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Micro-optical elements and their integration to glass and optoelectronic wafers

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Abstract Polymer replication technique enables for low cost devices even in the case of aspheric or irregular shaped surfaces, submicron or other challenging structures.

The use of UV-reaction moulding on semiconductors, glass or other inorganic substrates as the replication technique leads to a high degree of stability and allows for the simultaneous integration of optoelectronics or ion exchanged GRIN elements. Thin polymer layers on inorganic substrates show high flatness and lower wavefront deviations with respect to all-polymer elements. They show low lateral shrinkage during the UV-polymerisation, and the lateral thermal expansion is determined by the substrate. Furthermore, sensitive substrates can be used because the process does not involve high mechanical stress or elevated temperatures.

Original structures for the replication masters are fabricated by different resist technologies. Subsequently, they are proportionally transferred by dry etching (RIE) into glass or silicon, or, the resist structure is transformed into a metal master by electroplating.

The utilisation of UV-transparent replication tools allows for the use of opaque substrates (i.e. detectors). Locally UV-transparent replication tools enable a combination of replication and resist technology (leading to elements with new features) or can protect sensitive areas like bond pads from being coated with optical layers. The fabrication of isolated polymer elements on arbitrary substrates is an advantage of UV-reaction moulding against injection moulding or hot embossing.

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1
Introduction

Application fields of micro-optics are growing and the number of modules containing micro-optical elements to be used in telecommunications, data storage, sensing, manufacturing and medicine is increasing fast. The penetration of optics technology into these application fields is accompanied by a permanent miniaturisation of the optical and optoelectronic elements involved. The need for a variety of micro-optical elements like microlenses, microprisms and corresponding arrays, filters, beam shaping elements etc. with proven high optical quality increases tremendously. These elements have to be integrated into systems containing lasers, detectors and perhaps actuators by processes fulfilling the alignment, compatibility and additional requirements, and which can be transferred into efficient fabrication methods. Steps towards integration are, for instance, the amalgamation of two or more optical functions in a single element (with highly complex geometry), or the formation of subsystems with several elements on a common substrate [Harnessing Light (1998)]. Advantages are high stability and reliability, reduction of optical path length and of the number of optical surfaces, low mass and size etc., and, eventually, lower costs.

Integration of micro-optical elements and optoelectronic wafers has to start, as a matter of rule, with the electronic functions in a semiconductor wafer which needs lower feature sizes in width and height than any refractive optical function. This demands for micro-optics technologies which does not influence the electronic function by mechanical, thermal or other radiation treatment. To this end, in the Fraunhofer-Institute IOF in Jena UV-reaction moulding [Dannberg et al. (1994)] performed in a conventional mask aligner was developed.

In this paper, this modification of UV-reaction moulding is described. The methods used to generate the high accuracy master structures in UV-transparent and non-transparent replication tools for micro-optical arrays are reported. Different micro-optical elements with well defined optical properties are demonstrated on glass, quartz and optoelectronic wafers.

2
Technology

The principle of the UV-reaction moulding process [Tanagami et al. (1989)] consists in the UV-curing of a thin layer of liquid (pre)polymer resin between the repli-

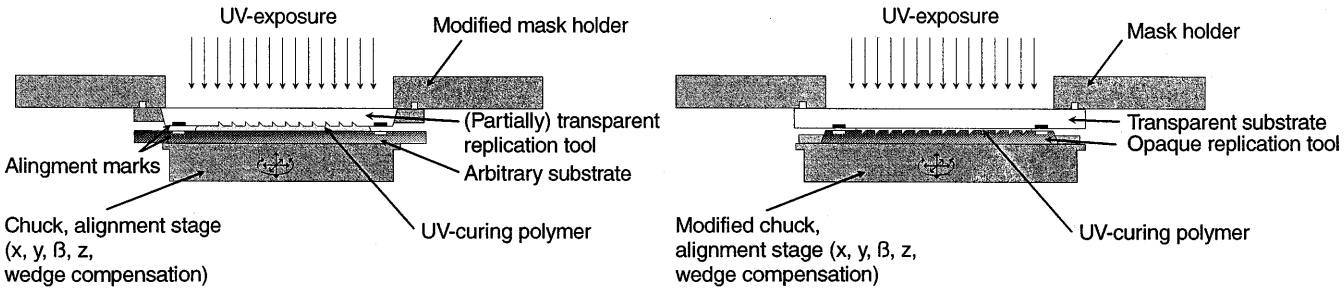


Fig. 1a, b. Modification of the mask holder and substrate chuck of a contact mask-aligner for wafer-scale replication using opaque substrates **a** and opaque replication tools **b**, respectively

cation tool (master) and a substrate. One part, substrate or replication tool, has to be UV-transparent. After curing, the substrate with polymer microstructures can be deformed from the master.

