TIDPAN

Taller de Instrumentación y Detectores en Física de Partículas, Astropartículas y Nuclear

Quantum Sensors

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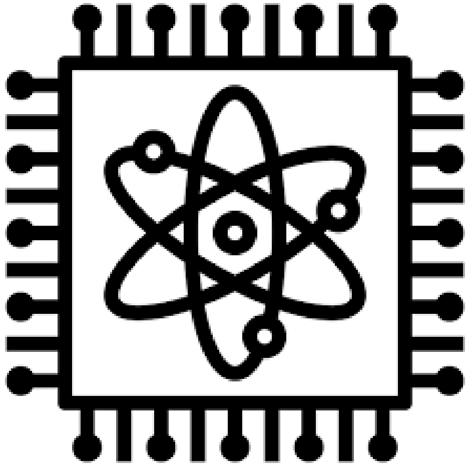
TIDPAN. Taller de Instrumentación y Detectores en Física de Partículas, Astropartículas y Nuclear

Detector and instrumentation categories

- Radiation detection and spectroscopy
- Imaging techniques
- Scintillation and photodetector technologies
- Semiconductor detectors and characterisation
- Gaseous detector technologies
- Calorimetric detection
- Low-rate and ultra-low-background event detection
- Electronics, trigger and data acquisition systems
- Simulation and advanced data analysis



Quantum Chips

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qchip.csic.es

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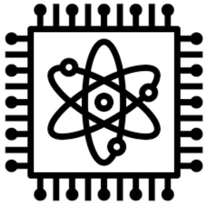
Quantum — of / in / for — PAN



CPAN NETWORK ON INSTRUMENTATION AND DETECTORS

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Quantum of PAN

Smallest indivisible unit of energy, matter, or interaction - Discrete amount of a physical quantity

Quantum Particles:

all particles described as quanta of underlying fields

- ***Photons*** - quanta of the electromagnetic field.

- ***Gluons*** - quanta of the strong interaction field (Quantum Chromodynamics, QCD).

- ***W and Z bosons*** - quanta of the weak interaction field.

- ***Gravitons*** - quanta of the gravitational field (hypothetical)

Quantum of Energy & Energy Levels:

quantized energy, which becomes important in view of:

- When **particles interact or collide**, as in particle accelerators, energy is transferred in discrete amounts - e.g. in the creation or exchange of particles.

- The term quantum of energy refers to the smallest possible **packet of energy** that can be transferred in a given interaction.

- **Discretization** of atomic or particle interaction energies

Quantum Science in PAN

Theoretical frameworks for HEP
Describe and understand the fundamental forces and particles
that make of the universe at all scales, from subatomic to cosmic scale

1. Quantum Mechanics: branch of physics that deals with the behavior of particles at microscopic scales (atoms and subatomic particles) - crucial for describing phenomena such as:

- Particle-wave duality: Particles like electrons and photons exhibit both wave-like and particle-like behavior.
- Superposition and entanglement: Particles can exist in multiple states simultaneously, and pairs of particles can be entangled, meaning the state of one particle is linked to the other.

2. Quantum Field Theory (QFT) : theoretical framework that combines quantum mechanics with special relativity – e.g. foundation for understanding how particles interact in HEP, such as LHC.
A central idea in QFT is that particles are excitations or quanta of underlying fields that permeate space.

3. The Standard Model of Particle Physics: QFT describes three of the four known fundamental forces (electromagnetic, weak, and strong forces) and classifies all known elementary particles (quarks, leptons, bosons).
The Higgs boson, discovered in 2012, is part of this model.

Quantum Science in PAN

Theoretical frameworks for PAN
Describe and understand the fundamental forces and particles
that make of the universe at all scales, from subatomic to cosmic scale

4. Quantum Chromodynamics (QCD) and Quantum Electrodynamics (QED):

- Quantum Chromodynamics (QCD) is the QFT that describes the strong interaction, which binds quarks together inside protons and neutrons via the exchange of gluons.
- Quantum Electrodynamics (QED) deals with the electromagnetic force between charged particles via photon exchange.

5. High-Energy Phenomena: Quantum effects dominate because at high energies/colliders (or equivalently, small scales), the classical (non-quantum) descriptions of particles and forces fail to explain, including:

- Particle creation and annihilation - particle-antiparticle pairs; Renormalization: dealing with infinities that arise in calculations by adjusting the values of physical quantities; mass and charge; Tunneling...

6. Beyond the Standard Model: Quantum theories are also being explored to explain phenomena that the Standard Model doesn’t account for, such as:

- Dark matter and dark energy - Supersymmetry; Gravity at quantum scales - Quantum Gravity, including theories like String Theory, to explain black holes or the early Universe

Quantum Tech for PAN

Application of Quantum Mechanics and Quantum Field Theory
Understand and describe response / behavior of particles and forces at their fundamental level
Useful in experiments in particle accelerators, cosmic events, …

How quantum principles, especially those from quantum mechanics and quantum field theory, are applied to study and explain fundamental particles and forces, e.g. at the highest energy scales.

It is essential for understanding the behavior of the universe at the smallest, e.g. most fundamental energy levels, and for advancing our knowledge in areas such as particle physics, cosmology, and nuclear. Nonetheless, one most established QTech is NMR.

Quantum State(s) = Quantum Information

Quantum Technologies

Quantum State(s) = Quantum Information

A **quantum state** is the fundamental mathematical description of a physical system in quantum mechanics.

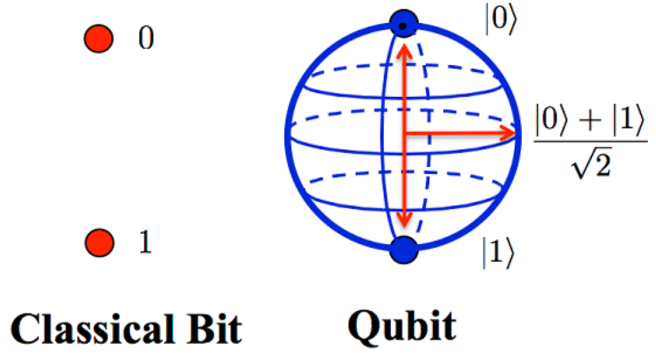
It holds of all the information that can potentially be known about that system:

energy, position, momentum, spin...

Different from classical states or computing units, a **quantum state** is probabilistic.

Until it is measured, it exists as a superposition of potential outcomes.

Analogy of coin spinning in mid-air: embodiment of the potential (in this case, for both) outcomes simultaneously, defined by a precise probability distribution.



QuantHEP

Quantum Computing Solutions for High-Energy Physics – QuantERA project

Investigate and assess the potential of quantum computation for experimental particle physics challenges.

Specifically, quantum algorithms as a solution to the increasingly challenging, and soon intractable, problem of analysing and simulating events from large particle-physics experiments.

1. **To develop quantum algorithms for event selection and event reconstruction**
2. **To use them to perform proof-of-principle analysis of real data from CERN**
3. **Benchmarking the potential advantage of this novel quantum-enhanced processing**

Deliverables:

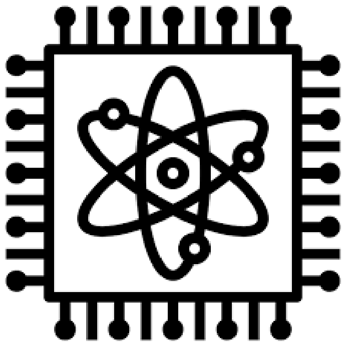
- Development of software libraries to simulate particle physics' objects (elementary particles, composite particles, jets…)
- Using them as building blocks to develop the quantum simulation of scattering processes
- Proof-of-principle scattering quantum simulation

By combining classical and freely-available quantum processors - benchmarking against CERN classical simulations to characterize a quantum advantage threshold for HEP processes.

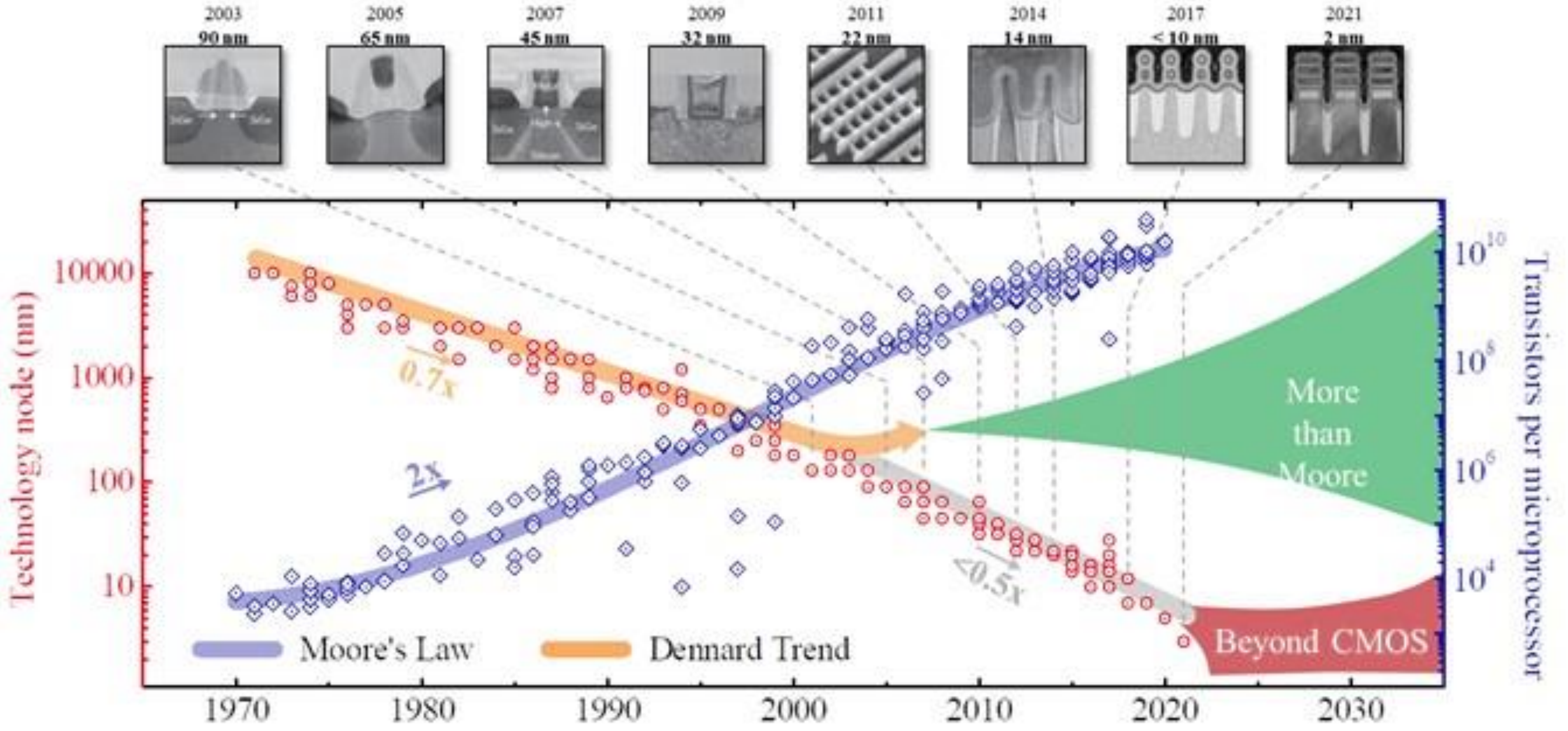
Feynman Vision(s)

*"What I want to talk about is the problem of manipulating and controlling things on a small scale. (…)
Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin?"*

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."



