glassPack – A 3D Glass Based Interposer Concept for SiP with Integrated Optical Interconnects

H. Schröder, L. Brusberg, R. Erxleben, I. Ndip, M. Töpper, N. F. Nissen, H. Reichl
Fraunhofer IZM
Gustav-Meyer-Allee 25, 13355 Berlin, Germany
henning.Schroeder@izm.fraunhofer.de

Abstract

We introduce thin glass for electrical-optical integration on module level. Glass is regarded as promising material for high frequency wiring to drive the e/o components having additional advantages in terms of transparency, waveguide and lens integration capability and PCB integration. Modeling results of vertical and horizontal electrical interconnects show the suitability for certain configurations. The integration schemes will be discussed and experimental results from thin film deposition, laser drilling of through vias and ion exchange for optical waveguides will be presented.

1. Introduction

In ITRS, optical on-chip and chip-to-chip interconnects within a System in Package (SiP) have been added as a volume technology in 2011. SiP is a combination of multiple active and passive electronic components of different functionality, assembled in a single unit that provides multiple functions associated with a system or sub-system. SiPs may optionally contain, MEMS, optical components as well as other packages and devices [1] (see **Figure 1**). To ensure system functionality, these SiPs have to be assembled on a PCB and hence, need appropriate wider contact pitches. For this purpose, interposer platforms are used and they provide the contact redistribution.

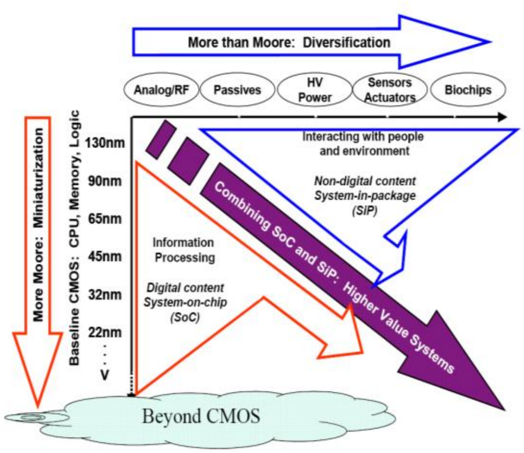

Figure 1. Byond CMOS-Scaling [1]

For high performance computing (HPC) systems, hundreds of high frequency electrical I/O beyond 20 Gbit/s are forecasted [2]. From the physical point of view, the main problems associated with these high data rate transmission using electrical interconnects are losses of the transmission channels as well as the driver and receiver energy required to overcome channel attenuation and noise. Due to the interconnection hierarchy and many different kinds of electrical wiring on different substrate materials, the signal latency becomes significant causing a performance problem in large shared memory multiprocessors for example. The basic advantage of the proposed optical interconnects here are the frequency independent losses. Thus bandwidth and latency of an optical link are virtually independent of the length, the fan-out/fan-in, and the overall density of the interconnections [3]. They provide a reduced design complexity and low power consumption, as well as the potential for high channel density by wavelength division multiplexing (WDM).

In general optical interconnects remove many channel limitations. The remaining limiting factors are available optical component power and cooling capacity. For the short distances on board and over backplanes embedded optical waveguides in combination with low power/high bandwidth components are necessary. The crucial point is to optimize the link budget using low power components of high data rates and efficient optical coupling schemes [4]. Furthermore, a higher integration level using direct chip attachment at receiver and transmitter modules can improve the system efficiency dramatically. Thus new packaging approaches are highly needed.

Our work focuses on such a novel SiP approach based on the use of thin glass as the interposer material. Active and passive as well as electro-optical components are integrated on the same interposer substrate. For vertical integration, different glass substrates are stacked and interconnected. The necessary optical interconnects can be integrated directly in the glass matrix. Our thin glass based packaging technology called *glassPack* offers high potential for applications in the field of high-speed data transmission and sensing. The main drivers for glass substrates can be summarized as follows:

- Optical interconnects have to be integrated within packaging substrates and interposer
- Organic substrates have to be replaced for higher I/O and thermo mechanical reliability (CTE match to silicon)
- Through silicon via (TSV) are challenging due to semiconductor properties and technological complexity but through glass vias (TGV) do not need any isolation
- Low price and large panel availability

First experimental results using thin glass substrates with integrated optical interconnects and functions as well as electrical wiring for sensor applications have been reported recently [5]. Within this paper a more general view on *glassPack* technologies and challenges will be given.