The realisation of this technology in a contact mask aligner is schematically shown in Fig. 1. The mask-aligner manages the loading and deloading of wafers (with the future capability of cassette to cassette handling), the wedge error compensation, lateral alignment with 1 μm precision, control of the exposure gap (which equals the thickness of the polymer layer), a nitrogen purge (if required), and the UV exposure in the same way as in photolithographic processes.

We modified the mask aligner (SUSS Model MJB-3) with respect to the following points: For the accommodation of the various 3″ replication tools we build a special chuck to which the tools are screwed. The flatness of the replication tool (typically <3 μm across the 3″ diameter) is not affected by the holding mechanism. Furthermore, this chuck allows for a compressed air assisted deforming step. The prepolymer resin is usually casted by a commercial dispensing device. In this case a nitrogen or inert gas atmosphere is not necessary. The final thickness of the polymer layer is determined by the respective exposure gap which is typically in the order of 20...200 μm. In the present configuration we use 4″ diameter substrates; the maximum diameter of the replicated area is 3″.

It turned out that it is convenient to use different replication tools according to the substrate material and the structures to be replicated. Conventional nickel shims can be electroplated using nearly every original microstructure, a copy with the inverse relief can be produced, but the flatness is critical and they are, of course, not UV-transparent. Silicon or fused silica masters with etched features show a better flatness, which can, for example, be realised by RIE proportional transfer of resist [Nakagawa et al. (1994)]. These structures show, however, underetching, additional surface roughness and a limited depth (see chapter 3). Finally, transparent polymer tools can be used for a limited number of replica. Corresponding to the type of master one has to choose configuration a) (for opaque substrates) or b) (for opaque replication tools) as sketched in Fig. 1. For the replication of microstructures on both sides of a glass wafer we used configuration a) in order to avoid damage of the first structures in the subsequent second replication process. Furthermore, we used glass wafers with metal or resist alignment marks on both sides, which had been adjusted to each other in a previous backside alignment process. The UV400 high pressure Hg-lamp with an intensity of 10 mW/cm^2 at 405 nm in combination with appropriate photoinitiators is sufficient for UV-curing through fused silica or glass, but also thin polymer layers on glass. Typical curing times are in the order of 1 to 100 seconds.

Thus, the replication process consists of the following steps: loading and wedge error compensation, pre-alignment, dispensing of prepolymer, alignment, exposure, deforming, and hard bake. Note that it is only necessary to replace the substrate chuck or the mask holder by special constructions, the device with the original parts can further on be used for conventional photolithography.

Structures with special features can be produced using locally transparent embossing tools, which are created by adding a metal mask to a transparent master.

So, one can define structures by a combination of replication and a resist technique in which the UV-curable polymer acts as negative resist. This is especially interesting for a combination of binary structures like waveguides, fiber grooves, stand-offs or other adjustment structures with replicated structures (prisms, lenses etc.) In this technique the exposure dose has to be adjusted not only for optimum deforming but so that unexposed resin can be dissolved in an additional development step, whereas the exposed parts remain as isolated polymer islands on the substrate. In this case the development, prebake and flood exposure steps have to be added after deforming.

3
Replication tool fabrication

The quality of the replication tool in an UV-reaction moulding process determines the optical parameters of the micro-optical elements. This demands for variable and high precision methods for the master structure fabrication and its transfer into the material of the replication tool. Fig. 2 shows the procedures used for replication tool fabrication. Products of micromachining and electroplating are bought from several companies. Gray tone masks were fabricated by the Institute of Applied Physics, Uni-

