HARDWARE QUANTUM EMULATORS AND QUANTUM AI/ML

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Director of Research
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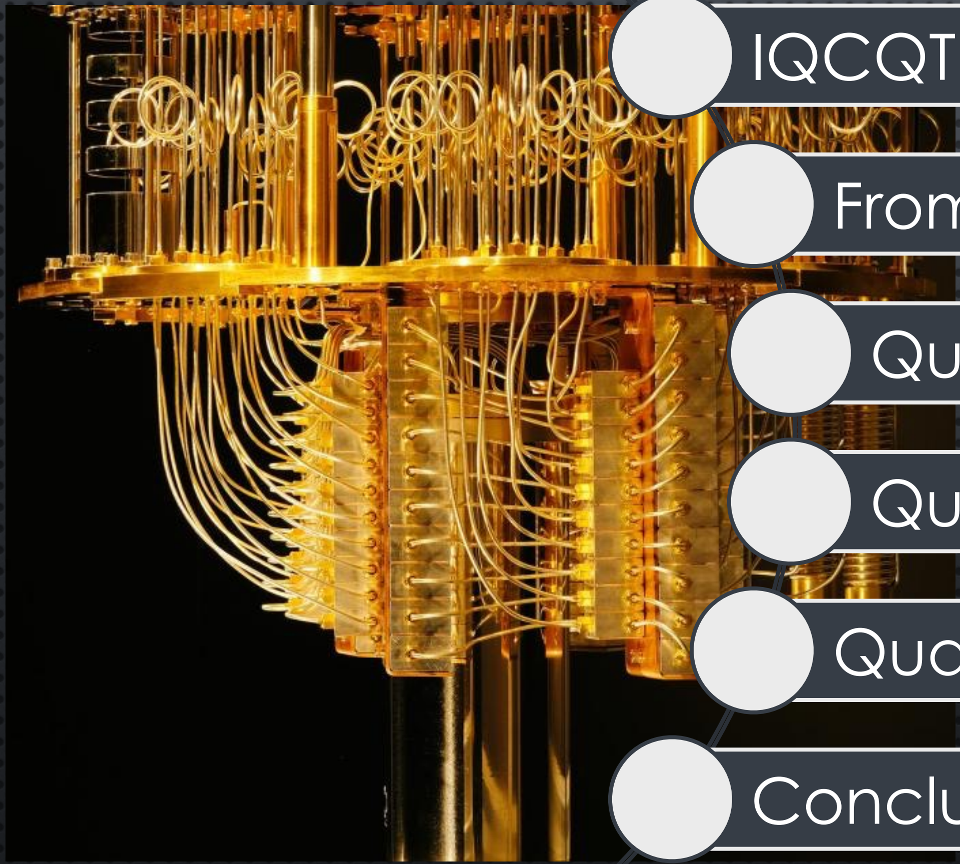
THE TEAM

- Dr. Panagiotis Dimitrakis, Dr Nikolaos Vassileiadis, Mr. Alexandros Mavropoulis
- Prof. Georgios Ch. Sirakoulis, Dr. Angelos Fyrigos, Dr. Konstantinos Rallis
- Prof Ioannis Karafyllidis, Mr George Varsamis, Mr Ioannis Liliopoulos
- Adjunct Researchers: Dr Antonios Gardikiotis, George Kourousias
- Infrastructure: Nanotechnology & Microsystems Lab, IBM and European |HPCQC>
- INFRACHIP (member of Nanotechnology Hub offer Transnational access)

OUTLINE



- IQCQT in Brief
- From Nano-to-Quantum
- Quantum Emulator
- Quantum Computing
- Quantum Sensing : SPD
- Conclusion

INSTITUTE OF QUANTUM COMPUTING & QUANTUM TECHNOLOGY

CURRENT STATUS

IQCQT: THE NATIONAL POLE FOR QUANTUM

2018

IBM-Q visit NCSR "D"

2020

The first MSc Course is established by **DUTh** & **NCSR "D"**

2021

Submission to ESETEK

2022

IQCQT

Government Gazette

A' 162 (Law **4965)**

(02.09.2022)

THE MISSION AND THE VISION OF IQCQT

- IQCQT aims to **promote excellence in quantum science**, quantum informatics and relevant technologies **at a world-class level**.
- IQCQT will gather scientists and engineers to do **fundamental and applied research on quantum science**, targeting to establish the necessary technology sectors by building applications based on quantum phenomena.
- IQCQT will **provide unique** opportunities for **education and training** contributing to the shaping of the future quantum workforce of the Country.

THE ROLE OF IQCQT

- IQCQT **aspires to become the national pole** for the advancement of quantum computing and quantum technologies, offering in parallel an effective link to private actors and a wider ecosystem of stakeholders in Greece and the world. **Avoid fragmentation and create critical mass for all QT pillars.**
- IQCQT has **access** to NCSR "D" infrastructures distributed among the 5 Institutes and mainly to **Nanotechnology & Microsystems Laboratory** for and quantum chip device fabrication. **Harnessing the existing Nanotech knowledge to create innovation.**

IQCQT CURRENT ORGANIZATION CHART

Director
Dr D. Angelakis

Deputy Director
Dr Dimitrakis P.

6 Associate Researchers
all from abroad

Researcher A’ (QC, **1 pos**)

Researchers C’ (QM, **2 pos**)

Researcher C’ (QC, Qcom, Qsen, **3 pos**)

IQCQT PROGRAMS COVER QUANTUM TECHNOLOGIES

QUANTUM COMPUTING

A technology for computation which leverages quantum mechanics to provide performance unattainable for classical computers (for some applications)

QUANTUM COMMUNICATIONS

Leverages quantum entanglement and teleportation to enable ultra secure communications channels

QUANTUM SENSING

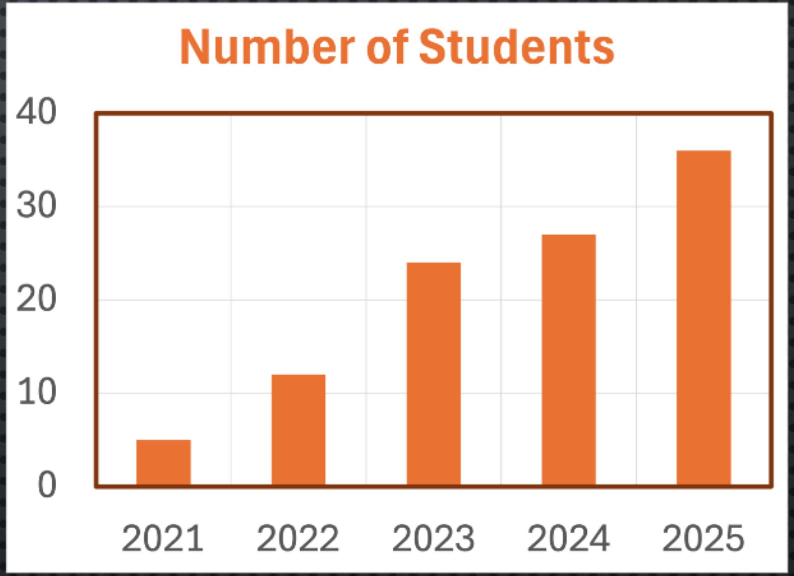
Exploits the inherent sensitivity of quantum systems to external perturbations, providing measurement and detection capabilities with unparalleled precision

IQCQT WORKFORCE CREATION

INTERNATIONAL MSc Course

Greek Government Gazette (ΦΕΚ Β' 7073/31-12-2022)

- ➢ Unique in Greece
- ➢ International
- ➢ 100% from distance
- ➢ 90 ECTS
- ➢ Under fee



4-5 Countries

NANO & QUANTUM TECHNOLOGIES

In-Brief

QUANTUM AND NANOTECHNOLOGY: A SYMBIOTIC RELATIONSHIP

Nanotechnology is the manipulation of matter on an atomic and molecular scale (typically 1 to 100 nanometers), has fundamentally transformed materials science and engineering over the past few decades.

it is the essential enabling force behind the emerging field of **Quantum Technology (QT)**. The critical connection lies in the fact that matter at the nanoscale begins to exhibit **quantum mechanical effects**—such as superposition, entanglement, and tunneling—which are the very phenomena QT seeks to harness for revolutionary applications.

QUANTUM AND NANOTECHNOLOGY: A SYMBIOTIC RELATIONSHIP

Fabrication Precision

Quantum Materials (QDs, 2DM, NWs)

Nanostructures for Qubit Isolation

Quantum Simulation (DFT)

Quantum Sensors (SQUID) & Metrology (SPD, e-charge)

