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A HIGH-THROUGHPUT PROCESS AND LOW-NOISE STRUCTURE FOR SILICON NEURAL PROBE

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Abstract

This paper focuses on the design and fabrication of the silicon neural probe with two improvements: the design of process for improvement in fabrication yield and the integration of ground layer for reduction of electromagnetic noise. First, we have found that fabrication yield is determined by wet-etch step for bulk micromachining on back side of wafer. In order to improvement of yield, a design of mask is modified that all probes are linked by micro tab located between probes and bars on the wafer. The micro tab is used to hold probes on wafer during wet-etch. Second, the main advantage of the internal ground layer located below conduction line contributes dramatic reduction of electromagnetic noise. To evaluate improvement due to the use of internal grounding at electrode level, we measured power spectral density (PSD) of noise in recorded signal. The noise PSD is reduced from -45dB to -100dB at 120Hz that one of frequencies came from external noises. These improvements will contribute to development on advanced neuroprosthetic devices using silicon neural probe.

Key Words

silicon neural probe, neural prosthesis, power spectra density, MEMS, neural recording

1. Introduction

Micromachined neuroprosthetic devices using silicon neural probe can be designed and fabricated to permit recording and stimulation of specific sites in the nervous system to restore their function, lost due to disease or trauma. These microfabricated device such silicon neural probes offer great promise for treating neurological disease and providing methods for a long term study of the central nervous system [1-2]. They have been used to record field potentials or single unit activity in the brain [3]. The number of microelectrodes on these silicon probes combined with their spatial density and resolution contributes to the study of neuronal activity in the various regions of the brain [4]. Some devices have on-board signal processing circuitry [5], including telemetry [6], and many of them have multiple electrodes some with complex three-dimensional array [7].

However, the promise of such micromachined devices is limited by inadequate electrode performance. In the design of silicon neural probe, the noise characteristic is a major issue, since it determines the required signal-to-noise ratio (SNR) of the recorded signal. Major noise source is electromagnetic interference (EMI) from external factors such as 60-Hz power line, coupled through various parasitic capacitances. Proper shielding, grounding and isolation are necessary, in order to reduce the coupling of EMI. In a silicon neural probe, careful layout design is required [8]. Wise *et. al* described the first photoengraved silicon probe formed by high-dose boron diffusion, with wet etching to define the probe shape [9]. However, this method gives a probe thickness limited range below about 15 μ m. We previously reported on the development of a silicon probe fabricated by deep-Si dry etch and wet etch that it is able to obtain over a 50 μ m shank thickness, well beyond that readily obtainable by boron diffusion[10]. Although easier to fabricate, a fabrication yield of this method is limited by wet-etch to release the devices from silicon wafer. This paper reports the development of new design and fabrication process of noise insensitive silicon probe fabricated by modified wet etch technique for increasing process yield.

2. Material and Methods

2-A. Design and Fabrication



Fig. 1. A schematic view of new mask design contained different probe type for high-yield process.

The silicon neural probe is fabricated from <100> oriented, p-type silicon, polished on both the front and back. The design of mask is also changed that all probes are linked by micro tab located between probes and bars

on the wafer. Fig.1 shows the mask design which probes connected by micro tab. Triple dielectric layers (SiO_2 1000Å / Si_3N_4 2000Å / SiO_2 5000Å) are used as the insulating layer. Poly-Si is deposited using a Low Pressure Chemical Vapor Deposition (LPCVD), at 625°C and 300mTorr, to a thickness of 3500Å. This layer is then doped, in a furnace at 950°C, with POCl_3 to a concentration of 10^{21} cm^{-3} , and patterned for recording sites and interconnections. The same type of triple dielectric layers, as described above, is then deposited on top. Subsequently, the deep-Si etching is performed using the Bosch process, to a depth of 50µm. This etching depth determines the final shank thickness of the neural probe. To attain improvement of fabrication yield, a new wet-etch technique is developed. In order to protect silicon surface from KOH contact, shielded Teflon bottle is used during wet-etch step (Fig. 2.) Nitride film is deposited on the side of electrode to protect surface and side of silicon shank, and then it is removed by reactive ion etching after wet-etch step. The micro tab can hold probes each by each silicon wafer during and after wet etching, which is contributed to uniformity of thickness and high-yield fabrication.

