Photonic System-in-Package Technologies Using Thin Glass Substrates

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Abstract

The novel packaging approach *glassPack* is introduced as a System-in-Package (SiP) technology. Wiring length can be reduced and integration density can be increased by stacking different assembled substrate layers and interconnecting them resulting in 3D-SiP. Glass is an excellent substrate material because of matched coefficient of thermal expansion (CTE) to silicon, high thermal load, dielectric constant and high optical transparency over a wide wavelength range. Commercially available thin glass foils can be used as substrate materials for electronic and optoelectronic modules. The goal of our ongoing development is to make glass based packaging competitive with polymer (e.g. chip-in-polymer) or silicon based packaging (e.g. silicon-through-via, stacked dies by wire bonding). Our work is focused on conductor trace and through-via realization as well as optical lightwave circuit integration using glass as a substrate. For through-glass-vias, holes were drilled in glass wafers by different laser technologies and evaluated. Also, optical integration of waveguides and mirrors in glass substrates were investigated. This paper presents basic design rules and a selection of technologies for glass based SiP as well as a process flow for glass interposer applications.

1 Introduction

Currently, decreasing pitch size of conductor traces, small scale through-vias and high alignment accuracy are the key requirements for high density integrated packages. The integration potential of organic laminates (e.g. FR4) is limited because of dimensional instability under thermal load. The alignment of interconnects between different layers is challenging where oversized patterns have to compensate the process tolerances. As a result the pitch size for devices assembled on FR4 is limited. Alternatively, the 3D-SiP based on silicon interposer platform is a very active area of ongoing research [1]. Due to the availability of wafer level processing, silicon substrates can be processed with the same pitch size and accuracy as the highly integrated components that will be assembled. Furthermore, the CTE matches perfectly if the substrate and die are made of the same material. The resulting stress on the solder join is reduced. A drawback however is the semiconductor property of silicon which requiresconductive through-via interconnects to be isolated from the semiconductor bulk material.

The presented glass based packaging technology overcomes the above-mentioned problems. The benefits of glass are dimensional stability under thermal load, alignment benefits as a result of transparency, wafer level processing, CTE matching to silicon and good dielectric properties. Beyond that, glass has excellent optical properties and is well known for its high potential in the field of integrated optics [2]. Thin glass sheets in wafer form are available at a minimum thickness of 30 microns. Wafer level processes can be adapted from CMOS processing. On the other hand, new processes for accurate micro-drilling and structuring of glass have to be explored in more detail [3].

Our work focuses on a novel SiP approach based on the use of thin glass as a substrate material. Active and passive as well as optoelectronic components are integrated on the same substrate. For vertical integration, different glass substrates are stacked and interconnected. Our thin glass based packaging technology, called *glassPack* offers high potential for SiP especially for applications in the field of sensing or high-speed data transmission.

Besides the electrical and optical benefits, glass is inert, resistant against most chemicals except hydrofluoric acid (HF) and has no moisture absorption. Fluidic systems made of glass are suitable for lab-on-chip devices [4].

We already demonstrated a *glassPack*-based optical sensor with integrated Mach-Zehnder interferometer (MZI) waveguides, fluidic channels, optoelectronic components and silicon dies as shown in Figure 1 [5,6].

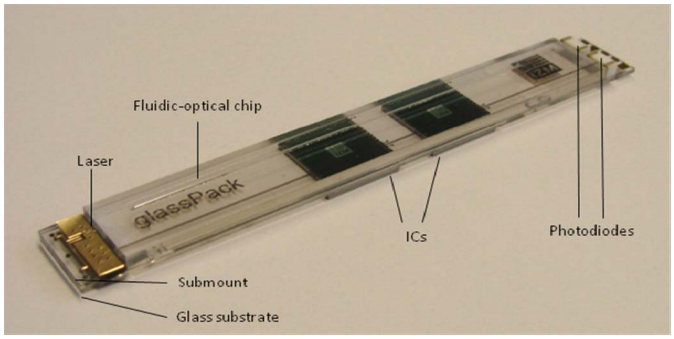

Figure 1: Optical sensor with integrated MZI and fluidic channels, optoelectronic components and silicon dies. Fluidic optical cell as stack of D263™T and two Foturan™ thin glass foils (center), laser (left) and photodiodes (right) are integrated on the top side of the glass substrate. On the bottom side two silicon dies having an edge length of 10 mm are assembled. The sensor has a length of 80 mm and a width of 10 mm.