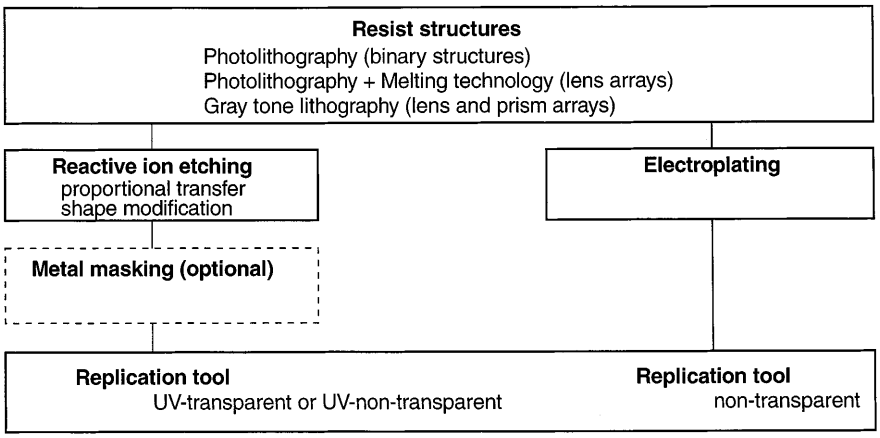


Fig. 2. Procedures for replication tool fabrication

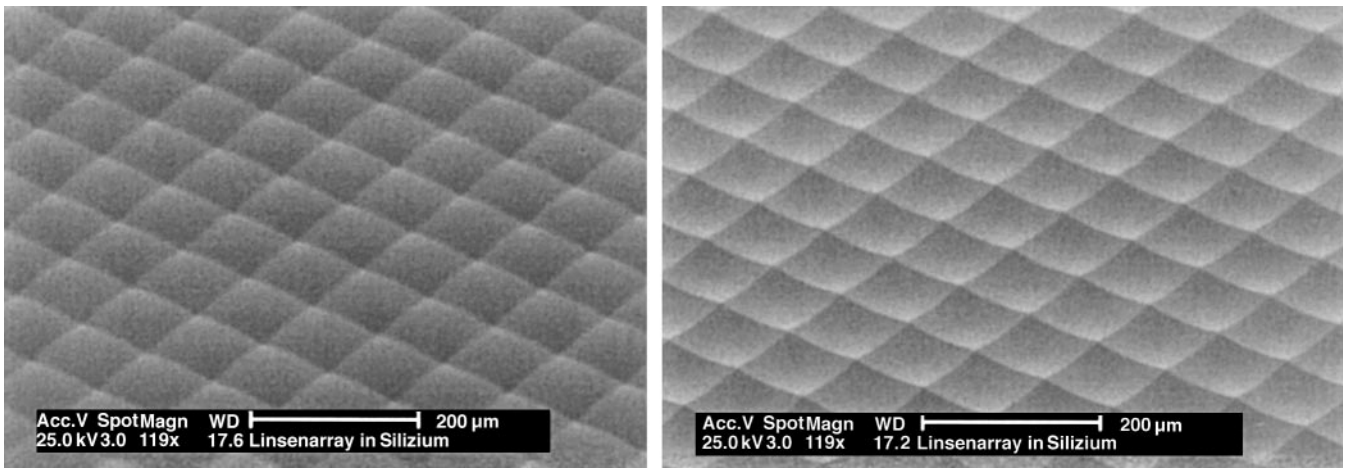


Fig. 3. High filling factor (95%), convex and concave lens arrays, etched into silicon; the resist structure was fabricated by gray tone lithography

versity of Jena. At IOF, the resist melting technology and the transfer of resist structures in glass and silicon were further developed [Erdmann (1998)].

The melting technology for fabrication of spherical microlenses is well-known from the literature [Haselbeck et al.(1993)]. The basic effect is the minimisation of the surface of a structured resist cylinder when it is heated above glass temperature. The shape of the lens fabricated in this procedure can be controlled up to a certain extent by melting time and melting temperature, which determines the surface tensions between resist, substrate and atmosphere, respectively. Problems occur due to hardening processes during the floating. This concerns especially the fabrication of microlenses with low numerical apertures. The uncontrollable hardening can be avoided, if solvent is indiffused into the structured resist [Erdmann and Efferenn (1997)]. This method is used e.g. for fine tuning of focal lengths. The uniformity of the focal lengths over a lens array is a very important parameter in many applications. It was improved by this method to a value of 2%. The minimum distance between two adjacent lenses (determining the filling factor of the lens array) which was obtained in the resist technology was 2 µm.