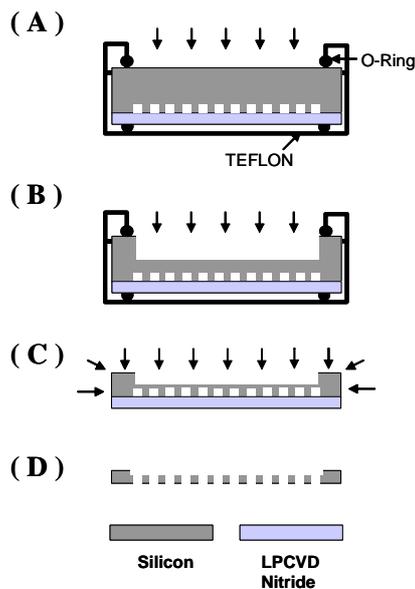


Fig. 2. Flow diagrams of wet-etch process using a sealed Teflon bottle to protect surface and side of silicon probe from KOH.

2-B. Measurement of Power Spectra Density and Impedance Spectra

The major noise sources can be grouped into two categories. One is EMI from external sources such as power lines or monitor. The other source is intrinsic noise, following the standard Johnson noise equation for the RMS voltage noise of resistor. In addition to noise considerations, electrode impedance reduction is required, because most of signal voltage would drop across the

largest between electrode and input impedance of the external system. To evaluate electrochemical performance, the impedance spectra are measured by a PC-driven potentiostat. All electrochemical measurements are performed in 0.1M phosphate buffered saline (pH=7.4) using the electrolyte in a three-electrode cell. The measurements are performed with AC signal between the counter electrode and a doped poly-Si electrode used as the working electrode. To evaluate improvement due to the use of internal grounding, we measured power spectral density (PSD) of noise in recorded signal. PSD is the frequency response of a random or periodic signal. It tells us where the average power is distributed as a function of frequency. The PSD of signal is measured to evaluate the performance of internal ground layer located over silicon substrate. This PSD is calculated from rate histogram of the signal. The final PSD value is the average of all spectra for the separate interval of bin length. In PSD measurement, the equivalent circuit of this silicon probe with internal ground layer immersed in an electrolyte solution is shown in Fig. 3.

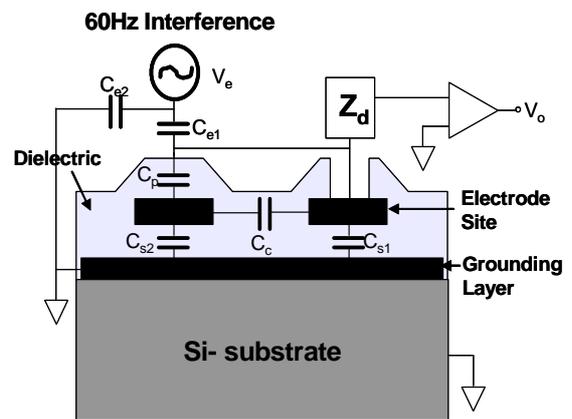


Fig. 3. A cross-sectional model of silicon probe. The probe is immersed in an electrolyte and exposed to 60-Hz noise.

2-C. Evaluation of Electrophysiological Performance.

Neural recording experiments are used to verify the electrophysiological performance of the silicon neural probe. Sprague-Dawley rats (250g) are anaesthetized with urethane (1g/kg, i.p.). All animals used in neural recording are treated in accordance with academic animal research guidelines of Seoul National University. The silicon neural probe is driven into the target region of the brain or spinal cord by a micromanipulator. A multi-channel acquisition system (Plexon Inc., Dallas, TX) is used to record the extracellular neural activity *in-vivo*. The signal is amplified for a gain of 10000; bandpass filtered at 150Hz to 5 kHz, and passed for storage and analysis to a personal computer. Detailed methods of surgery can be found in reference [11].

