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Implementation of Integratable PDMS-Based Conformable Microelectrode Arrays Using a Multilayer Wiring Interconnect Technology

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Abstract— **To meet the emerging demand of high-throughput intimate interfaces in neuroscience research and neural prosthetics, a multilayer wiring interconnect technology for implementing high-density, integratable polydimethylsiloxane (PDMS) based conformable microelectrode arrays (MEAs) is developed. This technology has two parts: first, multilayer interconnects are fabricated within PDMS, which provides the potential for implementing high-density, large-capacity PDMS-based MEAs; second, interconnects are fabricated between PDMS and a substrate material, e.g., glass or silicon, which provides the potential for directly integrating PDMS-based MEAs with silicon-based ICs to achieve an integrated system solution for neural interfacing. Preliminary muscle surface recording experiments using a connector-integrated MEA have successfully demonstrated multichannel recording capability with good device conformability to the muscle surface during contraction. Important and promising applications will be found in neural prostheses, functional electrical stimulation (FES), and basic electrophysiology research.**

I. INTRODUCTION

Recently, an emerging demand of intimate interfaces in neuroscience research and neural prosthesis development has stimulated the development of conformable MEAs using compliant materials, such as PDMS, to provide the device capability of conforming to the tissue surface in the pursuit of a uniform and tight contact on the target tissue surface [1], [2], [3], [4]. Usually, a sandwiched structure is used with thin film noble metals, such as platinum or gold, embedded between two PDMS layers as the conductors. While neuroscience research and neural prosthetics frequently require high-density implementations, all of the PDMS-based MEAs designed so far are implemented with only a single conducting layer, which has significantly limited the integration density and capacity of such MEAs due to the difficulty in wiring a large number of high-density electrodes.

Furthermore, packaging for such PDMS-based MEAs has long been a great challenge. The PDMS material cannot be soldered on, neither could the thin metal film on the contact pads withstand the high soldering temperature. The traditionally used methods for connecting the device to external circuits are (a) clamping on contact pads [2], [4], (b) gluing wires on contact pads using conductive epoxy/polymer, and (c) welding wires or riveting on contact pads [3] (metal foil was used here, so this method is not applicable for devices with deposited thin metal film). Our experience with the first two methods was not so pleasing, because (a) the resulting electrical connections were unreliable and unsustainable; (b) the bonding process was labor intensive; and (c) the contact pads required large size, thus expanding the device size significantly.

We have focused on addressing these issues by implementing multilayer wiring interconnects both within PDMS and between PDMS and another substrate. Our multilayer interconnect technology provides the potential for implementing high-density PDMS-based MEAs with an integrated packaging solution that makes the MEA easy to be connected to supporting circuits. Preliminary muscle surface recording experiments using a connector-integrated MEA have successfully demonstrated multichannel recording capability with good device conformability to the muscle surface during contraction.

II. METHODOLOGY

A. Fabrication Method for Multilayer Interconnects

Briefly, our basic PDMS-based MEA fabrication process involves curing a thin layer of PDMS (Sylgard® 184, Dow Corning) onto a glass slide, patterning gold features using a lift-off method, lithographically defining sacrificial posts on top of metal electrodes and contact pads to assist in the formation of openings, covering the sample with another thinner PDMS layer for encapsulation, and then removing the sacrificial posts to expose the electrodes and contact pads.

The core concept of our multilayer wiring interconnect technology lies in the combination of the anisotropic metal deposition method (electron beam evaporator, CVC Products, Inc.) used in our lift-off gold patterning process with a conically recessed via technique used in our soft-lithographically microelectrode opening process to make the interconnection between different conducting layers possible.

