Numerical method to predict and fabricate aspherical microlens arrays using 248-nm excimer laser ablation

C. T. Pan
National Sun Yat-Sen University
Center for Nanoscience & Nanotechnology
Department of Mechanical and Electro-Mechanical Engineering
Kaoshiung 804, Taiwan
E-mail: panct@mail.nsysu.edu.tw

S. C. Shen
Industrial Technology Research Institute
Mechanical Industry Research laboratories
Hsinchu 310, Taiwan

Chi-Chang Hsieh
Chi-Hui Chien
National Sun Yat-Sen University
Center for Nanoscience & Nanotechnology
Department of Mechanical and Electro-Mechanical Engineering
Kaoshiung 804, Taiwan

Yung-Chang Chen
National Pingtung University of Science and Technology
Department of Vehicle Engineering
Pingtung 912, Taiwan

Abstract. A method of numerical simulations is used to predict the profile of a 3-D aspherical microlens array. Based on the simulated results, the desired micro-optical lens profile is obtained through excimer laser ablation. The simulation method applied in the excimer laser ablation can significantly reduce the quantity of microablation experiments. The ablated microstructures with surface average roughness of Ra < 20 nm are successfully achieved for micro-optical components. The excimer laser ablation parameters include laser fluence, shot number, workstation scanning velocity, and repetition rate. Various profiles of microlens and microprism arrays with different dimensions can utilize numerical simulation and form desired geometries by laser ablation.

© 2004 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1794178]

Subject terms: excimer laser; fluence; ablation; aspheric; microlens array.

Paper 03049 received May 12, 2003; revised manuscript received Jan. 15, 2004; accepted for publication Mar. 22, 2004.

1 Introduction

Micromaching technology has a wide range of applications: optical-electro mechanisms are particularly attractive. Micro-optical functions and devices, such as focal plane optical concentration, optical efficiency enhancements, color separation, beam shaping, and miniature optical scanning have shown potential in the industry. The development of micromanufacturing technology has allowed compact and minifeature size to be fabricated. Micro-electromechanical system (MEMS) technology offers a wide variety of applications for the military, industrial, and consumer markets. Numerous academic and research institutions have been involved in the development of MEMS technology and commercial products. The miniaturization of components has been a common objective in all studies. Miniaturizing devices using micro-optics promises to revolutionize many electro-optical systems from video cameras, video phones, and compact disk data storage to robotics vision, optical scanners, and high-definition projection displays. Both higher accuracy and lower cost microlens array fabrication methods are needed to meet the rapid demand for these commercial devices.

Multimask-level photoresist patterning and sequential reactive-ion etching (RIE) to form binary optical spheric microlens arrays has been achieved. A laser writing system for the fabrication of continuous-relief micro-optical elements in photoresist was described by Gale et al. Polymeric materials are quite suitable for microstructuring due to their low ablation threshold, smooth etching behavior, and ablation rates at tenths of micrometers per pulse at very modest energy fluence. Zimmer, Hirsch, and Bigl developed efficient methods to fabricate analogous 3-D structures with dimensions in the micron range. Deep x-ray lithography processes, electroforming, and molding technology (also known as the LIGA process) to fabricate micro-optical components show great potential for mass production. It is time consuming to fabricate the desired profile of a microlens array. But, there is a little research...
focused on profile prediction and fabrication of spherical microlens arrays, not to mention aspherical microlens arrays.

In this study, an aspherical microlens array with the desired shape, smooth surfaces, lateral dimensions in the micrometer range, and heights up to 100 mm are achievable via excimer ablation. Following a molding process (hot embossing), micro-optical components such as microlenses and microprisms in polymer can be attained for mass production. Thus, the design, simulation, and fabrication process of aspherical microlens arrays are explored through theoretical study and verified by experiments of excimer laser ablation.

