Refractive Microlens Fabrication by Ink-Jet Process

S. BIEHL, R. DANZEBRINK, P. OLIVEIRA AND M.A. AEGERTER
Institut für Neue Materialien-INM, Department of Coating Technology, Im Stadtwald 43, D-66123 Saarbrücken, Germany

Abstract. Microlenses made of hybrid organic-inorganic materials have been fabricated on glass substrates using a commercial drop-on-demand ink-jet printing system with a 50 μm diameter nozzle driven by a piezoelectric device. After deposition the drops have been polymerized by UV light irradiation. Viscosity, solvent evaporation, drop-substrate wetting condition and drop and substrate temperatures are the main parameters which govern the production of reproducible lens shapes. The shape and surface roughness of the lenses have been characterized by atomic force microscopy and profilometry. Their optical properties have been determined by light microscopy and spectrophotometric techniques. The printing technique can produce plano-convex spherical microlenses with diameters varying from 50 to 300 μm, focal lengths from 70 μm to 3 mm and f-numbers as low as 0.6.

Keywords: ink-jet printing, hybrid organic-inorganic, microlens

1. Introduction

Micro-optics technology is becoming increasingly important in the development of optical systems. Optical components such as diffractive and refractive microlenses are now being incorporated in many systems and commercial products. They are used, for example, for focusing in detector arrays, fiber optics and sensors, for illumination in flat panel displays, computers and for imaging in photocopiers and lithography [1–3]. Refractive microlenses provide an attractive low cost alternative to diffractive components and for devices using short wavelengths (<1 μm) requiring low f-numbers ($F < 4$) they are still the only available components. Refractive microlenses have been fabricated in various ways. In the photolithographic process a substrate is coated with a polymer and polymerized through a mask by UV light irradiation. Small cylinders are obtained by etching the unpolymerized part of the polymer. The substrate is then heated until the cylinders melt and flow forming a refractive lens profile by surface tension [4–6]. Other processes involve the filling of a negative form with a polymer, which after heating, transforms into small plano-convex lenses. The polymerized droplets must, however, be polished to reduce the surface roughness [1, 7, 8]. Reactive ion etching and ion milling can also be used [3]. Micro-optic systems can also be prepared using graded refractive technology. These lenslets are cylindrical rather than spherical [1].

The ink-jet process is commonly used in computer-controlled printing [9, 10]. To our knowledge sol-gel based inks have only been proposed to decorate ceramic tiles using a continuous process [11]. In this paper we describe the use of such a technology to manufacture microlenses on glass substrates using sols prepared from hybrid organic-inorganic materials.

2. Experimental

There are two classes of ink-jet printers: continuous [10] and drop-on-demand [12]. The equipment used here is a drop-on-demand printer (Microdrop, SP-K 130), composed of a piezoelectric ceramic nozzle (50 μm diameter), connected to a reservoir by a capillary tube (Fig. 1). The reservoir can be heated to lower the ink viscosity. A high frequency computer-controlled generator generates an electrical signal which squeezes the nozzle and generates a drop. The

