Simulation and Experiment of Micro-Lens Fabrication Using Droplet Deposition Method

Chin-Tai Chen, Ching-Long Chiu, and Sz-Sheng Chen
OEAC, OES, Industrial Technology Research Institute
Tainan, Taiwan, R.O.C.

Abstract

The paper is aimed to study the profile evolution of micro-lens fabrication in short duration from several mini-seconds to seconds. Droplet deposition method, similar as inkjet-like printing, could be applied for the 3D lens-making process, in which optical liquid material was used here. The transient mechanism of lens-forming behavior is fully understood by using numerical simulation of fluid thermodynamics. Deposition results can be shown that concave and convex profiles are determined by a couple of physical parameters, such as solid content percentage and evaporation rate. With the experiments, it is expected that the rapid method can be further implemented in many manufacturing of small objects in the future.

Introduction

The increasing demands in miniaturization process of optoelectronic devices and growth of the fabrication technologies in micro-scale process have pushed the development of the optical-lens toward the micro-scale technology. Microlens is applied on many micro-optical and optoelectronic devices, such as collimator of fiber, on chip micro lens of imager sensor and laser diode pickup lens etc. The traditional fabrications of micro-lens and microlens array include MEMS etching, etching and melting, micro machining, ion-beam etching, molding, UV curving, inkjet printing and so on.

From the view point of the lens design principles, there are many types of microlens can be categorized as refractive lenses, diffractive lenses and so on. In common use, the refractive lenses usually used in the microlens and the plano-convex microlens are the most commonly.

The drop-on-demand inkjet printing technology has the ability of producing various volumes of droplets. According to the performance of the inkjet printing technology, the microlens can easily to form from hundreds micrometers to few micrometers. The transparent optical material can be dispensed from the inkjet print head to the target such as planar substrate. For producing various curvatures, the different driven signal can be applied on the print head to dispense one or many droplets. The method using the inkjet printing technology to dispense micro optical droplet onto the target to form microlens can be called droplet deposition method.

This paper shows the fabrication and numerical simulation of the microlens using solvent-based liquid optical material. The fabrication of the microlens used the droplet deposition method. The method could be applied for the producing the 3D microlens, on chip microlens etc. The numerical simulation shows the evaporation of the solvent-based optical material on the planar subtract.

The solvent-based optical material is different from the material used on the traditional inkjet printing technology. Those materials usually are single species material such as optical epoxy needed UV curing or double species material such as AB epoxy needed the addition of the harder. The solvent-based optical material is a compound which includes many chemical species. The main component is the solvent like water or organic material.

A phenomenon would appear at solidification process of the solvent-based droplet. The contact line problem would let droplet has a concave shape. The shape usually called coffee ring.[1]

Numerical Simulation Skill

The numerical simulation of forming microlens is a skill to solve two-phase, two-component, evaporation, free surface problem. The challenges of the skill are to track the interface between the liquid phase and gas phase and compute the distribution of the solvent and the solute of the droplet on subtract. The numerical skill used in this paper is developed by Dr. Yeh,[2] and it is a multi-phase interface unsteady flow solver.

The detail skill of the solver include,

- Finite element method
- Volume fraction of fluid
- Unsteady compressible flow
- Large eddy simulation
- Explicit time integration scheme

The solver includes two parts, one is the interface tracking, the other is the thin film evaporation calculation. The interface tracking of the solver includes continuum and momentum equations. From the above equations, the velocity, pressure can be attained.

The mainly domain force influences the thin film droplet evaporation include,

- Non-uniform evaporation
- Diffusion
- Osmotic pressure (gradient)
- Surface tension

For the complete calculation of the droplet evaporation, the grid system must be adaptive as flow field. The species flow equation inside thin film droplet is

$$\rho\frac{\partial u_i}{\partial t}+\rho(u_j-\dot{w}_{gj})u_{i,j}=(\delta_{ij}\sigma_{kk}+\tau_{ij})_{,j}+DWRTX_{,j} \qquad (1)$$

where u_i, u_j are the velocity component, $\dot{w}_{gj}$ is the grid speed, DWRT is the coefficient of the osmotic pressure gradient, and X is the concentration of the solvent or solute. The concentration equation is

$$\frac{\partial X}{\partial t}+(u_j-\dot{w}_{gj})X_{,j}=DIFF\cdot X_{,kk} \qquad (2)$$

where DIFF is the coefficient of concentration diffusion.

