Stereolithographic printed polymers on ceramic for 3D-opto-MID

Lorenz, Lukas, Ackstaller, Thomas, Bock, Karlheinz
Stereolithographic Printed Polymers on Ceramic for 3D-Opto-MID

Lukas Lorenz*,a, Thomas Ackstaller*, Karlheinz Bocka
aInstitute of Electronic Packaging Technology, Technische Universität Dresden, 01069 Dresden, Germany;

ABSTRACT

The combination of hybrid interconnection technology on ceramic as a carrier for the RF-electronics with excellent heat management and stereolithographic printing for 3D structures is a novel approach to achieve 3D-Opto-MID parts and, furthermore, to include mechanical properties. By directly printing polymers onto aluminum-oxide substrate (including an electrical circuit), brings together the advantages of both technologies. Using additive manufacturing makes this process suitable for small- to mid-scale productions with a very high design freedom.

To analyze the adhesion between Al₂O₃ substrate and printed polymers, we compare six different resins according to the minimal structure length and the adhesion on the substrate. A longer exposure time of the first layer (burn-in time) leads to sufficient adhesion of the print on the ceramic substrate. To realize smaller adherent structures, longer burn-in times are needed. In a shear test, the forces to lift off the prints from the substrate are measured. The experiments reveal correlation between shear force and contact area with little variance. Based on this evaluation, choosing materials for future applications is easier and design rules can be determined.

Furthermore, we present the application of flexible optical waveguides onto the 3D substrate (which will be directly printed in the future), as well as the passive alignment of laser and photodiode in this article. In a first test, we were able to prove the functionality of the 3D-Opto-MID package by launching the waveguide with the applied laser and measuring the current at the photodiode.

Keywords: additive manufacturing, 3D-packaging, stereolithography, 3D-MID, optical bus coupling, ceramic polymer hybrid package

1. INTRODUCTION

1.1 Current development in additive manufacturing and 3D-MID

The fourth industrial revolution, or Industry 4.0, is seen as a major step towards intelligent automation technology and drives the integration of intelligent production systems and information technology. Additive manufacturing is an important part of this turnaround, as it enables the necessary individualization of products and technologies. The resulting new materials and material combinations thus also offer new options for electrical engineering, such as printing circuits on 3D objects. Hence, by the 2030s, the variety of 3D printable products is expected to grow rapidly through multi-material printing and electronics integration [1].

Design- and function-oriented manufacturing means more cost-intensive tools and processes for conventional technologies such as injection molding. Additive manufacturing leads to almost unlimited design possibilities. Since no tools such as injection molds have to be manufactured, the development time is significantly reduced. This makes additive manufacturing not only suitable for fast product development, but also for the manufacturing of complex or individualized products in small to medium series production [2]. Also for mass production, additive manufacturing has a significant impact. Compared to the traditional production of a flex circuit laminated to an injection-molded volume, additive manufacturing can reduce the time from design to the first product by 75% in the example presented by Macdonald et al. [3].

The state-of-the-art technology for 3D electronics is – according to the new definition [4] – the 3D mechatronic integrated device (3D-MID) fabricated by injection molding (IM). For this purpose, thermoplastic materials are used. On this three-dimensional substrate, a laser most often structures the electric circuit after powder-coating [5]. Another approach is the additive manufacturing of substrates by fused deposition molding (FDM) or stereo lithography (SL) and inkjet or aerosol
jet printing for the electric circuit [6, 7, 8]. All of these approaches have a major disadvantage. The heat dissipation of the plastic substrate is not suitable for high power electronics or optical components, which need a stable temperature (e.g., lasers). The latter one is especially important for the work presented in this paper. A ceramic filler with up to 50% by volume can increase the thermal conductivity of polymers for injection molding or printing five to six times [9]. However, compared to ceramic substrates, it is still an order of magnitude smaller (24.0 W m⁻¹K⁻¹ [10] compared to 0.3...4.3 W m⁻¹K⁻¹ [11]). Furthermore, for injection molding a specially designed tool is necessary for the molding, which leads to high initial costs. Hence, injection molding is not suitable for prototypes, small series production or applications, which need individualized devices.

