Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Microelectronic Retinal Prosthesis: III. A New Method for Fabrication of High-Density Hermetic Feedthroughs

G.J. Suaning, *Member, IEEE,* P. Lavoie, J. Forrester, T. Armitage, and N. H. Lovell, *Senior Member, IEEE*

Abstract— **Therapeutic, electronic medical implants used in auditory, visual, functional, and behavioral neuroprosthesis often are required to maintain their function for the remaining lifetime of the implantee. This requirement presents a substantial engineering obstacle that has previously limited the practical upper quantity of electrodes, or other signal carrying channels such devices may possess. Hermetic encapsulation of any implanted electronics and the tendency of this encapsulation to leak is a well-known problem for biomedical engineers. Each "hard-wired" signal required by, or elicited from, the implant must pass through the encapsulation without breaching hermeticity. The present paper describes a method of fabrication of hermetic feedthoughs (leak $< 2 \times 10^{-9}$ std cc He/s) comprising materials with superior biological compatibility characteristics and able to accommodate relatively high numbers of signal carrying channels relative to existing methods, while allowing this to occur within small areas.**

Index Terms— **hermetic feedthrough, implant, vision prosthesis.**

I. INTRODUCTION

IT is often the case where an electronic circuit comprised of semiconductor and other components must be sealed within a leak-tight chamber so as to protect it from corrosive or otherwise damaging environmental conditions. While techniques exist to effectively encapsulate electronics to operate indefinitely in many corrosive environments, the materials used in these techniques are often precluded from medical implantation.

Consider a medical implant that requires internal electronics that must function inside the body for many years or decades - a period often dictated by the remaining lifetime of the patient in which the device is implanted. Unless protected, the sodium and other ions that are present within the body would rapidly begin to corrode the electronics, compromising the device's longevity. The cardiac pacemaker, for example, is a device which must function under such conditions. As such, the electronics of the cardiac pacemaker must be sealed within a chamber that is leak-tight (hermetic) while at the same time compatible with the biological system in which it is implanted. The latter requirement substantially limits the materials from which the chamber may be comprised.

Most of the pacemaker's hermetic chamber can be manufactured from a metallic material (e.g. Ti) and thus also serve to complete a cardiac stimulation circuit (the so-called active/hot-can approach). The electrical connection to the electrode placed within or near the heart must be insulated from the chamber without compromising the hermetic integrity of the pacemaker body containing the electronics. In this example, one electrical conductor must pass through the wall of the hermetic chamber so as to allow for the delivery of therapeutic electrical stimuli via an electrode outside of the hermetic chamber. In most cases, in order to pass the signal across the chamber, an electrical conductor is sealed within a glass or ceramic insulator thereby forming a hermetic feedthrough [1]. The hermetic feedthrough is normally attached to the remainder of the pacemaker body by way of brazing (e.g. [2]).

As the quantities of electrical conductors increase, as is required in many sensory and motor neurostimulation applications, the complexity of the hermetic feedthrough also increases. One method used in cochlear neuroprostheses involves placing multiple wires comprised of platinum (Pt) through a ceramic insulator (e.g. Al_2O_3) and co-firing the assembly at high temperatures with an aim to bonding the two materials. The assembly is then brazed to the implant body [3]. During the heating process, however, the coefficients of linear thermal expansion are $8.8 \times 10^6 K^{-1}$ and $8.5 \times 10^6 K^{-1}$ for Pt and Al_2O_3 respectively. As such, the tendency is for Pt to expand and contract to a greater extent than the Al_2O_3 thereby leaving behind a larger "hole" than the Pt can occupy. While other factors (described below) contribute to some alleviation of this problem, with the reliance upon tight dimensions to form a seal, the tendency nevertheless is a leak that approaches statistical certainty once the quantity of conductors becomes sufficiently large. In other words, as the quantity of conductors increase, so too does the probability of compromising the hermetic properties of the hermetic feedthrough.