The resist micro-optical elements generated either by the described technology or by gray tone lithography are transformed in silicon or glass (Pyrex) by reactive ion etching (RIE). For proportional transfer into Si an etching parameter set (flow of etching gas SF_6, discharge power, pressure, substrate temperature, bias voltage) was figured out leading to equal etching rates for substrate and resist (e.g. 180 nm/min, in dependence on resist type and etching machine). Pyrex glass was etched with a mixture of SF_6, C_4F_8, and Ar . Equalisation of the etching rates for photoresist and Pyrex was achieved by increasing the C_4F_8 gas flow. A typical result was 207 nm/min for the resist and 176 nm/min for Pyrex. The possibility to control etching rates was also used to fabricate aspheric lenses. An algorithm for discharge power and, consequently, selectivity control during the etching process was developed. Conical constants up to −9.9 have been realised so far.

In Fig. 3 two examples for high filling factor lens arrays etched into silicon are shown.

The technology described enables for fabrication of high precision replication tools with a large variety of parameters. The many different replicated lens arrays described in Table 1 are based on this technology.

Table 1. Shows data of replicated microlenses which had been fabricated on the basis of the reflow of photoresist structures

lens parameter	Experimental value	Remark
Polymer refractive index	1.49...1.56 (633 nm)	Adjustable by mixing of resins
dn/dT (633 nm)	1.8×10^{-4}/K	20 μm thick layer on glass
Wavefront aberration (example)	pv: 0.18 λ	90% of exit pupil
	rms: 0.09 λ	Diameter of pupil: 110 μm
	λ = 0.633 μm	(minimisation on pv, arrangement: focusing of a plane wave)
Uniformity of focal length	1%	
Deviation from nominal focal length (for f = 300 μm)	±4%	Melted resist, 1:1 etching in Pyrex glass
Range of lens sizes	Lens diameter: 5 μm–3000 μm	
geometry of lenses	Lens sag: 1 μm–100 μm	
	Minimal distance: 2 μm	

4
Micro-optical structures and sub-systems

4.1
Coupling prisms on wafers with detector chips

In hybrid transceiver modules, the coupling between singlemode waveguides and flip-chip bonded detectors has to be realised. To this end, the light emerging from the waveguide end face has to be deflected by approximately 90°, which can, for instance, be realised by forming micromirrors in the substrate [Terui et al. (1998)] in a difficult multistep process. Our alternative method consists in the wafer scale replication of deflecting prisms onto a semiconductor substrate followed by the separation into detector chips each carrying a polymer prism. Our first results were carried out with a silicon wafer comprising pin-photodiodes. The replication tool is consisting of long prismatic grooves in fused silica and an aluminium mask with rectangular openings defining the side walls of the deflecting prisms (which are no optical interfaces). Obviously, a proper pitch control is crucial because pitch differences accumulate across the wafer. Fig. 4 shows a micrograph of the microprisms after deforming and development. We proved that these diode chips can be separated in a dicing saw, and that the bonding process can be performed. The insertion loss of the prisms (measured at 633 nm) was about 1 dB.

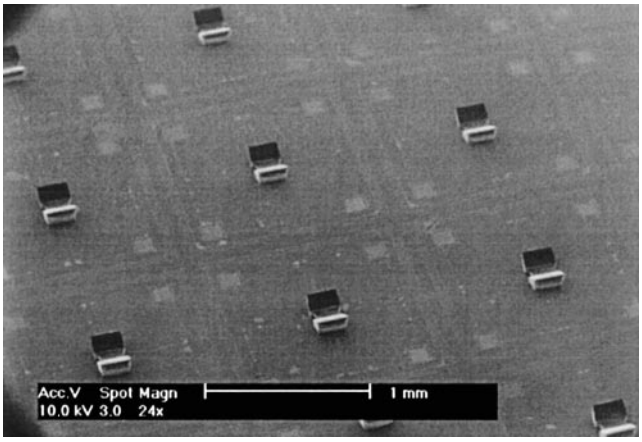


Fig. 4. Prism array on a silicon wafer with pin photodiodes. Prism dimensions are 100 μm × 100 μm × 200 μm

4.2
Deflecting prisms for POF

In the same way as in 3.1. we fabricated large deflection prisms for 250 μm diameter polymer optical fibers (POF). In this example the prism on top of a silicon wafer is integrated with a fiber snap in the structure [Eldada and Yardley 1998], which is produced simultaneously by the negative resist technique as illustrated in Fig. 5. The undercut of the side walls is produced automatically due to self focusing of the UV light during the exposure.