To overcome the heat management drawback, it is also possible to manufacture full ceramic substrates additively by stereolithography with high resolutions [12]. However, common defects of this production method are visible and invisible delamination, poor layer bonding and assembly errors, and even complete destruction of the component when it is detached from the printing platform, because safe cross-linking is not always guaranteed. The thermal reduction of the organic components and subsequent sintering takes up to two days. Furthermore, these assemblies often have pores and delaminated layers. Hence, this technology is still in an early state and not suitable for 3D-MID. [13, 14]

In this paper, we want to combine the flexibility of additively manufactured polymers with the excellent electrical and thermal properties of ceramic thick film technology to create a three-dimensional package for an optical waveguide application. The approach for this 3D-Opto-MID is presented in the next sub-chapter. After that, we briefly introduce the fundamentals of stereolithographic printing followed by the development of our manufacturing approach. Finally, we describe the assembly and testing of the prototype and conclude the results.

### 1.2 Approach for an 3D-Opto-MID assembly

The demand for 3D-Opto-MID emerges from new coupling principles for optical bus-systems. The asymmetric optical bus coupler (AOBC) allows for coupling – without interrupting the optical waveguides – by connecting the two coupling partners at the side faces of the core, as it is depicted in Figure 1 [15]. Crucial for the usability of such a coupling approach in optical bus-systems, are asymmetric coupling ratios depending on the coupling direction. Because of a defined bending of one of the coupling partners, we are able to achieve a higher coupling ratio from the bent waveguide (module or sensor) to the straight one (bus) than in the opposite direction, which we call asymmetric coupling [16]. Hence, the power level in the bus stays high enough for the coupling of several modules. To implement such an approach into a device, it is necessary to create a three-dimensional substrate to achieve the bending of the waveguide. Furthermore, we have to implement lasers and photodiodes onto the same substrate. According to that, the goal of our work is the development of a 3D-Opto-MID package for an AOBC.

![Figure 1. Asymmetric optical bus coupling at the side face of the waveguide core in the experimental setup (left) and the schematic of two coupled waveguide cores with the coupling area A and the displayed energy distribution within the core (right)](image)

The main idea of the presented work is the use of a ceramic Al₂O₃ substrate with the electrical circuit in combination with a stereolithographic printed structure for the optical waveguide, as well as for the mechanical alignment and fixing structures. Figure 2 shows a CAD model of the proposed 3D-Opto-MID. While the bus waveguide can be mounted on any
substrate or structure, the module with the defined bending needs to be a three-dimensional interconnect device. Hence, our work concentrates on the realization of the module. The fabrication steps are as follows:

1. The ceramic is perforated with a laser, so the single devices can be separated from the panel after the complete packaging process is completed. Therefore, the presented approach is a panel-level process.
2. The electric circuit is manufactured by standard thick-film technology. Even the components can be assembled because an embedding into the SL printed structure is possible.
3. With the SL printing, the three-dimensional structure is directly manufactured on the substrate. In an optional step, it is also possible to fabricate some electrical wiring onto the 3D polymer by inkjet or aerosol jet printing.
4. By the use of aerosol jet printing, the waveguides are printed onto the polymer and directly coupled to the electro optical converters.

In this article, we use waveguides on foil substrates manufactured by photolithography instead of printed ones, because the printing of optical waveguides onto 3D substrates is in a very early state and only confirmed for flat surfaces [17]. According to that, the electro optical (e/o) converters are mounted after the waveguide to visually align them to the core.

![Figure 2. CAD model of the 3D-Opto-MID approach for an asymmetric optical bus coupler](image)

**2. STEREOLITHOGRAPHIC PRINTING**

Additive manufacturing is the layered construction of a component from a material that is provided in different forms, depending on the process. The CAD software provides a 3D model, which is then converted into a Standard Triangulation Language (STL) model. When creating the STL file, the surface of the CAD model is divided into triangles. The printing driver then slices the model into layers for the individual printing steps [2].

In the printing process used in this article, the component hangs upside down on a build platform, which is drawn out of the resin bath after each step by the amount of one layer thickness. A UV projector – placed under the resin tank, which has a transparent bottom – exposes the layer. The printer (asiga PICO HD27) has a flexible Teflon foil under the tank. Before each exposure, the slider levels this film to obtain a precisely defined layer thickness. The manufacturer specifies tolerances of 1μm in z-direction and 27μm in x- and y-direction [18]. After the printing process, the component is cleaned of resin residues with a solvent and exposed to strong UV radiation for approx. 15 minutes to cure completely. Figure 3 shows the schematic of the used 3D printer.

