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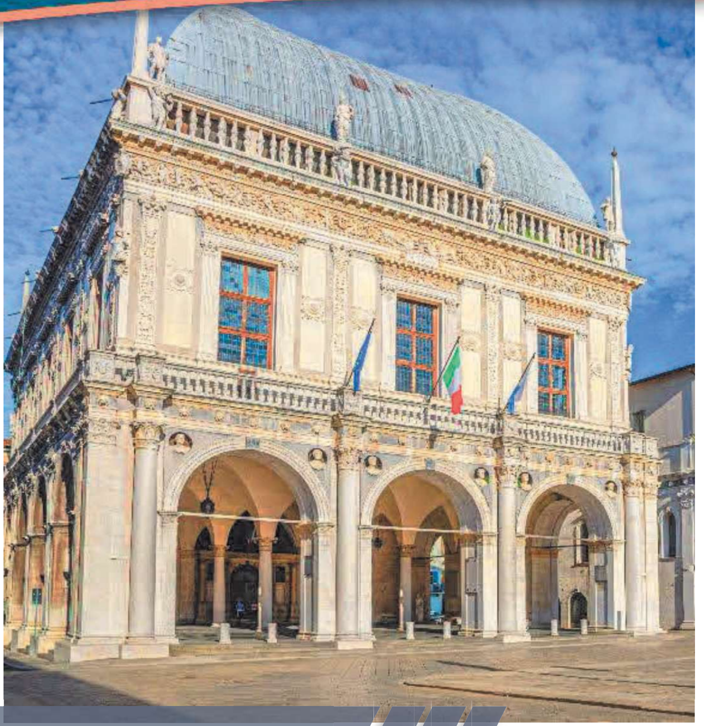

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Memristive devices as a potential resistance standard

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***Abstract* – The EMPIR [1] project 20FUN06 MEMQuD --- "Memristive devices as quantum standard for nanometrology" [2] has as one of its fundamental goals the development of technical capability and scientific knowledge for the implementation of a quantum resistance standard based on memristive devices characterized by high scalability down to the nanometer scale, CMOS compatibility and working in air at room temperature. In this work it is presented an overview of the project and highlighted relevant characteristics and working principles of memristive devices, applications as well as the last revision of the International System of Units (SI) that is the motivation and background for the aim of this project.**

I.INTRODUCTION

The redefinition of the SI units in 2019 [3] turns possible that all measurement units are now defined through fixed values of fundamental constants of nature, representing a significant and historic step forward where, for the first time, the definition of the 7 base units of the SI are based on fixed constants and not depending on any artefact, material properties or measurement descriptions. For electrical units, all units are now defined on the value of the elementary charge, e, and the Planck's constant, h, and are realized and disseminated via the Quantum Hall Resistance standard (QHRS) and the Josephson Voltage Standard [4]. The required systems for the implementation of a QHRS are complex and time consuming to operate, demanding high magnetic fields and low temperature values, near 1 K.

Memristive devices or memristors (from the contraction of memory + resistor) are a new class of nanoscale devices where ionics is coupled with electronics and where device functionalities rely on nanoionic effects. Initially theorized in 1971 from Prof. Chua [5], the ideal concept of memristor, was associated with the so-called resistive switching devices in 2008 by the group of Stanley Williams at HP labs [6]. These are two terminal devices where a switching film (usually a metal-oxide) is sandwiched in between two metal electrodes in a metal-insulator-metal (MIM) structure (Figure 1).

In these devices, the internal state of resistance depends on the history of applied voltage and current exhibiting the typical hysteretic loop in the I-V plane (Figure 1.b and 2.b). By exploiting these characteristics, it was demonstrated that memristive devices can have applications in next-generation memories, in-memory computing architectures and neuromorphic architectures. In particular, memristive devices under specific conditions of operation can show low resistance states activated in the device corresponding to values multiple (or half-integer multiples) of the fundamental conductance value, $G_0 = 2e^2/h$. This means that these devices offer a promising platform to observe and generate quantum resistance values in air, at room temperature, and without the need of any applied magnetic field as it is needed for the QHRS. Moreover they also can work at harsh conditions as low/high temperatures, presence of electromagnetic waves and X-ray and are high energy particles resistant. These quantum values of resistance are in line with the spirit and fundamental characteristic of the redefinition of the SI, depending only on the fixed values of the constants e and h.