2 Experimental Procedures

The Exitech 8000 type excimer laser was used in these experiments and the excimer laser workstation is schematically described in Fig. 1. The laser source was a Lambda Physik COMPEX-110 excimer laser whose wavelength, pulse energy, pulse duration, and repetition rate are 248 nm, 400 mJ, 25 ns, and 100 Hz, respectively. The laser beam
focused spot size used in this study was $0.25 \times 0.25 \text{ cm}^2$. Four times the demagnification factor of the excimer laser projection system was used in the ablation experiment. A constant discharge voltage mode and constant pulse energy mode are available during micromachining. The photomask projection method was applied for micromachining after a constant voltage or pulse energy mode was set up. A set of twin array energy density homogenizers and a projection lens were installed to make the laser beam power profile more uniform (uniformity $\leq 1.5\%$). The working parameters of the laser machine were pulse number, laser fluence, workstation velocity, and pulse repetition rate, ranging from 30 to 80, 0.3 to 0.7 J/cm$^2$, 8 mm/min to 2 mm/min, and 1 to 80 Hz, respectively. The laser ablated polymer microstructure surface measurement was scanned using an atomic force microscope (AFM) and a scanning electron microscope (SEM) micrograph to show the 3-D morphology. The ablated depth was measured using a Dektak II surface profiler (ablated depth $\leq 30 \mu\text{m}$) and optical microscope (OM).

3 Working Principle

The working parameters of the laser ablation process included width of mask pattern in the scanning direction, shot number, workstation scanning velocity, and pulse repetition rate. The relationship between these parameters can be expressed as,

$$f = \frac{S}{\frac{H}{V}}, \quad (1)$$

where $f$ is the pulse repetition rate, $S$ is the laser shot number, $H$ is the width of the mask pattern in the scanning direction ($\mu\text{m}$), and $V$ is the workstation scanning velocity (mm/min).

From this equation, it can be seen that through there are three laser machine variables, i.e., $V$, $S$, and $f$, only two of them are independent. Equation (1) can be rearranged as

$$H = \frac{SV}{f}. \quad (2)$$

Equation (2) reveals that $H$ is proportional to $S$. When a larger $H$ is exposed to the laser beam energy, deeper workpiece ablation thickness will be the result. Based on the previously mentioned facts, different mask patterns can be

Fig. 3 The excimer laser experimental result of ablation depth versus shot number for PI material.

Fig. 4 The experimental result of excimer laser ablation for PI material: (a) 0.4 J/cm$^2$, 50 shots, and (b) 40 Hz, 50 shots.
designed to obtain patterns with various $H$ dimensions. The laser energy profile in the mask pattern in terms of the laser shot number [Eq. (2)] can be calculated, with which the 3-D microstructure can be analogously predicted.

\[ D \approx S, \]  

where $D$ is the ablation depth (μm).

However, the substrate thermal and photochemical properties were not yet taken into consideration. This will play an important role in laser ablation. Thus, depth is a function of $S$ and $K$. $K$ can be treated as a calibration number. It is a function of the material thermal and photochemical properties. Besides, the laser fluence absorption rate of material also plays an important role during the ablation process. However, it is very complicated. In the future, further study will identify this effect on the process. Thus, the preliminary relationship can be expressed as follows:

\[ D \approx KS, \]  

where $K$ is the thermal and photochemical properties.

Based on Eqs. (2) and (3), as long as the mask pattern is defined, the 3-D microstructure produced using laser ablation can be predicted.

