INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

EURAMET

The EMPIR project MEMQuD

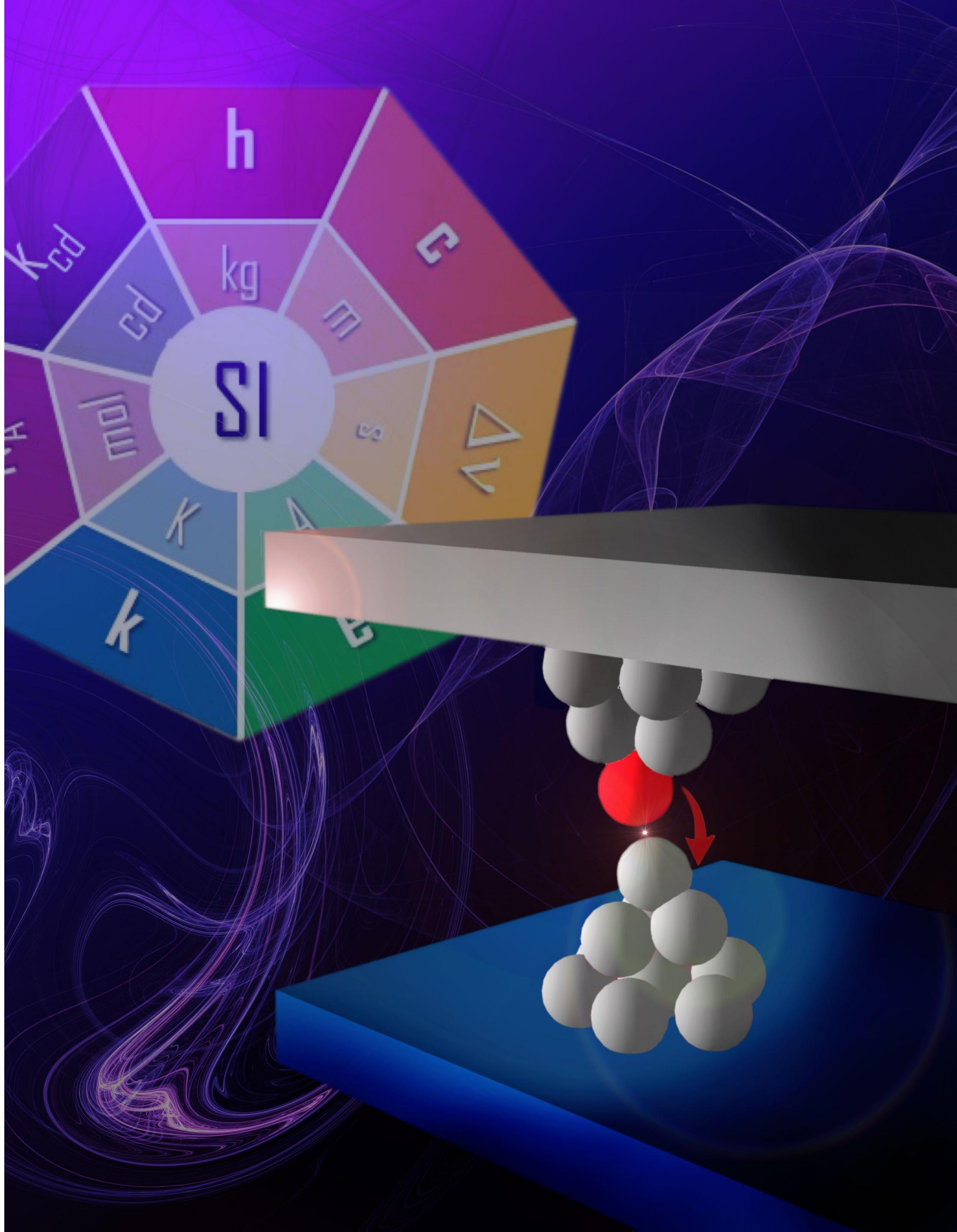
Memristive devices as quantum standard for nanometrology

MEMQuD

Gianluca Milano

Istituto Nazionale di Ricerca Metrologica (INRiM)

Workshop Quantum Metrology: the present and the future
Monday, 21 November 2022
Lisbon, Academy of Sciences and online



Background

Revision of the SI (metric system) in 2019 represents a **change of paradigm** for metrology

The 7 base units are now defined in terms of **fundamental constant of nature** that are **assigned to fixed exact value**

Each experiment able to correlate a measurable quantity to a fundamental constant of nature
(or a combination of fundamental constants)
becomes a direct realization of the corresponding SI unit.

Memristive devices for quantum metrology as a standard of resistance

MEMQuD goals

- **Realization of memristive devices (WP1)**

  - Development of memristive model systems
  - Influence of doping and mass impurities on switching materials
  - Selection of memristive devices with quantized conductance levels
    (Applications: metrology & neuromorphic computing)

- **(Nano)metrology for memristive devices (WP2)**

  Development of a metrological framework for the characterization of memristive materials
  (metrology of chemical, structural and ionic/electronic properties to investigate the switching mechanism)

- **Memristive devices for metrology (WP3)**

  To assess the possibility of using memristive devices as a standard of resistance