For this work, a vacuum holder for ceramic substrates replaces the base plate of the SL printer. Substrates of Al₂O₃ with a thickness of 600μm were placed on the holder and vacuum was applied. These ceramics have a grinded surface and are used as standard substrates in thick film technology. Before printing, they were cleaned with isopropanol to avoid poor adhesion due to contamination. For the post-processing, an ozone generator (novascan PSD PRO-UV) generates the UV radiation for curing.
3. DEVELOPMENT OF THE 3D-PRINTING PROCESS

3.1 Materials for the 3D-Printing

For the proposed coupling approach, we want to use two different materials: A rigid one for the bus and a more flexible one for the module. This is necessary to avoid damages on the waveguide surface because of the coupling pressure. From a selection of five different resins for SL printing, which are shown in Table 1, the most suitable ones have to be chosen.

![Schematic of a stereolithographic printer](image)

Table 1. Overview of the used polymers

<table>
<thead>
<tr>
<th>Material name</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible resins</td>
<td></td>
</tr>
<tr>
<td>Formlabs Flexible FLG01</td>
<td>GR1</td>
</tr>
<tr>
<td>Formlabs Flexible FLG02</td>
<td>GR2</td>
</tr>
<tr>
<td>Rigid resins</td>
<td></td>
</tr>
<tr>
<td>Formlabs Black FLG02</td>
<td>BK</td>
</tr>
<tr>
<td>Formlabs Clear FLG02</td>
<td>CL</td>
</tr>
<tr>
<td>Formlabs High Temp</td>
<td>HT</td>
</tr>
</tbody>
</table>

3.2 Printing size limits

Important for the construction of micromechanical structures and the embedding of components, is the achievable resolution of the print beginning with the first layer. The printer does not reach the resolution of 27µm in these layers. We assume that the structures require a minimum size to adhere on the substrate. An experiment confirmed this assumption. For that, squares with different edge lengths from 0.2 mm to 2.0 mm were printed.

Subsequently, the smallest, still adherent structures are measured, as it is depicted in Figure 4. It is clearly visible that longer burn-in times lead to smaller structures still adhering. For the resins, an asymptotically achieved, minimal structure size can be determined, which would not be further reduced even with a longer exposure. From this point on, the resin is completely cross-linked at the contact point, which is why the maximum adhesive force is reached. In the case of structures with smaller dimensions, this force is not sufficient to withstand mechanical stress in the printing process and they do not adhere. This effect has been observed for all resins equally. With the measured data (22 different lengths with eight samples each), we were able to determine the smallest possible edge length with a 95% certainty with the student’s t-distribution, which are shown in Table 2.

For the manufacturing of the 3D-Opto-MID, these results define a design rule, i.e. only structures with a footprint bigger than the determined ones are acceptable. However, the resolution of structures printed after the burn-in-layers are unaffected by this. Hence, structures, e.g. for alignment, can be printed with an accuracy of 27µm (x and y) and 1µm (z).
Figure 4. Comparison of the smallest possible edge length of a printed square (average) related to the burn-in time for different resins; Because of different material properties, every resin has a specific range for the burn-in time.

Table 2. Smallest possible square-edge length for the resins on ceramic substrates, which is reached with 95% certainty

<table>
<thead>
<tr>
<th>Resin</th>
<th>Minimal edge length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR1</td>
<td>0.41</td>
</tr>
<tr>
<td>GR2</td>
<td>0.52</td>
</tr>
<tr>
<td>BK</td>
<td>0.28</td>
</tr>
<tr>
<td>CL</td>
<td>0.33</td>
</tr>
<tr>
<td>HT</td>
<td>0.19</td>
</tr>
</tbody>
</table>

3.3 Adhesion results

Besides the printing size limits, the adhesive strength of the printed structures is crucial for the realization of a 3D-Opto-MID. As a relative indicator for the adhesive strength of printed structures, the force required to completely detach the structures from the substrate is measured. For this purpose, we print and cure cubes with different edge lengths and contact areas for each resin. After that, a shear tester (XYZtec Condor Sigma) shear these blocks off the ceramic to determine the adhesive force.

