Towards High Precision Manufacturing of 3D Optical Components Using UV-Curable Hybrid Polymers

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ABSTRACT

Hybrid polymers have been already widely applied in photonic applications to manufacture microlenses or 2D and 3D waveguides. Thus, they are promising candidates to manufacture optical systems down to the chip level. A brief review on hybrid polymers consisting of both inorganic and organic functional units and thus combine superior material properties in just one material class will be given in this report. The material properties, which can be adjusted to the application in wide ranges enable to fabricate micro-optical elements (e.g. microlenses) using replication techniques such as UV-assisted replication or nano-imprint lithography. Aside of their applicability in 2D, emphasis will be in particular on the evaluation of hybrid polymer materials for two-photon absorption lithography, which is employed to directly manufacture sophisticated 3D photonic structures impossible to be generated with conventional 2D techniques.

Keywords: hybrid polymer, micro-optical devices, optical interconnects, ink-jet, nanoimprint lithography, two-photon absorption lithography

1. INTRODUCTION

Since the early 2000, industry has shown a considerable interest in the use of micro optical devices [1]. For the easy, cost-effective and reliable manufacture of micro-optical devices, the availability of suitable materials plays a crucial role. To enable a broad range of applications, these materials have to satisfy numerous requirements such as excellent transparency, non-yellowing and defined refractive index as well as high thermal and chemical stability combined with an adjustable processing window. In this context, UV-curable inorganic-organic hybrid polymers[2] have been widely used for various optical applications such as microlenses, waveguides, gratings, or LED packaging[3].

Hybrid polymers exhibit both inorganic and organic units, and they thus combine superior properties in one material class (cf. Figure 1). On the one hand, the organic units bear polymerizable moieties and various functional groups which enable photon-induced curing, i.e. organic cross-linking (polymerization) known for processes commonly used for purely organic materials. This material concept provides multiple possibilities for customized variation of the material's physical and chemical properties. On the other hand, the inorganic backbone provides outstanding optical transparency, high thermal and chemical stability as well as excellent mechanical stability of the hybrid network.

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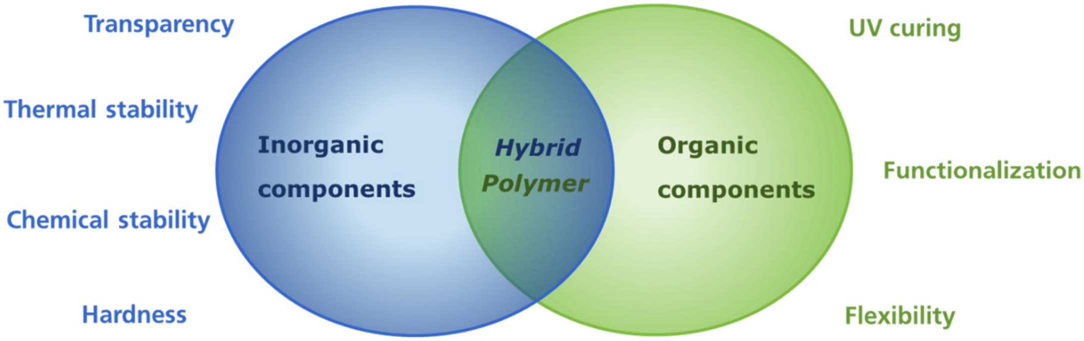

Figure 1. Properties of inorganic and organic units combined by hybrid polymer materials such as ORMOCER®s.

