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ORIGINAL ARTICLE

A promising thermal pressing used in fabricating microlens array

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Abstract This paper describes a simple and inexpensive technique for designing and fabricating polygon microlens arrays using a thermal pressing process. Polygon microlens array molds were fabricated using lithography and an electroforming process. The microlens patterns were designed on a photomask and transferred to a substrate through photoresist patterning. Electroforming technology was used to convert the photoresist microlens patterns into metallic molds. A hot pressing machine was then used to produce the microlens array in a polycarbonate (PC) substrate. The experimental variables were compression pressure, temperature, and the pressing time. The surface roughness of the produced microlens array was measured using atomic force microscopy (AFM). The average microlens radii of curvature ranged from 315 to 420 μm and the average sag heights were from 2.98 to 4.03 μm, respectively. The experimental result showed that this fabrication process is useful for microlens array production.

Keywords Micromolding · Polygon microlens array · Thermal pressing

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1 Introduction

There is great potential in the miniaturization of conventional optical components. The field of micro-optics plays an important role in visual display products such as, liquid-crystal displays (LCDs), mobile phone panels and personal digital accessories (PDAs). One major benefit of using microlenses is that they enhance the illumination brightness and simplify light-guide module construction. In a laptop display, a 25% increase in light output has been reported when using the microlens technology [1]. There are other potential benefits too, such as focal plane optical concentration, optical efficiency enhancements, color separation, beam shaping and miniature optical scanning. Micro-manufacturing technology allows compact, and mini-features to be fabricated. Micro-electro-mechanical system (MEMS) technology has a growing number of applications in military, industrial, and consumer markets. For this reason, many academic and research institutions are currently involved in MEMS technology product research and development. Component miniaturization is a common objective in electro-optical systems. Miniaturizing devices using micro-optics has revolutionized many electro-optical systems - including video cameras, video phones, compact disk data storage, robotic vision, optical scanners, and high-definition projection displays [2]. Higher accuracy and lower microlens fabrication costs are needed to meet the rapid growth in demand for these devices.

Micro-scale refractive lenses offer several important features: significantly reduced wavelength sensitivity compared to diffractive optics (necessary for broadband applications), the possibility of very large numerical apertures and high light efficiency [3]. Several fabrication techniques have been applied to the refractive microlens fabrication processes. One method of fabricating refractive microlenses is by melting cylindrical photoresist posts [4, 5]. This is known as microlens reflow processing. Photoresist cylinders are formed using a lithographic process and then heated above the photoresist glass transition temperature. Surface tension causes the photoresist cylinders to assume a spherical shape. Surface tension also leads to relatively short focal lengths in the resulting microlenses (i.e., high numerical apertures). The reflow process produces large microlens arrays. This process is extraordinary compared with conventional macro-optic fabrication methods. In very large scale integration (VLSI) based processing techniques, coherent refractive microlens arrays are made on a silicon surface using a combination of lithography and reactive ion etching (RIE) techniques [6, 7]. Multi-level photoresist mask patterning and sequential RIE are used to form binary optic microlens arrays.

A laser writing system for continuous-relief micro-optical element fabrication in photoresist was described by Gale et al. [8]. The photoresist-coated substrate was exposed using x-y raster scanning under a focused HeCd laser beam (λ=442 nm), synchronously programmable controlled in intensity to write two-dimensional (2-D) exposed patterns. Further development of 3-D microstructures with analogous topology using excimer laser ablation (λ=248 nm) produced versatile micro-optic applications [9]. Microlens arrays with lateral dimensions from 10 to 1000 μm and profile heights of up to 10 μm were fabricated using this technique. An optimal gray scale mask is required to produce fine roughness. Micro-optics printing technology prints a number of droplets onto a substrate to form circular microlens arrays [10]. Microlenses ranging in diameter from 20 μm to 5 mm have been fabricated in this way. The piezoelectric actuator-based and drop-on-demand ink-jet printing method was developed to control different fluid volumes. Liquid droplets were dispensed onto a substrate to form refractive microlens arrays.