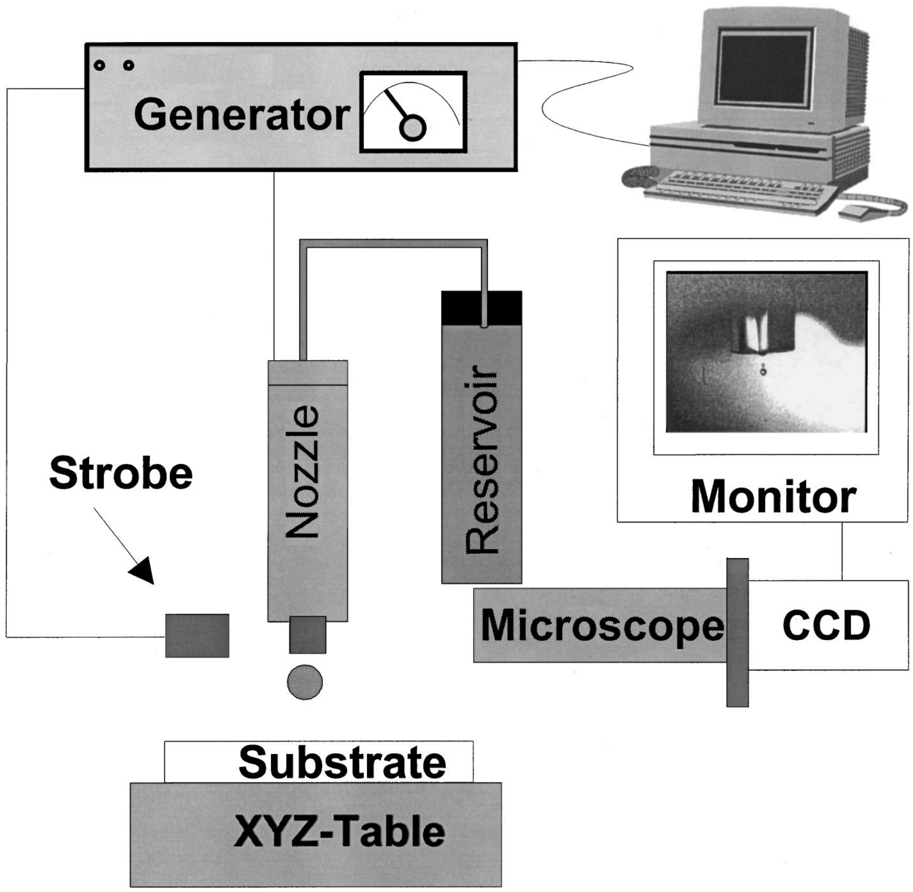

Figure 1. Scheme of the drop-on-demand ink-jet printing equipment.

rate can be varied from 1 to 2000 drops/s. The shape of the drops can be visualized by a CCD camera coupled to a stroboscope. After travelling a few millimeters at a speed of about 10 m/s, the drops become spherical, typically 50 μm in diameter. Single droplets have been deposited on clean glass substrates and glass substrates coated with a thin layer of a low surface energy perfluorated polymer (FTS/TEOS/MPTS/2-Propanol/Irgacure 184) [13] in order to vary the drop/substrate wetting conditions. The substrates can be moved in the XYZ-directions by stepper motors so that lines or arrays of drops can be printed.

Hybrid organic-inorganic sols have been prepared by hydrolysis of methacryloxypropyltrimethoxysilane (MPTS) mixed with an ethanolic solution of tetraethyleneglycoldimetacrylate (TEGDMA) and 1 to 10 wt% UV photoinitiator (Irgacure 184). After deposition, the drops have been polymerized by UV light irradiation (Kombistrahler Beltron). The polymerization of the sols during the UV irradiation has been followed by Fourier transform infrared spectroscopy (Bruker IFS 66V) particularly analyzing the C=C bonds band at 1636 cm^{-1}. The visible near-infrared optical transmission of the sol and polymerized material has been determined using a Varian Cary 5E spectrophotometer.

The shape and surface roughness of the lenses have been measured by atomic force microscopy (Topometrics Explorer 2000 AFM) and a Tencor P10 profilometer. The focal length of the plano convex lenses has been determined at $\lambda = 632.8$ nm using an optical microscope equipped with a scanning knife-edge device [14] and a silicon photodiode. The intensity image profiles of a parallel beam at the focus plane have been also recorded with a 3D Spiricon laser beam analyzer. The lens f-numbers have been calculated using the thick lens formula

$$F = \frac{1}{2z}\{n(1 - z^2) - [(1 - (nz)^2)]\}$$

where n is the refractive index (assumed $n = 1.5$) and $z = a/r$ with a the lens radius and r the radius of curvature.