Amongst hybrid polymers, ORMOCER®s, which were initially developed by the Fraunhofer Institute of Silicate Research (FhG ISC), Germany, are commercially used in many different fields of application. Beside micro-optical applications, they are also widely employed as anti-scratch coatings, dental materials, or as packaging materials in microelectronics. Detailed studies can be found elsewhere[3-5]. The synthesis of ORMOCER®-type inorganic-organic hybrid polymers is based on a sol-gel reaction, in which a hydrolysis-condensation reaction of organically modified silicic acid precursors (i.e. silicon containing monomers) leads to nano-scaled oligomers with inorganic backbones. A diligent formulation (i.e. adding various functional additives and photo-initiators) creates a viscous and solvent-free oligomer solution. This pre-polymer can be cross-linked upon exposure to UV light by a free-radical reaction which allows the defined formation of a multi-dimensional hybrid polymer network. For the purpose of industrial micro- and nanofabrication, this means hybrid polymers can be processed using standard UV exposure[3,6] setups as well as laser lithography systems[7]. This allowed hybrid polymers to be implemented into mass production environment, where one prominent example is microlenses in mobile device application[8,9].

2. MATERIAL SOLUTIONS FOR MIRCO-OPTICS

Based on the ORMOCER® technology by FhG ISC, several innovative hybrid polymer materials were developed in a scalable production process by *micro resist technology* GmbH for optical applications. Due to their tailored composition, these materials are adapted to fulfill requirements of both, the constantly growing optical performance as well as the state-of-the-art patterning techniques. In addition to conventional UV lithography and UV molding, also (nano)imprinting as well as ink-jet printing have been established as innovative alternatives for direct patterning of micro-optical components and devices.

The variety of hybrid polymer for micro-optics is summarized in Table 1 which also indicates their compatibility to specific micro- and nanofabrication processes as well as their favored fields of application[10]. Due to their excellent transparency and non-yellowing behavior, hybrid polymers such as OrmoComp® or OrmoClear® are able to meet the expectations for the material's optical performance. They also exhibit a high thermal, mechanical and chemical stability as well as a high UV sensitivity. Since the hybrid polymers are tailor-made, they can cover various fields of applications. Thus, OrmoComp® and OrmoClear® can be applied for the fabrication of optical components such as micro- and macrolenses, gratings, prisms or diffractive optical elements (DOEs) with a broad range of pattern sizes and dimensions[10]. Two exemplary results of mass-manufactured micro- and macro lenses made of OrmoComp® and OrmoClear®, respectively, are depicted in Figure 2.

Table 1. Specifications of hybrid polymers by *micro resist technology* GmbH as well as the compatibility to industrial micro- and nanofabrication processes and fields of applications. Dots illustrate the general capability in a respective process or application.

	OrmoComp®	InkOrmo	OrmoClear®	OrmoClear®10	OrmoClear®30	OrmoCore	OrmoClad	OrmoStamp®
Process Compatibility								
Photolithography (mask-lithography)	●		●	●	●	●	●	●
UV molding	●		●	●	●	●	●	●
(Nano-)imprinting	●		●	●	●	●	●	●
Direct laser writing, 2PP	●							
Ink-jet dispensing		●●						
Roll-to-roll / Roll-to-plate processing	●							●
Preferred Applications								
Micro lenses, gratings, prisms, DOEs	●	●	●	●	●			
Waveguiding	●		●	●	●	●●	●●	
Bio applications, lab-on-chip, microfluidics	●●		●	●	●			
Replication with hard molds (quartz, Ni etc.)	●	●	●	●	●	●	●	●
Replication with PDMS molds (no oxygen sensitivity)	●							●
Working stamp fabrication (e.g. for nanoimprint technology)								●●