We tested fiber holders with smooth sidewalls as well as those with additional vertical ribs (see Fig. 6). It turned out that vertical ribs are not necessary to achieve a suffi-

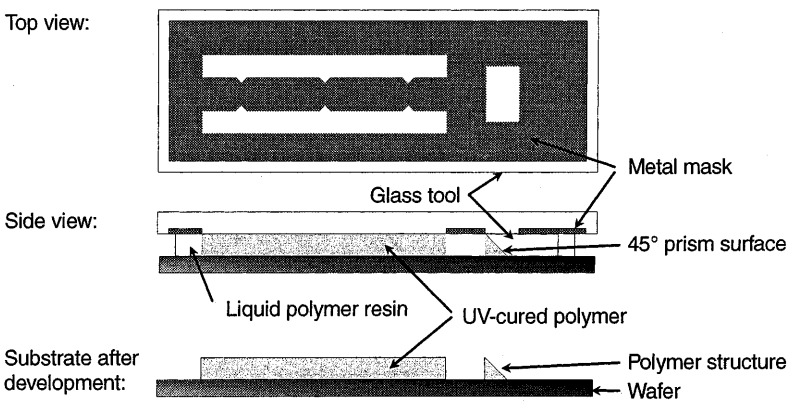
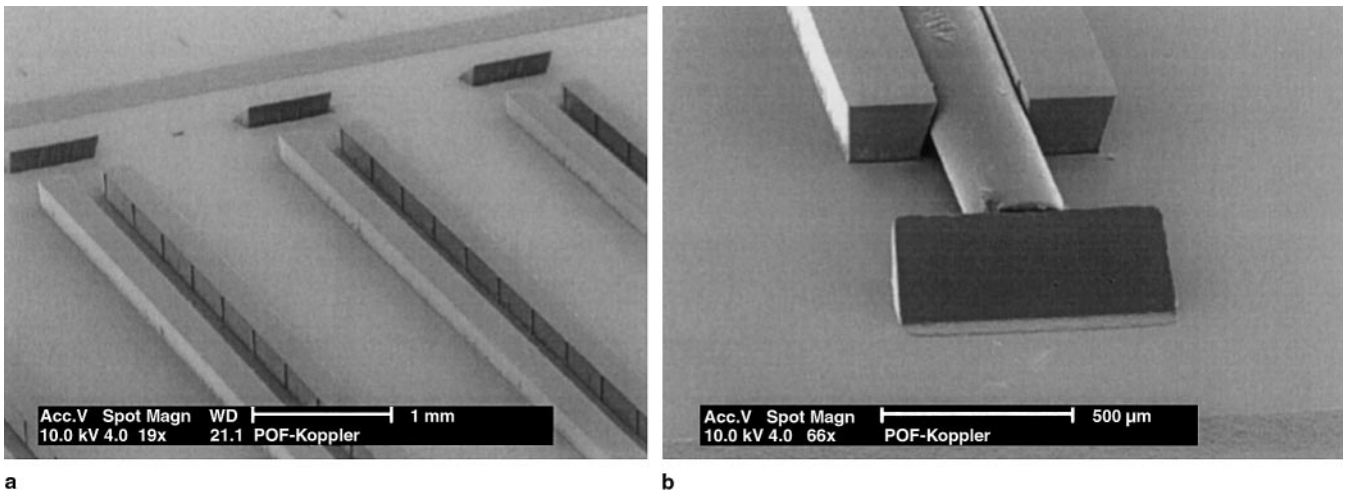


Fig. 5. Fabrication of a polymer fiber clamping structure and a deflection prism on a wafer;
- top view of the embossing tool with metal mask
- side view with substrate and polymer after exposure,
- substrate with polymer structure after development



a b

Fig. 6a, b. Integration of deflecting prisms and polymer fiber holding structures on a silicon wafer by, **a** combining replication (45° tilted prism surface) and **b** resist technique (all remaining structures)

cient gripping as well as a certain longitudinal displaceability (for a proper adjustment of the POF end-face). In the case of the POF-deflector it is necessary to metallize the reflecting plane through a shadow mask. Figure 6 shows REM micrographs of realised structures on silicon. We found that a sufficient length of the fiber holder is in the order of 1...2 mm, so that this structure can be realised on wafers with corresponding detectors.

The deflecting prisms can also be integrated with multimode integrated-optical waveguides instead of the fiber holders using completely the same technology.