Quantum Chips



❖ **Not only geometrical scaling**

Nano to Quantum

Quantum Technology allows us to organise and control the components of a complex system governed by the **laws of quantum physics**, instead of exploiting classical physics as in conventional technology.

Two essential drivers in quantum technology:

- **Miniaturization**, as the dominant trend in last decades: to build devices on a smaller and smaller scale.
Ultimately this will deliver devices at length scales of nanometres and action scales approaching Planck's constant.
At that point design must be based on quantum principles.

- **Principles of quantum mechanics**: the promise of a vastly improved performance over what can be achieved within a classical framework.

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ROADMAP

The 2021 quantum materials roadmap

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1. Introduction
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6. Ultrathin layered superconductors
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10. Superconductor and semiconductor qubits
11. Non-equilibrium phenomena in quantum materials
12. 2D hyperbolic materials
13. Spin torque materials
14. Magnetic skyrmions
15. Machine learning using experimental quantum materials data
16. Machine learning and DFT simulations of quantum materials

Quantum State – Quantum Information - Qubit

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

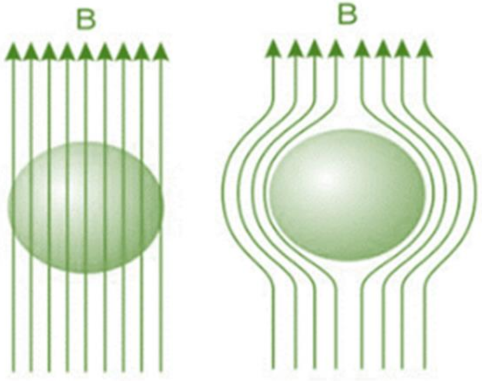
	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

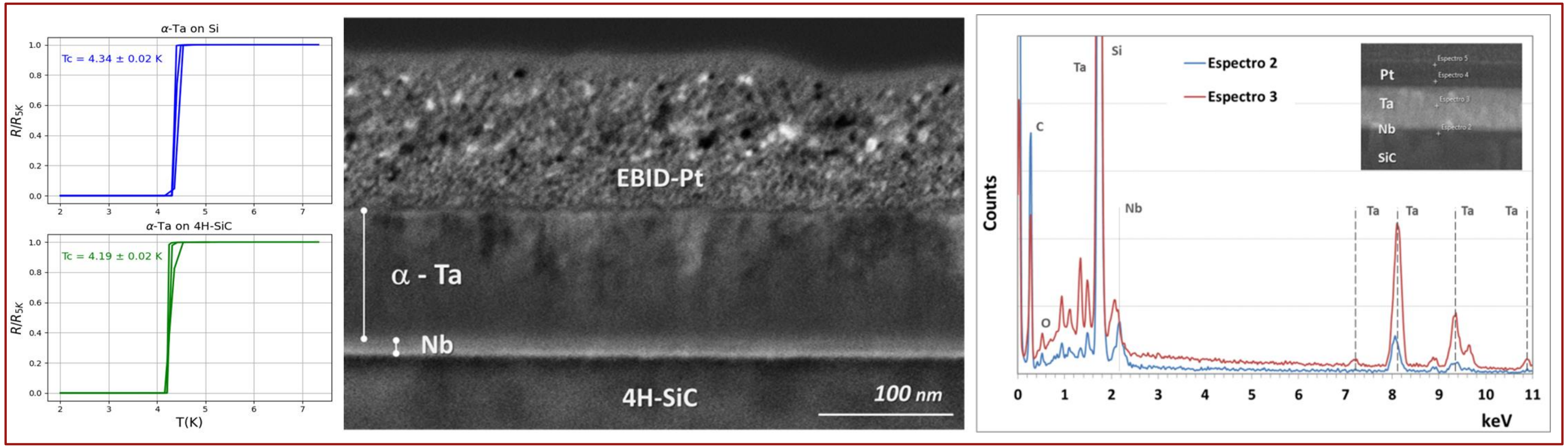
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

G. Popkin. The Quest for Qubits **Science (2016)**

Superconducting thin films are nanoscale to microscale layers of materials that exhibit zero electrical resistance and expel magnetic fields (the Meissner effect) when cooled below a specific critical temperature (Tc).

They are foundational for quantum computing, advanced sensing, and power electronics





From Quantum principles to cQED*

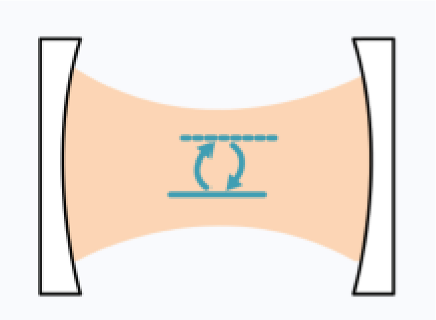
1920	1950	2020
QED	Cavity QED	Circuit QED

*Nobel of Physics 2025!

Cavity QED. Study of how light and matter interact at the single-photon and single-atom level.

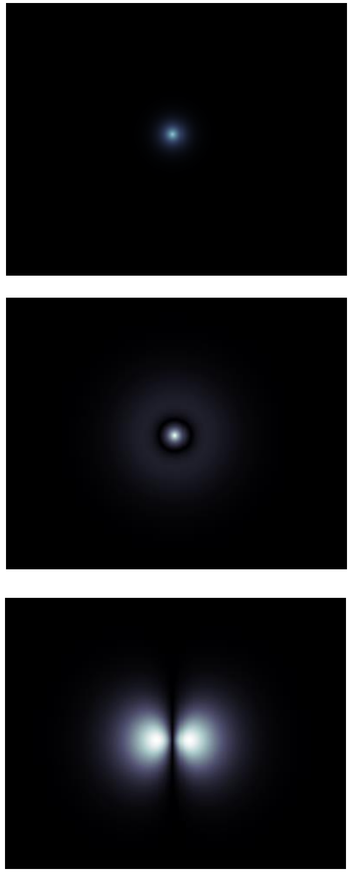
By trapping photons in a highly reflective resonator, the electromagnetic field is enhanced so strongly that a single atom or particle can coherently exchange energy with the light.

Strong coupling regime of two-level system to a photon field in a resonator

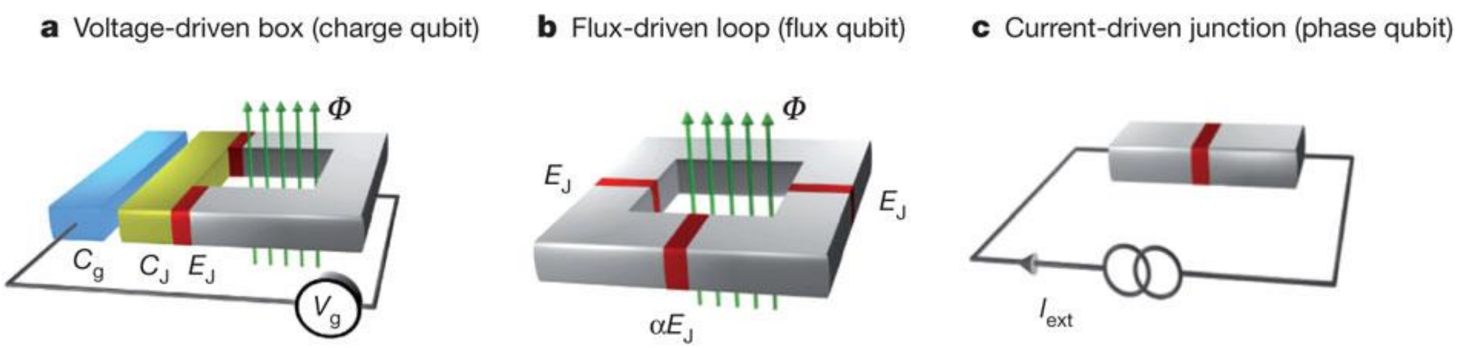


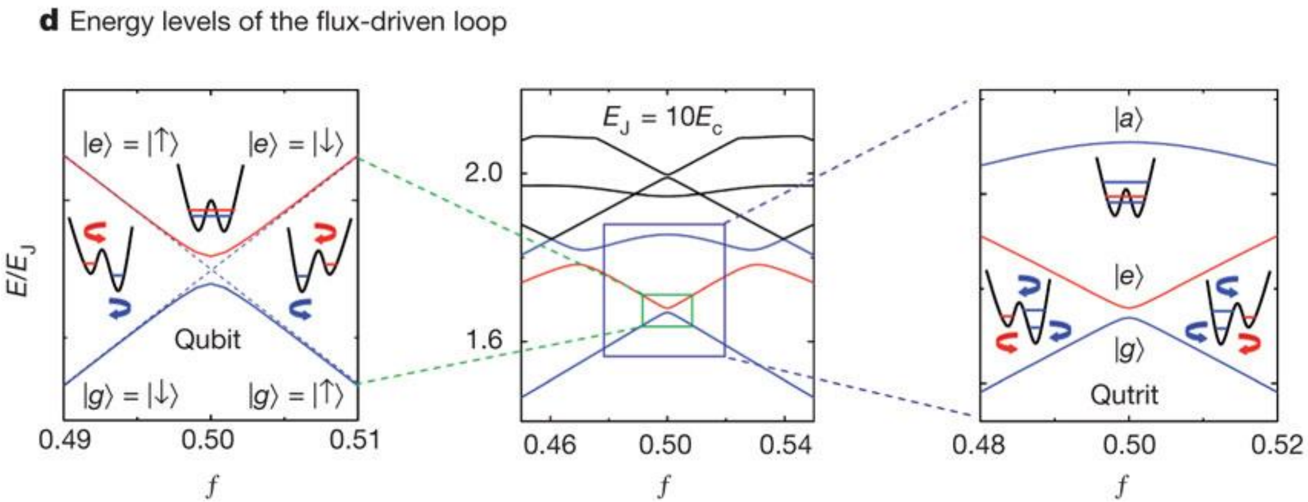
Circuit QED. Instead of traditional mirrors, this method uses superconducting transmission lines and artificial atoms, like transmon qubits, to **replicate cavity QED physics on a microchip**

Circuit QED.