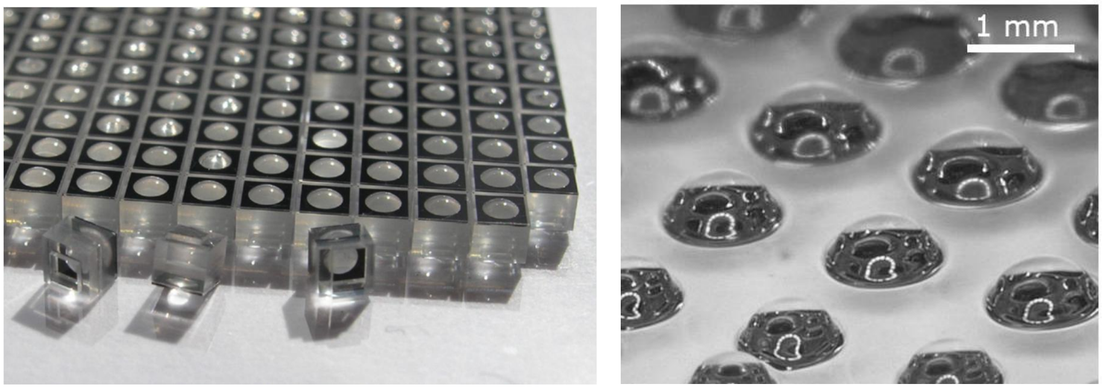

Figure 2. Left: Mass-manufactured OrmoComp® micro lenses (1.3 mm diameter, 250 µm height) on glass dies for sensing application. The individual components are produced in a parallel process by UV replication using 8" wafers with a total number of 9300 units per wafer (courtesy of Fraunhofer IOF, Jena, Germany). Right: Replicated OrmoClear® millimeter scale macro lenses with different dimensional scales (courtesy of HZB, Berlin, Germany).

In contrast, OrmoCore and OrmoClad have been developed as waveguiding materials for data and telecom applications (850, 1310, and 1550 nm) due to their low optical losses[11,12]. Furthermore, OrmoStamp® can be used for the fabrication of transparent working stamps with optimized release-properties in thermal and UV-based nanoimprint lithography (NIL), and therefore can serve as cost-efficient alternative to quartz stamps[13]. This allows NIL to be employed for the replication of optical micro- and nanopattern in hybrid polymers such as OrmoComp® or OrmoCore for a variety of applications, e.g. microlenses or optical ring resonators[14].

Due to their different precursors and types of synthesis, these inorganic-organic hybrid polymers exhibit slightly varying optical parameters. Figure 3 shows the transmittance curves as well as the dispersion curves of the most relevant hybrid materials for optical applications after processing. The transmittance of processed hybrid polymers is very high over a broad range of wavelengths. Especially in case of OrmoComp®, OrmoClear®, and OrmoStamp®, the transmittance is excellent even down to wavelengths in the near UV. The refractive indices of the (cross-linked) hybrid polymers (i.e. solidified materials) cover a range from approximately 1.52 to almost 1.56.

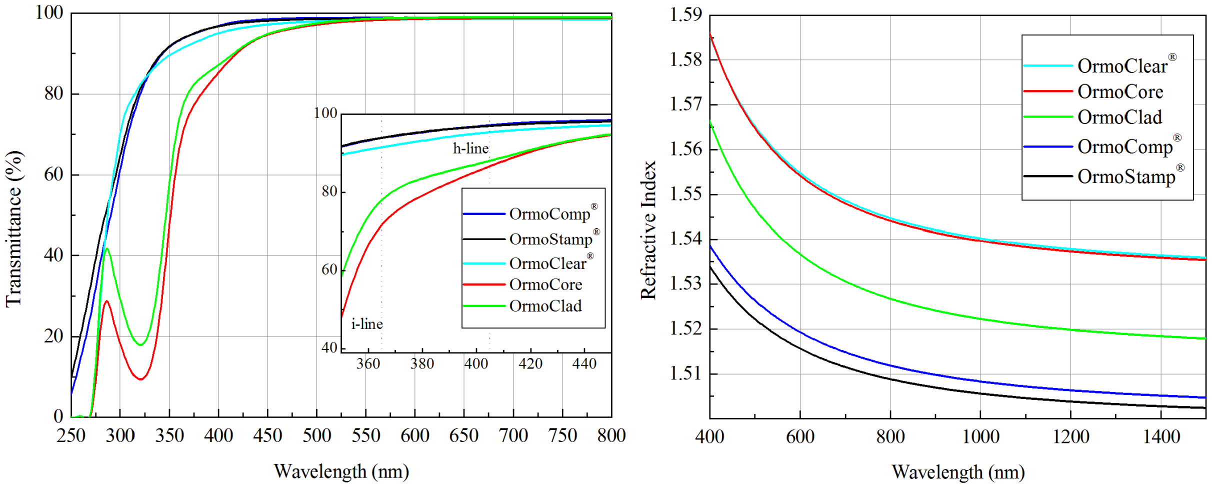

Figure 3. Transmittance curves (left) and dispersion curves (right) of commercial available hybrid polymers after cross-linking and subsequent hardbake step.