The following part of this paper is structured as follows: In section two the properties thin glass sheets are discussed in terms of their suitability for electrical and optical SiP, and in section three the integration potential into PCB based and optical fiber pigtailed packages will be discussed from a more system related view. In section four transmission line simulation results thermal considerations as well as experimental results on laser structuring of TGV are presented and discussed.

2. Thin glass material suitability

In order to combine optical and electrical interconnects within SiP physically, a suitable interposer material is needed. Thin glass as a carrier material has benefits compared to conventional materials like silicon, ceramic or polymer based laminates. These benefits will be elucidated by means of collecting some of the excellent dielectric and transparent properties that are getting important for electrical wiring of high-frequency signals as well as for optical waveguides.

The choice of the appropriate glass depends on the application. 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 is always a good choice related to high reliability of solder joints because of excellent CTE matching to silicon dies. But some technologies only work with specific glass types 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. If optical waveguide channels shall be implemented inside the thin glass substrates a high alkaline content is essential (such as D263™T eco, B270™, see **Table 1**). For electrical feed troughs and wires on the surface the dielectric behaviour versus signal frequency has to be taken into account. The integration of fluidic channels needs structuring technologies like wet chemical etching and has to maintain flat surfaces. Otherwise polishing processes before final layer stacking are required.

Table 1: Some basic thin glass types and properties compared in terms of *glassPack* suitability

Name	Lithosil®	BORO FLOAT®33	D 263™ T eco	B 270™	AF 32™ eco
Type	fused-silica	boro-silicat	boro-silicat	crone glass	al-boro-silicate
Process	micro-float		down-draw		
Thickness	700 µm	700 µm	30 µm	..	..
Format	Panel and wafer				
Alkaline content	alkali-free	4 wt%	13 wt%	17 wt%	alkali-free
CTE	0.5 ppm	3.3 ppm	7.2 ppm	9.4 ppm	3.2 ppm

Finally the integration potential is excellent because of the dimensional stability of glass under thermal load and the coefficient of thermal expansion matching to silicon ICs. Single mode or multimode waveguides can be integrated horizontally in the glass bulk by ion exchange technology and the light transmission through the carrier vertically between different optical layers is possible directly or with integrated lens optics within the substrate as well. Furthermore polished mirror surfaces for optical beam deflection can be realized. Integrated passive devices can be processed by thin film technology directly on the glass surface. A small pitch of conductor traces, small scale TGV and high alignment accuracy are the key requirements that can be achieved from glass carrier based packaging. Comparing glass with silicon, it is obvious that due to the good isolation behavior of the glass itself no additional isolation processes for TGV are necessary. In order to have an optimal design the dielectric parameters of the substrate material have to be known precisely. They can be extracted, by measuring the S-parameters of planar, resonant structures. Due to the low losses of glass materials the chosen measurement method has to be very sensitive to the Q-factor of the structure.

The thermal conductivity of glass is much less than silicon or some widely used ceramics. Here the material choice causes a problem which needs additional effort to be solved. For instance thermal vias have to be integrated in the interposer or forced convection has to be applied.

Considering these properties glass can be regarded as a very promising substrate material for e/o interposer, modules and sensors. In the following sections some general packaging schemes and suitable technologies are discussed and recent experimental results are presented. Our first approach has been focused on transceiver applications. Thus components like VCSELs and photodiodes were selected for the experimental investigations.