3. Requirements

The sols used in ink-jet printing must satisfy particular requirements. As the flow velocity in the nozzle is very high (10 m/s) and the aperture very small (50 μm), the shear rates are very high (500 s^{-1}), and this places constraints on the rheological properties of the sols. For the preparation used here, the kinematic viscosity of the ink at room temperature cannot exceed 3 mm^2/s. In addition conventional sols, which gel through hydrolyzation and polycondensation processes, are difficult to handle with a drop-on-demand system as they rapidly block the fine nozzle. After arriving at the substrate, the final shape of the deposit depends essentially on the equilibrium $\alpha_{12} = \alpha \cos\theta$ between the van der Waals forces which act at the border of the drop/substrate interface and which correspond to the surface tension of the liquid α and the interfacial tension α_{12} (attractive forces between liquid and solid), θ being the contact angle. These vary rapidly as the solvent evaporates and depend on the substrate temperature and the composition of both the drop and the substrate. Moreover, the final lenses should be transparent over a large optical wavelength range and homogeneous. All these parameters considerably restrict the composition of the sol. A good compromise has been found with the compositions of the sols proposed here.

4. Results and Discussion

A typical sol prepared as above has a room temperature kinematic viscosity $\eta = 3$ mm^2/s. Its value decreases slightly with increasing temperature. The effect of the UV irradiation (17.5 J/cm^2 total energy in wavelength range 280–320 nm) on the network building (polymerization) was analyzed by studying the evolution of the infrared absorption band at 1636 cm^{-1} of the C=C bonds of MPTS and TEGDMA as a function of the irradiation time using a 0.1 μm thick film deposited by spin coating on a Si-wafer. For 10 wt% photoinitiator, polymerization is completed after 200 s. For smaller amounts of the time exposure should be longer. The lenses have been obtained with photoinitiator concentrations of 1 to 10 wt%. Figure 2 shows the visible/near-IR optical transmission of precursor sols with and without photoinitiator and of the UV polymerized layer. The UV absorptions of irgacure 184 at 244 nm and at 285 nm are clearly visible for the sol. After polymerization the bands practically disappear and the final material is highly transparent in the region 375 nm $< \lambda <$ 2.7 μm. Its optical properties are therefore adequate for the preparation of lenses.

Typical shapes of lenses obtained with different sols and substrates are illustrated in Figs. 3, 4 and 5. Figure 3 shows the effect of excess ethanol in the sol (>40 wt%). The sol wets the glass substrate and spreads on it. The inorganic-organic material is transported to the border of the drop and creates a ring shaped lens due to capillary effects.

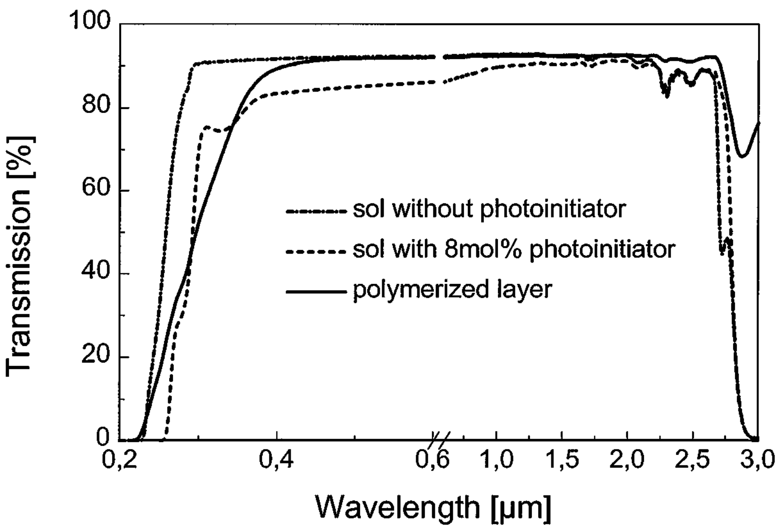

Figure 2. Optical transmission spectra of (———) polymerized layer, (------) sol with 8 mol% photoinitiator, (-·-·-·-) sol without photoinitiator.

