Resistance impact by long connections on electrical behavior of integrated Memristive Biosensors

I. Tzouvadaki[1] and A. Vallero[1,2], F. Puppo[1], G. De Micheli[1] , S. Carrara[1]

1. Integrated System Laboratory, EPFL, Lausanne, Switzerland
2. Politecnico di Torino, Torino, Italy

Email: ioulia.tzouvadaki@epfl.ch

***Abstract*— Integration of nanowire structures in more complex platforms combining microfluidics and multiplexing aspects may complex the electrical readout process. In the present work, fabrication of Aluminium (Al) lines for electrical connections is attempted followed by their integration to nanofabricated Memristive Biosensors that target at the label-free detection of cancer biomarkers. In addition a computational study is carried out investigating the impact of the resistance introduced by the additional Al connections to the electrical response of the Memristive Biosensors. Overall, the present study explores the restrictions and the possibilities of the Memristive Biosensors' integration with additional elements that would allow effective readout in more complex configurations.**

***Keywords*— Memristor; Biosensor; Silicon Nanowire; Aluminum connections;**

I. Introduction

The fourth fundamental circuit element, the Memristor, providing a functional relation between charge and flux, was first presented by Leon Chua in 1971 [1], [2]. Furthermore, new perspectives and possibilities for applications including memristive systems opened in 2011 following the statement that all two-terminal non-volatile memory devices based on resistance switching are memristors, regardless of the device material and physical operating mechanisms [3].

Among the different applications that memristive effect had already been introduced, a further approach presuming upon the memristive behavior of bio-functionalized nanofabricated wires, so-called Memristive Biosensors, has been suggested for sensing biomolecules [4], [5].

The importance of the integration of nanofabricated devices in a more complex platform such as microfluidics for enabling the biological reagent immobilization process on the nanostructures surface is widely discussed in literature. Recently, a lot of research effort has been made to add microfluidics to different types of biosensors dealing with fluid samples, since it allows reducing waste of material and detection time by guiding the sample directly to the core of the sensor [6] [7]. It is worth mentioning, that even sensors targeting at the detection of biological aerosols firstly transfer air particles into liquids in order to take advantage of microfluidic configurations [8].

In addition, a type of microfluidic used as probe is introduced in order to allow automatic functionalization and detection steps without the need of creating a specific microfluidic for each chip [9].

However, the integration of nanostructure configurations with a microfluidic platform is not straightforward. One of the reasons that complexes the system is the electrical readout process. Specifically, for the nanofabricated devices studied conducted so far deal with NiSi pads that serve as the electrical contacts of the system, the detachment of the microfluidic is necessary in order to perform the electrical characterization, while integration with fluidic systems typically requires long connections to bring signals to the electronics frontend. The Al connections would allow performing electrical measurements instead of directly on the NiSi pads, allowing integrated measurement procedure.

The incorporation of such Memristive Biosensors in complex systems-on-chip with the additional need of CMOS frontend integration for the readout of the biosensors is a complex and non-trivial process [10].

Moreover, the electrical response of the Memristive Device is importantly affected by the further introduction of resistive elements in the circuit. Specifically, the introduction of additional resistance might diminish or even completely mask the memristive effect of the device and consequently there is possible risk to affect the functionality of the biosensor.

Aim of the present work is to investigate such a possibility by studying the effect of long connections on Memristive Biosensors. Therefore, Al lines for enabling the electrical readout are fabricated and integrated to the nanofabricated devices. In addition a computational study is carried out via proper modification of the circuit suggested in [11] aiming at the investigation of the impact that the introduction of additional Al lines brings to the electrical response of the physical system.

The present study investigates the limits introduced by long connections in integrated Memristive Biosensor platforms in order to outline new possibilities for the integration of readout circuits that consequently allow the development of more complex platforms.

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II. Materials and Methods

A. Experimental -Fabrication Methodology

The Memristive Devices are fabricated through a top-down fabrication process, using commercially available (100) oriented Silicon-On-Insulator (SOI) wafer. The nanostructures are defined using electron beam lithography, etched through a Deep Reactive Ion etching process (DRIE) of crystalline silicon and anchored between two NiSi junctions that consist the contacts for the nanostructures' electrical characterization. The electrical response of those devices indicates a hysteresis loop at zero voltage.

In order to be implemented in biosensing field the Memristive Devices are converted to Memristive Biosensors by surface modification with commercially available antibodies. When biological substances are present on the surface of the device the hysteresis appears shifted from zero to different voltage values, namely a voltage gap is introduced in the semi-logarithmic electrical characteristics, leading to a label-free bio-detection method [4], [5].

