Publishable Summary for 20FUN06 MEMQuD
Memristive devices as quantum standard for nanometrology

Overview

Memristive devices are electrical resistance switches that couple ionics (i.e. dynamics of ions) with electronics. These devices offer a promising platform to observe quantum effects in air, at room temperature, and without an applied magnetic field. For this reason, they can be traced to fundamental physics constants fixed in the revised SI for the realisation of a standard of resistance. However, as an emerging technology, memristive devices lack standardization and insights in the fundamental physics underlying its working principles, hindering their use. The overall aim of the project is to investigate and exploit quantized conductance effects in memristive devices for the realization of quantum-based standards of resistance that operate reliably, in air and at room temperature with scalability down to nanometer precision. In particular, the project will focus on the development of memristive model systems and nanometrological characterization techniques at the nanoscale level in memristive devices, in order to better understand and control the quantized effects in memristive devices. Such an outcome would enable the realization of a standard of resistance implementable on-chip for self-calibrating systems with zero-chain traceability in accordance with the revised SI.

Need

Over the past decade, the rapid development of information and communication technologies opened new horizons for artificial intelligence and green technologies. These developments challenge the state-of-the-art of nanoelectronics in demanding new hardware architectures to overcome von Neumann computing by implementing neuromorphic-type of data processing. Memristive devices have recently gained tremendous interest not only in the scientific community but also in the semiconductor industry as building blocks for hardware implementation of in-memory computing and artificial intelligence, due to their ability to emulate neuromorphic type of data processing combined with high scalability down to almost atomic scale, low power consumption (<pJ for operation) and high operational speed (ps).

The revision of the SI in 2019 represents an historic change of paradigm for metrology, defining all the SI units in terms of fundamental constants of nature. The development of new experiments and devices are now needed for correlating physical observables to the fixed defining constants, paving the way for the realization of self-calibrating systems that can independently refer to the fundamental constants of nature with zero-chain traceability. In accordance with the revised SI, memristive devices exhibiting quantized conductance levels represent promising platforms for on-chip integrated and complementary metal-oxide-semiconductor (CMOS) compatible standard of resistance, which work in air and at room temperature.

While novel materials and devices for nanoelectronics indeed offer many potential benefits, they also bring challenges for testing and characterization. As an emerging technology, memristive devices lack standardization and insights in the fundamental physics underpinning its technology, hindering their further development. Understanding and controlling resistive switching behavior at the nanoscale is therefore highly challenging and high throughput metrology is urgently required. The development of new technologies for nanoelectronics, including quantum technologies, neuromorphic computing and related metrology, is in line with the European R&D programmes “Quantum Technologies Flagship” and the “Human Brain Flagship”. For this purpose, memristive model systems need to be developed, to establish a relationship in between material properties and device functionalities. The understanding of nanoionic processes involved in memristive devices requires i) advancements in nanoelectrical characterization techniques, ii) the development of a traceable quantification of chemical, structural and ionic/electronic properties of memristive devices and iii) the

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development of metrological cross-platforms measurement techniques. These are the key requirements for understanding and controlling quantized conductance effects in such devices for the realization of the standard of resistance.

Objectives

The overall objective and technological target of this project is to provide, in a metrological framework, technical capability and scientific knowledge for the *mise en pratique* of a resistance standard based on memristive devices characterized by high scalability down to the nanometer scale, CMOS compatibility and working in air at room temperature.

The specific objectives of the project are:

1. To **develop well-controlled memristive model systems** for establishing a relationship between the revealed material properties and actual device functionalities. This should include the 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.
2. To **investigate nanoionic processes by advancing reliable nanoelectrical characterization of memristive devices** by using metrological scanning probe microscopies (SPMs) for probing its local electrical properties by means of traceable conductive AFM (C-AFM), scalpel C-AFM for 3D reconstruction of the memristive cells and Scanning Tunneling Microscopy (STM).
3. To **develop a traceable quantification of chemical, structural and ionic/electronic properties of memristive devices** through scanning microscopy (AFM, SEM), Secondary Ion Mass Spectroscopy (SIMS), X-ray Spectrometry including X-ray Diffraction (XRD) and Energy Dispersive X-ray Spectroscopy (EDS) in order to achieve nanodimensional characterization at near atomic scale of the physical mechanism of the memristive cell.
4. To **develop metrological cross-platforms measurement techniques** with high resolution in space (< 10 nm) and time (< ms) for investigating device dynamics by correlating the variation of chemical/structural properties to the electrical response of memristive devices *in operando*. To also develop a quantum-based standard of resistance for nano applications including CMOS compatible and on-chip implementable resistance standards.
5. To **facilitate the take up of the technology and measurement infrastructure developed in the project** by the measurement supply chain (nanometrology), standards developing organisations (IEC TC 113, Versailles Project on Advanced Materials and Standards (VAMAS) TWA 2) and end users (nanoelectronics).