4.3 Microlenses and arrays

An interesting option of the technology consists in the wafer-scale fabrication of micro-optical subsystems by multiple replication steps, for instance onto both sides of a glass wafer. The glass substrate itself can contain further optical elements like ion exchanged index gradients, metal masks (apertures), or dielectric multilayer systems (filters, beam splitters). However, the formation of lens systems on a wafer scale requires (despite of the mutual lateral adjustment of the lenslets) an additional adjustment in the optical axis direction with an accuracy of typically 10 µm. This regards the flatness of replication tools, the control of the polymer film thickness as well as the focal length of the lenses.

Table 2 shows data of replicated microlenses which had been fabricated on the basis of the reflow of resist structures and RIE proportional transfer [Haselbeck et al. (1993)]. It can be seen that a good homogeneity across the lens array as well as low wavefront aberration can be realised. The actual focal length depends on many parameters, like resist volume, the ratio of etching rates and the polymer shrinkage. For the realisation of a confocal lens system the actual lens radii of the replication tools have to be measured in order to compensate for deviations by changing the polymer film or substrate thickness. We found that the thickness of the polymer can be adjusted with an accuracy of 3 microns. The flatness of the silicon replication tools is <3 µm and remains unchanged after insertion into the chuck. If necessary, the index of the polymer after hard bake can be matched within 10^{-3}.

4.4 Light concentrator structures on detector arrays

Lens arrays can be used to enhance the fill factor of detector arrays [D'Amato and Centamore (1991)], but it is difficult to design a lens configuration which fulfils all the requirements, namely: The fill factor of the micro-optics has to be close to 1; the light concentration onto the active area should be realised for a large range of incidence angles and with low misregistration. Additionally, the micro-optics should be replicated directly onto the wafer, and should be effective for various taking lenses.

Another approach uses light concentrating high index cones (see Fig. 7) or conic holes with reflecting walls instead of lenslets. Arrays of such structures can be fabricated with a combination of replication and resist technique on a wafer scale. Figure 8 shows cone structures on a silicon wafer. Note that the air spacing between the polymer cones has to be produced by washing out the

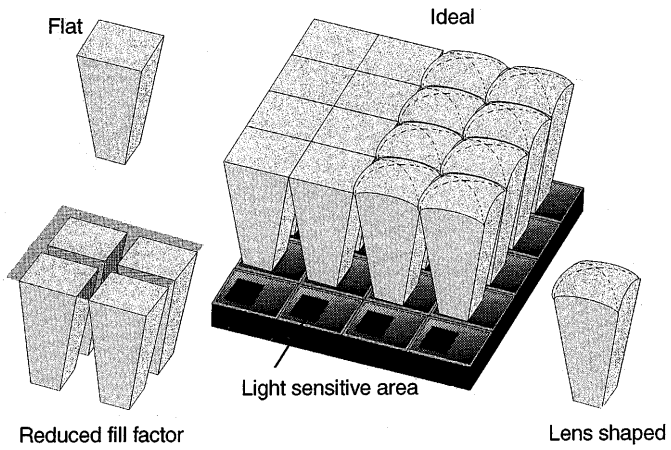


Fig. 7. Light concentrator structures with quadratic cross section on a detector array. The entrance surface can be flat or lens shaped using a replication tool with a microlens array

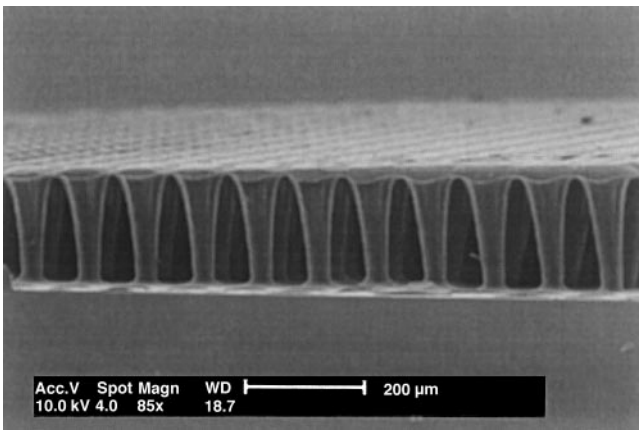


Fig. 8. Polymer concentrator cones on a silicon wafer. These initial structures have a round cross section, but the fabrication of quadratic structures with high fill factor is possible.

unexposed resin in a complicated development step which can produce sidewall roughness. So these initial concentrator cones show scattering loss which prevents a real fill improvement.