3. System considerations

The thin glass properties summarized above open the chance for more power efficient and higher integrated SiP for optically driven applications. Addressing the need for highly integrated optoelectronic modules for active optical cable and electrical-optical circuit board (EOCB) integrated subsystems, different interconnection schemes are necessary.

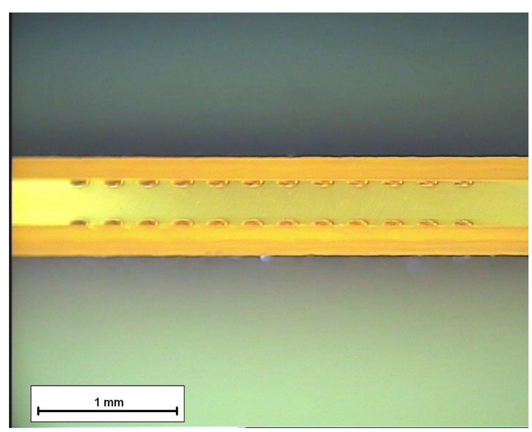

Figure 2: Thin glass foil with double layer optical waveguides made by ion exchange and laminated in between FR4

Figure 2 shows a thin glass sheet with PCB integrated optical waveguides. The waveguide technology is basically the same than for the module integrated ones. In **Figure 3**, three alternatives for transmitter module integration into EOCB are schematically shown. Vice versa, the receiver modules could be depicted respectively. In **Figure 3a,** a glassPack module is sketched without any internal optical beam deflecting element within the interposer. However, ion exchanged graded index lenses can be integrated for vertical beam collimation. The pads for the interposer TGV are redistributed in order to fit to the EOCB pitch. In the stacked concept version shown in **Figure 3b**, the optical and electrical interconnects are separated in two different layers. The top layer is similar to **Figure 3a**, but at the bottom side a glassy optical waveguide element is mounted. Both layers can be assembled using high precision wafer level technology. **Figure 3c** shows the highest degree of integration. The optical waveguides and the beam deflection element are integrated into the interposer to provide horizontal optical interconnects and short vertical electrical TGV gaining very high bandwidth and power efficient performance.

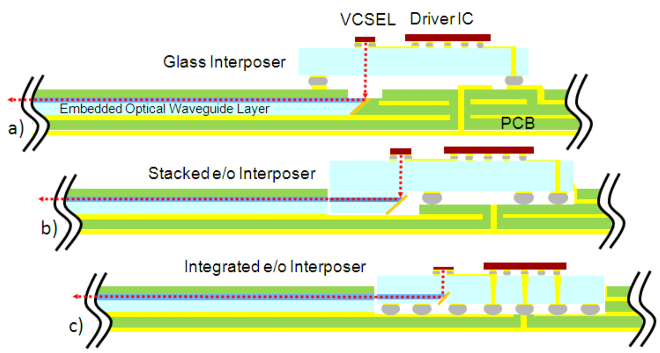

Figure 3: Schematic drawing of 3 different concepts for *glassPack* e/o modules and appropriate PCB integration schemes.

Depending on the system architecture (for example active cable) the optical input/output can also be interconnected using fiber ribbon as shown in **Figure 4** and described in [6] in more detail.

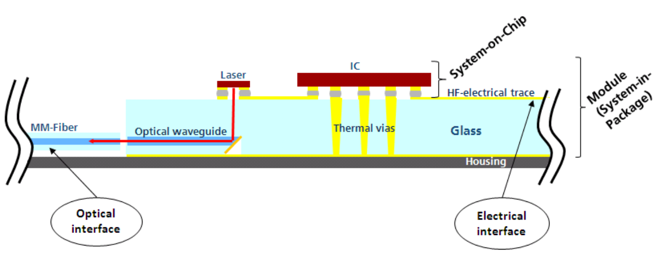

Figure 4: Schematic drawing of fiber ribbon interconnected *glassPack* e/o module

The main features of the concept are:

- Very well suited for high frequency wiring due to dielectric properties and very smooth surface suitable for thin film processing
- Through glass vias (TGV) for very short electrical interconnects from electronic components to optoelectronic Tx and Rx. Due to the very good isolation properties of the glass substrate there are no dielectric loss problems.
- Integration capability to electrical-optical circuit boards (EOCB) and MEMS-Packages. The optical waveguides can be integrated in the thin glass material and can be used within the module as well as within the EOCB to gain high coupling efficiency and low optical attenuation.

