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Hermetic Glass Soldered Micro-Packages for a Vision Prosthesis

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Abstract—**Micro-packages based on alumina ceramics hermetically sealed with glass solder were fabricated and tested over a 1.5 years period under accelerated aging at 85 °C. A device for sealing the 1.2 mm high, and ø10mm packages while cooling the critical centre of the package containing the electronics was developed. Heating of the rim up to 550 °C while maintaining the package centre below 300°C was successful, allowing a symmetrical heating of the device during the sealing procedure. The fabricated packages with an inner volume of 0.05 cc were backfilled with helium and tested for hermeticity with a fine leak tester. Samples passing the fine leak ($1 \bullet 10^{-12}$ atm•cc/s) test were attached to a larger chamber containing a humidity sensor. Some devices covered in PDMS and some directly exposed were stored at 85 °C in water to measure the humidity intrusion into the device due to deterioration of glass solder. 1 out of the 8 successfully fabricated devices failed after 5 years extrapolated lifetime. Two of the devices have kept constant humidity levels while others gradually rise. Nevertheless, 7 out of 8 have maintained a level below 17000 ppm humidity. Furthermore, the deterioration of glass solder was electrically and optically studied over a year's period showing no corrosion of glass if properly coated in PDMS.**

I. INTRODUCTION

Almost every research group fabricating implantable neural prostheses is confronted with the situation on how to package the electrical components to avoid corrosion in the harsh body environment. The choice of which technology to apply is defined by the available size at the implantation site and the amount of required electrical channels. Miniaturization remains a critical step and retinal prostheses are an example for this. The complexity of the vision to be restored combined with the very limited space at implantation site make the implementation of high number of stimulation channels complicated. The development of these devices has been hampered by the available robust technologies and their miniaturization capabilities. A small titanium/alumina package for a retinal prosthesis has been proposed recently [1], allowing the integration of hundreds of feedthroughs through the ceramic substrate. The use of metal allows laser-welding the Ti lid to a previously metallized alumina substrate, employing very high but localized heating of the material, creating a uniform seam. Packages using Ti casing are known from pacemakers, deep-brain stimulators and cochlear implants. Another method for ceramic/metal combinations was presented by the authors in [4], where a brass lid is soldered onto a screen-printed ceramic substrate. However, the horizontal fabrication of the hermetic feedthroughs increases the size of the device with increasing number of electrical contacts.. Wireless power transmission is complicated when metallic packages are used, as the induced electric currents in the package's casing hinder the wireless transmission. For powering devices containing metallic cases either a battery is implemented or the receiver coil sits outside and away from the package.

Another method for miniaturized hermetic sealing is chip-size or wafer-level packaging, which yet hasn't shown successes for neuroprosthetic devices with many contacts. The sealing procedures (e.g. anodic bonding or Au/Au thermocompression) introduce large amounts of stress into the materials, which add up to the intrinsic stress of the utilized thin-films, eventually leading to cracking or delamination of the layer combinations. These are unacceptable situations in miniaturized packaging for implantable devices since they reside unheeded during fabrication and eventually emerge (sudden stress relaxation through crack propagation) with catastrophic consequences regarding the permeability properties of the pacakge. Beyond this, the hermeticity requirements drastically increase with decreasing package size, as only very small amounts of water in the package would exceed the accepted humidity levels before corrosion of electric components begins.

The present study investigates a miniaturized package using alumina ceramic as substrate and lidding material, sealed with non-conductive glass solder. The aim is to provide a very small package capable of carrying hundreds of hermetic feedthroughs fabricated from very inert materials as presented by the authors in [2]. The use of solder glass allows the hybrid integration of the receiver coil into the substrate for inductively coupled powering and communication, avoiding losses by induced eddy currents as present in metallic seals. Due to the simplicity of the materials choice, the technologies applied easily allow the combined fabrication of a miniaturized hermetic package with reliable circuitry and feedthroughs as similar to that described in [3].

