we have taken the images of different samples with the help of confocal microscope.

In a confocal microscope a pair of lenses focuses light from the focal point of one lens to the focal point of the other. The practical effect of this is that the image comes from a thin section. Many thin sections are scanned and a very clean three dimensional image is obtained. The focal plane has different areas, light emits from them and gets block at the pinhole screen but this screen allows the light to pass through it that emits from a focal point (the black dot in figure 5). So a confocal microscope has a better horizontal and vertical resolution. We have used Leica DCM 3D for confocal microscopy, the DCM 3D combines confocal and interferometry technology for high speed and high resolution measurements down to 0.1nm.

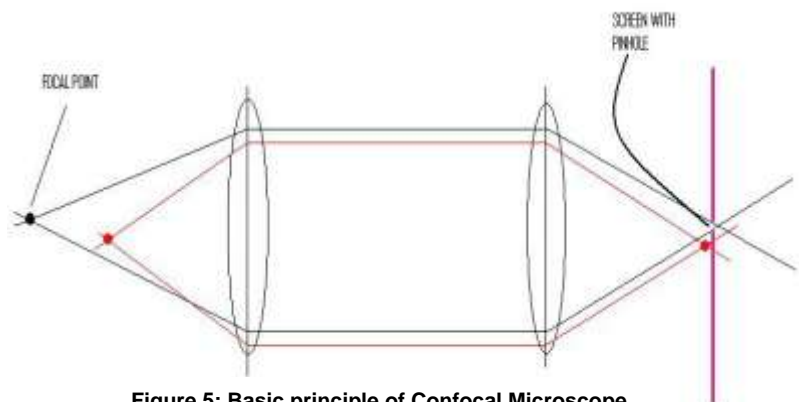
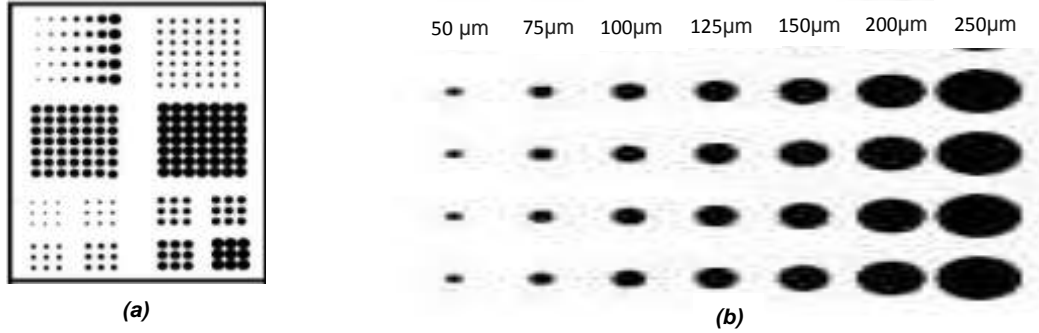


Figure 5: Basic principle of Confocal Microscope

## 6. Experimental results

### 6.1 Mask

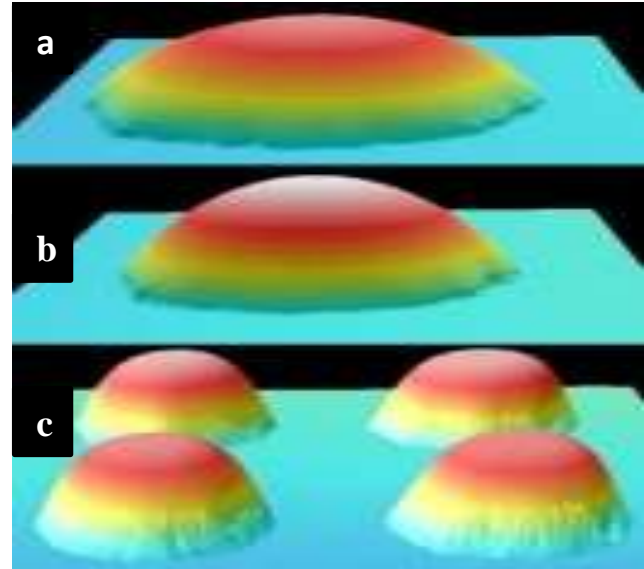
The below is the image of the mask used in our study and it is made of transparent plastic with the black printed patterns. This mask has been used because it has all sizes of spherical lenses that we wanted to investigate.