Shear load (force tangential to the reference plane) and shear stress are linearly proportional to each other in an ideally elastic object. For most real materials, this applies only to a small range, after which plastic deformation occurs and energy is absorbed in the structure. In the test performed in this case, the shear chisel starts at a height of about 100µm and generates a force on the block, which is not evenly distributed. This leads to a deformation of the test sample and a distribution of the force. Therefore, it cannot be called shear stress, but only the applied force in relation to the adherent surface of the test sample.

For every resin, we measured the force for cubes with different footprints, i.e. adherent surface on the ceramic substrate. The results are depicted in Figure 5. As expected, larger footprints lead to larger shear forces. The variation for larger footprints results from the force redistribution and deformation effects in the material, as described above. Lower adhesion values were observed for flexible polymers. Furthermore, we measured a flattening of the curve towards smaller footprints. This results from overexposure of the resin and the resulting formation of menisci, which changes the size of the footprint [19]. This enlargement of the area has a greater effect in percentage terms on small areas, thus, distorting the results. A variation of the burn-in-time, however, has no effect on the shear force.

Since flexible polymers have different mechanical properties, an additional dynamic mechanical analysis (DMA) [20] was carried out for GR1 and GR2. The DMA result revealed a higher storage modulus of 250 MPa for GR2 at 20°C compared to 180 MPa for GR1. Therefore, GR2 is preferred for the AOBC and used for further manufacturing steps, since the assembly is under mechanical stress during coupling. For the AOBC bus, we choose BK because of its better adhesion to the substrate.
4. ASSEMBLY AND TESTING OF THE PROTOTYPE

4.1 Waveguide and e/o converter assembly

Now that SL printing on ceramic substrates has been successfully developed, this technology is available for building a 3D-Opto-MID prototype. In this article, we focus on the module, while the fabrication of the bus, as well as the coupling of both partners will be presented in further works. As mentioned earlier, photolithographic waveguides on a foil substrate are used for the assembly in this work, as it is depicted in Figure 6. Furthermore, we use edge active electro optical converters to avoid additional beam shaping elements or mirrors (Fraunhofer HHI DFB 1346nm laser and Kyosemi KPEIMC-100). They are directly butt-coupled to the waveguides end facet. After printing the three-dimensional shape onto the ceramic, the waveguide is mounted on the substrate. For that, we used the adhesive Vitralit UV 2113, because of its low shrinkage and the high bond strength. The waveguides are aligned to mechanical structures on the printed part of the 3D-Opto-MID. Subsequently, laser and photodiode are placed using Vitralit 1605, an index matched adhesive. A chip bonder (Fineplacer Lamda) does the alignment to the waveguides visually, as it is shown in Figure 7.
4.2 First test results

After the assembly of the module, as it is depicted in Figure 8, we tested the prototypes with a needleprober (Microtech PM8). A constant current source (Keithley Source Meter 2400) at 3.0 V and 20.0 mA launches the laser. At the photodiode, a current of 0.7 µA is obtained (compared to 0.0 µA dark current). Because the printed waveform separates the two e/o converters, no direct coupling of both devices is possible. Hence, we are able to prove the functionality of the module assembly by this experiment.

5. CONCLUSION

In this paper, a new production process for 3D circuit carriers was introduced with direct SL printing on ceramic substrates. The technology works reliably with the identified parameters. The process can be used for the realization of mechanical functional 3D structures as well as for the encapsulation of chips and circuits. In a first application of the new process, a 3D-Opto-MID assembly was successfully manufactured and tested. By combining ceramic substrates with additive manufacturing, the electrical circuit can benefit from the advantages of conventional thick-film technology, while the printed structure assembly can fulfill mechanical functions.
In future works, the electrical circuit including laser driver and photodiode amplifier need to be implemented. Furthermore, the coupling of bus- and module assembly needs to be tested especially in terms of repeatability and long-term stability. With a matured technology for aerosol jet printed waveguides, directly printed optical paths can replace the flexible substrates.

ACKNOWLEDGEMENT

The authors would like to thank the “Deutsche Forschungsgemeinschaft (DFG)” for funding the research group and therefore providing the opportunity of doing fundamental progress in this seminal field of technology. The authors are wholly responsible for this publication. This work was supported in the Research Group OPTAVER (BO 3438/4-1; AOBJ: 648318).

REFERENCES


