



Silicon Nanowire Interface Circuit for DNA Detection

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ABSTRACT

Detection and quantification of DNA is critical to many areas of life sciences and health care, from disease diagnosis to drug screening. The transduction of DNA through electrochemical methods have a fast response rate and with a conductometric device like the silicon nanowire which can be fabricated to have a similar diameter of the DNA molecule being targeted, detection is real-time. Critical to this is the interfacing of a current-source and an amplifier capable of achieving a maximum of 10 pico ampere input bias. In this project, we fabricated a silicon nanowire using the top down approach and built a circuit that can mimic the output signal as low as 12 nA and achieved a gain of 1 million to be interfaced with the nanowire for real-time DNA detection.

Keywords: Silicon nanowire, nanoelectronics, interface circuit, DNA detection

INTRODUCTION

Recently, biochemical sensors have attracted interest among research areas in different applications due to their efficiency in monitoring and regulating certain areas such as food industry, toxicology testing, medical

diagnostics, environmental monitoring and drug industries (Yuan, Duan, Yang, Luo, & Xi, 2012). Biochemical sensors are defined as analytical devices that incorporate sensing materials with molecular recognition elements (enzyme, protein, antibody, nucleic acid, hormone, chemical compounds, etc.) that gets integrated within the transducers (Usman & Hamidon, 2015).

DNA detection is one area that drives innovation of biochemical sensing and with the rapid development of advanced nanotechnology, many nanomaterials for sensing with unique properties, favoured size, and chemical compositions have been fabricated to be incorporated within the

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transducer to aid DNA detection. One of them is the application of one-dimensional (1D) nanostructures (nanotubes, nanowires, nanorods, nanobelts and heteronanowires). Silicon nanowire (SiNW) is one of the 1D nanostructures that has emerged as the promising sensing nanomaterial upon its unique optical properties, mechanical and electrical (Gao et al., 2011). The SiNWs have gained popularity in the field of sensor development due of their ultrasensitive nature and high surface-to-volume ratio, fast response, biocompatibility, good reversibility, and H-terminated surface, which allows easy attachment to various functional groups. Additionally, the reliability and reproducibility of their fabrication process make them promising candidates for highly sensitive sensors. (Talin, Hunter, Leonard, & Rokad, 2006; Vu et al., 2010).

Nano-scale bioelectric devices achieve extraordinary sensitivity when used to detect molecular interactions (Vu et al., 2010). These devices are useful in the analysis of biomedical diagnostics. Most diseases are diagnosed based on symptoms which can sometimes be misleading. Biological molecules such as lipids, proteins and nucleic acid are related to the primary cause of disease.



Figure 1. The molecules in the nanoscale

Figure 1 shows why the SiNW is very useful in detecting biological molecules because they can be designed to match the scale of the target molecule. Disease diagnosis can be successful by screening for disease biomarkers which has given rise to the need for ultrasensitive bioassays making bio-functionalisation of nanomaterials in high demand.

The SiNW with widths (1 μm , 80 nm, 60nm, 40nm and 20nm) were characterised using a voltage source of 1 V and it demonstrated a linear ohmic behaviour. It generated current outputs of 115 pA, 146 pA, 201 pA, 327 pA and 2.6 nA respectively. For DNA hybridisation

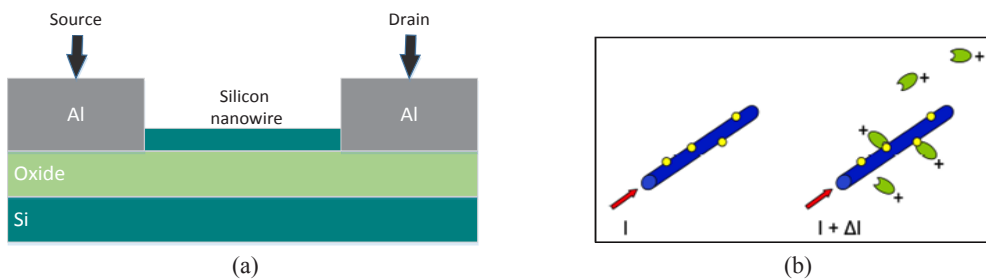


Figure 2. (a) cross-sectional diagram of top-down fabricated SiNW. (b) Schematic showing the principle of the NW sensor. The surface is coated with receptor molecules (yellow). As charged molecules (green) attaches to the receptor molecules the current is changed

of concentration 10 μM , 1 μm width showed output of 4.25 nA demonstrating the quality of transduction of SiNW (Nuzaihan et al., 2016). When utilised as an electrochemical sensor, detection is based on redox reaction as a result of chemical reaction between immobilised biomolecule or chemical species on working electrode and target analyte which finally produces measurable electrical current (Monošík, Středanský & Šturdík, 2012).