For the realization of the Al metal lines for the electrical connections, first a photolithography mask for the Al lines configuration is designed and fabricated. The design of the mask is prepared using CADENCE Virtuoso software and patterns as set of different layouts are defined, in order to verify the effect of different connection lengths on the final resistance value that the metal lines add in series to the nanowires. Then, the lines pattern is imported onto a commercially available (100) oriented SOI wafer that already includes fully prepared, two-terminal, Schottky-barrier, silicon nanowire devices anchored between two NiSi junctions. The wafer is first coated with a bilayer photoresist consisting of AZ1512 positive photoresist and LOR (Lift-Of-Resist) serving at the efficient exposure and liftoff process respectively. The metal lines are created through Physical Vapor Deposition (PVD) of 100 nm Aluminium on the wafer surface followed by a liftoff in SVC-14 solution. The final chip structures on the SOI wafer are presented in Fig.1. Finally the wafer is diced in single chips in order to allow the integration with the microfluidic platform and used for biodetection purposes.

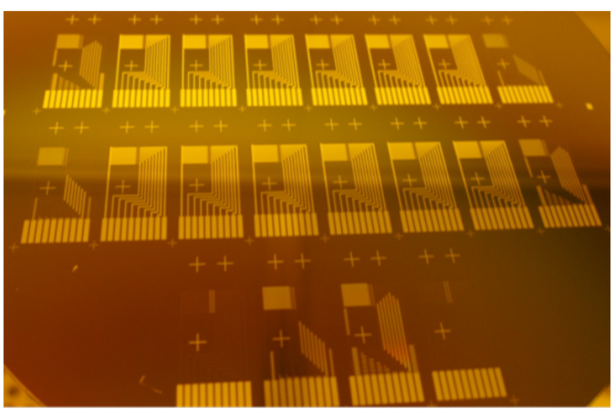

Fig. 1. SOI wafer including different configuration chips with different Al metal lines in series for assuring electrical contacts to memristive nanowire devices.

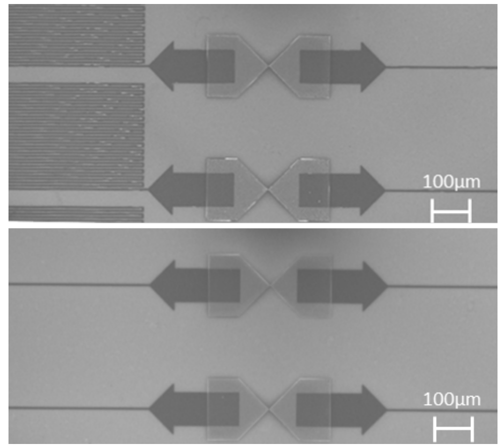

Fig. 2. Morphological SEM analysis of chips with two different configurations of Al metal lines: 10 kΩ (above) and 1 kΩ (bottom) in series to memristive nanowire devices.

B. Computational Methodology

In previous work [11], equivalent circuits have been designed using CADENCE OrCAD consisting of a memristor model in combination with analog circuit elements connected in series and in parallel. The suggested equivalent circuits targeted at emulating the electric response of the two-terminal, Schottky-barrier silicon nanowire devices that exhibit memristive behavior in their electrical response, before -Memristive Devices- as well as after the bio-modification with antibodies -Memristive Biosensors-. The modeling of the memristor is based on the theoretical aspect introduced by [1-3] and realized through the design and the addition of the memristor element in the CADENCE electronic design software.

An equivalent circuit consisting of a memristor (M) sandwiched between two non-identical head-to-head Schottky barriers models the Memristive Devices where the Schottky barriers are represented by sub-circuits consisting of a diode in parallel to a resistor. These two barriers are modeling both Schottky junctions at the ends of the wire as well as excess capacitances [11].

For modeling of the Memristive Biosensors an equivalent circuit consisting of a memristor (M), electrically contacted to non-linear (RC) sub-circuits is introduced. The aforementioned circuits were designed for computationally reproducing the electrical response of the physical system and achieving a successful fitting with the experimental data.

In order to investigate the impact of the Al lines on the electrical response of the Memristive Biosensors and, consequently, at the efficiency of the bio-detection method, the equivalent circuits in [11] are accordingly modified to include the introduction of the Al lines.