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II. MATERIALS AND METHODS

A. *Concept and Materials Choice*

The materials choice is defined by the desired properties of the package. On the one hand, a robust interface between the materials is required. On the other hand, the thermally induced stress in the materials during sealing is to be kept minimal. Alumina ceramics and glass create stable interfaces due to diffusion of the glass into the ceramic and the diffusion of glass frit contained in the ceramic into the glass. This interdiffusion can reach 10 µm to 50 µm deep, depending on the sintering temperature, time, and the composition of glass and ceramic. Solder glasses are glasses with relative low melting temperatures (~550 °C) fabricated to join glass to ceramics or metals. The coefficient of thermal expansion (CTE) is matched to the materials to be joined and so avoid thermally induced stresses after fabrication. Choosing a screen-printable solder glass, with a CTE matched to that of 96% alumina, a micro-package as presented in figure. 1 is proposed. The volume of the package is dimensioned so, that a fine helium leak detection of $<10^{-12}$ atm·cc/s would lead to a mathematical lifetime prediction of around >100 years. This prediction is based on the Howell-Mann equation and it only involves water-induced failure. Biological stability is not considered an issue, as the final device would be fully coated in PDMS, providing the device with structural biocompatibility, as in common implantable products.

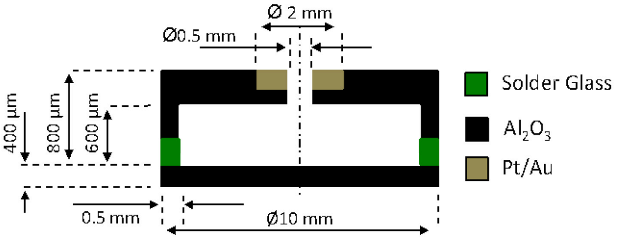

Figure 1: Sketch of proposed micropackage using alumina ceramics and solder glass as joining material. The opening and metallization on the top allows drying, helium backfilling before final sealing.

B. *Package parts fabrication*

To create a lid, Al_2O_3 tape (HTCC 44000 by ESL Europe, Reading, England) is laminated to a 1 mm stack (figure 2 - a). Using a marking laser (Nd:YAG, CAB GmbH, Karlsruhe Germany), the tape is ablated on both sides to create cavities and cut to the desired circular shape (figure 2 - b, c). The substrate consists of a 400 µm laminate stack cut into a Ø12 mm disc. The structured tape is sintered at 1500 °C to a 96% Al_2O_3 ceramic (figure 2 - d). Pt/Au paste (5837-G, ESL Europe) is screen-printed onto the surroundings of the top cavity of the lid and fired at 1000 °C (figure 2 – e). The lid opening permits drying and helium backfilling of the capsule once the lid and substrate have been joined. The metallization provides a small pad for final solder sealing of the capsule in Helium atmosphere as presented in [5]. Glass paste (4026-G, ESL Europe) is screen-printed onto the outer ring of the lid and substrate (figure 2 – f). By firing at 600 °C, a homogeneous glass layer on both, lid and substrate is formed. This step triggers the bond formation between glass and ceramic. The top side of the lid is slightly grinded and polished (MD-Piano Diamond discs, Struers GmbH, Germany) to remove asperities and warping coming from the firing procedures, which becomes critical for the subsequent sealing procedure.

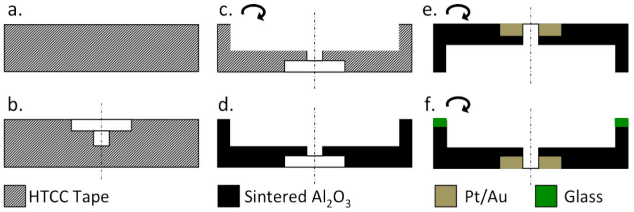

Figure 2: Sketch of fabrication procedure of alumina lids. The arrow indicates that the substrate is flipped-over for back or front side treatment.