In this paper basic design and technology issues are discussed with the main focus on high-speed data transmission for data and telecom applications. For this application optoelectronic multi-channel transmitters and receivers have been integrated into a package that can be mounted on a PCB (printed circuit board) for optical board or have a fiber interface for rack-level interconnection. State-of-the art are multi-mode transceiver modules using a silicon, ceramic or polymer core material as carrier for the optoelectronic devices such as photo detectors and vertical cavity surface emitting

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lasers (VCSEL) as well as the laser driver and amplifier integrated circuits (IC) that are all flip-chip mounted for a small footprint. The optics are mainly separatly attached and require post processing. These optoelectronic transceiver modules target optical high-speed data communication where electrical signals in gigahertz frequency range have to be transformed to optical signals or vice versa for replacing electrical wires and transporting a huge amount of date over a distance on board or even further. Such applications require transceiver modules that are located close to the processor or memory units in a super computer or between servers in a data center. Glass as substrate material for electric and optical interconnects on the other hand, has benefits compared to conventional materials especially for active interposers when electrical high-frequency signals and optical elements should be integrated in the same package. Figure 2 shows a sketch of a parallel electro-optical transceiver module based on our glass based packaging concept. Glass substrates offer excellent dielectric properties that are getting continuously more important for electrical high-frequency wiring and allow the simultaneous integration of optical waveguides.

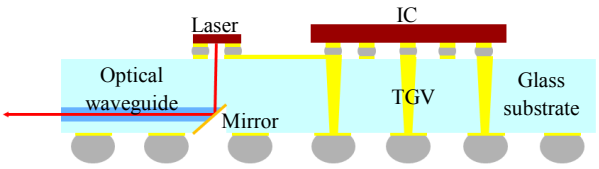

Figure 2: Sketch of a transceiver module using glass as substrate material. Devices like laser, photo detector, ICs are all mounted on top side. Through-glass-vias (TGV), optical mirrors and optical waveguides are implemented in a system-in-package for PCB assembling.

2 Design

2.1 Selection of suitable thin glass substrates

An immense amount of different glass brands are offered by the glass industry today. The right selection of glass for applications in a given electronic or opto-electronic field depends on the glass properties and the suitable process routines. The available format and thickness play a significant basis for decision-making such that standard process routines (e.g. CMOS) can be adopted by just changing the substrate from silicon to glass for selected applications.

Table 1: Glass brands of Schott AG suitable for wafer level packaging [7].

Brand	**Lithosil®**	**BORO FLOAT®33**	**B 270™**	**D 263™ T eco**	**AF 32™ eco**
Type	fused-silica	boro-silicat	crone glass	boro-silicat	al-boro-silicate
Process	micro-float		up-draw	down-draw	
process thickness	700 µm	700 µm	800 µm	30 µm	100 µm
Format	Panel and wafer				
Alkaline content	alkali-free	4 wt%	17 wt%	13 wt%	alkali-free
CTE	0.5 ppm	3.3 ppm	9.4 ppm	7.2 ppm	3.2 ppm
tanδ (1MHz)	$14 \cdot 10^{-4}$	$37 \cdot 10^{-4}$	n.a.	$61 \cdot 10^{-4}$	$28 \cdot 10^{-4}$
ε_r (1 MHz)	3.8	4.6	7.0	6.7	5.1

A selection of brands offered by Schott AG, a world leading glass company, are introduced in Table 1 that are suitable for wafer level packaging. The glass thickness is dependent on the manufacturing. For the down-draw process the glass thickness is much smaller than for the micro-float or up-draw process but can be reduced by surface polishing to a final thickness of around 500 µm for instance. The BOROFLOAT®33 from Schott AG and the equivalent glass brand Pyrex™ from Corning have a CTE that perfectly matches that of silicon. For that reason and also due to its alkaline content BOROFLOAT®33 and Pyrex™ highly significant materialsfor anodic bonding of glass to silicon wafers in the field of MEMS and sensoric packaging [8]. An example of the importance of glass in the field of electronics is the growing flat panel display (FPD) market that has lead to a mass production of borosilicate thin glass foils such as D263™Teco having a thickness of 0.03 to 1.1 mm and consistently high quality. These two examples illustrate the processing of glass for mass production, high reliability in combination with silicon or electronic wiring. Furthermore glass has excellent dielectric properties as well as the ceramic materials that are often used for high-frequency applications (Al_2O_3: $\varepsilon_r = 9.6$, $\tan\delta = 5 \cdot 10^{-4}$). In summary glass has excellent properties for photnic packaging and the introduction of glass as an very important material for electronic packaging is obvious in the near future.

