An Efficient Electronic Measurement Interface for Memristive Biosensors

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***Abstract*—Reducing sensing time is one major concern in clinical diagnostics. In the present work, a robust measurement system is developed aiming at the faster and easier signal acquisition of memristive biosensors. Sensing chips consisting of nanofabricated silicon wires exhibiting memristive electrical response and metallic extension electrodes allowing an integrated measurement procedure are designed and fabricated. Furthermore, the electrical response of these particular nanofabricated structures is for the first time acquired using an embedded-system-based measurement front-end. The suggested prototype significantly simplifies the measurement procedure and provides conveniently the response signal of the devices. Such optimized co-design of memristive biosensors with electronic platforms hold great promise for PoC (point-of-care) applications.**

Keywords— Memristive devices; Silicon nanofabricated wires; Embedded systems; Metal electrodes; Biosensor

I. INTRODUCTION

As part of the non-linear dynamic systems family, the fourth fundamental circuit element, the Memristor, was first introduced by L. Chua in 1971 [1-2]. Considering this theoretical aspect [3] as starting point, a plethora of different types of memristive devices based on various material and physical operating mechanisms have been suggested, giving inspiration for many applications [4-6].

In this framework, silicon nanowire arrays anchored between NiSi pads and exhibiting memristive electrical response are emerging as promising building blocks for miniaturized bioassays. Those nanostructures achieve label-free detection of biomarkers, by leveraging the hysteresis modification appearing in the electrical characteristics upon treatment of the surface with biological molecules [7, 8]. Ultrasensitive detection reaching atto-molar concentrations of target molecules has been achieved using memristive biosensors [9], demonstrating their immense potential for precise biosensing.

So far, the electrical characterization of memristive biosensors was performed using a probe station and tungsten needles to directly contact the NiSi pads of the nanostructures. This experimental setup is cumbersome and unpractical. In addition, it is difficult to ensure that the needles are always placed ideally and exactly at the same spot and with the same pressure when moved from one device to the other, a fact that may introduce inaccuracies in the output signal. Moreover, the measurement of individual devices using a probe station makes the measurement process overall time-consuming. Nevertheless, in medical applications, reducing time in diagnostic procedures is highly crucial. Thus, the biosensor platforms should provide a functional and practical measurement procedure.

The development of a new, compact electronic measurement interface for memristive biosensors that considerably decreases the measurement time, while increasing the reproducibility of the sensing output, is hereby presented. First, memristive silicon wires are fabricated. Moreover, co-integrated Pt extension electrodes are designed, realized and tested for enabling the efficient electrical readout of the nanodevices and to allow incorporation of the chip in an embedded-system-based measurement front-end. Finally, a board enabling individual device measurements is designed, realized and tested, successfully replacing the probe station configuration. This novel approach is a necessary step towards advantageous memristive biosensing platforms.

II. MATERIALS AND METHODS

A. Nano-Engineering of Memristive Wires

Vertically stacked, two-terminal, Schottky-barrier silicon wires anchored between nickel silicide (NiSi) pads and exhibiting memristive electrical properties, are acquired through a top-down nanofabrication process using lightly doped, (100) oriented, Silicon-on-Insulator (SOI) wafers. First the NiSi pads that play the role of the electrodes for the electrical characterization of the devices are defined. In order to ensure precise alignment between the nanowires and the upcoming metal lines that will serve as the extension electrodes of the structures, alignment marks are also defined in this stage for the alignment with the lines layout. The substrate is first coated with PMMA (poly (methyl methacrylate)) and e-beam lithography is applied to pattern the first mask for metal contacts. The contacts are realized through a 25nm-thick layer of Nickel (Ni) evaporated onto the device followed by a liftoff process and NiSi pads are obtained through an annealing procedure. Then, the nanowires are defined by e-beam lithography using a Hydrogen SilselsQuioxane (HSQ), negative tone resist. The nanostructures are finally etched through Deep Reactive Ion Etching (DRIE) cycles of the Si. A Bosch process alternating a standard, nearly isotropic plasma etch mode and a deposition of a passivation layer mode, allows us to create high aspect ratio vertical structures, etching the silicon layer and creating the suspended nanowires.