**Figure 6: (a). Plastic mask showing spherical lenses patterns ranging from 50μm - 250μm. The figure at right hand side (b) is the close up image of (a)**

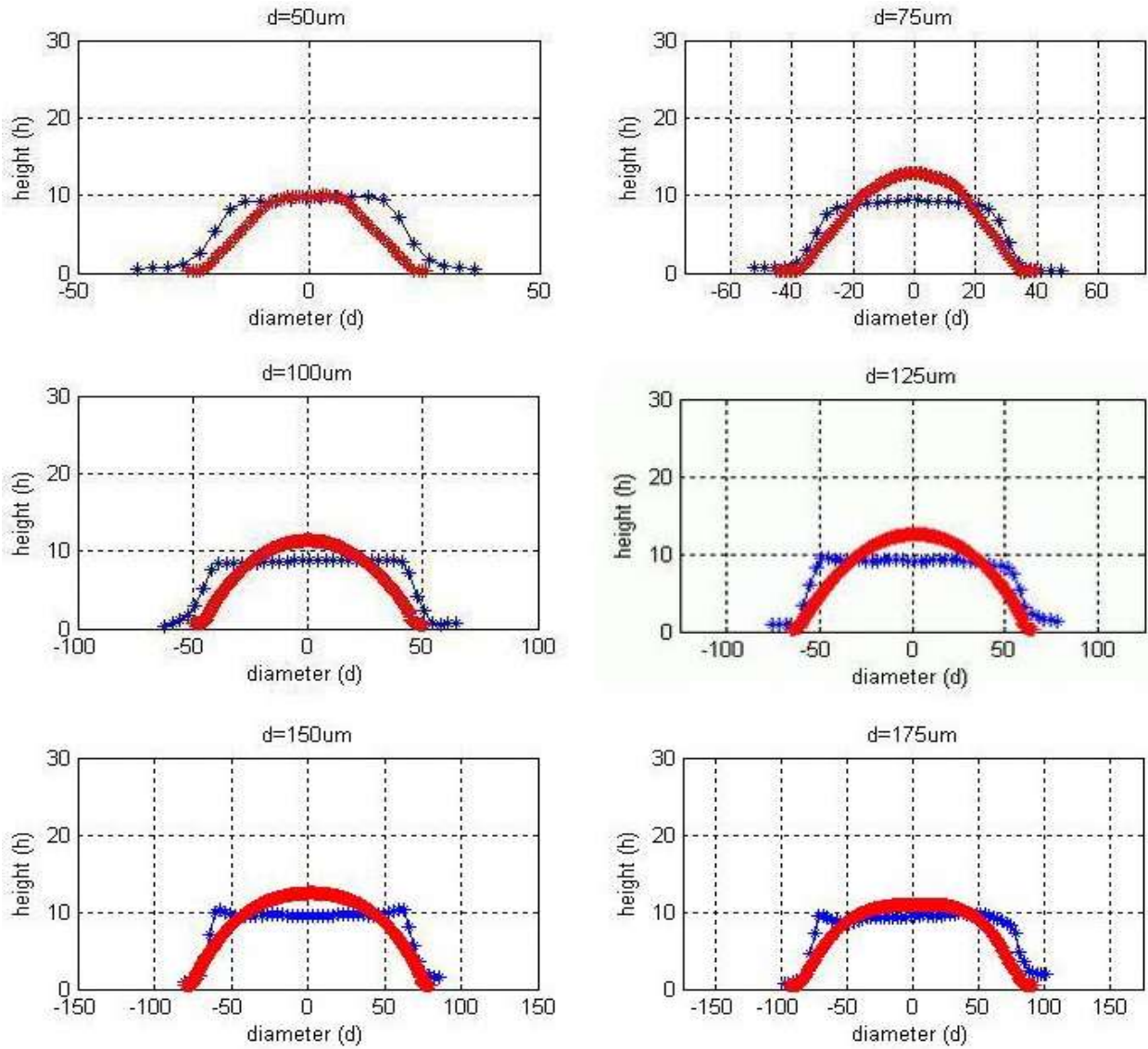
### 6.2 Results and discussion

By using confocal microscopy, we have carried 3D images of the convex lens (see Figure 7) and by using real data of these lenses, different profiles are also obtained by using MATLAB software (see Figure 8). In figure 8, the surface profile in “blue” represents a microlens before reflow and “red” represents a microlens after reflow. The microlens profile shown in red is different from the profile shown in blue because the polymer particles on the smooth surface of a substrate have been shrunk into a hemispherical lens due to the surface tension when heated above their softening temperature. By setting thermal reflow temperature at 150°C for a reflow time of 45 minutes; a perfect convex lens profile can be achieved as it can be clearly seen in Figure 7. Microlenses without thermal reflow have almost straight