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A Parylene-Silicon Cochlear Electrode Array with Integrated Position Sensors

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***Abstract* — A thin-film cochlear electrode array has been developed for a cochlear prosthesis to achieve improved sound perception and position accuracy. The array is fabricated using a bulk-silicon micromachining process that allows parylene deposition and patterning at wafer level, followed by a wet silicon release etch that is compatible with the use of boron etch-stops. The process is capable of realizing arrays with substrates stressed to hug the modiolar wall in the rest state and whose stiffness can be adjusted over a wide range. Built-in tip and curvature sensors respond to tip contact and bending-induced shank stress, respectively during *in-vitro* and *in-vivo* implants. The process is also compatible with the integration of parylene ribbon cables for lead transfer to an implanted electronics package.**

***Index Terms* — Cochlear Prosthesis, Parylene, Strain Gauge**

I. Introduction

WORDWIDE, nearly 100,000 people have received cochlear implants to date, where a bundle of (16-22) wire electrodes is inserted into the cochlea to electrically stimulate receptors in the auditory nerve, bypassing defective hair cells and restoring hearing to the profoundly deaf. Replacing the traditional wire electrodes with thin-film silicon electrode arrays [1] can not only allow higher-density stimulation sites, perhaps leading to significantly higher frequency discrimination, but can also conveniently allow additional features, such as the inclusion of position sensing (and eventually control) to achieve real-time non-radiological implant monitoring in a cochlear implant. Fig. 1 shows a recently-developed hybrid cochlear microsystem, which consists of a hermetically-sealed electronics package, a polymeric cable, and a flip-chip bonded electrode array[2].

Although thin-film electrodes can be realized with flexible silicon shanks (3-4µm thick) to achieve a perimodiolar shape, fitting the cochlear application, they are brittle and can break during implants. They are also relatively stiff for insertion using some thin polymeric backing/insertion tools [3]. Our earlier work [4] used post-processed parylene encapsulation that enhanced array robustness/flexibility and generated the desired shape, but the parylene had to be deposited after array release and required the high-density sites and output pads to be opened individually using laser ablation [5]. This is time consuming and not particularly attractive as a manufacturing technique. As an alternative, S. Takeuchi *et al.* [6] has reported pure parylene recording probes; however, they are not compatible with on-chip active sensing structures that require high-temperature processing.

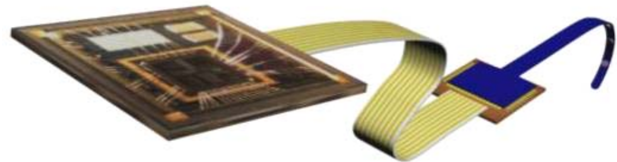

Fig. 1: A cochlear prosthesis under development at the University of Michigan. The microsystem includes an electronic circuit package, a polymeric cable, and a hybrid electrode array.

This paper reports a bulk micromachining process that accomplishes wafer-level parylene-silicon integration while maintaining the ability to adjust the silicon substrate thickness so that flexible and robust cochlear electrode arrays (Fig. 2) can be fabricated. The stimulation sites and bonding pads are opened lithographically pre-release, and the flexible dielectric substrate can not only integrate electrode sites and position-sensing capability, but can integrate ribbon interconnect cables as well.

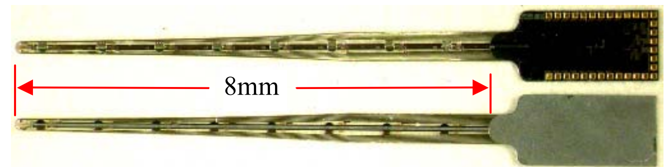

Fig. 2: The front and back sides of a parylene-covered silicon electrode array with built-in position sensors. The 8mm-long shank of the array is transparent and includes eight segments, each of which integrates an electrode site and one position-sensing bridge.