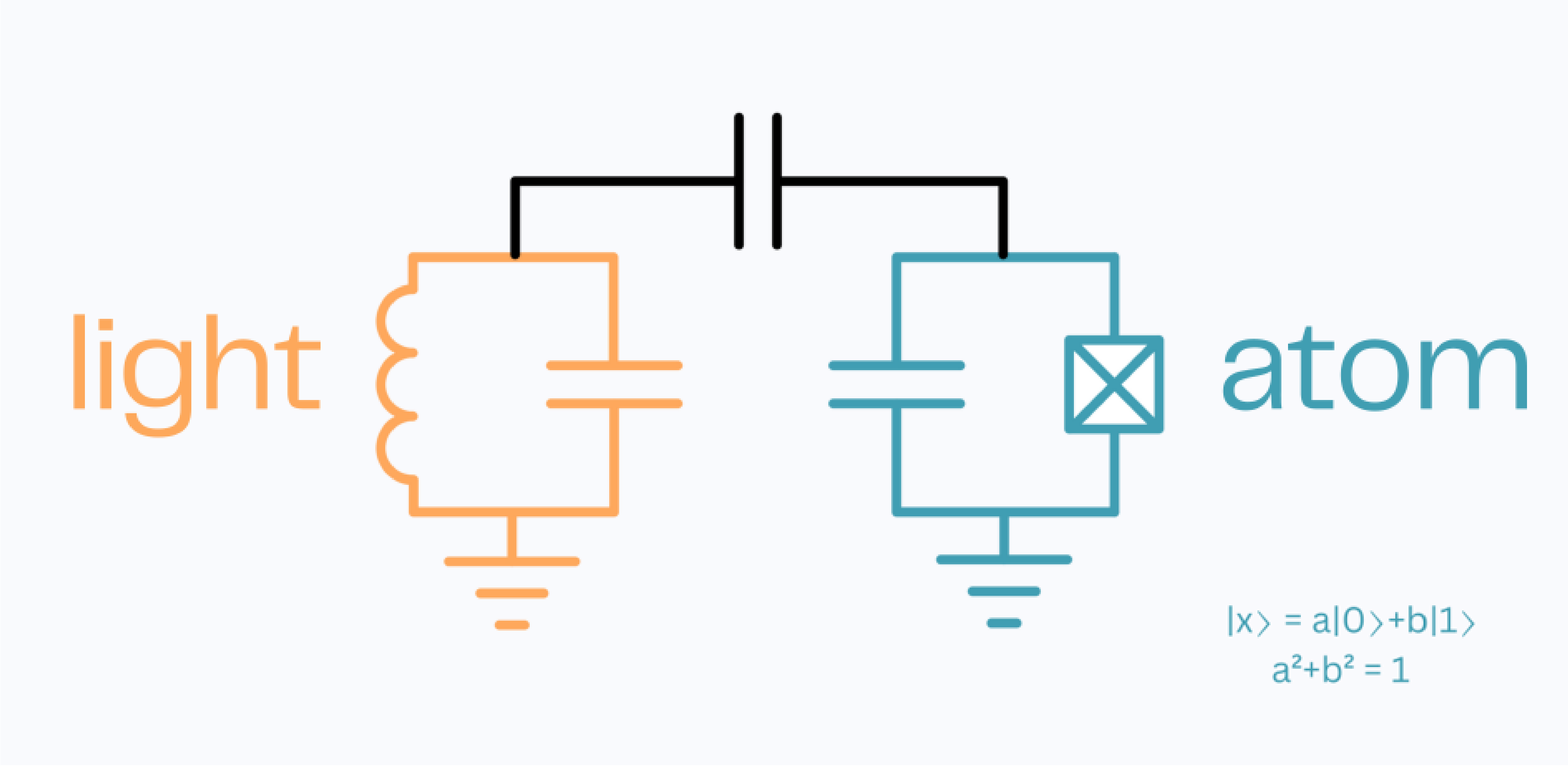


N. Crescini





You, J., Nori, F. Atomic physics and quantum optics using superconducting circuits.
Nature **474**, 589–597 (2011). Doi:10.1038/nature10122



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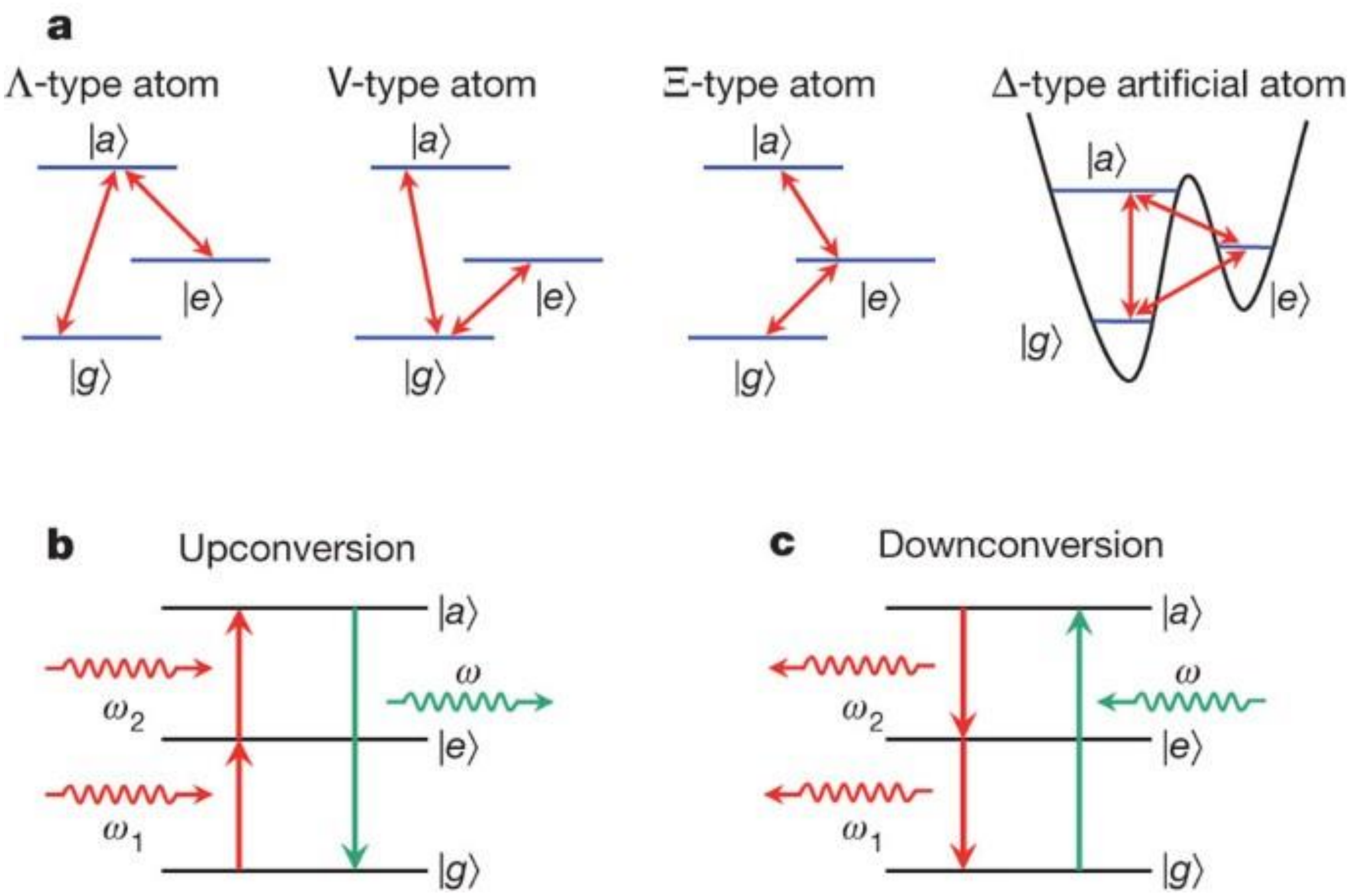
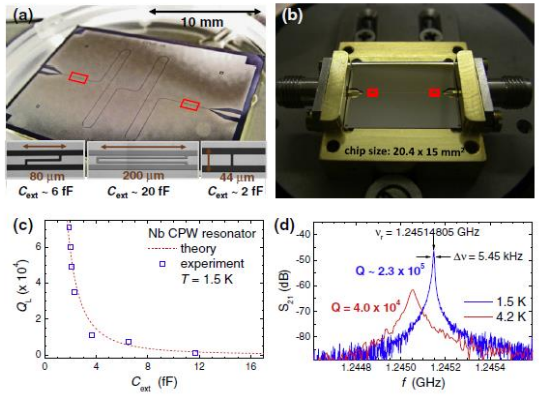
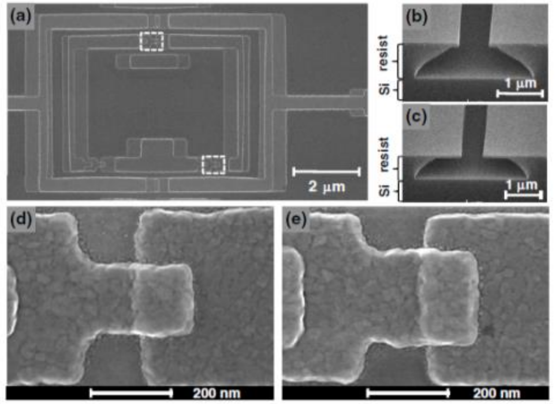


