Accepted Manuscript

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Authors: Federico Vittorio Lupo, Daniele Scirè, Mauro Mosca, Isodiana Crupi, Luca Razzari, Roberto Macaluso

DOI: https://doi.org/10.1016/j.sse.2021.108049

Published in: Solid-State Electronics, Volume 186, December 2021

Article Number: 108049

Received date: 14 April 2021

Revised date: 19 May 2021

Accepted date: 25 May 2021

Custom measurement system for memristor characterisation

F. V. Lupo [1]*, D. Scirè [1], M. Mosca [1], I. Crupi [1], L. Razzari [2], R. Macaluso [1]

[1] *Dipartimento di Ingegneria, Università degli Studi di Palermo, Palermo, Italy*

[2] *Institut National de la Recherche Scientifique – Centre Énergie Matériaux Télécommunications, Montreal, Canada*

* *Corresponding author. E-mail address: federicovittorio.lupo@unipa.it (F. V. Lupo)*

Abstract

A cheap, compact and customisable characterisation system for memristor devices, working between ±10 V, is presented. SPICE (Simulation Program with Integrated Circuit Emphasis) simulations are performed to verify the circuit feasibility and a proper software is developed to drive the system. The potentiality of the realised system is tested by performing several electrical measurements on both Cu/HfO_2/Pt memristors and two-terminals commercial devices.

Keywords: *Memristor, ReRAM, electrical characterization system, current compliance, endurance, retention*

1. Introduction

Memristors are resistive non-volatile memory devices that are attracting significant interest within the scientific community because of their simple structure, high speed, low power dissipation, and high scaling capability [1-4].

The DC I-V characteristic of these devices presents a hysteresis cycle [1-4]. A current limitation is usually imposed, during electrical characterisation, to avoid any damage to the device especially during the switching to the ON state [2]. Moreover, the long-term reliability of memristors as memory devices is typically evaluated through a pulsed characterisation, assessing both endurance and retention capabilities [1,2]. To perform these characterisations, specialised equipment, such as semiconductor parameter analyser or source-meters are needed. These tools are very expensive and general purpose: once acquired, the user has to invest some time to develop a software tailored for memristor characterisation, employing commercial software to interface the instrumentation with a controlling PC.

With the present work, we aim to develop and build up a low-cost system tailored and easily customisable for memristors characterisation. Such system was designed with the aid of SPICE simulation with Micro-CAP 12® and then assembled on a printed circuit board (PCB), where the components employed are listed in Table 1. Furthermore, a dedicated software was developed by using the Qt library [5]. Finally, the characterisation setup was tested with some commercial two-terminals devices and with Cu/HfO_2/Pt memristors fabricated in our laboratory.

Table 1 Components employed for the design of the characterisation system.

Name	Part number	Manufacturer
X1	TL072	TI
X2	TLV172	TI
X3	LT1010	Analog Devices
X4	AD8227	Analog Devices
X5	LM7322	TI
X6	LMC662	TI

2. Circuit and software development

Since memristors are voltage driven devices, the characterisation system requires a voltage generator circuit that can be operated with user-imposed parameters and constraints which allow spanning the applied voltage over a range between ±10 V. Therefore, a digital to analogue converter (DAC) integrated into an STM32 microcontroller [6] was used together with the circuit reported in Fig. 1, which allows extending the capabilities of the DAC to larger voltages. In particular, the maximum output voltage coming from the DAC is amplified to ∓10 V by the operational amplifier (op-amp) X1 reported in Fig. 1b and then inverted by X2 to ±10 V; the maximum delivering current is boosted to ±150 mA by X3. For this system, the 12-bit DAC gives a 2.4 mV resolution. A finer output could be obtained by employing an external DAC with a better resolution.

