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Multichannel 5 × 5-Site 3-Dimensional Si Microprobe Electrode Array for Neural Activity Recording System

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Multichannel 5 × 5-site Si microprobe electrode array has been developed for neural activity recording. Si microprobes were fabricated successfully at predetermined sites on a chip using Au dots and Si_2H_6 gas source molecular beam epitaxy (GS-MBE), a method based on vapor-liquid-solid (VLS) growth. Selective VLS Si growth allowed the design of three-dimensional (3D) microprobes with 40 μm spacing in a 5 × 5 array. The diameter and the length of the Si probe can be widely changed by changing the Au dot size and the Si growth time, respectively. In addition, the circular-cone-shaped Si probe has a shape suitable for penetration into neural tissues, and can be realized by increasing growth pressure. The mechanical strength of the Si probe was evaluated with observation of its bending and penetration into a gelatin membrane, which indicated that the Si probes are strong enough to withstand the application. Signal recording with the same amplitude as neural activity was also performed using the fabricated Si probe array chip. These results confirm that high-density neural signals from neural tissues can be obtained with the multichannel 3D VLS Si microprobe array chip. [DOI: 10.1143/JJAP.42.2473]

KEYWORDS: multielectrode array, vapor-liquid-solid growth, microelectrode, neural probe, neural interface

1. Introduction

Multichannel penetrating microelectrode will accelerate the study of neuron and brain science. The microelectrode is needed for neural recording as well as for stimulation. The microelectrode must be a few microns in diameter for recording of a neuron. And the electrode array must have spacing on the order of 10 μm to 100 μm as same as that of neurons. Furthermore, the electrode with needle-like shape is desirable, so that it can penetrate easily into neural tissues. Some applications of the microprobe include the signaling of a retina, and investigation of human sickness under micro-gravity in space. Another application of the probe is as an electrode for human interfaces, which can transmit neural signals between brain/neuron and electric/mechanical devices. These human interface devices could be used to restore the sensory and motor functions of an injured person.

For applications in neuroscience, previously fabricated multichannel penetrating electrode arrays are based on Si technology. An example is the MEMS-based electrode array with on-chip signal processing circuits reported by Gingerich and Wise,[1] which allows 256-site recording in neural tissues. Another example is the brush-type electrode array fabricated with a dicing process developed by Normann *et al.*[2] Although these electrode arrays are capable of recording neural activity, high-density recoding has not been performed because they are spaced a few hundred microns apart.

As a microelectrode array which will solve the above problem, we have proposed a Si microprobe array fabricated by selective vapor-liquid-solid (VLS) Si growth, with on-chip integrated circuit (IC) for signal processing.[3,4] In the fabrication process, the VLS Si probes are grown after the on-chip IC is fabricated. The diameter and the position of the Si probe were controlled using a SiO_2 window mask and a lift-off method by photolithography. These Si probe sites can be designed so that they are close to the on-chip IC, and thus a smart electrode array can be realized.

In the present paper, focusing on the Si microprobe, we report on the design and fabrication of a 5 × 5 Si probe array chip with 40 μm in site spacing for high-density neural signal recording. The strength of the VLS probes for penetration and their electrical capability for neural recording were also discussed. The controlled diameter of each probe was less than 2 μm, and probes with 15 μm and 60 μm lengths were fabricated using two different VLS growth times, for use in different applications. In addition, tapered Si probe the shape is ideal for penetration can be realized by VLS growth. We also discuss the strength of the Si probe through observation of bending and penetration into gelatin membrane. In order to achieve probes with electrical capability to record the neural activity, conductive Si probes were realized by doping with phosphorous diffusion, and the Si probe successfully recorded neural potentials. In this work, a signal with 1 mV amplitude and 10 kHz frequency was stimulated at the Si probe tip, and the signals were recorded by the Si microprobe chip. In neuroscience, this VLS Si microprobe can be used to record the high-density neural activity distribution.