In order to expand the application scenarios for hybrid polymers, these materials were particularly tailored towards two-photon absorption (TPA) lithography, which emerges as an innovative production method for directly manufacture individual 3D photonic structures not accessible by generic 2D techniques. Exemplary 3D optical patterns in OrmoComp® are shown in Figure 4, which were fabricated by TPA on an academic level, where it is used mainly for biocompatible complex three-dimensional micro-structures such as cell scaffolds[7,15,16]. The prospect to use TPA lithography for patterning hybrid polymers offers various opportunities for simplifying the creation of optical modules and devices. However, the process depends also on the usage of materials that have very specific processing properties, and their evaluation concerning the fabrication of optical elements and modules is described in the following section.

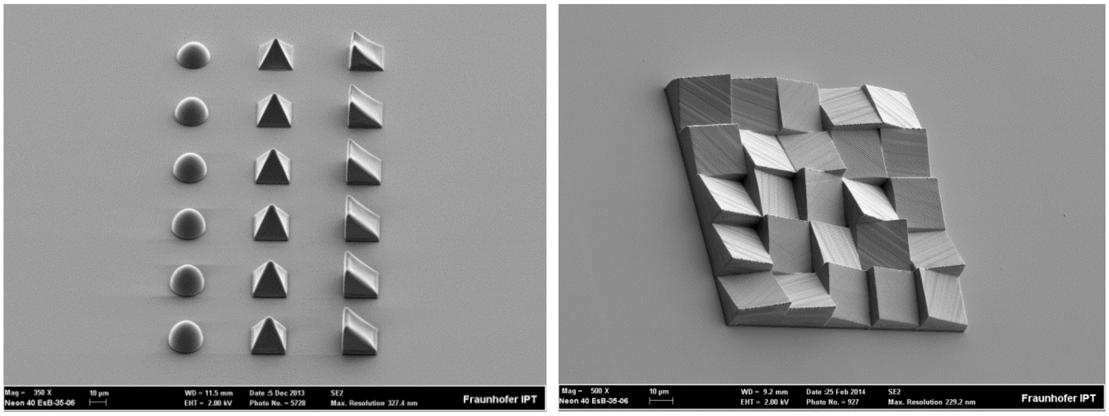

Figure 4. Optical microstructures with varying 3D shapes obtained by two-photon polymerization of an OrmoComp® modification on a glass substrate (courtesy of Fraunhofer IPT, Aachen, Germany). Left: The side lengths and diameter, respectively, of the structures measure approx. 20 µm. Right: complex 100 x 100 µm prism array with different angle of inclination.

3. TECHNOLOGY INNOVATIONS FOR 3D WAVEGUIDE APPLICATION

The performance of high-performance computing systems for data centers or exascale computing systems has to be significantly increased with respect to increasing their efficiency while significantly decreasing their energy consumption. Nowadays, many different approaches are followed to increase their efficiency, among which are a highly efficient allocation of the necessary power and very challenging cooling concepts[17,18]. For example, the efficiency of an exascale system with a power of 25 MW has to be around 40 GFLOPS/W[19]. It has been realized the last decade that despite all efforts having been made considering power consumption as well as sophisticated cooling and packaging concepts, copper technology is limited to about 6 GFLOPS/W, independently of the architecture employed[17-19].