It is very important that the behavior on the interface between liquid and vapor phase. There exists evaporation flux and force balance on the interface. The solvent near interface could evaporate toward to vapor phase and form flux on the normal direction of the interface. The force action on the tangent direction of the interface is the surface tension. There could be described by two equations listed below,

$$J=X_{solvent}\cdot VAPO(1-\frac{r}{R})^{-REXP} \qquad (3)$$

$$T=TENS\cdot c \qquad (4)$$

where VAPO is the evaporation rate of the solvent, J is the evaporation flux normal to the interface, R is the maximum distance of the droplet on the subtract, r is the radius distance, $REXP$ is the exponential factor of the evaporation, $TENS$ is the surface tension of the solution, T is the shear stress tangent to the interface. The fluid properties of the optical material made by the components using linear relationship, such as,

$$\rho=X_{solvent}\cdot\rho_{solvent}+(1-X_{solvent})\cdot\rho_{solute} \qquad (5)$$

where $\rho_{solvent}$ is solvent density. Other properties such as viscosity and fluid elastically modulus use the similar equation.

Experiment

The fabrication of the microlens in this paper is a new micro fluidic method shows in Fig. 1. The Teflon was deposited on a planar subtract before drop deposition. The Teflon forms the hydrophobic thin films, so the drop dispensed onto subtract could form a spherical cap. Solvent content of the droplet was finally evaporated to produce a microlens of solid content.

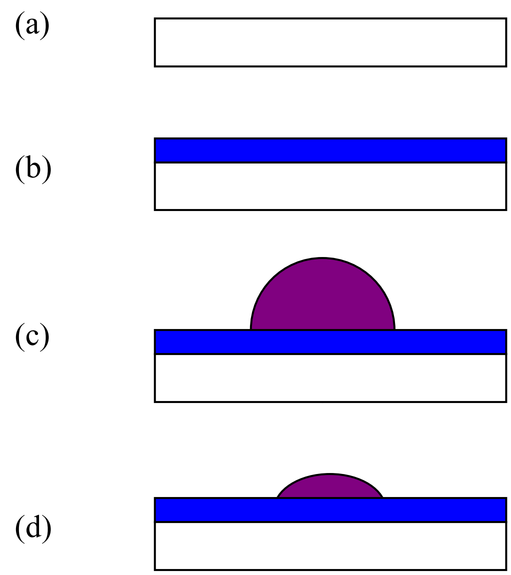


Figure 1. The Fabrication method of the microlens, (a) planar subtract, (b) coating a thin film of Teflon, (c) dispense drops onto subtract, (d) microlens solidification.

The solvent-based optical material is the water-based solution in this paper, since the solvent, water is a well known, safety solvent. The solution was dispensed by inkjet print head or pipette. The inkjet print head could be the thermal-bubble type or the piezoelectric type.

Results

Simulation Results

The simulation of the drop deposition method used the finite element method, free surface tracking method and evaporation model. Figure 2 shows the computational domain. The blue region shows the solution position.

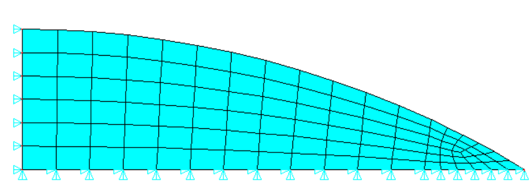


Figure 2. The computational domain of drop deposition method.

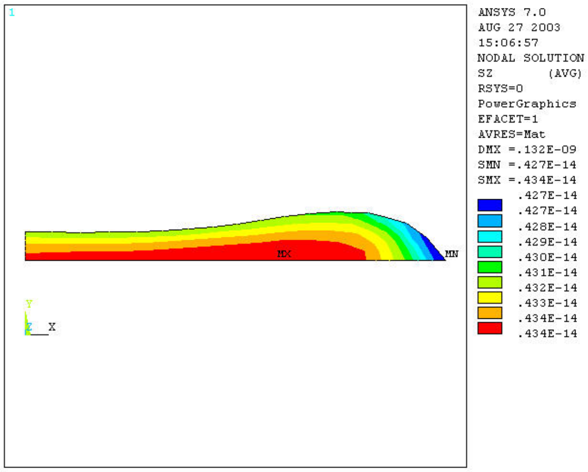


Figure 3. The contour of drop at 2 sec after dispensed on the subtract.