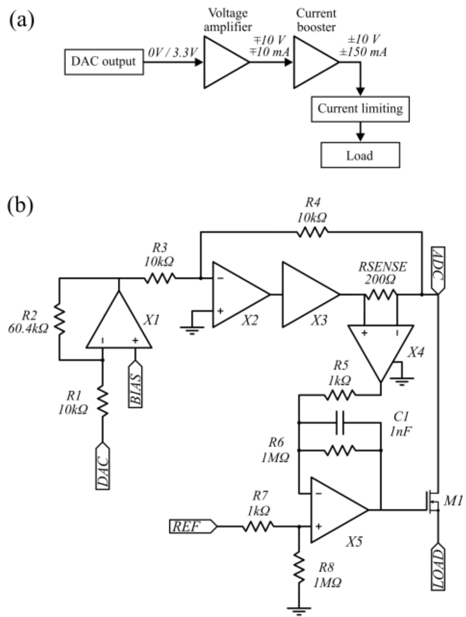

Fig. 1 Block diagram (a) and simplified schematic (b) of the realised voltage generator and current limiting circuit.

The MOSFET M1 implements the current limiting feature through a feedback loop: the gate of M1 is fed with the comparison, performed by X5, between a reference value (*REF*) and the current that flows into the load, measured by X4 through a sense resistor (*RSENSE*). If the current exceeds the reference value, the MOSFET drain-source resistivity rises, limiting the current flowing into the load. In this condition, the current is fixed at the compliance current (I_{CC}), i.e., the reference value, until the current drops to values lower than I_{CC}.

Driving the current limiting MOSFET could be challenging for the op-amp X5. Indeed, the capacitance seen at the output of X5 affects the loop stability and may compromise the entire measuring process triggering strong oscillations. To overcome this problem, an op-amp with large capacitance driving capability is required. Moreover, a capacitor is added in parallel to the feedback resistor (*R6*) to effectively limit the influence of the parasitic capacitances on the feedback stability. Using a 200 Ω sense resistor and the external and dedicated MAX5216 DAC (5 V maximum output) for the reference I_{CC}, the current can be limited gradually and reliably from a maximum of 5 mA to a minimum of 10 μA.

To verify and prove the circuit working principle, SPICE simulations are performed in the simplified circuit shown in Fig. 1 using Micro-CAP® 12. In particular, the following parameters have been implemented for the simulations: (i) voltage sweep at the input (*DAC*) performed from 0 V to 3.3 V, (ii) voltage reference (*REF*) of 5 V at the current limiting circuit to achieve a 5 mA current compliance, (iii) 200 Ω resistive load. The simulations outcome is presented in Fig. 2, which shows the whole circuit capability to generate the desired voltage sweep between 0 V and +10 V and a current limitation of 5 mA.

To accurately measure the current that flows into the memristor, an operational amplifier is used as a transimpedance amplifier, as illustrated in Fig. 3. This configuration allows to measure very small current values (as low as 10^{-12} A [7]) as a function of the feedback resistor: a higher resistance corresponds to a smaller measurable current. On the other hand, to achieve such current sensitivity, a feedback resistor ranging between hundreds of MΩ and few GΩ is needed, and proper shielding and circuit arrangement must be adopted to avoid measuring parasitical currents.

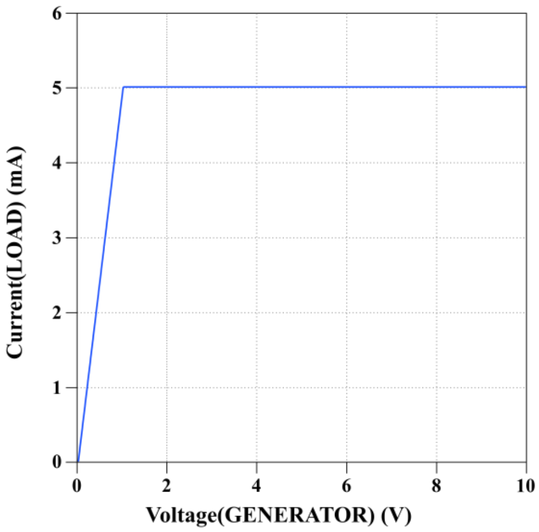

Fig. 2 SPICE simulation of the circuit reported in Fig. 1, showing the feasibility of limiting the current that flows over a generic load. The figure is a current vs voltage plot of a 5 mA limited 200 Ω load.