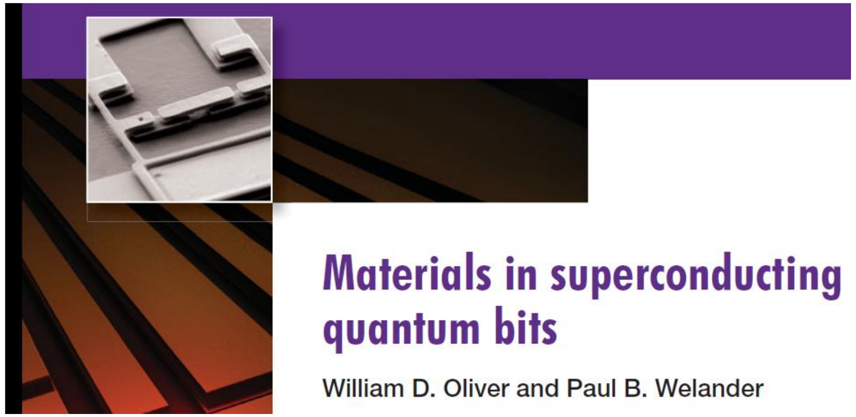
You, J., Nori, F. Atomic physics and quantum optics using SC circuits. *Nature* **474**, 589–597 (2011) 10.1038/nature10122



Nb CPW resonator



Dolan bridge processing qubits



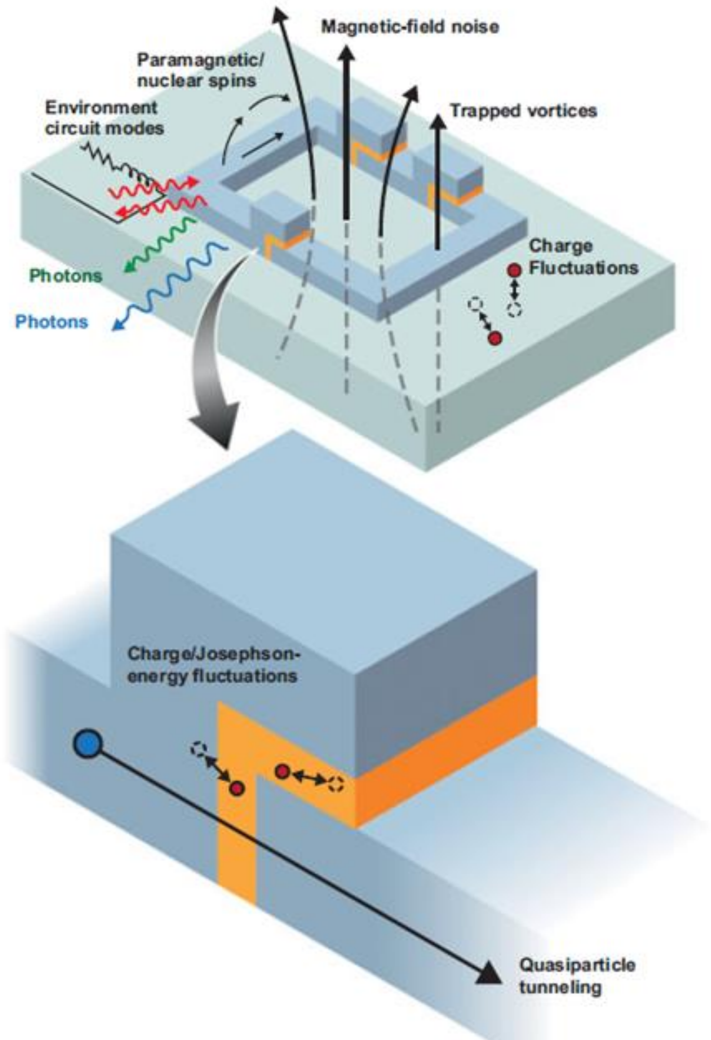
Materials in superconducting quantum bits

William D. Oliver and Paul B. Welander

Superconducting qubits are electronic circuits comprising lithographically defined Josephson tunnel junctions, inductors, capacitors, and interconnects. When cooled to dilution refrigerator

Summary

The past 10–15 years have witnessed coherence times in superconducting qubits increase dramatically—a full five orders of magnitude—bringing these devices to the threshold of technical reality. This evolution has been driven by innovations in qubit design, device fabrication, and materials science, and further research in these areas will be required to make superconducting qubit technology truly scalable. We have attempted to demonstrate how qubits and their constituent components have been useful in identifying previously unknown underappreciated material defects, and how new materials and new fabrication processes can help improve device performance.

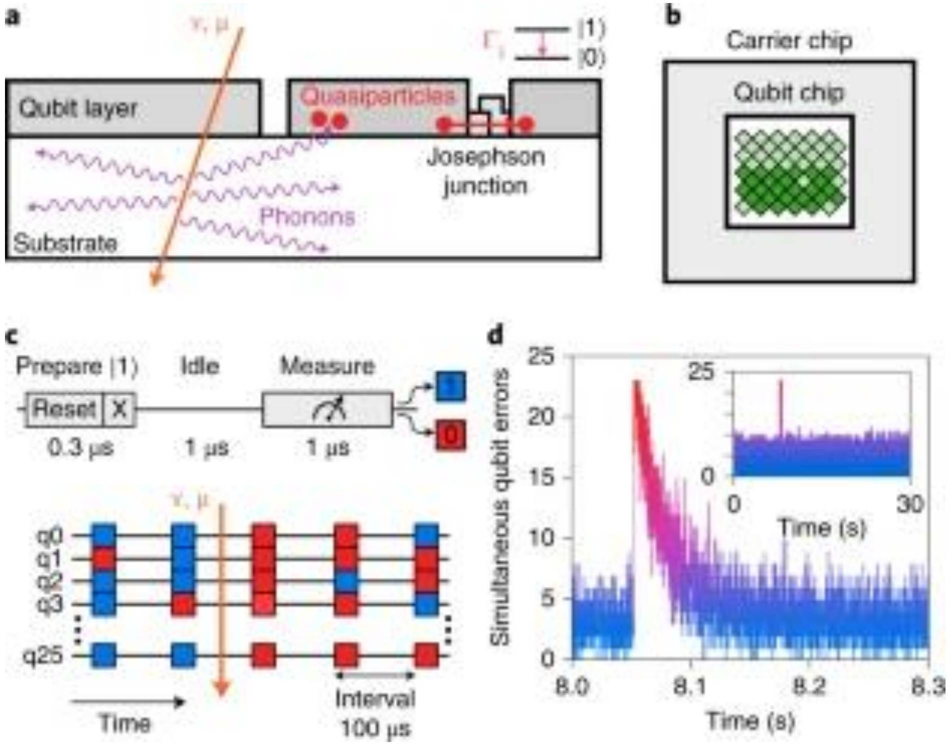


MRS BULLETIN • VOLUME 38 • OCTOBER 2013 •

Superconducting Qbits are vulnerable to external factors and noise

Leading to decoherence o variability.

- **Exploration of new or engineered materials, resilient design and improving fabrication processing of devices, circuits or addition of mitigation elements.**



Approaches for mitigation

Off-chip issues

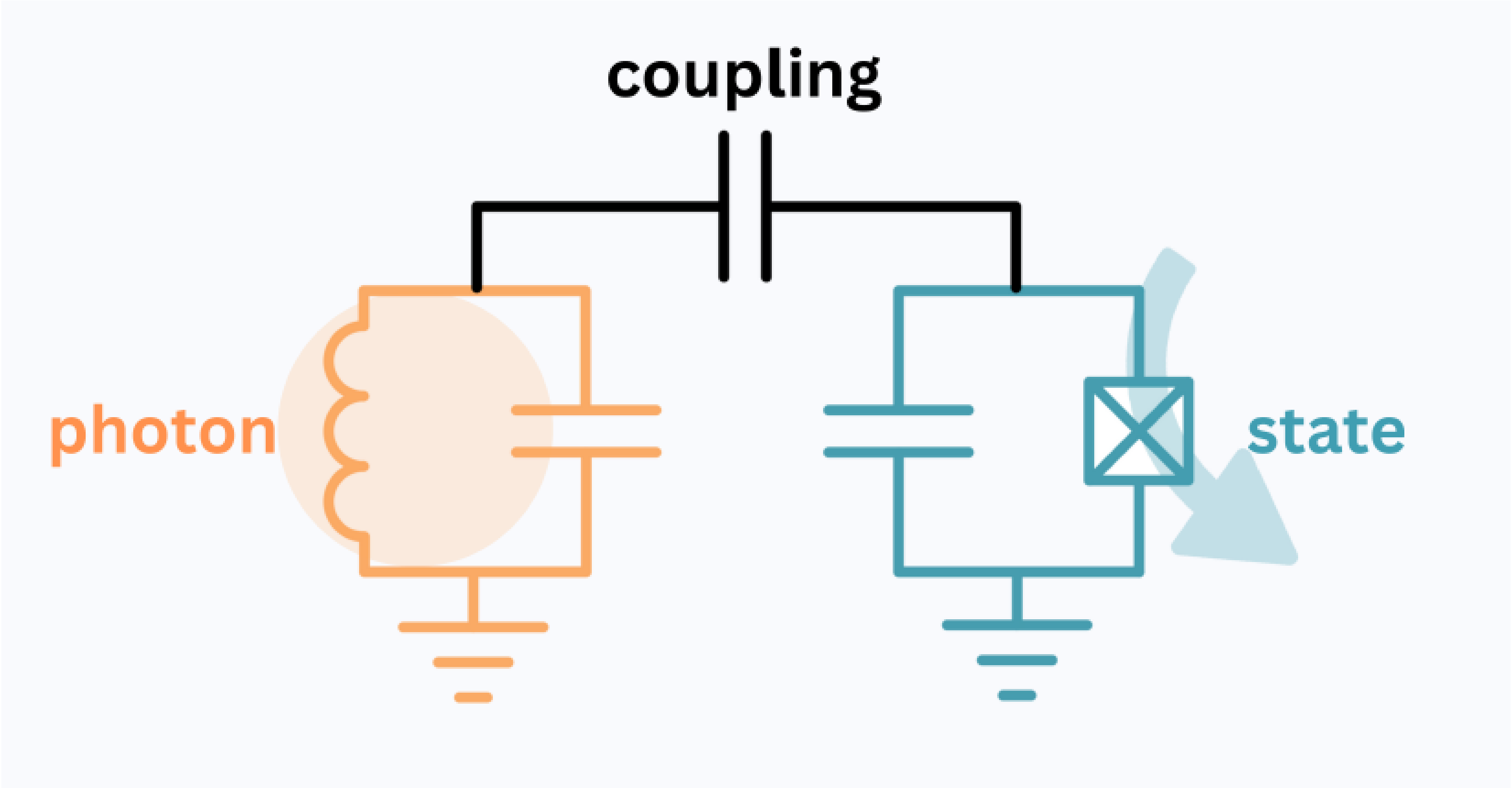
On-chip solutions

Materials: Selection and combination of materials or substrate

Fabrication of structures or architectures:
- Locally suspended - membranes
- Periodical structures – vortex mitigation