THE COLLABORATION BETWEEN THESE TWO FIELDS

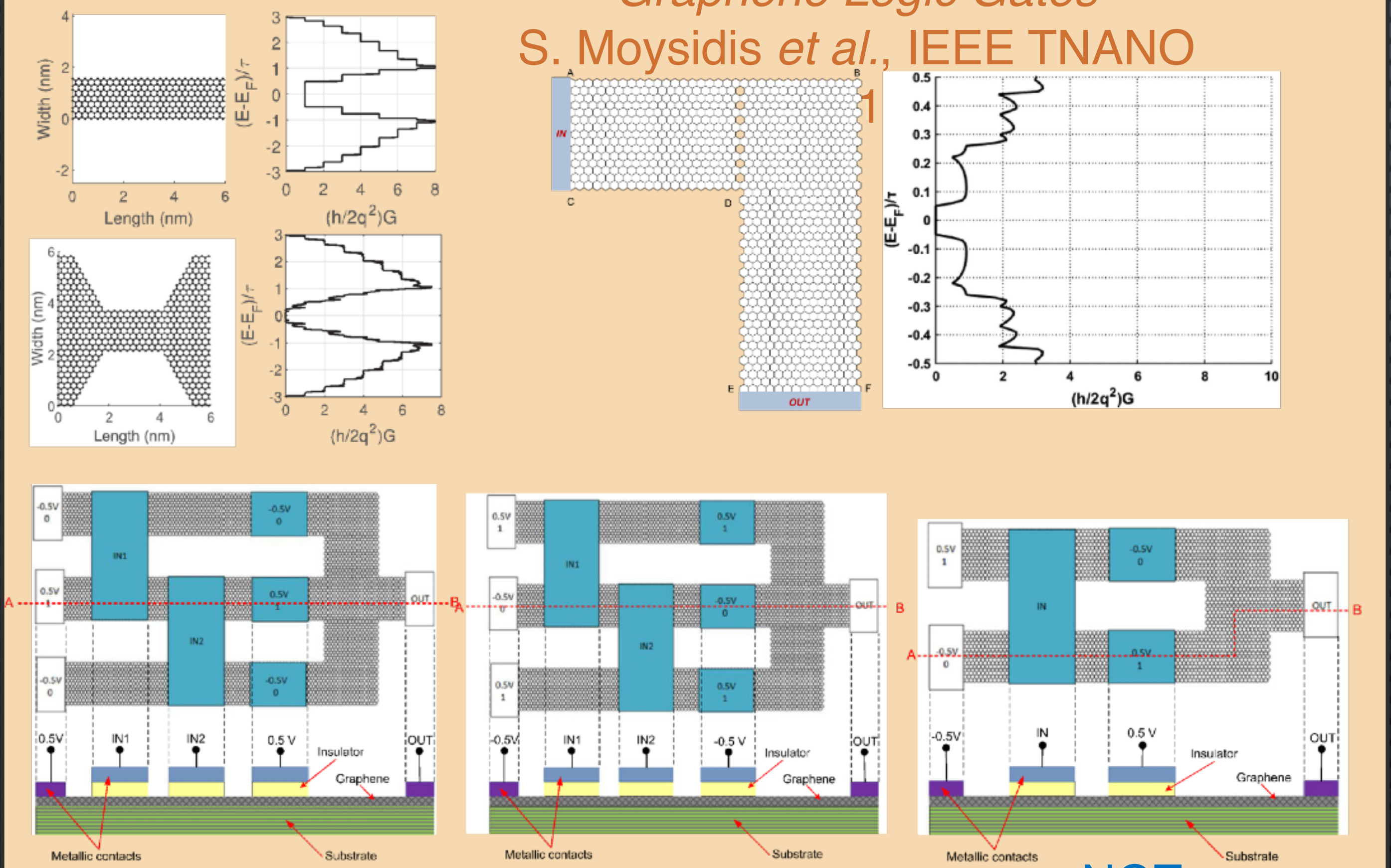
Quantum Technology Pillar	Nanotechnology's Contribution	Example Applications
Quantum Computing	Qubit fabrication and scaling, chip architecture design, noise mitigation.	Superconducting circuits, Silicon spin qubits (using quantum dots), Ion traps, Topological qubits.
Quantum Communication	Single-photon sources/detectors, integrated photonic circuits for quantum key distribution (QKD).	**Nanowires** and **nanophotonics** for efficient quantum light sources and waveguides, ensuring secure data transmission.
Quantum Sensing/ Metrology	High-precision nanoscale probes and materials with superior quantum coherence.	**NV centers in diamond** for ultra-sensitive magnetic and temperature sensors in biological or electronic systems, Quantum-enhanced atomic clocks.

NANO & QUANTUM TECHNOLOGY PARADIGIMS

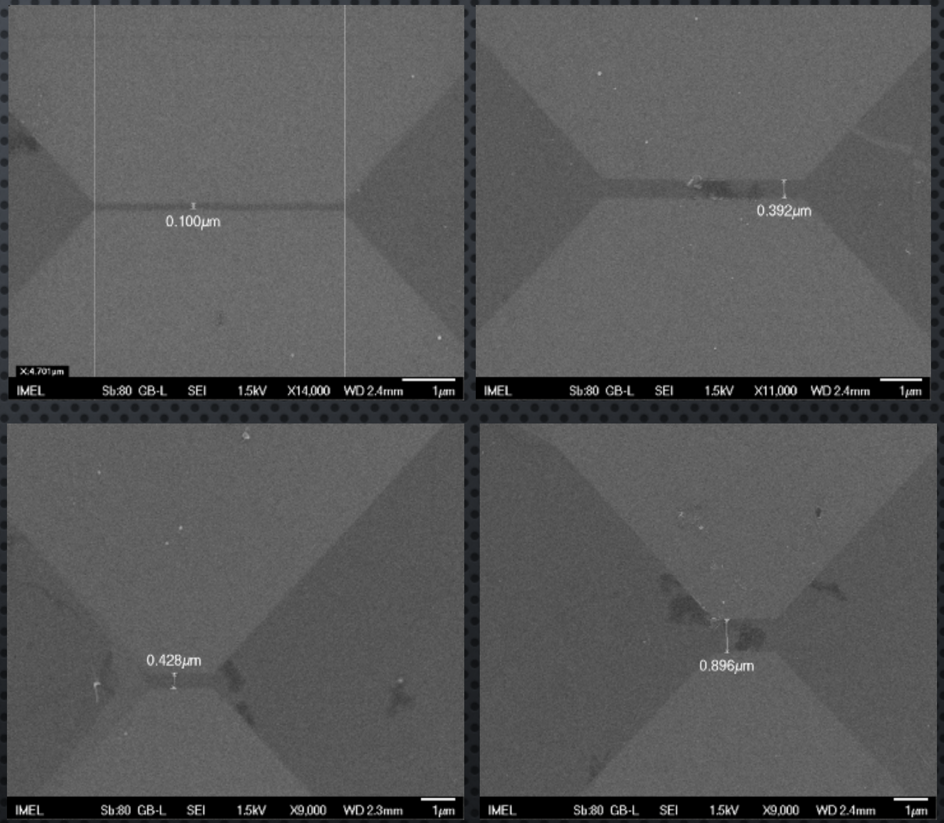
GRAPHENE NANORIBBONS FOR DIGITAL ELECTRONICS

Graphene Logic Gates

S. Moysidis *et al.*, IEEE TNANO



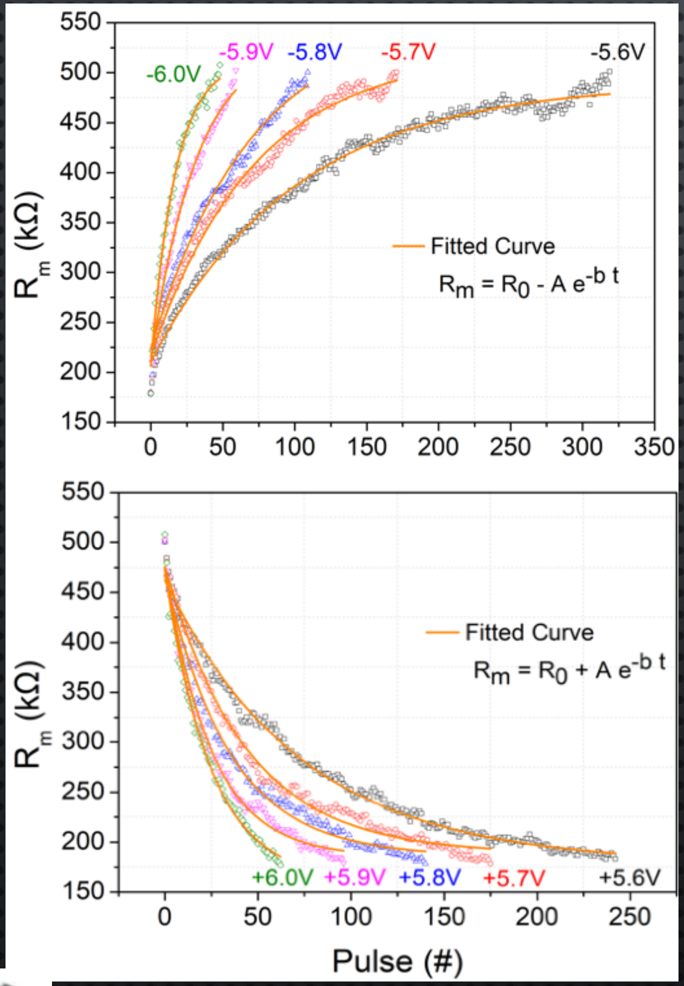
EBL – HSQ

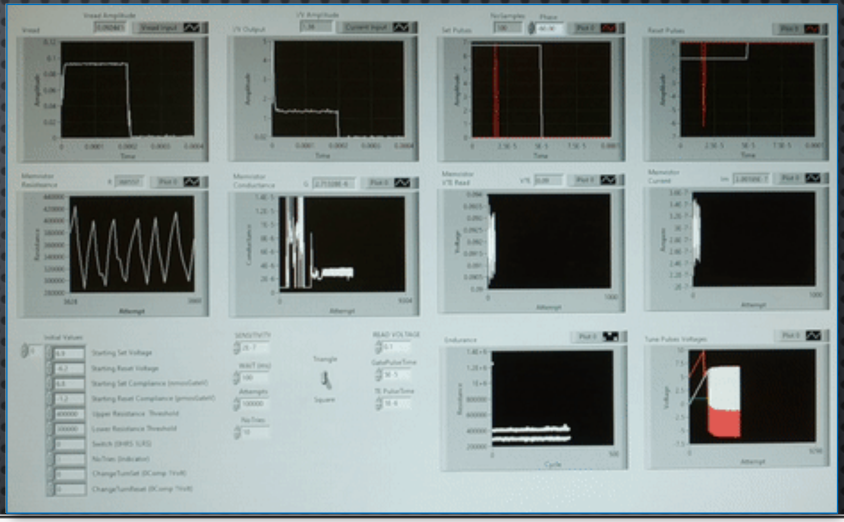


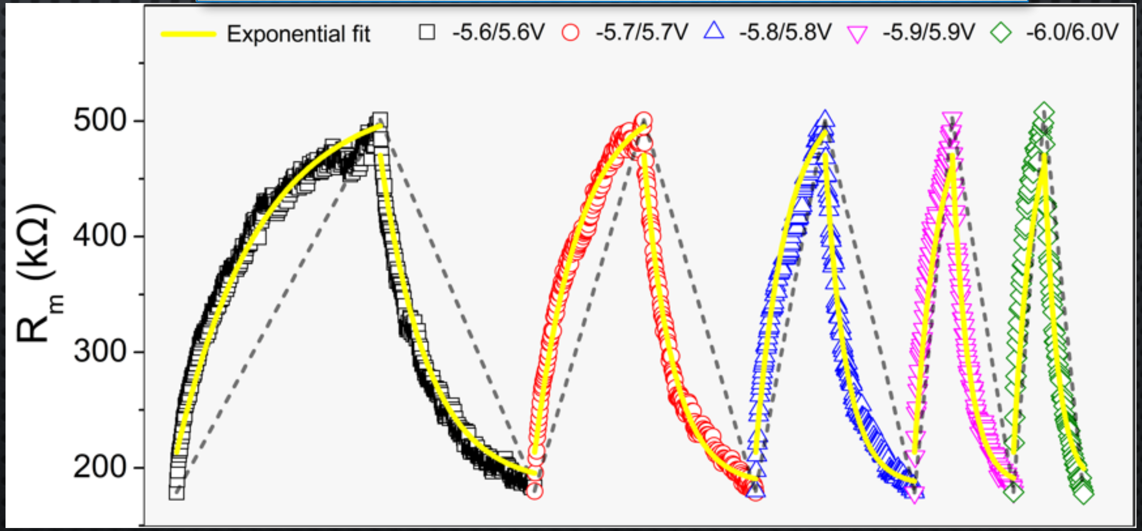
Unpublished results, G. Papageorgiou, P. Dimitrakis