The SiNWs-FET sensor consists of three electrodes: source, drain, and gate and its functions based on conductive change of the carrier on the surface of SiNWs either accumulation or depletion charge. When negatively charged, molecules bind on the n-type SiNW surface resulting in accumulation of the negative carriers thus, increasing the resistance reading and vice versa if using p-type SiNWs (Zhang & Ning, 2012).

There are many studies on SiNWs with most examining the latter's effects of a biosensing event, for example, protein detection or pH measurement on the electrical properties of the nanowire (Kargar & Christen, 2008). They have also been used for glucose detection (Shao, Shan, Wong, & Lee, 2005). DNA hybridisation detection (Stern et al., 2007), viral detection (Patolsky et al., 2004), and even for extracellular recording from electrogenic cells (Patolsky, 2006). Despite the great potential of the SiNW, no device based on specific SiNW has been integrated with all-day-life in the last decade. This is mainly due to the need to interface these nanomaterials with nanoscale platforms (Serre, Ternon, Stambouli, Perival, & Baron, 2013). The proposed sensing schemes implemented on silicon nanowire are inherently compatible with modern CMOS process (Ramírez-Angulo, Carvajal, & Torralba, 2004). Although the signal generated is ultra-small, it can be amplified using a pico-Ampere sensitive amplifier (Steadman, Vogtmeier, Kemna, Quossai, & Hosticka, 2005). Current modules on a single chip makes it possible to realise ultralow-current-mode circuit as they suffer less fluctuations (Halloran & Sarpeshkar, 2004; Linares-barranco & Serrano-gotarredona, 2003). This helps in maintaining the integrity of the signal.

This work investigates the ohmic properties of a top-down fabricated SiNW for its optimised electrical sensitivity for biosensing applications and proposes an interface circuit that will make the device readable and portable thus, enhancing the utility of silicon nanowire to be a point-of-care device which can be integrated with all-day-life.

MATERIALS AND METHOD

For the purposes of this research, SiNW biosensor was designed with electron beam lithography (EBL) using the top-down fabrication method. The device structure was formed by implementing reactive ion etching (RIE) in order to integrate the fabrication with a CMOS process. A p-type silicon on insulator (SOI) wafer with a 160 nm silicon layer on a 200 nm buffered-oxide (BOX) insulating layer with a resistivity of 1-20 $\Omega\text{-cm}$ was used as the starting material. Standard cleaning procedure using RCA1, BOE and RCA 2 were employed to remove all contaminants on the surface of the sample before it was washed in de-ionised water and dried on a hot conduction plate at a temperature of 200°C for not less than 5 minutes to eliminate the water residue and cooled down to room temperature for not less than 10 minutes.

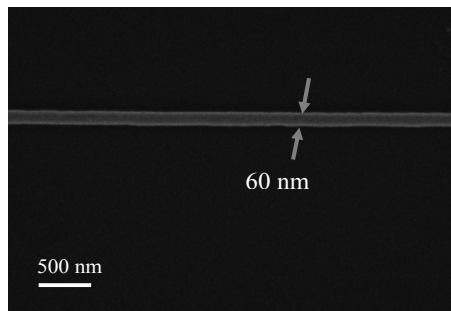


Figure 3. FESEM image showing the morphology of fabricated SiNW

Figure 3 shows the morphology of the SiNW with a width of 60 nm we have developed as a high-performance sensor that is label free and direct time for DNA detection using SiNWs-FET sensor top-down approach. We also managed to improve the sensitivity of SiNWs-FET sensor by optimising probe concentration, buffer ionic strength, and the gate voltage. The Keithley 4200 Semiconductor Parameter Analyzer (SPA) is used to demonstrate the usefulness of the fabricated sample.

