Carbon Nanotube-based Nanoprobe Electrode

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Abstract—This paper reports a 10-nm in diameter nanoprobe electrode made of carbon nanotube (CNT) for possible electrophysiological measurements for biomedical applications. The nanoprobe is based on an individual carbon nanotube fabricated by a controlled local growth process and subsequently encapsulated with an insulating layer of Parylene-C. It is integrated with a silicon microstructure with a total length of 5µm and its tip at the distal end is locally heated to expose about 100nm-long CNT as the sensing port. We believe this nano scale CNT probe, with its high strength and Young’s modulus, may act as a low-invasive intracellular electrode for measurements inside cells or neurons.

Keywords- carbon nanotube; assembly; nanoprobe; neural electrode; intracellular electrode

I. INTRODUCTION

Microelectrodes made by conventional microfabrication technology have been applied for electrophysiological measurement of neuronal tissue, opening the door for acquisition of biological signals from cells or neurons [1-3]. However microelectrodes can only measure outer cell (extracellular) potential due to the large electrode size. The typical magnitude of recorded extracellular signals is less than 100 µV, which is significantly lower than signals inside a cell (intracellular) with ~ 100 mV. Furthermore, there are other issues associated with extracellular electrode, such as; 1) large size of electrode may cause damage to the tissue as well as cells; 2) signal-to-noise ratio may be too low for meaningful detection; and 3) the recorded signal could originate from several cells. These limiting factors might be addressed by next-generation cell recording devices using smaller probe electrode such as nanoelectrode for intracellular detections. Figure 1 illustrates and compares possible applications of cell recording using extracellular microelectrode and intracellular nanoelectrode.

The intracellular signals might have significantly higher magnitude, which translates to higher measurement accuracy and resistance to noise fluctuation. Recent advancements in nanotechnology have demonstrated fabrication processes for electrodes with diameter less than 1 µm [4-6]. This could enable electrodes to penetrate into cell for direct intracellular electrical potential measurements as well as to provide higher spatial resolution of cell recording. Carbon nanotube (CNT) is one of the potential electrode candidates due to its nano size, mechanical robustness and high conductivity. Here we propose a single CNT-based, nanoprobe electrode for intracellular electrophysiological measurement as illustrated in Figure 2. We envision placing the CNT probe at the tip of an overhanging silicon structure and using MEMS actuating technology to control the movement of the probe. Moreover it is necessary to passivate the conductive-CNT with biocompatible insulator, while exposing its tip for electrical measurements. This work proposes techniques on the fabrication of CNT nanoelectrode with preliminary results.

Figure 1. Illustration and comparison between extracellular and intracellular electrodes.

Figure 2. Image shows a proposal carbon nanotube-based nanoprobe with a silicon support.

Takeshi Kawano is funded by the JSPS Postdoctoral Fellowships for Research Abroad from Japan. This work is supported in part by the NSF grant (EEC-0425914).

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II. PROCESS FLOW OF PROBE

Figure 3 (a-d) shows the schematic diagram of the fabrication process sequence. The multiwalled CNT (MWCNT) is grown by the local synthesis process from the silicon growth structure, which is coated with a 5-nm-thick Ni-Fe layer as the catalyst. With the applied voltage $V_1$, the silicon structure is heated up by joule heating (850 ~ 900°C) [7]. The voltage $V_2$ is used for the local electric-field-assisted growth, achieving the self-assembly of CNT between the two silicon structures [8, 9]. The length of CNT can be controlled by adjusting the distance between the growth and the counter side microstructures. Parylene-C is chosen as the insulator, because of its high electrical resistivity, biocompatibility with tissue and the capability of a highly-conformal deposition. Finally, Parylene at the CNT tip region is removed by heating the secondary side silicon bridge, which also functions as a MEMS heater. Figure 5 shows several SEM images arranged following the process sequence in Figure 3. Figure 5(a) is the as-grown CNT; 5(b) is result after Parylene deposition; and 5(c) is after CNT-tip is exposed. We suspect that the detachment of the CNT from the secondary silicon structure is caused by the thermal contraction of the Parylene during the heating. Figure 6 shows TEM images of the tip region of a single CNT. The diameter of the nanotube body is 10-nm and the thickness of Parylene-C is 50 nm. The inset image is the Close up view of the exposed CNT.