During the design phase of a glass based package the selection of a suitable glass mainly depends on reliability and process issues. For instance BOROFLOAT®33 and AF32™ are always a good choice related to high reliability of solder joints because of good CTE matching to silicon dies. But some technologies only work with specific brands because the process parameters are strictly dependent. For instance, the integration of optical functions inside the substrate using the ion-exchange technology remarkably increases the integration density but works only with alkali content glasses like Schott D263™Teco.

2.2 Electrical circuit design

Electric wiring in a three-dimensional manner is possible using conductor traces and through-via interconnects. As a result much focus is placed on focus on thin film processing for 2D interconnects on the glass surface and through-glass-via technologies for interconnecting the front and backside of the substrate.

The adhesion on glass especially by using chrome as an adhesion promoter is well known good. By adapting CMOS thin film processing the line and pitch width limitations are dependent on the process and there is no difference between processing a glass or silicon wafer.

A bigger challenge is the electrical feed-through in glass. By studying the literature a few research groups mostly from the MEMS community have discussed different approaches for hermetically-sealed glass packaging [9]. An excellent approach is presented by NEC/Schott. Tungsten pins having a diameter of 100 µm are hermetically sealed in BOROFLOAT®33 glass wafers having a thickness of 500 or 600 µm [10]. For that case the package design is fixed on this specific glass and the process starts with specially processed

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wafers form NEC/Schott according to a defined through-glass-via) layout.

Another way for getting electrical feed-throughs in glass are drilling holes and filling them with metal by electroplating. For making such through-holes powder blasting [11], wet-etching [12], deep reactive ion etching [13] or laser ablation [14] are possible glass structuring technologies. Each technology has benefits and drawbacks. The requirements for through-holes are a short process time, a high aspect ratio, a small pitch and a hole diameter of some tens of microns to achieve current requirements for high integration density [15]. Most of the introduced glass drilling technologies can't fulfill all of needs. Using innovative laser manufacturing methods laser drilling has the most potential for drilling very small holes. Laser drilling will be introduced in more detail in later sections of this paper. The design for electrical through-glass-vias is totally dependent on the drilling process that defines the hole-shape and dimensions as well as the pitch size.

2.3 Optical circuit design

High light transmission and the refraction effects make glass a suitable material for different photonic applications. The integration of optical waveguides, lenses and beam deflection units like mirrors is part of the *glassPack* concept. First the waveguides and lenses are implemented in a planar way using the ion-exchange technology which is dependent on alkaline content glass. Both single and multimode waveguides can be processed using this technology. Because of the low refractive index contrast between the bulk glass and the integrated waveguides the bending radius is in the range of approx. 20 mm [16, 17]. Optical structures like straight and bended waveguides, coupler, and Mach-Zehnder interferometers can be designed and integrated in a planar way. Also the integration of optical mirrors for out-of-plane coupling is supported by the glassPack concept. Both the waveguide technology as well as the micro-polishing for mirror processing is introduced below.

On the transparent substrate surface, electro-optical devices like VCSELs and photo detectors can be mounted that are optically connected via integrated mirrors to the waveguides as shown in Figure 2 by the red line. The laser beam has to be collimated for illumination through the substrate and efficient coupling into the waveguide. For that reason the optical design implements the selection of suitable lenses that are attached to the optical component [18], planar implemented in the substrate [19] or mounted on the glass surface [20].

2.4 Thermal management and reliability

Glass is a fragile material and has a very low thermal conductivity which should be considered when designing and processing of glass based packaging. Components like ICs and lasers dissipate heat which has to be spread by the substrate and conduct to a heat sink. Because glass is a poor heat spreading material t metallization should fulfill this task and a high density of thermal vias is required to direct the heat through the glass. The thermal issue has to be carefully considered during the design phase. Of course the dimensions of the metallization and thermal vias are limited in size and capacity but the trend shows a development to high power efficient devices [21, 22]. As a result glass packaging gets more and more interesting for low power optical interconnects.

The fragile behavior of glass plays a significant aspect during processing. Temperature intensive processes and micro-crack inducing structuring methods have to be avoided or carefully evaluated if process yields are to be kept. In the following sections we develop the *glassPack* technology more fully in light of these issues.