Progress beyond the state of the art and results

Objective 1: Development of well-controlled memristive model systems

A set of memristive devices exhibiting quantized conductance phenomena will be developed through the combination of deposition of functional layers, structuring methods, and surface treatment and engineering. These will be characterized to establish a relationship between material properties and quantized conductance phenomena for the first time. Quantized conductance phenomena will also be investigated for the first time in low-dimensional systems such as nanowires and 2D materials, which will be explored for use in neuromorphic data processing.

Memristive model systems exhibiting quantized conductance phenomena will be developed for the first time through surface/interface modifications and device structuring, providing suitable platforms for the investigation of ionic processes underlying resistive switching effects and Quantum Point Contact (QPC) phenomena.

The project will go beyond the state of art by advancing the metrological electrical characterization of quantized conductance phenomena in memristive cells by analysing time stability, device-to-device variability, dependence on temperature and environment and noise of quantized states. For the first time, a statistical approach to analyse experimental data, including quantized conductance state fluctuations and inter laboratory measurements, will be developed, while the uncertainties associated to quantized state levels in memristive devices will be analysed. As a result, proper guidelines for the fabrication of memristive cells with quantized conductance phenomena will be established.

Objective 2: Investigation of nanoionic processes by advancing reliable nanoelectrical characterization

Improvement of dimensional traceability of operando SPM techniques including C-AFM and STM will allow the investigation of local electrical properties of memristive cells and QPC constructions. In particular, the improvement of scalpel C-AFM including the development of a new technique based on a two-probe analysis scheme will be adopted for 3D tomographic reconstruction of a memristive cell with 1 nm spatial resolution.

Objective 3: Development of a traceable quantification of chemical, structural and ionic/electronic properties of memristive devices

New high throughput and reference-free XRF technique will be used to characterize memristive materials, unveiling the influence of doping and impurities on memristive and quantized conductance phenomena. The XRF traceable technique is exploited to qualify appropriate calibration samples that will be employed for independent characterisation techniques, such as SIMS or XPS.

New high throughput operando XPS and SIMS techniques will be developed for the first time, for the investigation of resistive switching mechanism, to provide new insight on local composition of memristive materials at the nm scale, as well as their evolution over time under electrical stimulation.

Objective 4: Development of cross-platforms measurement techniques and a quantum-based standard of resistance

High resolution (< 100 nm) ex situ, in situ and operando XRS experiments will be performed for the first time on memristive cells to investigate elemental, chemical, crystalline, structural and dynamic analysis of local properties of memristive cells operating in the QPC regime. The spatial resolution required actually depends on the spectral discrimination capability of the XRS techniques employed, e.g. regarding oxygen elemental or species mass depositions as against the spectral background induced by matrix and object elements.

As a result, the development and the complementarity of the operando and cross-platforms measurement techniques will provide a detailed understanding of the resistive switching mechanism of memristive cells working in quantized conductance regime as well as making significant advances in the development of metrology at nanoscale.

New theoretical and compact models including variability and fluctuations effects in memristive devices in the QPC regime will be developed and the consistency will be validated on experimental data from the project. Novel numerical approaches based on non-equilibrium Green functions will be explored for modelling QPC effects.

As a result of this project, a resistance standard demonstrator based on memristive devices working at room temperature, in air and without an applied magnetic field will be developed. Performances will be evaluated in terms of accuracy, time stability and reproducibility and compared with the conventional resistance standard based on the Quantum Hall Effect (QHE).