C. *Sealing Unit*

Joining of the substrate and lid is the most important part of the presented study. The glass has to be softened at 550 °C while the electronics on the inside of the capsule are to be kept below 300 °C (healing temperature of CMOS chips), assuming the package contains an integrated circuit and some silicon-based capacitors with wire-bonds as interconnection (instead of metallic solder). This means, that a high temperature gradient of at least 200 K along a 2 mm distance is to be established in order to protect the electronics from overheating, without leading to crack formation in the ceramic. The heating element of the sealing unit consists of $Ni_{80}Cr_{20}$ wire (Ø200 µm) evenly wrapped around an ring-shaped alumina carrier (Rubalit 708s, CeramTec AG, Germany). To achieve a uniform temperature distribution, thermally high conducting aluminium nitride (AlN) ceramic (Curamik Electronics GmbH, Eschenbach, Germany) is mounted and fixated to the alumina ceramic, clamping and creating intimate contact with the heater wire. Both ceramic parts are laser structured with an Nd:YAG laser (StarWeld SWMP 6002 Rofin Baasel Lasertech, Starnberg, Germany). The wire is connected to a digitally controlled power source, permitting the regulation of the heater temperature. Type K thermocouples mounted on to the AlN provide the required temperature information, which is also used to monitor the sealing procedure. A sketch of the unit is presented on figure 3.

The cooling elements, being at the same time the holders for both, lid and substrate are made out of copper. Spring suspended bolts allow adjustment of the gap between top and bottom parts of the device. A central opening permits vacuum fixation of the substrate to the top holder while the bottom opening allows a thermocouple insertion into the device for temperature control during sealing. After both parts are carefully positioned and approximated into contact, the heating element is brought into position and the heating procedure begins. To characterize the device a validation measurement was conducted: the temperature was recorded simultaneously at the heating element between the Al_2O_3 and the AlN substrates and at the centre of a lid while increasing the electrical current in the heating element in 0.5 A steps, allowing for 2.5 min the temperature to settle. Sauereisen cement (Sepp Zeug GmbH, Boeblingen, Germany) was used to glue the thermocouple to the ceramic, allowing pure diffusive heat transfer and avoiding any cooling caused by environmental irregularities.

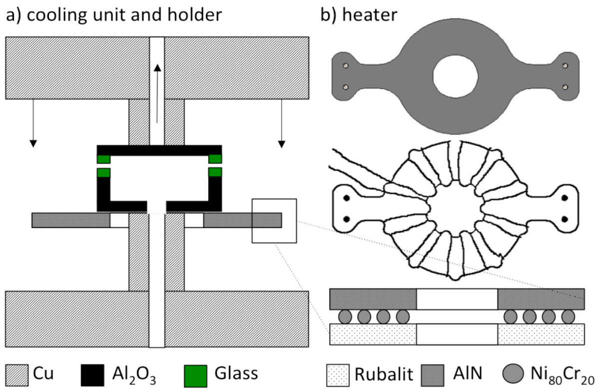

Figure 3: Sketch of the sealing unit composed from a cooling and holder unit (a) and a heater (b). The heater is conformed out of three parts: wire sitting on an Al_2O_3 carrier with AlN ceramic on top, to provide a proper temperature distribution along the ring.

D. Hermeticity Testing

To ensure that the sealing procedure was successful the probes are solder shut in helium atmosphere at 1.2 atm absolute pressure using the hermetic packager for electronic systems (HERPES) [5]. For subsequent gross leak testing, the samples were immersed in water inside a chamber that was exposed to a weak vacuum. If no rising bubbles were visible, they are further tested with a fine leak tester (SmartTest HLT570 by Pfeiffer Vacuum Technologies, Asslar, Germany). After successful testing (leakage rate below 10^{-12} atm·cc/s) the samples are re-opened at the top by heating up just to the melting temperature of the utilized sealing solder (250 °C). The helium inside expands and blows the lid open at the pre-defined hole, keeping the solder outside the chamber (figure 4 - a). The samples are soldered upside-down to a punctured brass lid as shown in figure 4 - b Subsequently, the brass lid is soldered on to a ceramic substrate (Rubalit 708s) containing a humidity sensor (SHT15, Sensirion AG, Staefa, Switzerland) and hermetic feedthroughs as presented in [6], (figure 4 - c). The whole device is again helium backfilled and solder shut (figure 4 - d, e).