THE MEMRISTIVE COMPUTING TECHNOLOGY – THE MEMRISTOR (RERAM CELL)

SIN$_X$ RERAM – NEUROMORPHIC CHARACTER





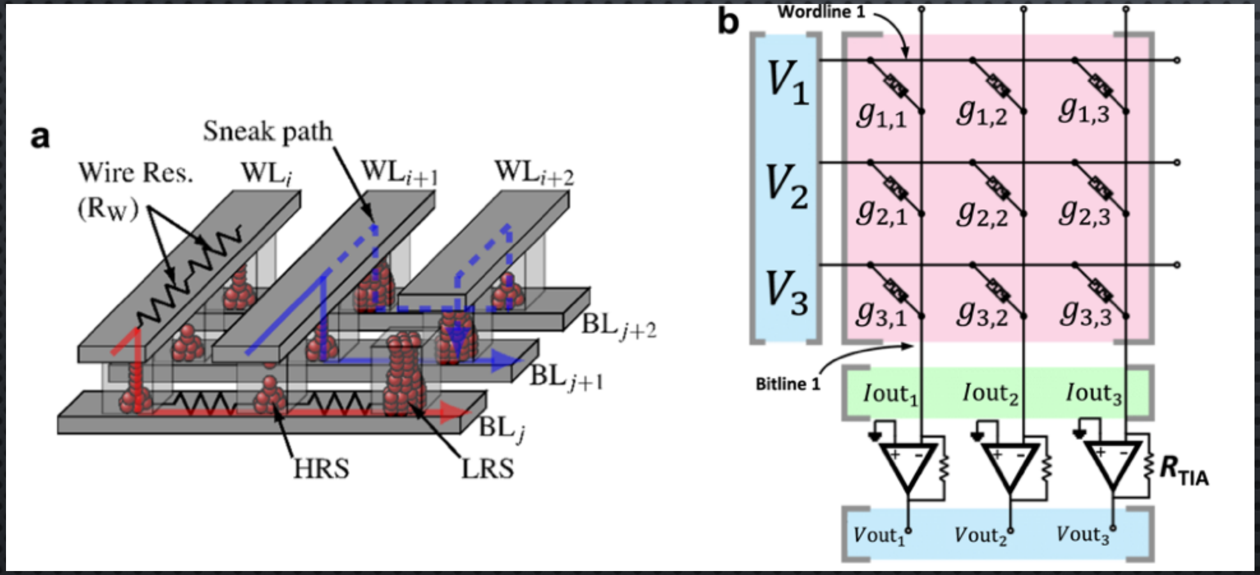


Dedicated Tuning protocol was applied

Pulse width: 10-200 μs

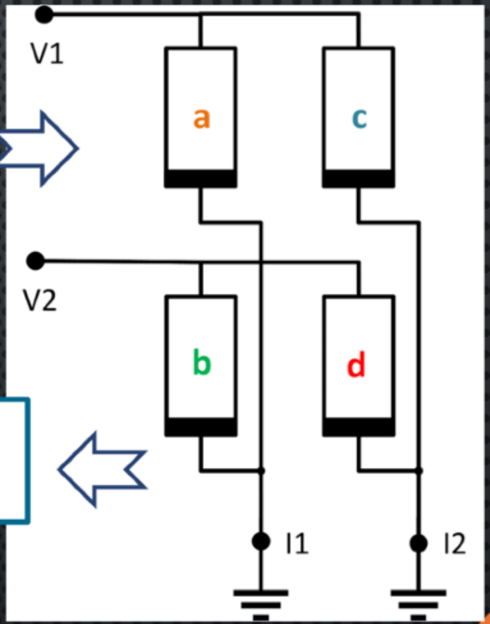
WHY MEMRISTORS?

In Xbar architecture perform matrix maultiplication easily (MAC)



Memristor Crossbar implicit vector-matrix multiplication

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \times \begin{bmatrix} V1 \\ V2 \end{bmatrix} = \begin{bmatrix} I1 \\ I2 \end{bmatrix}$$

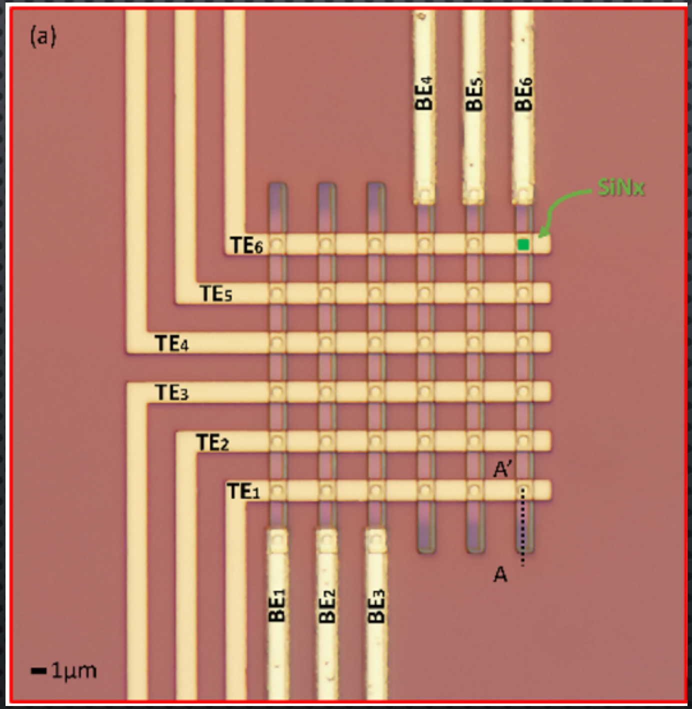


$$I_1 = V_1 * a + V2 * b$$
$$I_2 = V_1 * c + V_2 * d$$

Voltages = input Vector
Memristor Conductance = Matrix Elements
Currents = Output Vector

XBAR IMPLEMENTATION

Cell footprint 200nm x 200nm using our technology



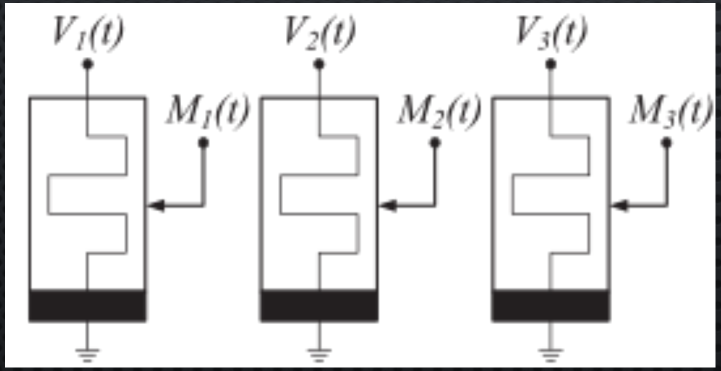
QUANTUM COMPUTING EMULATOR

CMOS Analog & Digital Approaches

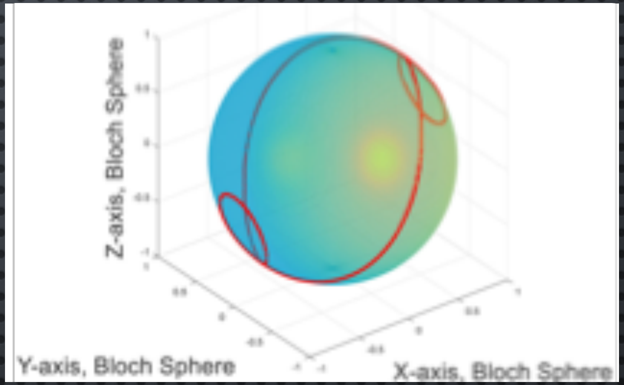
1QUBIT=3MEMRISTORS

I. Karafyllidis, G. Ch. Sirakoulis, and P. Dimitrakis,
IEEE NANOARCH, July 2018, Athens, GREECE

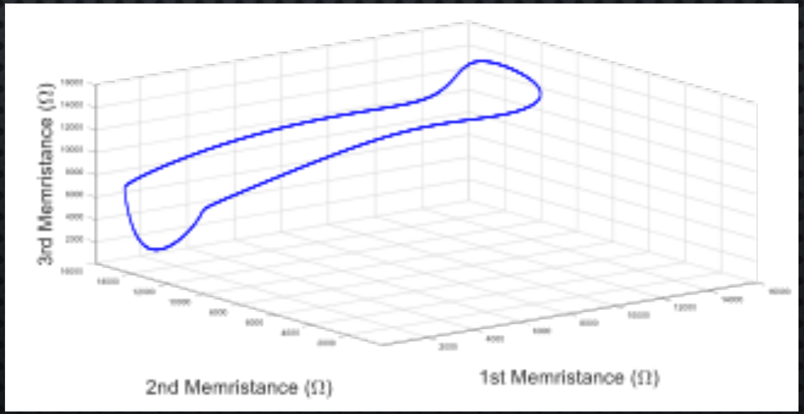
$$|q\rangle = \cos\frac{\theta(t)}{2}|0\rangle + \cos\varphi(t)\sin\frac{\theta(t)}{2}|1\rangle + i\sin\varphi(t)\sin\frac{\theta(t)}{2}|1\rangle$$