2. Microprobe Design and Fabrication

The fabrication of the array of VLS Si probes with a few micron diameters has been previously demonstrated using selective VLS Si growth.[3] The Si probe on the chip with interconnection wiring was also fabricated with 100 μm in site spacing.[5] To achieve the multichannel probe array for recoding the distribution of neural potentials, the diameter and the spacing of the probes must be the same as those of neurons, the diameters of which vary from 10 μm to 100 μm. Using the VLS Si growth and IC process, the array with the penetrating Si microprobe can be designed with closely spaced probe sites, which should have the same density as neurons.

In this work, each Si probe with a few microns diameter was designed for selective recording of neurons, and the probe length was controlled with the VLS growth conditions. The Si probes were connected to the bonding pads on the chip using 10-μm-wide wiring. As a result, the multichannel penetrating VLS Si probes were realized with 40 μm spacing in a 5 × 5 array. This site spacing allows recording

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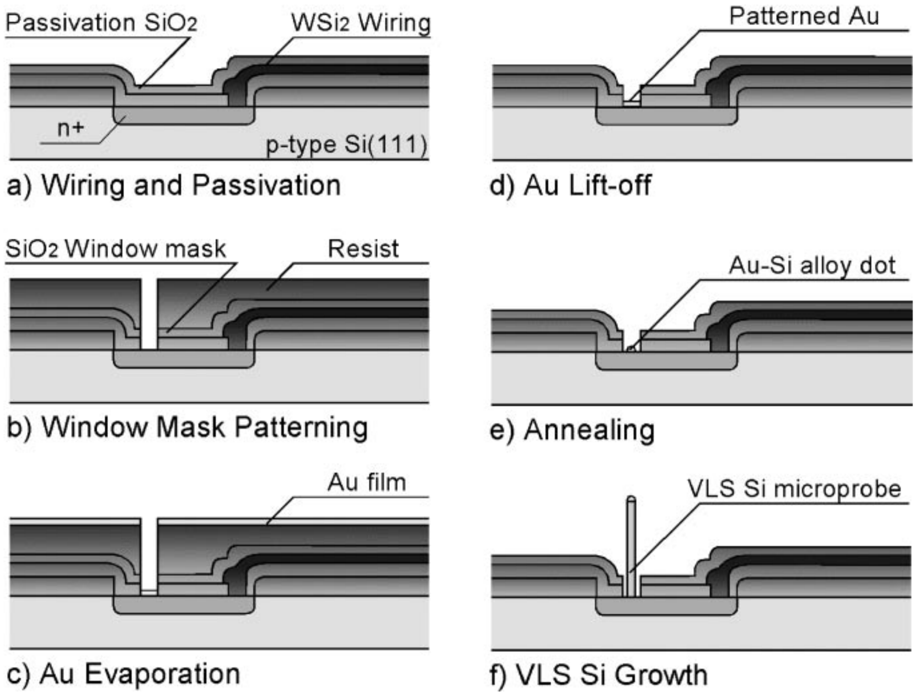

Fig. 1. Schematic diagram illustrating the major steps for the selective VLS Si microprobe fabrication on IC chip.

of high-density neural activities. The array of Si probes was located in a 200 μm × 200 μm sensing area. The Si probe array was fabricated on the chip with 2.5 mm × 5 mm size.

Figure 1 shows the schematic overview of the process for the selective VLS Si microprobe fabrication on an IC chip. This process is similar to the procedure used in our previous work.[5)] For the VLS Si probe growth, a Si (111) wafer was used.[4)] The fabrication process can be divided into six segments: a) n-type active region formation, interconnection WSi_2 wiring, and passivation SiO_2 film deposition; b) a SiO_2 window mask formation; c) Au evaporation; d) Au dot formation at predetermined Si probe site by the lift-off method, e) sample introduction into the vacuum chamber and annealing of substrate for Au-Si dots formation; and f) Si probe fabrication by VLS growth with Si_2H_6 GS-MBE. These processes can be carried out after the on-chip IC fabrication with one mask.