The aforementioned fabrication method for cochlear neuroprostheses with conductors oriented perpendicular to the wall of the hermetic chamber does not lend itself to the application of pressure during manufacturing unless the pressure can be applied in all directions at the same time. While isostatic pressing during sintering is indeed possible, this approach substantially complicates the fabrication procedure and, in the experience of the authors, does not offset the effects of differential expansion.

G.J. Suaning, P. Lavoie, J. Forrester and T. Armitage are with the School of Engineering, University of Newcastle, Callaghan NSW 2308, Australia. N.H. Lovell is with the National Information and Communications Technology Australia (NICTA), Eveleigh NSW 1430, Australia. G.J. Suaning and N.H. Lovell are also with the Graduate School of Biomedical Engineering, University of New South Wales, Sydney NSW 2052, Australia.

The authors would like to thank the University of Newcastle's Research Management Committee, and the Australian Federal Government (Australian Research Council) for funding this study.

Klomp and later de Bruin and colleagues were among the first to identify a phenomenon wherein an extremely thin (Angstrom order) bond is formed between ceramic oxides and several metals, including Pt [4] [5]. The present paper shall illustrate how this bond may be used to advantage in a planar method of fabrication of hermetic feedthroughs.

II. METHODS

Schuettler and co-workers, including one of the present authors, recently published a technique for fabrication of planar electrode structures using silicone elastomer and Pt foil [6]. In this technique, a numerically controlled laser cuts a pattern in the foil, thereby forming both the electrodes and the interconnections to the electronics as one array. Subsequent coating of silicone elastomer and removal of said elastomer at the locations where exposed Pt is necessary (e.g. the electrodes) forms a flexible and robust mechanical structure. An extension of this technique is applied in the formation of hermetic feedthroughs in the same structure as the electrode array (i.e. no interconnections from feedthrough to electrode array).

A. Implant Assembly Process

By way of illustrative example of the employment of the feedthrough assembly technique, the steps necessary to construct an implant (shown in Fig. 1) are described.

1) A pre-sintered disk of pure Al_2O_3 is laid flat upon the workspace;
2) A thin layer of Al_2O_3 particulate suspended in a viscous liquid (slip) is laid upon the disk;
3) Pre-patterned Pt foil in the desired shape is overlaid upon the slip. Fig. 2 illustrates how a partial formation of an electrode may be utilized for purposes of handling with the remainder of the array formed subsequent to the high-temperature feedthrough formation processes. In Fig. 2, the right-hand side of the foil is the area of interest - 16 connections are to be made to the internal electronics. Accordingly, 16 circular "pads" are pre-formed with connecting wires leading to the left for (subsequent) laser formation into an electrode array. The semi-circular Pt material surrounding the "pads" is present for purposes of handling and is cut away once the foil is in position on the slip;
4) An additional layer of slip is placed over the foil and exposed underlying previous layer of slip;
5) A second pre-sintered disk of pure Al_2O_3 is laid upon the top of the slip;
6) The assembly is allowed to dry in air then heated to a temperature sufficiently high to promote crystal regrowth in the Al_2O_3, thereby combining the pre-sintered and Al_2O_3 particulate within the slip to form a contiguous Al_2O_3 structure around the foil;
7) A secondary (and lower temperature) heating procedure sees the brazing or diffusion bonding of an annulus of Ti about the circumference of the inner surface (the surface to be internal to the hermetic chamber);
8) Holes corresponding to the location of the "pads" are drilled into the Al_2O_3 from inner surface and plated with gold, copper, or other appropriate conductor to facilitate subsequent bonding to electronics within the hermetic chamber;
9) Laser formation of the remainder of the electrode array, followed by silicone elastomer encapsulation and electrode surface exposure, is completed;
10) Internal electronic components are bonded to the "pads";
11) A pre-sintered "cup" with the desired hermetic chamber shape, and with a corresponding annulus of Ti about the circumference of the inner surface, is abutted to the feedthrough/electronics assembly and the circumference laser welded to hermetically seal the electronics within the chamber.