PROJECT CONSORTIUM

5 NMI

INRiM Istituto Nazionale di Ricerca Metrologica

GUM

IPQ

PTB

Laboratoire National LNHB Henri Becquerel

TÜBİTAK

3 Research Institutes

JÜLICH Forschungszentrum

INESC MN Microsystems and Nanotechnologies

instituto imdea nanociencia

4 University

Politecnico di Torino

UAB Universitat Autònoma de Barcelona

TOBB ETÜ University of Economics & Technology

tu technische universität dortmund

3 Companies

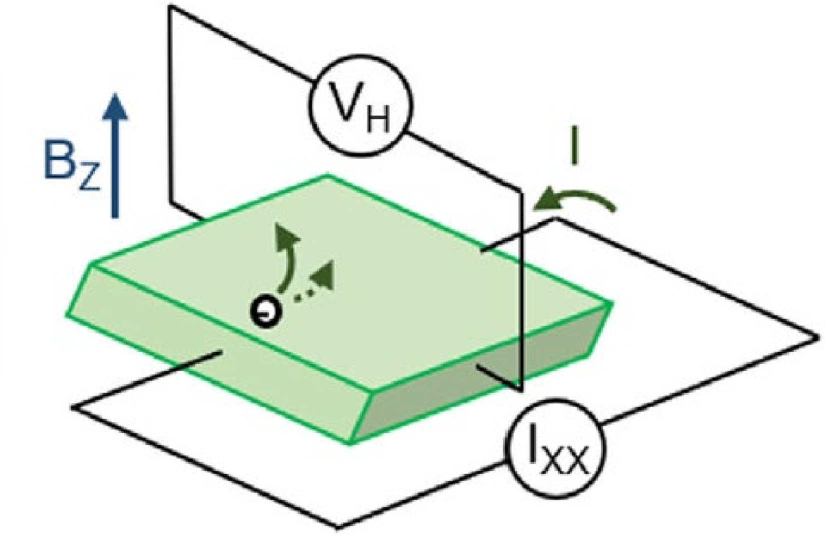
imec

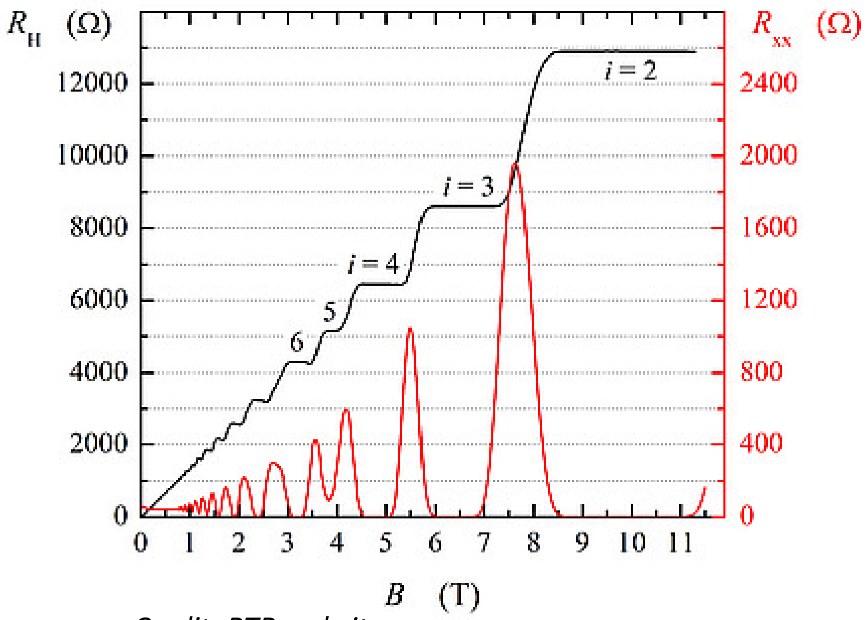
VTT

cpi

Background – the standard of resistance

Quantum Hall effect device





Credit: PTB website

First observed in 1980 by Klaus von Klitzing

Nobel prize in 1985

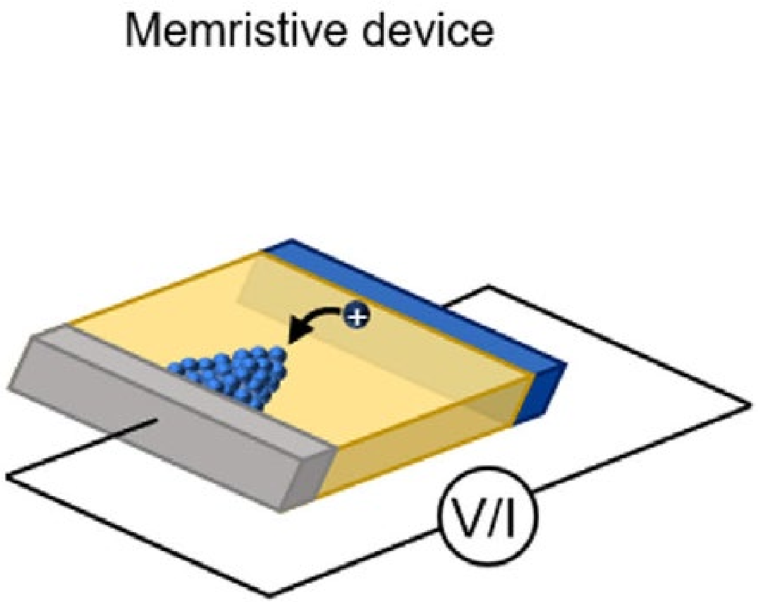
The Hall conductance is quantized in units of e^2/h (quantum of conductance)

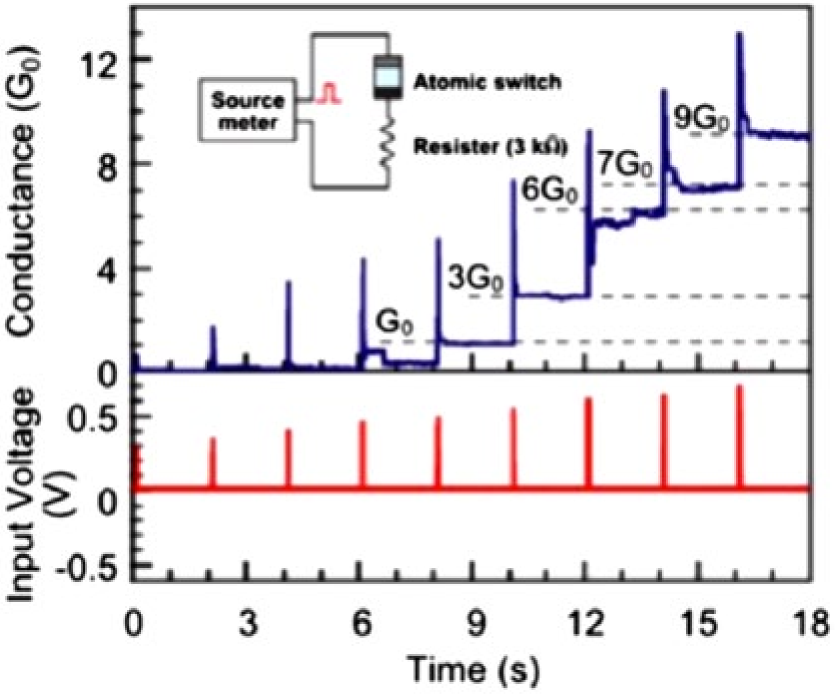
relative uncertainty of few parts in 10^8 can be obtained

Exploited for practical realization of the standard of resistance

Klitzing, K. V., *Physical Review Letters* 45.6 (1980): 494.

A new standard of resistance





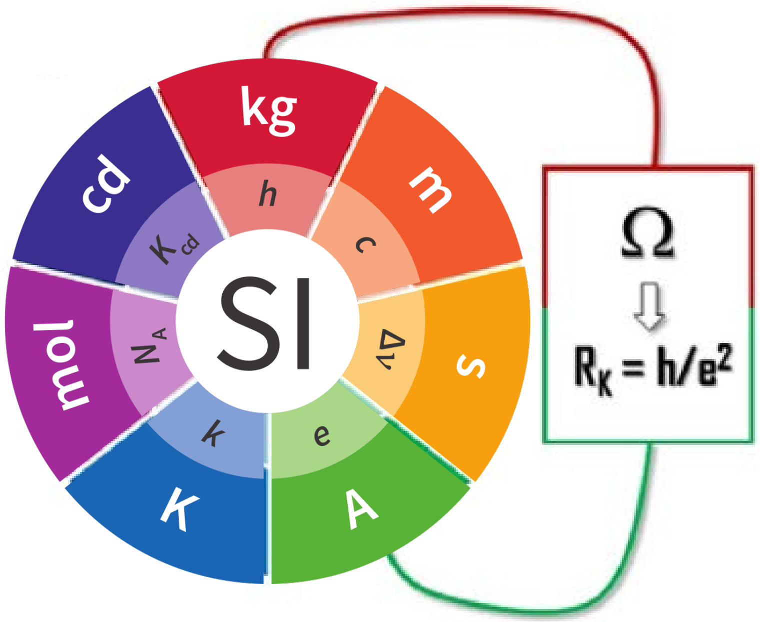
T. Tsuruoka et al. *Nanotechnology* 23.43 (2012): 435705.

