HIGH-DENSITY, BIO-COMPATIBLE, AND HERMETIC ELECTRICAL FEEDTHROUGHS USING EXTRUDED METAL VIAS

K. G. Shah[1*], *T. DeLima*[1], *S. Felix*[1], *H. Sheth*[1], *V. Tolosa*[1], *A. Tooker*[1], *and S. Pannu*[1]
[1]Lawrence Livermore National Laboratory, Livermore, California, USA

ABSTRACT

Implanted medical devices such as pacemakers and neural prosthetics require that the electronic components that power these devices are protected from the harsh chemical and biological environment of the body. Typically, the electronics are hermetically sealed inside a bio-compatible package containing feedthroughs that transmit electrical signals, while being impermeable to particles or moisture. We present a novel approach for fabricating one of the highest densities of bio-compatible hermetic feedthroughs in alumina (Al_2O_3). Alumina substrates with laser machined vias of 200 µm pitch were conformally metallized and lithographically patterned. Hermetic electrical feedthroughs were formed by extruding metal stud-bumps partially through the vias. Hermeticity testing showed leak rates better than 9×10^{-10} torr-l/s. Based on our preliminary results and process optimization, this extruded metal via approach is a high-density, low temperature, cost-effective, and robust method of miniaturizing electrical feedthroughs for a wide range of implantable bio-medical device applications.

INTRODUCTION

Background and Context

Electrically active bio-medical devices (such as pacemakers and neural prosthetics) have the ability to diagnose, monitor, and treat a wide range of diseases [1-2]. In many of these applications, it is necessary to chronically implant the electronics that enable interactions with the tissue using electrical signals.

In the example of cochlear implants, it is desired that the implant continue to function over the patient's entire lifetime without causing any adverse cytotoxic reaction from the tissue [3]. Thus, the non-bio-compatible components (integrated circuits, passive components, batteries, etc) are hermetically sealed in order to separate them from the body. At the same time, the electronic circuits need to be protected from the harsh biological environment of the body which can cause electrical shorts or corrosion, and ultimately lead to open circuits. Typically, these issues are overcome by encapsulating or protecting the electronics inside a biocompatible and hermetically sealed electronics package. The electronics package often incorporates an array of electrical feedthroughs that allow the transmission of electrical signals between the interior and exterior of the package, while maintaining a seal that prevents transfer of particles or fluids [4-5]. It is desirable that the feedthroughs be fabricated from chronically bio-compatible materials, while meeting stringent specifications for hermeticity.

In the case of retinal prosthetics, the number of electrical feedthroughs or channels may directly affect the image quality that can be restored to the patient. Simply increasing the number of feedthroughs is typically not feasible because it increases the size of implant, which may make it impractical for implantation. It is therefore necessary to increase the density of electrical feedthroughs so that the channel count can be increased without significantly affecting device size [6-7].

State-of-Art

A common method of making hermetic feedthroughs is by brazing metal pins inside the vias of an insulating substrate. While this method can consistently result in hermetic feedthroughs, the pitch is limited, in many cases to as high as 400-500 µm.

Another common approach is to laser machine vias into an insulating substrate, and to fill the vias by stencil printing a metal paste and co-firing at high temperature. Since the metal paste contains organic binders or thinners that are driven out during the firing process, it is common for voids to form, which may negatively impact the hermeticity of the feedthroughs. Commercially available feedthroughs using this technology for bio-medical applications have a pitch in the range of 400-600 µm.

Methods such as LTCC (Low Temperature Co-Fired Ceramics) use thin ceramic-glass sheets, into which vias are punched or laser machined, and filled with metal paste. Multiple ceramic layers are aligned and sintered at temperatures up to about 1000 °C. A major limitation with this technology in addition to lack of scalability, is the misalignment of individual feedthroughs due to uneven shrinkage of the ceramic during the sintering process. In contrast, the electronic components that are attached to these feedthrough arrays are lithographically patterned, and have a high repeatability and accuracy of both size and location of bond pads. Due to the mismatch in pad versus feedthrough locations, it becomes necessary to use more compliant attachment processes, further limiting scalability of this technology [8].

State-of-art electrical feedthrough technologies including those mentioned above are high-cost, lack scalability, and have inherent material incompatibilities [4]. Importantly, limited density (or pitch) can directly affect the performance of a bio-medical device, for example, as cochlear implants with limited fidelity, or retinal prostheses with limited image resolution. Thus, there is currently an unmet need for high-density, bio-compatible electrical feedthrough arrays.