The technical implementations of this concept are described below in more detail.

3.1 RF modeling of different transmission line configurations on glass interposer

The dependency of the RF performance of planar transmission line configurations on their geometrical parameters was analyzed to obtain an optimal setup for glass. These line configurations are microstrip, coplanar waveguide, grounded coplanar waveguide and stripline. The geometrical parameters of interest are substrate thickness, h, and metal thickness, t (see **Figure 5**). The analysis was performed using full-wave electromagnetic field simulations in conjunction with closed form transmission line expressions.

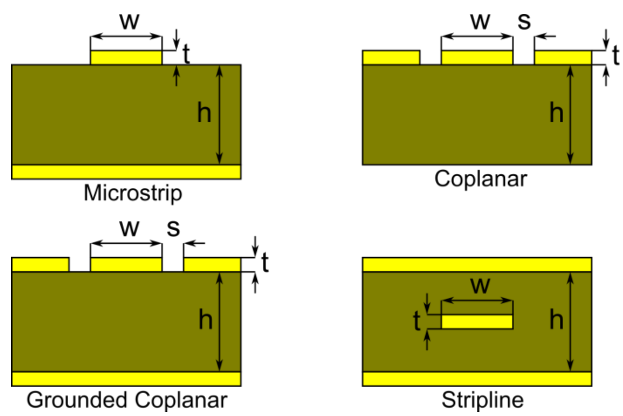

Figure 5: Transmission line configurations

Since glass has very low dielectric loss, the conductor losses dominate the signal transmission behavior. These losses arises from skin and proximity effects. Due to these effects, the resistance of the conductors increases proportionally to the square root of frequency. At higher frequencies, current crowds on the surface of the conductors, thus reducing the effective conductor area. This effect is strongest for both coplanar waveguides.

Since the current crowds on the horizontal signal line surfaces for microstrip and stripline, the metallization thickness, t, only plays a minor role for the conductor loss. But then, for coplanar waveguides, the current concentrates on the vertical surfaces of the signal line. Increasing the metal thickness would decrease the attenuation.

The substrate thickness has a negligible influence on the signal transmission for the coplanar waveguides, since the substrate thickness is usually larger than the slot ,s, between the signal and the reference conductors. For microstrip and stripline the substrate thickness, h, and the strip width, w, depends on each other for a given characteristic impedance. Therefore, the larger the substrate thickness, the larger the strip width has to be, thus reducing the conductor loss. Due to space limitation, only a brief overview of the results obtained from the study of the impact of geometrical parameters on the RF performance of transmission lines is presented here. An in-depth discussion of these results can be found in [7].

3.2 Experimental study of TGV structuring using laser ablation

The challenge for TGV structuring in any substrate is minimizing of the hole diameter. The dry etch technologies usually used for silicon are not fast enough in glass. The size of holes in glass depends on the glass thickness by structuring technologies like laser drilling, powder blasting and wet etching. The aim was to achieve holes having a diameter of 200 microns or smaller in 500 micron thick glass wafers.

For our experiments the glass thickness was fixed to 500 microns to ensure safe handling and to limit the risk of fracture of structured glasses. Each drilling technology has a limit in diameter and shape of the hole. Also, the drilling process can cause cracks and outbreaks on the exits that limit the following processes and reliability of the substrate material. Excepting for laser structuring the results obtained have been regarded unsatisfying for the specifications we are focusing on.