Components: passive (quasiparticle traps, on chip-grounding), active (QEC redundancy…)

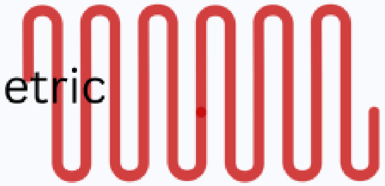
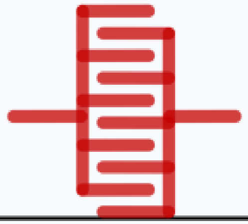
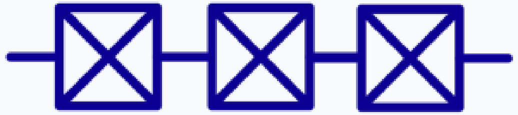
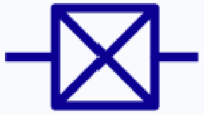
McEwen, M., Faoro, L., Arya, K. *et al.* **Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits.** *Nat. Phys.* **18**, 107–111 (2022). https://doi.org/10.1038/s41567-021-01432-8



N. Crescini

Atomic physics, quantum optics, nanoscience and condensed matter physics are partly merging as **new interdisciplinary areas** form to involve all of these traditionally separate subfields, **Quantum Tech**.

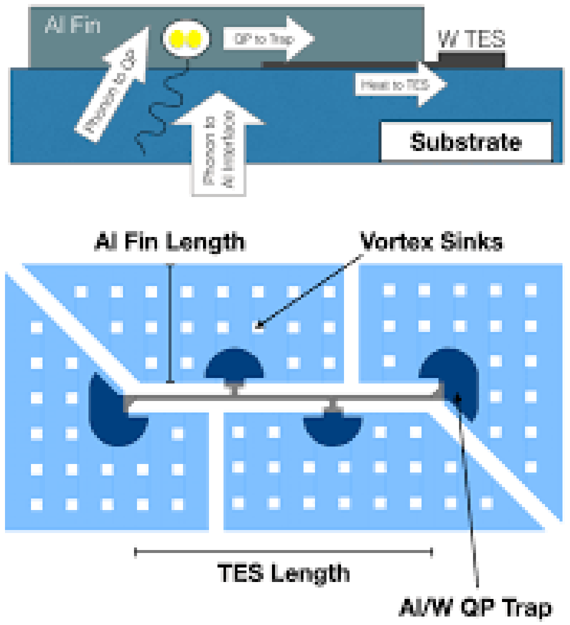
Superconducting circuits can be engineered to exhibit **quantum phenomena** that are normally associated with atomic systems, and so provide a **platform for testing various ideas** in atomic physics and quantum optics.

Inductors	Capacitors	Resistors
Geometric 	Geometric 	Metallic materials: • gold • chromium (also inductive) • platinum
Nonlinear inductors 	Nonlinear capacitors 	• high impedance • probably, with high currents • heating is a problem
Large junction low impedance	Small junction high impedance	Impedance/dissipation engineering

N. Crescini

❖ Quantum Sensing in Specific Substrates

Substrate as target for phonon sensing

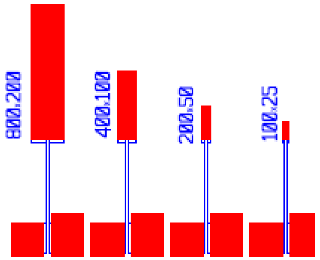


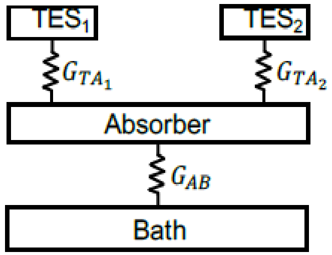
TES, QET in W, Al, Nb… Sapphire, SiC or more exotic e.g. polar single crystal materials…

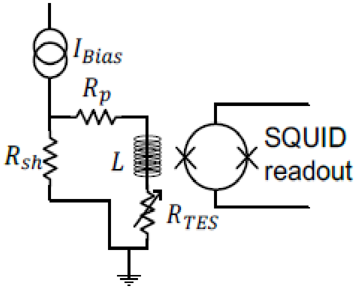
Design and characterization of a phonon-mediated cryogenic particle detector with an eV-scale threshold and 100 keV-scale dynamic range (2021) R. Ren *et al.* Phys. Rev. D 104, 032010 https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.032010

❖ Calorimeters and Bolometers

Transduction to quantum electronic signal







Hf, Ta, alloys …
Evaporation, Sputtering, …

https://link.springer.com/chapter/10.1007/978-3-319-24091-6_2

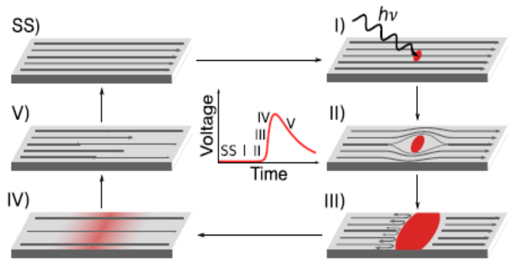
TABLE III. Performance of state-of-the-art TES single photon calorimeters/bolometers.

TES	T_c [mK]	V_{TES} [μm^3]	σ_E [meV]	$\frac{\sigma_E}{\sqrt{V_{TES}}}$ [$\frac{meV}{\mu m^{3/2}}$]	Method
W[28]	125	21.88	120	25.7	measured
Ti[29]	50	0.13	47	128.2	measured
MoCu[30]	110.6	2000	295.4	6.6	estimated[b]
TiAu[31]	106	90	48	16	measured
TiAu[32]	90	202.5	~23	1.6	estimated[b]
W (this)	40	1600	40	1	estimated

[b] The energy resolution is estimated with Eq. (1) from the given NEP and sensor bandwidth.

Trends

❖ **Other Quantum Sensing devices for photon detection**
Engineering very thin films and their properties or characteristics



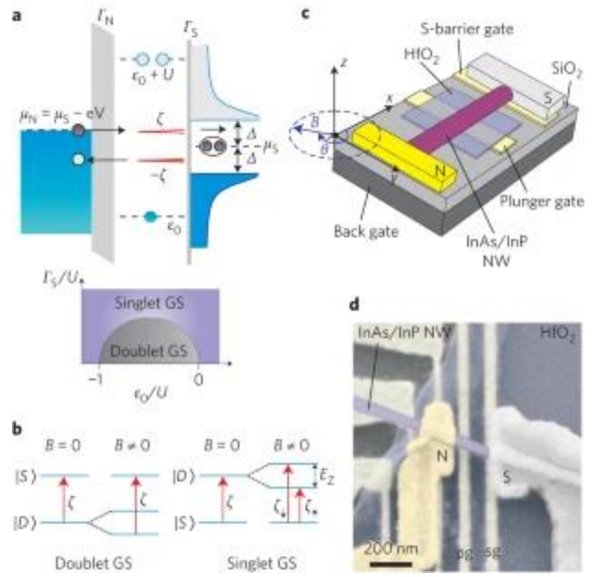
SNSPD, nanoTES… Superconducting alloys, amorphous

TABLE I. Overview of some SNSPD leading works on different material platforms.

Material	Efficiency/time jitter	Temperature	Wavelength
NbN (Refs. 43 and 45)	92%–98.2%/40–106.1 ps	0.8–2.1 K	1550–1590 nm[a]
NbTiN (Refs. 42 and 46)	92%–99.5%/14.8–34 ps	2.5–2.8 K	1290–1500 nm[b]
WSi (Refs. 41 and 44)	93%–98%/150 ps	120 mK–< 2 K[c]	1550 nm
MoGe (Ref. 106)	20%/69–187 ps	250 mk–2.5 K	1550 nm
MoRe (Ref. 107)	—/—	9.7 K	—
MoSi (Refs. 108–110)	80%–87% /26–76 ps	0.8–1.2 K[d]	1550 nm
NbRe (Ref. 111)	—/35 ps	2.8 K	500–1550 nm
NbTiN (Ref. 76)	15%–82% /30–70 ps	2.5–6.2 K	400–1550 nm
NbSi (Ref. 112)	—/—	300 mK	1100–1900 nm
TaN (Ref. 113)	—/—	0.6–2 K	600–1700 nm
MgB_2 (Refs. 114–116)	—/—	3–5 K	Visible

Superconducting nanowire single-photon detectors (…) Appl. Phys. Lett. 118, 190502 (2021) https://doi.org/10.1063/5.0045990

❖ **Hybrid integration in Quantum Sensors, e.g. semiconducting or magnetic with superconducting devices or microwave circuits Challenging principles of oporation, interfaces**



Nanowire - Thin Films Semiconductor-Superconductor

Lee, E. *et al.* **Spin-resolved Andreev levels and parity crossings in hybrid superconductor–semiconductor nanostructures**. *Nature Nanotech* **9**, 79–84 (2014). https://www.nature.com/articles/nnano.2013.267

Synergies and Vision of Quantum Technologies - PAN

1. Connecting quantum information, quantum field theory, gravity, …
2. Tradition of HEP theory as asset and contribution
3. Quantum Computing intrinsically fitting HEP fundamental physics problems
4. Quantum Metrology bridging theory and sensing
5. HEP as early adopter of new technologies

Single qubit ≠ computer,
but it can be an **ideal sensor**

Both **discrete and collective** Quantum states as crucial information of energy and matter

Learn from previous success **on micro/nanochip** development**:**

HEP-Microelectronics

- Solid State detectors
- DAQs

Superconducting and Hybrid Quantum Chips Research Line at IMB-CNM-CSIC

On-going QTech related Funded Projects

QUTE - CNS2023-145234
Resonant –IKUR2025-QT11
KICK-IN – Internal IMB-MdM - Trigger Call
SUHY – Intramurales CSIC