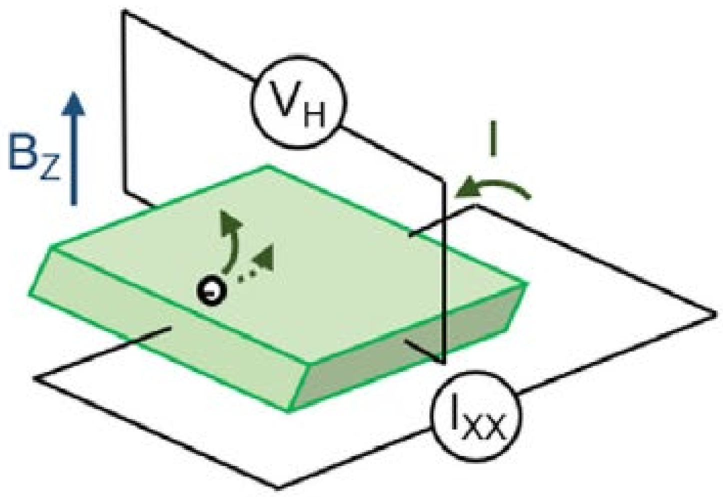
The conductance can be quantized in units of e^2/h (quantum of conductance)

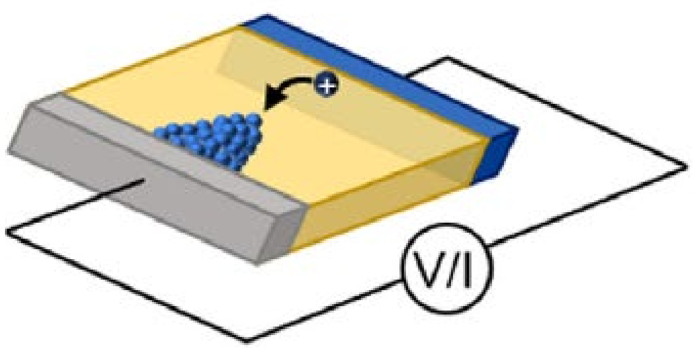
Can be exploited for practical realization of the <u>standard of resistance!</u>

G. Milano, et al., *Advanced Quantum Technologies* 3.5 (2020): 2000009.

QHE devices vs memristive devices





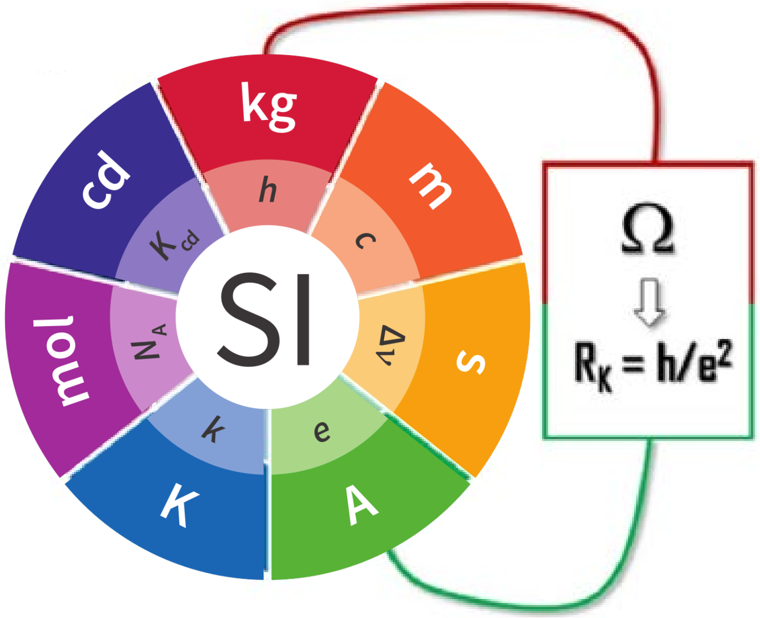


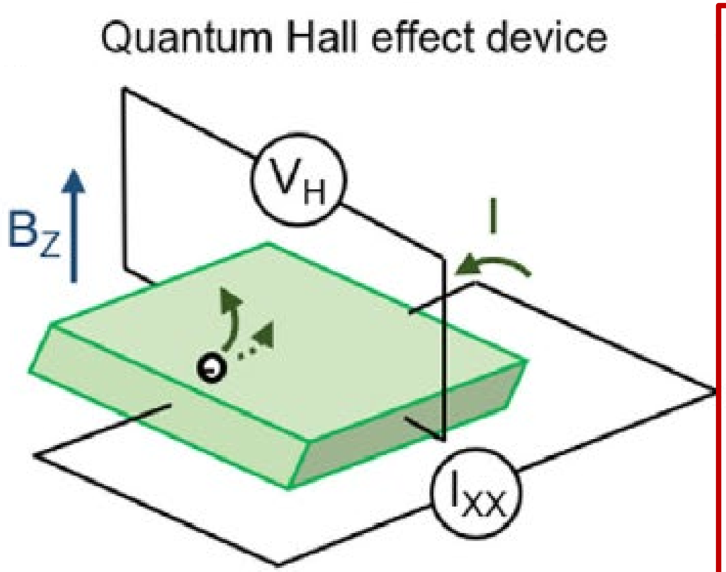
- High Magnetic field is required
- Low temperature is required
- Low uncertainty

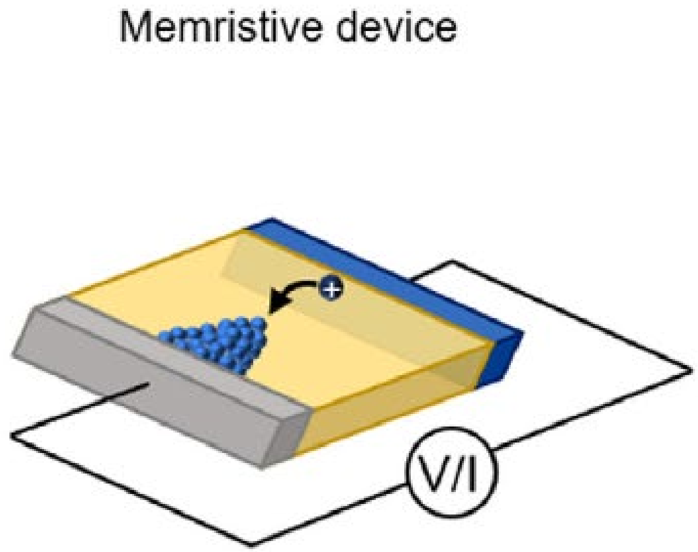
- Magnetic field is NOT required
- Works at room temperature in air
- Higher uncertainty (to be evaluated)
- Works in a wide range of temperatures, In harsh environment, CMOS compatible

G. Milano, et al., *Advanced Quantum Technologies* 3.5 (2020): 2000009.

QHE devices vs memristive devices







Implementable on-chip for self-calibrating systems with zero-chain traceability

(in the spirit of the revised SI)

G. Milano, et al., *Advanced Quantum Technologies* 3.5 (2020): 2000009.

MEMRISTIVE DEVICES

Leon Chua, 1971

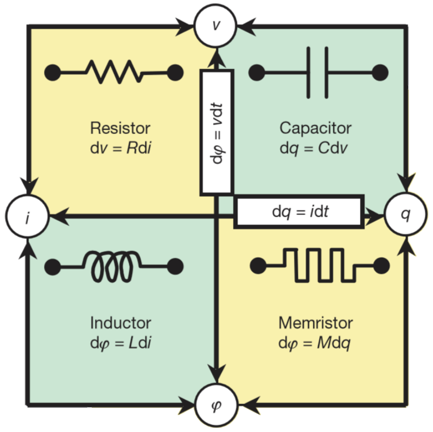
IEEE TRANSACTIONS ON CIRCUIT THEORY, VOL. CT-18, NO. 5, SEPTEMBER 1971

Memristor—The Missing Circuit Element

LEON O. CHUA, SENIOR MEMBER, IEEE

Symmetries: *i, v, q, φ* ➡ $d\varphi = M(q(t),\omega)dq$

ω State Variable
(not necessarily electrical)