METHODS

Extruded Via Concept Overview

We present a novel approach for fabricating high-density hermetic feedthroughs from chronically bio-compatible materials using an extruded metal via process (Figure 1).

First, a non-conductive alumina substrate (Al_2O_3) is laser machined to form an array of densely-packed vias. Next, the ceramic is conformally metallized (Ti/Au) and lithographically patterned on both sides of the ceramic substrate. The novel step involves forming metal stud bumps centered over the vias. Since the stud bump diameter is greater than the via size, the metal partially extrudes through the via while bonding to the metallized ceramic. The combination of extrusion, ultrasonic energy, elevated temperature, and force is expected to form a hermetic seal. Simultaneously, the diffusion of the stud bump into the conformal metallization provides an electrically conductive path between the two surfaces of the alumina substrate. Optionally, after stud bumping, the bumps are coined by thermo-compression to drive the metal deeper, and to provide a flat ceramic surface onto which electronic components may be assembled.

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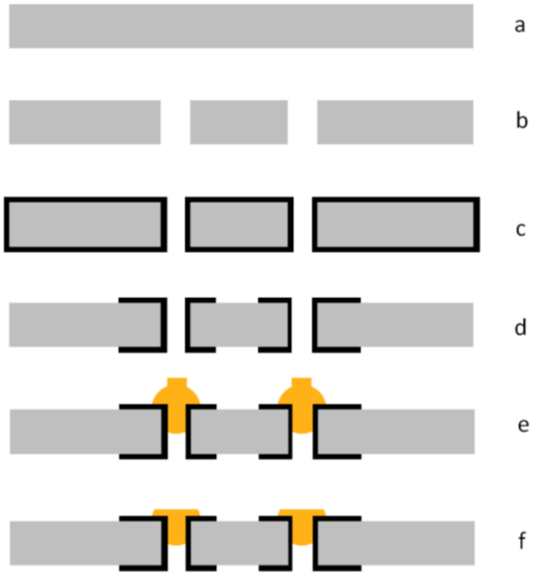

Figure 1. Fabrication process of extruded metal vias:
- *a. Starting alumina substrate*
- *b. Via-holes laser machined into substrate*
- *c. Substrate conformally metallized*
- *d. Lithographic patterning on both sides of substrate*
- *e. Metal extruded into vias by stud bumping*
- *f. Coining*

Fabrication Process

Alumina (Al_2O_3) was chosen as the insulating material because of its demonstrated bio-compatibility, chemical inertness, and use in bio-medical devices, such as retinal prostheses, cochlear implants, and neural stimulators [9]. As the starting substrate, this study used 99.6% purity alumina substrates with a thickness of 250 μm and a surface roughness of 25-50 nm Ra. An array of vias was laser machined using commercial CO_2 laser processing technology at a pitch of 200 μm (equivalent to a density of ~2500 vias/cm^2). It is important to note that the laser machined vias have an inherent taper that results in the via openings on the laser entry-side to be larger in diameter than the exit-side. The average exit-side via diameter for our samples was 53 μm (standard deviation 2.7).

The laser machined substrates were conformally metallized on both sides with a sputtered Ti/Au thin film. The metal is lithographically patterned on one side for the attachment of the electronics, and patterned on the opposite side for attachment to an implantable microelectrode array [10].

The critical aspect of the extruded via process is the optimization of process parameters for stud-bumping such that a consistent hermetic seal can be formed. It is expected that the seal is formed along the wall of the via when a stud bump of larger diameter than the via is extruded through it. A five-factor, half fractional factorial design of experiments containing 16 unique stud bumping parameter sets was performed to find the optimal combination of process conditions that result in hermetic feedthroughs. The critical bumping parameters selected for optimization were ultrasonic bonding power, time that ultrasonic energy is applied (or ultrasonic time), bond force, substrate temperature, and wire hardness. Commercially available 25 μm diameter gold bonding wire of high and low hardness was utilized. Stud bumps were formed with an F&K Delvotec 5610 bonder. A variety of bonding parameters were utilized to determine the appropriate upper and lower bounds of bonding parameters for the design of experiments.