The Al lines presence in the system is achieved via the introduction of additional resistances in series to the initial circuit. These resistances correspond to the resistance values of the Al lines that are connected as extensions to the NiSi pads of the silicon nanowires.

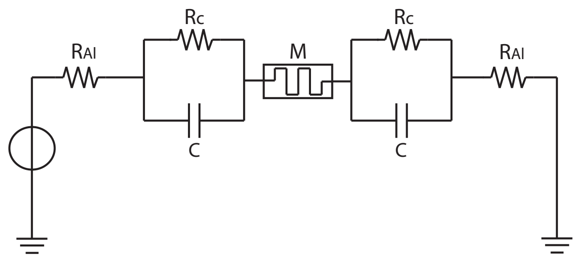

Fig. 3. Equivalent circuit for the simulation of the electrical behavior of a Memrsitive Biosensor by [11] extended here to include long electrical connection by Al lines.

Different values for the equivalent resistance (Table I) are introduced in series to the initial equivalent circuit corresponding to the different Al lines surface and length configurations added to the physical system.

In Fig. 2 two different configurations of Al lines of 10 kΩ (above) and 1 kΩ (bottom) in series to memristive nanowire devices anchored between two NiSi pads are presented using Scanning electron Microscopy (SEM) analysis.

Simulations are implemented for the modified equivalent circuits of Memristive Device as well as for the Memristive Biosensor shown in Fig.3, under a sinusoidal input voltage, keeping the same input values parameters [11]. It is worth mentioning that these parameters are accordingly selected to match the experimental values of the conductivity [4], [5].

III. Results and Discussion

A. Al connections impact on Memristive Devices

According to the simulation outcomes, the introduction of additional resistances to the equivalent circuit modeling the Memristive Device masks the memristive effect even before the bio-functionalization process.

This fact is indicated in Fig.4 by the narrowing of the hysteresis curve in the semi-logarithmic electrical characteristics with increasing values of the additional resistance.

Finally, for a total value of 1 kΩ resistance in series to the initial equivalent circuit, the memristive curve seems totally closed, the memristive effect disappears and resistive behavior dominates the electrical response.

B. Al connections impact on Memristive Biosensors

The introduction of additional resistance to the equivalent circuit is modeled also for the Memristive Biosensor, the device after the bio-functionalization that lets the voltage gap appear in the semi-logarithmic electrical characteristics.

It is found that the voltage gap decreases with increasing resistance value for both cases of bio-modification: for bio-functionalization of the device surface with antibodies and for the antigen sensing “Fig.5”.

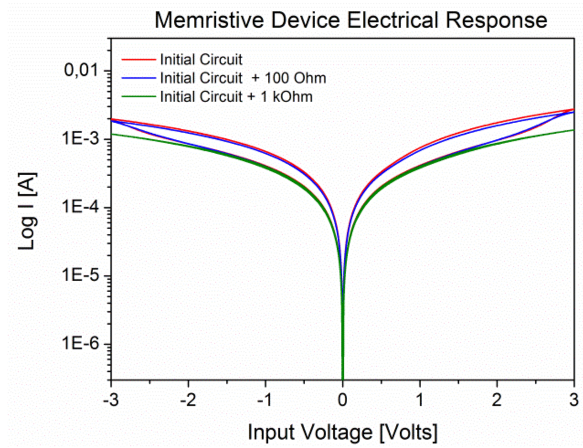

Fig. 4. Computantionally obtained semi-logarithmic current to voltage results for the case of Memrsitive Device. The initial memristive curve becomes narrower for the addition of 100Ω resistance in series to the Memristive Device and totally disappears for a total resistance of 1kΩ.

Furthermore, as expected, an increasing tendency in the maximum current difference is observed with increasing the resistance value. As maximum current difference (Max ΔI) we consider the difference between the maximum current value originating from the initial circuit concerning the Memristive Biosensor’s electrical response and the maximum current value corresponding to the Al lines-modified circuit as in

$$Max\ \Delta I = |Max\ I_{Initial\ circuit} - Max\ I_{with\ Al\ lines}| \quad (1)$$

Another interesting point is that, for the Memristive Biosensor, the memristive effect expressed through the semi-logarithmic electrical characteristics curve presented in Fig. 6 is affected by the increasing resistance value but not as significantly as in the case of the Memristive Device.

This finding indicates that for the bio-modified devices the virtual all-around gate created by the electrical field brought by the extra charges surrounding the channel due to the presence of biomolecules on the device surface interacts deeply with the channel’s conductivity, significantly affecting the electrical response of device.