We have investigated fs- and eximer laser drilling in more detail to realize the micro vias without defects such as debris and micro cracks. Since glass has a low thermal conductivity we preferred fs-laser technology. The very short pulses promise a “cold” ablation with direct glass sublimation into the gas phase without too much thermal load on the bulk material around. However the fs-laser requiring some minutes is still quite slow in comparison with excimer laser manufacturing rates of some seconds. So we conducted experiments with both lasers for comparison. The results are depicted in **Figure 6** and **Figure 7**. The layout data are given on top and the measured hole diameters are arrow marked with arrows within the photographs. It can be seen by comparing both figures that the dimensional measures are in good agreement. But the inner surface roughness of the micro vias processed by excimer laser is much higher than by fs-laser processing. Furthermore the surface edges obtained using fs-laser do not show any cracks..

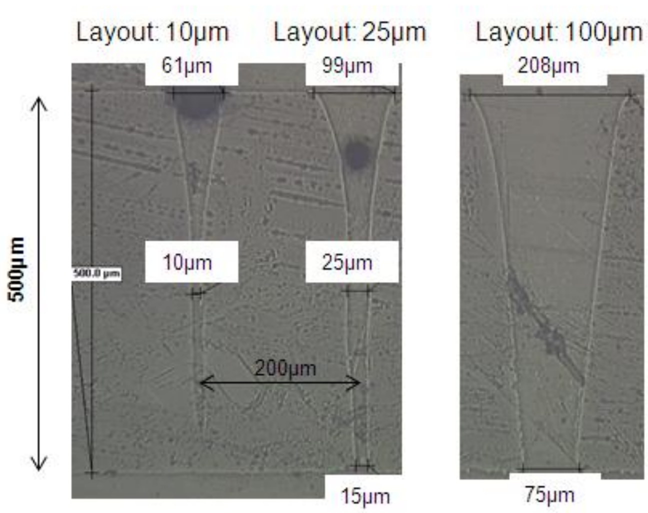

Figure 6: Micrograph of TGV cross section processed using fs-laser. Wafer thickness: 500 µm

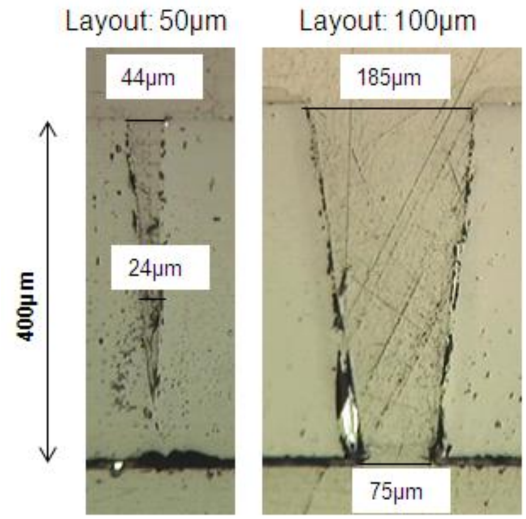

Figure 7: Micrograph of TGV cross section processed using Excimer laser. Wafer thickness: 400 µm

Another issue is the TGV filling with conductive material. We are working on the most suitable technique currently. The smaller the vias are the more challenging becomes the void free filling. So, titanium-tungsten and gold is deposited as plating base. Instead of gold the deposition of copper is possible too, depending on the followed plating process. The deposition of the plating base occurs holohedral at the walls inside the holes. As a result for 200 µm thick vias, uniform metal deposition inside the hole is possible during the plating process. Instead of gold, electro-plating of copper in various thicknesses from 10 to 100 µm in combination with a nickel barrier and finally deposited 100 nm flash gold provides a suitable metallization for soldering and wire bonding [8].

The HermeS™ approach of NEC/Schott using tungsten pins having a diameter of 100 µm that are hermetically sealed in BOROFLOAT®33 glass wafers having a thickness of 500 µm is another very promising TGV solution and is used for the demonstrator package we have realized within these investigations. As a result of using BOROFLOAT®33 for the HermeS™ wafers (see **Table 1**), the waveguide integration into the same layer is not possible. Instead, we benefit from the stacking capability of an optical layer beneath [9,10].