B. Micro-Fabrication of Extension Electrodes

The metal lines are integrated on top of the already nanofabricated wire structures and serve as extension electrodes to the NiSi pads of the nanodevices (Fig. 1). However, the introduction of additional resistive elements may affect or completely mask the memristive properties of the nanodevices [10]. In addition, the resistance introduced on each current path must have the same value for all the devices. Taking these conditions into consideration, a theoretical study is first carried out for the calculation of the potential resistance that the integration with the extension electrodes would introduce to the system. The thickness of the lines is considered constant, while the cross-section area is varied by changing the width of the lines. The theoretical values for the resistance are calculated through the following equations:

$$R = R_s \frac{L}{W} \quad (1) \qquad \text{and} \qquad R = R_s \frac{L}{W_1 - W_2} \ln\frac{W_1}{W_2} \quad (2)$$

where, R_s is the sheet resistance, L the length of the conductor and W its width. Eq. 1 is valid for conductors of constant cross-section. For conductors where cross-section varies linearly along the length, Eq. 2 gives the total resistance as a function of the width at both ends W1 and W2. The computed resistance of the current path for the short-circuited version of the designs is 29 Ω and the resistance of the metal lines without the short-circuit is computed as well and stands for 25.1 Ω. This is the value of the resistance for the total current path in the metal, i.e., from the Pt source pad to the NiSi source pad and from the NiSi drain pad to the Pt drain pad. Finally, the resistance originating only from the extension electrodes is also experimentally estimated for metal lines without the presence of the devices. The parts of the metal lines designed to contact the NiSi pads of the wires are short-circuited and the resistance of the metal lines is measured using a Süss PM8 probe station and Agilent HP 4155C Semiconductor Parameter Analyzer, for a voltage sweep in the range of 0 to 3 V and 0.15 V step. The mean resistance of the current path is computed as the mean value of the resistances measured at the different voltages. Same value for the resistance for all the lines of the design (variation <1.25 %) are noted and giving an average value of 44.28 ± 0.55 Ω. The values obtained experimentally are compatible to the values expected from the theoretical calculations confirming the sound fabrication of the metal lines. It is expected that the measured resistance to be slightly higher than the theoretically calculated one since also the contact resistance introduced by the measuring probe needles is added to the measurements.

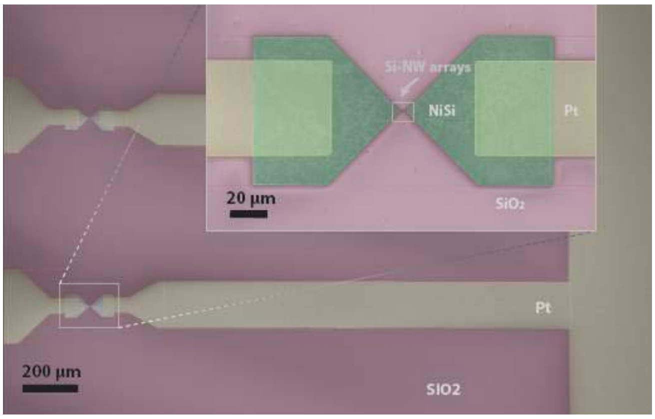

Fig. 1. SEM micrograph illustrating the nanofabricated wires anchored between the NiSi pads, integrated to the extension Pt electrodes.

The layout of the metallic structures is designed using the Tanner L-Edit software. A common source and separated drains are considered for individual measurement of the 12 integrated sensors. The metal lines are made using platinum (Pt) deposition that presents a resistivity of 10.6×10^{-8} Ω·m.

First, a photolithography process is implemented in order to define the pattern of the lines. A resist bi-layer (a lift-off resist (LOR) followed by a positive photoresist) is spin-coated on the surface and the exposure of the lines design is performed through maskless direct laser writer (MLA150, Heidelberg Instruments).

A Pt layer with a thickness of 100 nm is introduced through physical vapor deposition (PVD) followed by a liftoff process for the creation of the metal electrodes. A 20 nm layer of titanium (Ti) is beforehand deposited on the surface to promote the adhesion of Pt on the SiO_2. Then the wafer is diced into single chips of 1 cm × 1 cm. The final chip structure on the SOI wafer is presented in Fig. 2(f).

C. Measurement Set-up Realization

The suggested new measurement setup consists of a compact electronic measurement interface for memristive biosensors connected with a Semiconductor Device Parameter Analyzer, and it is also compatible to all equivalent measure unit configurations.