vertical sidewalls but after heating for a specific time the sidewalls of the microlens become spherical. Moreover, we have tested different samples for different reflow time (e.g. 15 and 30 minutes) to see and observe the difference. According to our observation, a spherical lens profile is not only dependent on the reflow temperature and reflow time but is dependent on the diameter of the lens as well <sup>[4]</sup>. According to theory, microlens of diameter equal or greater than 100μm comes up with edge beads. We have produced microlenses of diameter 175μm without any edge effects while the edge beads can only be seen for lenses having diameter equal to 200μm or above (see Figure 9).

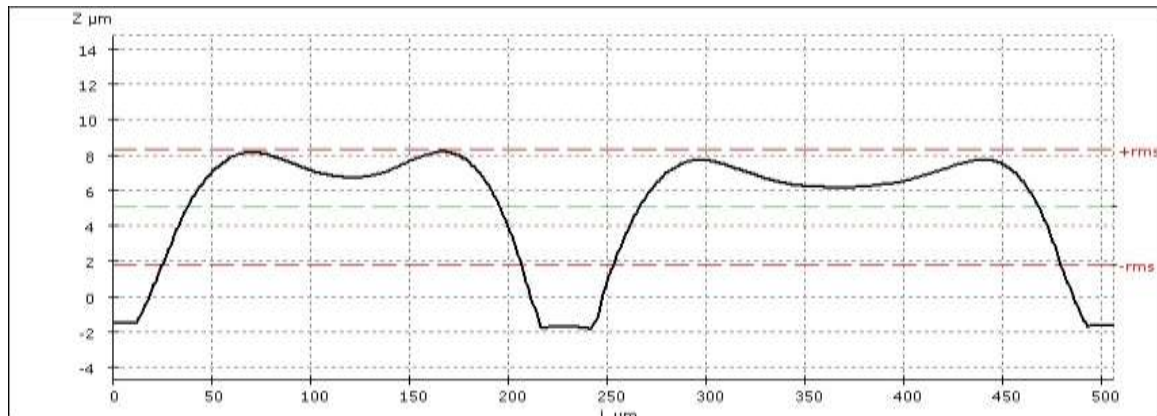


**Figure 7: Perfect spherical lenses are obtained after putting the sample under temperature of 150°C for 45 minutes (a). 3D surface profile of 125μm diameter microlens produced in the cleanroom. (b). 3D surface profile of 150μm diameter microlens. (c). 3D surface profile of 175μm diameter microlens.**