These initial structures have a round cross section, but the fabrication of quadratic structures with high fill factor is possible.

5
Stability and reliability tests

Stability and reliability of the fabricated hybrid integrated systems depend primarily on the material properties of the polymer used in our experiments. Relevant questions in this concern are the homogeneity of the UV-cured and hard baked elements, mechanical stability (mar resistance) of the surfaces, the adhesion to the substrate under temperature changes, and the long term stability of the geometry and of the optical properties under various conditions (heat, humidity, laser light). In the following we evaluate some results with respect to the impact on the optical function.

The polymers used belong to the class of inorganic-organic copolymers on the basis of acrylate alkoxysilanes [Rose et al. (1992)]. In comparison to thermoplastic materials they show better thermal and mechanical stability and better adhesion to glass or semiconductor substrates as a matter of principle. Especially the mar resistance is improved by the inorganic network.

Our investigation showed that the adhesion of the polymer to glass, fused silica, silicon, silica and silicon nitride (passivation layers on detectors) is good. Even large area polymer films (3″ diameter) did not separate from the substrate (and did not crack) neither by thermal load (1 month, 180 °C) nor by moisture (1 month at 85 °C, 85% r.h.) or temperature shocks (20×200 °C $\leftrightarrow$ 20 °C). At elevated temperatures we measured an increase of the absorption (especially in the shorter wavelength region) which is not significant for micro-optical elements (because of their thickness lower than 1 mm). Corresponding refractive index changes were in the order of 10^{-3}, which is also negligible for micro-optics applications. 5 min under 300 °C at air atmosphere led to an absorption increase of <0.5 dB/cm in the visible, <0.1 dB/cm at λ = 1.5 µm. This means that a treatment like bonding or soldering is possible without significant loss of performance.

A very sensitive method to detect changes in the surface geometry is the interferometric measurement of spherically shaped lens surfaces. Radii of curvature and rms deviations can be determined with sub-micron accuracy and the influence on wavefront deviations or changes in the focal length can be estimated in a simple way. The main results on spherical lenses from gray tone resist structures [Däschner et al. (1997)] are as follows:

- The differences in the curvature radii between the same lens on the silicon master and on all 10 measured polymer replica were below 200 nm. The rms deviations from an ideal sphere were the same for all samples (40 nm).
- The same is true for different lenses of the same array (which is a result regarding the gray tone process and the RIE etching).
- The polymerisation shrinkage in the hard bake step leads to a systematic change in the radius of about +1.7% (R = 390 µm) which can be pre-compensated. The deviations from an ideal sphere remain unchanged.
- Stability tests of hard-baked samples led to a very good results: thermal load (4 h at 250 °C) did not change the lens diameter (>0.1%); damp heat (240 h at 85% r.h., 85 °C)results in a small systematic increase of the diameter of 0.4%.
- As expected from transmission spectra, the UV-cross-linked material turned out to decompose under high power laser light, especially at wavelengths below 550 nm. In all experiments performed so far, a micro-optical element was damaged after <30 min in a 488 nm cw-laser spot at 400 kW/cm^2. That means, the polymer in its present state cannot be used in high power or blue laser applications.

6
Summary

We presented a replication technology which is capable of the fabrication of high performance micro-optical elements on a wafer scale. The most important advantages of this technique are the following:

Process steps and equipment of photolithography can be used. It is sufficient to modify substrate chuck and mask holder of a contact mask aligner. UV-curing of inorganic-organic copolymers on rigid substrates allows for short cycle times (comparable to conventional lithography), low mechanical stress, room temperature operation, high moulding precision, low wavefront aberrations and low lateral shrinkage, and good stability properties.

Transparent replication tools enable the integration of the polymer elements with optoelectronics. The mask-aligner precision (1 µm lateral, 3 µm in the polymer film thickness) is suitable for the fabrication of mutually aligned subsystems. The combination of replication and resist technique allows for structures as high as 250 µm, i.e. fiber holder and deflection prisms for polymer optical

fibers. Uncoated wafer regions turned out to be suitable for electrical bonding.

The approach does not compete with mass production techniques like injection moulding or roll embossing of thermoplastics. We rather try to show the cost effective manufacturing capability by wafer-scale integration of more complex systems and the subsequent separation of the modules.

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