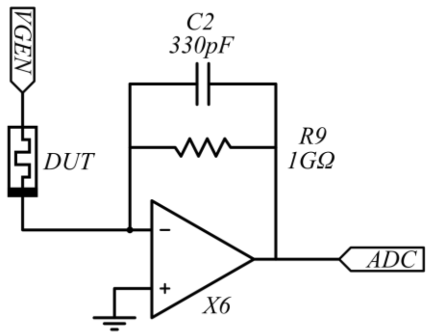

Fig. 3 Simplified transimpedance current measuring circuit. The capacitor in the feedback loop is needed to compensate for any input parasitic capacitance.

To address this problem, as suggested in the op-amp datasheet [8], we routed the high impedance portion of the circuit in the air using bare copper cable, as shown in Fig. 4, where a photo of the realised system is presented.

To switch between different current measurement ranges, multiple feedback resistors are interchanged by some relays controlled by the microcontroller. An alternative to this approach could be the implementation of a logarithmic amplifier, which uses two diodes in the feedback path instead of resistors [9]. Nevertheless, the response of this kind of amplifiers is non-ideal [10] and presents temperature-dependent coefficients that need to be found by a proper fitting between ideal and real transfer characteristic [9].

The transimpedance amplifier configuration is stable as long as a capacitance is present at its input [7]; therefore, to stabilise the circuit, a capacitor (*C2*) is added in parallel to the feedback resistor (*R9*). With a 1 GΩ feedback resistor and a 330 pF capacitor, we achieved potential fA readings with 1 Hz bandwidth.

To acquire the generated voltage and the current, an analogue to digital converter (ADC) is used. In our solution, we adopted the 24-bit LTC2402 ADC to achieve the best resolution possible; however, due to its slow conversion time [11], faster events than 0.5 s cannot be detected. With this limitation, the AC pulsed measurements are limited to a frequency of 1 Hz.

Fig. 4 PCB picture of the assembled characterisation system. The blue square includes the circuit reported in Fig. 1, whilst the red region circumscribes the circuit displayed in Fig. 3.

To manage the whole system, the USB controller integrated into the microcontroller [6] is used as a virtual serial port to handle the communications between the computer and the microcontroller. To control the system from a computer, a dedicated and easily customisable software was developed in C++ language with the aid of the Qt library [5]. The software interface allows the user to set the DC voltage sweeps and perform the AC characterisation with arbitrary voltage, current limit, and pulse-width settings.

3. System validation

Preliminary uncalibrated measurements were first carried out systematically on several two-terminal commercial devices such as resistors and diodes.

The system was also used to characterise the dark current of a PIN photodiode in a dark chamber, obtaining a mean value of 1.1 nA, which is compatible with the value reported in the datasheet [12]. Subsequently, both DC and AC measurements were performed on bipolar Cu/HfO_2/Pt memristors to prove the system capabilities. Fig. 5 shows 35 hysteresis loops with an I_{CC} set at 4.5 mA, whilst Fig. 6 and Fig. 7 show the retention and endurance characteristics, respectively.

The performance of the current limiting circuit is also shown in Fig. 8, where a memristor is characterised between +1.5 V and -0.8 V by imposing five different current compliances ranging between 5 mA and 10 µA.