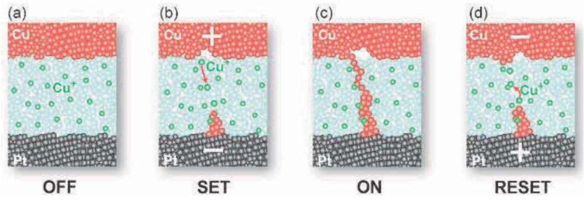

Figure 1. Schematic presentation of the operation principles of cation based ReRAM memory cells with a Cu active electrode and Pt counter electrode. (a) depicts the initial or OFF state. (b) shows the dissolution of metallic Cu to Cu+ ions and the formation of the metallic filament in the 'program' or 'set' operation. (c) is the short-circuited ON state. (d) shows the dissolution of the filament in the 'erase' or 'reset' step under reverse bias and the return to the OFF state. [7]

The project MEMQuD aims to study in details quantum effects in memristive devices and to investigate fundamental aspects underpinning memristive technology. The simpler way to operate this new device, its particular characteristics as low scalability and on-chip integration open the possibility of new applications with relevant impact in metrology field and industry, meeting the challenges opened by the revised SI where new experiments and devices can be explored for allowing integration of fundamental units as internal standard references.

II.OVERVIEW OF THE MEMQUD PROJECT

The three year duration (2021-2024) MEMQud project is formed by a consortium of 15 european participantes [2]: 6 National (or Designated) Metrology Institutes and 9 research and university institutes gathering diverse technical and scientific knowledge that bring to project the needed interdisciplinary skills to implement and underpinning the defined project activities and goals.

The project activities are grouped in three workpackages: *1)* Memristive device fabrication and characterisation, *2)* Nanoelectrical and nanodimensional characterisation of memristive devices and *3)* Development of a quantum-based standard of resistance based on memristive devices.

The first group of activities is focused on manufacturing of memristive cells by the combination of depositing functional layers, structuring methods, surface treatment and engineering supported by traceable analytical and dimensional characterisation techniques.

The second workpackage investigates nanoionic processes by advancing reliable nanoelectrical and nanodimensional characterisation at near atomic scale of the physical mechanism of the memristive, including the development of a traceable quantification of chemical, structural and ionic/electronic properties of memristive devices through microscopy techniques such as Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Secondary Ion Mass Spectroscopy (SIMS), X-ray Spectrometry including X-ray Diffraction (XRD) and Energy Dispersive X-ray Spectroscopy (EDS).

The third group of activities is focused on metrological electrical characterisation of quantized conductance levels in memristive devices including the investigation of quantized state stability, influence of ambient conditions and noise analysis. Also, a statistical approach and protocols for analysing quantum conductance phenomena, modeling and experimental evaluation of uncertainty associated with quantized states, device-to-device variability and inter laboratories variability will be addressed. Finally, it will be assessed the possibility to develop and test a resistance standard demonstrator in a CMOS circuit, meeting the challenges opened by the revised SI where new experiments and devices can be explored for allowing integration of fundamental units as internal standard references.

III.CHARACTERISTICS AND OPERATION OF MEMRISTIVE DEVICES

The operation of memristive devices is achieved with an electrical stimulus applied to its terminals that is responsible for the transition between an high resistive (HRS) state and a low resistive state (LRS). This resistive switching mechanism is related to the formation/rupture of a conductive path (filament) bridging the two electrodes that is responsible for an increase/decrease of the device conductivity (Figure 1 and Figure 2a).

Among several different types memristors redox-based memory cells (ReRAMs) show particluar promises. Depending on the materials, mobile ions and redox reactions one can distinguish between electrochemical metalization cells ECM (also called CBRAM or PMC); valence change memories VCM or OxRAM and thermochemical memroies (TCM). In the case of ECM, the formation of the conductive filament has been shown to be related to redox reactions involving dissolution of metal atoms from active electrode (Ag, Cu, Ni, Fe etc.) to form metal ions that migrate in the insulating matrix (e.g. an oxide), under the action of the applied electric field. In the case VCM cells, the variation of the internal state of resistance is related to reactions and transport of oxygen-related defects such as oxygen vacancies.