The diameter of the Si probe depends on the patterned Au dot diameter, and the Si probe length depends on the VLS growth conditions. It means that various Si probe shapes can be realized. In our applications, the Si probe must be conductive to record neural activity with amplitude of less than 100 mV. The VLS-grown Si probes were doped with phosphorous diffusion in order to control the conductive-Si probe array. Figure 2 shows a multichannel Si probe array chip fabricated using this process. Figure 3 shows the sensing area of the chip. The Si probe sites are spaced on 40 μm in the 5 × 5 array.

VLS growth is very effective method for the probe fabrication. This growth method allows the control of Si microprobe length with in a few microns using a constant VLS growth rate. Figure 4 shows the scanning electron microscope (SEM) image of the Si microprobe in the probe array after selective VLS growth. Si microprobes with predetermined length were fabricated. The Si probe 2 μm in diameter and 15 μm in length can be fabricated at pre-

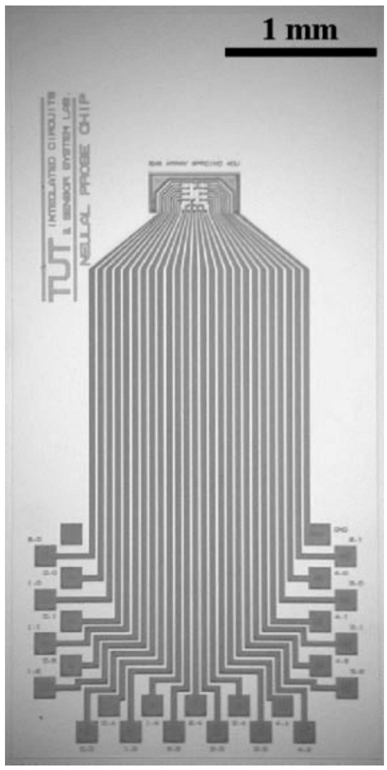

Fig. 2. Photograph of a fabricated 5 × 5-site Si microprobe array chip. Chip has a Si microprobe array area, interconnection wiring and bonding pads.

determined site with the interconnection wiring. The Si probe was grown at a temperature of 600°C, and a Si_2H_6 gas pressure of 3×10^{-3} Pa. The growth time was 30 min. Such as the Si probe electrode with short length can be used for study of the surface of the skin. To achieve a longer Si probe, the growth time was increased to 2 h, at a fixed

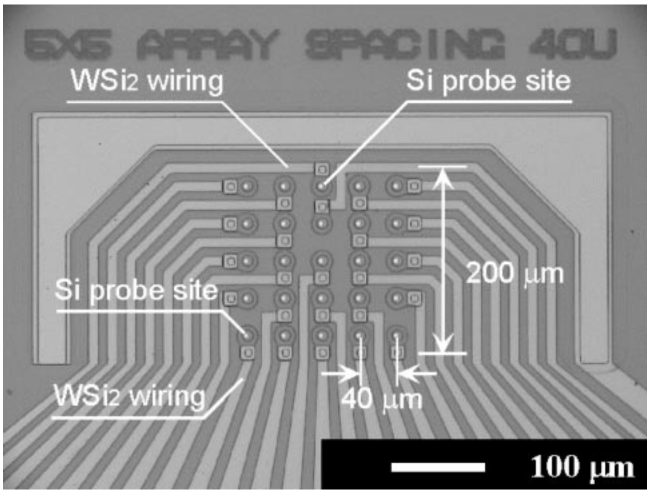

Fig. 3. Photograph of the sensing area of the microprobe array chip. The Si probes with 40 µm in site spacing in a 5 × 5 array. The chip is 2.5 mm × 5 mm.