Stanley Williams, 2008

nature Vol 453|1 May 2008|**doi:10.1038/nature06932**

LETTERS

The missing memristor found

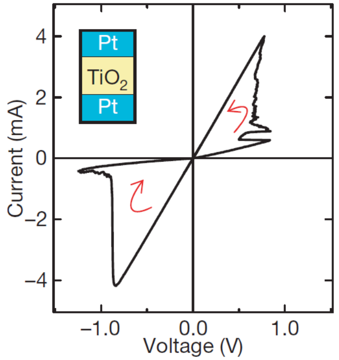
Dmitri B. Strukov[1], Gregory S. Snider[1], Duncan R. Stewart[1] & R. Stanley Williams[1]

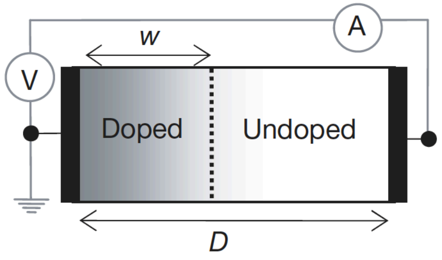
Concept of memristor associated to resistive switching phenomena

⬇

Ionics is coupled with electronics

Nanoionic devices





MEMRISTIVE DEVICES

MEMQuD
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

➢ For in-memory computing

- **Multilevel** storage capability
- High **endurance** and **retention**

➢ For neuromorphic applications

- Emulates **synaptic strength**
- **Analog** programmability
- **Short-term and long-term** memory dynamics
- **Large and dense arrays** as neural networks

nature nanotechnology | REVIEW ARTICLE
PUBLISHED ONLINE: 27 DECEMBER 2012 | DOI: 10.1038/NNANO.2012.240

Memristive devices for computing

J. Joshua Yang[1], Dmitri B. Strukov[2] and Duncan R. Stewart[3]

ARTICLES | nature electronics
https://doi.org/10.1038/s41928-017-0002-z

Analogue signal and image processing with large memristor crossbars

Can Li[1], Miao Hu[2,5], Yunning Li[1], Hao Jiang[1], Ning Ge[3], Eric Montgomery[2], Jiaming Zhang[2], Wenhao Song[1], Noraica Dávila[2], Catherine E. Graves[2], Zhiyong Li[2], John Paul Strachan[2*], Peng Lin[1], Zhongrui Wang[1], Mark Barnell[4], Qing Wu[4], R. Stanley Williams[2], J. Joshua Yang[1*] and Qiangfei Xia[1*]

nature materials | ARTICLES
PUBLISHED ONLINE: 26 SEPTEMBER 2016 | DOI: 10.1038/NMAT4756

Memristors with diffusive dynamics as synaptic emulators for neuromorphic computing

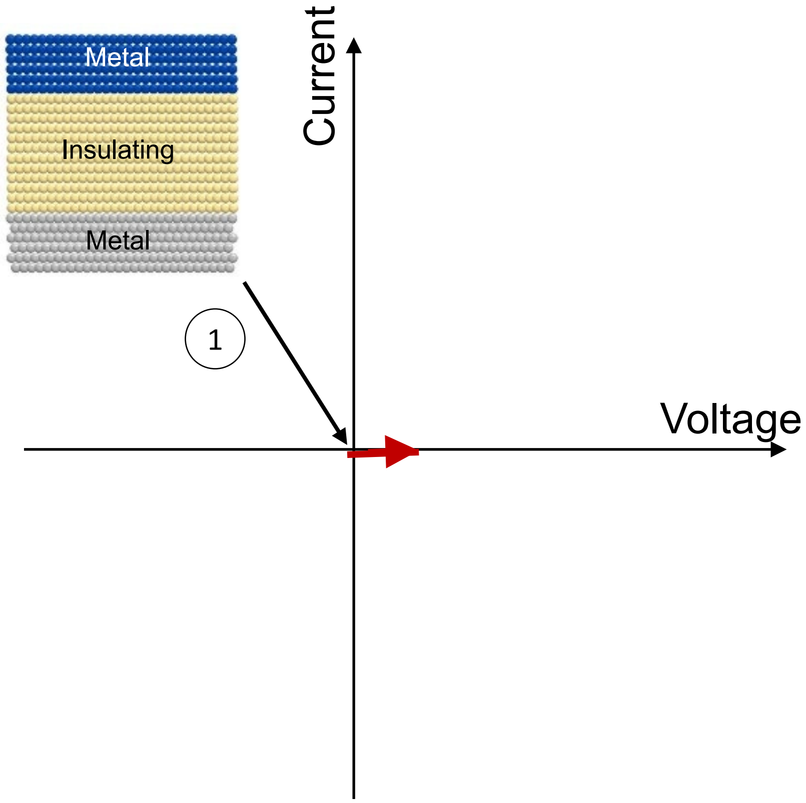
Zhongrui Wang[1†], Saumil Joshi[1†], Sergey E. Savel'ev[2], Hao Jiang[1], Rivu Midya[1], Peng Lin[1], Miao Hu[3], Ning Ge[3], John Paul Strachan[3], Zhiyong Li[3], Qing Wu[4], Mark Barnell[4], Geng-Lin Li[5], Huolin L. Xin[6], R. Stanley Williams[3], Qiangfei Xia[1] and J. Joshua Yang[1*]

MEMRISTIVE DEVICES

Resistive switching mechanism

Nanoionic devices:
ionics coupled with electronics

Functionalities rely on the formation/rupture of a conductive filament



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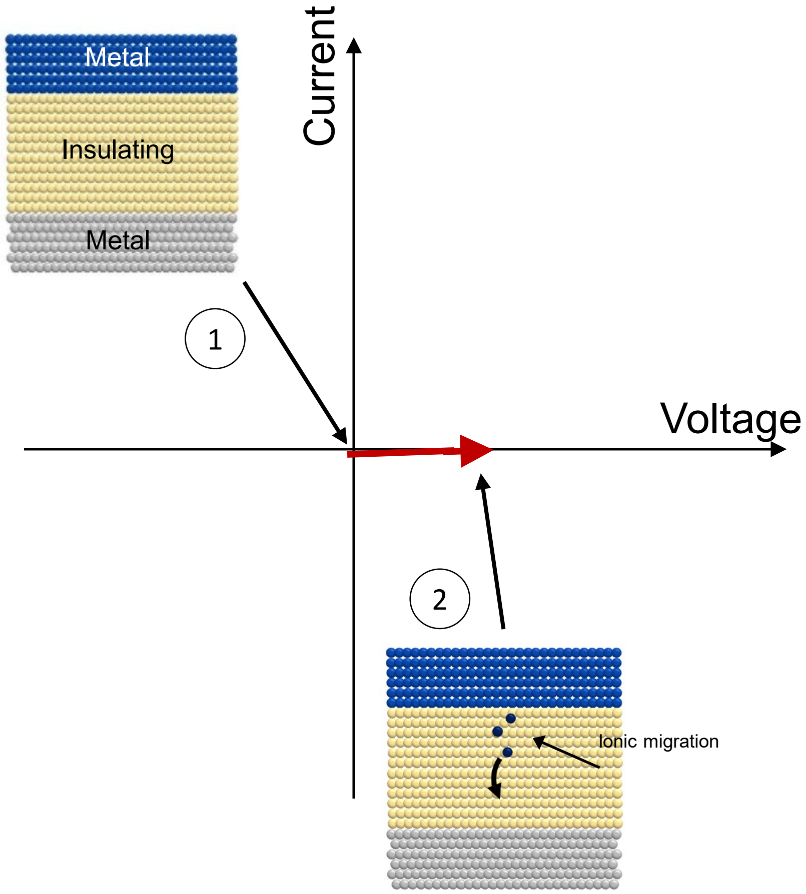