3. Results and Discussion

Fig. 4 is optical picture showing that silicon neural probe can be fabricated by new high-yield process without the loss of silicon probe. A large number of probes are fabricated in a single wafer as shown by the projection light micrograph (Fig. 4A).

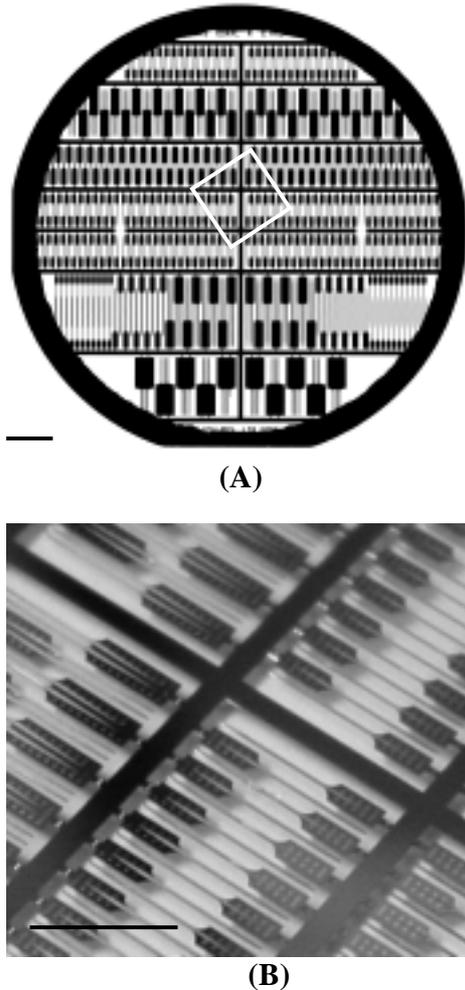


Fig. 4. (A) A projection light micrograph of whole wafer contained a large number of probes. (B) A magnified view of the marked area in the upper image. Scale bars are 10mm.

This design of process is capable of high-yield exceeding 95 % of very small and various structures on the same substrate. Each of probes has a micro tab with a break-away connector which attached them to the wafer for holding. All probes are not separated from silicon wafer even after bulk micromachining on the back side of the substrate in KOH solution. All etching processes are highly selective and the thickness of the probe can be controlled very easily. Probes are 5 mm and 10mm long and $50\ \mu\text{m} \times 128\ \mu\text{m}$ in cross-section of single shank. Each probe has eight recording sites with edge-to-edge spacing of $150\ \mu\text{m}$ and $250\ \mu\text{m}$, respectively. Fig. 5A

shows a scanning electron microscopy (SEM) view of the probe as well as a magnified view of the tip. The probe tip is tapered to less than one micron for easy penetration into the neural tissue.

Fig. 5B shows the 32-CH silicon neural probe bonded to a printed circuit board (PCB) for connection with external recording systems. To permit handling and placement of the probes, a special PCB is designed to separate two parts. Probes are bonded to 1st PCB, then insulated and stabilized with epoxy. It can be exchanged easily from 2nd connector PCB if probe is damaged or broken.

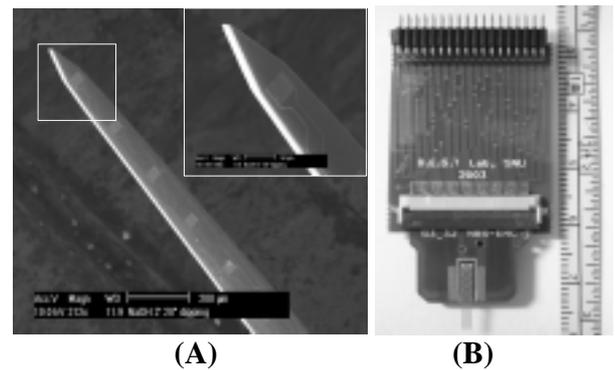


Fig. 5. (A) SEM views of electrode tip and sites. (B) A whole picture of neural probe mounted on PCB with connectors.

