Photonic system integration by applying microelectronic packaging approaches using glass substrates

Henning Schröder
Fraunhofer Institute for Reliability and Microintegration
13355 Berlin, Germany
henning.schroeder@izm.fraunhofer.de

Oliver Kirsch
Fraunhofer Institute for Reliability and Microintegration
13355 Berlin, Germany
oliver.kirsch@izm.fraunhofer.de

Daniel Weber
Fraunhofer Institute for Reliability and Microintegration
13355 Berlin, Germany
daniel.weber@izm.fraunhofer.de

Hendrick Thiem
TOPTICA eagleyard
12489 Berlin, Germany
hendrick.thiem@toptica-eagleyard.com

Abstract—Advanced photonic system-in-package (pSiP) technologies are proposed to enhance functionality of photonic packages featuring electrical, thermal and optical components including laser diodes, modulators, isolators, photonic integrated circuits, beam-splitters and micro lenses. We discuss thin glass as a suitable base material for packages made on panel level, precise glass structuring, electrical wiring and the related high precision assembly techniques. In particular, the concept is characterized in detail and proven by realizing the building blocks for a master oscillator power amplifier.

Keywords—photonic system in package, thin glass, panel level packaging, master oscillator power amplifier, micro-optics, assembly

I. INTRODUCTION

Photonic systems have revolutionized the way we communicate, process information, and sense our environment. However, to fully realize the potential of photonic systems, integration of various photonic components and subsystems is necessary. Device performance advances in photonic systems increasingly rely on advances in packaging. Efficient manufacturability and cost are important parameters to be considered as well. In addition, there is a need for heterogeneous and hybrid integration driven by the growing demand for compact multi-functional products like advanced sensors, memory, AR/VR headsets, and IoT devices. Microelectronic packaging approaches have the potential to obviate some of the difficulties associated with traditional packaging technologies and can become an attractive alternative for small-scale integration of components.

In this work, we demonstrate hybrid integrated photonic systems in the size range from centimetre to millimetre focusing on miniaturization, small module integration, and manufacturing utilizing thin glass as a base material. The main challenges associated with the packaging of photonic devices at this scale are related to thermal management due to possible heat dissipation issues on reduced size, alignment of optical components for efficient optical coupling and mismatch of material properties and manufacturing processes.

For many photonic applications miniaturized optical benches have to be protected by transparent (hermetic) housings with integrated optical features like lenses, gratings or fiber feed troughs. To configure such micro-optical benches, glass-like retainers, adapters and posts are structured to not only align various micro-optical or electrical-optical components to the optical axis, but to also include visual and handling features for automated assembly. Especially aspherical or free form optical components often have to be aligned with all six degrees of freedom, often with precisions of less than 500 nm and a few arc seconds.

Fig. 1: Glass-based electro-optical micro-bench for optical spectrum analysis including micro-optics (filters, isolators, lenses), assembled by sequential active alignment with temporary fixing of components using integrated vacuum-channels, and metallization (solderable, and wire-bondable) to include electro-optical and electronic features (EOM, TIA, PIC) [1].

Fig. 1 shows an example of a rather thick and stiff optical bench-like board concept made of glass with housing containing micro-optic, opto-electronic, and electronic components and connectors.

Targeting higher miniaturization, here we present the adoption from a common strategy in micro-electronic packaging to photonics: “photonic Systems-in-Package” (pSiP) introduced firstly by our group for sensor applications [2]. It makes use of featured parts of the housing or vice versa the package itself provides system functions like optical interconnects. Generally, the SiP approach aims at functional electronic system or subsystem that incorporates multiple chips into a single, heterogeneous package. Here, this is demonstrated by establishing a novel, scalable solution for the integration and assembly of laser diode systems based on a glass package providing not only the optical functions but also a higher
stiffness causing higher alignment reliability and coupling efficiency.

Today the most common packages for photonic micro-systems are metallic TO cans and butterfly housings of diverse form factors. But both suffer from high cost and need a lot of space. There is no efficient way to further miniaturization as well as flexible optical, high frequency, and thermal design improvements. Thus, we propose the paradigm shift explained above to more tailored form factors and strategies leaned from chip scale packaging and multi-chip module approaches to overcome the metallic housings in photonics using thin glass (Fig. 2).