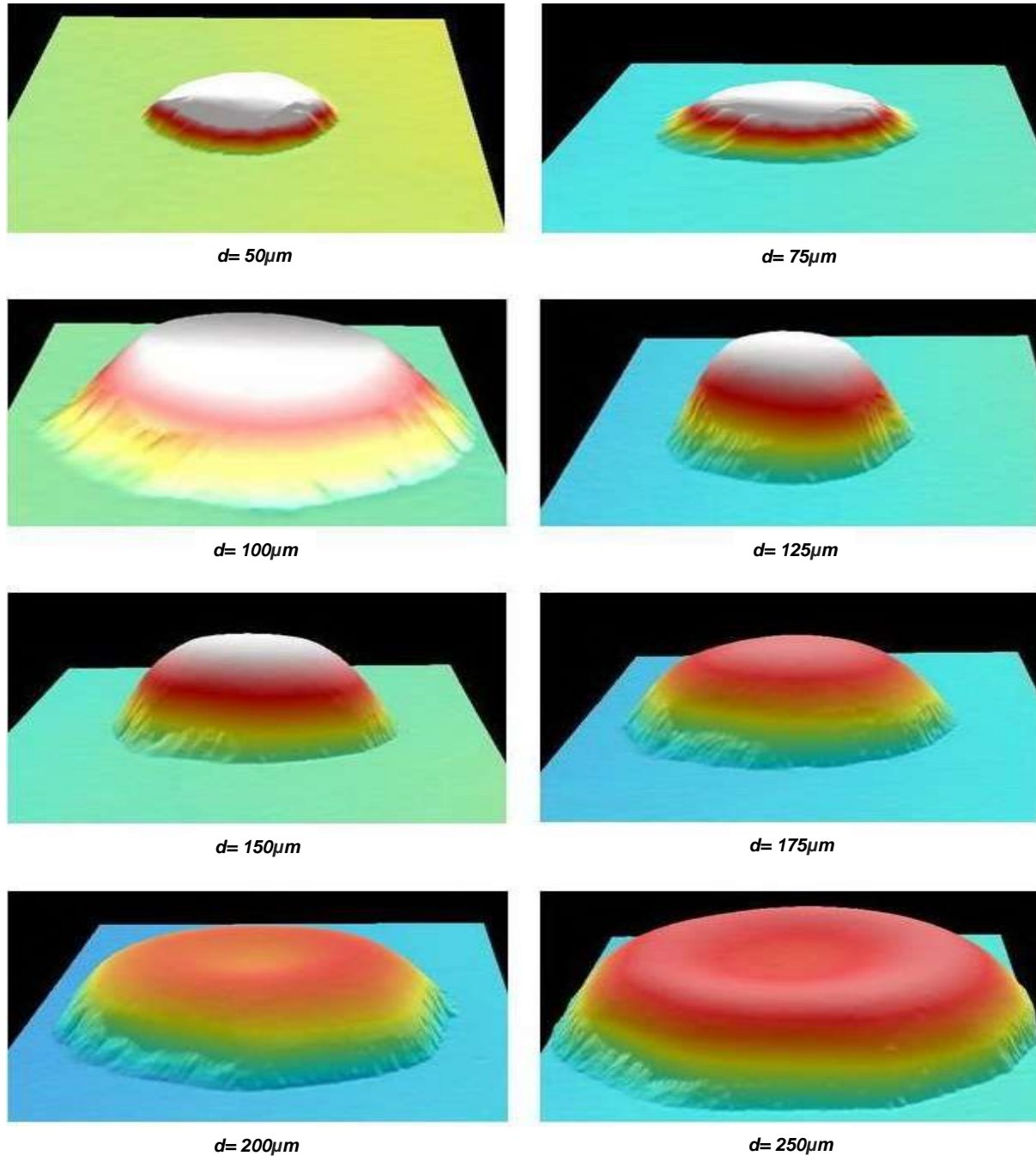
**Figure 8: surface profile of microlenses having diameter ranging from 50 $\mu$ m - 175 $\mu$ m. A convex lens surface is achieved by setting the reflow temperature at 150 $^{\circ}$ C for a reflow time of 45 minutes.**