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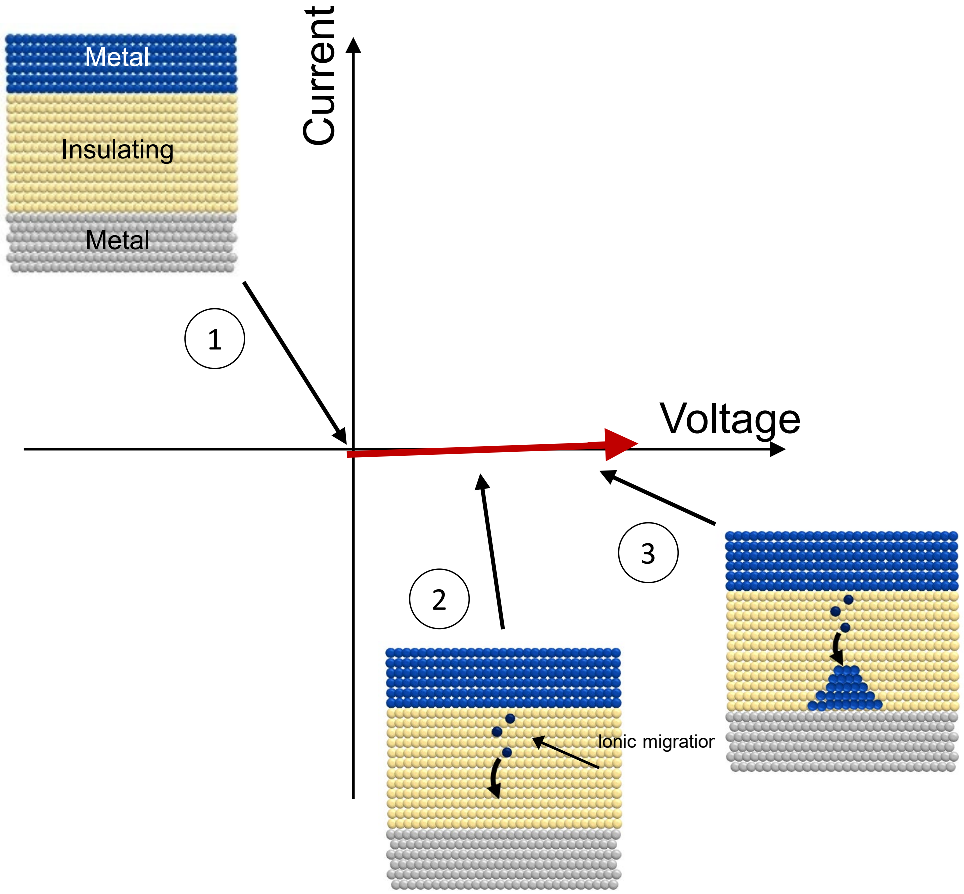

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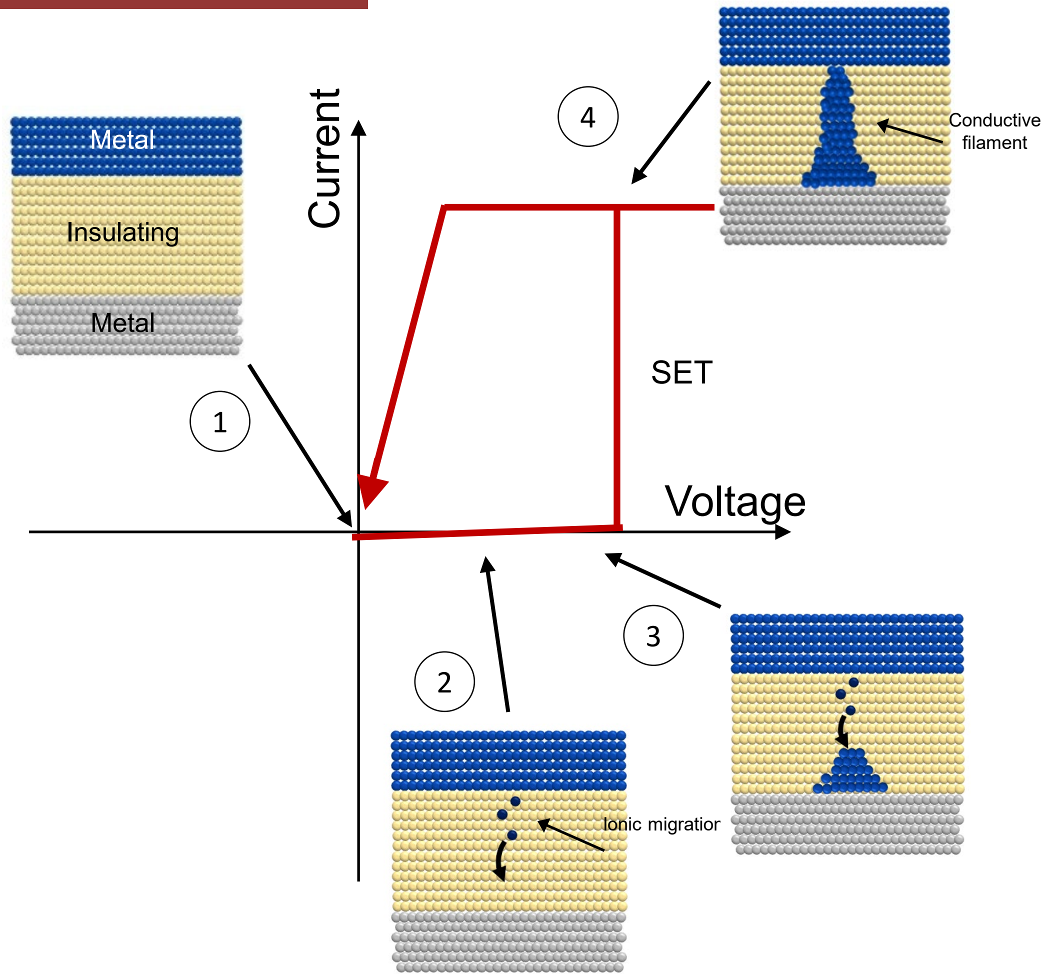