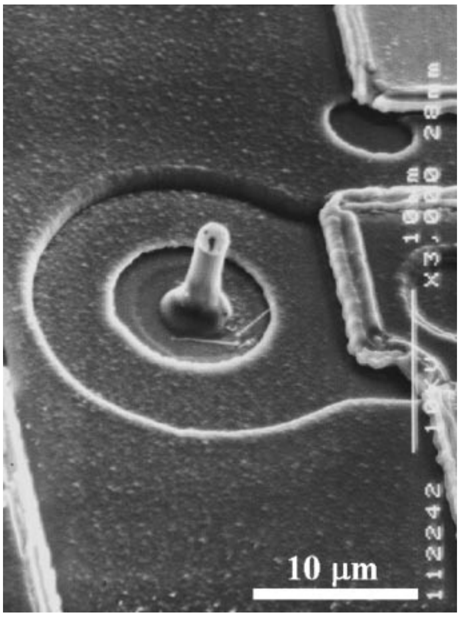

Fig. 4. SEM image of a Si microprobe 15 µm in length and 2 µm in diameter VLS-grown at Si_2H_6 pressure of 3×10^{-3} Pa, at 600°C for 30 min.

temperature of 600°C and a Si_2H_6 pressure of 3×10^{-3} Pa. Under these VLS conditions, Si probes 60 µm in length were grown as shown in Fig. 5. Si probes of this length will be used for recording neurons at deep regions in the tissue. The probe length depends linearly on the growth time, so another probe length can be realized for various Si microprobe applications.

3. Mechanical Strength

The mechanical strength of the VLS Si microprobe is an important characteristic. To penetrate the Si probes into neural tissues, these Si probes must be tough without fracturing, which causes errors in recoding the distribution of neural potentials. The Si microprobe must be able to easily penetrate neural tissues. In this work, the mechanical strength of the VLS-grown Si microprobes is described.

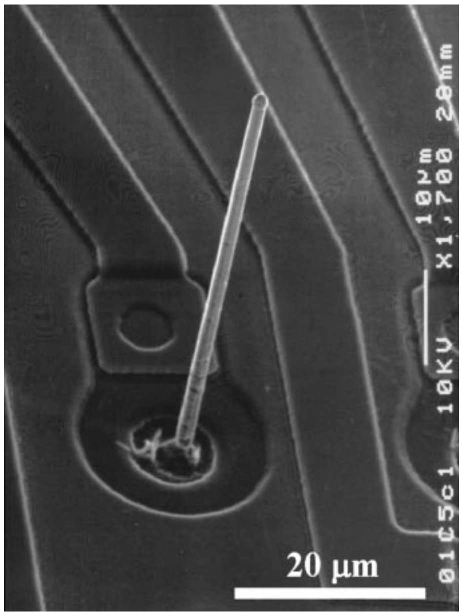

Fig. 5. SEM image of a Si microprobe 60 µm in length and 2 µm in diameter VLS-grown at 3×10^{-3} Pa, at 600°C for 2 h. Note that the predetermined length of the VLS Si probe can be realized by changing the growth time.

To ensure mechanical strength of the VLS Si probe, a W microneedle was used. The W needle was mounted on a *x-y-z* micromanipulator, which was in contact with the Si probe tip. It is well known that single-crystalline Si is reliable in strength. In fact, the Si probes shown in Fig. 4 exhibited excellent strength under the external force applied at the probe tip using the W needle. Although single-crystalline Si has good strength properties, the Si microprobe with a few hundred microns in length with a spindly column shape may break near the base of the probe under the stress of penetration.

The best shape for achieving a tough Si microprobe is a circular cone. By increasing Si_2H_6 gas pressure during VLS growth, probes of various circular cone shapes have been fabricated.[5] The mechanical strength of the circular-cone-shaped Si probe with the diameters of 22 µm at the bottom, and 3.5 µm at the tip, and is 270 µm in length was measured. Under the external force applied at the Si probe tip using the W needle with the above-mentioned manipulation system, the bending of the circular cone Si probe was observed as shown in Fig. 6. This Si probe can endure displacement of about 30 µm near the Si probe tip without bending at the bottom. The Si probe was bent more than the amount shown in Fig. 6, when the W needle was still forced as indicated downward arrow in the photograph. However, the Si probe showed no fracturing, and returned to its original state by dodging the W needle.