The proposed interface consists of a 75 mm × 54 mm board (Fig. 2) including a custom socket for the integration of the chip in the measurement front-end module, and is hereby introduced at the place of the cumbersome probe station. The placement of needles on the electrodes of each device is now substituted by an on board switch that allows the selection of the output of each device individually. The board can be easily connected to any measure unit through two BNC (Bayonet Neill–Concelman) connectors.

The schematic of the board is realized using Altium Designer. A single input (common source) and single output (selected individual drains) are taken into consideration through the two BNC connectors. In order to acquire the output current form each single device, a drain selection capability is taken into account through a mechanical switch (dual in-line package) integrated to the design, as shown in Fig.3.

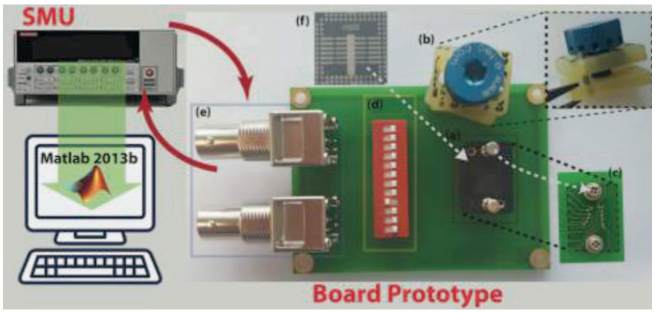

Fig. 2. Illustration of the manufactured board. The custom socket (a), its cover (b), connexions as seen at the bottom (c), DIP switch 12 I/O (d), BNC connectors (e), chip including twelve nanodevices (f).

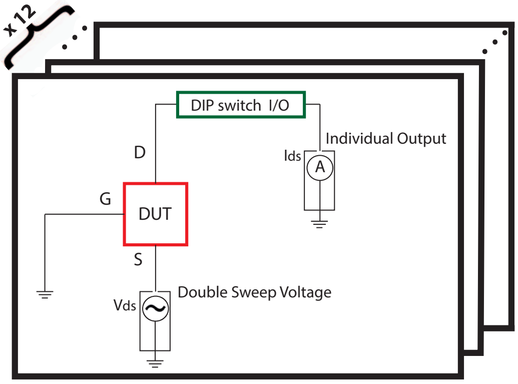

Fig. 3. Schematics of the measuring circuit for the twelve nanofabricated memristive biosensors (DUTs) on single chip.

A pin connecting the common source and twelve pins connecting the individual drains of each nanodevices are taken into consideration and the way pins and metallic pads are paired is defined in the footprint of the custom socket. This configuration serves the integration and stabilization of the chip on the board. Good contact is ensured by mechanical pressure, using a custom made cover with a screw to hold the chip against the socket contacts. The use of the custom socket allows us placing the chip on the board without any wire bonding. The chip is placed backward in the custom socket, fitting ideally. Since one can easily insert and remove chips from the custom socket, it is easy to proceed with bio-modification and to use as many chips as desired with the same socket.

III. RESULTS AND DISCUSSION

A. *Analytical Performance of the Extension Electrodes*

In order to evaluate the direct influence of the metal lines to the acquired electrical response, the current to voltage characteristics are measured first by placing the needles directly on the NiSi pads (reference) and then on the Pt pads. The electrical response of the devices is obtained using a Signatone 1160 probe station connected to a Keithley 6430 Source Measure Unit (SMU) interfaced with a PCI eXtensions for Instrumentation (PXI) platform (NI PXIe-1071) through a NI interface adapter controller (IEEE 488 GPIB-USB-HS), for a double voltage sweep in the range of -2.5 V to +2.5 V and 250 mV step. The comparison of the electrical characteristics curves is shown in Fig. 4.