Previous or Recent QTech-related Funded Projects

QS4DM - QTP2021-03-014
HYFAB – TED2021-13029B-C44
MINARE – PID2021-122140NB-C32

Current Team Members

María Benito **– PreDoc**
Carlo Pepe **– PostDoc**
Gemma Rius **– Tenured Scientist**

plus two Master Students

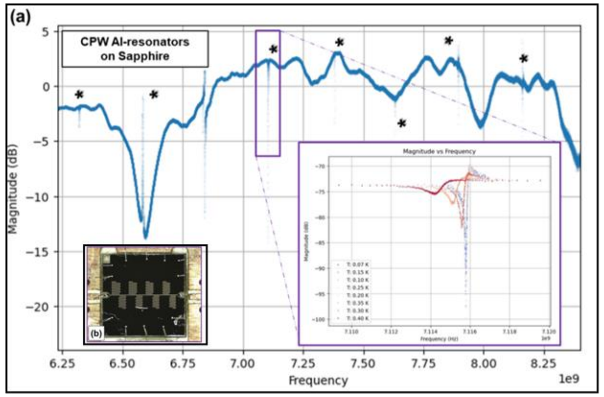
Institut de Microelectrònica de Barcelona
40 anys fent grans les coses petites CNM
EXCELENCIA MARÍA DE MAEZTU
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Quantum environment
IMB-CNM Research

Superconducting & Hybrid Quantum Chips Research Line

Baseline Superconducting Devices. Design, Fabrication and Testing

Microwave Resonators, e.g. Al and Ta



2 Manuscripts in Prep.

Baseline Supercond. Thin films & Devices

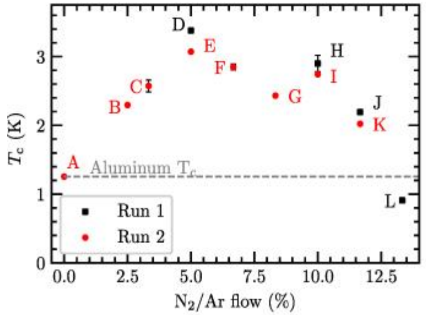
Material	Tc
Aluminum	1.2
Tantalum	4.2-4.4
Niobium	~ 4.5
α-Tungsten	< 100mK

2025 *Supercond. Sci. Technol.* ***38*** *095004*

Paper on Ta-Nb to be submitted

Customized or Advanced Superconducting Thin films

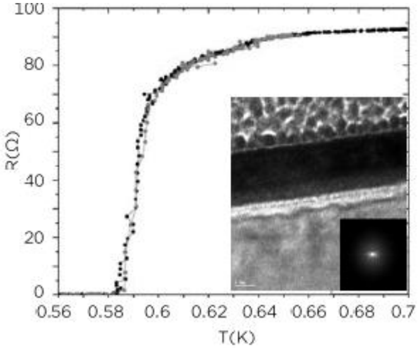
Nitridized Aluminum



2024 *Supercond. Sci. Technol.* ***37*** 035017

2026 *J Low Temp Phys* 222, 55 doi.org/10.1007/s10909-026-03390-y

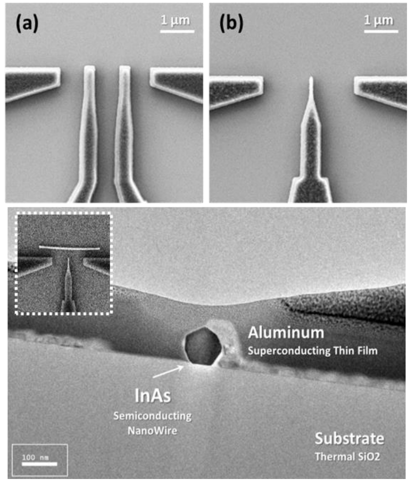
Ultrathin Amorphous WSix



2026 *IEEE Trans. Appl. Superconductivity* 36, 5, 1-5 doi.org/10.1109/TASC.2026.3673788

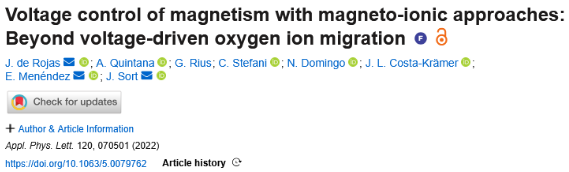
Hybrid Devices and Unconventional Systems

Semiconductor-Superconductor



Manuscript in Prep.

Quantum Materials Integration


Voltage control of magnetism with magneto-ionic approaches: Beyond voltage-driven oxygen ion migration

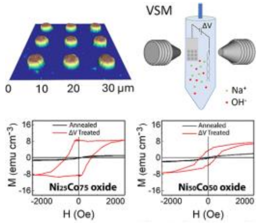
J. de Rojas; A. Quintana; G. Rius; C. Stefani; N. Domingo; J. L. Costa-Krämer; E. Menéndez; J. Sort

Check for updates

+ Author & Article Information

Appl. Phys. Lett. 120, 070501 (2022)

https://doi.org/10.1063/5.0079762 Article history



Micro – Nano Technologies for the realization of Quantum Materials and Devices

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Superconducting & Hybrid Quantum Chips Research Line

Baseline Superconducting Devices. Design, Fabrication and Testing

Baseline Supercond. Thin films & Devices

- ✓ Qualifying existing (metal) thin films
- ✓ Developing deposition conditions
- ✓ Fabrication of devices – based on available equipment and target materials at the ICTS IMB-Clean Room

Basic Methods:

- ○ Sputtering
- ○ Evaporation
- ○ Micro and Nano Patterning

- ❖ Intended for both cryogenic electronics and quantum devices
- ❖ Design fabrication and testing of DC and MW devices & circuits
- ❖ Resilience of materials and devices to operation, such as B

Material	Tc
Aluminum	1.2 K
Tantalum	4.2-4.4 K
Niobium	~ 4.5-6 K
α-Tungsten	< 100mK
Titanium	400 mK
Proximitized films	Tunable
Layer stacks	Tunable

2025 *Supercond. Sci. Technol.* **38** 095004

Superconducting thin film & processing By G Rius Team	Material(s)	Evap	Sputt	CMOS	Patterning or Transfer
Pure Element / Target	Nb	x			x
	Ta		x		x
	Al	x	x	x	x
	$Al_{95}Cu_5$	x			x
	Ti	x			x
	W		x		x
Proximitized layers or Stacks	EG-SiC-Al	x	x		x
	EG-SiC-Ti/Au	x			x
	Al-Ti	x			x
	Al-Ti-Au	x			Planned
	Nb-Au	x			Planned
	Ti-Au	x			Planned
	W-Au	x	x		Planned
Compounds & Alloys	AlN_x	x	x	x	x
	$AlAu_x$	x	x		x
	AlAl	x	x	x	Planned
	$AlHe_x$	x	x		x
	$AlGa_x$	x	x		x
	$AlSi_x$	x	x	x	
	WSi_x		x		x
	WGe_x		x		
	NbN_x	x			
	$NbSi_x$	x			
	TaN_x		x		
	$TaSi_x$		x		
	TiNx		x		

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Superconducting & Hybrid Quantum Chips Research Line

Baseline Superconducting Devices. Design, Fabrication and Testing

MINARE Project

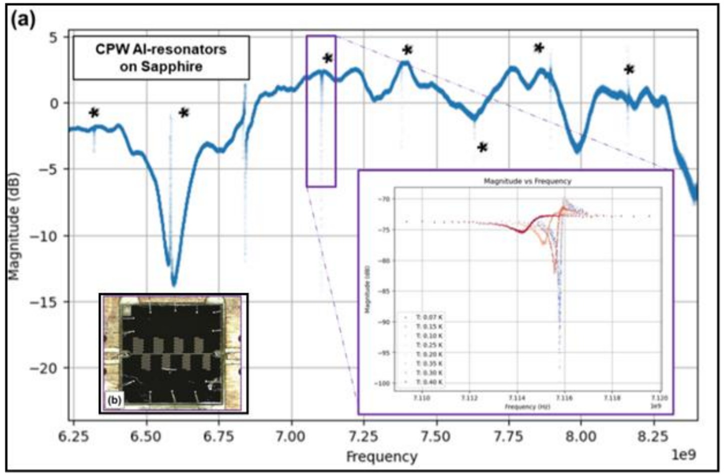
LSC-LNGS / IFAE / IMB-CNM

Microwave Resonators, e.g. Al and Ta

- ✓ Designs of circuits, including arrays of multiplexed resonators
- ✓ Fabrication of devices and external interfacing (pcbs and sample box)
- ✓ Analysis of performances upon testing in dilution fridge (cryo-characterization not on-site)

Modelling and simulations for device and chip design and evaluation:

- o Sonnet
- o COMSOL



- ❖ Parametric comprehension of actual characteristics and performances: freq, Ql, power, T, SPR…
- ❖ Optimization by layout design and fabrication processing
- ❖ Diagnostic and mitigation of effects and sensitivity or resilience to environment /off-chip experimental conditions, e.g. ionizing radiation

→ *APL Quantum* 3, 020901 (2026)
doi.org/10.1063/5.0319835

40 anys fent grans les coses petites CNM
Institut de Microelectrònica de Barcelona

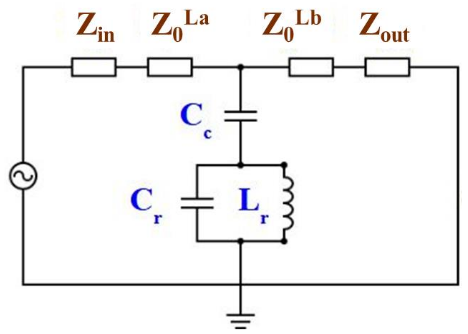
EXCELENCIA MARÍA DE MAEZTU

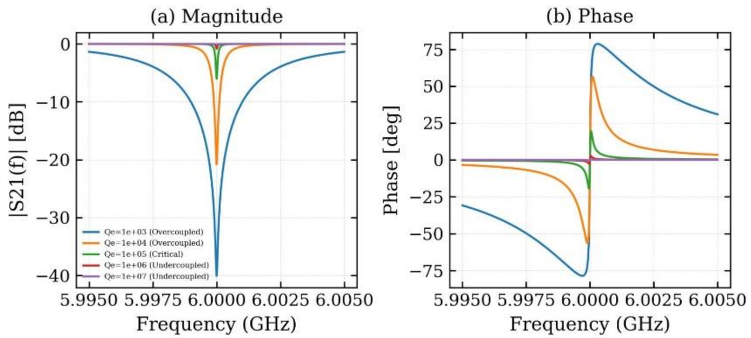
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Quantum environment