A relevant characteristic of this mechanism is observed when the size of filament is reduced to the atomic scale. In this case, the conductive filament bridging the two electrodes results in a ballistic electron conduction path constituted by discrete conductive channels [9,10]. Each of these conduction channels contributes with a maximum amount of one fundamental quantum of conductance G_0 ($G_0^{-1} \approx 12.9\ \mathrm{k\Omega}$) to the total conductance, G:

$$G = TNG_0 \tag{1}$$

Where T is the transmission coefficient and N is an integer number representing the number of conducitve channels. However, half-integer multiples of G_0 were also observed for certain types of memristive devices configuration.

The control of the conductance states it is possible with different types of external electrical stimulation: voltage and current sweeps, pulse or constant voltage or current signals. By properly adjusting the external electrical stimulation signal it is possible to control the filament formation/dissolution and the related quantum conductance states achievable in that process [8,9].

The current compliance value of the electrical signal applied to the device (in a sweep voltage signal) to define the transition of the resistive state of the device from the HRS to the LRS will determine the obtained ON resistance value corresponding to the LRS. Experimental data obtained in exploratory measurements made within the scope of this project and presented in Figure 2.b, for a crossbar cell of Pt/SiO2/Cu/Pt, show that the value of the ON resistance decreases with the value of the applied current compliance. This shows that current compliance determines the size of the conducting filament in the switching layer and the corresponding conductance (or resistance) of the device in the LRS. Current compliance adjustment will therefore be one of the external electrical signal parameters to be controlled to induce resistive states corresponding to multiples of G_0.

In this framework, the materials used as electrodes as well as switching layers play an important role in the electrochemistry of the cell and ionic transport properties.

Figures of merits and recommended methods are being discussed at the scientific level in ref. [10],[11]. Already identified figures of merit in the scientific community include device reliability (memristive endurance), state retention (time that device remains in a conductive state after being programmed), switching time, energy consumption, variability and scalability to cite a few. These figures of merit could be in the future recognised as key control characteristics for industrial electrotechnical products based on, or involving, memristive devices. From the point of view of a potential metrological application, as a quantum standard of resistance, retention times of the order of some seconds or minutes (conductive filaments can spontaneously dissolve over time) as has already been demonstrated are sufficient to access and transfer (e.g. by potentiometric method) the quantum resistance value.

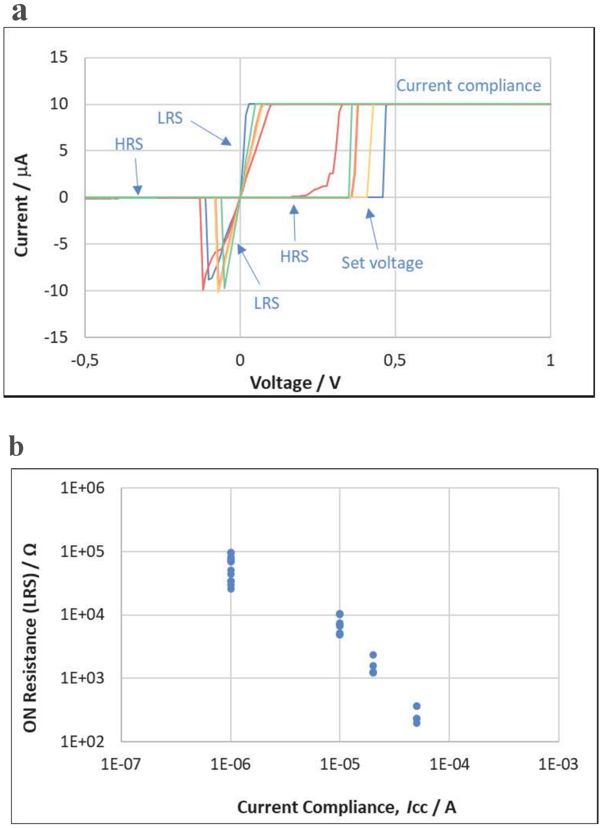

Figure 2. (a) I-V curve characetristic of a crossbar cell based on Pt/SiO$_2$/Cu PT (30nm/30nm/50nm/30nm) obtained for a sweep voltage signal and a current compliance of 10 µA. The different curves correspond to several consequent set/reset cycles. (b) Value of the ON Resistance obtained as function of the current compliance (I$_{cc}$) applied in the activation of the low resistve state (LRS) of the device. Crossbar cell fabricated and experimental data obtained in exploratory measurements done in the framework of the MEMQud project.