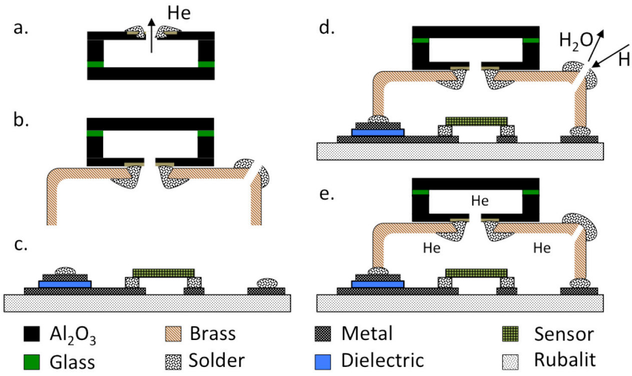

Figure 4: Scheme of fabrication procedure of samples for long-term accelerated aging studies of humidity intrusion into packages.

All fabricated samples are then stored at 85°C in tap water and the humidity inside the chamber is monitored over time by temporarily removing them from the water and measuring the inside humidity once the samples are cooled down to 25 °C (temp. of lowest sensor error).

E. Long-Term Glass Dissolution Studies

To study the behaviour of the glass in a body-similar environment, electrical impedance spectroscopy tests under 85 °C in 0.01 M phosphate buffered saline were conducted. The samples consist of an alumina substrate with a screen-printed metal layer (Ag/Pd 9695, ESL Europe), which is covered with the glass under investigation. A wire is soldered through an opening onto the metal layer. The solder spot is insulated with silicone rubber (Med1000, NuSil Technology LLC). After a thorough cleaning procedure of the surface half of the samples are fully covered with a thin PDMS layer to observe the difference in the behaviour of the material when not in direct contact with the ionic environment during the long-term tests. Profilometer surface roughness measurements of the samples before and after aging were done to consolidate the results of the electrical measurements.

III. RESULTS

A. Characterization of the Sealing Device

The validation test confirmed that it is possible to achieve a temperature of 700 °C in the heating device while maintaining a temperature below 300 °C on the lid for the 2.5 min that each set current was held.

B. Hermeticity Studies

Out of fourteen samples, seven were tested in the accelerated aging experiments. Four samples (No 3, 8, 12 and 13) failed the gross leak test. One sample (No 14) held a leak rate of $6.5 \cdot 10^{-6}$ mbar•cm^3/sec while two samples (No 1 and 7) broke along the way due to improper handling.

All the other samples that passed the gross leak test showed fine leak rates of $<1 \cdot 10^{-12}$ atm•cc/s, which is the detection limit of the leakage tester. With an estimated internal volume of ~0.04 cm^3 (volume displaced by electronic components subtracted) and setting a conservative limit of maximum humidity inside the chamber to 5000 ppm it is theoretically expected that the device reaches this limit after 100 years. This assuming that there is no deterioration in the material like crack formation or glass dissolution. All of the devices show an immediate increase in the humidity after the first hours at 85 °C. After 5 years (estimated accelerated age for 37 °C) the first sample showed complete failure. The humidity development is presented in figure 5. The rest of the samples have maintained a very slowly increasing humidity up to the day of submission of this publication. Two of the samples, both covered in PDMS keep their humidity below 5000 ppm after 17 years of extrapolated age. The rest of the samples haven't reached the 17000 ppm mark, a humidity level that permits the continuation of corrosion reactions of aluminium thin-film tracks, used here as the least conservative limit for humidity in electronic packages. Figure 7 shows some of the fabricated lids, substrate and a successfully sealed device.

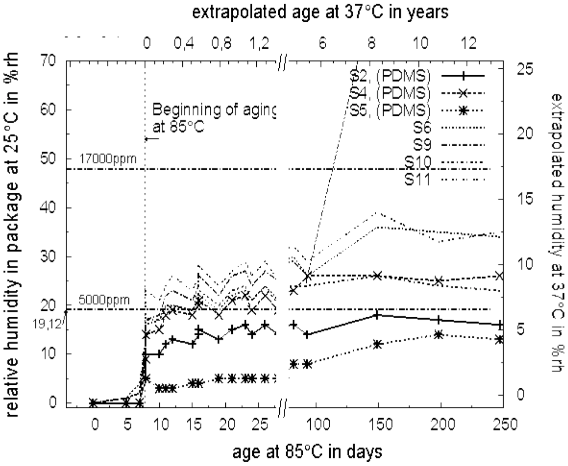

Figure 5: Development of humidity inside the fabricated micro-capsules under accelerated aging conditions.

