Direct fabrication of polymer microlens arrays having tunable optical properties using drop-on-demand ink-jet printing technology

Joo Yeon Kim[1], Vahid Fakhfouri[1], Karl Pfeiffer[2], Anja Voigt[2], Marion Fink[2], Gabi Gruetzner[2], and Juergen Brugger[1,*]; Microsystems Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland, [2] Micro Resist Technology GmbH, D-12555 Berlin, Germany, *corresponding author: juergen.brugger@epfl.ch

Abstract

Ink-jet printing technique allows locally and precisely dispensing materials for the manufacturing of micro-scale structures. We present the fabrication of plano-convex microlenses using a hybrid organic-inorganic photo-curable polymer diluted in gamma-butyrolactone (GBL). Microlenses are printed on a glass substrate having different number of drops per lens and different surface conditions. We investigated the influence of the surface conditions on the size and shape of the printed microlenses, which can be affected by wetting properties. Further geometrical and optical characterizations are presented in detail.

Introduction

Microlenses and microlens arrays can be widely applied to imaging sensors and photodetectors due to their excellent light collecting efficiency [1]. As reported in a recent review [2] several fabrication techniques of micro-optical components have been proposed. These include for instance photoresist reflow, photopolymerization and microjet printing. Recently the fabrication techniques have been adapted in view of the microstructuring of polymer with high optical grades, which can provide improved optical transmission as well as mechanical and thermal stability.

In a previous work, ink-jet printing technology has been used for the fabrication of microlenses in SU-8 [3]. Using ink-jet printing technology, materials can be dispensed on the substrate without contacting the substrate outside the drop impact area. It is applicable to large area printing while simultaneously reducing the material waste in drop-on-demand (DOD) mode. In DOD, ink drops are generated individually in due times and positions allowing programmable surface pattern generation. The diameter of a drop generated from the ink-jet head is approximately equal to the aperture size of the nozzle.

In this work, we present the fabrication of microlenses using hybrid polymer, which is knows for excellent optical properties [4].

Experimental technique

Ink-jet printing equipment

Ink-jet printing was performed by using a piezo-actuated ink-jet printer. The nozzle is actuated in squeeze mode. The generation of drops was observed with a stroboscopic system when tuning the signal amplitude and pulse length of the piezo-actuator. The pressure in the ink-jet nozzle was controlled to optimize the liquid flow, the wetting on the nozzle and ejection properties.

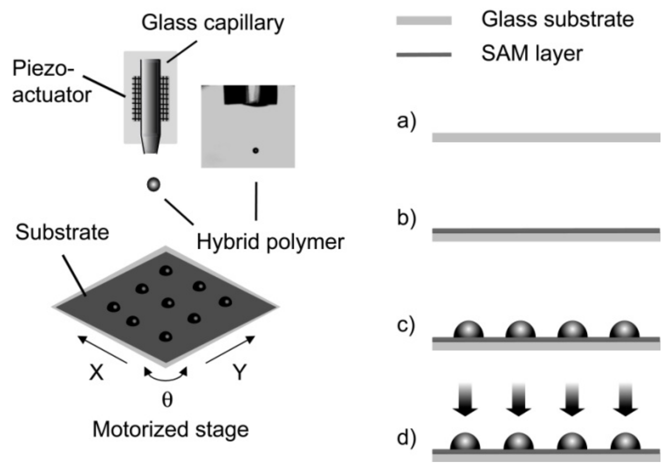

Figure 1. *Left: Schematic diagram of the DOD ink-jet printer with stroboscopic image of the drops, generated by ink-jet printer. Right: the process flow used to fabricate microlenses a) Untreated (cleaned) glass substrate, b) SAM-treated glass substrate (dark grey), c) Ink-jet printing of hybrid polymer and pre-bake, d) UV-exposure and post-exposure bake*