Fig. 6 shows the difference of power spectra density of the signal from probes without ground layer, and fabricated internal ground layer, respectively. Y axis is power spectra density with scale unit dB.

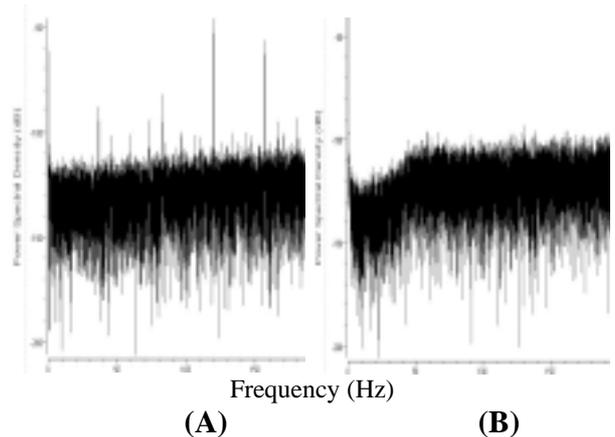


Fig. 6. Plots of power spectra density. Plot (A) is taken from control probe without ground layer, Plot (B) is taken from test probe with internal ground layer located below the lower dielectric layers.

This shows that the frequency responses of these signals are generally different. Fig. 6 A looks more flat across the low frequency band, however, Fig 6 B shows clearly the effects of internal ground on reduction of external EMI noise such 60-Hz harmonic frequency. In order to evaluate of electrochemical characteristics, Impedance spectra is measured at 1 kHz. The area of the electrode site is $30 \times 30 \mu\text{m}^2$, and 0.1% phosphate buffered saline is used as the electrolyte. The impedance of the electrode is $1.96 \pm 0.18 \text{ M}\Omega$ ($n=13$), which is slightly lower than the impedance of a gold site in the same area. The phase is $-87.2 \pm 3^\circ$ ($n=13$). This result indicates that the doped poly-Si is dominated by its capacitive component. A capacitive characteristic of an electrode is helpful when the microelectrode serves in the recording of neural signals.

The recording sites of the probe can be determined *in-vivo* by monitoring the unit neural activity and the amplitude versus the depth distribution of the evoked potentials. To ensure that the electrode interfaces well with the external recording system, neural activity is recorded using the silicon neural probe, and is shown in Fig. 7. The electrode sites with an area of $900 \mu\text{m}^2$ and separated from each other by $300 \mu\text{m}$, are located perpendicularly through the spinal cord. The recording sites residing in cell body layers provide units with very large signal-to-noise ratios (SNR).

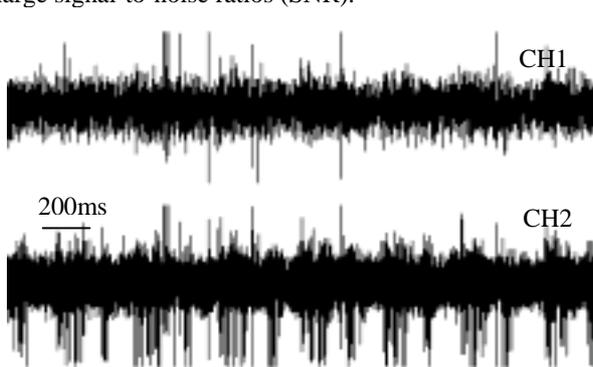


Fig. 7. Acute recording from rat spinal cord. The action potentials being recorded at the different sites are shown to be independent.

4. Conclusion

We have developed a silicon neural probe with low-noise characteristics through high-yield process using new wet-etch technique which allowed for a wide range of shank thickness. In this study, we describe a silicon neural probe, which shows a favorable performance with respect to impedance spectra, noise reduction and acute neural recording. We strongly believe that these studies will lead to advances in our understanding of neural network in the brain, and to the realization of micromachined neuroprostheses.

5. Acknowledgement

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