A TSV-Based Bio-Signal Package With μ-Probe Array

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***Abstract*— Bio-signal probes providing stable observation with high quality signals are crucial for understanding how the brain works and how the neural signal transmits. Due to the weak and noisy characteristics of bio-signals, the connected interconnect length between the sensor and CMOS has significant impact on the bio-signal quality. In addition, long interconnections with wire bonding technique introduce noises and lead to bulky packaged systems. This letter presents an implantable through-silicon via (TSV) technology to connect sensors and CMOS devices located on the opposite sides of the chip for brain neural sensing applications. With the elimination of traditional wire bonding and packaging technologies, the quality of bio-signal can be greatly improved.**

***Index Terms*— TSV, CMOS MEMS, bio-signal probe.**

I. Introduction

In recent years, advanced micromachined/assembled micro probe arrays with electrical stimulation/recording ability have come to play an essential role in exploring central nervous systems. Simultaneous observation of a larger number of cell activities has become the general requirement to understand the nervous system [1]. Advances in neuroscience and neuroprosthetics now require microelectrode arrays that are able to access numerous neurons simultaneously with high spatial resolution [2]. Recording of the extracellular action potentials has been accomplished by surgically implanting neural probes into the target neurons of interest, which resulted from neural activities [3]. Probes that could insert a large number of recording sites into neural tissues with minimal tissue damage are therefore needed. In addition, the design of the probe arrays should be optimized for an experimental purpose that an electrode diameter of a few micrometers could support single-unit recording.

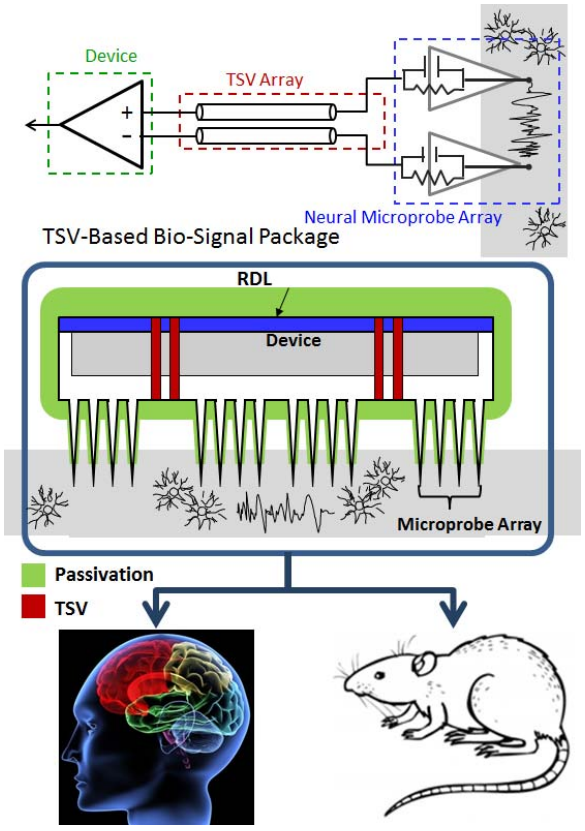

Fig. 1. Structure of the integrated microsystem.

Conventional long interconnection from sensor to CMOS circuit including wire and flip-chip bonding with solders, can induce many effects, such noise and bulky packaging, while excessive interfaces may cause signal attenuation. In this letter, an implantable TSV-based bio-signal package with microprobe arrays is proposed. By using TSV technology, new approach with a short length from μ-probe tip to CMOS circuit with the small package size is developed.

II. Integrated Probe-TSV-CMOS Technology

Fig. 1 illustrates the structure of the integrated microsystem. The MEMS neural microprobe array and low-power CMOS sensing devices are fabricated on the opposite sides of the same silicon substrate. Cu TSVs are used to form

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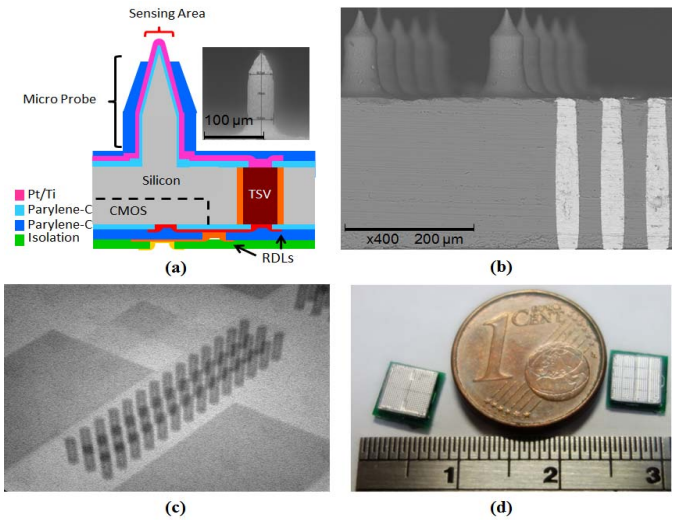