Ink-jet printing of hybrid polymer

Figure 1 shows the schematic diagram of the ink-jet setup and the experimental process flow. A piezo-actuated ink-jet printer with a nozzle aperture of 50 μm was used to print hybrid polymer drops to fabricate microlenses. Dispensing a single drop of hybrid polymer is created either by continuous or drop-on-demand (DOD) mode. The DOD mode enables generating microdrop individually on the desired position. To generated stable and reproducible drops, the ink-jet printing parameters of the actuating signal (voltage, amplitude and pulse length) have been adjusted. We used both untreated glass and self-assembled monolayer (SAM) modified glass to investigate the wetting properties of dispensed drops. Each single drop forms a microlens after deposition on the substrate. The pattern is created by a computer controlled motorized X-Y-θ stage. After the printing, the hybrid polymer is baked at 95 °C for 30 min, UV-exposed at400 mJ/cm^2 and post-baked at 130 °C for 30 min.

Characterization technique

The ink-jet printed hybrid polymer microlenses were imaged by optical microscopy. The size and 3D shape of the cured microlenses on the two different substrates of untreated and SAM-treated glass were measured using a digital holographic microscope (DHM™ T1000). A Scanning Electron Microscopy (SEM) was used to inspect the 3D shape of the printed microlenses coated by a 30 nm-thick layer of gold on top of the samples.

Results

The optimum ink-jet parameters obtained experimentally correspond to the cases where we obtained stable generation of the drops, without any satellite-drop generation.

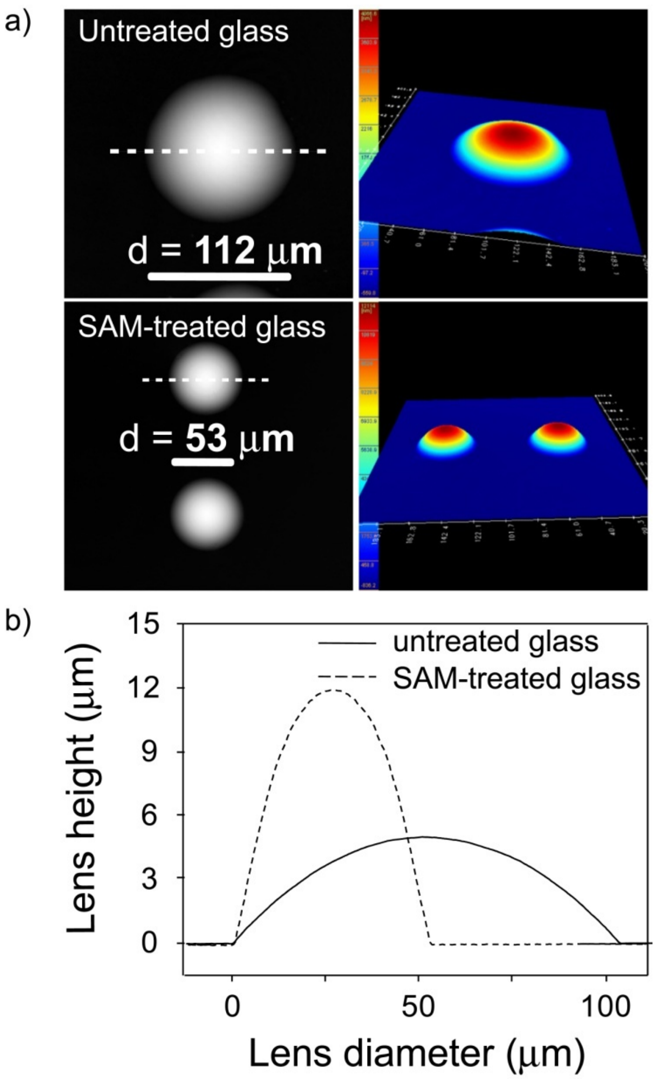

Figure 2. *(a) Unwrapped phase and 3D perspective images of part of ink-jet printed cured hybrid polymer microlens arrays on the untreated glass (diameter 112 µm and height 5 µm) and the SAM-treated glass (diameter 53 µm and height 12 µm) obtained with DHM™ T1000 and (b) height profile taken along the dashed line in unwrapped phase image*

The shape and diameter of microlens can be tuned by the surface wetting properties. Figure 2 presents the unwrapped phase and 3D perspective images of the ink-jet printed microlenses on the untreated and SAM-treated glass substrates obtained with DHM in transmission mode. As expected, the lens diameter is strongly dependent on the surface wetting properties. The lens diameter and height of a single-drop lens printed on the untreated glass are 112 µm and 5 µm, respectively. Randomly selected 10 microlenses in the 64 x 64 microlens array printed on the SAM-treated glass were analyzed and an average value for diameter and height was measured to be 53±2 µm and 12±1 µm, respectively.