The OPA129 is a monolithic operational amplifier manufactured by Texas instruments with ultra-low current using dielectrically-isolated FET (DIFET) with advanced geometry which makes the amplifier achieve a high level of performance. Dielectrically-isolated FET fabrication eliminates leakage current at isolation-junctions which is a contributing factor to input bias current with the traditional monolithic FETs. This decreases input bias current by a factor of 10-100. The OPA129 has an offset current unit of femto ampere and is fitted with a noise-free cascode which makes the device capable and efficient in handling nanoscale sensitivity.

RESULTS AND DISCUSSION

The idea behind SiNWs as conductometric devices for electrochemical sensing is to monitor the conductance across the surface by measuring its resistance which is altered by the charges along its surface. When molecules bind with the SiNWs, their ability to conduct is altered and this change serves as the mechanism for detection. Depending on the surface-to-volume ratio, the resistance of the NWs increases with the decreasing width of the NWs. The I-V characterisation of the SiNW illustrates the effectiveness of the fabrication sample as a DNA detection device and gives us a target-range of Gain for our interface circuit. Figure 4 shows the ohmic properties of the SiNW and presents the device as a useful sensor.

Using a Keithley 4200 Semiconductor Parameter Analyzer (SPA) and supplying the SiNW with a sweep voltage of 0-2 V (Figure 4b), 39 data points were generated indicating an increase in resistance from $6.05E8 \Omega$ at 0.05 V to $6.81E9 \Omega$ at 1.95 V leading to a decrease in conductance.

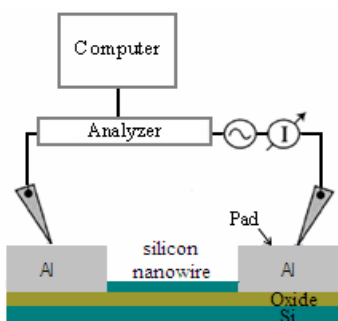


Figure 4a. Measurement setup

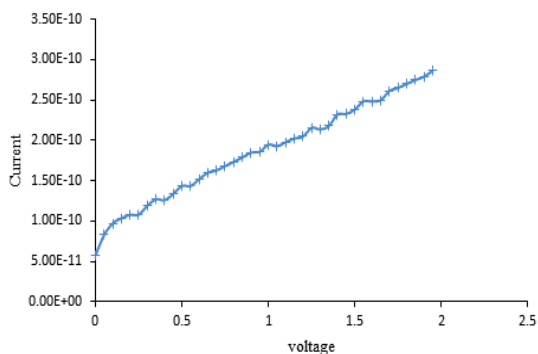


Figure 4b. I-V graph of the SiNW with 60nm width

Considering the I-V properties of the SiNW derived from I-V characterisation, the range of current to be sensed is (0.8E-11 to 2.8E-10) Ampere although a significant hike is expected after the sensing event. There are very few CMOS components designed for nanoelectronics as this field is still widely untapped but the OPA129 operational amplifier is one that has the capability to be integrated in nano range. In trying to amplify the signal, there was unwanted interaction between the feedback resistor of the op-amp and the SiNW which caused the current to be unpredictable. In order to successfully amplify this sort of signal, we designed a current source that will mimic the output signal of the SiNW. The quality of such a circuit must be such that it isolates the signal it produces to prevent unwanted interaction in the next phase. We used the diamond buffer topology which is primarily used in audio applications. Using this famous configuration as a current source model, we were able to design a constant current source that can isolate capacitive loads and boost op-amp signal.

