

Flexible Interconnect and Packaging for MEMS Moveable Neural Microelectrodes

Nathan Jackson and Jit Muthuswamy
 Harrington Department of Bioengineering Arizona State University
 Arizona State University ECG334
 Tempe, AZ 85287
 480-965-1699 jit@asu.edu, njack@asu.edu

Abstract

Interconnect integrity and packaging of implantable microdevices are crucial for their longevity. MEMS devices involving microactuators have special packaging challenges because of moveable parts that can fail if any debris gets trapped in the chip. Additional challenges arise when interfacing such devices with biological tissue. The device presented here is the first MEMS device with electrodes extending off the edge of the chip that are implanted in the brain to monitor neuronal activity. The devices are fabricated using Sandia's SUMMIT-V process, and use thermal actuators to move highly doped polysilicon electrodes bi-directionally. This research presents a MEMS Microflex Interconnect (MMFI) technology approach that uses polyimide (PI-2611) as the flex circuit. Gold stud bumps are used to "rivet" bond the flexible circuit to the bond pads on the MEMS device. In our approach, we use dual stud bumps in order to allow sufficient room for the actuators and other mechanical structures to move without hindrance. The gold-to-gold bonding eliminates intermetallic formation and gives acceptable strength without the need of an underfill. A backside dry etch is performed on the flexible circuit in order to create micro-channel openings for the moveable electrodes to extend off of the chip. Reliability testing including 85%/85°C, high temperature, thermal cycling, and thermal shock are presented using the MMFI approach. Humidity testing has shown a slight increase in contact resistance from $5.84 \pm 0.19 \text{ m}\Omega$ to $6.00 \pm 0.18 \text{ m}\Omega$ after 500hrs at 85%/85°C. High temperature (300°C) has shown significant increase $6.4 \pm 0.45 \text{ m}\Omega$ to $59.97 \pm 38.94 \text{ m}\Omega$ after 250hrs. This approach offers a lightweight, flexible, biocompatible package, which can be batch fabricated, allowing SMD to be easily bonded and the connector to be mechanically isolated from stresses. MMFI technologies can be a viable approach to package any MEMS device that interfaces with biological systems. In addition, it readily allows for scaling up to high-density devices and systems.

Keywords: microprobes, brain, neural prostheses, implants, microflex, polyimide, polysilicon

Introduction

Packaging and interconnects remain a vital component in the longevity of microelectromechanical systems (MEMS). MEMS packaging can exceed 80% of the total cost of the MEMS device [1, 2]. MEMS packaging is costly and challenging because there are no standards when compared to IC packaging. Most MEMS devices have unique features that require special packaging considerations, which require application specific packaging. Bio-MEMS devices have additional packaging challenges associated with

biocompatibility and operating in a harsh environment [3].

In this paper we present a novel packaging and interconnect technology to be used by our Bio-MEMS device. Our Bio-MEMS devices use electro-thermal actuators to move polysilicon microelectrodes in the brain post-surgery in order to monitor neural activity. The moveable microelectrodes extend off the edge of the chip, which does not allow us to use any current MEMS packaging technique. To our knowledge this is the first MEMS device with moveable parts extending off the edge of the chip.

An implantable device has several needs that are not required in most other devices such as: 1) biocompatibility, 2) flexibility, and 3) lightweight and small size. Our packaging approach is a modified version of Meyer et al. microflex interconnect technology (MFI) [4], which we call MEMS microflex interconnect technology (MMFI). This approach uses a double gold stud bump rivet bonding technology along with a polyimide backside etch in order to create a flexible cap wafer bonding and interconnect package for MEMS devices. The backside etch is necessary to create micro-channels for the electrodes to extend and to allow a raised sidewall around the perimeter of the device.