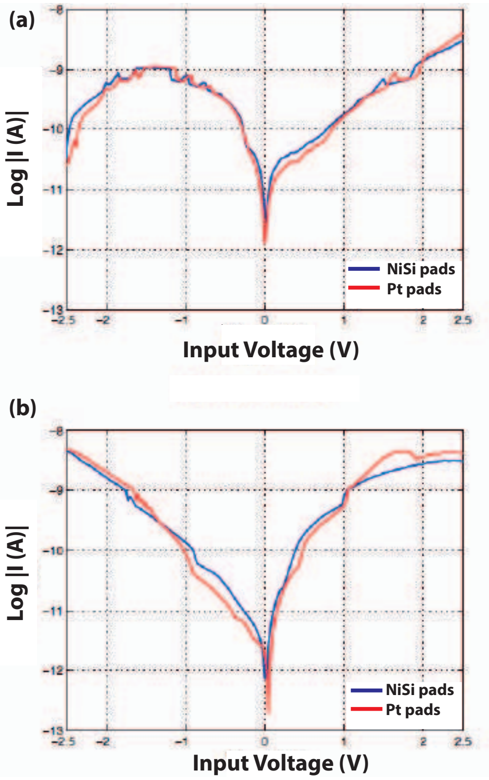

Fig. 4. Electrical characteristics acquired for a nanodevice measured at the NiSi pads (blue line) and at the Pt pads -metal lines and on the pads- (red line) for (a) Forward sweep (-2.5 V to 2.5 V) and (b) Backward sweep (2.5 V to -2.5 V).

The electrical response follows the same scheme and the main characteristics of the reference curve are conserved with the metal lines. The hysteretic behaviour is still present, verifying that the metal extensions may fulfill the integration purpose without affecting the electrical response of the devices.

B. *Analytical performance of the realized board*

The new measurement setup is tested to verify that the developed apparatus allows signal acquisition from the devices without eliminating their particular electrical characteristics. The measurements are performed using the realized board connected with an Agilent B1500A Semiconductor Device Analyzer, for a double voltage sweep in the range of -2.5 V to 2.5 V and 50 mV step. The resulting electrical characteristics are shown in Fig. 5.

First, it can be seen that although narrow, the hysteresis is still present, proving that the board is operating in the intended way. A slight masking effect on the hysteresis is expected due to the incorporation of the chip on the board. In addition, the obtained results are significantly improved in terms of noise effects that were occasionally present mainly at the branches of the semi-logarithmic curve.

Moreover, it is worth highlighting that, the electrical characteristics and most importantly the current minima positions that are the main information of interest occur at the same current range as for the measurements performed using the probe station. This is a further evidence of the board successful performance. The small voltage difference between the current minima in Fig. 5 can be attributed to the increased ambient humidity and not due to the board. It is proven that relative humidity (rH%) has an important effect to the electrical hysteresis of the wires [11]. For this reason the integration of a humidity sensor will be also taken into consideration in future designs.

Furthermore, the realized board allows successful acquisition of the signal from the individual devices thanks to the mechanical switch. The inconvenience of the measurements performed using probe station needles is thus overcome as well as the inaccuracies due to the non-identical placement of the needles on the electrodes.

Finally, a very important benefit of the suggested new measurement configuration is the significant decrease of the time needed for a singe measurement acquisition from ≈ 2 minutes to ≈ 20 seconds. This result indicates that the suggested apparatus finally results in a more functional measurement procedure.

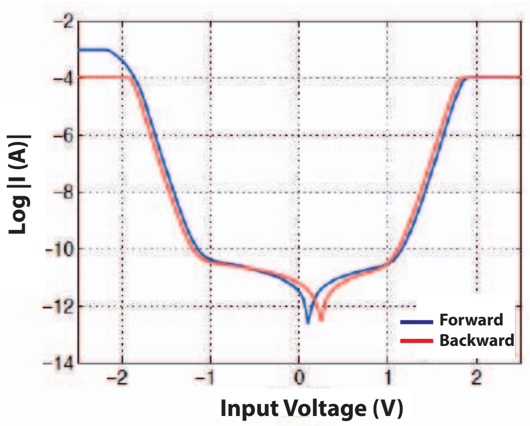

Fig. 5. Electrical characteristics aquired for a nanodevice with the new measurement setup and the board implementation.

IV. CONCLUSIONS

In the present work, the potential to develop a more functional and practical measuring system for memristive biosensors is for the first time studied and hereby designed and realized. The suggested prototype facilitates the experimental procedure and significantly reduces the measurement acquisition time. Memristive silicon wires are nanofabricated and metal interconnect tracks designed to comply with the resistance tolerance limitations of the system are realized and integrated to the memristive nanodevices enabling the signal acquisition when conjugated to an embedded-system-based measurement front-end. The realized electronic measurement interface for memristive biosensors presents successful performance, demonstrating easy and efficient signal acquisition of individual devices. Forthwith plan is the implementation of the hereby-presented prototype for the antigen detection, as well as, the incorporation of readout circuits and power supply that will pave the way for fully independent memristive sensing platforms.

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