Figure 3 shows the solute concentration distribution of the droplet at 2 seconds after dispensed onto the subtract. The whole solute concentration is about 4.3X10^{-14}, it shows the droplet almost solidification, that is to say, there is no solvent in the droplet. The contour of Fig. 3 shows the right half spherical cap of the droplet. The color layers show the distribution of the solvent concentration. From the calculation result, the concentration of the solvent is gradually decreased as the radius increasing.

In Fig. 3, the interface shape indicates a concave topography, which is called "coffee ring". For the purpose of the microlens, the phenomena make the lens as a planar concave microlens. However, the difference of the ring between maximum and minimum height is concerned. The rate of height difference is defined,

$$\text{Rate of height difference} = \frac{|H_{min} - H_{max}|}{H_{min}} \times 100\%$$

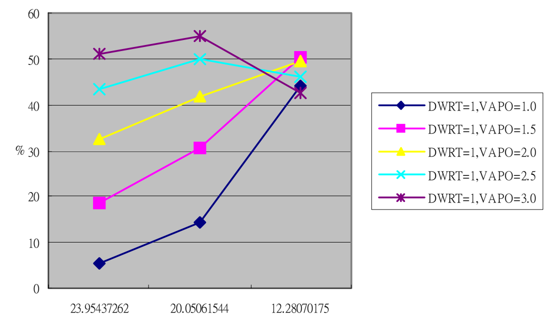
The rate of height difference could take as the extent of the coffee ring. If the rate toward to zero, the ring could not exist and the droplet maintain the shape of the spherical cap.

Figure 4 shows the comparison of the rate of height difference with three concentrations solution under 5 VAPO parameters. At the higher concentration, high evaporation rate would cause higher difference. However, as the concentration decreased, the difference between 5 conditions would not have evident different. The reason of that is, the solute would evaporate faster in lower concentration solution than higher one.

■ Experimental Results

Polyvinyl alcohol (PVA) was used in the solution of the experimental. The fluid properties such as viscosity, surface tension were list in Table 1. The concentration of the PVA solution was modulating as many consistencies. The solution was filled and dispensed by use of pipette or inkjet print head. When using the pipette to dispense the solution to form microlens, the volume of the solution must be setup in advance. When the solution was dispensed by the ink jet print head, the controlled data driven signal was transfer to the print head to dispense constant numbers of the droplets.

The PVA solution was dispensed on the subtract which coated the thin film layer of the Teflon. The microlens would form a series lens after time evolution. Figure 5 shows the top-view images for the microlens with diameter about 1.9mm.



concentration of solute (wt%)

Figure 4. The comparison of the rate of height difference with concentration solution and 5 parameters.

Table 1. The Properties of the Polyvinyl Alcohol Solution

Solute density	1.26g/cm^3
Solvent density	1.00g/cm^3
Solvent viscosity	1cps
Solution surface tension	30 dyne/cm
Solution viscosity	1100cps @ 20%solute

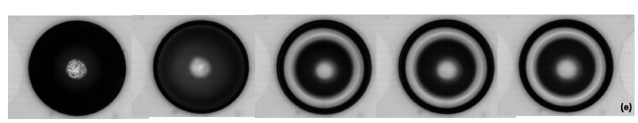


Figure 5. Time evolution of top-view images with diameter 1.99mm.

It is significant that there found a single white ring, coffee ring, after many time of the evaporation. Meantime, tilted-view image has indicated the concave topography of the microlens was produced with maximum heights of the lens at the tip of the ring and minimum heights at the center of the lens.

Figure 6 shows the tilted-view image. The 3D distribution of color intensity was shown in Fig. 7. Figure 8 shows the planar concave microlens by the droplet deposition method using other optical material. The material would dispensed on the subtract which coated the Teflon thin film also. After the solid content form, the microlens would be a planar convex lens.