Optionally, the stud bumps on the alumina substrate are coined by thermo-compression on a flip-chip bonder. The coining process was designed to make the substrates planar, but as will be discussed later, it improved the hermeticity of feedthroughs.

Testing methods

The performance of the extruded metal vias was quantified by measuring their hermeticity and electrical properties.

Electrical testing consisted of verifying electrical continuity of the feedthrough and measurement of the electrical resistance with a multimeter. An acceptable electrical resistance of the via is highly dependent on application, and will be discussed in the later section.

Hermeticity of the feedthroughs was measured using a helium leak test. An Adixen ASM 182 TD+ helium leak detector (detection limit ~5x10^{-12} torr-l/s), was fitted with a custom sealing fixture that allowed a vacuum (of 1x10^{-3} torr) to be applied between the ceramic substrate and the helium mass spectrometer. Once vacuum was achieved, helium was flooded on the outer surface of the ceramic while recording any fluctuations in the leak rate. We considered a hermetic feedthrough if the leak rate was better than 9x10^{-10} torr-l/s, which exceeds the MIL-STD-883 specification for the expected internal volume of our package.

RESULTS

The extruded via process was successfully optimized to create hermetic electrical feedthroughs in alumina substrates. In the design of experiments, each test of bonding parameters was performed on alumina substrates containing single laser machined vias.

Figure 2 shows a top-view and cross-sectional view of a single hermetic electrical feedthrough, with and without the optional coining step. The coining step planarized the extruded vias to the alumina substrate, which is preferred for subsequent processing and assembly steps.

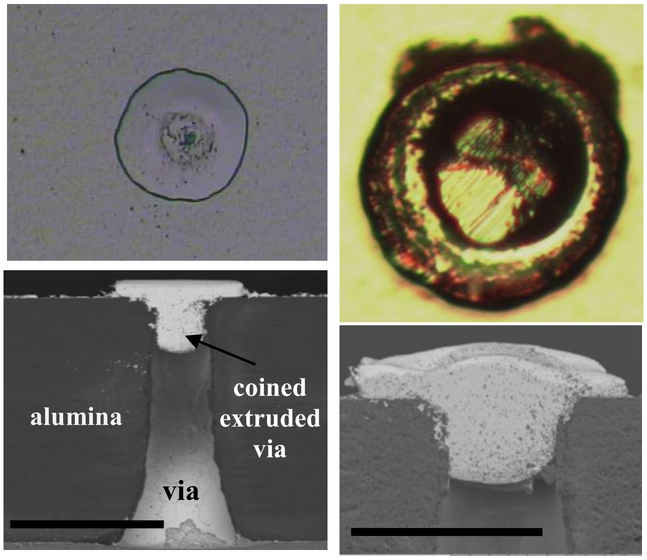

Figure 2. Left: Top-view and cross-sectional view of extruded via after coining; Right: Top-view and cross-sectional close-up of extruded via, no coining. (scale bars = 100 μm)

A preliminary analysis of the settings that resulted in hermetic feedthroughs shows a wide process window for the parameters chosen for the design of experiments (Table 1). Six of the sixteen tests yielded hermetic feedthroughs with leak rates better than MIL-STD-883 specification.

However, a closer look at the electrical testing results showed that only two of these six substrates have acceptable electrical performance (highlighted in Table 1). Test #4 had an electrical resistance of 50Ω, while Test #1 had a resistance of 250Ω. The remaining tests had resistances over 1000 Ω, which may not be acceptable for some device applications.

Table 1. Process parameters that resulted in hermetic feedthroughs. Highlighted rows indicate tests with acceptable electrical performance

#	**Wire Hardness**	**Force**	**Ultrasonic power**	**Ultrasonic time**	**Bonding temperature**
1	Hard	Low	Low	Low	Low
2	Soft	Low	Medium	High	Low
3	Hard	High	Medium	High	Low
4	Hard	High	High	Low	Low
5	Soft	Low	Low	Low	High
6	Hard	Low	Medium	High	High

An unexpected outcome of the optional coining process was an improvement in hermeticity. Five extruded metal vias that initially failed hermeticity testing were thermo-compressively coined using a flip-chip bonder. Two of these five samples were hermetic when subsequently leak tested.

Figure 3 shows an array of 12 vias (200 µm pitch), before and after extruding vias with gold stud bumps.