3 Technologies

3.1 Glass laser drilling

The selection of a suitable laser drilling process for micro system packaging is mainly guided by the quality and dimensions of a resulting hole as well as the process speed. Here we present the experimental results of laser drilling tests that were performed by 3D-Micromac AG [23] using a TiSa-laser station having a pulse width of 50..150 fs and a Excimer laser station having a pulse width of 10..35 ns. The main difference is in the ablation behavior because of different pulse width and insertion power density. It is well known that fs-laser drilling is characterized by reduced heat penetration into adjacent material and without debris at the material surface. The benefit of high hole-quality paid for by a reduced process speed for fs-laser drilling. There are research activities for improving this by increasing the pulse repetition rate are ongoing but today's commercially available fs-laser stations are not ready for wafer-scale processing because of the long processing time [24]. Excimer laser promises to be much faster but the quality and requirement of holes smaller than 100 microns have to be evaluated. For this purpose drilling tests on a test layout using both lasers were performed and compared. In Figure 3 a scanning electron microscope (SEM) picture of the fs-laser drilled glass sample is shown.

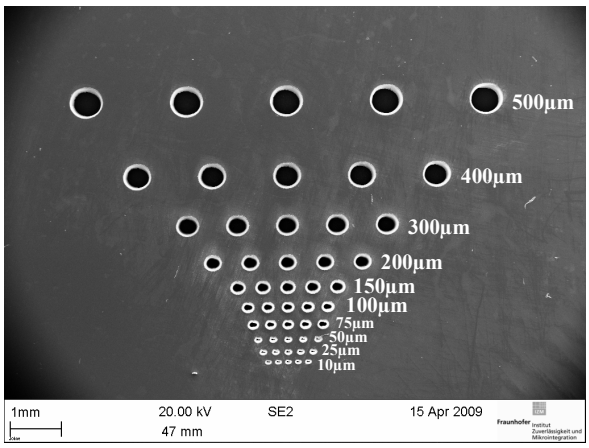

Figure 3: Overview of the drilling results in Schott D263™T *performed by a fs-laser station of 3D-Micromac AG.*

The requirement was to achieve holes having a diameter between 10 and 500µm. The shape of the resulting hole depends directly on the glass thickness. The experiment was performed on Schott D263™T glass with a thickness of 400µm for ns-laser and 500 µm for fs-laser tests. As shown in Figure 4 the resulting holes have a conic shape with the larger opening on the beam incident side. A test layout specified the

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through hole position and diameter. Because of the beam divergence the smallest holes in the layout with 10 µm or more couldn't be drilled through the substrate. The smallest diameters for a through hole were a center diameter of 26 µm for the ns-laser and 25µm for the fs-laser as shown in the polished micrograph cross-section in Figure 4. The ns-laser drilled hole doesn't have an increasing taper on the beam incident side that doubles the opening width of the fs-laser drilled hole. In summary the ns-laser station produces tiny holes in 400µm thick glass with a high aspect ratio and a conic shape. A drawback is the surface contamination that can be reduced be using a protecting mask during drilling which is afterwards removed. The benefit of ns-lasers compared to fs-lasers is the faster processing speed.

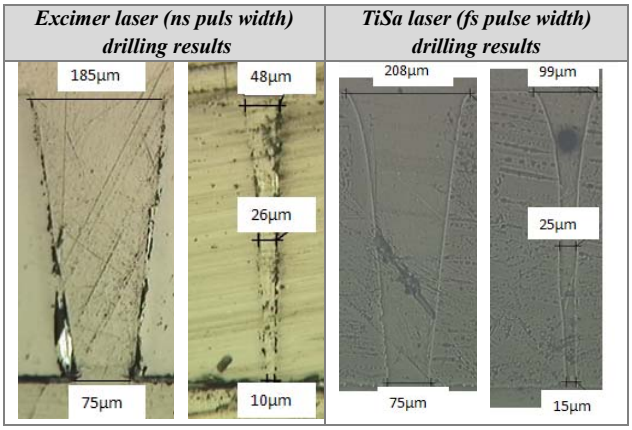


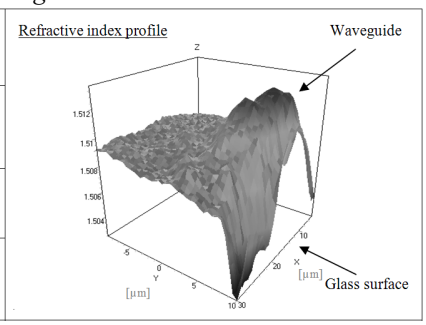
Figure 4: Polished micrograph cross-sections of a through-holes in D263T™ thin glass foils having a thickness of 400 µm for the Excimer laser and a thickness of 500 µm for the TiSa laser drilled holes.