Impact

Impact on industrial and other user communities

The development of metrological nanoelectrical and nanodimensional characterization tools and techniques represents a breakthrough in the detailed understanding of the physical mechanism underlying memristive phenomena, paving the way for the realization of design rules and roadmaps for rational design and ultimate scaling of memristive devices. The development of these techniques represents a milestone not only for the realization of metrological devices but also for the development of next-generation neuromorphic hardware architectures for brain-inspired neuromorphic computing and AI applications. In addition, the development of methods and best-practices to extract meaningful and quantitative information of electrical and chemical properties at the nanoscale can impact the entire sector of nanoelectronics and nanotechnology. To promote the uptake of the project results by the industrial community, the project outputs will be presented at international conferences attended by the interested communities.

Impact on the metrology and scientific communities

In the framework of the revised SI, the realization of a standard of resistance based on memristive devices will fundamentally change electrical nanometrology. The realization of a nanosized resistance standard based on CMOS compatible and memristive devices working in air at room temperature can overcome the limitations of the QHE based resistance standard which requires working in vacuum at cryogenic temperatures and high magnetic fields. This allows the integration of a memristive resistance standard on-chip for the realization of self-calibrating systems with zero chain traceability.

The multidisciplinary aspect of this project, involving modelling, analysis of physical and chemical properties, growth technologies, dimensional and electrical metrology based on different techniques (AFM, SIMS, XRS, C-AFM) cannot be addressed by a single NMI. The development of hybrid and complementary nanodimensional and nanoanalytical metrology requires a broad collaboration between a relevant number of laboratories from different but complementary branches at the European level. With this established partnership, capabilities of European R&D laboratories and NMIs will be enlarged and knowledge exchanges reinforced.

The scientific community will benefit from this project through the advancement in understanding of fundamental physical and nanoscale electrochemical processes to regulate resistive switching and quantized conductance phenomena in memristive devices. Due to the multidisciplinary interest in memristive devices the project will have impact not only to the metrology and physics community but also to the chemistry, electronic engineering, computer science and biology community for further development of quantum technologies and artificial intelligence. To maximize the uptake of the project outputs, the project plan includes convening special sessions at international conferences and specific training courses. It is anticipated that these will be well-subscribed.

Impact on relevant standards

The different nanoanalytical techniques investigated will provide substantial input to the four ISO/TC 201 subcommittees: SC6 (SIMS), SC7 (XPS), SC9 (SPM) and SC10 (XRR and XRF) with respect to improved traceability and uncertainties by means of the qualification of appropriate nanoscale calibration samples as well as mutual validation procedures. Moreover, outputs will be presented at the steering committee Versailles Project on Advanced Materials and Standards (VAMAS) on the closer Technical Working Areas (TWA) such as “Surface and Chemical Analysis (TWA 2)” or by proposing new TWAs. This includes the development of inter-laboratory studies for reproducibility and to assess new protocols for incrementing measure expertise. Also, the project will engage with technical committees and metrology organisations such as the EURAMET TC-EM, EURAMET TC-EM SC DC & Quantum Metrology, EURAMET TC-EM SC Low Frequency, COOMET TC 1.3 Electricity Magnetism, GULFMET TC-EMFT, IMEKO TC4 and IEC TC 113. At the national level, results will be disseminated through standardization technical committee such as the CT 194 - Nanotecnologias and DIN NA 062-08-17.

Longer-term economic, social and environmental impacts

The outcomes of this project will contribute to the development of new technologies and advancement of nanoelectronics and nanotechnology, including new hardware for brain-inspired neuromorphic computing and quantum technologies for development of artificial intelligence, autonomous systems and Internet of Things (IoT).

The metrology developed within the framework of this project will contribute to the development of nanoelectronic devices for the realization of new hardware architectures, capable of tackling societal challenges such as the development of artificial intelligence. The development of new computing paradigms could reduce power consumption by orders of magnitude compared to conventional computing technologies, helping Europe to reduce the impact of information technology on carbon emission and to reach net-zero energy targets to combat climate change.

The integration of an on-chip memristive resistance standard for the realization of self-calibration systems with zero-chain traceability will allow a significant reduction in the direct and indirect costs of maintaining the calibration status of a wide range of measuring instruments used in different metrology areas (e.g. electrical, temperature, optics, and others) that need resistor standards as an external reference to ensure metrological traceability to the revised SI.

Project start date and duration:		01 June 2021, 36 months
Coordinator: Gianluca Milano, INRiM Tel: +39 011 3919344 E-mail: g.milano@inrim.it Project website address: memqud.inrim.it		
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