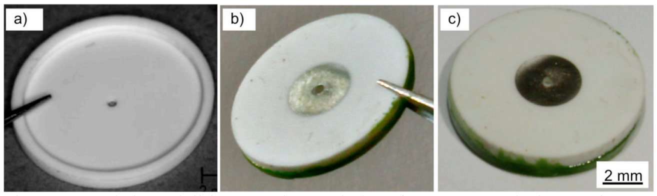

Figure 6: Fabricated lids (a) prior and (b) after screen-printing and (c) a fully sealed package.

C. *Long-Term Dissolution Studies of Glass*

Impedance spectroscopy analysis of the glass coatings shows a purely capacitive behaviour on all of the measurements directly after fabrication. After 34 days (real-time) a resistive behaviour could be observed on all of the samples indicating a change in the glass. Profilometer measurements established an increase in the roughness by 80 % on the layers aged without PDMS. Scanning electron micrographs (Figure 8) corroborate corrosion and the large increase in surface area. PDMS coated samples neither changed its electrical behaviour nor its optical appearance.

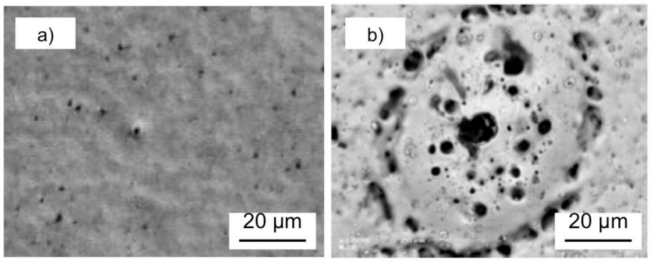

Figure 7: Scanning electron micrographs of glass after aging (a) with a PDMS coating and (b) without. Discussion and Conclusion

Different to laser welding of glass, the thermally induced stress is kept minimal and equal along the material contributing to a bond formation. The fact that the capsule parts need to be in intimate contact with both, the heating and the cooling surfaces makes the procedure very susceptible to unwanted variations caused by handling (e.g. positioning). A critical situation was given if the AlN surface providing the heat wasn't perfectly aligned with the copper surface holding the lid. This led to either improper cooling of the lid or to inhomogeneous heating of the glass, which was visible due to irregular changes in the color of the glass when approaching the softening point. A device re-configuration will include a proper holding unit for the final version of the heating element, which for the present study was only held in position by alligator clips. Furthermore, the heat transfer should take place by radiation instead of diffusion.

The long-term hermeticity testing shows an increase in the humidity inside the device immediately after starting the accelerated aging. This effect however is not attributed to the permeability of the fabricated devices, but to an improper (forgotten) drying of the devices. Drying is crucial previous to sealing to remove adsorbed water off the surfaces and plastic packaging (e.g. the sensor). The cause of increased humidity in the devices is unknown and the cause of failure of sample 6 hasn't been discovered so far, but a failure of the substrate instead of the glass sealed package is not redlined. Nevertheless, it is very encouraging to see that 6 samples have kept the humidity under critical levels for 13.3 years of time extrapolated to 37 °C body temperature, even without proper drying.

The glass dissolution experiments confirm the stability of the glass covered by a PDMS layer. This is relieving, as silicone rubber is by default an indispensable part of our concept of an implantable retinal stimulator, since it maintains ions away from the surfaces while improving the structural biocompatibility of the implant.

The glass for the current study was chosen for its adapted coefficient of thermal expansion to 96% alumina. The green-colored version of the glass was taken to facilitate the visual control during fabrication. However, a proper study with different glasses has to be undertaken to find the best applicant for a definitive device fabrication.

ACKNOWLEDGEMENTS

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