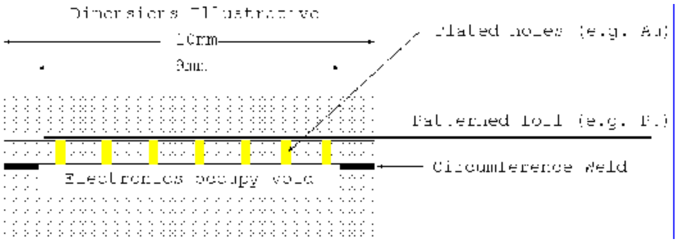

Fig. 1. Illustrative example of implant assembly using the new process.

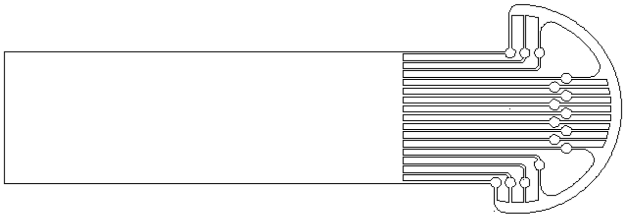

Fig. 2. Partial formation of an electrode array/feedthrough. Following the high-temperature operations of feedthrough formation, subsequent laser patterning and silicone elastomer coating can occur.

B. Test Sample Fabrication

The materials used in the method described herein are long-established and widely-used biomaterials (see [7]). Following the sintering process, all that remains are Pt and Al_2O_3 as any organic material would vaporize at the high temperatures. Accordingly, the material composition is not in question and thus the testing focussed upon establishing hermeticity in accordance with electronics industry standards [8].

A sample prepared using the above steps 1 through 6 with 20 mm diameter alumina disks, and a Pt foil pre-form shown in Fig. 3 was sectioned in half at the mid-line with the cut being perpendicular to the tracks shown in the same figure so as to maximize the potential for leakage. One half of the sectioned part was cleaned in ethanol and in an ultrasonic bath before being embedded around the outside perimeter of the cut within epoxy to provide a leak-tight surface upon the test interface of a mass spectrometer-based leak detector (Varian 959, Varian Vacuum Products, Lexington Massachusetts, USA). Careful attention was given to ensuring that all potential leak points were exposed at both the top and bottom of the part. This included ensuring that no residual epoxy, dust, or other material was present on the exposed surfaces that might otherwise artificially "clog" any leaks thereby providing a false-positive result. The sensitivity of the mass spectrometer was such that it was sufficient to detect leaks greater than or equal to a rate of 2×10^{-9} std cc He / s. The other half of the sample was prepared for imaging using a scanning electron microscope (SEM) so as to view the interface between the Pt and Al_2O_3.

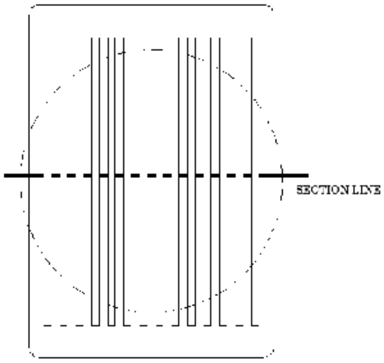

Fig. 3. Sample preform: 25 μ m thick, 99.99% Pt patterned to provide 15 conductors. Dashed circle indicates the location where the Al_2O_3 pre-sintered disks and slip are applied.

III. RESULTS

No leaks were detected by the mass spectrometer indicating that the combined leak rate, if indeed any were present, was less than 2×10^{-9} std cc He / s.

The Pt/Al_2O_3 interface is seen in the SEM micrographs (Fig. 4 and Fig. 5).