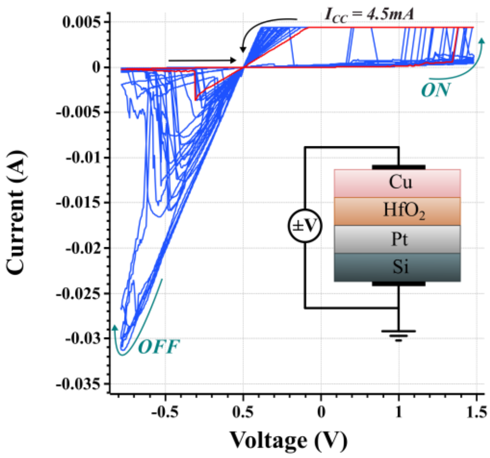

Fig. 5 I-V characteristic of a bipolar Cu/HfO_2/Pt memristor. During the positive voltage sweep, a compliance current of 4.5 mA is imposed. The first hysteresis cycle is shown in red, while the other 35 cycles are shown in blue. The arrows indicate the voltage sweep direction and mark the switching to the high resistance state (HRS) or OFF state and to the low resistance state (LRS) or ON state of the device. The inset shows a sketch of the measured memristor. The HfO_2 film was deposited by Pulsed Laser Deposition (PLD), whilst the Cu top contacts (0.785 mm^2) were obtained by thermal evaporation through a shadow mask.

4. Conclusion

The low-budget characterisation system developed in this work is capable of reliably characterising and extracting the most significant properties of memristors as memory elements. Furthermore, any other two-terminal devices, such as resistors, diodes and solar cells, can also be characterised.

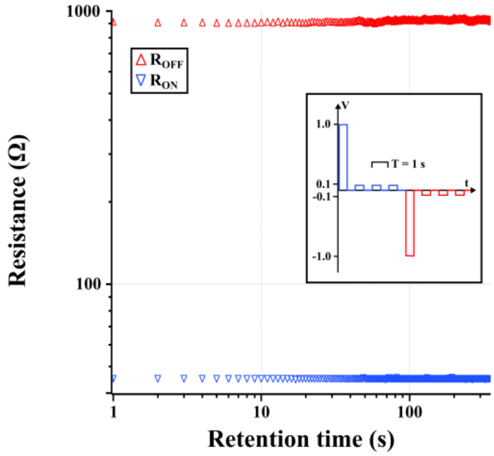

Fig. 6 Measured retention of a Cu/HfO_2/Pt memristor. The inset shows the programmed voltage pulses train. After a writing pulse of +1 V which switches the device to the ON state, a train of 350 reading pulses of +0.1 V is applied, then an erasing pulse of -1 V switches the device to the OFF state and a train of 350 reading pulses of -0.1 V is applied. Each pulse lasts 0.5 s.

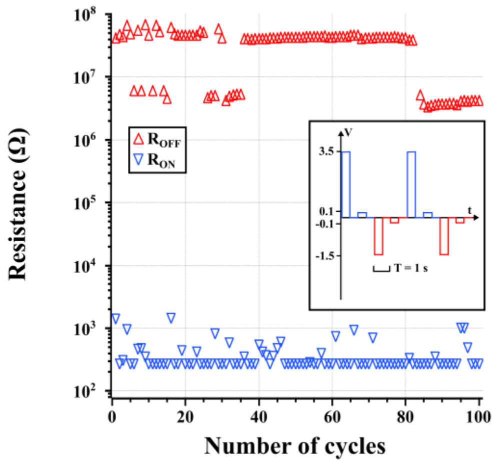

Fig. 7 Measured endurance of a Cu/HfO_2/Pt memristor. The inset shows the programmed voltage pulses train. After a writing pulse of +3.5 V a reading pulse of +0.1 V is applied, then after an erase pulse of -1.5 V a reading pulse of -0.1 V is applied. This cycle is repeated 100 times. Each pulse lasts 0.5 s.

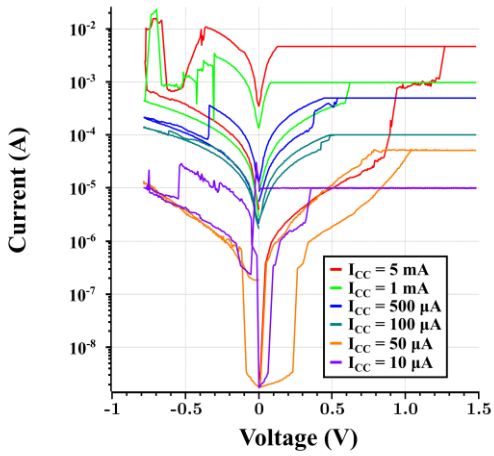

Fig. 8 I-V characteristics of a bipolar Cu/HfO_2/Pt memristor for different current compliances.

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