3.3 Circuit patterning using thin film technology

As a major advantage of thin glass substrates they can be patterned using thin film technology. The polished wafer like smooth surface and the excellent dielectric properties of the glass itself are becoming continuously more important in high speed electro-optics for electrical high-frequency wiring. In our investigations we used standard processes successfully as follows: After cleaning and pre-treatment of the thin glass TiW/Au/TiW was sputtered. The layout pattering by means of standard lithography was followed by TiW etching and Au plating. Instead of Au we tried Cu plating as well with good adhesion results on different glass substrate materials.

3.4 Thermal management

As noted above the thermal conductivity of glass is less than for silicon or ceramics. Therefore, even with high efficiency components the removal of heat is an intrinsic challenge for every geometric setup. To get the heat away from for example the driver and VCSEL chips there are three solutions, which can also be employed in parallel. The receiving amplifier has the highest power dissipation, but the VCSEL has a far higher power density, so the VCSEL is usually the most sensitive hot spot.

First, heat spreading has to be considered. To achieve a usable level of heat spreading the top metallization needs to be thick enough and should be designed to leave as much metal as possible under and around the ICs. With suitable heat spreading it is as a second option possible to use thermal vias, either below the large ICs or in a fan-out configuration. This approach has merit, if a thermal sink can be accessed below the mounting area of the glass module.

As a more standard approach a micro heat sink assembly has been demonstrated on top of the flip-chip ICs. This results in very good free convection cooling parameters, but leads to other limitations. The heat sink must be fixed suitably, so as not to put too much stress on the chips and the flip-chip interconnects. Also non-planarity of the assembly and the differing heights of the chips have to be accommodated. Differing layers of thermally conductive foils and paste have been combined to achieve the right trade-off.

The results show, that the thermal behavior has to be carefully designed into the geometries of a GlassPack realization. With full custom TGV (including filled thermal vias) a host of design options will be accessible.

3.5 Optical waveguide integration and optical interconnects

The 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 our *glassPack* concept depicted in **Figure 8**. First the waveguides and lenses are implemented in a planar way. Depending on the application, optical mirrors are integrated for out of plane coupling (**Figure 8b**), resulting in the possibility of 3D optical routing. On the transparent substrate surface, electro-optical devices like VCSELs can be mounted that are optically connected via integrated mirrors to the waveguides as shown in **Figure 8c**. Optical devices or fibers are mounted in front of the waveguide end faces in case of in plane coupling (**Figure 8c**).

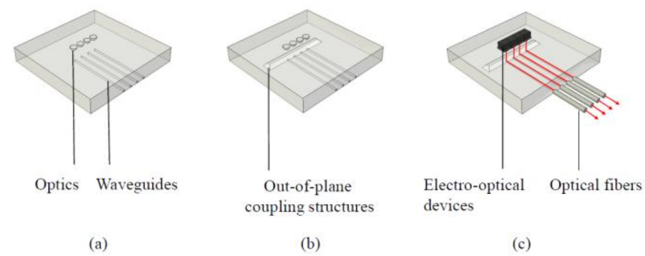

Figure 8: Planar optical integration is possible inside the electrical thin glass substrate as shown in (a). Lenses and waveguides can be realized using ion-exchange technology. Integrated mirror (b) couples light in/out of the plane. Assembled electro-optical components as well as optical fibers or planar waveguide arrays can be interconnected (c).

In our investigations planar integration of optical waveguides below the surface of a thin glass sheet is done by ion-exchange technology [11]. The resulting single- or multi-mode waveguide is characterized by a graded refractive index profile. 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 sheet (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 places 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 [12,13]. The following second thermal ion-exchange in pure sodium nitrate mobilizes 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 waveguaide can be adjusted by the process parameters such as temperature and process time. The resulting index profile of a single-mode waveguide having a propagation loss less than 0.3 dB/cm at 1310 nm wavelength is depicted in **Figure 9**. Also, multi-mode waveguides having losses less than 0.1 dB/cm at 850 nm wavelength were developed and optimized [5].