II. Fabrication and Device Design

Parylene is integrated at wafer level after the thin-film cochlear array is fabricated using traditional bulk silicon micromachining [7], allowing high-temperature deposition of polysilicon sensors and dielectric encapsulation. A boron etch-stop defines the silicon portion of the substrate, producing an adjustable thickness (0-15µm) (Fig. 3a), and oxide-nitride dielectrics support aluminum interconnects to the IrO sites and polysilicon strain gauges (Fig. 3b-d). A layer of 3µm-thick parylene is then deposited using physical vapor deposition at room temperature and is patterned (Fig. 3e) using an oxygen plasma before the wafers are isotropically thinned to 100-150µm and then released in 10

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wt% TMAH (with ammonium persulfate and dissolved silicon) (Fig. 3f) under 85˚C.

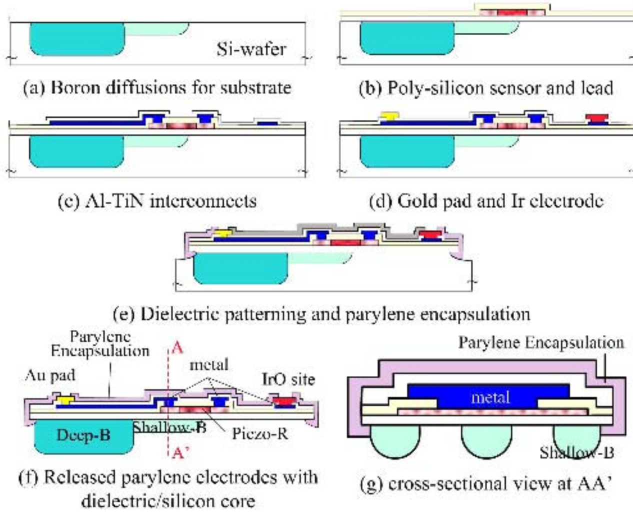

Fig. 3 The parylene-silicon integrated fabrication process flow

The major challenge in integrating parylene into a process involving bulk silicon micromachining is the need for a post-processing release procedure that will not degrade the parylene. EDP (ethylenediamene pyrocatecol), TMAH (tetra-methylammonium hydroxide) and KOH (potassium hydroxide) are three commonly-used anisotropic etchants for silicon that can be used to form boron etch-stops and define thin silicon substrates. EDP has been used at 110˚C to release silicon electrode arrays, exhibiting an etch rate of 80µm/hour. Unfortunately, EDP is damaging parylene at 110˚C and is difficult to use at lower temperatures because of problems with solidification. However, if TMAH is used instead of EDP and the release temperature is lowered to 85˚C, an etch rate of about 70µm/hour can be maintained while the etch rate of the underlying mask dielectrics is negligible (Fig. 4). Also, the etch also results in good surface smoothness if buffer chemicals such as ammonium persulfate and dissolved silicon are used [8].

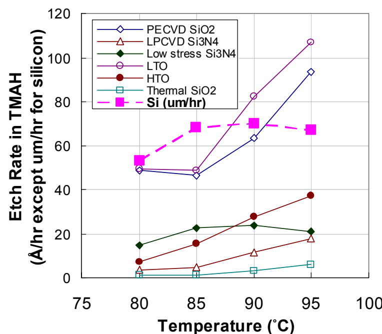

Fig. 4: A comparison of the etch rates of silicon and various passivating dielectrics in TMAH solution at various temperatures.

The present arrays contain eight segments covering the 8mm-long shank; each segment has one electrode site and one polysilicon piezoresistive sensing bridge (Fig. 2). In the bridge, the reference resistor is oriented transverse to the array shank whereas the piezoresistive sensor is longitudinal in order to minimize mismatch and temperature differences between the sensor and reference. Fig. 5 shows the front and the back sides of the transparent tip region embracing the first segment and a tip contact-sensing bridge.