Figure 3-a) shows representative SEM images of the cured uniform microlens array, single drop printed on the SAM-treated glass. The single drop lenses have a center-to-center pitch of 100 µm showing that microlens array can be fabricated with accurate pitch and with uniform structures. Figure 3-b) shows an optical microscope image showing the top view of ink-jet printed microlenses. The diameters from border to center enlarge due to increased number of drops per microlens (from border to center, the number of drops increased from 1 to 6). These results show that the ink-jet printing technology allows direct fabricating of microlenses without any additional processing.

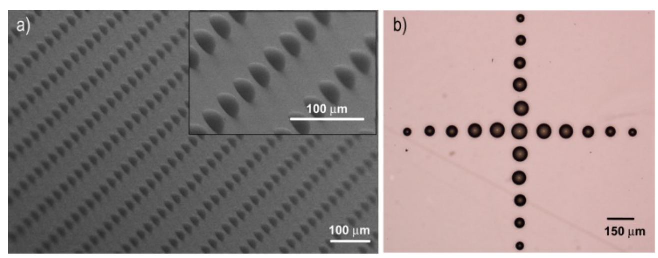

Figure 3. *(a) SEM images of ink-jet printed cured hybrid polymer microlens arrays (part of 64 x 64) on the SAM-treated glass with high magnification inset. The diameter and the height of the microlens are 53 µm and 12 µm, respectively. (b) Optical microscopic image having different number of drops per lens. From border to center, 1 to 6 drops per lens.*

From the measured diameter and height we can calculate the focal length f and the numerical aperture (NA) of the microlenses, assuming plano-convex microlenses with semispherical shape and known refractive index. Table 1 summarizes the calculated f and NA. Here, f is related to the radius of curvature (Rc) of the microlens related to the radius a and the height h, by

$$f = R_c/n_s - 1 = (D^2 + 4h^2)/8h(n_s - 1) \qquad (1)$$

NA is also related to f by $NA = D/2f$. For the calculation, we assume the refractive index (ns) of the sample to be ~ 1.55 at 635 nm after baking, which yields f = 574.7 µm and NA = 0.10 for a single drop lens on the untreated glass, and f = 64.1 µm and NA = 0.41 for a single drop lens on the SAM-treated glass. The properties of the multiple drops lens (1 to 6) are shown in Fig 3b). The focal length is increased from 64.1 µm to 175.1 µm with increasing # of drops, and NA is decreased from 0.41 to 0.30.

Table 1. Measured values of the diameter and the height as well as calculated values of the focal length and the NA of ink-jet printed cured hybrid polymer microlenses on the SAM-treated glass having different number of drops.

	Number (#) of drops / microlens					
	1	2	3	4	5	6
D [μm]	53	65	78	90	98	106
h [μm]	12	11.3	12.2	13.4	14.4	15.9
f [μm]	64.1	95.2	124.4	149.6	164.7	175.1
NA	0.41	0.34	0.31	0.30	0.30	0.30

D: the diameter, h: the height, f: the focal length

Conclusion

We demonstrate a simple, yet powerful method to directly fabricate polymer microlens arrays by programmable drop-on-demand ink-jet printing of hybrid polymer with excellent optical qualities. Hybrid polymer microlenses were successfully ink-jet printed on two different surface conditioned substrates, untreated and SAM-treated glasses. The diameters of the microlenses vary from 53 to 112 μm depending on the surface treatment, and from 53 μm to 106 μm on SAM treated glass depending on the # of drops per microlens. With increasing the # of drops per microlens, we obtained the focal length from 64.1 μm to 175.1 μm, and the numerical aperture ranged from 0.41 down to 0.30. Lens diameter and hence *f* and *NA* can be controlled by SAM coating and by varying the number of drops per lens. Further optical characterization is underway to confirm the uniformity and reproducibility of the lens arrays and to fine tune the optical values with high precision.