Bloch Sphere



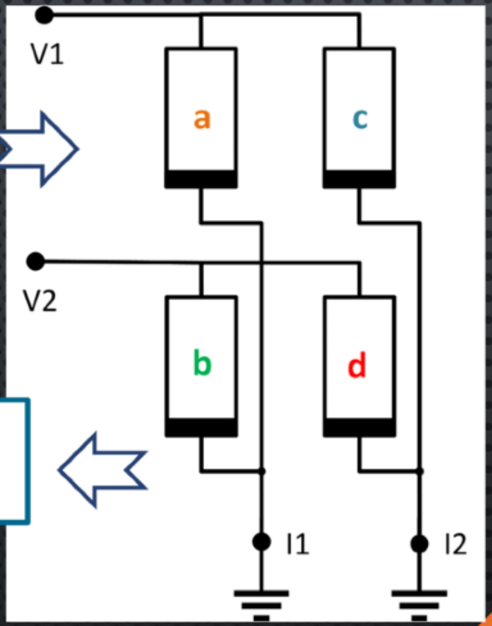
Memristance space



THE MEMRISTIVE COMPUTING TECHNOLOGY – THE MEMRISTOR XBAR ARRAY (RERAM ARRAY)

Memristor Crossbar implicit vector-matrix multiplication

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \times \begin{bmatrix} V1 \\ V2 \end{bmatrix} = \begin{bmatrix} I1 \\ I2 \end{bmatrix}$$



$$I_1 = V_1 * a + V2 * b$$
$$I_2 = V_1 * c + V_2 * d$$

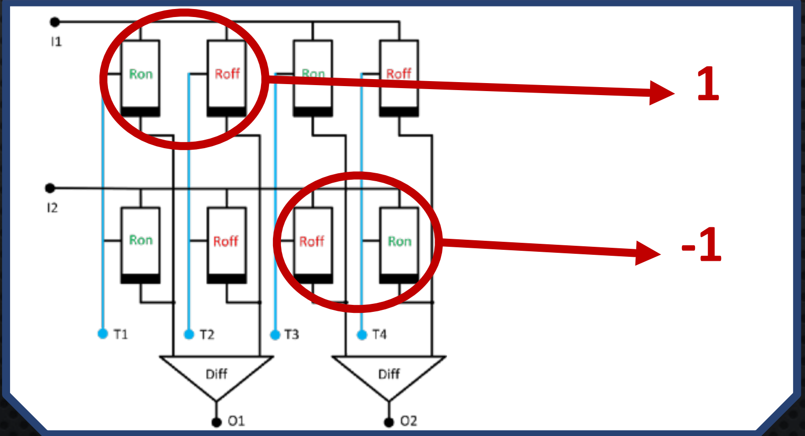
Voltages = input Vector
Memristor Conductance = Matrix Elements
Currents = Output Vector

A universal set of quantum gates capable of being implemented through binary memristor crossbar arrays

+

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Differential Crossbars were utilized to represent negative values of the matrices



THE MEMRISTIVE COMPUTING TECHNOLOGY – THE EMULATOR CHIP

The representation of a qubit for quantum computing simulations can be performed by a column vector

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle = \alpha \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \beta \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Where: $|\alpha|^2 + |\beta|^2 = 1$

1 Qubit Gate

H $\quad \dfrac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

2 Qubit Gate

CNOT $\quad \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

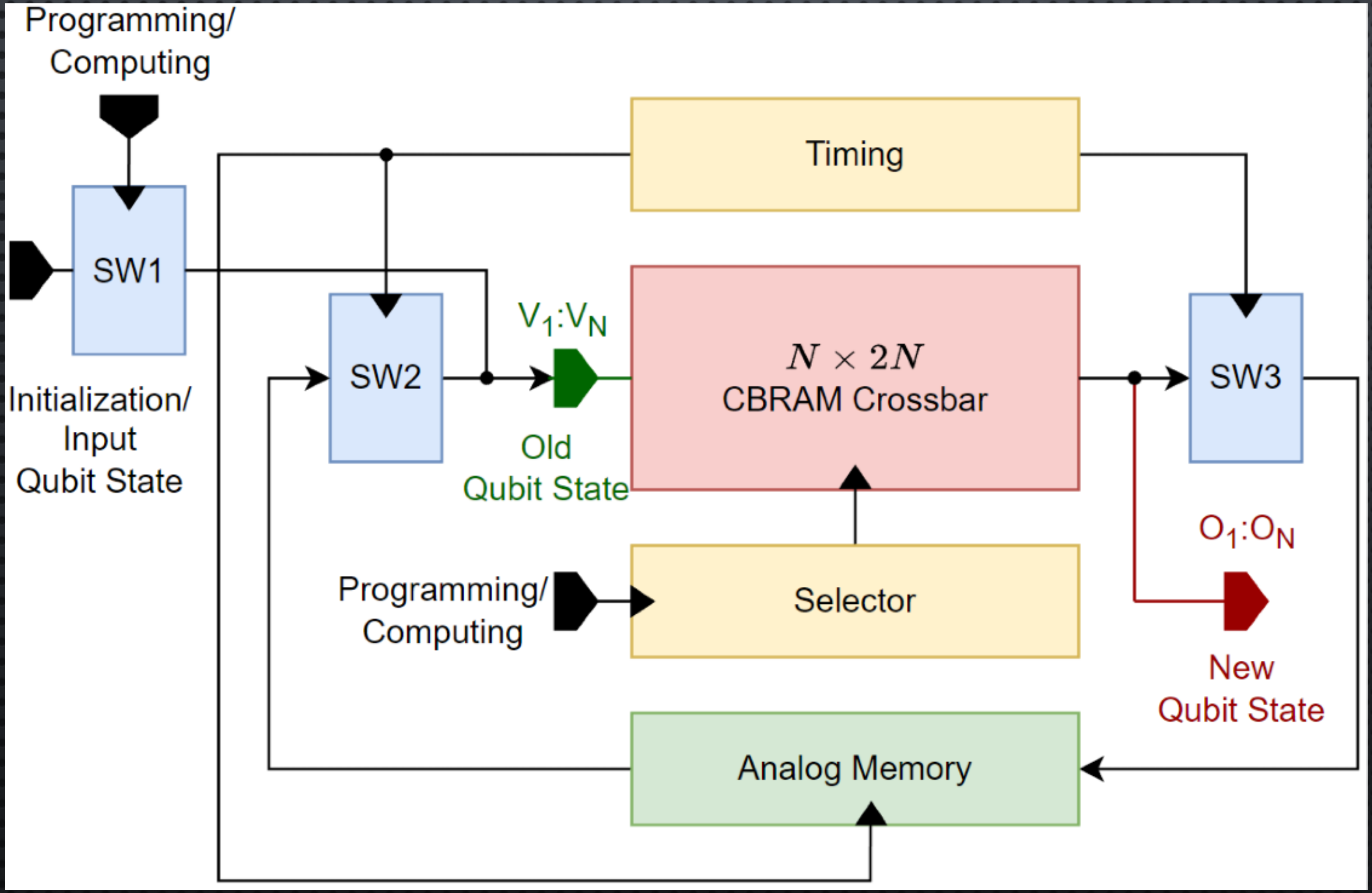
- Quantum logic gates are represented by unitary matrices
- A gate which acts on n qubits is represented by a $2^n x 2^n$ unitary matrix

The action of quantum gates on qubits can be performed through a matrix-vector multiplication

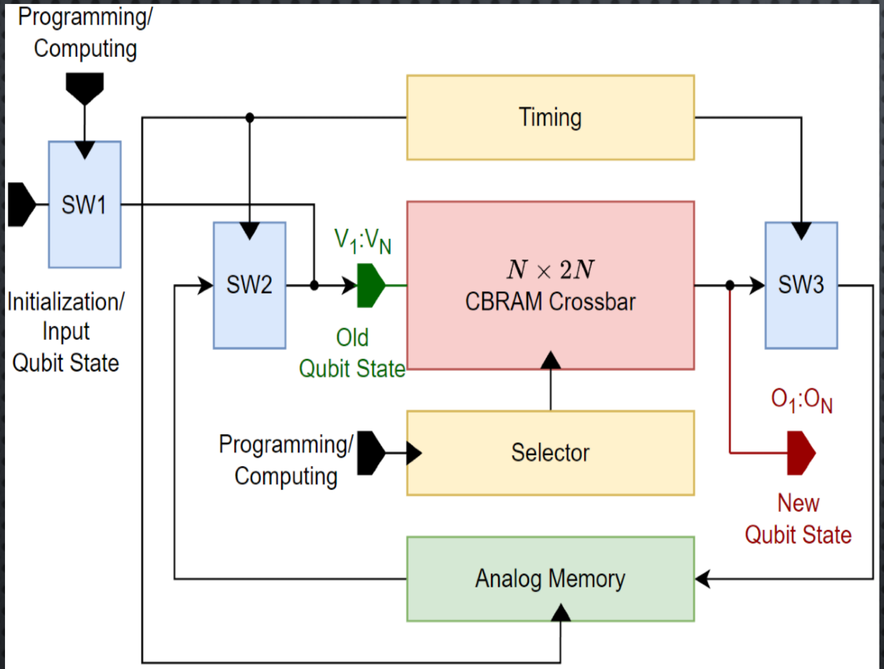
$$H\,|0\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$$

$$H\,|1\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix}$$

CLOSED-LOOP RRAM CROSSBAR SYSTEM CAPABLE OF QUANTUM COMPUTATIONS



COMPARISON WITH CONVENTIONAL SIMULATORS



1. High efficiency and performance gains
2. Lower power consumption
3. Scalability and flexibility for various quantum algorithms

	Power (Joule)	Execution Time (s)	Performance/ Watt
Proposed Circuit	17.55nJ	1.95us	56.98M
CPU MATLAB	674uJ	27.8us	1.47K
CPU Qiskit	10.6mJ	505.9us	0.09K
GPU CUDA	709.4uJ	5.63us	1.41K
FPGA	3.37uJ	3.84us	297K