The use of deep x-ray lithography to fabricate micro-optical components shows great potential for mass production [11]. Lee et al. used a modified LIGA (German acronym for LIthografie, Galvanoformung, and Abformung) process to fabricate microlenses by melting the deep x-ray irradiated pattern onto a PMMA (poly-methyl methacrylate) substrate [12]. Using this technique, micro-optical components of any desired shape can be fabricated. The resulting components have smooth and vertical sidewalls, lateral dimensions in the micrometer range, and sag heights of several hundred micrometers. A molding process (either injection molding or hot embossing) is required before mass production can be achieved [13, 14]. The microlens array mold or mold inserts play an important role in the mass molding production process. This replication process promises the desired profile as final products. A new method for producing microlens array with large sag heights was investigated for integrated fluorescence microfluidic detection systems [15]. Three steps in that production technique were included for concave microlens array formations to be integrated into microfluidic systems. The micro concave lens molds were then finished and ready to produce convex microlens in PDMS material.

Using a LIGA-like process to fabricate microlens arrays is considerably less expensive using a UV exposure tool instead of deep x-ray lithography. A new microlens array fabrication method using a UV proximity printing method has been invented [16, 17]. It uses a slice to control the gap size, resulting in microlens array formation in the resist. However, this method was limited to round microlens arrays with low sag heights. Lin et al. combined silicon processing and hot embossing to replicate plastic microstructures [18]. They produced microstructures with smooth surfaces, high yield rates, and good reliability. The LIGA-like process provides microlens array fabricators with high optical quality at low cost. By using the vacuum pressure to form a microlens array was investigated [19]. This vacuum suction technique is feasible for certain microlens array fabrication sizes. Based on the LIGA-like technology development, this paper will present the promising technique using the LIGA-like process to pressing microlens array and investigate the processing parameters for making microlens array.

2 Experiments

The LIGA-like process was applied to a series of microlens array fabrications. Figure 1 shows the experimental procedure. The first step is to pattern designed patterns in photoresist onto the substrate as shown in Fig. 1(a). The square, hexagon, and round microlens array patterns were designed and fabricated on a polyethylene terephtalate (PET) based mask. This plastic mask used PET as the mask membrane and was patterned with a laser. This method is quite common in the manufacture of printed circuit boards (PCBs). A stainless steel plate was used as the substrate. The plate was cleaned and coated with an 18 μm thick photoresist (JSR THB-120N) using a spin coater. The spin condition was 800 rpm for 10 s. This sample was prebaked in a convection oven at 90°C for 10 min to remove excess solvent from the photoresist. The plate was then exposed through the PET-based mask for 25 s using a UV mask aligner (EVG620). The aligner is equipped with near ultra-violet (NUV) wavelength 350–450 nm. The power of the lamp ranged between 200 and 250 W. After dipping the substrate in the developer for 3 min, the designed column array in photoresist was formed onto the substrate as illustrated in Fig. 1(a). Table 1 shows the lithography process and experimental parameters.