CNT grown by the local synthesis shows metallic behavior with highly conductive characteristics [9, 10]. Figure 7 shows the current $I$- voltage $V$ measurement of an integrated, single CNT prior to the Parylene deposition. In this measurement, a single CNT grown from the silicon microstructure is making contact
contact with a gold counter electrode, achieving lower contact resistance at the CNT-metal interface [11]. This CNT is 30 nm in diameter and 22 µm in length. Repeatable \(I-V\) characteristics with measured resistance of 12 MΩ at ± 500 mV, give a resistance per micron of about 600 kΩ/µm. In the design of the CNT probe, the CNT length should be small, in order to realize lower resistance.

IV. DEVICE PACKAGING

The fabricated CNT probe device also requires specific packaging techniques for use in the experimental measurements with cells. For this particular experimental procedure, we have designed the elongated, overhanging silicon support with the growth heater structure positioned at its tip. Figure 8 shows the proposed device layout. Similar to the localized growth discusses in the previous work, local electric field is used to align the grown CNTs. Upon successful connection, the opposing heater can be heated to detach the CNT. A horizontal groove is also factored into the design such that half of the substrate can be physically broken along this pre-designated line, exposing the protruding silicon support.

Figure 9 (a-b) shows a photograph of the device overview. The probe device is mounted on a conventional IC-package, which is cut with a diamond saw, in order to expose the long silicon support portion. Typically, the length of the protruding silicon support from the edge of the package results is ~ 1.7 mm. Contacts on the device chip and the IC-package are electrically connected via aluminum bonding wires. Figure 9 (c-d) shows SEM images of the overhanging silicon support and the CNTs grown at the growth heater structure (located at the tip of the support).

The design of the protruding silicon support will allow the CNT probe to accurately access the targeted cells. In the eventual cell recording test, the target cells can be placed in front of the CNT probe with \textit{in-situ} observation under a microscope. The combination of the built-in comb-drive stage as well as the standard \(X-Y-Z\) probe station will facilitate greater control the precise position of the CNT nanoprobe.

V. CONCLUSION

We have described techniques for fabrication of CNT-based nanoprobe electrode for minimally invasive intracellular recording. Using the heater microstructure and the counter side microstructure, the single CNT can be locally grown and connected between the two structures. The advantage of this fabrication process is that the length of the CNT can be controlled by the predetermined gap between the silicon structures, an important characteristic of the electrode. The use of Parylene-C also promises biocompatible and conformal deposition around the CNT for insulating purposes. Finally, the Parylene at the CNT tip can be removed selectively by heating up the counter silicon structure. While work is still under way for the actual intracellular recording, we have highlighted our design of the overhanging silicon support with integrated growth heater, which will greatly facilitate accurate positioning during the probing process.
In conclusion, the present work has proven the feasibility of our approach to the intracellular recording. There are some questions unanswered, such as impedance characteristics of the single CNT in saline solution, the precise positioning and visual observation of the small CNT as well as the cell during the measurement. However, this CNT-based probe might offer significant improvement over other intracellular solutions due to its high conductivity and extremely small feature size of the electrode. In addition, recent papers [12, 13] have also reported on the sensitivity of CNT to specific chemical/molecular changes, which suggest possible application of the CNT probe for chemical/molecular detection inside the cell.

ACKNOWLEDGMENT
Authors would like to thank Brian Sosnowchik for creating our data-collection software, as well as staff at the EML (Electron Microscopy Laboratory) at UC Berkeley, for their TEM work, and staff of the Berkeley Microfabrication Laboratory.

REFERENCES

Figure 9. The device preparation including the overhanging silicon support and the CNT probe at the tip. (a) Photograph showing the device packaging and U.S. one cent. (b) Close-up view of the photograph image (a). (c) SEM image of the silicon support and the heater structure for the growth of CNT. (d) SEM image of a single MWCNT grown from the heater structure.