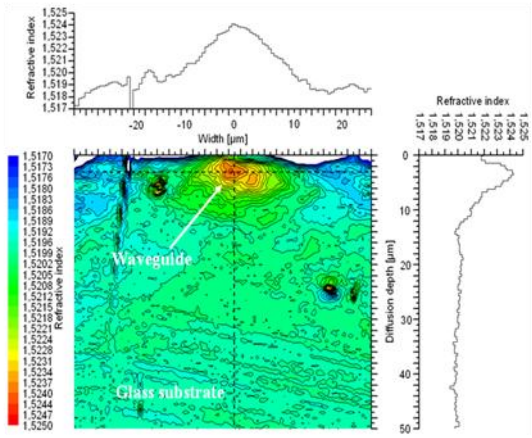

Figure 9: Refractive index profile of a single-mode waveguide in Schott D263T™ glass measured at a wavelength of 1550 nm after a two step thermal ion-exchange in molten salt mixture of sodium and silver nitrate at 350°C.

The introduced silver ion-exchange technology is suitable for optical circuits containing straight or curved waveguides, tapers, splitters, and Mach-Zehnder interferometers (MZI) below the surface of the thin glass sheet [14].

The light coupling between optical circuits and a light source, detector or fiber is realized by polished end faces of the glass sheet. One benefit of using glass sheets is the possibility of direct fusion bonding to silica fibers. The fiber end face is positioned in front of the polished end face of the integrated waveguide (**Figure 8c)**. A CO_2-Laser beam focused on the bonding zone can be used to melt both bond partners above the annealing point and fuses them together [15]. Optical coupling in plane or out of plane is performed by positioning the electro-optical device or fiber in front of the waveguide or using a 45°-polished mirror [16,17].

3.6 Glass stacking

A huge benefit of the presented approach is the possibility of stacking glass sheets having electrical or optical interconnects. On top of the stacked glass layers components are mounted for vertical integration. For example mounted VCSELs can beam through the transparent substrate and couple light into waveguide layers underneath. For interposer purposes the stacking has to be done by soldering and an appropriate ball printing or bumping of the components is crucial. Here the vertical optical interconnects can be designed using glass integrated lenses, lensed e/o components, and optical under filling with certain refractive index or air gaps. In case of directly laminated thin glass sheets a direct bonding technology is desirable to realize hermetic sealing, transparent, and reliable bonds. The surfaces have to be activated before the thin glass sheets are brought in contact and remain joined as result of a very complex phenomenon which involves chemical bonding, static electrical charges, Van-der-Waals forces etc. [8]. For our first complex e/o transceiver we have used adhesive bonding to stack the optical waveguide layer with mirror surfaces directly beneath the electrical HermeS™ layer [6].

3.7 Environmental impact study

A separate aspect from the technical features is an investigation of the environmental properties of optical interconnects and thin glass technologies in particular. Through environmental screening it can be shown that glass has the potential for a green technology solution regarding toxicity of materials used, the total environmental impact of the materials employed and the energy efficiency of the data transmission. Critical points raised in the investigations – as in most new microelectronics concepts – are the use of precious metals (should be minimized for commercialization) and the potentially toxic properties of GaAs in opto-electronic components (which is a characteristic of high speed communication channels, rather than a result of the new glass techniques).

4. Conclusions

We studied the feasibility of thin glass sheets for advanced packaging. We have been focused on optical integration and high frequency properties. By means of simulation models for transmission lines design rules have been derived. Summarizing the experimental results we have obtained glass can be regarded as a suitable substrate material for electrical-optical SiP with the capability to be connected using fiber optical cables. Moreover the thin glass based modules can be integrated in electrical-optical circuit boards (EOCB) targeting higher performance and lower power consumption. Some basic technologies have been investigated like ion exchange, laser via structuring, and thin film technology showing the critical pathways. The remaining challenges we are currently working on are thermal management issues which have to be designed in and the high quality via processing of smaller vias with diameter below 100 µm.

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