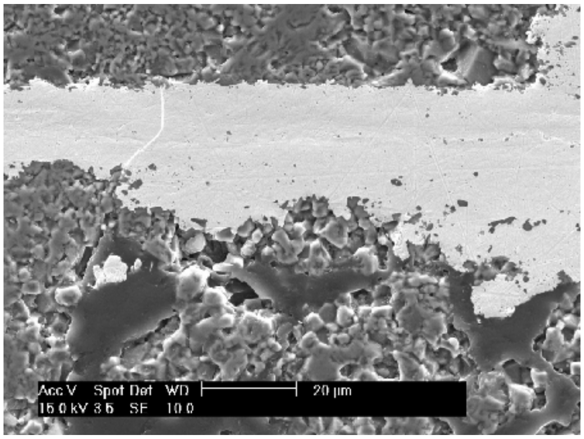

Fig. 4. SEM micrograph overview of the Pt - Al_2O_3 interface (Pt shown crossing from right to left in the center of the image). Dark, reflective surfaces (lower part of the image) are residual epoxy from sample preparation that has infiltrated into voids left behind from imperfect densification of the slip. Such epoxy infiltrations did not exist in the leak test sample and thus did not impede any potential leaks.

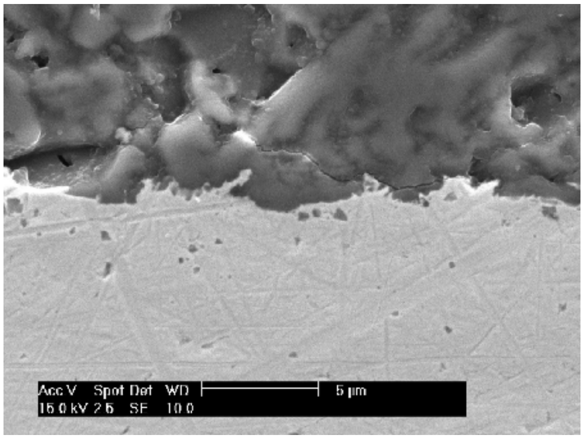

Fig. 5. High magnification SEM micrograph of the Pt - Al_2O_3 interface (Pt shown in the lower half of the image).

IV. DISCUSSION

Bonds between metals and ceramic oxides are formed in several ways. In the case of sub-melting point bonding (as opposed to brazing for example) non-noble metals bond with ceramic oxides through the formation of a visible, intermediate oxide layer whereas for noble metals, the bonding interface is characterized by an abrupt material change, or an extraordinarily thin transition layer [9]. The former type clearly includes a diffusion mechanism whereas the nature of the noble metal - ceramic oxide bond (e.g. Pt-Al_2O_3) is not yet fully understood. Klomp's study [4] suggested a mechanism of evaporation of the metal into the oxide as the physics behind the bond but this is yet to be conclusively affirmed. While the existence of the noble metal - ceramic oxide bonds have been known for many years, not until now have they been used to advantage in neuroprosthesis.

The method of feedthrough formation described herein produces an arduous path for any ions tending to breach the hermetic barrier. In the test sample a minimum of 4 mm of track is produced with track lengths increasing towards the apex of the sample shown in Fig. 3. Given the simplicity of manufacturing the Pt foil (see [6]), serpentine or "zig-zag" track structures can be used to further the path through which ions must pass. Indeed if any cross-section of a given track (along which is the site of a potential leak) possesses a contiguous Pt/Al_2O_3 bond, the flow of ions is precluded.

The degree of hermeticity produced in the results presented here exceeded the sensitivity of the authors' test equipment. The so-called "allowable" leak-rate is dependent upon several factors including the hermetic chamber volume, the differential pressure within this chamber, the initial chamber environmental conditions (e.g. noble gas filled, evacuated, etc.), the presence of desiccants within the chamber, and the environment into which the device is to be implanted.

The presence of infiltrated epoxy from the sample preparation process seen in Fig. 4 is an indication that the application of slip, and the removal of all voids therein prior to the sintering step, is an area that requires further work. This said, however, given the leak-tight structure the procedure produces and the appearance of the interface shown in the SEM micrographs of Fig. 4 and Fig. 5, any voids are clearly discontinuous and isolated and thus of little consequence to the overall result.