Aperture Diffraction has been used in backside exposure of thick negative photoresist SU-8 to create tapered pillars [5]. We employ this phenomenon to manipulate the UV light intensity profile during the exposure process of the negative photoresist (NR5-8000, Futurrex, Inc.) for making sacrificial posts with a tapered shape. Fig. 1 describes the concept of our multilayer interconnect technology. In Fig. 1(a), after passing through a microhole in the photomask, parallel UV

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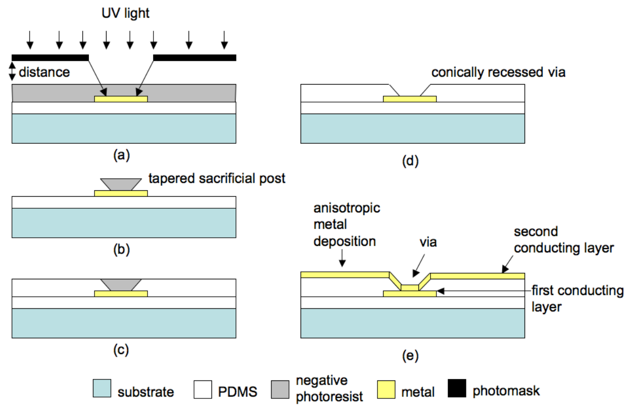


Fig. 1. Concept for implementing multilayer interconnects on PDMS substrate. (a) Aperture Diffraction is used in exposing thick negative photoresist. (b) Upon exposure using the configuration in (a), a tapered sacrificial post is created on top of the metal where a via is to be formed. (c) PDMS is spun on and cured for encapsulation. (d) The sacrificial post is removed and a conically recessed via is created. (e) The second conducting layer is patterned using a lift-off method, in which anisotropic metal deposition is used. The two conducting layers are interconnected by the metal film deposited on the tilted sidewall of the conically recessed via.

light diffracts and casts a Gaussian-like intensity profile in the central area. When a thick negative photoresist layer is positioned at a distance away from the photomask (we placed a 1mm-thick glass slide between the photomask and the sample), the exposure will result in a tapered profile [Fig. 1(b)]. Subsequently, the tapered sacrificial post is used in molding the encapsulation PDMS layer [Fig. 1(c)] to create a complementary conically recessed via where necessary [Fig. 1(d)]. Next, the second conducting layer is patterned using the lift-off method. In the presence of a conically recessed via, the two conducting layers are electrically interconnected by the metal film deposited on the tilted sidewall of the conically recessed via [Fig. 1(e)]. By iterating these processes, more than two interconnected conducting layers can be achieved. The concept described herein is also applicable between the PDMS base layer and the substrate material, which enables the formation of interconnects between PDMS and the substrate.

B. Integrated Packaging Solution for the MEA

Initially, we had used two methods for connecting the MEA to external circuits. Fig. 3(a) shows a clamping method. However, the thin gold film on the contact pads could easily be rubbed off by rigid contacts on the clamp (inset), limiting the re-usability of the MEA. Moreover, the electrical connections were not reliable at the contact pads. In Fig. 3(b), thin wires were glued to the contact pads using conductive epoxy (Loctite® 3880™), followed by PDMS encapsulation (inset). The bonding process was labor intensive, and when the number of electrode channels becomes large, it is simply impossible to wire the MEA manually. Furthermore, the electrical connections were not reliable, either, because the conductive epoxy was cured at 90℃ rather than at the recommended 125℃ to prevent the thin-film gold conductors from cracking and the connections could be lost at the joints when the wires were subject to strain.

In spite of the attractiveness of PDMS-based MEAs, the lack of a good packaging solution for the MEA had limited its applications to a small number of electrode channels with unreliable electrical connections to external circuits. Excitingly, as part of the concept of our multilayer wiring interconnect technology, the conducting traces on the PDMS base layer could potentially be interconnected to traces on the rigid substrate which would provide better properties for connecting to external circuits. Such a design will offer us an integrated packaging solution that will make the MEA easy to be connected to supporting circuits. Many different materials will be eligible for the connecting substrate, provided that: (a) the material is compatible with the MEA fabrication process; (b) PDMS adheres to it strongly enough; and (c) it provides better properties for connecting to external circuits. PCB, silicon, glass, and polyimide, for example, are candidates among this category.