**Figure 9: Surface profile of 200 $\mu$ m and 250 $\mu$ m microlenses with edge effects at the sidewalls**

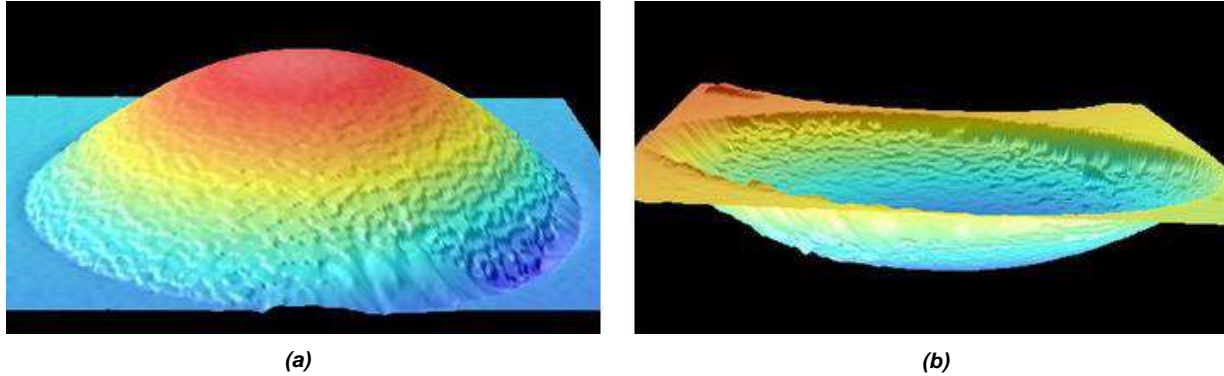


Hemispherical microlenses of diameter  $d = 50\mu\text{m} - 175\mu\text{m}$  have been produced successfully (see figure 10) while  $d=200$  and  $250\mu\text{m}$  show edge beads i.e. the height of the side walls of microlens is greater than its central area (see figure 9). The surface profile of lenses produced with 45 minutes of reflow time is smoother than that of lenses produced with 30 minutes. The modification in surface starts from the borders and if we stop the thermal reflow the border effect will remain there after getting cool. If we continue with reflow, the two side lobes go towards the center and finally you will have a hemispherical surface.



**Figure 10: 3D images of microlenses produced in the clean room environment. These convex profiles were achieved by setting the reflow temperature=  $150^\circ\text{C}$  and reflow time= 45 minutes. Diameter ranging from  $50\mu\text{m} - 175\mu\text{m}$  showing near perfect hemispherical surface while  $d=200\mu\text{m}$  and  $250\mu\text{m}$  have bends at their centers resulting in edge beads.**

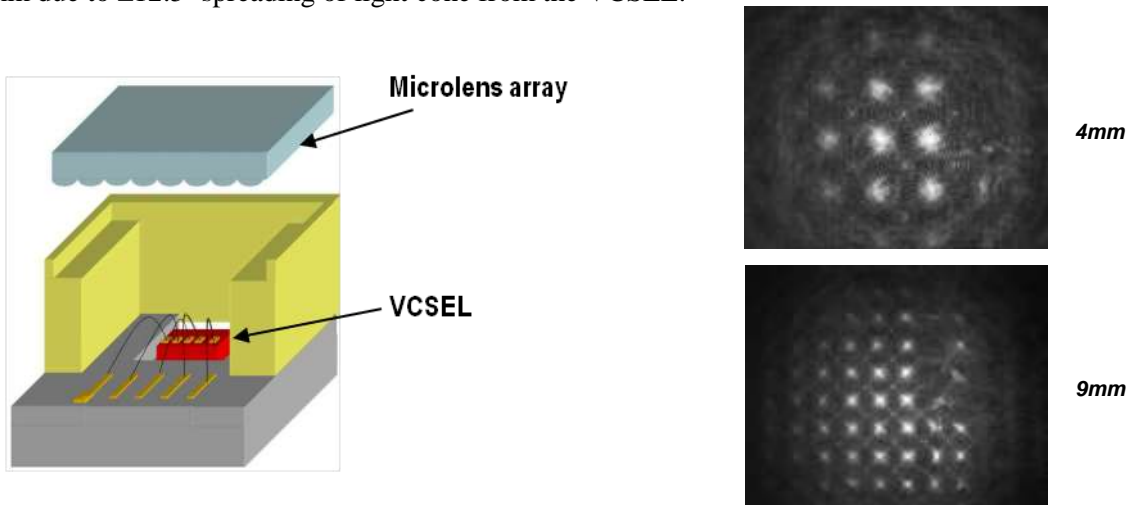
An array of microlens manufactured by a Swiss based company known as Suss<sub>+</sub>MicroOptics has been used as the master lens to obtain its replica by depositing PDMS over it. Master lens has a convex profile as it can be clearly seen in the Figure 11(a). PDMS was deposited on the master lens substrate then it was left to dry and was peeled off it. Figure 11(b) represents the first replica of the master lens having a concave profile. Then PDMS was deposited on the first replica (concave) to obtain an array of convex microlenses of the same size and dimension. An array of microlenses produced by depositing PDMS is a cheap way and the cost becomes significantly low as compare to microlenses produced on a glass. With the ROC=0.297mm of the original microlens (Suss MicroOptics) and the refractive index of PDMS,  $n=1.45-1.47$  <sup>[7]</sup>, expressions in section 2.3 give us an estimation for the focal length  $f=0.66\text{mm}$ .