The traditional methods of fabrication of hermetic feedthoroughs wherein Pt wires are cast within or forced into and subsequently co-fired with a ceramic oxide possess a tendency to leak, apparently owing to the differential expansion properties of the two dissimilar materials (fortunately the leaky feedthroughs can be detected during the implant fabrication process using similar detection methods described herein). The present method most certainly does not change the nature of physical properties (i.e. the expansion coefficients) so the question remains as to why this method is an improvement over the traditional methods. The authors hypothesize that it is a combination of factors that contribute to the success of the procedure including:

- the wetting of the Pt with the Al_2O_3 particulate within the very small volume of slip used;
- the use of relatively large, pre-sintered components within the procedure (thereby reducing the effects of shrinkage);
- the relatively long, contiguous path through which ions (or atoms in the case of leak detection) must pass in order for there to be a leak;
- careful control of process parameters.

Allen and Borbidge [10] described how the application of compressive forces during the sintering process increased the strength of the Pt/Al_2O_3 bond. de Bruin et al. [5] assert that bonding occurs both with and without applied forces - a result consistent with ours as even without the application of these forces, a tight interface is formed (see Fig. 4 and Fig. 5). The application of force, however, may be a plausible way to reduce the presence of voids within the slip in addition to vacuum degassing, ultrasonic shaking, etc.

Beyond the physical bonding characteristics of the present method, a number of manufacturing advantages are realized. These include:

- elimination of the need for bonding an electrode array to the feedthrough;
- the ability to form complex shapes (e.g. serpentine tracks and complex electrode array configurations);
- ease of manufacturing;
- rapid prototyping and design changes.

V. CONCLUSION

A method for fabricating complex, hermetic feedthroughs is described. The method provides flexibility towards design, as well as providing a means of eliminating the need to attach electrodes to the feedthrough as the electrode array itself forms an integral part of the assembly.

REFERENCES

[1] M. Black, R. van Noort, and P. Drury, "Medical applications of biomaterials," *Phys. Technol.*, vol. 13, pp. 50–56 & 65, 1982.

[2] G. Jiang, D. Mishler, R. Davis, J. Mobley, and J. Schulman, "Zirconia to Ti-6Al-4V braze joint for implantable biomedical device," *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, vol. 72B, no. 2, pp. 316–321, 2005.

[3] D. Backous, R. Dunford, P. Segel, C. Muhlocker, P. Carter, and N. Hampson, "Effects of hyperbaric exposure on the integrity of the internal components of commercially available cochlear implant systems," *Otology & Neurotology*, vol. 23, no. 4, pp. 463–467, July 2002.

[4] J. Klomp, "Solid state bonding of metals to ceramics," *Science of Ceramics*, vol. 5, p. 501, 1970.

[5] H. de Bruin, A. Moodie, and C. Warble, "Ceramic-metal reaction welding," *Journal of Material Science*, vol. 7, no. 8, pp. 909–918, 1972.

[6] M. Schuettler, S. Stiess, B. King, and G. Suaning, "Fabrication of implantable microelectrode arrays by laser-cutting of silicone rubber and platinum foil," *Journal of Neural Engineering,*, vol. 1, no. 2, pp. 121–128, 2005.

[7] D. Merrill, M. Bikson, and J. Jefferys, "Electrical stimulation of excitable tissue: design of efficacious and safe protocols," *J Neurosci Meth*, vol. 141, pp. 171–198, 2005.

[8] ASTM, "Standard test method for hermeticity of hybrid microcircuit packages prior to lidding," ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshokocken, PA 19428, USA, 2003.

[9] H. de Bruin, "Interfacial noble-metal corrosion in metal to ceramic reaction welding," *Nature*, vol. 272, pp. 712–713, April 1978.

[10] R. Allen and W. Borbidge, "Solid state metal-ceramic bonding of platinum to alumina," *Journal of Materials Science*, vol. 18, no. 9, pp. 2835 – 2843, Sept. 1983.