Mater. Res. Soc. Symp. Proc. Vol. 1350 © 2011 Materials Research Society
DOI: 10.1557/opl.2011.1243

Array of silicon field effect transistors to detect charges propagation in neurons circuit

C. Delacour, G. Bugnicourt, G. Bres, T. Crozes and C. Villard
Institut Néel, CNRS-Université Joseph Fourier-Grenoble INP, BP 166, F-38042 Grenoble, France.

ABSTRACT

We present transport properties of silicon nanowires field effect transistors realized on SOI substrates and their application to probe electrical activity of biological objects. Devices are sensitive to short and weak voltage pulses (ms, mV) applied in an electrolyte solution, allowing a future efficient detection of neuronal activity. For that purpose, the organized growth of neuronal cells along chosen patterns has been obtained, leading to an accurate coupling with silicon nanowire field effect transistors. Both network architectures, neural and semiconducting, have been designed to study some aspects of the propagation and the processing of information by the nervous system.

INTRODUCTION

Silicon nanowire field effect transistors (FET) are promising tools for probing electrical activity of biological objects at the sub-cellular scale. As the detectors are non-invasive, recording the activity of the cell could be done during its growth over several days. Cell should act as a gate electrode and induced a shift of the nanowire conductance when a variation of membrane potential occurs, ie when cell is carrying information.

Unlike conventional micro-electrodes (MEA), silicon nanowires are more sensitive [1], CMOS compatible for a large-scale integration and can address a smaller area (10 nm). Coupled to neurons, this allows to detect, stimulate or inhibit their electrical activity. Some proofs of concepts have already be obtained. Few years ago, a short voltage pulse related to the propagation of charges in a neuron has been detected with silicon nanowires [2]. More recently the coupling between a neuron and an array of nano-FETs has been obtained [3].

Our goal is to measure a real propagation of neuronal signals in an array of connected neurons. For that purpose, pre-defined neurons network had to be coupled with silicon nanowires field effect transistors (SiNW-FETs), which are measured in parallel. This project would help to go deeper in our understanding of the information processing by the nervous system and in a distant future would contribute to the study of abnormal neural activity involved in pathologies.

RESULTS&DISCUSSION

Silicon nanowires field effect transistor

SOI substrates of 50 nm silicon thickness are previously doped with boron atoms. Contacts are made, on highly doped areas (10^{21}at/cm^3) by optical lithography followed by a *Ti/Au* bilayer deposition and a lift-off of metals. Silicon nanowires (Fig. 1) are then realized by electron beam lithography followed by an reactive ion etching step within an active area characterized by a lower doping (10^{15}-10^{19}at / cm^3). Devices are then encapsulated with silica layer (500nm) except nanowires that are protected by a thin gate HFO_2 oxide (10nm).

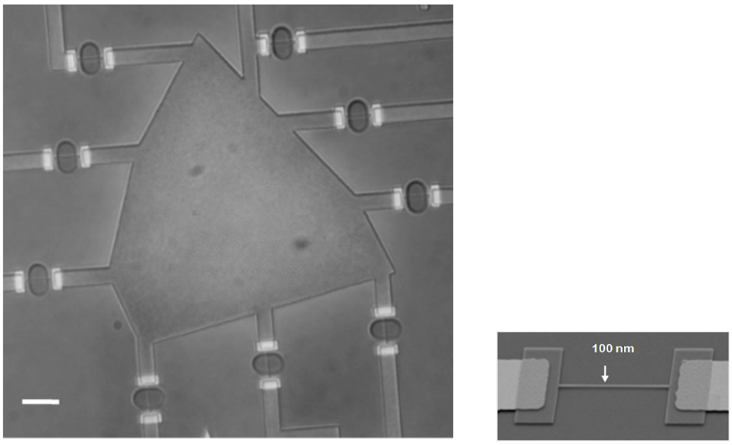

Figure 1. *Left: silicon nanowires array designed to analyse a 3 neuron network (see FIG3). A thick oxide (SiO_2-500 nm) isolates the chip except on the top of the nanowire covered by a thin oxide layer. Scale bar length is 10 µm. Right : MEB micrograph of Si-nanowire performed before oxide depositions.*

To measure the electrical activity of the neuron network in a range of hours or days, a culture chamber contain the electrolyte required for neuron growth is glued on the chip. We show the ability of these devices to detect weak changes of charge applied in the electrolyte solution (Fig.2) and investigate their possibility of coupling to complementary patterns of neurons (Fig.3). In figure 2, the sampling rate limited by data processing (see "electronic interface" part) was not enough to relate shape and amplitude of spike to real value of the wire impedance but allowed detection of a event that changes impedance of the Si-wire. To go further in the details of each spike, electronics setup could be used in burst mode to increase the sampling rate and solve the amplitude of the pulse and its shape.