IMB-CNM Research

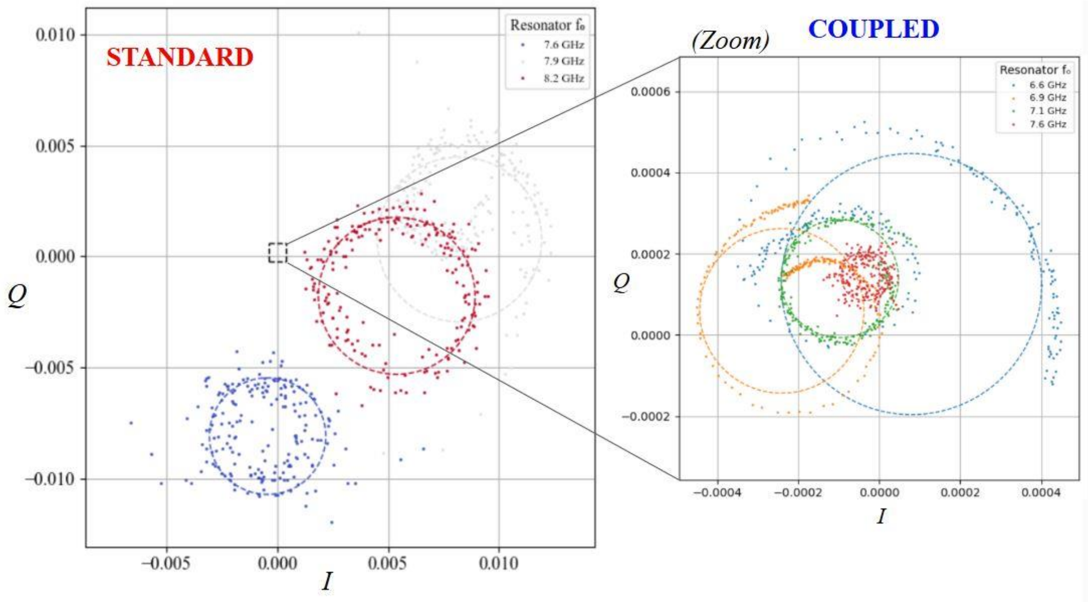
Superconducting & Hybrid Quantum Chips Research Line

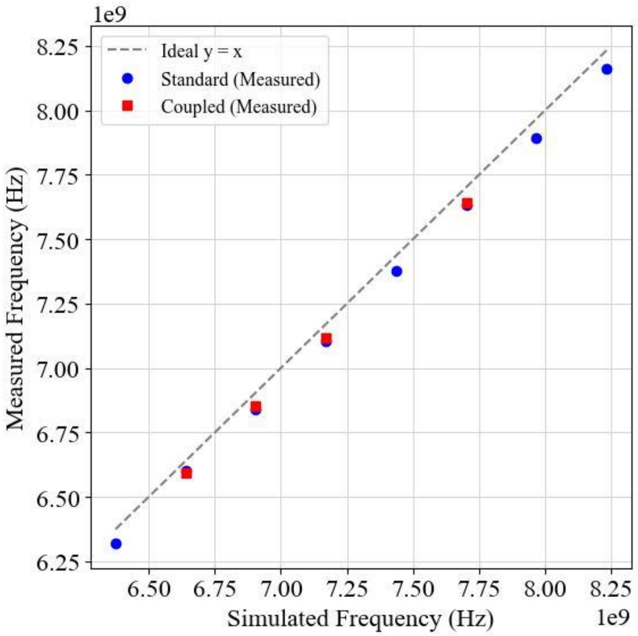


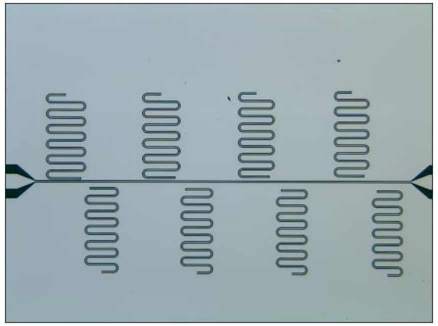


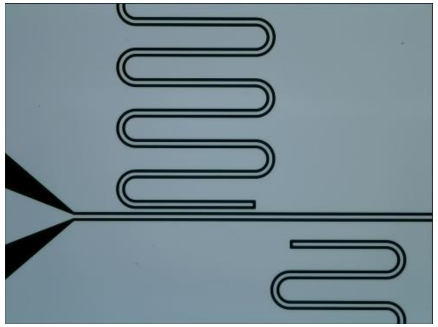
Baseline Superconducting Devices. Design, Fabrication and Testing

Microwave Resonators, e.g. Al on Sapphire









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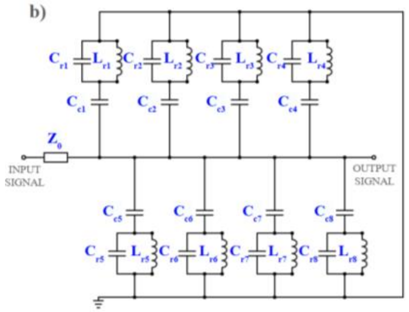
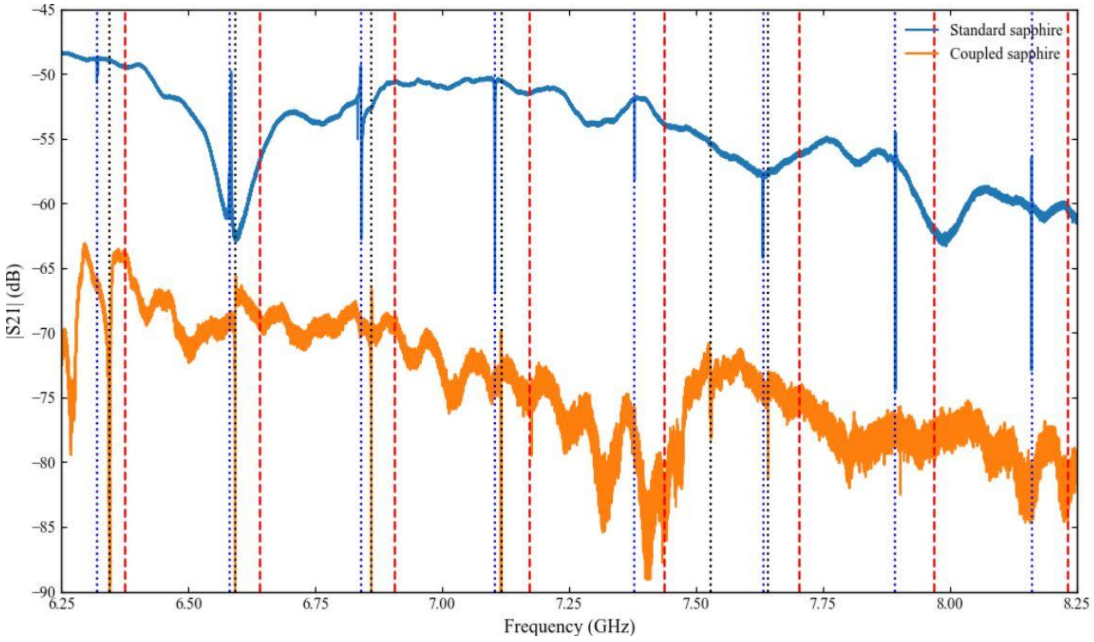
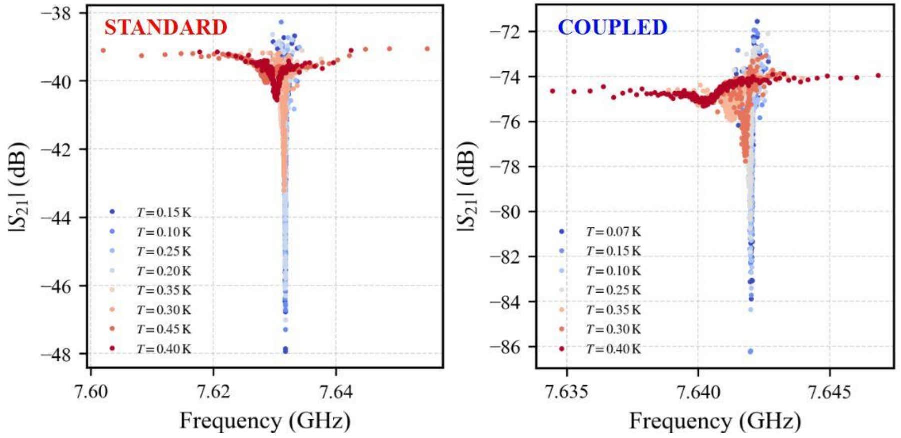
Superconducting & Hybrid Quantum Chips Research Line

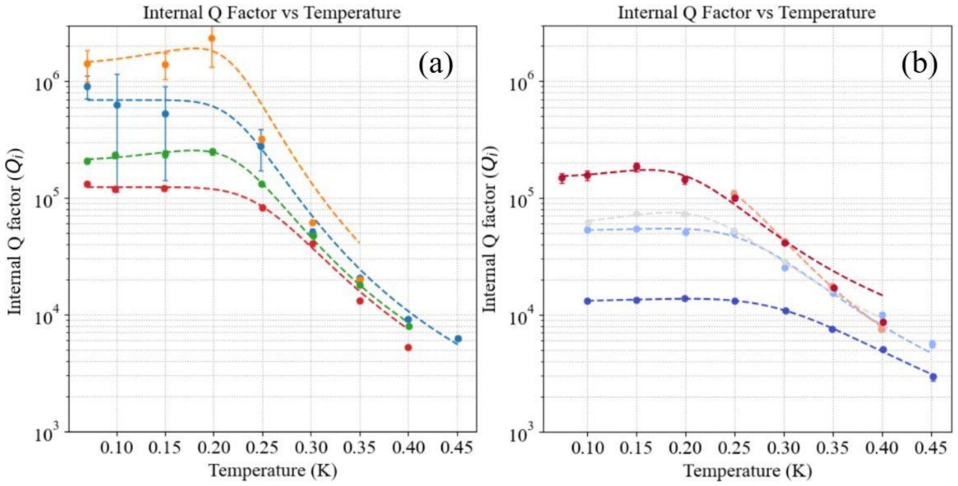
Baseline Superconducting Devices. Design, Fabrication and Testing