**Figure 11:** Figure (a) shows a closeup 3D image of the master microlens (convex) used to produce replica PDMS microlens. Figure (b) is showing replica PDMS concave microlens.

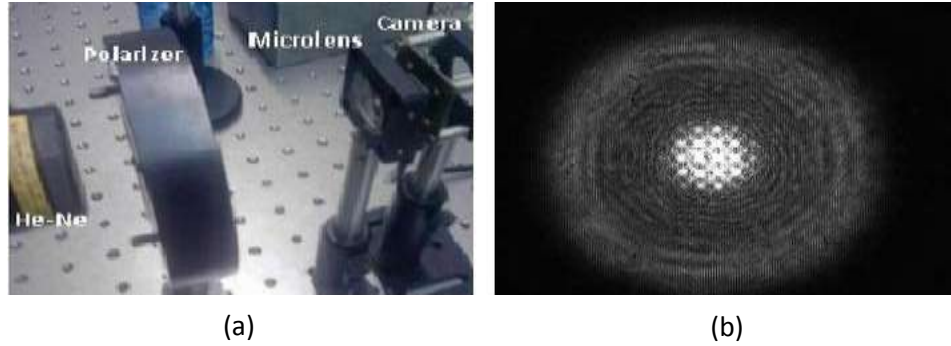
## 7. Optical experiment

Finally, two experiments have been performed in order to check the fabricated micro-optical devices and are described in figure 12 and 13 respectively. In the first experiment (figure 12), the microlens array is placed in front of an array of 4 VCSELs (Vertical Cavity Surface Emitting Laser). There is a spacer in order to prevent from the contact between microlens and VCSEL and break the wire-bonding. The distance between VCSEL and camera is 2cm and the length of the spacer is 1mm. In this experiment, the array is moved and the image is captured with a CMOS camera. In the same figure, some captures can be seen for distances of 4mm and 9mm. The number of illuminated microlens is less for 4mm distance than of 9mm due to  $\pm 12.5^\circ$  spreading of light cone from the VCSEL.



**Figure 12:** Left picture represents geometrical description of the optical package. Microlens array (gray), spacer (yellow), VCSEL (red), contacts (gold), wafer (dark gray). Right: Images of 4mm (up) and 9mm (down) between VCSEL and microlens array.

In the second experiment, PDMS microlens array is directly illuminated by a 5mWatt He-Ne laser with a  $1/e^2$  beam diameter of 0.81mm, see figure 13(a). A CMOS camera is mounted at the nearest possible distance to the microlens array (around 1-2mm). A polarizer is in the optical path in order to attenuate the light beam so that the CMOS camera does not go beyond the saturation level. In the figure 13(b), we can see a photograph of the acquired image, where we can see a set of bright illuminated circles that belong to the focused light from each particular microlens and a set of rings can also be observed that belongs to the Fresnel diffraction of a circular aperture.



**Figure 13: (a): setup of the experimental work and (b): result obtained from the experiment**

### Conclusion:

This study has confirmed the existence of a competition between the action of surface tension and the photoresist crosslinking reaction that occurs during the hard bake of the microlenses process. A low-cost technique for the fabrication of microlens arrays has been demonstrated. In this paper the production of microlens arrays has been discussed. Different fabrication techniques, the specific fabrication technique used in this study and the photoresist reflow method has been discussed. The fabrication of microlens arrays has been described and the resulting profiles measured. Our goal was to produce an array of hemispherical microlens by using thermal reflow technique in a clean room environment and we are successfully done with that. Microlens array of a near perfect hemispherical surface profile has been produced of diameter ranging from 50-175  $\mu\text{m}$  and then PDMS replicas of the master lens array have also been produced. Finally, the microlens array was tested in a lab to check its output.

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