Since more than one decade, the fabrication and performance of optical interconnects (OI) based on polymer materials is thoroughly investigated for different packaging levels such as board-to-chip and chip-to-chip, respectively. Particularly the processing of optical links on board level has been widely investigated worldwide for creating optical boards with low power consumption, high bandwidth, and at low cost[20]. Typical technologies for creating optical links are lithography[4], printing[21], laser-direct writing[22,23], laser ablation[24], or replication[25]. All these technologies have in common that they are two-dimensional, thus not suited to be simply employed for the creation of optical interconnects from, e.g. the chip level to the next packaging level. Aside of their inability of creating OI over several orders of magnitude, also their capability concerning feature dimensions and precision has to be considered for the different 2D methods. Optical interconnects are seen on most interconnect levels to be a feasible solution, but limitations to the existing technical solutions still have to be overcome with respect to the enabling fabrication technologies and materials.

The understanding of the requirements of optical interconnects has been advanced over the past years, and the main challenge has been addressed: rising numbers of high-speed OI for data center and telecom head-end-use have raised a demand for lower cost and scalable manufacturing processes which allow to implement optics closer to the chip, supporting a significant reduction in energy consumption of the end users products and, thus efficient computing.

Mainly driven by telecom and datacom applications, the development of OI strategies that allow manufacturing of optical or optoelectronic systems similar to the way that electrical systems are built today are pushed[26]. In particular, the challenges for advancing optical technology closer to the printed circuit boards and chip package, or into packaging levels 1 (chip or component package) and levels 2 (circuit board assembly) are in focus (Figure 5).

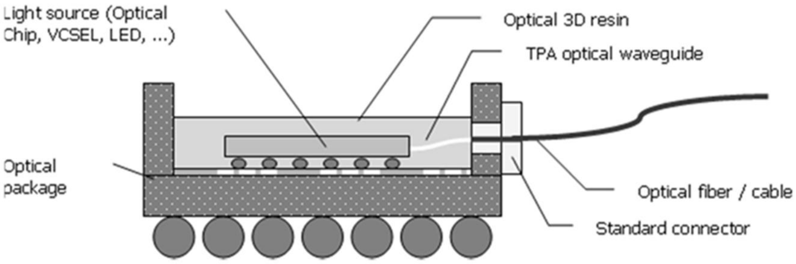

Figure 5. Schematics of a 3D waveguide connecting an optical component/chip with an optical output, yielding an OCM (Optical Chip Module). Sketch after [26].

While for the fabrication of optical interconnects scaling is still a challenge, scaling of manufacturing of products to very high volume manufacturing in electronics manufacturing services (EMS) has been demonstrated over the past 20 years, particularly for mobile devices. There are many examples how innovation in miniaturization and integration enabled new features in mobile consumer products and supported volume manufacturing, mainly the implementation of SMT components for automated and reliable assembly processes, the miniaturization of components (thinner buildups on a smaller footprint), the use of various generations of area array technology (ball grid arrays, land grid array, …), allowing the reduction of number of assembled components, and the stacking of components to die stacks, yielding highly integrated system-in-packages, just to name a few. Electronics manufacturing has come a long way of putting more computing power into silicon, and more integration capability into level 1 and level 2 packaging. Considering this development and transferring this as a role model for the optoelectronics industry, paradigm shifts in the view on connectivity between the different physical interconnect layers appear. This requires technologies which enable an efficient OI manufacture, thus allowing optical technologies to advance into interconnect levels 0 to 2.

Aside of manufacturing equipment for creating optical packages, suitable polymer materials are an essential key for cost-efficient production. They have to satisfy numerous requirements concerning their optical (e.g. optical loss) and processing properties (e.g. temperature stability). As hybrid polymers have been already applied in photonic applications as microlenses or 2D and 3D waveguides, they are promising candidates to manufacture optical systems down to the chip level. The materials can be particularly tailored to the fabrication method to be used, which was already reported by Houbertz et al. [4,7,26,27]. The evaluation of hybrid polymer materials developed from *micro resist technology* GmbH and adapted materials by Fraunhofer ISC with support from Houbertz et al. for high-precision 3D lithography was performed [28]. Complex 3D photonic structures were manufactured by means of TPA lithography as already reported in the literature[7,29].