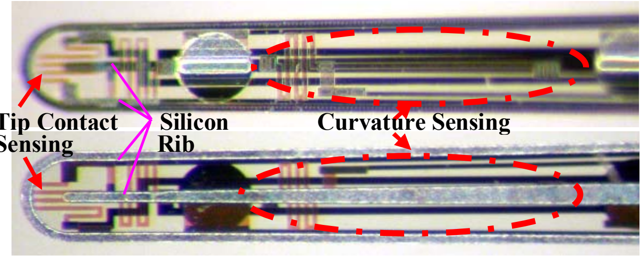

Fig. 5: The front and back sides of the tip region of a transparent parylene-silicon thin-film electrode array with silicon rib support.

III. Results and Discussion

A. *Parylene Encapsulation*

A smooth parylene film having well-defined pads and sites was obtained after release (Fig. 6); however, a high-quality parylene film with good adhesion to the dielectric substrate is required so dry-etched anchors and undercuts are used to integrate the parylene into the silicon substrate process. After patterning the field dielectrics, a deep reactive-ion etch (DRIE) is used to undercut the silicon along the probe edge and the field dielectrics creating holes (anchors) along important features such as gold pads. The 3µm-thick conformal parylene coating then wraps the probe and fills the anchor holes (similar to [9]), mechanically locking parylene in place (Fig. 7).

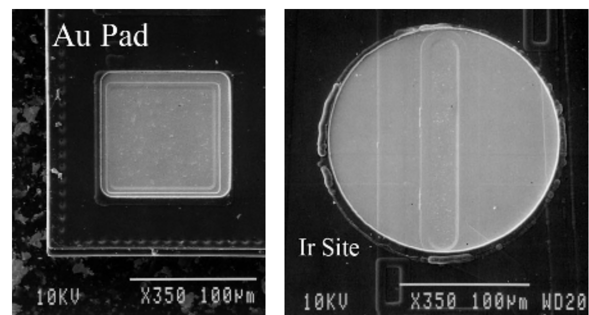

Fig. 6: In-situ pad/site openings can be achieved by dry etching the parylene prior to release.

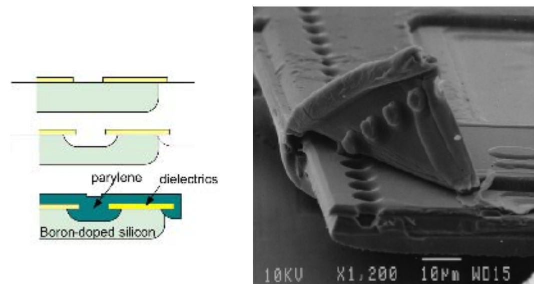

Fig. 7: The edge wrapping and anchoring of parylene on a silicon substrate. Isotropic DRIE etching undercuts the Si substrate along shank edge and creates undercut anchor holes.

Parylene is not thought to be a particularly reliable material for electrical insulation compared with inorganic

dielectrics. Therefore, the latter films are used for electrical isolation, and parylene encapsulation is mainly used for mechanical support and as a biocompatible interface in this cochlear application.

B. Electrode Stiffness and Robustness

Parylene, as a biocompatible polymer, reduces the array stiffness and enhances its robustness. The Young's Modulus of parylene-C is only 2-5GPa, two orders lower than that of silicon (169GPa) or dielectrics (silicon nitride: 222GPa; silicon dioxide: 70MPa). Array flexibility is obtained by eliminating/minimizing the thickness of the silicon substrate (Fig. 8a) or optimizing the width of the rib support (Fig. 5). Encapsulating the array with parylene then allows the strength of the array to be maintained without stiffening the array. As a result, the stiffness of the electrodes can be reduced by one order while still maintaining enough strength (Fig. 8b). Moreover, the integration of parylene facilitates real-time monitoring of implant depth because of its transparency (Fig. 9a), minimizes any chance of breakage, and avoids substrate separation should any breakage occur (Fig. 9b).