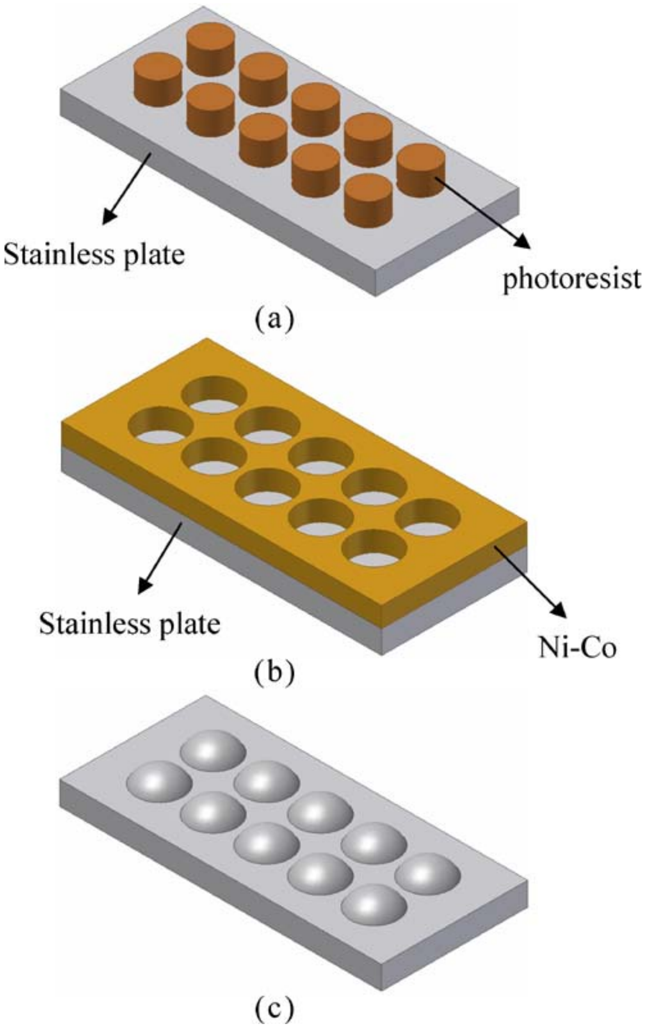

Fig. 1 Illustration of the experimental procedure; (**a**) photoresist patterning via lithography process, (**b**) Ni-Co electroforming to make mold inserts, and (**c**) microlens array formation using thermal pressing

Table 1 Lithography process and parameters

Process step	Parameters	Equipment
Cleaning procedure	1. DI water for 2 min 2. Acetone for 5 min 3. DI water for 2 minutes 4. IPA for 5 min 5. DI water for 2 min 6. N_2 dry	1. Chemical hood 2. Ultrasonic cleaners
Photoresist coating	Spread : 500 rpm for 10 s	Spin coater
	Spin : 1100 rpm for 25 s	Resist : JSR THB-120 N
Soft bake	5 min at 90°C	Oven
Hard bake	2 min at 120°C	Oven
Exposure	8 s	(EV 620) Mask aligner
Development	50 s with agitation	THB-D1

Nickel cobalt (Ni-Co) electroforming was applied to form a 10 μm thick mold on the stainless substrate as illustrated in Fig. 1(b). The related experiment can be found in our publication [14]. This process provided a reversed pattern in Ni-Co from the photoresist patterns on the substrate. The rigid mold can be used to fabricate microlens array in mass production. A laboratory-use hot pressing machine was then used to press the mold for microlens array formation as illustrated in Fig. 1(c). One of the research objects was to study the microlens array formation in polycarbonate (PC) material during thermal pressing. The results indicate that a pressing temperature less than 135°C is not hot enough to produce a microlens array. The optimum temperature range is between 135 and 140°C. The sag heights of the polygon microlens array are directly related to the pressing temperature. All polygon microlens array surface properties were measured using AFM to determine that their surface roughness was less than 5 nm. The polygon microlens array measurement results were carried out using optical microscopy (OM) for the lateral dimensional measurement. Three dimensional profile observations were studied using scanning electron microscopy (SEM) and the Taylor Hobson's profiler.

3 Results and discussion

A microlens fabrication process capable of producing high quality microlenses using standard IC processing materials has been developed. The results of this research indicate that large high quality microlens arrays can be fabricated monolithically on planar IC wafers. With a view to cost-effective mass production and a wider range of suitable optical materials, replication techniques applied in a LIGA technique are being developed. After the microlens prototype is finished, the next step is to transfer the microlens array into a metallic mold using an electroforming technique for the molding process. Mass production of these optical components can then be achieved. A thermal reflow technique is commonly used to fabricate a spherical microlens arrays by melting cylindrical resist posts onto the substrate. The material surface melts once the temperature rises above the material glass transition temperature. Surface tension effects on the melted material result in a spherical profile. The advantages of using the thermal reflow technique include: a simpler process, lower material and facility costs, easier control and greater fabrication parameter stability. The final product shape can be assured using an electroforming replication process. Figure 2 shows various microlens array mold inserts with different shapes including round, square and hexagonal. These specimens were fabricated using lithography and Ni-Co electroforming onto stainless steel plates (5×6 cm^2).