C. Muscle Surface Recording Experiment

The experiment setup for multichannel muscle surface recording is shown in Fig. 4(a). The gastrocnemius muscle from frog hind leg was dissected with sciatic nerve attached, fixed at the ankle end, and attached by suture to a force transducer at the knee end. A connector-integrated MEA [Fig. 3(c)] was wrapped around the muscle surface radially with the four electrodes used labeled corresponding to the respective recording channels. The MEA connector was plugged into a PCB pre-amplifier. The recording reference electrode was placed on another piece of muscle that was in a resting state throughout the experiment. The sciatic nerve was stimulated using a hook bipolar electrode with 100μs/1mA monophasic current pulses. Four-channel EMG signals and the contraction force were recorded. The amplifier settings for EMG recording were: gain=1000, lowpass=2kHz, and highpass=1.0Hz.

III. RESULTS

A. Implementation of Multilayer Interconnects within PDMS

During fabrication, we found that we could control the sidewall profile of the sacrificial post by fine-tuning the UV light exposure energy to create sacrificial posts with different sidewall slopes. A top/base diameter ratio between 2:1 and 3:1 was found to be optimal for both fabrication and electrical performance. Fig. 2(a) shows a tapered sacrificial post with a top/base diameter ratio of about 3:1. The designed hole diameter in the photomask is $100\mu m$, and the resulting tapered sacrificial post has a top diameter of $\sim 130\mu m$ and a base diameter of $\sim 45\mu m$. Fig. 2(b) shows a conically recessed via created by a tapered sacrificial post with a top/base diameter ratio of approximately 2:1. In Fig. 2(c) and (d), a simple two-layer LED demo circuit is shown. The total thickness of the PDMS film is $\sim 90\mu m$, including a $70\mu m$ base layer and two $10\mu m$ encapsulation layers. Two LEDs and two silver wires were glued to their contact pads using conductive polymer. The power was supplied to the

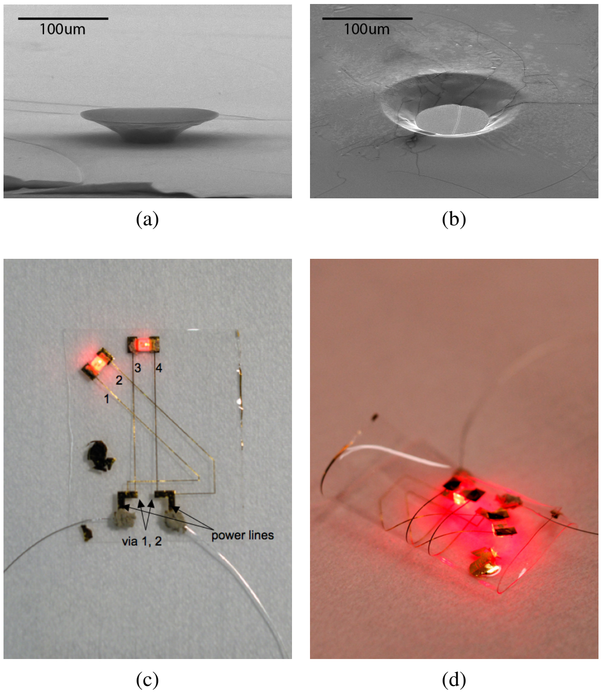


Fig. 2. Demonstration of multilayer interconnects within PDMS. (a) A tapered sacrificial post. (b) A conically recessed via. (c) A simple two-layer LED demo circuit. (d) While folded, the device still maintained its functionality.

device through the two silver wires. In Fig. 2(c), Trace 1, 2 and power lines are on the first conducting layer; Trace 3 and 4 are on the second conducting layer, and are interconnected to the power lines through Via 1 and 2, respectively. In Fig. 2(d), the flexibility of the device was tested by being folded, and the device still maintained its functionality under such a deformation.

The resolution that our fabrication method can achieve is $10\mu m$ width for gold traces and $10\mu m$ base diameter for conically recessed vias. When applying this multilayer interconnect technology, high-density, high-throughput PDMS-based MEAs with an electrode diameter/electrode center-to-center distance ratio up to 1:2 can be easily achieved.