Fig. 2: Schematic size comparison of a butterfly package for laser diode, SAC and FAC (left), and a glass based pSiP consisting of the same components and discussed later in this paper as part of a MOPA system (right)

Thin glass has several advantages over other widely used substrate materials, such as silicon and organic materials [3,4]. It offers high structural integrity, resistance to vibration and temperature, environmental ruggedness, and low electrical loss, making them ideal for next generation micro-electronic demands. The specific dielectric properties of glass provide a high integration potential by combining electrical and optical functionalities in a single substrate [5]. Despite being very thin, panels, as well as the machinery to handle and structure them, are continuing to increase in size and decrease in cost driven by the display market. The composition and tempering of glass, to increase its robustness, e.g. in mobile electronic devices, has also progressed remarkably.

Thin glass has been used for many years for new approaches for electrical-optical circuit boards and optical backplanes by embedding it in a EOCB, and integrating the optical waveguides into the glass by using an ion exchange technique [6,7,8,9]. Such glass boards host optical and electrical signal distribution, supplemented by free-space optical elements and transparent windows with or without additional beam shaping optics, hermetically sealed capping and interfaces to optical fiber links. To create such complex systems, photonic design for packaging, advanced glass structuring technologies and electronic packaging have been merged with high-precision assembly. Recent results on substrate level give a good promise to be merged with photonic system in package approaches proposed here for photonic modules. This will conceivably enable 3D photonics systems in packages that can interconnect PICs and electronics with free-space and fiber optical interconnects in a very compact manner.

II. PACKAGING CONCEPT

For the electro-optical micro-bench concept characterized in Fig. 1 we benefit from glass in many regards but persist to traditional optical bench paradigms which suits if space is needed due to optical design constrains or large components to be integrated. But in order to achieve increasing miniaturization and cost reduction goals we started to concentrate on manufacturability on panel level including automated assembly.

The glass features a structured thin metallization that can be electrically bonded allowing the co-packaging of discrete and diverse electronics in the direct vicinity of optical sources or detectors. Component and alignment accuracies are in the 1 to 20 μm range depending on the intended optical performance in free space beams that are split, coupled, combined on the optical substrate. In Fig. 3 the packaging concept is given in more general including fibre pigtail which is not used in the MOPA demonstrator later on.

Fig. 3: Conceptional drawing of a glass based photonic system in package laser module (left) and exposition view (right) with top capping (5), middle frame (4) including fiber optical interconnect (green), and bottom substrate (1). The middle layer cut-out creates clearance for laser on ceramic submount (red), fast- and slow-axis collimation lenses (blue). The formed laser beam passes through an optical grade window created in the package walls.

The main features of the proposed pSiP concept are depicted in Fig. 3: 1.) Commercial display glass is being used on large panel up to 600 mm x 600 mm, 2.) the substrate glass layer on bottom is structured by thin film and galvanic processing as well as laser structuring to provide electrical wiring and through glass vias (TGV) for electrical and thermal interconnect on panel level. 3.) If optical waveguides are needed it can be integrated by ion exchange, 4.) A glassy frame panel of minimal height is structured by laser cutting or selective laser etching (SLE) [10] serving as part of the housing while providing optical windows, fiber feed throughs or other. 5.) The cover glass panel is structured in a similar manner and may have integrated lenses, gratings or coatings. 6.) All panels have features for hermetic sealing (laser soldering, laser welding or adhesive gluing) and 7.) perforation features for simple singulation after assembly and bonding without sawing or laser dicing. 8.) The electrical bottom contacts can be realized by bumping or balling. 9.) The functional components are assembled at panel level using automated active or passive alignment for the optical and optoelectronic components, and electronic bonding (wire and flip chip bonding). 10.) After panel level sealing of all of the at least 3 layers (substrate, frame, cover) 11.) The completely packaged modules are singulated by breaking along the perforation features.
design software. It is easy to change footprints as well as routing, obstacles to fabricate edge-emitting pSiP as depicted in Fig. 4. In the following we discuss the technology steps to realize this concept to enable more complex systems by dedicated interface standardization in the future.