In laser ablation processing, the liquid polyimide (PI) is spun on 4-in. wafers at different rotational rates, resulting in controllable PI thin film thickness. The rotational speed of the spin coater determined the layer thickness of PI. The higher the rotational speed, the lower the thickness. Speeds of 600, 800, 1000, and 1200 rpm produce thicknesses of 30, 26, 20, and 14 μm, respectively. A curing process under 350 °C in an oven for three hours is then followed by the spin process to obtain concrete films. The laser dragging method with various laser fluence, repetition rate, workstation scanning velocity, and shot numbers are applied to form the 3-D microstructures via laser ablation. The procedure is described in Fig. 2. Figure 2(a) shows the PI material on the Si wafer after the curing process. Figure 2(b) shows the photomask to produce a semicylinder shape. When the laser beam impinges on the designed photomask, the laser beam will go through the transparent portion of the photomask onto the material surface and ablate the material. Since the PI material is moving relative to the photomask at a constant scanning velocity ($V$), the semicylinder profile can be made. Later, the workpiece was rotated 90 deg (y direction) relative to the original position (x direction) and ablated again. Thus, a microlens can be fabricated. Figures 2(c) and 2(d) show that first, the laser is dragged in one direction to form a semicylinder shape, then another laser is dragged perpendicular to that direction to form another semicylinder shape. When the two semicylinder shapes cross each other, the desired microlens profile can be produced.

4 Results and Discussion

This experiment is based on the laser pulse number, energy fluence, and pulse repetition rate. Therefore, the relationship between the prior parameters and ablation rate has to be investigated and established completely. Ablation depth versus laser shot number is discussed next. Figure 3 shows the ablation depth versus the laser shot number. It makes sense that a higher laser shot number results in a higher ablation depth at a constant repetition rate. It is worth noting that the relationship between ablation depth and shot number shows an excellent linearity. Figure 3 verifies experimentally with Eq. (2). On the other hand, Fig. 4 shows the experimental results of the excimer laser ablation rate as a function of repetition rate and fluence, respectively.

The profile of a 3-D microlens array can be simulated using numerical analysis in Eqs. (2), (3), and (4). The simulation profile qualitatively. This simulation method can be applied to an aspherical microlens array. The preliminary simulated result of an aspherical microlens array is shown in Fig. 6(a). An experimental result of an aspherical microlens array is illustrated in Fig. 6(b) with different laser fluence from 0.3 to 0.7 J/cm². It also shows that the experimental ablated microlens profile was compared with simulated results. It shows that the experimental result has an excellent agreement with the simulation result. Thus, the desired profile of an aspherical microlens can be made efficiently with the help of the simulation method. It will reduce the experimental quantity significantly.
Fig. 6 The comparison between the experimental and simulated results with different laser fluence for PI material.

(i) Laser fluence 0.3 J/cm²  (ii) Laser fluence 0.5 J/cm²  (iii) Laser fluence 0.7 J/cm²

Fig. 7 The comparison between the experimental and simulated results with different workstation scanning velocity for PI material.

(i) 8 mm/min  (ii) 4 mm/min  (iii) 2 mm/min
On the other hand, the relation of workstation scanning velocity and ablation depth is explored. Different scanning velocity from 2 to 8 mm/min was performed in the study. When the dragging velocity is lower, the higher aspect ratio of the microlens profile will be obtained. Lower dragging velocity means more laser energy into raw material (PI). It will result in a higher ablation rate, and a higher aspect ratio of a microlens profile will be made. The proper laser fluence and scanning velocity can control the geometric shape and surface roughness of an aspherical microlens array (shown in Fig. 7).

Also, complex geometric structures can be simulated and patterned using the laser dragging method. A micro prism array can also be predicted using this method. Figure 8(a) displays the simulation result. Microprism arrays [Fig. 8(b)] cannot be machined using the conventional lithography process, but they can be easily ablated using an excimer laser. Various shapes and sizes can be controlled using...
different laser ablation machining parameters. The sharpness of these prisms are very obvious [shown in Figs. 8(b) and 8(c)], though the ablation depth was not deep enough due to an insufficient number of shots or laser fluence. The proper laser energy and shot number can improve the geometric shape. Besides, some debris and micropor can be observed in the microlens surface as shown in Fig. 8(c). It may be caused by the defect of polymeric material. Based on the current simulation method, the roughness of the ablated microlens due to material defects cannot be simulated using this method.