Based on commercial success of ORMOCER®-based hybrid polymers, a technology was developed that allows to link electro-optical and optical components, respectively, by linking them via optical interconnects. Compared to other approaches, the interconnection of optical components within a component package can be fabricated in a standardizable fashion. This allows one to particularly use of existing infrastructure for the assembly, for scalable manufacturing of optical component packages (OCP).

Figure 6 shows a fluorescence/Raman image of waveguides processed using Multiphoton Optics 3D Lithography technology, where waveguides of different diameter were fabricated in just one individual hybrid polymer material, particularly adapted to the technology setup. The image illustrates the impact on the processing parameters for a given hybrid material system. By varying the photon flux in each row, the waveguide's diameter and their refractive index differences can be tuned. For the given processing conditions, waveguide diameters ranging from approximately 4.75 µm for the lower first row to about 8.6 µm for the top row, demonstrating the tremendous processing window achieved with this particular hybrid material formulation. An increase in OI diameter of about 80 % can be achieved without changing the processing setup, enabling many different structures with the same equipment. In addition, the reproducibility of the repeatedly written waveguides is extremely high, where no deviation can be detected among the waveguides in each row.

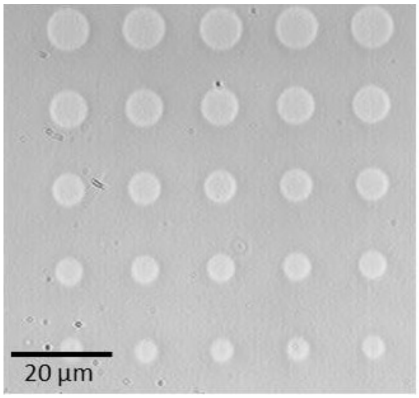

Figure 6: Fluorescence/Raman image of a cross-section of a waveguide array written by TPA with varying photon flux (courtesy of R. Houbertz, S. Steenhusen, SPP 1327/HO 2475/3-1).

In Figure 7(a), a set of TPA-written waveguides in one hybrid material is displayed, whose core diameter is approximately 4 µm. As for Figure X, also these waveguides have been fabricated reliably reproducible in the hybrid polymer cladding matrix. Figure 7(b) shows exemplary a corresponding focal intensity distribution.

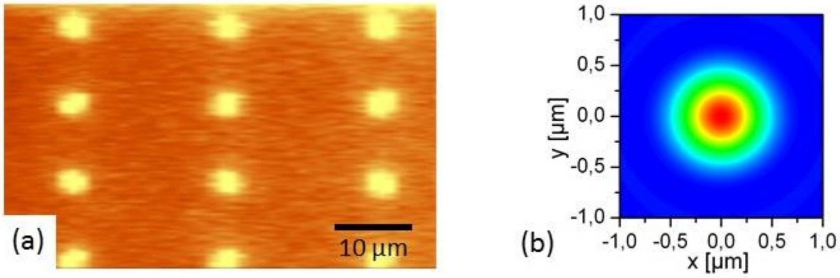

Figure 7. (a) Fluorescence/Raman image of a 3 x 4 waveguide array, and (b) example of the focal distribution (courtesy of R. Houbertz, S. Steenhusen, T. Grunemann, SPP 1327/HO2475/3-1).

Aside of optical interconnects written by Multiphoton Optics' 3D lithography[30], many other photonic structures are enabled due to the flexibility of both the employed materials as well as the underlying technology which can be used as a platform for many applications [7]. In Figure 8, specially designed microlenses are displayed which were fabricated in below 2 min, enabling the reproducible generation of large arrays of custom-designed microlenses in short time. It was demonstrated that the technology accounts for high accuracy and excellent surface finish (low surface roughness), which are prerequisites for functional photonic structures aside the material's suitability. This is again determined by the fabrication parameters such as photon dose and writing strategy, analogously as for the fabrication of optical interconnects. The work on microlenses and their characterization will be published elsewhere [31].