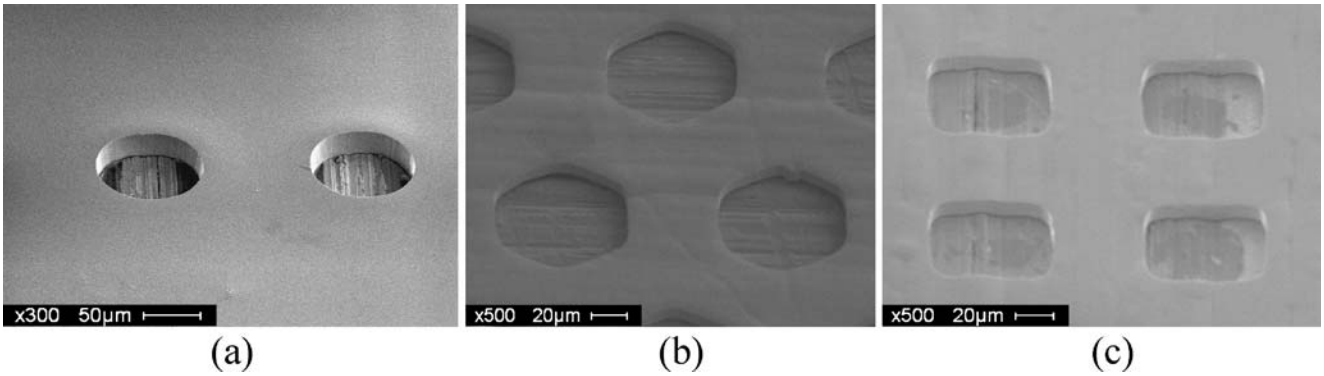

Fig. 2 Various microlens array mold inserts with different shapes; (**a**) round, (**b**) hexagon, (**c**) square

Two processing parameters were investigated; working temperature and pressure. The working pressure in the fabrication process was in the range of 5 to 20 kg/cm^2 and holding time was 180 s. However, no significant difference was found in the microlens array formation at different pressures. Thus, working temperature is a more critical parameter in this process. Figure 3 shows microlens array optical graphs at various working temperatures. Figure 3(a)