Fig. 2. (a). Cross-section view of the structure. (b). Cross-section view of the device after ICP. (c). The bio-chip and TSV array under X-ray microscopy. (d). Photograph of the integrated probe microsystem.

low impedance interconnection between the microprobe and CMOS devices, thus providing the shortest signal transmission distance from sensors to devices [4], [5]. Fig. 2(a) shows the cross-section view of the structure. The overall chip is 5×5 mm^2, 350 μm in thickness including 150-μm-height probes and 200-μm-height TSV, respectively. The pitch distance of two probes is 200 μm, based on the density of cortex column on the gray matter. The columns are ranged from 200 μm to more than 1 mm in diameter [7]; each may comprise up to hundred of neurons. This μ-probe is constructed by two cylinders, and the diameters of the top and bottom cylinders are 30 μm and 50 μm, respectively. By modifying the process parameter, a narrow head and wide base result, similar to a cone shape, of the probe shape can be achieved. According to the shear force formula (1), under the same force and the same shear modulus (G), it means that the shear strain (γ) is lower when the area of thrust surface (A) becomes larger:

$$\tau = P/A = G \cdot \gamma \tag{1}$$

τ is the shear force G is the shear modulus

P is the force γ is the shear strain

A is the area of thrust surface

Obviously, the wide base will be able to provide good strength to avoid the damage during implantation. A total of 480 microprobes is fabricated and divided into 2×2 and 4×4 sensing areas, forming 4 and 16 bio-signal recording channels [6]. Fig. 2(b) is the cross-section view of the device with probe array and TSV. In Fig. 2(c), the X-ray microscopy images show the bio-chip with Cu TSVs without visible voids, indicating the fully Cu filled results. These experiment results validate the TSV sidewall insulation, electrical performance, and fabrication quality. Fig. 2(d) shows the integrated microsystem including the probe arrays, PCB and connector. The total size of the integrated system is 5 mm * 5 mm.

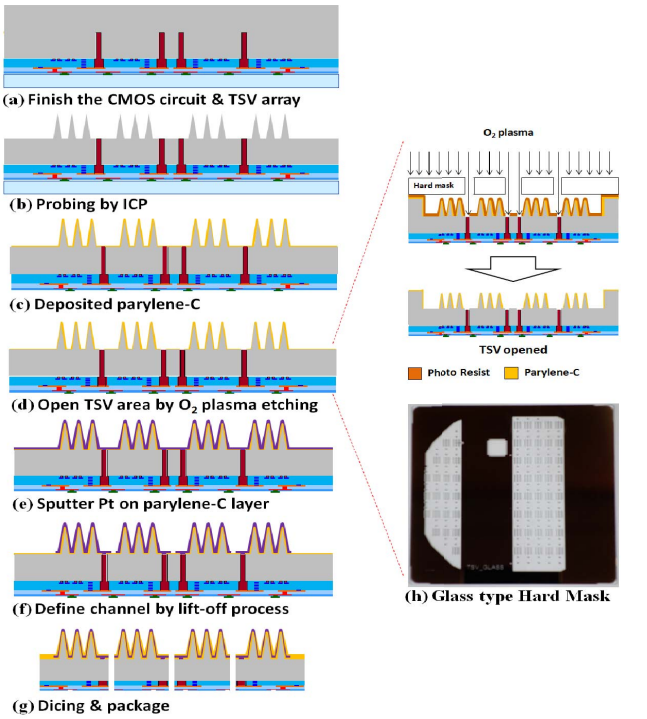

Fig. 3. Detailed process flow, include post processing and hard mask design for O_2 plasma etching.

The left side of Fig. 2(d) is 4 channels system and the right side of Fig. 2(d) is 16 channels system.

III. Fabrication

Fig. 3 illustrates the detailed process flow. In the front-side process, CMOS devices are fabricated using UMC 0.18 μm process on 8 inch wafer, followed by a fully-filled Cu plating process for fabricating Cu TSVs with 200 μm depth (height) and 25–30 μm diameter. Next, RDL is fabricated for the connections between TSV arrays and circuit input pads, as shown in Fig. 3(a). It should be mentioned that each channel has one individual set of CMOS circuit. Thus, the bio-signal does not need to be separated after recording. Then, a deep ICP etching process is applied on the back side of the wafer to form the microprobe array, as shown in Fig. 3(b).

At the beginning of the ICP etching process, isotropic etching is used to etch the probe tip area into a hill. Then, anisotropic etching is used to etch the probe height to 150 μm. Finally, isotropic etching is applied again to etch the tip of probe. To insert the probe into the *in vivo* brain, tip diameter must be less than 5 μm.