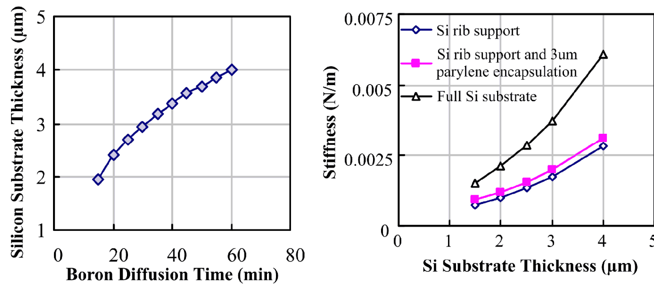

Fig. 8: (a) Silicon substrate thickness can be adjusted by varying the boron diffusion time. (b) Coventor simulations demonstrate that electrode stiffness can be reduced using a rib-supported silicon substrate of reduced thickness even if an encapsulating layer of 3µm-thick parylene is applied.

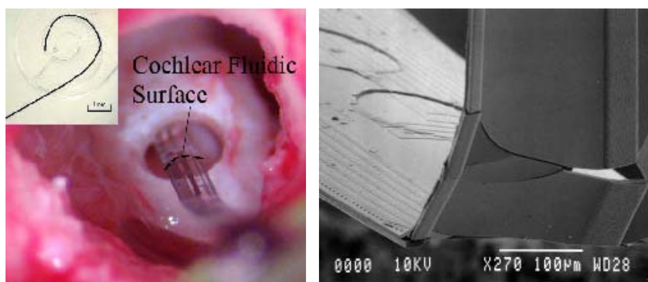

Fig. 9: (a) The implant depth of a parylene-encapsulated dielectric electrode can be monitored using the transparency of the substrate. (b) A shattered cochlear electrode array is held together by parylene after breaking.

C. In-Vitro Bench Testing

The wafer-level integration of parylene maintains the use of the polysilicon piezoresistive bridges for position sensing. The sensor resistance is typically 40kohm. Fig. 10a shows the response of a tip sensor on one array, detecting wall contact while being inserted in a 2D model of the guinea pig cochlea. The signal levels varied as the strength of touching varied (Fig. 10b). The positioning of the eight curvature sensors were also recorded (gain=30) as the electrode array was bent at various shapes (Fig. 10c). Immunity to noise and temperature fluctuations is enhanced by using a transverse reference resistor close to each position sensor.

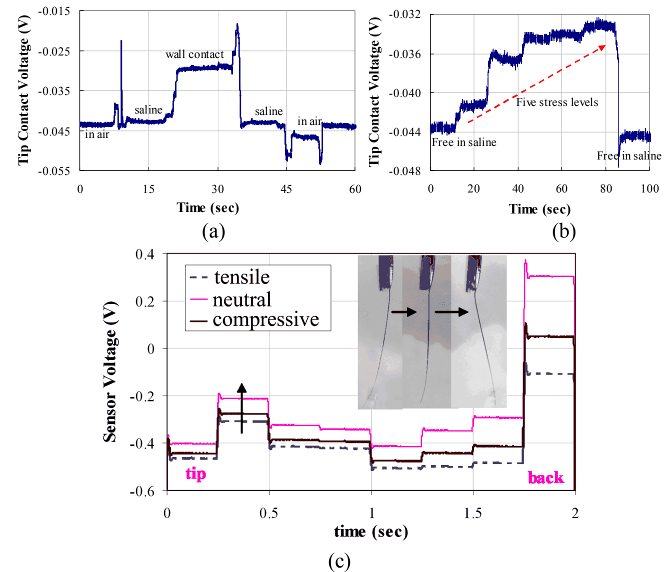

Fig. 10: (a) Tip contact response during the in-vitro insertion of a parylene-encapsulated dielectric probe (Gain=10), and (b) five discrete stress levels were observed. (c) The curvature sensor outputs varied as a parylene-encapsulated electrode was stressed at different levels (Gain=30).

System integration can be achieved by integrating the arrays with 30mm-long cables at wafer level as shown in Fig. 11. Both aluminum and gold leads have been used as interconnects, sandwiched between the dielectric stacks and encapsulated by parylene. Gold leads have a resistance of about 180Ω, 10% that of aluminum and less than 1% that of the piezoresistive bending sensors.