For more accurate results, mechanical finite-element modeling (ANSYS) was used to analyze the stress distribution during bending of the Si probe, which is shown in Fig. 6. The result of the stress distribution of the circular-cone-shaped Si probe is shown in Fig. 7. Maximum displacement of 30 µm is obtained for 0.15 g loading. The maximum stress (MX) is found near the tip of the probe. This stress is 1/50 that of a column-shaped Si probe 3.5 µm in diameter even though both probes have the same length of

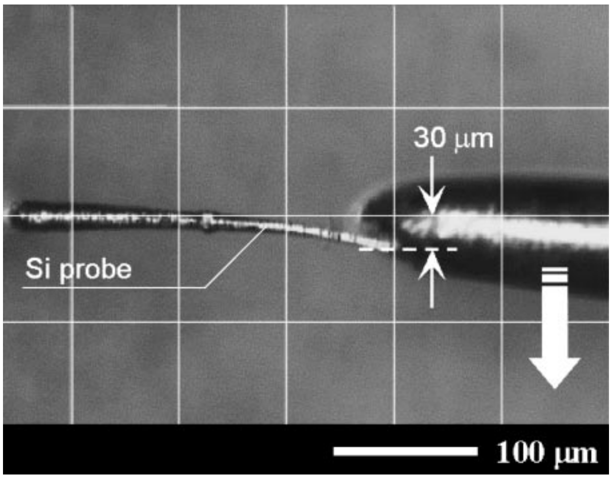

Fig. 6. Photograph of bending of the circular-cone-shaped VLS Si probe. The photograph confirms that the probe is tough enough to endure deflection without fracturing.

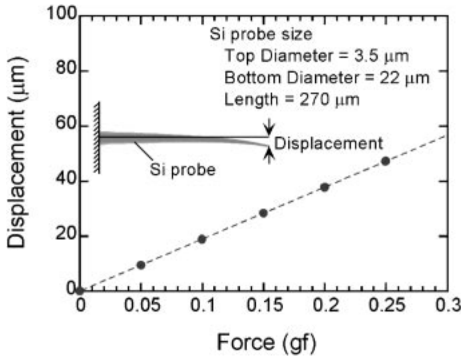

Fig. 8. The bending of a circular-cone-shaped Si microprobe.

270 μm. ANSYS modeling was also used to find displacements of both the circular-cone-shaped and the column-shaped Si probes for various loadings. The circular-cone-shaped Si probe has a good spring constant, which is 200 times larger than that of the column-shaped one. Figure 8 shows the bending of a circular-cone-shaped Si microprobe.

When recording neural activity, the Si probe will puncture and be penetrated through neural tissues, which causes compressive forces. To ensure the mechanical reliability of the Si probe during the penetration, a penetration experiment was performed using a gelatin membrane. Figure 9 shows the penetration of the Si probe into the gelatin membrane: a) before penetration, b) state of penetration and c) after extracting from the gelatin membrane. In this experiment, the Si probe penetrated easily without a vibration system or a high-velocity penetration system, because the Si probe has a very small tip. No fracturing of the probe was observed during continuous penetration. The Si microprobes can easily penetrate into neural tissues and reach the targeted single neuron cell.

4. Signal Recording

In our applications, the Si microprobe must record the neural activity with amplitude of less than 100 mV, and the activity potential lasts for about 1 ms. For the recording, a well conductive microprobe is needed. Another advantage of using the Si probe for the recording is conducting of the probe can be controlled by impurity doping. The Si probe fabricated by the VLS growth with Au dot as the liquid-forming impurity and Si_2H_6 gas source MBE, showed a high resistance of 10^4 Ω·cm due to non-doping Si growth. In order to fabricate a conductive probe, the Si probe was doped by phosphorous diffusion after the Si probe growth,