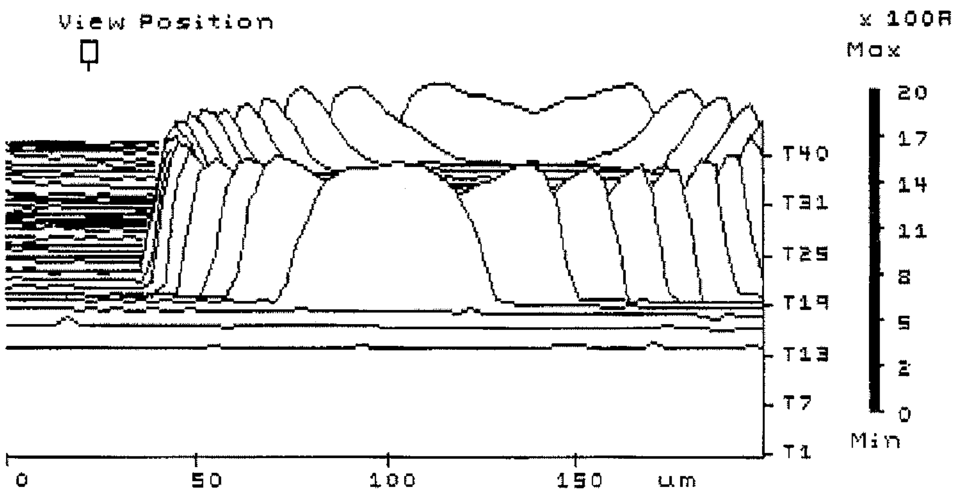

Figure 3. Ring shape of a lens obtained on a glass substrate measured by profilometry. The sol has a high ethanol content (40 wt%).

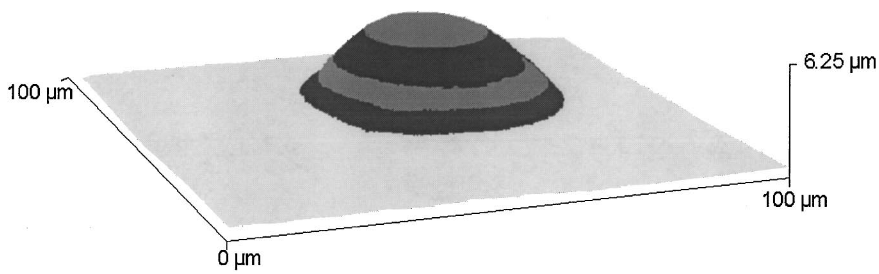

Figure 4. AFM micrograph of a lens obtained on a glass substrate with optimized ethanol content (30 wt%).

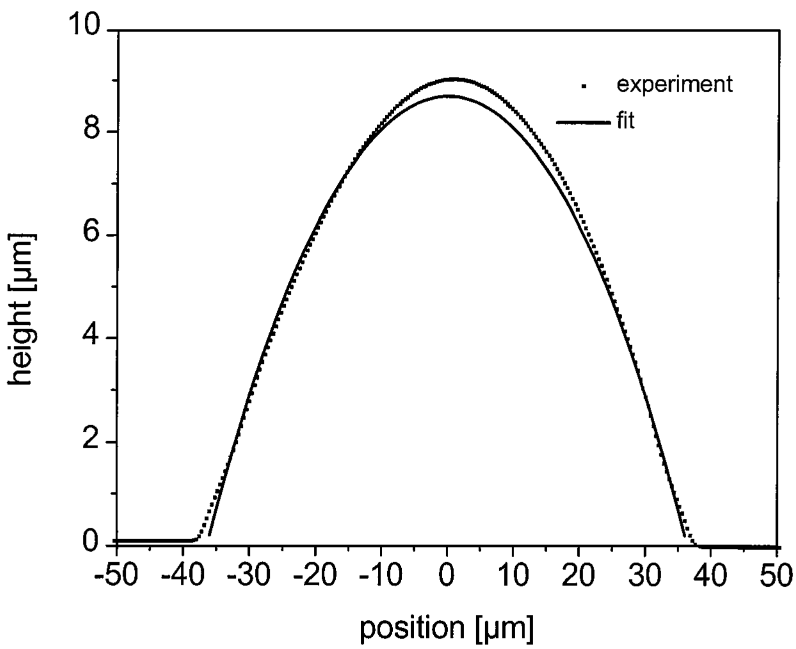

Figure 5. Profilometer plot of the shape of a lens deposited a modified glass substrate.