A. Package design

Chip scale packaging of edge-emitting devices is not yet as widely adopted as surface-emitting lasers as it is for surface emitting components, since prior configurations require additional features due to the high divergence and better optical characteristics of the laser radiation coming from the cavity. Novel manufacturing techniques such as selective laser-induced etching (SLE) and laser micro-welding combined with advanced design techniques are used to overcome these obstacles to fabricate edge-emitting pSiP as depicted in Fig. 4 schematically in cross-section. The package is adaptable in a way that all features are implemented using state of the art PCB design software. It is easy to change footprints as well as routing, while having design rules in place to reflect technological limitations. Machine specific CAM-layouts are then derived from those designs for short implementation cycles.

B. Glass structuring

Cutting-edge state-of-the-art glass processing technology is crucial to enable customized pSiP solutions on panel formats. In our industrial laser cutting machine for display glass structuring, the green laser light (532 nm) with ns-pulses is used. The thermal stress induced in the glass by the laser is a limiting factor for the package footprint and the fill factor of the panel (which can be seen in Fig. 7). This is due to micro cracks caused by the thermal processing as well as the large edge lengths of the panels of up to > 300 mm compared to the low thickness of the glass layers of 500 to 700 μm used for this package. The panel fill factor decreases further in this instance optical windows are generated by a laser induced “scribe and break” process (Fig. 10). Overall, 75% of the panel is excess material and is needed to ensure sufficient panel integrity and therefore acceptable yield. Structural integrity is needed since bending forces need to be applied on the packages to remove them from the panel structure by breaking them away in a controlled manner and generating the outer optical facet. With those requirements, the relatively low fill factor doesn’t matter as glass is a low-cost material. Furthermore, there is room for improvement by optimizing the laser cutting processes in the future. But advantageously, this approach allowed us to eliminate the need for any post processing in order to achieve optical grade surface roughness and flatness of the optical window in the middle frame while singulation the package from the panel. The flatness of the facet was simply improved optimising the scribe and break process by more than 2 orders of magnitude in critical areas, where the optical power is transmitted (Fig. 5). The radius of curvature of the critical area between 100 and 450 μm calculates to ~30 centimetres, which will have insignificant influence on the collimation of the beam, when close to the laser diode. Subsequently, the metallization layer is lithographically patterned to produce electrical conductors, pads, vias, micro-weld structures, and other functional features (see Fig. 4).

In previous works, through-glass-vias (TGV) has been deployed for vertical DC and RF interconnections due to the superior electrical properties of glass [11,12]. A frequently mentioned drawback of using glass in assemblies is the low thermal conductivity, which can pose a big challenge in higher power applications with critical thermal management. Recently, this disadvantage was tackled by using localized arrays of copper fully filled TGVs [13]. In this work, large via diameter TGV were filled with conductive paste by screen printing and afterwards thermally cured. For vias shapes such as hour glass or conical drills as shown in Fig. 6, it is best to use a combination of sputtering and galvanization processes to ensure a complete, hermetic filling of the vias with solid metal. The utilization of the SLE process is key in achieving those geometries.

Many different manufacturing technologies have been developed over the last couple of years for the formation of TGVs [14]. Among them SLE have turned out to be the preferred choice for keeping processing time low while
maintaining quality and yield. Furthermore, in the meantime SLE reaching a high level of technological readiness and being integrated into the well-developed process chains of PCB manufacturing, opportunities for more sophisticated and even smaller formats are emerging. SLE is a two-step process consisting of selective modification of the glass matrix (minimal voxel size $\sim 1 \text{μm}^3$) with an ultrashort pulse laser (USPL) focused into the bulk material. In this way, the desired final structure is written into the glass. To develop the structure, the glass batches are placed into a potassium hydroxide or hydrofluoric acid etch bath for several hours.