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Author Biography

Joo Yeon Kim received her Ph.D. in material science and engineering from the Hannam University in 2006. She then worked at Korean Institute of Materials and Machinery (KIMM) as a research fellow to improve the hydro-philic/phobic properties of the materials for UV nanoimprinting lithography (UV-NIL). In 2007, she joined Prof. Juergen Brugger's group at Ecole Polytechnique Fédérale de Lausanne (EPFL) as a post-doctoral research fellow with her interests in ink-jet printing for micro-/opto-electronic applications with electrical/optical grade polymers and polymer nanocomposites.

Vahid Fakhfouri obtained his master in Microengineering from Ecole Polytechnique Fédérale de Lausanne and started his PhD work in 2004. His research was focused on Inkjet printing and high aspect ratio structuring for polymer-based micro and nano systems. In 2008, he obtained his PhD degree. Since 2009, he has a postdoctoral position in EPFL where he focuses his research on alternative micro/nano patterning techniques, particularly inkjet printing, micromolding and stencil lithography.

Karl Pfeiffer, senior chemist, is well experienced in different fields of polymer science (e.g., allyl compounds, polymethacrylates, non linear-optical polymers, e-beam-lithography), since 1997 polymer chemist at micro resist technology GmbH in R & D, engaged in the field of optical wave guiding, e-beam- and nanoimprint-lithography with special care to materials chemistry and process technology.

Anja Voigt received the Ph.D. degree in 1998 from the Humboldt-University of Berlin, Germany, for the investigations of the chemistry of photolytically generated arylnitrenes in polymeric matrices. This work about the mechanism in conventional negative-tone photoresists led to one new product series commercially available at micro resist technology GmbH. At micro resists technology GmbH she is the product manager of negative photoresists and works in R & D of photosensitive materials.

Gabi Gruetzner received her MS degree in chemistry from the University of Jena, Germany, in 1983. Next she worked more than 8 years in R & D as a process engineer for semiconductor technology and application on III-V device materials. In 1991 she was one of the founders of the micro all resist GmbH, now micro resist technology GmbH in Berlin. Currently, she is the president of the company.

Juergen Brugger (Dipl. Electronique-Physique and Dr.sc. from the University of Neuchatel) joined the Ecole Polytechnique Federale de Lausanne (EPFL) in 2002 as tenure-track assistant professor within the Faculty of Engineering Science and Technology (STI). In 2008 he was appointed associated professor and vice-director of the Institute of Microtechnology (IMT). Before joining EPFL, he was SRO "Nano-Link" Program Coordinator at the MESA+ Research Institute of Nanotechnology at the University of Twente, The Netherlands, research staff member at the IBM Zurich Research Laboratory, and research fellow at the Hitachi Central Research Laboratory, Tokyo. Since 1995, he works in the field of interdisciplinary and experimental micro and nanotechnologies towards integrated micro/nanosystems with components at mesoscopic scales. In his research, he combines methods of clean-room technologies with emerging micro and nanopatterning methods, such as scanning probes, stencil lithography and inkjet printing, to be applied to the field of information technologies and life-sciences. Dr. Brugger has published over 80 peer-reviewed scientific publications. He serves as editorial board member of the IOP journal "Nanotechnology. He served on the IEEE-IEDM program committee, is nominated General Chair for the Eurosensors XXIII, to be held in Lausanne, 2009, and serves as Program Chair of the IEEE-NEMS conference, Shinzen, China, 2009. His own laboratory presently consists of 4 postdocs and 6 PhD students. He is co-inventor of at least 10 patents and received two IBM research awards.