Moveable Microelectrodes for Neural Recording

The Bio-MEMS devices that were packaged in this paper were fabricated using the SUMMIT-V™ process at Sandia National Laboratories, Albuquerque, NM. A brief description of the device is given below, however further details have previously been reported [5, 6]. The devices consist of three highly doped thin-film ($\sim 4\mu\text{m}$) polysilicon electrodes that move bi-directionally using electro-thermal actuators (Fig. 1). The actuators move the microelectrodes, using low voltage (8-10V) square wave pulses. The microelectrodes are implanted in the brain and record neural activity. Most microelectrodes fail over time due to the formation of scar tissue (gliosis). This device allows us to move through the scar tissue and increase the longevity of the neural recordings. This device is the first MEMS device to have moving parts extended off the edge of

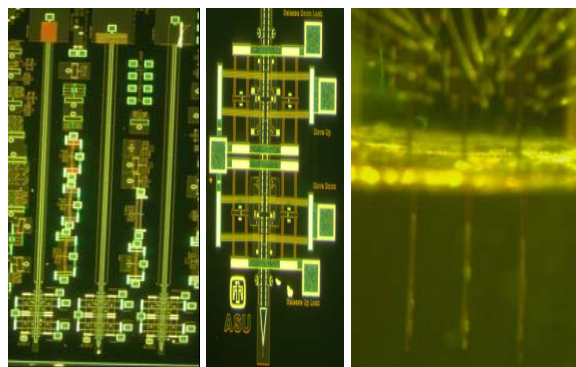


Figure 1- Micrographs of Moveable Microelectrode devices (left) whole chip, (center) a close up of a single electrode and actuators, (right) microelectrodes extended off the edge of the chip

the chip. That combined with the harsh environment of operating in biological tissue increases the challenges associated with packaging the device. Below we will discuss a novel post-packaging and interconnect technology that was developed for the above product. However, it can easily be modified and used by future MEMS devices that have moveable parts extending from the chip or MEMS devices that require a flexible cap package.

Fabrication of Flex Circuit

We have developed a post-packaging technology using a flexible interconnect and cap-based package for MEMS devices. The flexible substrate includes metal traces, bond pads, holes for rivet bonding, a sidewall on the perimeter of the substrate, and micro-channels for the extended probes. The flex circuit that was fabricated was designed specifically for MEMS devices with moveable parts (microelectrodes) that extend off the chip. This unique device does not allow for a hermetically sealed package, which increases the likelihood of failure due to debris or fluid entering the chip and affecting the actuators.

A brief description of the fabrication process of the flexible circuit is given below (Fig. 2). A thin layer of polyimide (PI2611, HD Microsystems) is spun on a bare silicon wafer and cured at 350°C for 1 hour. Then using wet-etch technology a patterned aluminum layer (200nm) is deposited for backside etch mask (Fig. 2a). This step is followed by a thick polyimide layer and a patterned aluminum layer (200nm), which is used as the stop layer for both front and backside etching (Fig. 2b). Another layer of polyimide is spun and cured and is followed by a Cr/Au deposition (Fig. 2c). The Au layer is used as the interconnect and bond pad layer. After the interconnects are patterned another polyimide layer is spun and cured, which acts the insulation layer. This is followed by another patterned aluminum layer, which acts as the mask during the front-side etch process (Fig. 2d). Etching is done using a reactive ion etch (RIE) machine. The first etch was used to open the bond pads and create the via (Fig. 2e). After the RIE etch process the polyimide film was released from the silicon wafer by tweezers and flipped up side down (Fig. 2f). Another RIE step was performed on the backside of the flex circuit in order to create the micro-channels and the sidewall perimeter for the cap (Fig. 2g). Then

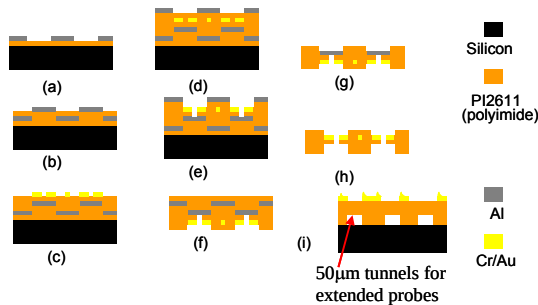


Figure 2 - Process for fabrication of thin flexible polyimide cap and interconnect circuit with patterned traces, via's, bond pads, and micro-channels.

the aluminum layers were wet-etched and the flex circuit was cleaned in IPA and DI water.