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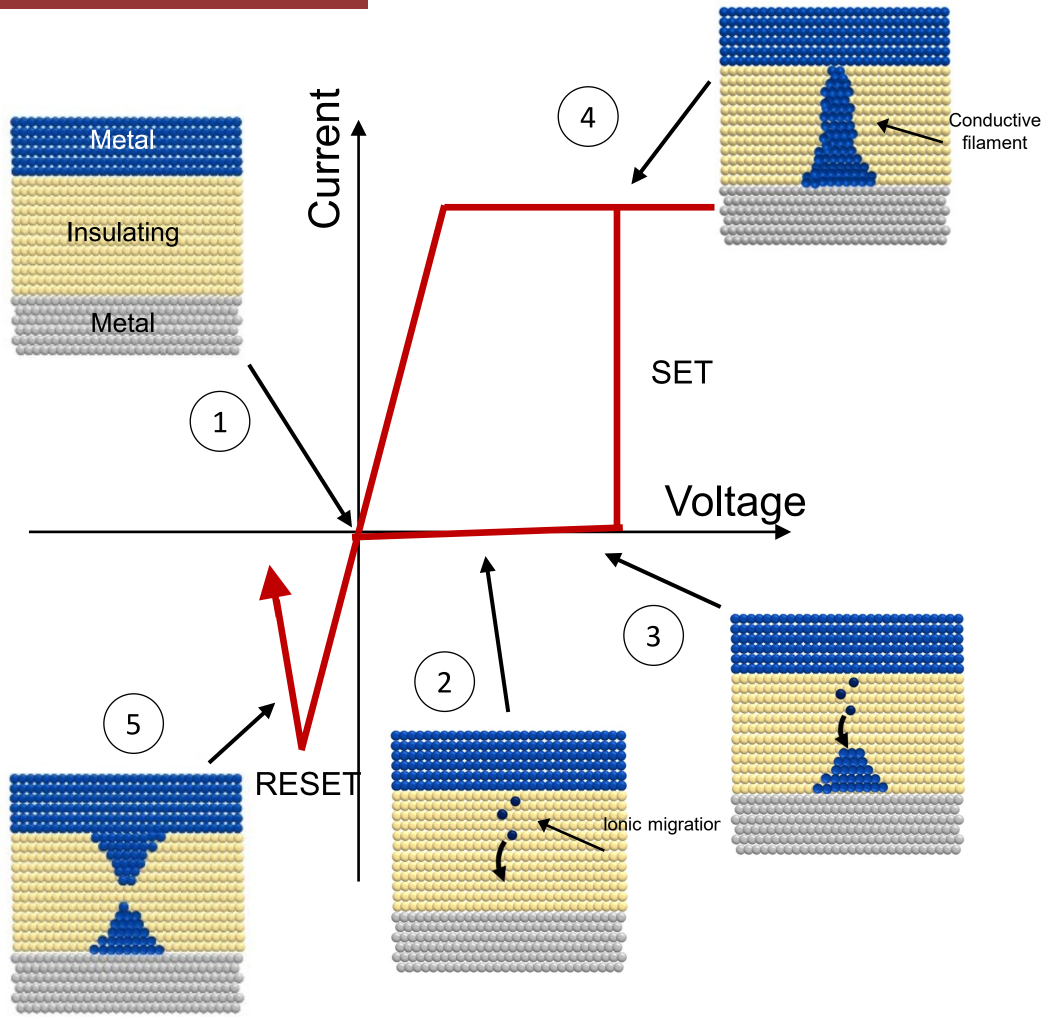

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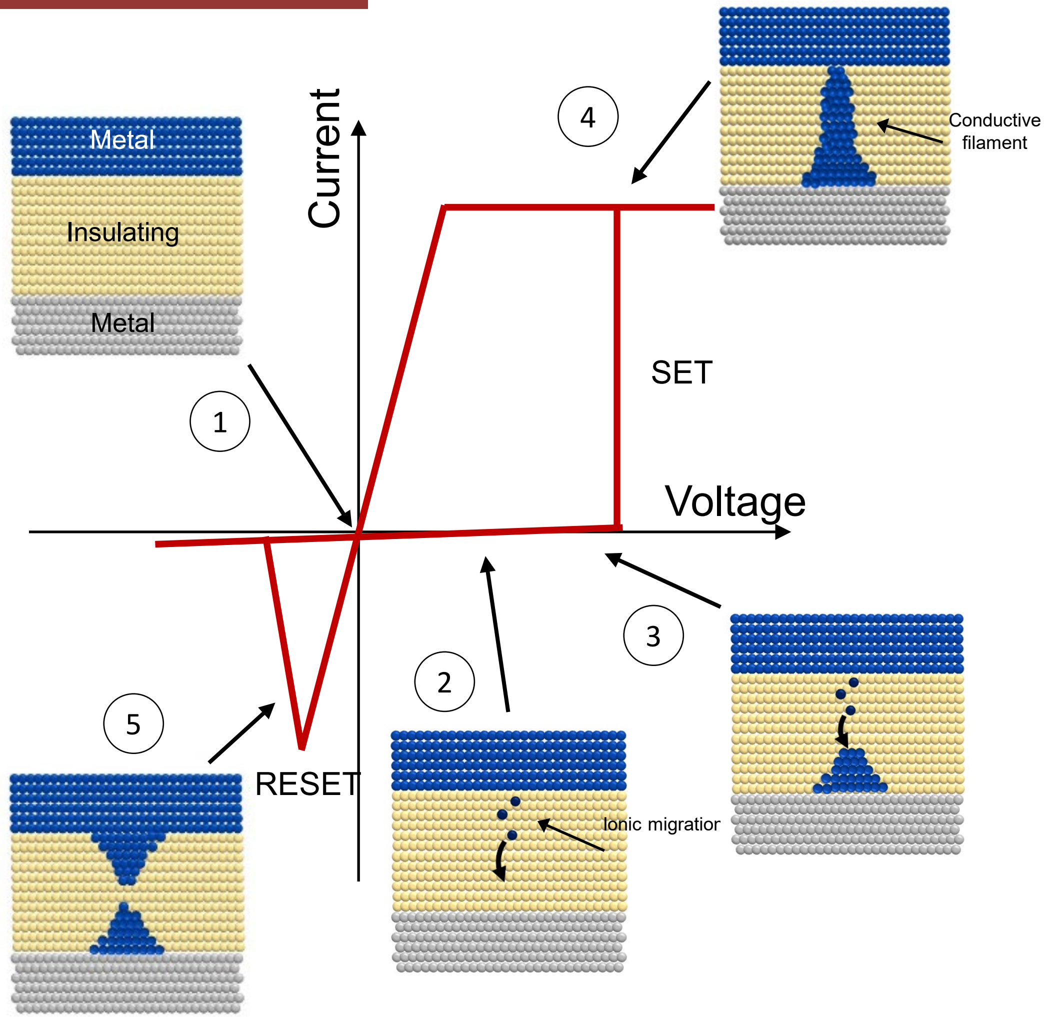