Fig. 6: Micro drill generated by SLE process in borosilicat glass, with selectivity of $\sim$50:1

Depending on the selected glass as well as laser parameters [10] the etch rate in the previously exposed glass regions is significantly higher than the bulk material allowing for small holes with high aspect ratios and nearly perfect vertical features, as well as an high degree of design flexibility.

C. Assembly

After that the components (opto-electronics, micro-optics) are assembled on the bottom substrate using industrial automated micro-assembly equipment on panel level. By this way, semiconductor lasers on sub-mount are mounted to the panel. Later, micro lenses are assembled by probing the lasers on the panel and using active alignment. Since FAC-lenses are usually located in immediate proximity to the semiconductor laser they need to be enclosed in the packages (Fig. 4). SAC lenses, however, are not limited to being inside the package, even though this has been demonstrated in this way (see Fig. 7). There are considerations that suggest that moving the SAC lens out of the package has both cost benefits (reduce package footprint) and performance advantages depending on the type of application.

Fig. 7: Automated assembly of small (9x9x1.7) mm$^3$ laser packages with appropriate lenses and optical edge windows on panel-level prior to stacking, hermetic sealing, and subsequent laser-based singulation.

Depending on the required components in the final package (tolerances, design) the assembly may become the most challenging and costly part in terms of time and yield. Thus, since the machine layout its derived from requirements for automated and active alignment of those pSiP the assembly strategy (sequence, adhesive glues, solder etc.) needs to be considered carefully in advance when designing the package (“Design for Packaging”).

D. Layer stacking and sealing

After assembling of all lasers on panel level, the packages are finally sealed. This is done by simply stacking of the bottom substrate, middle frame and capping layers. Guide pins allow for quick and precise registering. The layers are then welded by using the metallic absorption structures for the IR - laser radiation. By choosing suitable process parameters (see Fig. 8) we are able to form different types of bonds. Thus, it is possible to achieve a permanent bond between two metallic absorption structures on the glass layers (see Fig. 9 top). This process is mostly stress free and causes no harm to the borosilicate Glass. By increasing the energy density of the process, the metal layers dissolve into the glass matrix and a, alternatively, glass-glass bond is formed instead. The welds have a minimum width of 40 μm and are formed within fractions of a second. Shear testing of these joints shows a higher yield strength of the metallic bonds, close to the values of bulk metals (Sn in this case).

Fig. 8: Diagram of laser-welded samples under shear test. Shown is the formation regimes of various bonds in the interface between the glass layers. The minimum achievable energy density in these experiments was $\sim 4.77 \text{J/mm}^2$ limited by the minimum output power of the laser as well as the maximum laser scanning speed. The dip in shear strength around 7 J/mm$^2$ represents the transition between metallic and glass bond, where the metallization begins to dissolve into the glass matrix.

While the strength of glass is actually higher than those of any metal, glass is also more brittle. The values shown in Fig. 8 can be considered competitive when compared to ultra-short pulse welded glass samples as explored in [15]. However, as a result of the higher power density the glass is exposed to much higher temperatures during the process. This will result in residual strain within the glass matrix once temperature has dissipated which will often cause micro cracks (see Fig. 9 bottom). In turn those microcracks reduce glass yield strength and if long and numerous enough will make the package non-hermetic. Tempering is not an option for us to apply here, since components, especially adhesives used for the assembly of micro-optics inside the package, will not withstand temperatures above 100 °C over an extended period of time.

The interconnection technology described above is advantageous in a way that there is no interference of the welding process with the internally assembled components.
Since the assembly of the FAC lens is done with UV-curable adhesive and is optimized for minimal post bond shrinkage it is unfavourable to expose the bond to elevated temperatures from a reflow process or similar thermal procedure.

Fig. 9: SEM images of cross sections of different micro-weld types as a result of welding energy (and geometry). Topmost SEM image shows a pure metallic (brighter areas on all images) joint, while the bottom image shows a joint where the metallic layer is dissolved in the glass (darker areas in all images), thus forming a very characteristic eye-shaped direct glass-glass bond. The bottom image also shows the cracks caused by the residual stress after cooling of the sample.