B. Implementation of a Connector-Integrated MEA

In Fig. 3(c), a connector-integrated MEA is shown. The electrode channels embedded in PDMS were routed through conically recessed vias (inset) to a connector pattern on the substrate (glass in this case). An anti-adhesion gold layer had been coated on the glass substrate to help to peel off the MEA body. But, no anti-adhesion gold had been coated in the area surrounding the vias, so that PDMS could adhere to the bare glass substrate strongly. A connector was glued onto the connector pattern using conductive epoxy. Excess glass substrate was cut off. Such a device was tested in multichannel muscle surface recording experiments below.

C. Multichannel Muscle Surface Recording

In our preliminary MEA muscle surface recording experiments (Fig. 4), we have successfully demonstrated the multi-

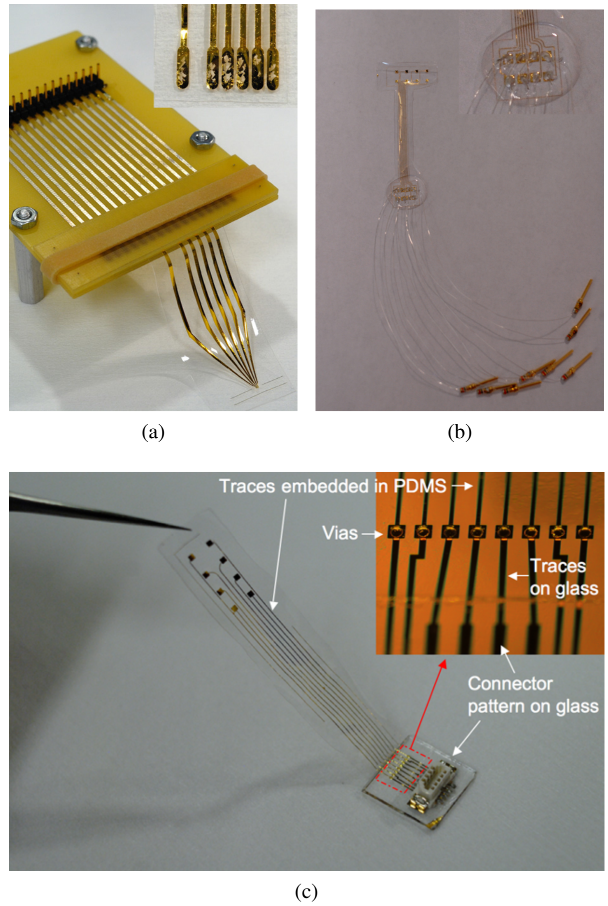
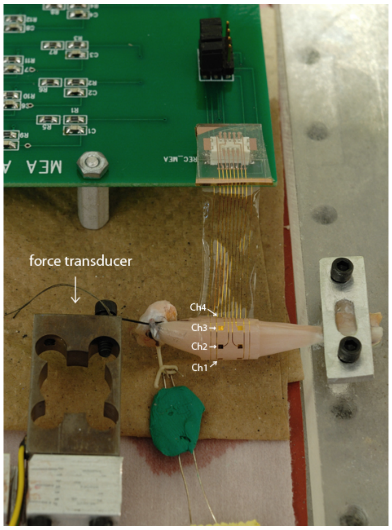


Fig. 3. Different packaging solutions for PDMS-based MEAs. (a) A clamping method. (b) Thin wires were glued to the contact pads using conductive epoxy/polymer, followed by PDMS encapsulation. (c) Integrated packaging solution using our multilayer wiring interconnect technology.