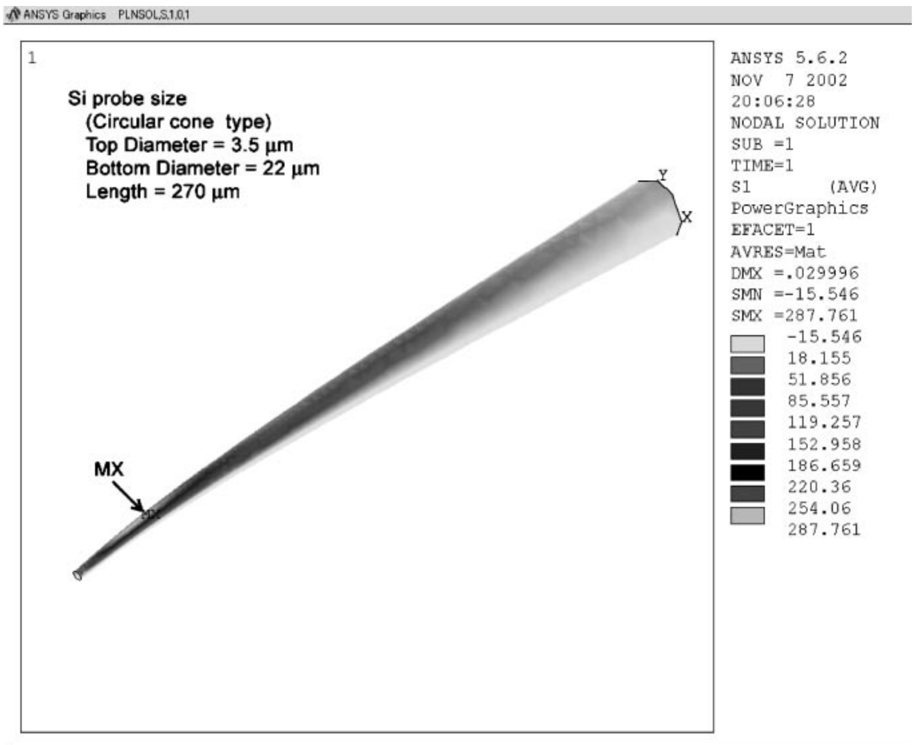

Fig. 7. Stress distribution in the circular-cone-shaped Si microprobe with loading applied at the tip.

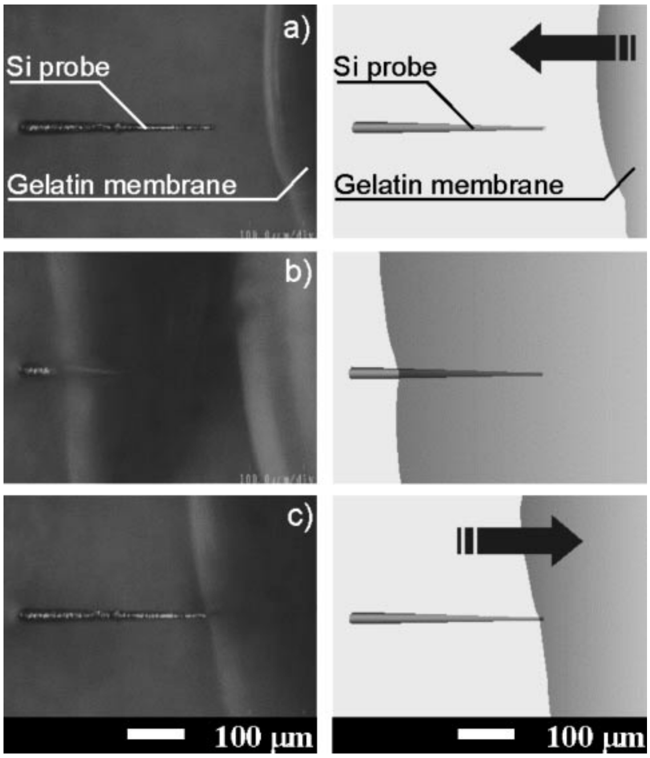

Fig. 9. Photographs and schematic diagrams of the penetration experiment. Si probe on the chip was penetrated and extracted from the gelatin membrane.