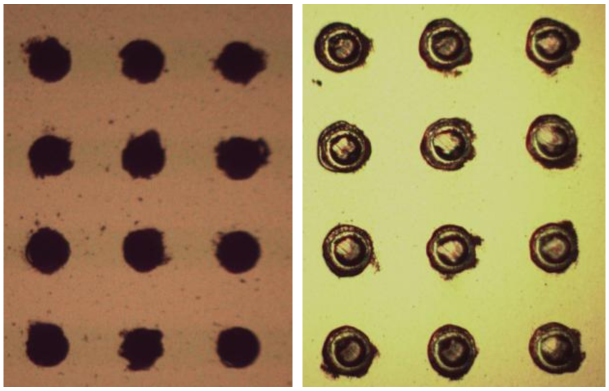

Figure 3. Left: metallized bare ceramic substrate with laser machined vias of 200 µm pitch (Schematic in Figure 1c). Right: gold vias extruded through ceramic vias (schematic in Figure 1e)

DISCUSSION AND CONCLUSIONS

We have demonstrated a feedthrough pitch of 200 µm, which is one of the lowest shown in literature, especially when compared with conventional bio-medical feedthrough technologies that achieve pitches in the 350-600 µm range.

In addition, the extruded feedthrough process minimized the required thickness of the ceramic substrate (250 µm). Conventional processes that use metal pastes often create voids in the feedthroughs because the organic binders or thinners outgas during sintering or thermal processing. The presence of voids necessitates a larger ceramic thickness (greater than 400 µm) to reduce the likelihood that a series of voids will form a leakage path through the ceramic, and render it non-hermetic. The extruded via process can achieve hermetic feedthroughs at roughly half the thickness of conventional feedthrough technologies because it uses bulk metal wire to seal the via openings.

In addition to the high density, this approach can be used to form hermetic feedthroughs at extremely low processing temperature (150 ^{0}C), and has the ability to rapidly create feedthroughs without complicated processing steps. In contrast, existing technologies often require high processing temperatures, which amplifies problems with feedthrough failure due to mismatch in thermal coefficient of expansion between the ceramic substrate and the metal feedthrough.

Another advantage of the low-temperature processing is the flexibility that our method provides for bio-medical device assembly. Currently, many devices are assembled by first fabricating the feedthrough array (at high temperature), followed by a high-temperature brazing process to attach the ceramic to a bio-compatible metal ring. The braze process often results in hermeticity failure due to strain induced from a mismatch in thermal expansion between the ceramic and metal. The extruded via process would enable a “via-last” assembly, in which all electronic components can be assembled first. This would reduce the chance of failure of the feedthrough array, and also make it easier to perform electrical testing of the assembled components before they are hermetically sealed.

Currently, a disadvantage of the extruded via process is the relatively high electrical resistances. However, this may be acceptable for many neural prostheses applications that use microelectrode arrays. Microelectrode arrays attached to feedthroughs often have trace resistances on the order of 1-10 kΩ. Moving forward, we propose to reduce the electrical resistances either by electroplating a thicker metal layer, or by using atomic layer deposition processes to achieve a more conformal metal coating in the vias.

Table 2 qualitatively compares the extruded via process with conventional feedthrough technologies.

Table 2. Comparison of extruded metal via process with state-of-art bio-medical feedthrough technologies.

Method	Hermeticity	Density	Electrical resistance	Processing temperature
Brazed pins	High	Poor	Excellent	High
LTCC	Moderate	Moderate	Excellent	Moderate
Stencil-printed metal pastes	Moderate	Moderate	Excellent	High
Extruded metal vias	High	Excellent	Moderate	Low

FUTURE WORK

Moving forward, we hope to improve and expand the extruded metal via process. First, further optimization of the design of experiments will be performed to find the reliable process window for stud bumping. Second, improvements will be made to the metallization process to reduce resistances so that this technology can have broader applications, especially for semiconductor devices. Third, platinum bonding wire will be adopted due its superior bio-compatibility in the presence of a corrosive environment. Finally, we hope to extend this process to insulating substrates that can be lithographically etched, which will enable further miniaturization of feedthrough densities, and ultimately lead us to realize neural prostheses with ultra-high channel counts.

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CONTACT

* Kedar G. Shah, Tel: +1-925-422-7296; kshah@llnl.gov

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