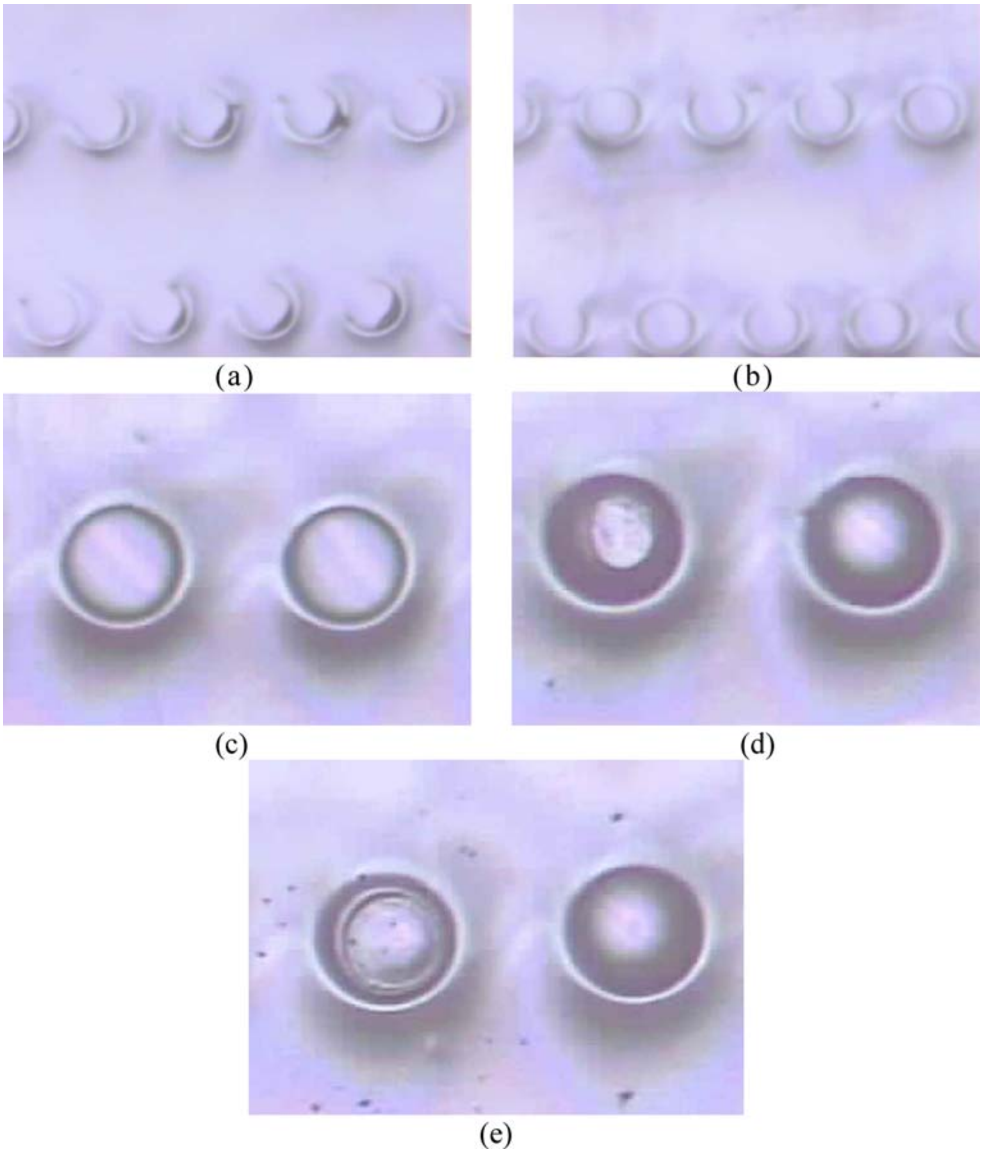

Fig. 3 Microlens array formation at various temperatures; (**a**) 130°C, (**b**) 135°C, (**c**) 138°C, (**d**) 140°C, (**e**) 145°C

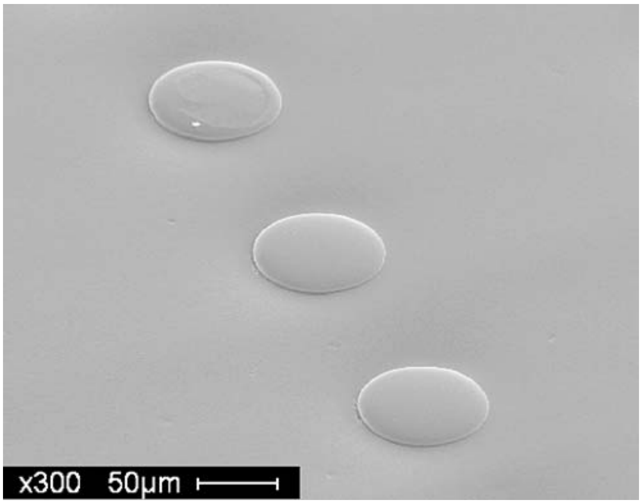

Fig. 4 SEM micrograph of microlens array

and (b) show incomplete microlens array formation due to low temperatures. Figure 3(d) and (e) show tiny bubbles produced in the microlens array due to high temperatures. They were over-heated and surface damage was the result. Figure 3(c) shows the successful formation of a microlens array. An SEM micrograph of a microlens array is shown in Fig. 4. The surface profile was measured using a Taylor Hubson's surface profiler as shown in Fig. 5. The curve profile of the microlens had a 90% similarity when compared to a theoretical optical lens profile.