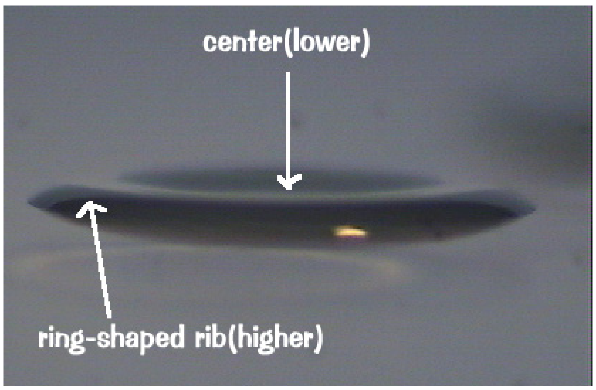


Figure 6. The tilted-view image of PVA droplet with 1.9mm[3].

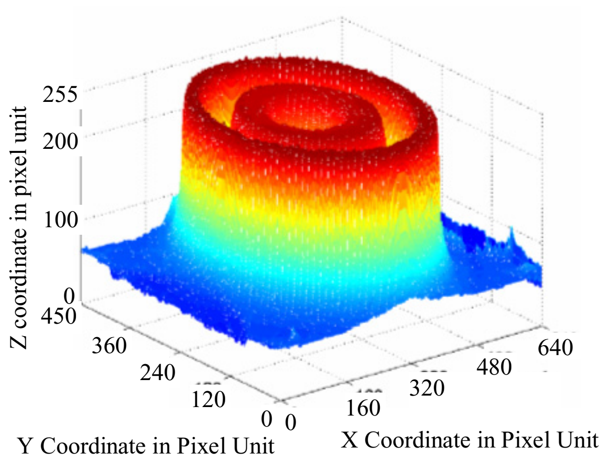


Figure 7. 3D color intensity distribution of droplet with 1.9mm[4].

Conclusion

From the results of the simulation and experimental, it shows that the Teflon film successfully worked as a virtual surface to keep the higher contact angle than that of without the film.

From the results of the simulation, it shows that the rate of height difference of various solutions would change with the concentration, and it also shows the tendency of that. The formation mechanism of the coffee ring has proved in the simulation results, that is, the model of the simulation is well done.

Since, the appearance of the coffee ring causes the microlens form a concave shape. Some treatment process maybe form other lens shape.

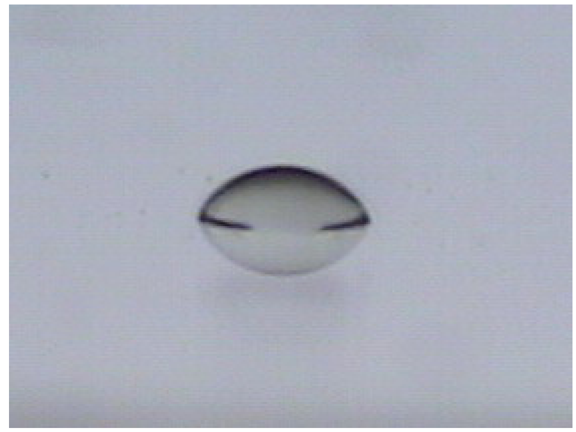


Figure 8. The planar concave microlens.

References

1. Deegan, R. D., "Deposition at Pinned and Depinned Contact Lines: Pattern Formation and Applications," The Thesis of Ph.D, The University of Chicago, 1998.
2. Yeh, J. T., "User manual of YFLOW-Mult: A Unique Virtual Lab. for Multi-Phase Flow," MRL/ITRI, 2003.
3. Chen, C. T., and Su, H. W., "Experimental Study of Microlens Fabrication using Polyvinyl Alcohol Solution," Tamkang Journal of Science and Engineering, Vol.7, n.2, pp.119-122, 2004.
4. Chen, C. T., Chiu, C. L., and Horng, J. B., "Design and Fabrication of Microlens by Microfluidic Deposition Method," 49th SPIE Annual Meeting, 2004(in pressed).

Biographies

Chin-Tai Chen received his B.S. degree in Engineering Science from the National Chung Kung University in 1992 and an Engineer Degree in Aeronautics and Astronautics from Stanford University at Palo Alto of USA in 1997. He joined the Printing Technology Division of OES/ITRI in 1998. His current research focused on the system integration of thermal inkjet printer, including mechanical design, micro-lens etc. He is the project manager of Technology Division in OES/ITRI.

Ching-Long Chiu joined the Printing Technology Division of OES/ITRI in 1998. He received his M.S. and Ph.D from Institute of Aeronautical and Astronautical Engineering of National Cheng Kung University. His interest lies in the field of computational fluid dynamics.