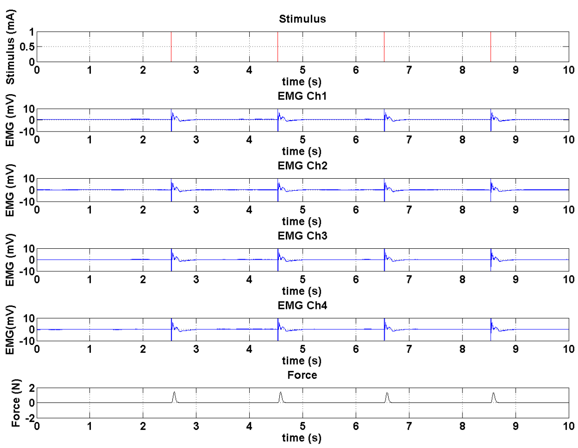
channel recording capability of our device, an eight-electrode connector-integrated MEA [Fig. 3(c)]. The MEA showed good surface conformability with reliable signal recording during muscle contraction. Because the whole sciatic nerve was stimulated synchronously and, as a result, all the motor units were activated at the same time, the commonly known high-frequency interference pattern of the compound action potential (CAP) caused by asynchronous activation of the many motor units was not seen, instead, low-frequency EMG signals [Fig. 4(b)] were recorded, which were the CAPs under the synchronous activation. Such synchronous CAPs comply with the single-motor-unit action potentials extracted from the high-frequency interference EMG signals [6], [7]. In addition, because the four recording electrodes were placed on the muscle surface along a circumference perpendicular to the fiber direction, the monopolar recording data in Fig. 4(b) indicates identically distributed and synchronized electrical potentials under such a whole-nerve stimulation condition.

IV. DISCUSSION

There are numerous applications in neuroscience research and neural prosthetics that employ surface stimulation and recording techniques, for example, spinal-cord surface stimu-



(a)



(b)

Fig. 4. Muscle surface recording experiment using a connector-integrated MEA. (a) Experiment setup. (b) Recording data: stimulus (top), four-channel EMG signals (middle), and contraction force (bottom).

lation for prosthetics, electrocorticography (ECoG) recording for epilepsy detection, and retinal prostheses for vision restoration. These applications thus desire a conformable interface to adapt to the complex soft tissue surface. Furthermore, the ability to achieve such a conformable interface with a high spatial resolution and a high throughput capability will be of great significance in advancing these applications. Previously developed MEA technologies on either rigid materials or flexible materials have problems with mechanical impedance matching to the soft tissue and intimate contact on the tissue surface. Elastomeric materials, such as PDMS, offer excellent potential for better impedance matching, but are very challenging from a fabrication perspective. MEAs fabricated on PDMS substrate [1], [2], [3], [4] not only face with a limitation on spatial resolution, but the interconnection of such devices to external circuits has also pose a great challenge. These two hurdles have significantly suppressed the otherwise promise of such conformable devices. Fortunately, with the introduction of our PDMS-based multilayer wiring interconnect technology, these two hurdles have been overcome and promising applications of such PDMS-based MEAs are lighten up. MEAs with a higher density can now be achieved, as the great number of high-density microelectrodes can be wired using our multilayer interconnect technology. The MEA becomes reliable and easy to use with a compact size as a result of our integrated packaging solution. When used as an implant, e.g. in an epiretinal prosthesis, the high-density MEA can be directly integrated with a silicon chip. Such integratability appears to be very promising in implantable neural prostheses. In the near future, as the first application of such integratable PDMS-based MEAs, we are going to use high-density epimysial (i.e., on the muscle surface) recording to explore the underlying muscular dynamics that can only be revealed from data with a high dimensionality.

V. CONCLUSIONS

We have developed a new conformable MEA technology that will greatly enhance the capability of surface stimulation and recording on neural tissue and muscle. The promise of our integratable PDMS-based conformable MEA technology lies in two aspects: (a) Taking advantage of our multilayer wiring interconnect technology, we are able to implement high-density, high-throughput conformable MEAs with feature size as small as $10\mu m$ and an electrode diameter/electrode center-to-center distance ratio up to 1:2. (b) An integrated packaging solution derived from our multilayer technology makes the MEA easy to be connected to supporting circuits, thus significantly promoting the usability of such MEAs. Important and promising applications will be found in neural prostheses (e.g. high-resolution epiretinal prosthesis), FES, and basic electrophysiology research.

VI. ACKNOWLEDGMENTS

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