MEMS Microflex Interconnect technology

When packaging MEMS devices the actuators and other moving components need sufficient space to operate. Along with the flexible cap design described above we have developed a process using Microflex Interconnect Technology (MFI) [4] that gives us a flexible, small, thin, and biocompatible package, that allows MEMS components to operate normally. We termed this technique MEMS Microflex interconnection (MMFI) (Fig. 3). Like MFI we use a via located in the center of the bond pads on the flexible circuit described above. A 50 μm diameter via was made through the 100 x 100 μm gold bond pad.

The first step in the MMFI process is to make a gold stud bump on bond pad of the MEMS device or die using a thermosonic ball bonding device. Then epoxy or photoresist is applied on the perimeter of the device, which is used to bond the cap to the silicon device using

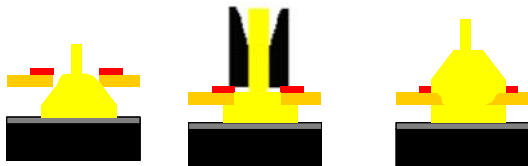


Figure 3- A schematic drawing of the MMFI bonding process using a double gold stud bump rivet bonding approach.

adhesive bonding techniques. The flexible circuit created above is then aligned so the tail of the stud bump is through the via (Fig. 4). The via is only 50 μm in diameter and the width of the gold stub bump is 100 μm at the base. The polyimide

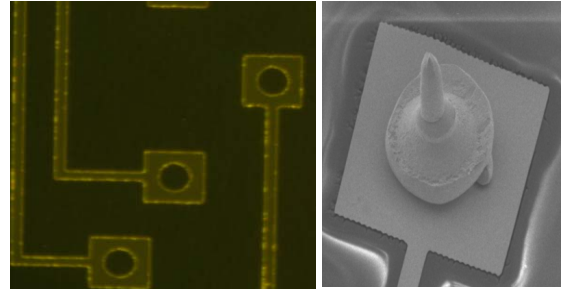


Figure 4- (left) micrograph of flex circuit and via's, (right upper) a micrograph of an aligned stud bump with tail through the via, (right lower) an SEM image of a single MMFI bonded contact pad

device will rest on the gold stud bump with a spacing of around 25 μm prior to the next step. Then the second gold stud bump is formed in the same manner as before, and the two stud bumps form a rivet bond with the flexible circuit. The first gold stud bump height is decreased from the pressure of the second stud bump, but it still maintains a height of around 15-25 μm on average, which is sufficient space to allow normal functioning of moving structures such as actuators on the chips.

Reliability of MMFI

A test structure was designed and fabricated to test the electrical reliability of the MMFI technology. A custom "4-point" probe structure was created based on the design by Pai et al. [7-9] (Fig.6). The test substrate (bottom) layer, which represents the MEMS device, is first patterned with an aluminum layer (1 μm) since it is widely used in IC chips. A flex circuit was created with the new pattern to match the bond pads of the test substrate. The test devices were bonded in the same manner using MMFI technology as described above. Contact resistance was measured by applying a 10mA DC current through two of the probes while recording the voltage drop in the other two probes. The contact resistance is calculated by using Ohm's law $R=V/I$.

The following reliability tests were carried out according to MIL standard 883 using an environmental chamber (S241, ESPEC Inc.) and the contact resistance was measured before and during each test.

1. An accelerated high humidity test was performed for 500 hours at 85% relative humidity and 85°C. After 500 hrs of exposure there was a marginal increase in resistance from

$5.84 \pm 0.19 \text{ m}\Omega$ before exposure to $6.00 \pm 0.18 \text{ m}\Omega$ after exposure as shown in Fig. 5.

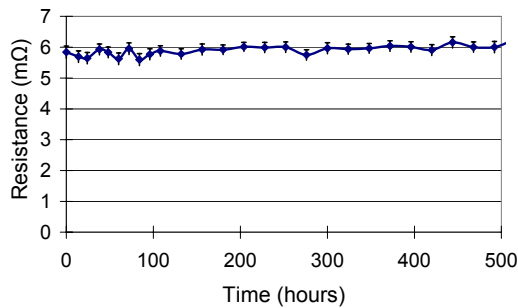


Figure 5 - Effects of 85% relative humidity and 85°C on the resistance of the MEMS MicroFlex interconnects during 500 hours.