More relevant and challenging is the intrinsic stochasticity process associated with the filament formation/rupture and dynamics due to the atomic rearrangement phenomenon. Another source of variability is observed as electronic noise due atomic fluctuations near the point contact.

The combination of the sources of variability affects the repeatibility and the reproducibility of these devices as can be seen with the dispersion of the values obtained for the ON resistance corresponding to each current compliance value and resulting from several activations of the device (Figure 2.b).

Besides these relevant sources of uncertainty, the presence of parasitic resistances [9] should also be taken into account in the assessment of quantum resistance value. Figure 3 schematically shows an equivalent

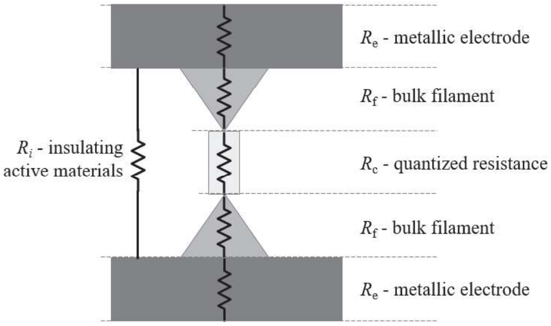

Figure 3. Equivalent electrical circuit of a memristive cell. Besides the quantized contact resistance R_c, the equivalent circuit is composed of the bulk filament resistance R_f, the resistance of the insulating active materials R_i and the resistance of the metallic electrodes R_e.

electrical circuit for memristive cell where the quantized resistance R_c due to the filament constriction is associated to parasitic resistances.

An overall uncertainty estimation will have to take into account these contributions: the systematic error of parasitic resistances should be estimated and corrected (the uncertainty of that estimate will be accounted for as one of the uncertainty components of the combined uncertainty); the variability corresponding to the resistance value obtained at each activation of the device could be first reduced with programming techniques to validate before accessing the desired quantum level of resistance.

IV.METROLOGICAL AND OTHER APPLICATIONS

The properties of memrisitve devices as scalability, high operational speed, compatibility with CMOS technology (both in terms of materials and processes) have been exploited and demonstrated in applications as a new generation of nonvolatile memories as well as in the emulation of neural and synaptic processes.

The integration of memrisitve devices in CMOS circuits also opens the possibility of obtaining a "zero chain traceability" resistance standard available in situ and with the capacity to be integrated in any type of electronic measurement instrumentation to support auto-adjustment and auto-calibration process.

Other specific relevant applications are being identified with the help of the stakeholders of this project. In sensors networks, the calibration of each sensor is usually difficult and a distributed and statistical approach is exploited, where the traceability is propagated among sensors. In this context, the traceability of each sensor can be achieved by integrating memristive devices.

The use of devices in harsh environments (ionizing environments and cosmic rays can strongly affect not only active components such as transistors but also passive components, including resistors. As an example, neutron irradiation damages the material crystallinity (embrittlement effect), thus strongly modifying its resistance. This strongly affects the functionalities of integrated circuits and sensors. The nature of the memristive devices and its application as resistance standard is promising to overcome these effects and to be stable in ionizing environments and under cosmic ray irradiation.

In certain kind of programmable gain amplifiers, its gain (or also the cut-off frequency of a filter) can be modified by changing the value of an associated resistor. The internal programmable resistance state of the memristive devices can also be exploited for programming the gain of amplifiers in analog circuits.

V.CONCLUSION

The potential of the quantum conductance effect in memrisitve devices is for the first explored to be applied in the metrology field as a quantum resistor standard. This specific application highlights the need to improve the control and domination of quantum conductance levels to obtain stable and reproducible steps of resistance. To achieve that, the proper operation parameters (voltage/current stimulation modes) related to the materials used (for electrodes and switching films), the effects of temperature and moisture and device engineering still have to be investigated and tested.

Improving the understanding of the relationship between this quantum phenomenon and the discrete atomic structures of the conductive filaments also need further investigation.

All these aspects will be investigated throughout the activities planned in the MEMQuD project in an integrated multidisciplinary technical and scientific approach.

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