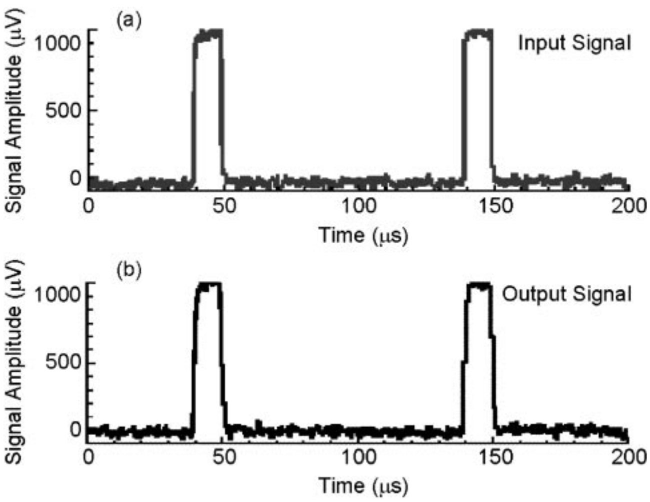

Fig. 10. Signals recorded with Si probe array chip: a) signals stimulated at the Si probe tip with 1 mV amplitude and 10 kHz frequency; b) signals recorded by the Si probe chip.

which results in the realization of uniformly conductive Si probes on the chip.[5] In this work, the phosphorous diffusion temperature was 900°C. The Si probes shown in Fig. 5 were also doped, which resulting conductive Si probes of the order of $10^4\ \Omega$. The conductive Si probes with interconnection wiring on the chip were used in signal recording experiment.

Using the same signals as neural activity 1 mV in amplitude and 10 kHz in frequency, the Si probe fabricated on a interconnection wiring chip was evaluated. Figures 10(a) and 10(b) show both signals stimulated at the tip of the Si probe (input) and signals recorded with the conductive Si probe on the chip (output). These signals in Figs. 10(a) and 10(b) indicate that the stimulated signals were recorded through the Si probe chip with satisfactory results and that the VLS Si probes are capable of recording signals from neuron cells in tissues. These results confirm that the multichannel 3D Si microprobe array is a useful electrode for recording neural activity distribution with high density.

5. Conclusions

The VLS Si growth allows us to fabricate the multichannel 3D Si microprobe array chip for neural activity recording. In this work, selective VLS Si probes with 40 μm spacing in a 5×5 array were fabricated on a Si chip. The predetermined length of the Si probes was realized by the VLS growth for various applications. The strength of the Si probe was evaluated by observation of bending and penetration into gelatin membrane, the results of which indicated the Si probe has reliable strength. The recoding capability was evaluated, which also showed satisfactory results.

The applications of this VLS Si microprobe in neuroscience are numerous as mentioned above. The VLS Si probes can be fabricated on predetermined sites on signal processing circuits with predetermined diameter, length and shape. These probes can recode as well as stimulate neuron cells in the tissues with high performance. Furthermore Si microprobe technology can be applied as an electrode to transmit signaling between neuron and electrode in human interface devices.

Acknowledgments

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1) M. D. Gingerich and K. D. Wise: *Proc. 11th Int. Conf. Solid-State Sensors and Actuators, Munich, 2001*, p. 416.
2) A. Branner, R. B. Stein and R. A. Normann: J. Neurophysiol. **85** (2001) 1585.
3) M. Ishida, K. Sogawa, A. Ishikawa and M. Fujii: *Proc. 10th Int. Conf. Solid-State Sensors and Actuators, Sendai, 1999*, p. 866.
4) R. S. Wagner and W. C. Ellis: Appl. Phys. Lett. **4** (1964) 89.
5) T. Kawano, Y. Kato, M. Futagawa, H. Takao, K. Sawada and M. Ishida: Sens. & Actuat. A. **97–98** (2002) 709.