2. A thermal cycling test between -40°C and 125°C with 10-min dwell time was performed for 100 cycles or approximately 250 hrs. After 100 cycles there was a marginal increase in resistance from $4.43 \pm 0.38 \text{ m}\Omega$ before exposure to $4.56 \pm 0.37 \text{ m}\Omega$ after exposure as shown in Fig. 6.

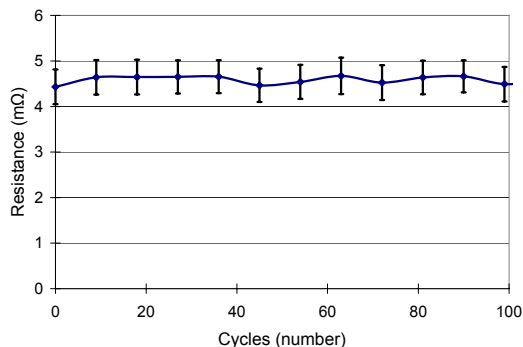
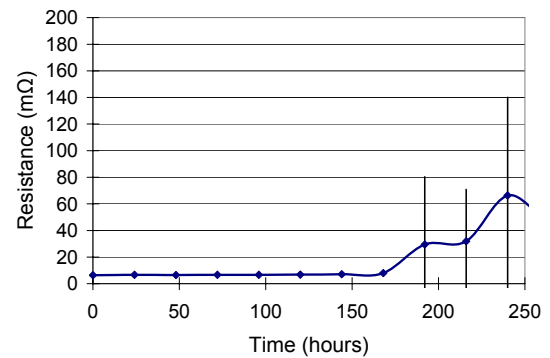


Figure 6 - Resistance measurements of MEMS MicroFlex interconnects when exposed to temperature cycles ranging from 125°C to -40°C with 10 minute dwell times for over 250 hours corresponding to 100 cycles.

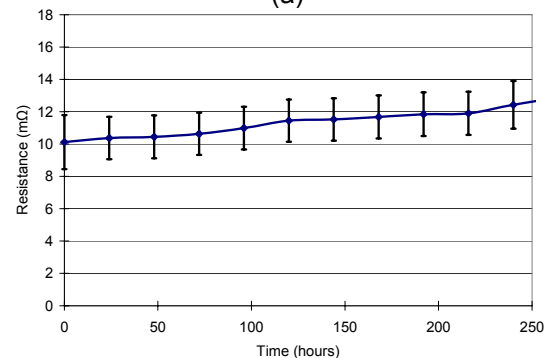
3. A high temperature test was performed at 300°C for 250 hrs with measurements taken every 24 hrs. Contact resistance increased significantly from $6.40 \pm 0.45 \text{ m}\Omega$ before exposure to $59.97 \pm 38.94 \text{ m}\Omega$ after exposure as shown in Fig. 7a. Bond failures result if any of the bonded traces fail, which would result in an open circuit. Almost half of the devices tested failed at around 250 hours of 300°C temperature.

The failed bonds are likely due to Kirkendall's or Horsting voids [10, 11] as seen in

the micrographs of the cross sectioned bonds. In order to solve this problem a new test substrate was fabricated having gold patterns instead of aluminum, in order to remove the intermetallic formation during high temperature testing. Figure 7b shows the results of the gold tested substrate. There was still an increase in resistance from $10.19 \pm 1.67 \text{ m}\Omega$ before exposure to $12.78 \pm 1.81 \text{ m}\Omega$ after exposure. However, the contact resistance increase was significantly reduced and no bond failures were seen.



(a)



(b)

Figure 7 - Contact resistance measurements when exposed to high temperature 300°C (a) aluminum test substrates (b) gold test substrates

Discussion:

To address our need for a flexible package and interconnect technology for our MEMS based implantable moveable microelectrodes in the brain, we have developed the MEMS MicroFlex Interconnect (MMFI) technology. This packaging technology is a modified version of MFI [4]. This technology allows us to have a flexible, biocompatible, small

light package. It does not require the use of an underfill, which is essential for moveable parts. The MMFI technology allows hybrid connection and bonding techniques such as SMD technology. This technology only requires the use of a gold wire bonder to package the device, which is an attractive feature for low-production companies or University labs.