MEMRISTIVE DEVICES

Resistive switching mechanism

Nanoionic devices:
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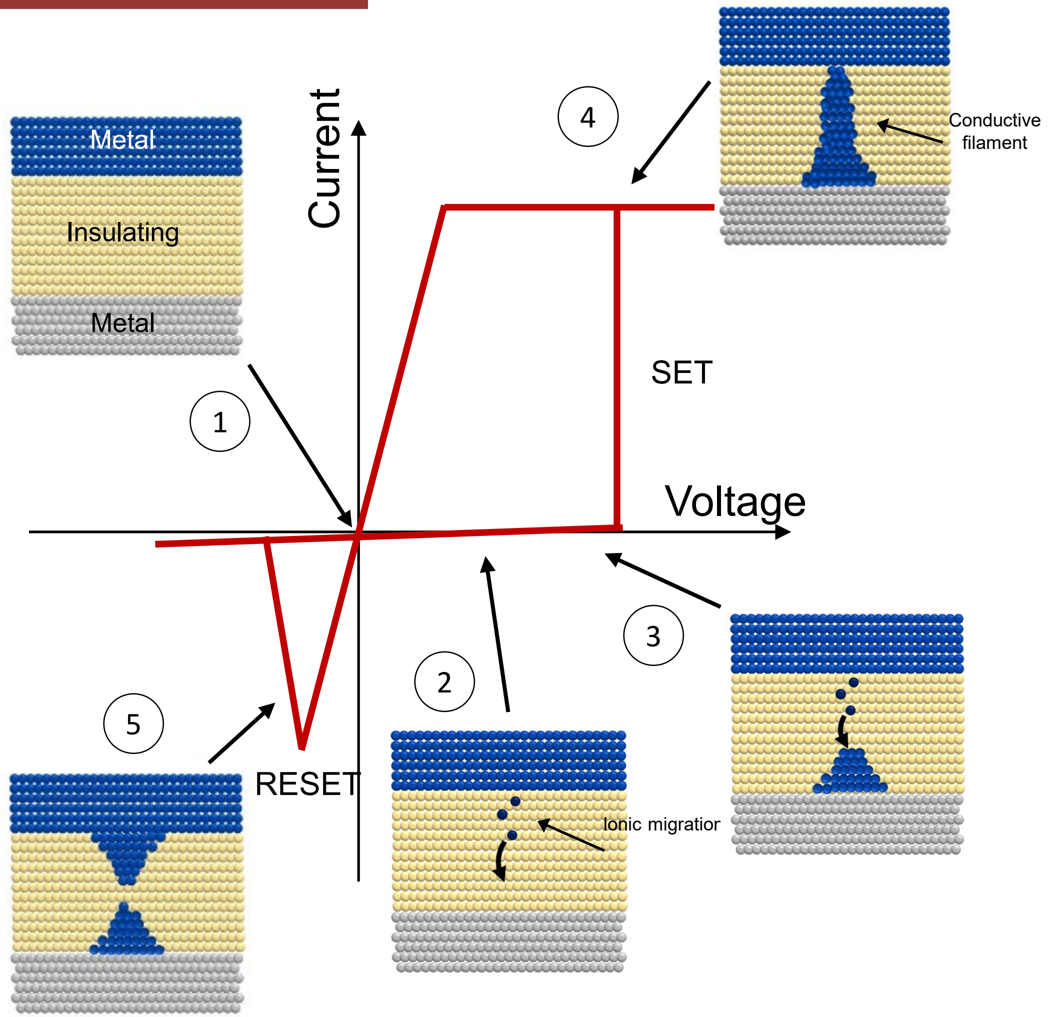
Functionalities rely on the formation/rupture of a conductive filament

The internal state of resistance depends on the history of applied voltage/current

- Memory applications
- Analogue computing
- Artificial synapse (neuromorphic computing, AI)



Memristive devices – working principles

Resistive switching and quantum conductance effects in memristive devices

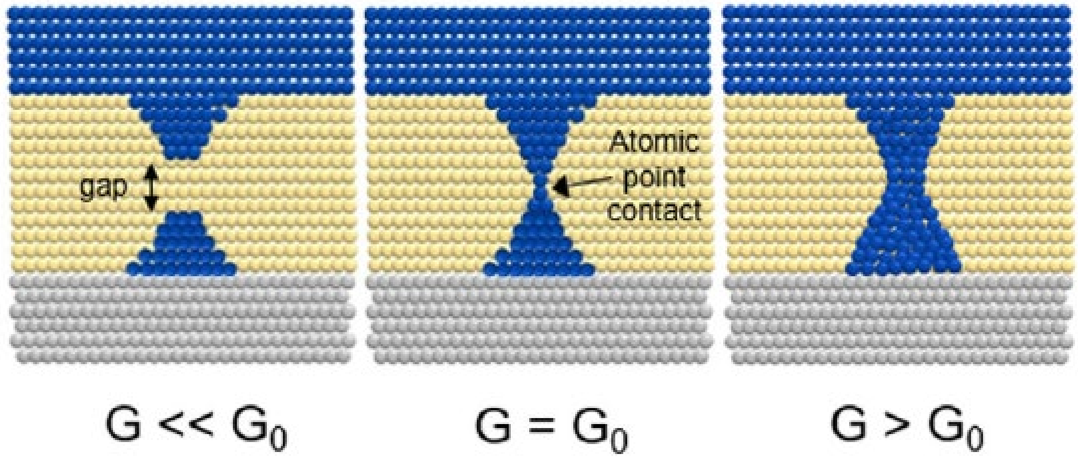
Electrical control of filament morphology

Quantized conductance effects

$$G = N\,G_0 = N\,\frac{2e^2}{h}$$

G_0 is related only to fundamental constants of nature fixed in the revised SI

Quantum conductance effects



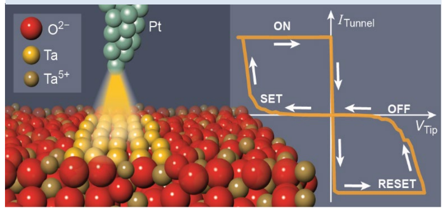
Quantized conductance phenomena can be observed by electrically manipulating atoms

NANOSCALE METROLOGY

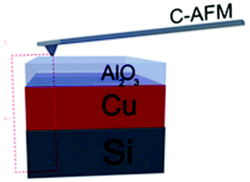
Nanoelectrical and nanodimensional characterization of memristive devices

- **<u>Investigation of resistive switching mechanism</u>** and local electrical properties **<u>by means of scanning probe microscopies</u>** (SPMs)

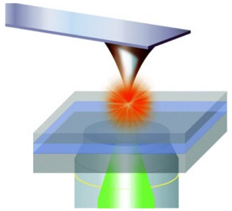
***Operando* STM**



***Operando* C-AFM**



TERS, TEPL



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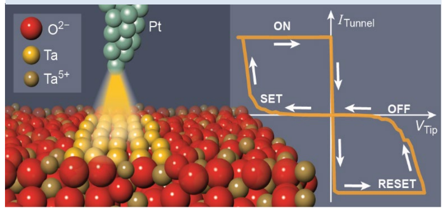

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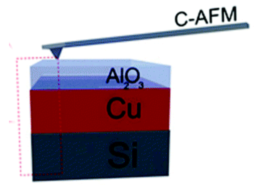

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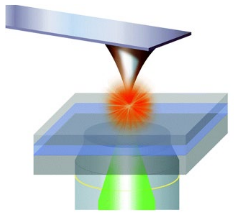
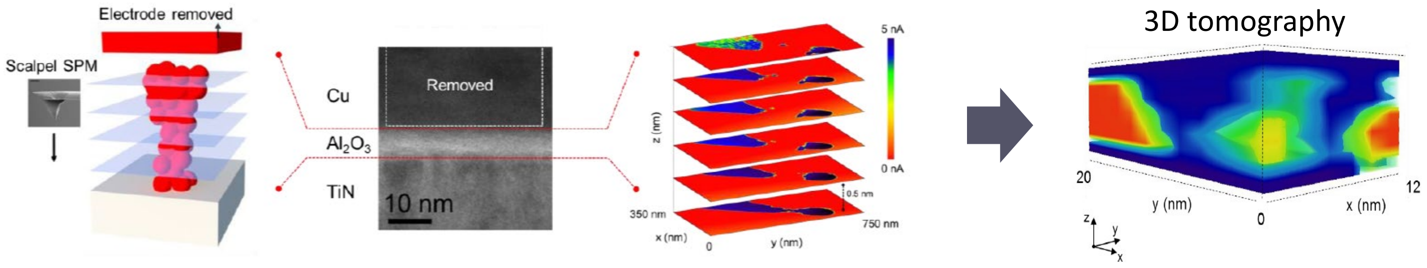