Several microlens arrays including round, square, and hexagonal were produced using the microlens array mold inserts through the thermal pressing process. The relationship of the working temperature and microlens sag height is shown in Fig. 6. Only the working temperature ranged from 135 to 140°C can produce a microlens array in PC material. The graph shows that there is a linear relationship between the working temperature and the sag height. The microlens array surface roughness was measured using an atomic force microscope (AFM). The measured size was 5×5 µm^2 on the PDMS microlens top as shown in Fig. 7(a). It shows that the microlens surface roughness (Ra) was about 7.4 nm in Fig. 7(b). It is based on five cross-sectional views to obtain the surface roughness. Such microlens surface roughness has proven its surface quality for optical applications.

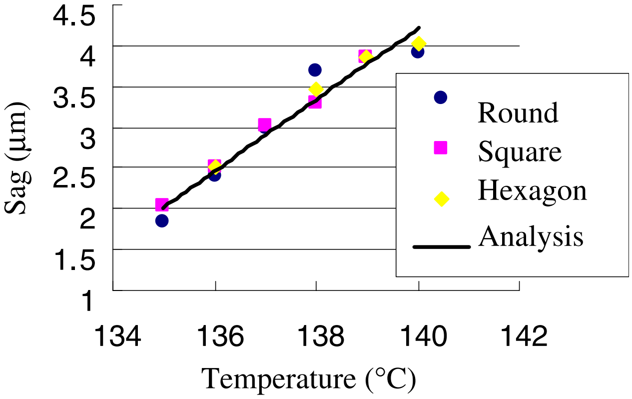

Fig. 6 Relationship of working temperature versus microlens sag height

Fig. 5 Surface profile of the microlens measured using Taylor Hubson's surface profiler

Raw Profile 1 - 10.1mm/Jenny Hsu/Jenny Hsu 06/19/03 10:13:30 AM

Current Point
X 3.1147 mm
Z 2.2569 µm

Reference Point
X -173.9870 mm
Z 0.0000 µm
PV 16.4009 µm

Difference
ΔX 177.1017 mm
ΔZ 2.2569 µm
Pitch 177.1018 mm

Fig. 7 Microlens surface roughness measurement result using AFM; (**a**) surface roughness measurement in 3D profile, (**b**) average surface roughness