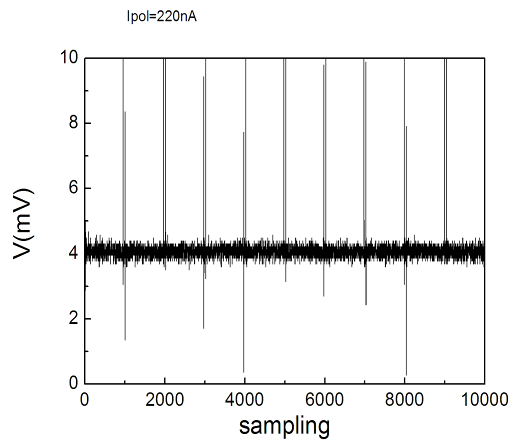

Figure 2. *Response of silicon nanowire immersed in an electrolyte solution to periodic short pulses (1ms duration, 5mV amplitude with repetition rate of 2.5Hz) applied with a liquid-junction Ag/AgCl electrode. Silicon FET are polarized with low bias current (220nA). Sampling rate is 2.5kHz, enough to detect the occurrence of an action potential-like event that leads to a significant change of Si-wire impedance. Moreover, electronics setup may be used in burst mode (see "electronic interface" part) to increase the sampling rate for an higher resolution of the amplitude and shape of the pulse. This will allow us to go further in the details of each spike.*

Neurons network

The growth of neuron is guided with poly-lysine patterns realized by conventional optical lithography (Fig.3) [4]. These patterns select the axon (i.e. the process that sends the action potential toward the next cell) position along the straigth paths of adhesion in order to monitore the direction of the information flow with a network.

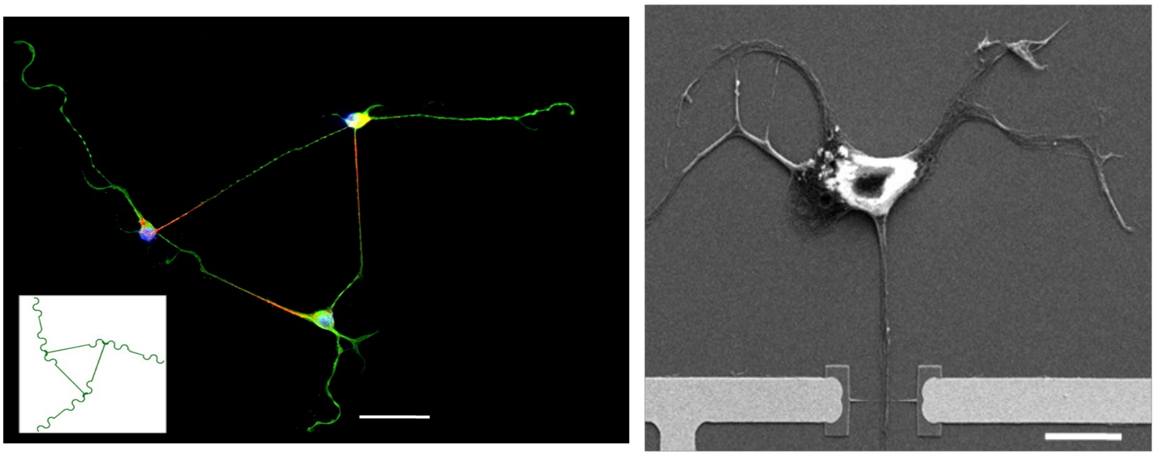

Figure 3. *Left : fluorescent micrograph of a three-neurons network. Axons are marked with a red fluorochrome. Scale bar length is 40 μm. Inset : poly-lysine pattern performed by optical lithography. Right : MEB-micrograph shows a proof of concept of the neuron-nanowire coupling. Scale bar length is 8 μm.*

Electronic interface

To record neural propagation, we have developed a specific electronic card allowing a synchronous detection of silicon nanowires field effect transistors. The electronic card allows to measure 12 impedances of silicon nanowires. Impedances of the 12 FETs are measured in parallel at 25kHz (burst mode). Moreover, to overcome capacitive effects and thermal drift, average values of their impedances are obtained from at least 10 periods such the switching of all the 12 devices could be recorded over half a millisecond (overall mode). In both case, detection times (40 µs and 400 µs respectively for burst and overall modes) are short enough to detect a neuronal spike (typ. ms) occuring near the Si-wire (Fig.2).
Polarization and measurement of the devices are made by a microcontroller with ADCs and DACs. The 4-wires measurement is performed in AC regim to eliminate thermal drifts and offsets of the amplifiers. Communication to the PC is done through a USB port via a RS232/USB converter that ensures a speed 1Mb /s. At the present time, this card appears to be a promising tool to study charges transport through single and coupled nerve cells.

CONCLUSION

This work deals with the detection capability of silicon nanowires in an electrolytic environment as a first step of the implementation of silicon/neural interfaces aimed to record the propagation of action potentials in model networks. This work could contribute to go further in our understanding of the charge transport in excitable cells like neurons and of the role of the neuron network architecture on the processing of information. It also opens the way to the implementation of neurological circuits [5].

[1] A. Fujiwara et al. Appl. Phys. Lett. 88, 053121 (2006).
[2] R. Alexander Kaul, Naweed I. Syed, and Peter Fromherz, PRL 92, 038102-1 (2006).
[3] F. Patolsky et al. Science 313, 1100-04 (2006) .

[4] S. Gory-Fauré, J. Brocard, P.O. Amblard, A. Depaulis, P. Salin, E. Dumas, S. Roth and C.Villard. Proceedings MEA Meeting 2006. Stuttgart: BIOPRO Baden-Wuerttemberg GmbH 2006; 194-195.
[5] Feinerman O, Rotem A, Moses E, Reliable neuronal logic devices from patterned hippocampal cultures. Nat Phys 4: 967-973 (2008).