Up to x15 speedup

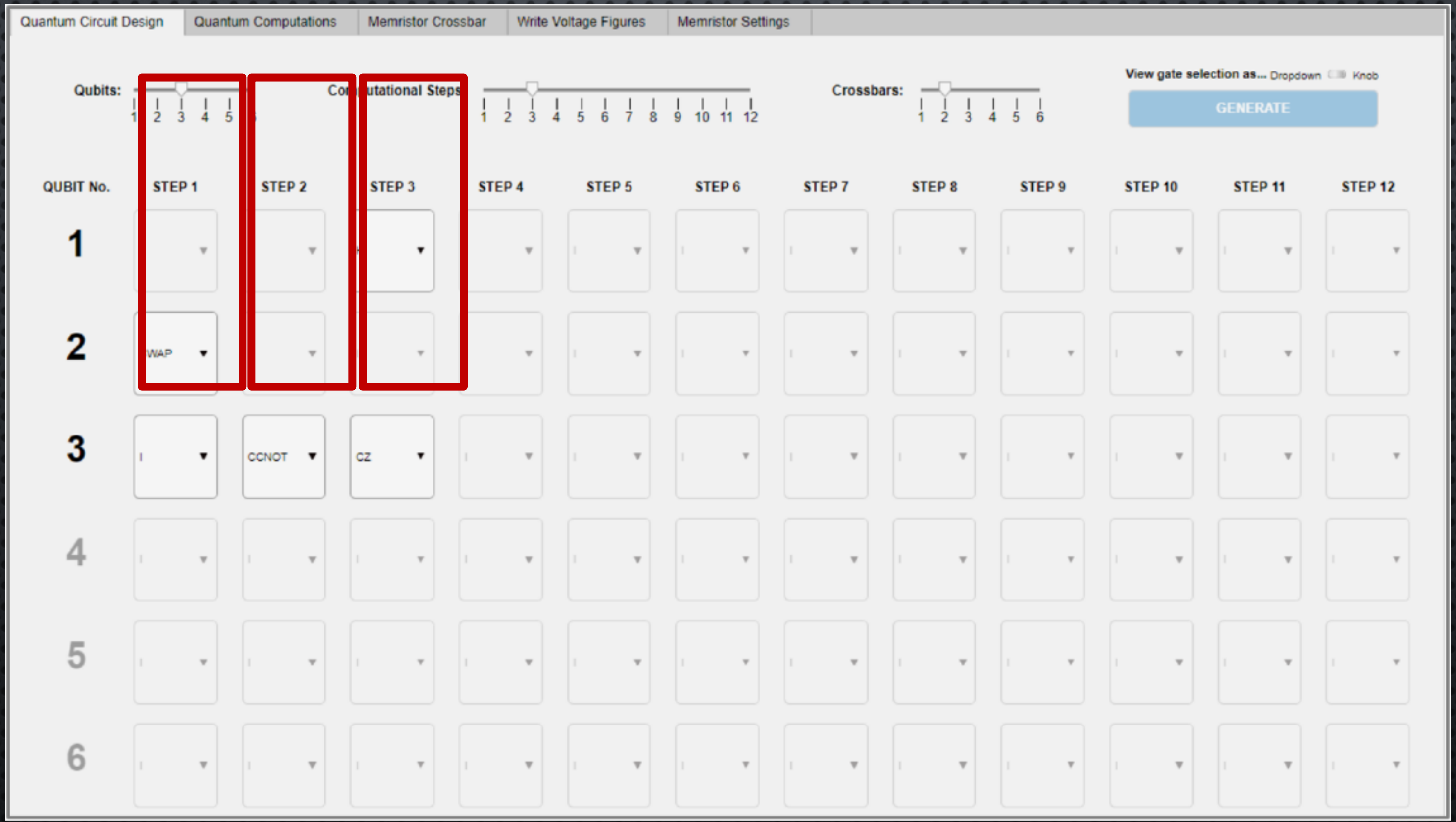
Up to x40.000 reduction in power consumption

MEMRISTOR FRAMEWORK

https://github.com/DUTh-FET/Team-Research/tree/master/4.%20Technical%20Material/1.%20Quantum%20Computing%20on%20Memristor%20Crossbars

EXAMPLE DEMONSTRATION

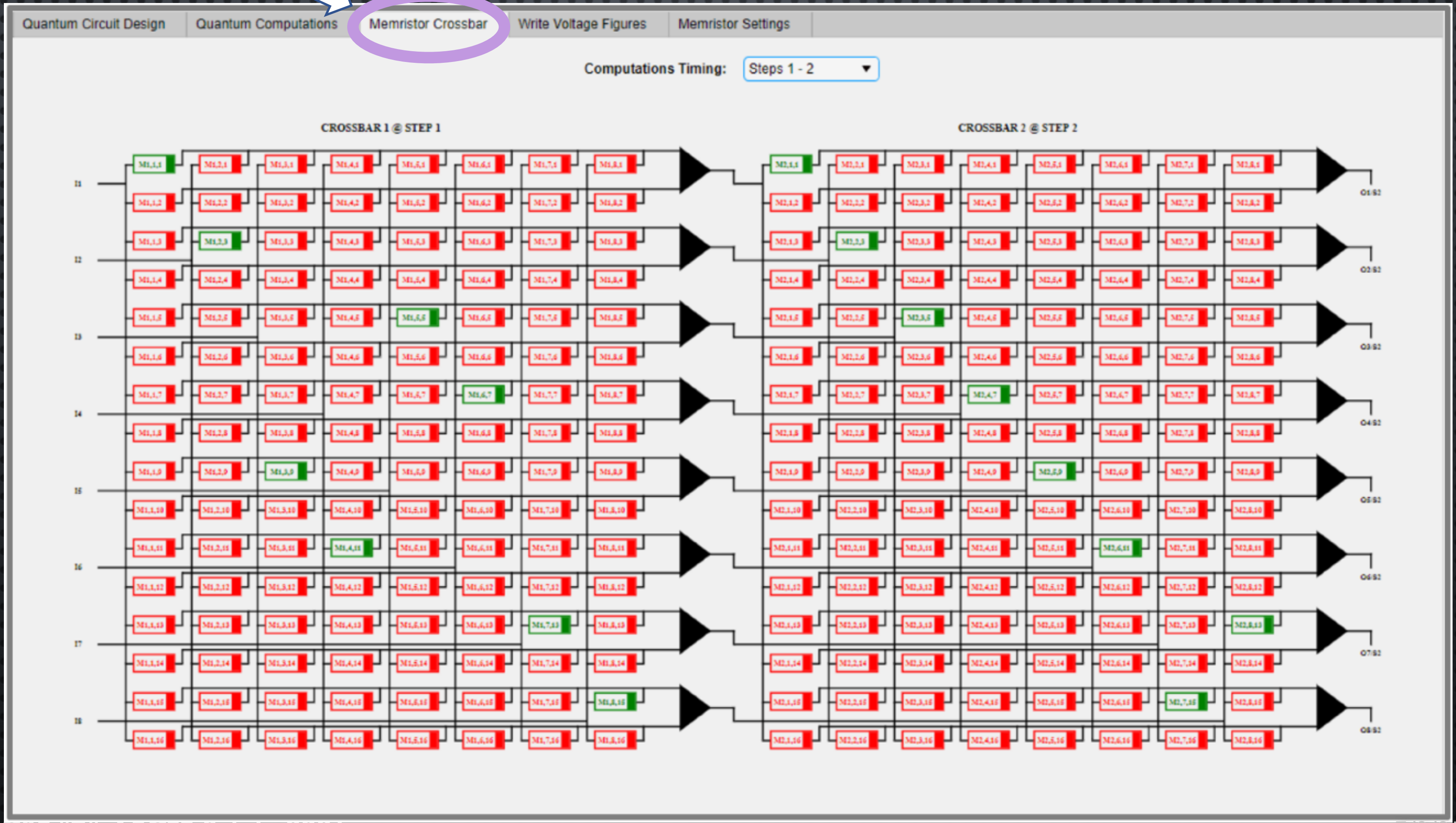
$$|\psi\rangle = (H \otimes CZ)\; CCNOT\; (SWAP \otimes I)\; |Q\rangle$$