3.2 Ion-exchange

In our investigations planar integration of optical waveguides below the surface of a thin glass foil is done by ion-exchange technology. The resulting singlemode or multimode waveguide has a graded refractive index profile.

Table 2: Singlemode waveguide characteristics

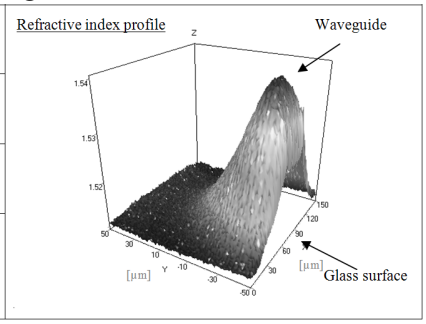
Diffusion mask size	2 µm
Normalized index difference	0.003
Propagation loss	0.3 dB/cm
Mode field diameter	9 µm (v) 13 µm (h)



The waveguide manufacturing consists of two processes. The first process is performed in a molten salt mixture of sodium and silver nitrate at a temperature of 350°C. A structured alloy mask deposited on the surface of the glass foil (diffusion mask) supports the locally confined diffusion process between the glass and the salt melt. Silver ions of the salt melt diffuse into the glass and exchange takes place with sodium ions of the glass network. As a result of differences in electric polarizability and ionic radii between the exchanged ions, the refractive index increases [16, 17]. The subsequent thermal ion-exchange in pure sodium nitrate buries silver ions near the surface as a consequence of reverse diffusion behavior. Furthermore, potassium ions of the glass network diffuse out and an index decrease over the whole glass surface results. The index profile of the waveguide can be adjusted by the process parameters such as temperature and process time. The resulting index profile of a singlemode waveguide having a propagation loss of less than 0.3 dB/cm for a wavelength of 1310 nm is depicted in Table 2.

Table 3: Multimode waveguide characteristics

Diffusion mask size	30 µm
Normalized index difference	0.021
Propagation loss	0.1 dB/cm
Mode field diameter	11 µm (v) 26 µm (h)



Also, multi-mode waveguides having a loss of less than 0.1 dB/cm for a wavelength of 850 nm were developed and optimized and depicted in Table 3.

3.3 Micro-polishing

For optical out-of-plane coupling a mirror has to be integrated at the end of the waveguide to deflect the propagating beam perpendicular to the glass surface. Such a mirror has been realized by mechanical micro-polishing of the end face by an angle of 45 degree. Such a resulting coupling element is shown in Figure 5.

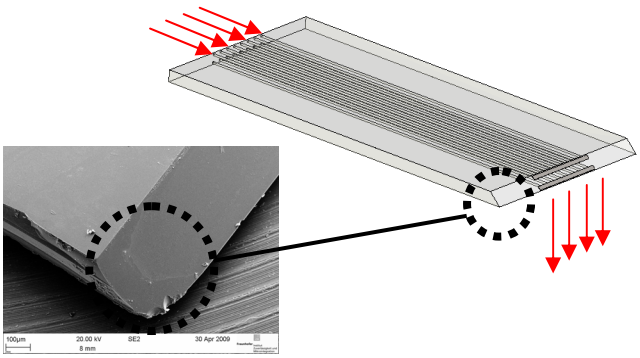


Figure 5: Planar double layer single-mode or multi-mode waveguide element with waveguide arrays on top and bottom of the coupling element and SEM picture of the coupling element edge that shows the excellent surface quality after micro-polishing.

After the waveguide process a modified fiber polishing machine with a specially constructed mounting for thin glass probes is used for high quality end face polishing. The polish procedure follows by using polishing paper having different grain size until the end face has optical quality. After polishing the surface roughness of the mirror was measured by

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atomic force microscope (AFM) and the arithmetic average (R_a) is 15 nm. In Figure 5 a SEM picture shows the excellent surface quality of the mirror.