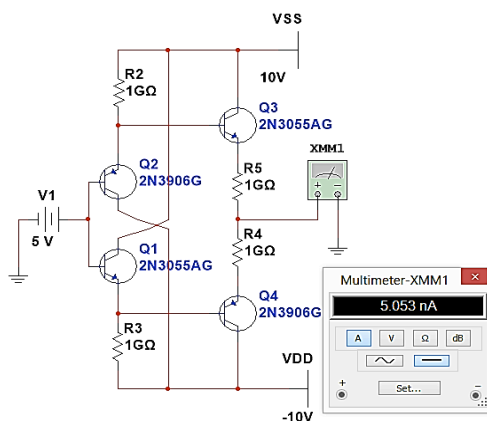


Figure 5. Simulation of the current source

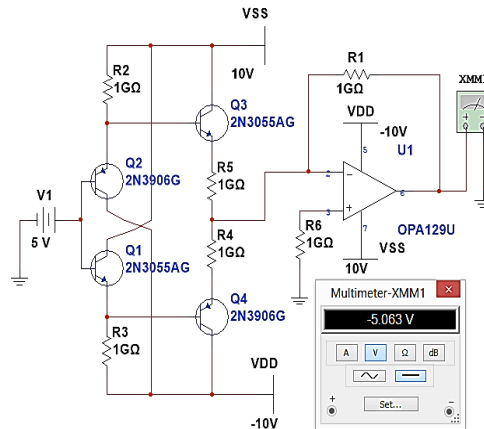


Figure 6. Simulation of the OPA129 Op-Amp

Figure 5 shows the classic diamond buffer structure renowned for isolation, transistors Q1 and Q3 are identical devices, and so are Q2 and Q4. These four transistors must operate at the same bias current. This symmetry is essential and results in exceptionally low distortion and isolation.

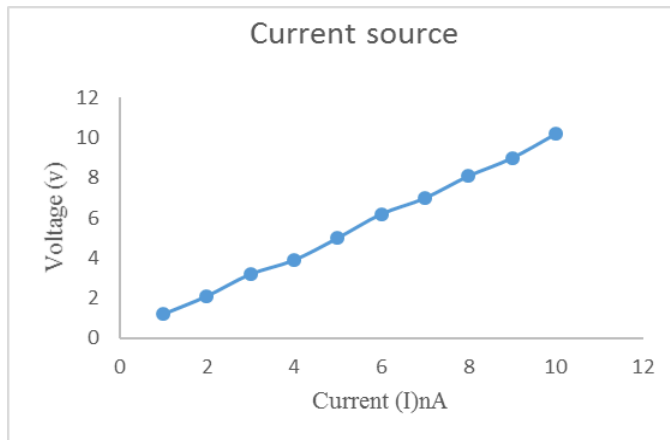


Figure 7. Current source measurement

The current voltage graph in Figure 7 shows the measurement of the output current from the prototype using a keithley 480 picoammeter with voltage ranging from 1-10 volts. Figure 8 shows the output signal from the amplifier in volts. The similarity of the curves indicates a very high integrity in the amplification of the signal.

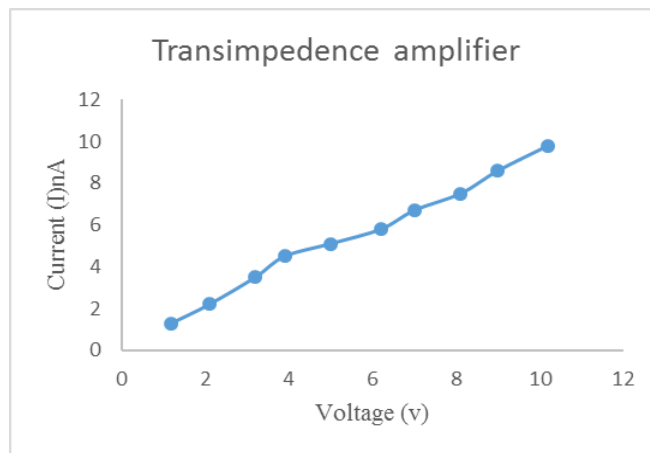


Figure 8. Current source amplifier

CONCLUSION

In order for interfacing to occur with a SiNW, it has to be fabricated with the top-down approach for good ohmic contact and easily integrated with nanoelectronic components. Our circuit has proven to be capable of signal isolation and amplification but we are not yet convinced of the method of integrating the SiNW onto the circuit due to lack of interfacing projects in nanoelectronics. In designing a nano range current source, isolation can be achieved using a diamond buffer configuration. The successful amplification of this ultra-small signal indicates that the SiNW can be interfaced for further utility, making the SiNW a portable sensing device with numerous applications in everyday life such as; point-of-care or field testing for bioassays.

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