MEMRISTOR CROSSBAR VISUALIZATION

$(SWAP \otimes I)$

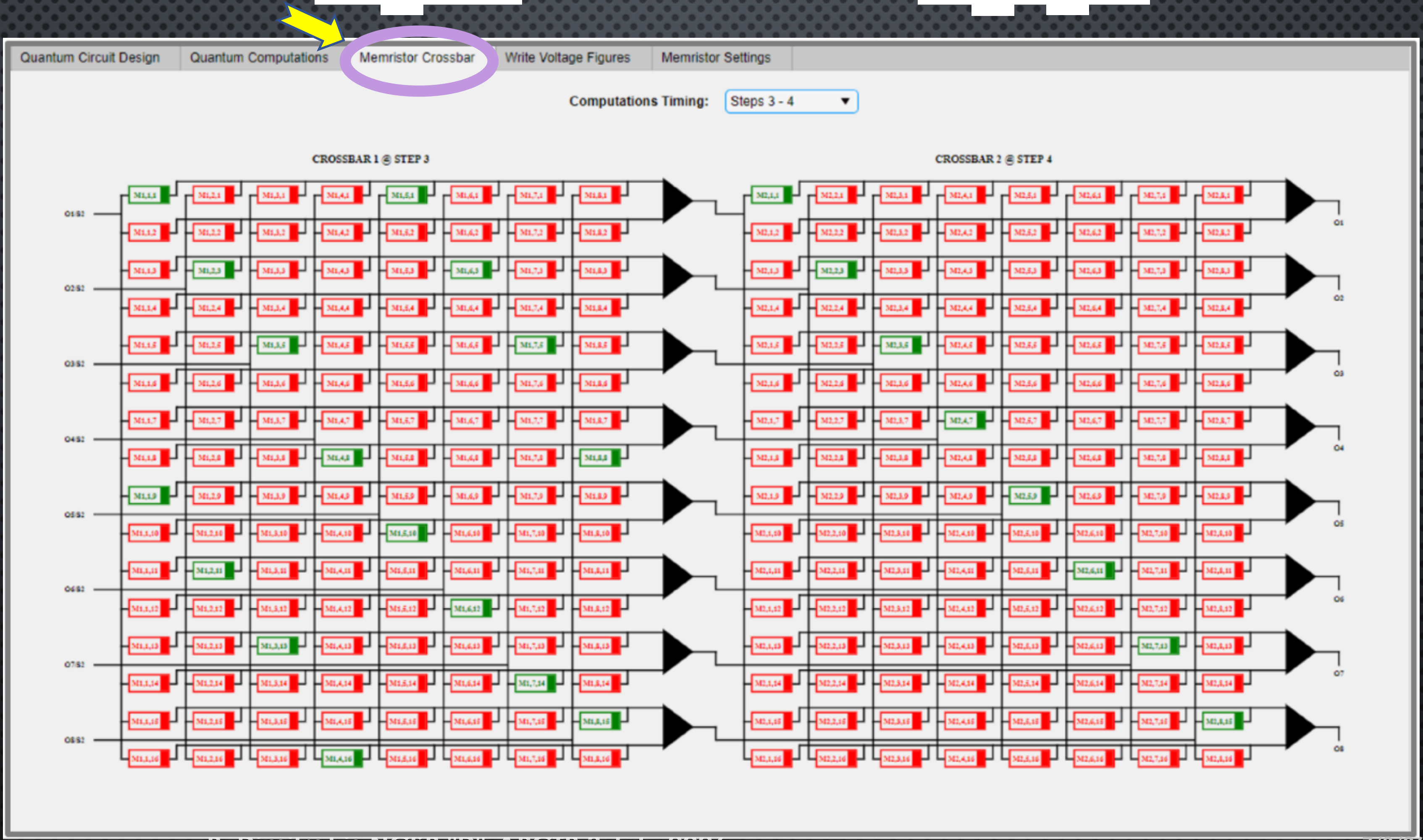
$CCNOT$



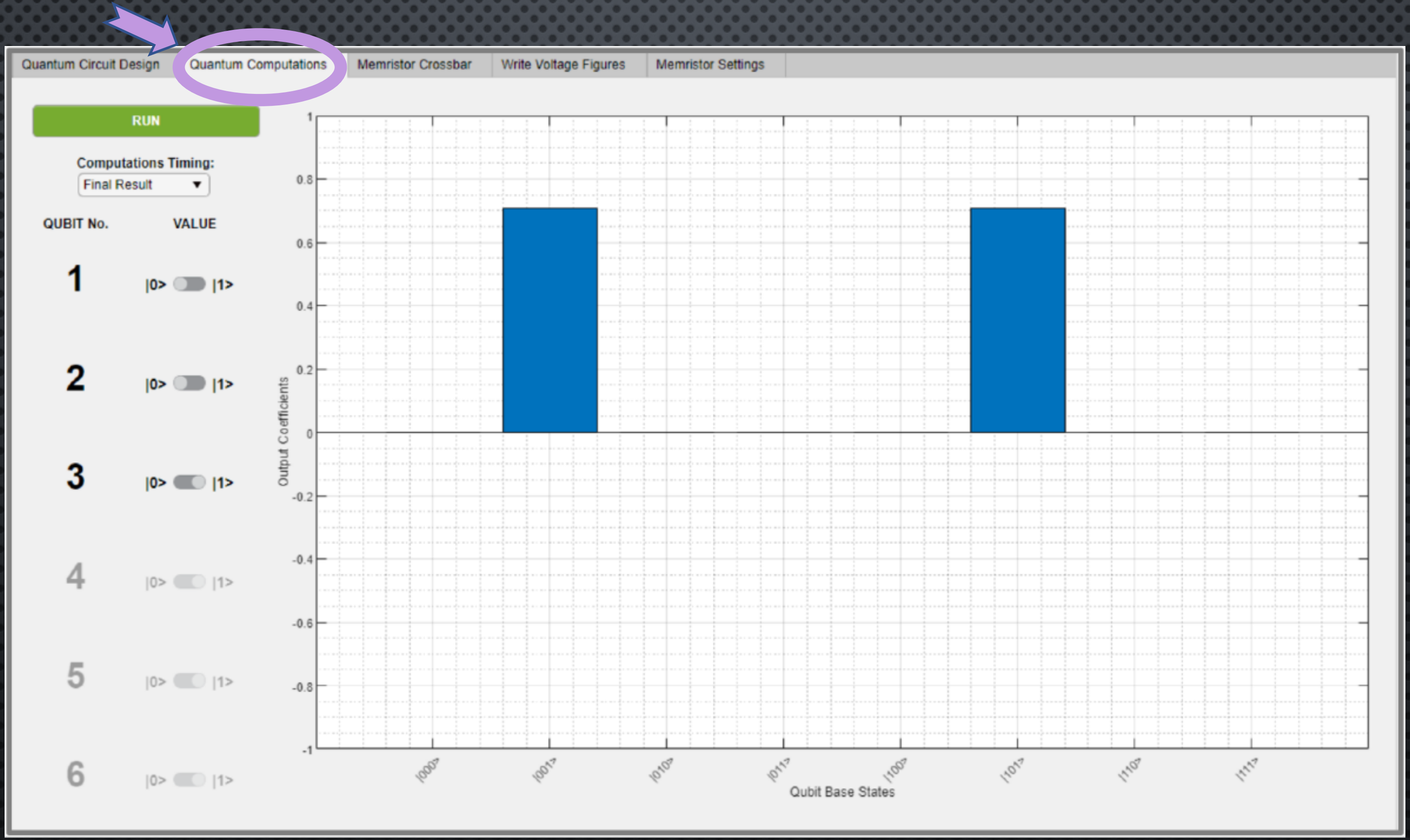
MEMRISTOR CROSSBAR VISUALIZATION

$(H \otimes CZ)$

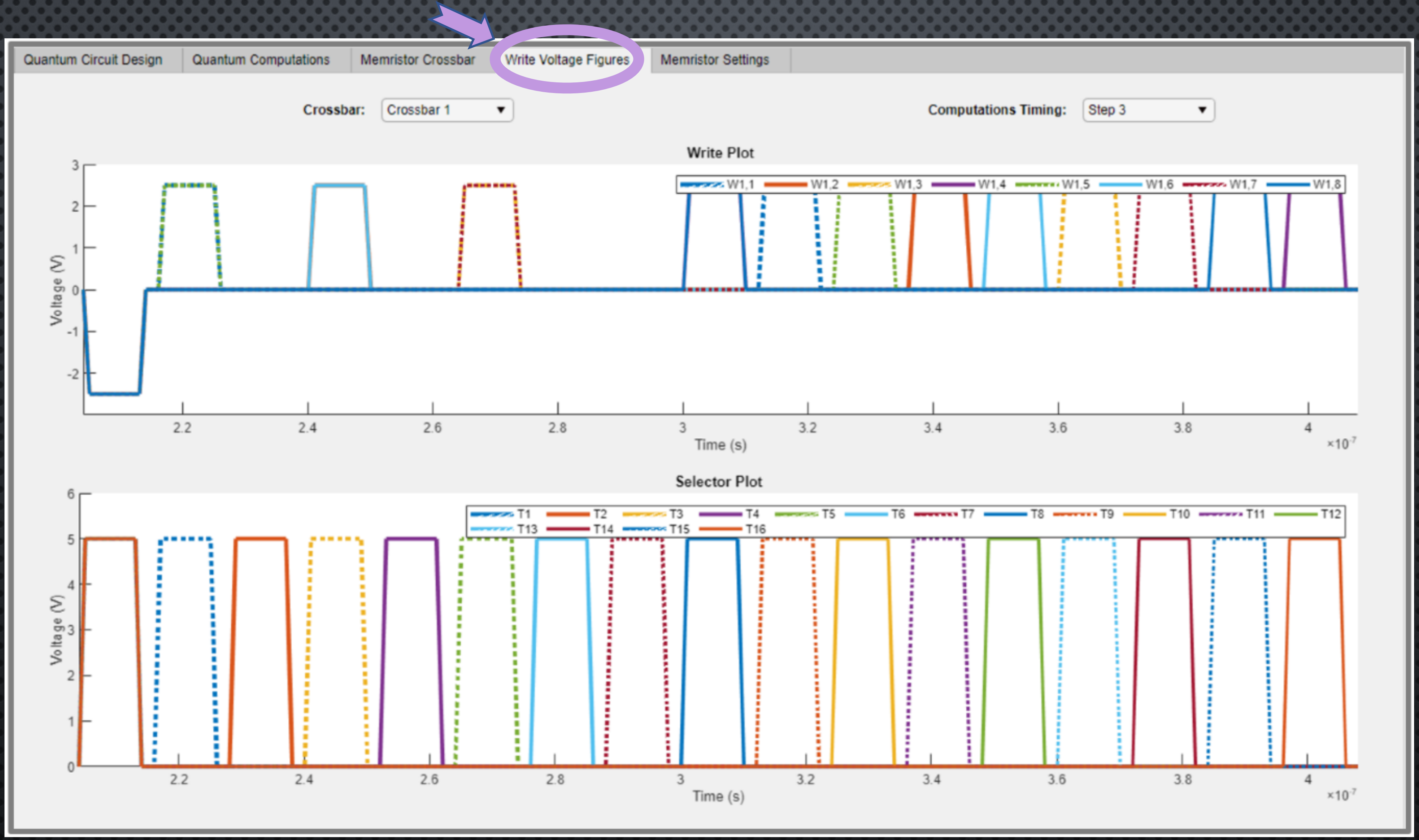
$(I \otimes I \otimes I)$



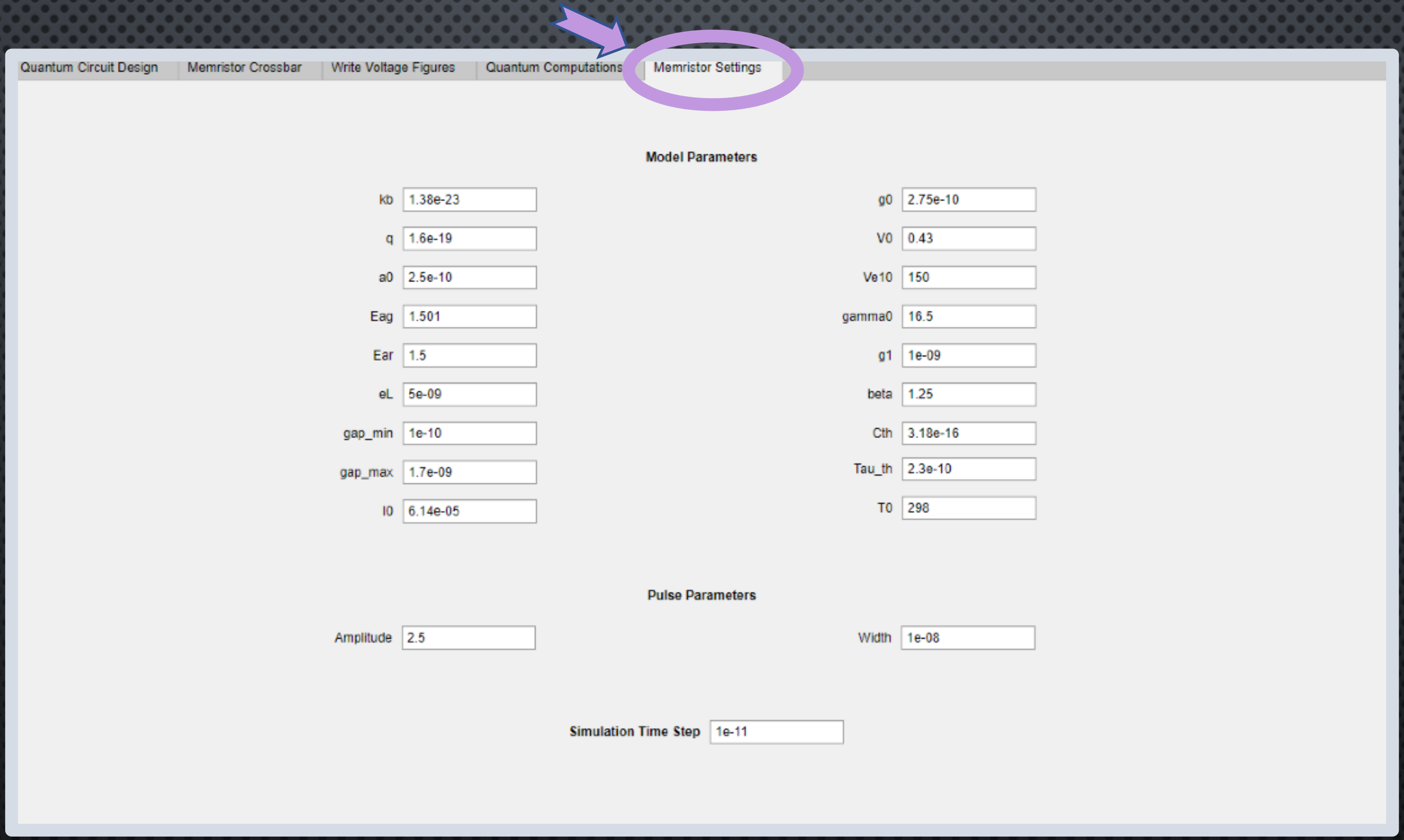
QUANTUM CALCULATION



CROSSBAR INITIALIZATION



PARAMETERS' CONFIGURATION



QUANTUM ALGORITHMS PARADIGMS

Building a better working world

EY Global, Private funding **2023, 2024, 2025** and we are expect to establish a **long term strategic alliance**

Quantum World Congress 2023: Quantum DNA Sequencing

Computational Biology and Chemistry 107 (2023) 107959

Contents lists available at ScienceDirect

Computational Biology and Chemistry

journal homepage: www.elsevier.com/locate/cbac

Quantum gate algorithm for reference-guided DNA sequence alignment

G.D. Varsamis[a], I.G. Karafyllidis[a,b,*], K.M. Gilkes[c], U. Arranz[c], R. Martin-Cuevas[c], G. Calleja[c], P. Dimitrakis[b], P. Kolovos[d], R. Sandaltzopoulos[d], H.C. Jessen[c], J. Wong[c]