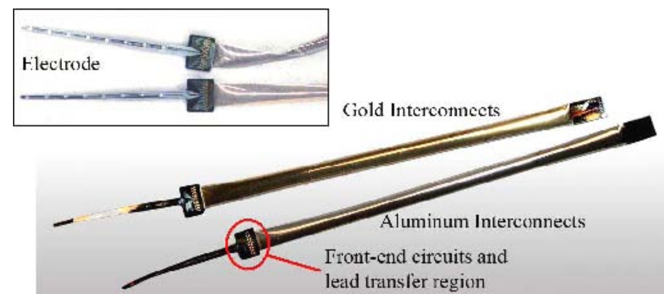

Fig. 11: A parylene-silicon electrode array (8mm) integrated with a cable (30mm) directly at the wafer level. In the future, front-end multiplexing and preamplification circuit will be integrated close to the electrode, improving noise immunity and minimizing the number of the leads transferred.

D. In-Vivo Position Sensing

The position sensing system was used to record tip contact and recover probe shape during an *in-vivo* implant in a paralyzed guinea pig. Immunity to media variation was observed as the tip was inserted into the cochlear fluid; touching the tissue along the cochlear wall resulted in a 4mV signal variation (Fig. 12). The averaged outputs of the curvature sensors were recorded at discrete implant

positions, and the preliminary shape recovery was obtained to illustrate the array positions inside the guinea pig cochlea (Fig. 13).

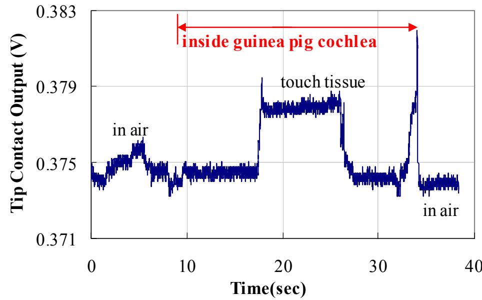

Fig. 12: The real-time response of a sensor bridge shows tip contact during an in-vivo implant into guinea pig cochlea. The signal level is reduced due to the soft touch of the tip with the cochlea tissue

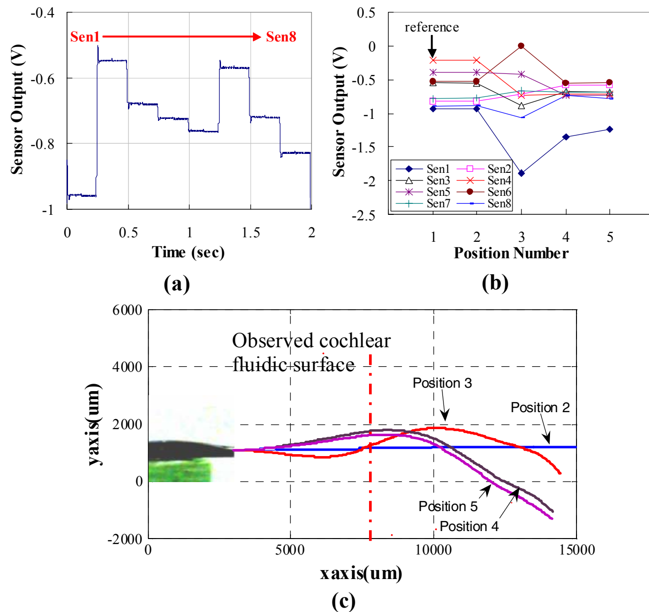

Fig. 13: (a) The curvature sensors were scanned every 2 seconds as a parylene-encapsulated electrode was implanted into a guinea pig cochlea. (b) Output from the eight sensors was averaged at five implant positions, and (c) the positions were recovered with respect to the PC board support.