After the ICP step for probe formation, a 5 μm parylene-C is deposited on the structure to isolate different channel, as shown in Fig. 3(c). Parylene-C is biocompatible and commonly used *in vivo* body. In Fig. 3(d), to transfer the signal from the probe to the device, the area of the TSV must be open using O_2 plasma. However, with the same etching rate of photoresist (PR) and parylene-C of parylene-C near the probe tip can be easily over etched. A hard mask is implemented using a standard 4-inch glass mask to solve this issue. The TSV open area is drilled by laser to let the O_2

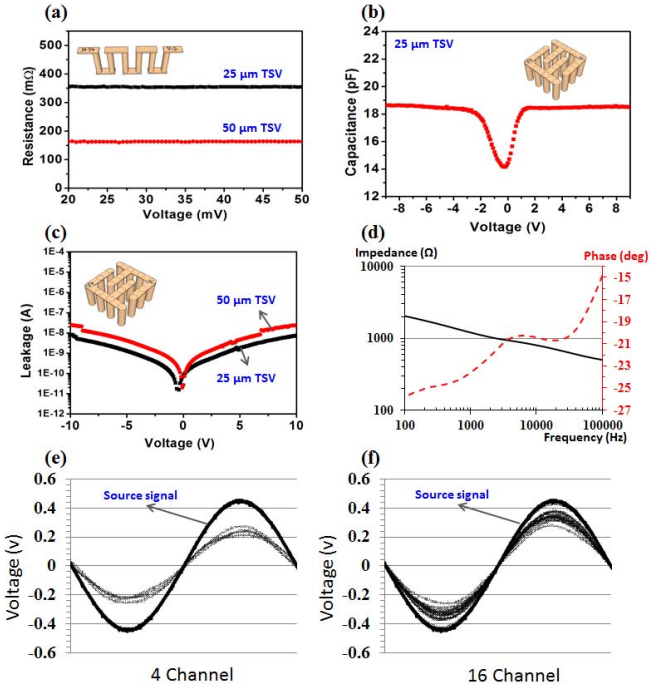

Fig. 4. (a) Resistance measurement of a Cu TSV array in the microsystem; (b) C–V sweeping of multiple TSVs using comb structure; (c) leakage current measured between +/− 10 V on 100 Cu TSVs; (d) measured impedance of the probe (solid line: impedance; dash line: phase); (e) and (f) the characteristics of the 4-channel and 16-channel μ-probe array.

plasma pass the hard mask, while the tip area of the probe is protected by hard mask, as shown in Fig. 3(h).

After the TSV is opened by O_2 plasma, a 3000 Å platinum (Pt) is sputtered and then lifted off to define different channels, as shown in Fig. 3(e) and Fig. 3(f). In this step, biocompatible Pt is used instead of gold to avoid the corrosion of the biosensor. After dicing and packaging, a bio-signal recording package is completed, as shown Fig. 3(g). Notably, only platinum and parylene-C layer will directly contact the brain tissue.

IV. Electrical Characteristics of TSV

Daisy chain and comb structure are fabricated to investigate the electrical characteristics of 25- and 50-μm-diameter TSV. Fig. 4 shows the resistance measurement of 30 Cu TSV arrays. The measured daisy chain resistance shows stable value under current stressing. To ensure the insulating capability of the sidewall TSV, the comb structure is designed for measuring the capacitance and the leakage current.

Fig. 4(a) shows the capacitance measurement between −10 and 10 V. The average measured capacitances for 25- and 50-μm-diameter Cu TSV are 0.74 and 0.88 pF, respectively, as shown in Fig. 4(b). Fig. 4(c) shows that the leakage current of TSV structure is low and around nA scale. These experiment results validate the electrical property of TSV sidewall and filling. Fig. 4(d) presents the probe impedance measurement result in 0.9% saline which emulates the in-vivo environment. Besides, impedance of single TSV is 5.5 mΩ, much smaller than that of the conventional long transmission wires. Fig. 4(e) and (f) present the characteristics of the 4 channel and 16 channel μ-probe arrays, respectively. The solid line in the Fig. 4(e) and (f) is the 880 mV sine wave source signal and others dotted lines are the recording signal from different channel of the μ-probe array.

V. Conclusion

In this letter, a novel through-silicon-via-based double-side bio-signal recording device is demonstrated and investigated. By using TSV technology, the shortest path from signal to CMOS device is established. With the elimination of the conventional wire bonding, the quality of bio-signal can be greatly improved. The percentage of exposed metal on the tip of μ-probe array is 1.7×10^{-4} % for 4-channel unit and 1.52×10^{-4} % for 16-channel unit, respectively. Impedance of the device is 1.2 KΩ/1 KHz. The total size of the chip is only 5 mm × 5 mm. There are 3 × 8 TSV arrays for each channel. The survival rate of rat can increase due to the small size of the device. There are 30 microprobes in one block of 16 channels die and 140 microprobes in one block of 4 channels die. Different channel can record different neural cell signal, thus more channels can record more signals, and it is helpful for neural-signal analysis. All the post processes is done and this bio-signal package is ready for bio-signal application.

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