BioSystems 233 (2023) 105037

Contents lists available at ScienceDirect

BioSystems

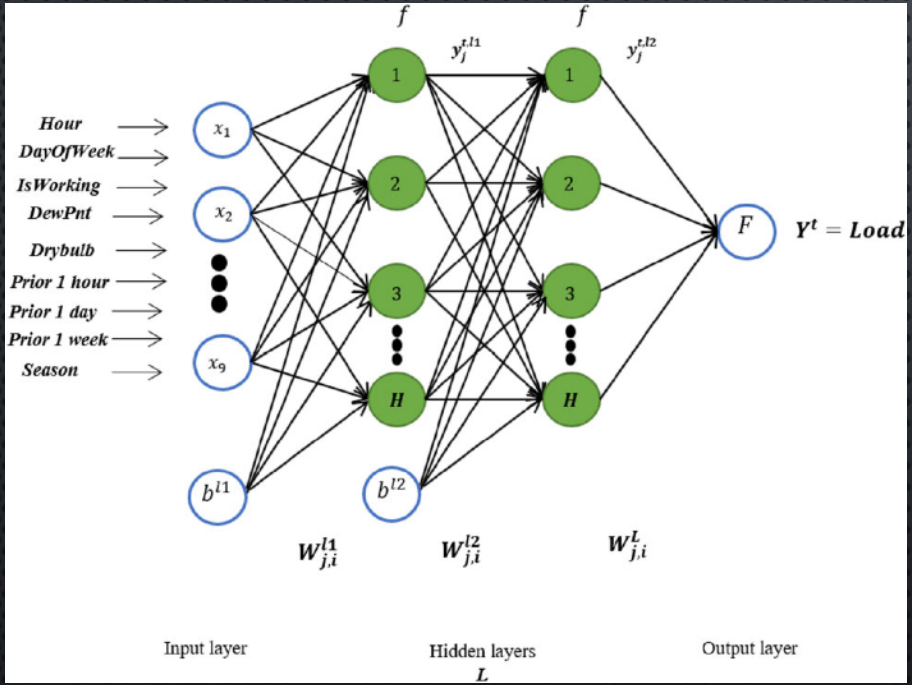
journal homepage: www.elsevier.com/locate/biosystems

Quantum algorithm for *de novo* DNA sequence assembly based on quantum walks on graphs

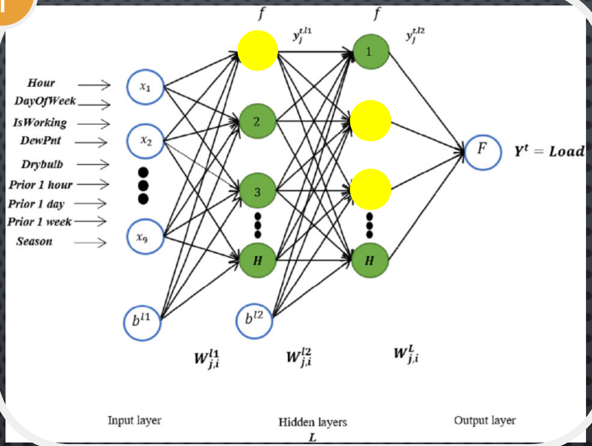
G.D. Varsamis[a], I.G. Karafyllidis[a,b,*], K.M. Gilkes[c], U. Arranz[c], R. Martin-Cuevas[c], G. Calleja[c], J. Wong[c], H.C. Jessen[c], P. Dimitrakis[b], P. Kolovos[d], R. Sandaltzopoulos[d]

HYBRID <HPC|QC> COMPUTING

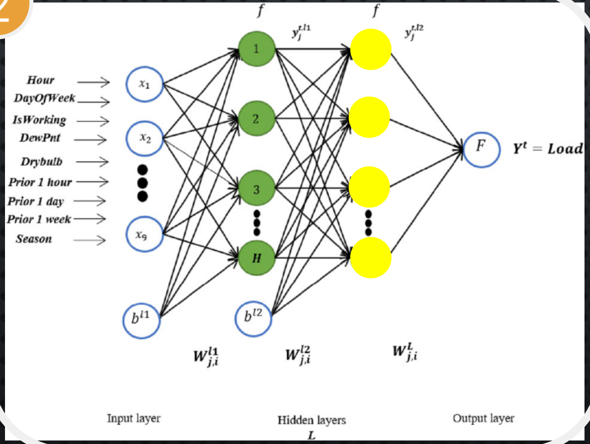
- Quantum Neuron
- Classical Neuron



1



2



<u>Two different NN architectures:</u>

1. Some Quantum Neurons in different layers
2. Only Quantum Neuron layers (Quantum Layers)

<u>Quantum Neurons</u>: A quantum circuit replaces a classical neuron and acts as part of a classical neural network

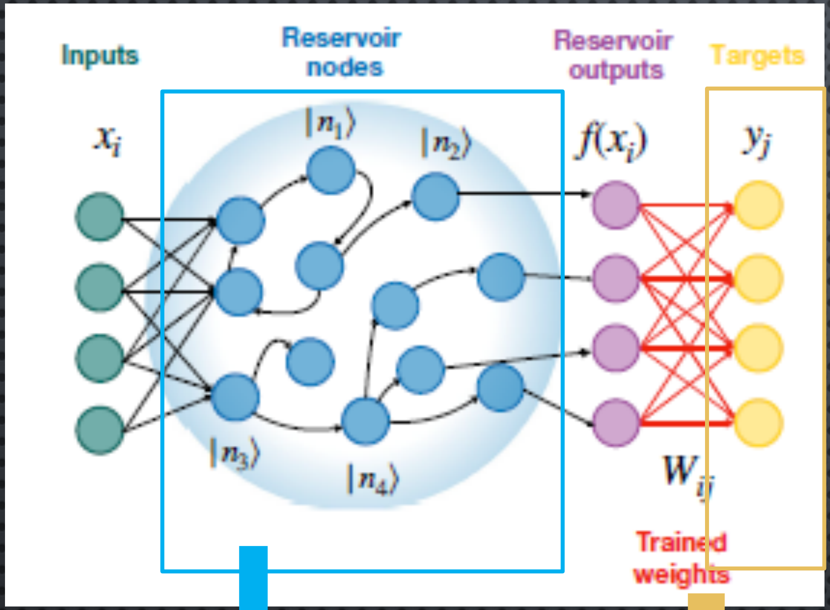
<u>Achieves</u>: Improved accuracy (better training).