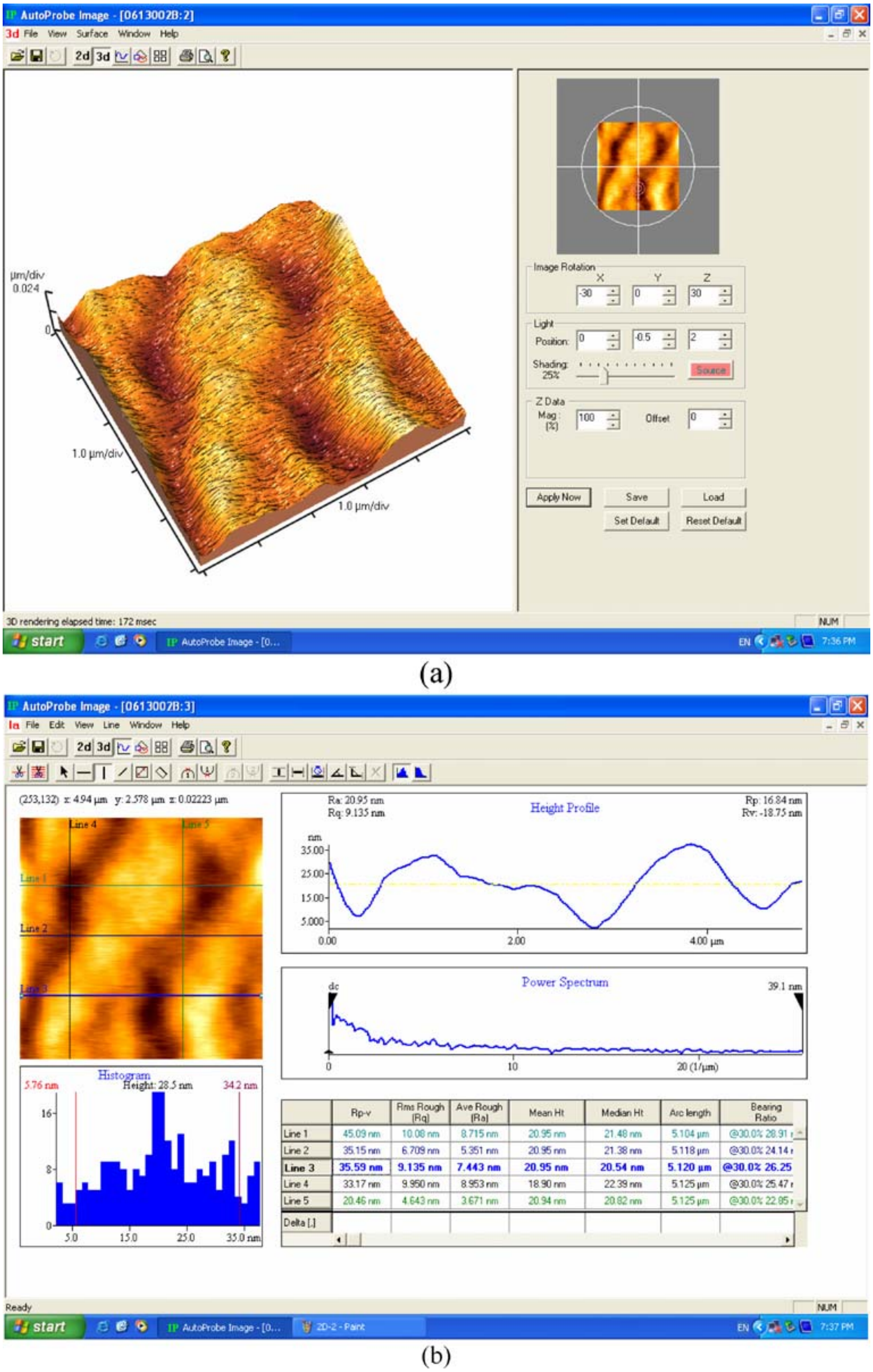

Image Rotation X -30 Y 0 Z 30

Light Position: 0 -0.5 2

Shading: 25%

Z Data Mag: (%) 100 Offset 0

3D rendering elapsed time: 172 msec

(a)

(253,132) x: 4.94 µm y: 2.578 µm z: 0.02223 µm

Ra: 20.95 nm
Rq: 9.135 nm

Rp: 16.84 nm
Rv: -18.75 nm

Height: 28.5 nm

	Rp-v	Rms Rough (Rq)	Ave Rough (Ra)	Mean Ht	Median Ht	Arc length	Bearing Ratio
Line 1	45.09 nm	10.08 nm	8.715 nm	20.95 nm	21.48 nm	5.104 µm	@30.0% 28.91
Line 2	35.15 nm	6.709 nm	5.351 nm	20.95 nm	21.38 nm	5.118 µm	@30.0% 24.14
Line 3	**35.59 nm**	**9.135 nm**	**7.443 nm**	**20.95 nm**	**20.54 nm**	**5.120 µm**	**@30.0% 26.25**
Line 4	33.17 nm	9.950 nm	8.953 nm	18.90 nm	22.39 nm	5.125 µm	@30.0% 25.47
Line 5	20.46 nm	4.643 nm	3.671 nm	20.94 nm	20.82 nm	5.125 µm	@30.0% 22.85
Delta [.]							

Ready

(b)

4 Conclusion

Microlens array formation using thermal pressing was investigated in this paper. The sag height has a linear relationship with the working temperature through the formation of different microlens shapes. The working pressure is independent of the formation process. This may be due to the small microlens array area compared to the substrate size. It was not easy to observe this effect. The optimum working temperature was in the range of 135~140°C. The achievable microlens array sag heights were 2.98~4.03 µm. The smooth microlens surface roughness also showed a fabrication result suitable for optical applications.

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