Microstructures can be applied as micro-optical components in many fields. Surface smoothness in optical components is a required property. The laser ablated 3-D microstructures adapt to this requirement and the surface average roughness of microstructures with Ra<20 nm was measured using AFM (Fig. 9). The measurement setup and results are illustrated in Fig. 10. Figure 10(b) shows the energy distribution profile of a 785-nm laser diode before coupling into a microlens, whereas Fig. 10(c) shows the energy distribution profile of an 785-nm laser diode after coupling into a microlens. A test microlens was fabricated at the process condition of $f=0.5 \text{ J/cm}^2$ and $V=4 \text{ mm/min}$.

5 Conclusion

A micromachining process to fabricate micro-optical components using excimer laser ablation is explored. Various shapes and sizes can be controlled using different laser beam ablation machining parameters. Aspherical microlenses and microporism arrays are simulated. The surface quality of these eximer laser ablated components meets the critical requirements of micro-optical components. Experiments proved the feasibility of excimer laser ablation on micromaching optical components at the micro-scale.

Acknowledgment

The authors would like to thank Dr. Tung-Chuan Wu and Dr. Min-Chan Chou at MIRL of ITRI in Taiwan for their guidance, and National Science Council (NSC) for their financial supports to the project (grant numbers NSC92-2622-E110-009-CC3 and NSC92-2212-E110-029).
References


C. T. Pan received his MSE and PhD in 1993 and 1998, respectively, from the power mechanical engineering department of National Tsing Hua University in Hsinchu, Taiwan. He was a researcher in the field of laser machining polymer in the TU Berlin (IFW) in Germany from 1997 to 1998, and a researcher of MEMS Division in the MIRL/ITRI, Hsinchu, in Taiwan from 1998 to 2003. He joined National Sun Yat-Sen University, Kaohsiung, Taiwan, as an assistant professor in 2003. His current research interests focus on MEMS, NEMS, and LIGA process.

S. C. Shen is now a researcher of the MEMS Division in MIRL/ITRI, Tainan in Taiwan. His research focuses on LIGA, UV-LIGA, laser-LIGA, and advance biomedical systems. He received the BE and MS degrees in automatic control engineering from Feng Chia University, Taiwan, in 1996 and 1998, respectively. He received his engineering PhD in 2002 from the engineering and system science department of National Tsing Hua University in Hsinchu, Taiwan. His thesis work involved the development of design and fabrication MEMS device application.

Chi-Chang Hsieh received the BE and ME degree from the Department of Mechanical and Automation Engineering, Da-Yeh University, Taiwan, in 1999 and now is the doctoral Candidate in Department of Mechanical and Electro-mechanical Engineering, National Sun Yat-Sen University. His current research includes MEMS process, applied optical metrology, interfacial adhesion of the IC package, etc.

Chi-Hui Chien received the BE degree from Tamkange College, Taiwan, in 1977, and the MS degree from Auburn University, Alabama, in 1980, both in mechanical engineering, and the PhD degree in theoretical and applied mechanics from University of Illinois at Urbana-Champaign, in 1984. He joined National Sun Yat-Sen University, Kaohsiung, Taiwan, as an associated professor in 1984. Currently, he is a full professor in the Department of Mechanical and Electro-Mechanical Engineering in the same university. His current research interests include glass fiber buckling, the study of warpage, fatigue life, and interfacial adhesion of the IC package, and optical methods in nanoscale measurement.

Yung-Chang Chen received the BE and ME degree in industrial education from National Taiwan Normal University, and the PhD degree in mechanical and electro-mechanical engineering from National Sun Yat-Sen University, Taiwan, in 2003. He joined National Pingtung University of Science and Technology, Taiwan, in 1996. Currently, he is an associate professor in the Department of Vehicle Engineering. His primary research interests lie in the areas of optical metrology, microsystems packaging, microresistance welding, etc.