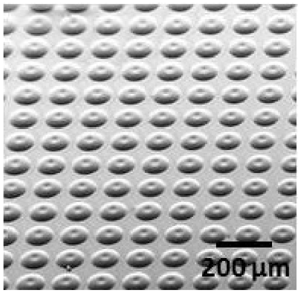

Figure 8: Array of custom-shaped microlenses fabricated by TPA in a specially adapted hybrid polymer (courtesy of R. Houbertz, S. Steenhusen, SPP 1327HO2475/3-1).

CONCLUSION

A brief review on hybrid polymers consisting of both inorganic and organic functional units and thus combine superior material properties in just one material class was given in this report. As described by giving a few examples of industrial processing situations, tailored ORMOCER®-based hybrid polymers are ideal candidates for micro- and nanofabrication purpose. They have been successfully applied in photonic applications as microlenses or 2D and 3D waveguides. Due to their broad processing window as well as superb optical performance, which are enabled by the diligent formulation of inorganic and organic units, they are highly attractive to industrial micro- and nanofabrication. Furthermore, they are promising candidates to manufacture optical systems down to the chip level using TPA 3D lithography. In a first evaluation phase, the applicability of hybrid polymer to high-precision 3D lithography by means of TPA was positively demonstrated. Since the materials can be particularly tailored to match the fabrication method requirements, complex 3D photonic structures were manufactured by TPA lithography which impossibly can be generated with conventional 2D techniques. This shows that hybrid polymers will continue to meet the increasing expectations of dynamically growing markets for micro-optical devices, Silicon Photonics among others, and related application also in future.

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REFERENCES

[1] Voelkel, R., Duparre, J., Wippermann, F., Dannberg, P., Brauer, A., Zoberbier, R., Gabriel, M., Hornung, M., Hansen, S., Suess, R., "Technology Trends of Microlens Imprint Lithography and Wafer Level Cameras (WLC)", Proc. MOC'08, Conf. On Micro-Optics, Brussels (2008).

[2] UV-curable hybrid polymers (ORMOCER®s) for micro optics based on a license granted by the Fraunhofer-Gesellschaft zur Förderung der Angewandten Forschung in Deutschland e.V.

[3] Sanchez, C., Julian, B., Belleville, P. and Popall, M., "Applications of hybrid organic–inorganic nanocomposites", J. Mater. Chem. 15, 3559-3592 (2005).

[4] Houbertz, R., Wolter, H., Dannberg, P., Serbin, J. and Uhlig, S., "Advanced packaging materials for optical applications: Bridging the gap between nm-size structures and large-area panel processing", 8th Topical Conference on Photonics Packaging and Integration held as part of OPTO 2006 in conjunction with the Photonics West 2006 Symposium, San Jose (2006).

[5] Obi, S., Gale, M.T., Kuoni, A. and De Rooij, N., "Replication of optical MEMS structures in sol–gel materials", Microelectron. Eng. 73–74, 157–160 (2004).

[6] Streppel, U.; Dannberg, P.; Waechter, C.; Braeuer, A.; Nicole, P.; Froehlich, L.; Houbertz, R.; Popall, M., "Development of a new fabrication method for stacked optical waveguides using inorganic-organic copolymers," Polymers and Adhesives in Microelectronics and Photonics, 2001. First International IEEE Conference on , vol., no., pp.329,335, 21-24 Oct. 2001.

[7] Houbertz, R., Steenhusen, S., Stichel, T., and Sextl, G., In book: Coherence and Ultrashort Pulse Laser Emission Source: InTech (2010). ISBN: 978-953-307-242-5.

[8] Wippermann, F., "Miniaturized digital imaging systems based on UV-curable polymers", VDE Seminar Berlin (2013).