The major concern in in-vivo testing is noise reduction. Compared with the noise sources in a well-controlled bench environment, the real-time animal testing setup introduces difficulties in noise screening and involves extra noise sources, such as 60Hz power supplies and the impact of body temperature. Procedures were taken to suppress such noise by using low-pass output filters and coaxial cables. As a long-term solution, the multiplexing and preamplification circuitry should be moved closer to the sensors.

During the acute testing, the parylene-integrated dielectric probe has improved flexibility, robustness and visibility during implant; however, for a chronic cochlear implant, a backing device or an insertion tool is still necessary in order to achieve a deep and accurate positioning of this thin-film electrode. Pneumatically-actuated backing/insertion devices [2] are being developed, and the possibility of on-chip actuation using thermal bimorphs or piezoelectric actuators is being examined.

IV. Conclusion

Thin-film cochlear electrodes have been utilized in a cochlear prosthesis to achieve improved perceived sound quality and the ability to do real-time electronic position imaging. In this paper, a bulk micromachining process was developed to integrate parylene encapsulation into the cochlear electrodes at wafer level. Stimulation sites were opened lithographically pre-release. Because of the introduction of parylene, the silicon part of the substrate can be engineered in thickness and width while maintaining a flexible and robust dielectric substrate that can integrate electrode sites and sensing capability. Built-in tip and curvature sensors respond to tip contact and bending-induced shank stress, respectively. Moreover, in the longer term, the integration of ribbon cables provides the potential to fabricate the entire front-end cochlear system monolithically.

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References

[1] T. E. Bell and K. D. Wise, "A flexible Micromachined Electrode Array for a Cochlear Prosthesis", *IEEE Int. Conf. on Solid-State Sensors and Actuators (Transducers'97)*, Chicago, June 16-19, 1997

[2] J. Wang, M. Gulari and K.D. Wise, "An Integrated Position-Sensing System for a MEMS-based Cochlear Implant", *IEEE International Electron Devices Meeting (IEDM 2005)*, Washington, DC, pp. 121-124, December, 2005

[3] B. Y. Arcand, P. T. Bhatti, N. V. Butala, J. Wang, C. R. Friedrich, and K. D. Wise, "Active Positioning Device for a Perimodilar Cochlear Electrode Array", *High Aspect Ratio Micro-Structure Technology Workshop*, June 2003

[4] J. Wang, M. Gulari, P.T. Bhatti, B.Y. Arcand, C.R. Friedrich and K.D. Wise, "A Cochlear Electrode Array with Built-in Position Sensing", *18th IEEE Int. Conf. on Micro Electro Mechanical Systems (MEMS 2005)*, Miami, pp. 786-789, January 2005.

[5] J. D. Weiland, D. J. Anderson, C. C. Pogatchnik, J. J. Boogaard, "Recessed Electrodes Formed by Laser Ablation of Parylene-Coated, Micromachined Silicon Probes," *19th Int. IEEE EMBS Conf.*, Chicago, pp. 2273-2276, November 1997

[6] S. Takeuchi, T. Suzuki, K. Mabuchi, and H. Fujita, "A 3D Flexible Parylene Probe Array for Multichannel Neural Recording", *1st International IEEE EMBS Conference on Neural Engineering,* Capri Island, Italy, pp. 154-156, March 20-22, 2003.

[7] K. D. Wise and K. Najafi, "Fully-Implantable Auditory Prostheses: Restoring Hearing to the Profoundly Deaf," *IEEE International Electron Devices Meeting (IEDM 2002)*, San Francisco, pp. 499-502, December 2002.

[8] G. T. A. Kovacs, N. I. Maluf and K. E. Petersen, "Bulk Micromachining of Silicon", *Proceedings of the IEEE,* Vol. 86, No. 8, August 1998

[9] M. Liger, D. C. Rodger, and Y.-C. Tai; "Robust Parylene-to-Silicon Mechanical Anchoring", *16th IEEE Int. Conf. on Micro Electro Mechanical Systems (MEMS 2003)*, Kyoto, pp. 602-605, January 2003