TABLE I. Results by simulations concerning the Impact of Al connections on the electrical behavior of Memristive Biosensors.

Capacitance	**36 nF**	**24 nF**	**15 nF**
Antigen Concentration	**0 fM**	**5 fM**	**10 fM**
Al lines Resistance	**Voltage gap [Volts]**		
0 Ω (Initial System)	0,844	0,56	0,366
2 x 50 Ω	0,802	0,534	0,336
2 x 100 Ω	0,762	0,504	0,316
2 x 210 Ω	0,684	0,446	0,288
2 x 500 Ω	0,534	0,356	0,228
2 x 1 kΩ	0,396	0,268	0,1684
2 x 2 kΩ	0,258	0,1782	0,109
2 x 10 kΩ	0,0694	0,0496	0,0298

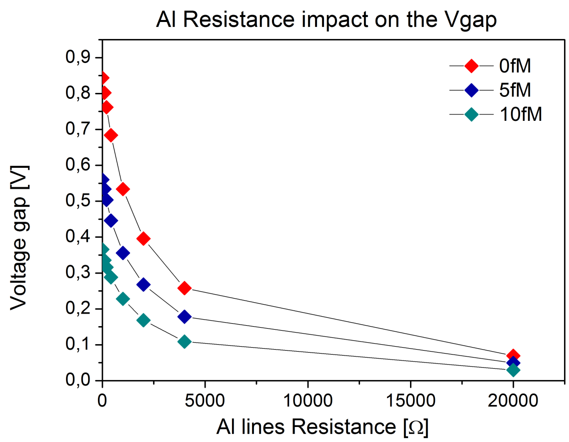

Fig. 5. Results by simulations concerning the impact of the resistance introduced by Al connections on the electrical response of the Memristive Biosensors with increasing concentration of antigen uptake: 0 fM (red); 5 fM (blue); 10 fM (green).

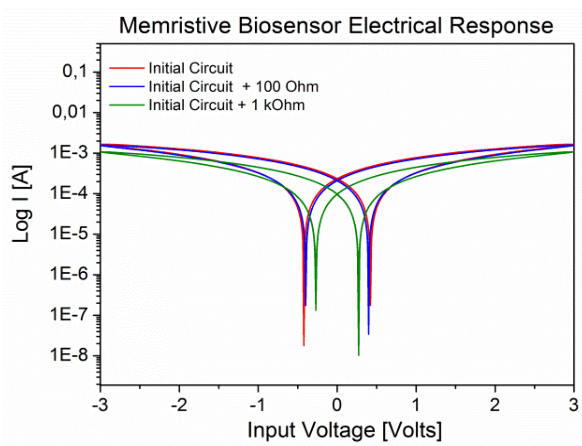

Fig. 6. Computantionally obtained semi-logarithmic current to voltage results from the equivalent circuit (Fig.3). The initial memristive curve becomes narrower for the addition of a total resistance of 100Ω and 1kΩ with respect to the initial Memristive Biosensor equivalent circuit.

IV. CONCLUSIONS

In the present work the possibility of the integration of a remote circuit with Memristive Biosensors is investigated, targeting at future integrations of memristive multi-panel more complex platforms integrating also microfluidics. In this investigation, series of Al lines have been developed, characterized and simulated in order to study the impact of metal connecting lines on memristic bio-detection. Al lines are designed as set of different layouts with respect to the potential resistance value that the metal lines introduce to the system. The metal lines are fabricated through PVD of Al followed by a standard liftoff process and integrated to the nanofabricated Memristive Biosensors for enabling the electrical readout when the sensor is conjugated to a more complex configuration. A computational study is in parallel carried out for the investigation of the impact that additional Al lines introduce to the electrical response of the physical system, pointing out the limitations brought to the biosensor's functionality. To this end, equivalent circuits designed for simulating the electrical response of the Memristive Biosensor are accordingly modified including the presence of the Al lines. It is demonstrated computationally that the memristive effect is affected by the introduction of the Al lines in series to nanofabricated Memrsitive Device. The memristive curve is not that much affected after bio-functionalization and this finding is correlated to the fact that extra charges are surrounding the channel due to the presence of biomolecules and then interact with the channel's conductivity. In addition, it is found that the voltage gap decreases with increasing resistance value for the Memristive Biosensor as well as for the case of antigen uptake. This fact highlights the need for proper design in Memristive Biosensor platforms in order to assure reliable sensing outputs.

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