[9] Thienpont, H., Choquette, K.D., Taghizadeh, M.R., "Wafer-scale replication and testing of micro-optical components for VCSELs", Proceedings of SPIE Vol. 5453 (2004).

[10] For further information and specifications to the hybrid polymer products please refer to the product information on www.microresist.com

[11] Mohamed, R., Razali, N., Ehsan, A. A., Shaari, S. "Characterisation and process optimisation of photosensitive acrylates for photonics applications", Sci. Tech. Adv. Mater. 6, 375–382 (2005).

[12] Houbertz, R., Domann, G., Cronauer, C., Schmitt, A., Martin, H., Park, J.-U., Fröhlich, L., Buestrich, R., Popall, M., Streppel, U., Dannberg, P., Wächter, C., Bräuer, A., "Inorganic–organic hybrid materials for application in optical devices", Thin Solid Films 442, 194-200 (2003).

[13] Schleunitz, A., Vogler, M., Fernandez-Cuesta, I., Schift, H., Gruetzner, G., "Innovative and Tailor-made Resist and Working Stamp Materials for Advancing NIL-based Production Technology", J. Photopolym. Sci. Technol. 26, 119-124 (2013).

[14] Kirchner, R., Finn, A., Landgraf, R., Nueske, L., Vogler, M., Fischer, W.-J., "UV-based Nanoimprint Lithography: Toward Direct Patterning of Functional Polymers", J. Photopolym. Sci. Technol. 25, 197-206 (2012).

[15] Greiner, A. M., Richter, B., Bastmeyer, M., "Micro-Engineered 3D Scaffolds for Cell Culture Studies", Macromol. Biosci. 12, 1301-1314 (2012).

[16] Klein, F., Striebel, T., Fischer, J., Jiang, Z., Franz, C. M., v. Freymann, G., Wegener, M., Bastmeyer, M., "Elastic Fully Three-dimensional Microstructure Scaffolds for Cell Force Measurements", Adv. Mater. 22, 868-871 (2010).

[17] Coteus, P.W. et al., IBM J. Res. Dev. 55, 14:1 (2011).

[18] Haney, M., Nair, R., Gu, T., Proc. SPIE 8267, 82670X1 (2012).

[19] Gioiosa, R., 18th IEEE/IFIP Intern. Conf. on VLSI and System-on-Chip 270 (2010).

[20] Immonen, M. (TTM Technologies), IBM Printed Circuit Board Symposium (2011).

[21] Chan, B., Lin, H., Carver, C., Huang, J., Berry, J., ECTC (2010).

[22] Bosman, E., Fotonica Event (2013).

[23] Götzen, R., Reinhard, A., Intern. Conf. on Additive Technologies, iCAT, Ptuj, Slovenien (2008).

[24] Van Steenberge, G., Hendrickx, N., Bosman, E., Van Erps, J., Thienpont, H., Van Daele, P., IEEE Photonics Technol. Lett. 18(9), 1106 (2006).

[25] https://biblio.ugent.be/input/download?func=downloadFile&recordOId=2035179&fileOId=3145427.

[26] Riester, M., Houbertz, R. (Multiphoton Optics GmbH), World Telecommunications Congress (2014).

[27] Houbertz, R., Satzingera, V., Schmid, V., Leeb, W., Langer, G., Proc. of SPIE 7053 70530B-1 (2008).

[28] Houbertz, R., Steenhusen, S., Grunemann, T., Stichel, T., Tucher, N., German Science Foundation Priority Program SPP1327, grant: HO 2475/3-1.

[29] Th. Stichel, B. Hecht, R. Houbertz, and G. Sextl, J. Laser Micro/Naoengineering 5, 209 (2010)

[30] TPA Lithography license granted by the Fraunhofer-Gesellschaft zur Förderung der Angewandten Forschung in Deutschland e.V.

[31] Steenhusen, S., Burmeister, F., Nolte, S., Houbertz, R., Opt. Expr. (submitted).