Both single and multimode waveguide samples were polished and optically characterized by light propagation measurements. The attenuation due to beam deflection was 1.4 dB for singlemode and 1.1 dB for multimode waveguide samples respectively.

Because of the excellent experimental results the next step will be to implement optical mirrors at arbitrary positions on a glass wafer to realize a full wafer processing as shown in Figure 6.

4 Packaging process

On the basis of the introduced design rules and the presented technology knowledge we developed two process flows for wafer level packaging of photonic system-in-packages for photonic modules like transceivers.

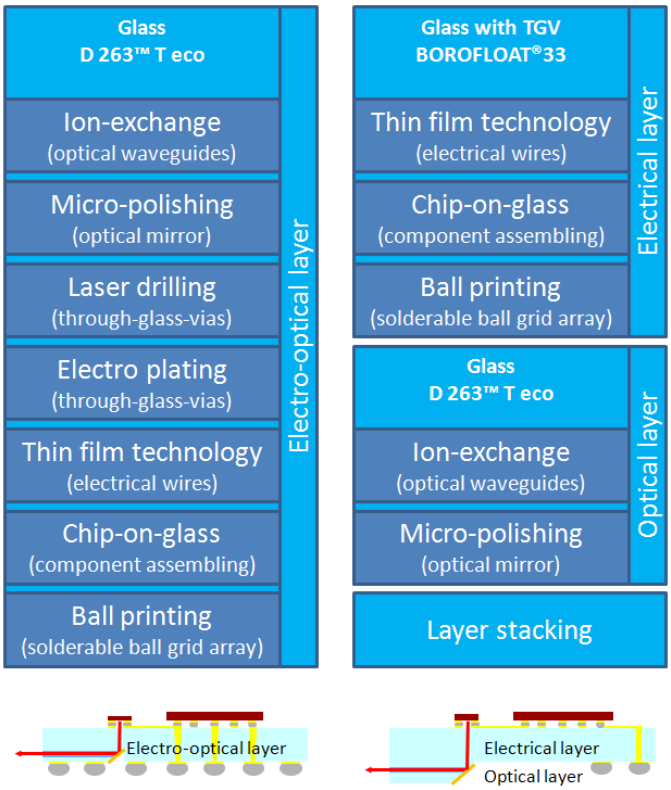

Figure 6: Two different process flows dependent on the use of glass suitable for ion-exchange like D 263™ T eco (left side) or glass with through glass vias (TGV) (right side). The main different results in a two layer concept on the right side made of an electrical layer and an optical layer.

On the left side of Figure 6 the process of a single layer SiP is presented in which a glass with low-level mobility alkali ions is used that is a requirement for implementing optical waveguides. The waveguide process using the ion-exchange technology is firstly processed because of the high process temperature of 350°C and the resulting material stress. Next the mechanical structuring like optical mirror integration and hole-drilling is performed. Afterwards the holes are filled for electrical through-glass-vias and thin film technology is processed for electrical circuitry. The introduced process integrates electrical and optical functions in the same substrate.

Two layer approaches where electrical and optical layer are processed independently and finally stacked are shown on the right side of Figure 6. For the electrical layer a glass wafer having already through-glass-vias like the introduced NEC/Schott approach is used and thin film technology and chip-on-glass [25] assembly brings the electrical functionality onto the substrate. For mounting on a PCB a solderable ball grid array is printed on the bottom side of the wafer. Parallel to this the optical layer is processed and then attached to the electrical layer.

Both introduced process flows result in different system-in-package solutions for PCB mounting. As published in [26] electrical optical circuits boards (EOCB) with thin glass layers are perfectly matched to the kind of transceiver modules introduced in that paper. For that reason the optical plane of the transceiver has to be on the same level as the optical layer in the EOCB.

5 Conclusions and Outlook

The interest on SiP solutions will increase in the next years. Also, the integration of optical, fluidic, and electronic applications into one system will be an ongoing development with many important applications. Our packaging solution is perfectly suitable for 3D SiP and the realization of complex and reliable microsystems. The benefit of glass leads to excellent optical, electric, chemical, and thermal properties. In conclusions, *glassPack* as a novel SiP technology using the benefit of the excellent properties of thin glass foils as substrate material has been presented andsuitable technologies like ion-exchange, laser drilling, and micro-polishing for processing glass substrates have been introduced. A process flow for a glass based system-in-package module for transceiver applications has been described. The design and processing of a transceiver module using glassPack is currently underway.

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