E. Singulation

The ability to singulate the pSiP from the panel is realized by innovative perforation approach in combination with the micro-welding of the individual layers into a more rigid stack (see Fig. 10). As bending resistance increases with thickness in a cubic manner, it allows precise confinement of the bending stress into the separation area previously defined by design and introduced by mechanical stress into the glass with CO2-laser scribing. Using this approach the optical window is protected by the additional layers of glass connected to the middle layer. Otherwise, double-sided breaking of a < 2 mm thick optical window would not be possible at all. The setup furthermore improves the flatness of the window, as already shown and discussed in Fig. 4.

Fig. 10: Schematic cross-section drawing of a pSiP focusing on the mechanical principle of the self supported scribe and break process, see for reference Fig. 4

Based on the glass technology presented here, pSiP have already been successfully implemented. Fig. 11 shows the schematic layout of a glass-based pSiP for a collimated DFB laser diode including SAC and FAC.

IV. FUNCTIONAL TEST

As shown in Fig. 12 the optical output power depending on the injection current was measured. An optical output power of more than 100 mW could be achieved at temperatures between 15°C and 35°C (measured near the thermally stabilized laser chip). The heat loss was effectively dissipated through the bottom layer with thermal vias. The thermal resistance of the pSiP was found to be 1.0 K/W, which is comparable to the conventional butterfly assembly of 0.9 K/W.

Fig. 12: LIV-curve of a DFB-laser at 852 nm operating wavelength in a pSiP glass package. The temperature of the laser was varied between 15°C and 35°C. The seed laser shows the desirable linear powerslope event at elevated temperatures.

Fig. 13: Optical Micrograph of tapered power amplifier pSiP, due to the more complex optical coupling of the gain chip (1) the footprint is approximately twice the size of the seed-pSiP. There ist a “symmetric” configuration of fast-axis-collimators (2) as well as slow-axis collimators to couple in and out of the
chip. An additional requirement for this package is two optical windows (4) at the opposite sides of the package, which have been realized.

To realize higher optical power a tapered amplifier was used at for the same wavelength of 852 nm to build the miniature MOPA. The use of semiconductor amplifiers with a tapered design offers the advantage of a high amplification of the optical power with nearly diffraction limited beam quality at the same time. Thus, the frequency stability of a so-called seed laser (here a DFB laser) with low output power is amplified to several watts.

The amplifier chip was first soldered to a CuW submount for optimal heat spreading, and then soldered to the bottom layer of the pSiP package. Collimating lenses were mounted on both sides to optically couple the laser light in and out. The setup is shown in Fig. 13. The results demonstrate a good usability of such pSiP at small and medium optical output powers up to 500 mW. However, the optical amplifier must be collimated in seed mode due to their strongly astigmatic radiation characteristics. Though, this is currently not possible at panel level. For lens mounting at the output, the amplifier pSiP must be isolated from the panel and collimated separately in seed mode. This indicates the limitations of the panel process shown here. Mixed panels with seed and gain- pSiP in tandem would be able to overcome that limitation.

For optical output powers in the range of several watts and thus high thermal power dissipation, high performance diamond sub-mounts such as CVD and special copper alloys such as CuW are commonly used [16]. For small and medium power dissipation or in QCW operation, glass-based pSiP offer some advantages. In the field of quantum technology, e.g. atomic and molecular optical clocks smaller, more compact and more reliable laser components are needed [17]. In this context, the requirements for the laser increase very strongly.

In order to obtain a very narrow linewidth, the lasers have to be additionally stabilized by external cavities [18]. The modularity of glass-based packages offers numerous possibilities for this. Gas cells, external gratings or photodiodes can be packed into the same or additional sub- pSiP and coupled to the seed-pSiP as desired. The possibility to couple and decouple the laser light in almost all spatial directions allows a very high variability on system level.