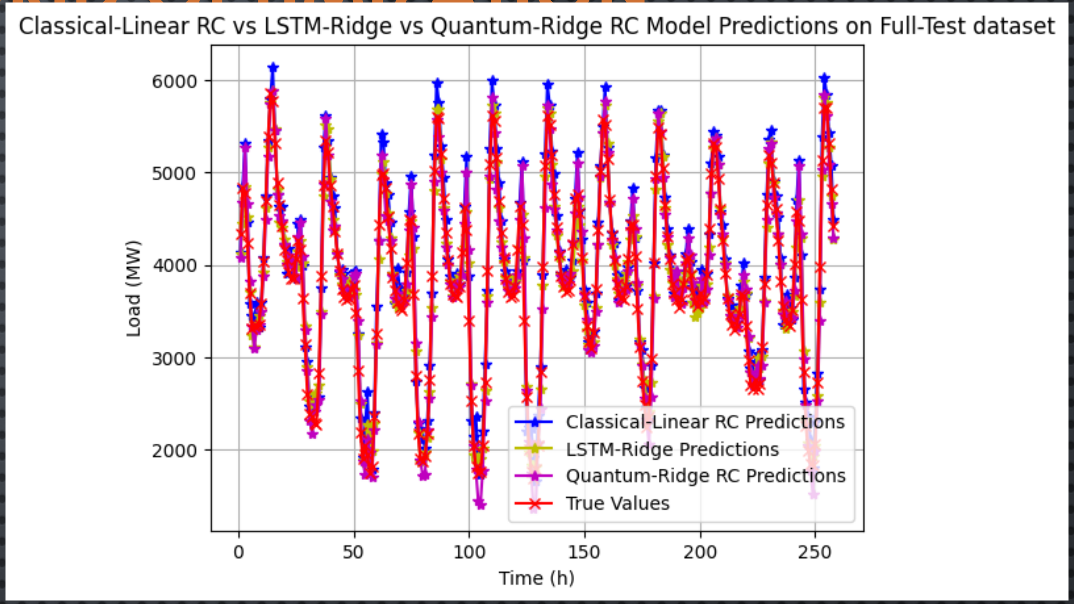
"NOUS" EU PROJECT
(PROJ: 101135927 — HORIZON-CL4-2023-DATA-01)

NOUS is a 36-month EU-funded project, which aims to develop the architecture of a European cloud service that allows computational and data storage resources to be used from edge devices as well as supercomputers, through the HPC network, and Quantum Computers.

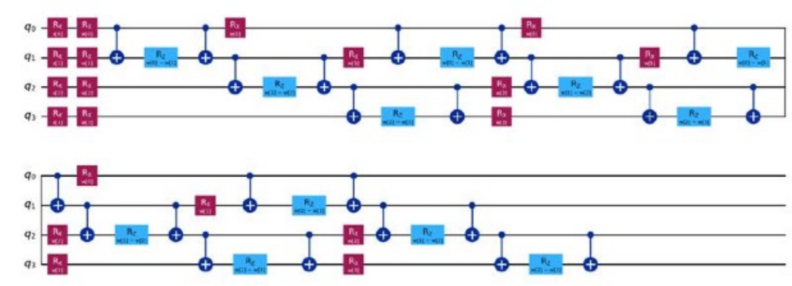
Funded by the European Union

"NOUS" EU PROJECT – ENERGY GRID OPTIMIZATION

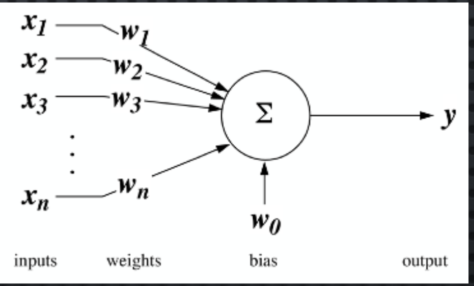




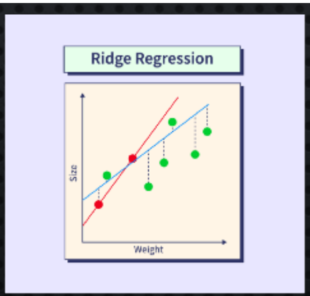
Reservoir Neuron = Quantum circuit



1. Linear Outputs



2. Ridge Outputs



Funded by the European Union

IQCQT – KOREA PROJECT: GRASP PROPOSAL (HORIZON EU-KOREA CALL)

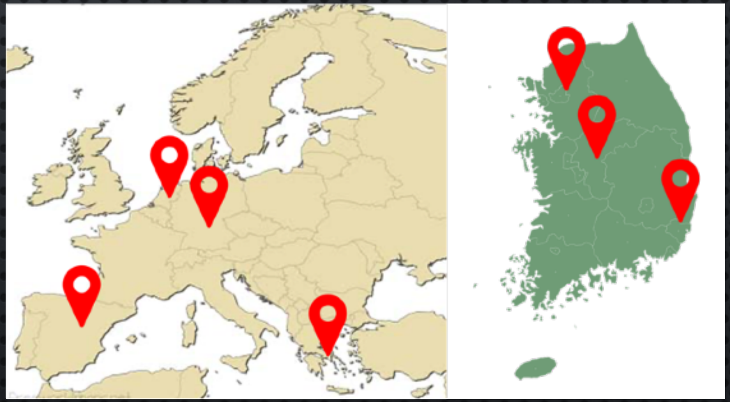
Graphene Josephson Bolometers for Quantum Sensing and Dark Matter Detection (GRASP)

GRASP

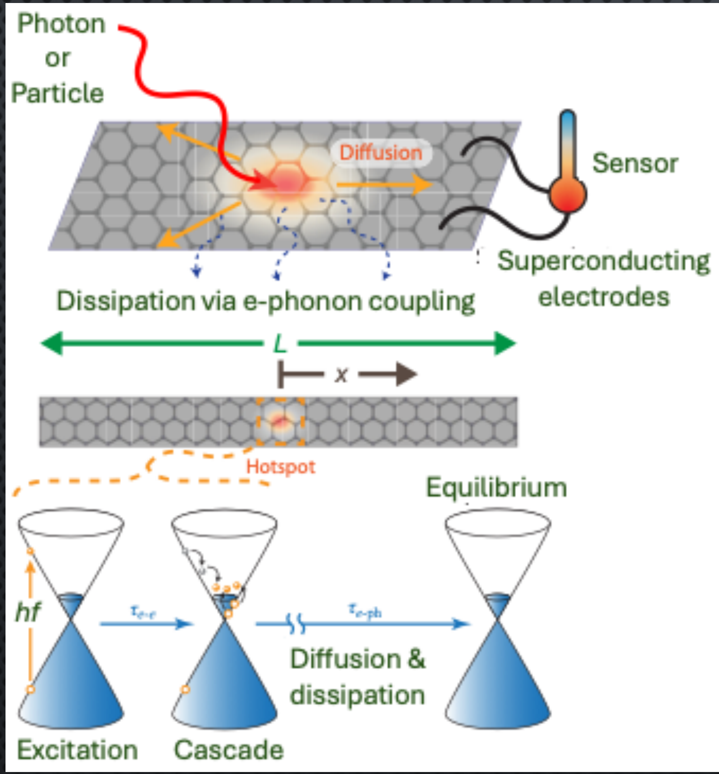
Participant organisation name

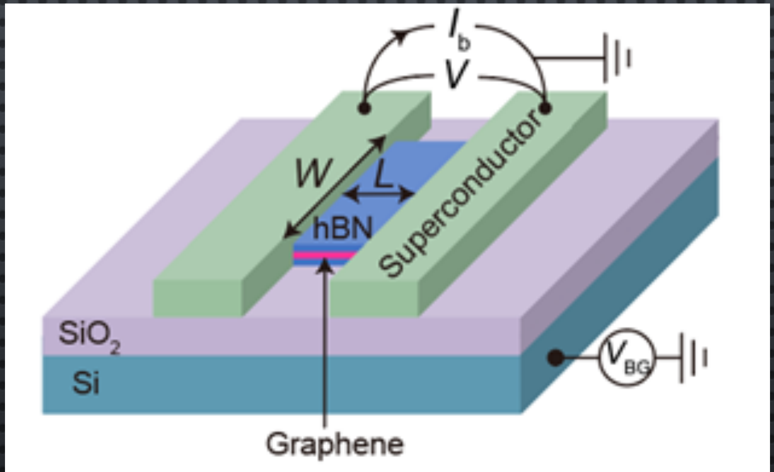
NATIONAL CENTER FOR SCIENTIF RESEARCH “DEMOKRITOS” (NCSRD) EL
UNIVERSITY OF HAMBURG (UHAM) DE
UNIVERSIDAD DE GRANADA (UGR) ES
UNIVERSITEIT TWENTE (UTW) NL

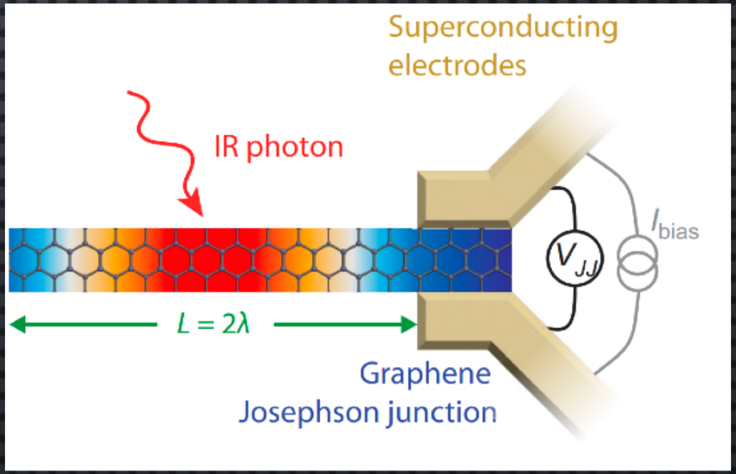
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY (POSTECH) KR
SOGANG UNIVERSITY (SOGANG) KR
CHUNGNAM NATIONAL UNIVERSITY (CNU) KR



GRASP : THE GJJ BOLOMETER PRINCIPLE







CONCLUSIONS

There is huge space for bilateral collaboration!

Theodore von Kármán

"Scientists study the world as it is; engineers create the world that has never been".

THANK YOU FOR YOUR ATTENTION !

Dr Panagiotis Dimitrakis

p.dimitrakis@qi.demokritos.gr

Greek Quantum Gate

www.greekquantumgate.com

Theodore von Kármán, who said,
"Scientists study the world as it is;
engineers create the world that has never
been".

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