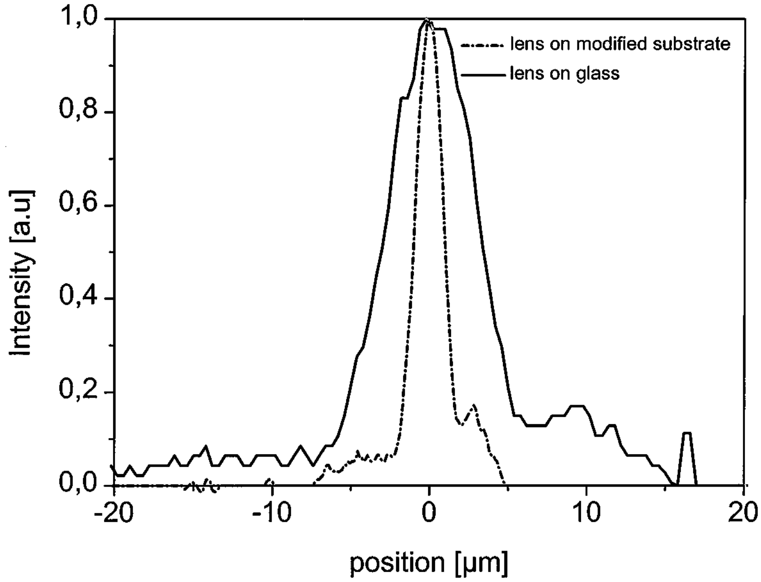

Figure 6. Fit of a vertical cross-section of a lens deposited on a perfluorided glass substrate showing the spherical shape.

Sols containing less than 30 wt% ethanol have a high viscosity $\eta > 5\,\text{mm}^2/\text{s}$, and tend to block the piezoelectric nozzle. Spherical lens formation was obtained on glass substrates with a mixture of 50 mol% MPTS and 50 mol% TEGDMA is 30 wt% ethanol fraction (Fig. 4).

This lens is spherical and has the following properties: radius $a = 25\,\mu$m, height $h = 6.25\,\mu$m, radius of curvature $r = 53.1\,\mu$m, focal length (at 632.8 nm) $f = 100\,\mu$m, lens power $F = 0.62$ and a surface roughness $R_a = 40$ nm.

In order to reduce the effect of the spreading of the high ethanol content sols lenses have been fabricated on a substrate whose interface has been coated with a thin layer (0.1 μm) of a low surface energy polymer. Figure 5 shows a fit of a vertical cross-section passing through the center of the lens by a semicircle. The agreement is good.

This lens has the following properties: radius $a = 37.5\,\mu$m, height $h = 9\,\mu$m, radius of curvature $r = 82.6\,\mu$m, focal length at 632.8 nm $f = 125\,\mu$m, lens power $F = 0.72$, surface roughness $R_a = 40$ nm.

Two-dimensional intensity profiles of the light spot created at the focal plane by a collimated 632.8 nm laser beam travelling on the substrate side of the lenses are shown in Fig. 6.

Their shapes are practically Gaussian with a full width at half maximum (fwhm) equal to 1.8 μm and 6.2 μm, respectively. These values are small and can be compared to those calculated for a perfect diffraction limited lens (fwhm $\sim$0.7 μm). The smallest fwhm value was obtained for the lens deposited on the modified surface substrate.

5. Conclusion

A drop-on-demand ink-jet process has been successfully used to fabricate refractive microlenses on glass substrates from an organic-inorganic sol containing MPTS, TEGDMA and a photoinitiator. These components have been polymerized by UV-irradiation at room temperature and are transparent from 375 to 2700 nm and have a refractive index $n = 1.5$. Plano-convex spherical shapes have been obtained for optimized sol composition and drop/substrate wetting conditions with a diameter and f-number as small as 50 μm and 0.62 μm, respectively, and a surface roughness $R_a = 40$ nm. The fabrication of one and two dimensional closely spaced microlens arrays should be possible.

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