The development of photonic integrated circuits (PIC) allows the realization of complex laser properties such as frequency combs [19]. Here, substrates made of silicon nitride or even glass are already used for waveguides and are thus ideal for packaging as pSiP. Especially the connection to further electrical circuits is much easier to realize with a glass-based package than with a conventional butterfly package. These can be effectively amplified to high optical powers using the popular MOPA configuration. The pSiP shown here in Fig. 13 can then be used as the optical amplifier. The pSiP package can be shrunk to the minimum necessary size, so that at most only the required fast-axis lens is integrated. Other components such as thermoelectric coolers, ceramics, optical bench, photodiodes, additional lenses and fibres are then integrated outside the hermetic (dry) pSiP on subsystems.

V. DISCUSSION

From this work, we were able to show that the pSiP approach based on laser-structured and stacked thin-glass layers can meet key requirements needed for the integration of hybrid photonic systems. Taking the example of the integration of semiconductor lasers demonstrated here, this was validated by several means. The most important feature in packaging such lasers is the thermal management, which is especially critical for pump lasers with high performance demands. Through careful consideration of the methods and tools, as well as proper process development of the integration and thermal concept based on metallized vias, a thermal resistance of 1 K/W which is comparable to conventional butterfly assemblies (0.9 K/W) was achieved. The overall pSiP design based on thin glass allows for high mechanical stability to protect the photonic system from mechanical stress and vibration that could cause failure or performance degradation. No impairment or change in optical performance was observed in the assemblies shown, generally ensuring optical features such as a narrow linewidth. When it comes to the optical alignment of components inside the package, the packaging should provide a mechanism for adjusting the alignment to accommodate manufacturing tolerances. This must be considered during the development of the packaging, as well as the requirements for automatic and active alignment based on the given machine layout.

While enabling the miniaturization of integrated laser packages with our glass-based pSiP approach, the low material and processing cost of glass make it the superior choice to
conventional butterfly packages based on costly materials such as CuW, Kovar, or CuMo. using a complete process flow on panel-level allows for a high degree of scalability and thus for cost effective manufacturing. Electrical connection to laser can be directly integrated on the glass substrate with low electrical noise and minimal parasitic capacitance. Stacking of laser structured thin glass has much potential for cost-effective further development: The assemblies as introduced here can be hermetically sealed with glass frames and lids, creating compartments with optical windows and ensuring protection of the laser from moisture and other contaminants. Future fiber-pigtailed packages, as shown in Fig. 3, would allow easy coupling to optical fibres while reducing the insertion losses. The concept is scalable to multi-fibre-termination without any limitation. This is achieved by the novel self-supported scribe and break process, which allows for high flatness and low roughness optical windows below λ/20 which is considered a critical threshold in optical applications. In addition, microfluidic channels could be integrated into the thin glass substrate using SLE to make the pSiP package attractive for further applications in the field of sensor technologies as well as to test new thermal concepts based on fluidic cooling combined with thermal vias instead of the current approach in butterfly packages using a thermistor and TEC.

As an aside, this concept can be varied in several ways, for example we have demonstrated electrically interconnected glass layers with PCB (Fig. 15). Other materials such as ceramics and silicon are also possible joining partners for glass.

Fig. 15: 20 mm x 20 mm sized package consisting of a PCB base layer and multiple glass layers. The layers and electrical interconnects are joined by the laser welding technique formally described. Electrical and optical components are arranged in two superimposed cavities within the package. Further component layers can be added if required. The package compartments enclose (1) SMT resistors and capacitors (1210), a (2) SOP 8 Package and (3) VCSEL Diode. Components are connected by (4) metal traces which are interconnected to components on other layers by (5) vias in the glass frame.

**SUMMARY**

Advanced photonic system-in-package (pSiP) have been introduced to miniaturize and to enhance functionality of glass-based packages featuring electrical, thermal and optical components. Thin glass is a suitable base material for packages made on panel level, enabled by precise glass structuring, electrical wiring, and the related high precision automated assembly techniques. The concept has been validated by realizing the building blocks for a master oscillator power amplifier. Such glass-based packages can be made either from display glass layers on large panels or more mini-bench-like on larger scale. Optical free-space and fiber interconnects, plugs, and electrical-optical integration platforms can be used for higher level system integration.

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