In this study we have shown that MMFI technology bonding is reliable. When aluminum was used as the test substrate there were several failures due to high temperature, which is likely due to Kirkendall's or Horsting voids. However, bio-implantable devices operate in an environment of $\sim 37^{\circ}\text{C}$. If this packaging were to be used by another MEMS device that required operating under high temperatures, we would recommend using gold instead of aluminum for the bond pads. According to our results gold had a significantly less increase in contact resistance and no failures under high temperature conditions.

Conclusion

The MEMS MicroFlex Interconnect technology (MMFI), which uses a flexible circuit for the cap and interconnect is reported. The flexible cap forms a mechanical and electrical connection by using a double stud bump rivet bonding technique. Reliability tests show that this novel packaging mechanism is durable if gold to gold bonding is performed. Although this technology was specifically designed for use with the moveable microelectrodes it can easily be modified to be used by any implantable MEMS device.

References:

- [1] A. Malshe, C. O'Neal, S. Singh, W. Brown, W. Eaton, and W. Miller, "Challenges in the Packaging of MEMS," *The International Journal of Microcircuits and Electronic Packaging*, vol. 22, pp. 233-241, 1999.
- [2] T.-R. Hsu, "Packaging Design of Microsystems and Meso-Scale Devices," *IEEE Transactions on Advanced Packaging*, vol. 23, pp. 596-601, 2000.
- [3] T. Velten, H. Ruf, D. Barrow, N. Aspragathos, P. Lazarou, E. Jung, C. Malek, M. Richter, J. Kruckow, and M. Wackerle, "Packaging of Bio-MEMS: Strategies, Technologies, and Applications," *IEEE Transactions on Advanced Packaging*, vol. 28, pp. 533-546, 2005.
- [4] J.-U. Meyer, T. Stieglitz, O. Scholz, W. Haberer, and H. Beutel, "High Density Interconnects and Flexible Hybrid Assemblies for Active Biomedical Implants," *IEEE Transactions on Advanced Packaging*, vol. 24, pp. 366-374, 2001.
- [5] J. Muthuswamy, M. Okandan, A. Gilletti, M. Baker, and T. Jain, "An Array of Microactuated Microelectrodes for Monitoring Single-Neuronal Activity in Rodents," *IEEE Transactions on Biomedical Engineering*, vol. 52, pp. 1470-1477, 2005.
- [6] N. Jackson, P. Stice, M. Okandan, and J. Muthuswamy, "Long-term cortical recordings with Microactuated Microelectrodes," in *IEEE EMBS Conference on Neural Engineering*, Kohala Coast, Hawaii, 2007.
- [7] M. Uddin, M. Alam, Y. Chan, and H. Chan, "Adhesion strength and contact resistance of flip chip on flex packages--effect of curing degree of anisotropic conductive film," *Microelectronics Reliability*, vol. 44, pp. 505-514, 2004.
- [8] R. Pai and K. Walsh, "The viability of anisotropic conductive film as a flip chip interconnect technology for MEMS devices," *Journal of Micromechanics and Microengineering*, vol. 15, pp. 1131-1139, 2005.
- [9] Y. C. Chan, S. C. Tan, S. Nelson, S. Lui, and C. W. Tan, "Electrical Characterization of NCP- and NCF-Bonded Fine-Pitch Flip-Chip-on-Flexible Packages," *IEEE Transactions on Advanced Packaging*, vol. 29, pp. 735-740, 2006.
- [10] E. Philofsky and E. Hall, "A Review of the Limitations of Aluminum thin Films on Semiconductor Devices," *IEEE Transactions on Parts, Hybrids, and Packaging*, vol. 11, pp. 281-290, 1975.
- [11] C. W. Horsting, "Purple Plague and Gold Purity," in *Reliability Physics Symposium, 10th Annual Las Vegas, NV*, 1972, pp. 155-158.