- **3D reconstruction of the memristive cell** through scalpel C-AFM for investigating the conductive filament formation/rupture underlying resistive switching mechanism

Scalpel C- AFM



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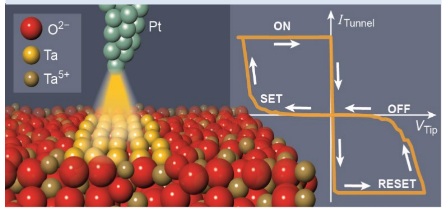
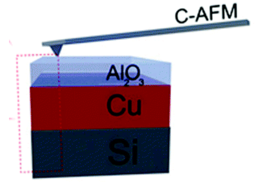


Operando C-AFM



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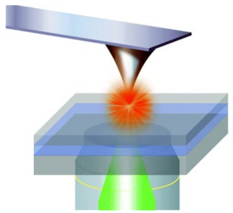

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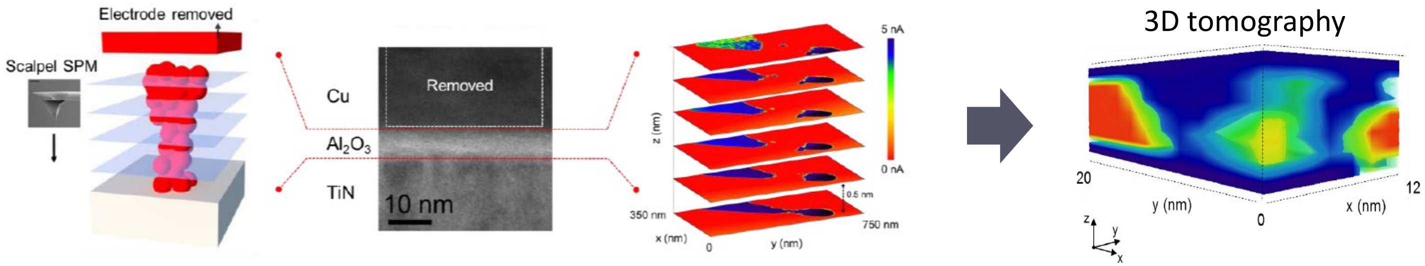
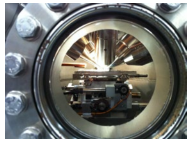
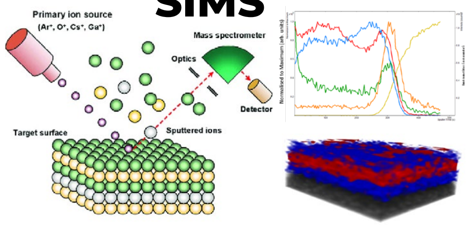


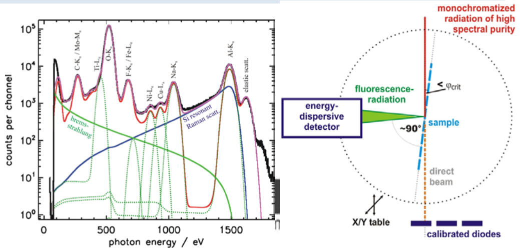
- **<u>Operando quantification and metrology of chemical, structural and ionic/electronic properties</u>** of memristive devices



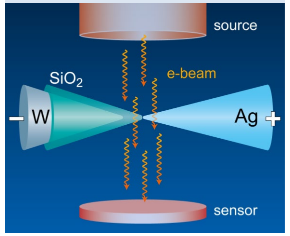
Operando XPS and SIMS



High resolution XRS



Operando TEM



SUMMARY

Memristive devices for quantum metrology
as a standard of resistance
by coupling ionics with electronics

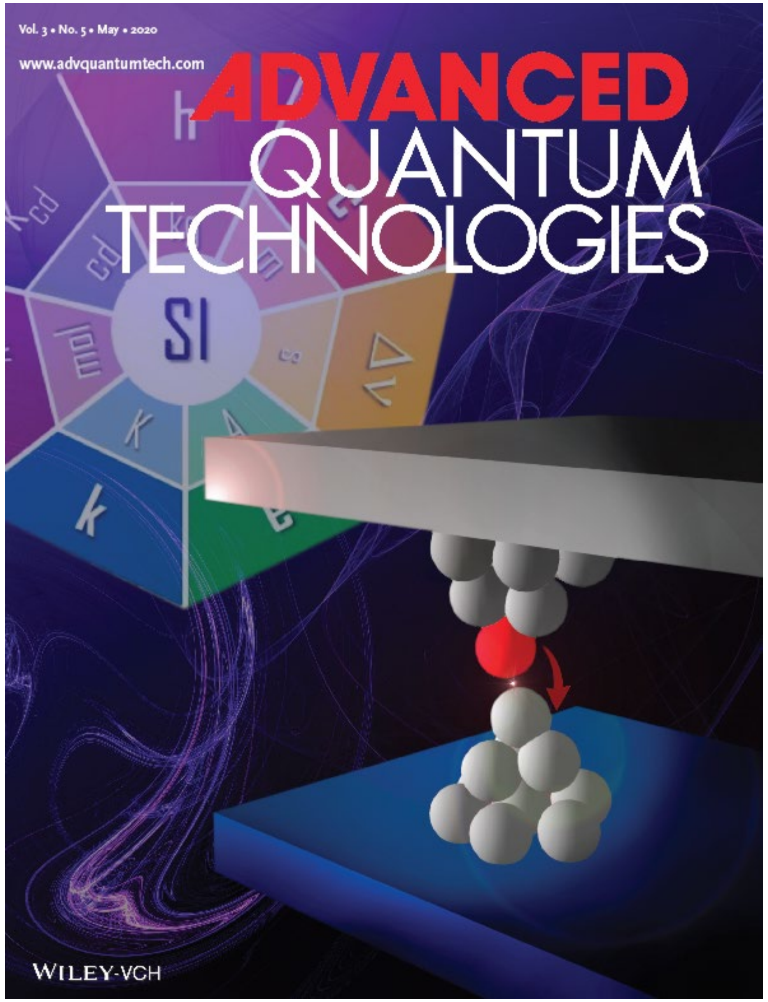
Quantized conductance levels can be programmed
in air at room temperature, without applying a magnetic field

CMOS compatible

Implementable on-chip

Scalable to the nm

Towards self-calibrating systems with zero-chain traceability



G. Milano, et al., *Advanced Quantum Technologies* 3.5 (2020), Cover Image

FUNDING AND ACKNOWLEDGEMENT

2021 - 2024

MEM QuD

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Call 2020: Fundamental

EMPIR

EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

EMPIR 20FUN06 MEMQuD has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

Website: https://memqud.inrim.it/home

CONTACTS

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Websites

https://sites.google.com/inrim.it/adv-mat-dev/home

http://www.nanofacility.it

Images from the nanoworld - Nanofacility at INRiM