Arrays of CPW Microwave Resonators, e.g. Al on Sapphire







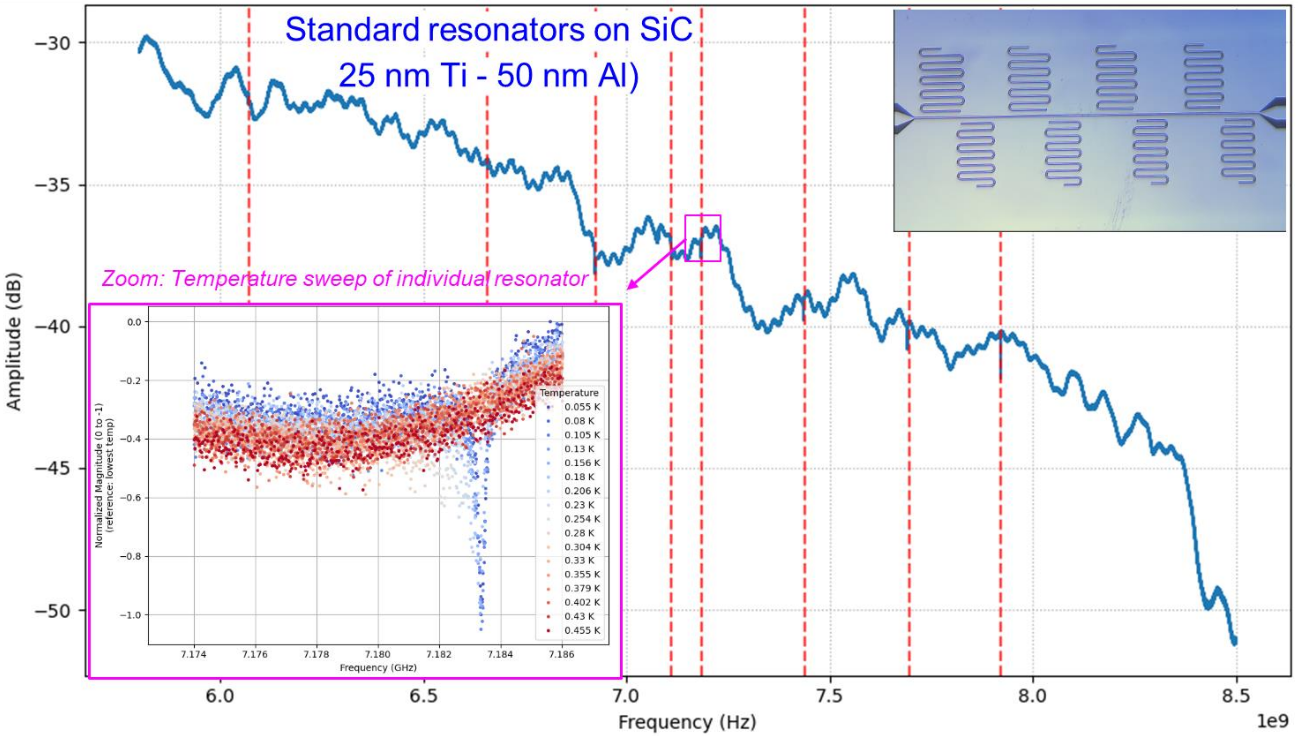


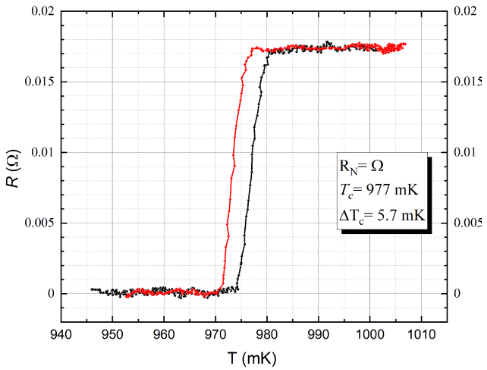
$Q_i^{mean} \approx 5 \cdot 10^5$; $Q_i^{max} = 10^5$; $Q_i^{min} = 2 \cdot 10^4$

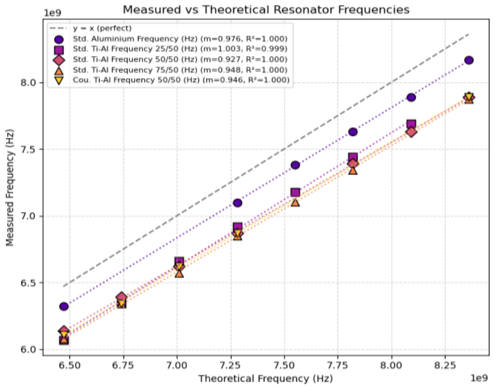
Superconducting & Hybrid Quantum Chips Research Line

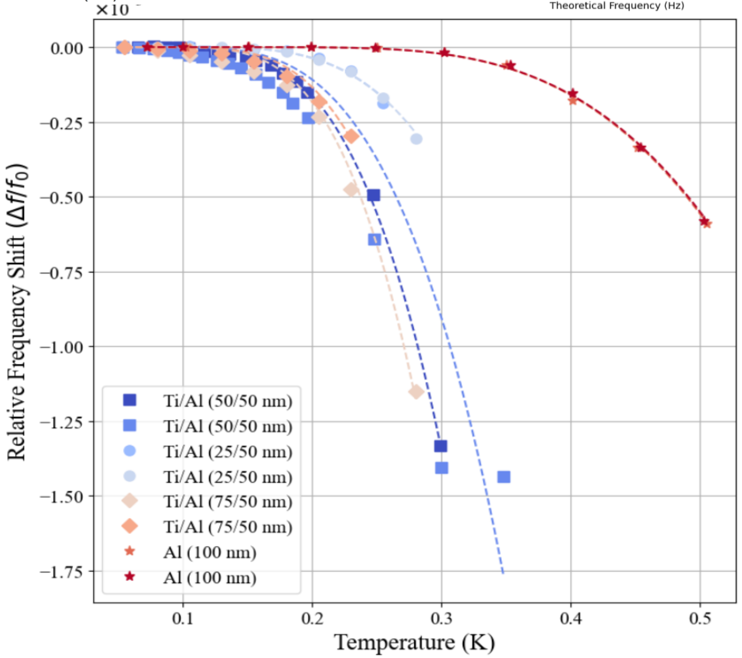
Baseline Superconducting Devices. Design, Fabrication and Testing + **Enginnering or Advanced Superconducting Thin Films**

Microwave Resonator Technology, single metals vs Stacks of Thin films. Ex. substrate/Ti/Al









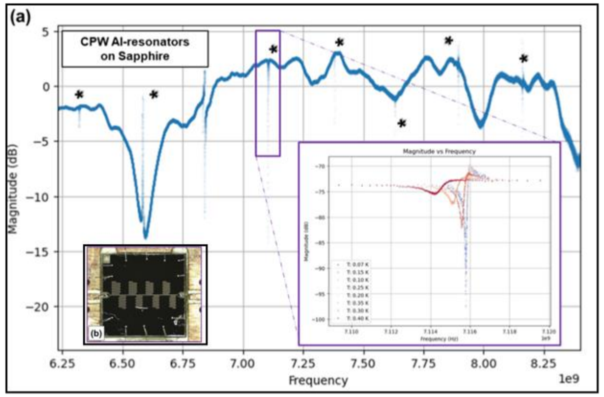
Superconducting & Hybrid Quantum Chips Team - Overview

Quantum environment

IMB-CNM Research

Baseline Superconducting Devices.
Design, Fabrication and Testing

Microwave Resonators. Arrays on Al or Ta



2 Manuscripts in Prep.

Superconductor Thin films & Test Structures

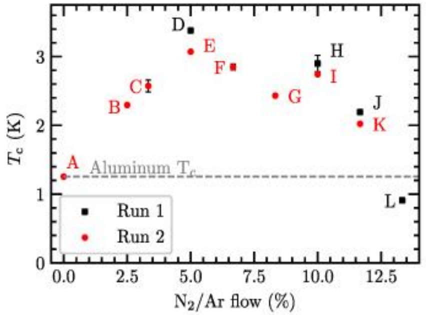
Material	Tc
Aluminum	1.2
Tantalum	4.2-4.4
Niobium	~ 4.5
α-Tungsten	< 100mK

[**2025** *Supercond. Sci. Technol.* **38** 095004]

Alpha-Ta Sc thin films TBS

Customized or Advanced Superconducting Thin films

Nitridized Aluminum

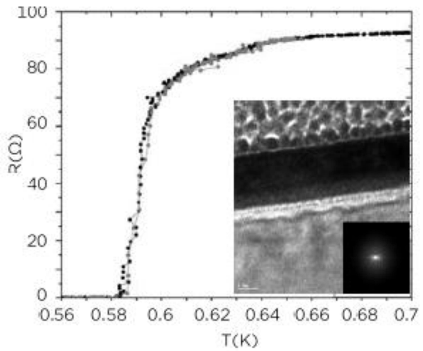


[***2024*** *Supercond. Sci. Technol.* ***37*** 035017]

2026 *J Low Temp Phys* 222, 55 doi.org/10.1007/s10909-026-03390-y

Ion Irradiation for Thin Film Tuning

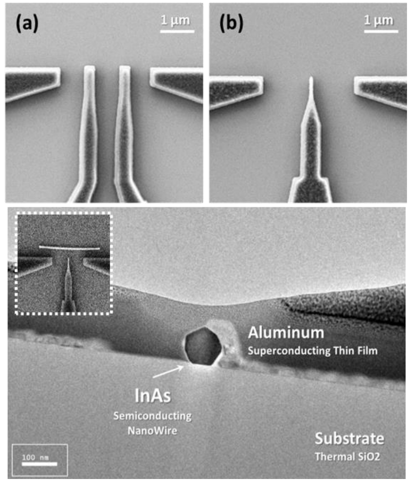
Tuning Tc in ultrathin W



2026 *IEEE Trans. Appl. Superconductivity* 36, 5, 1-5 doi.org/10.1109/TASC.2026.3673788

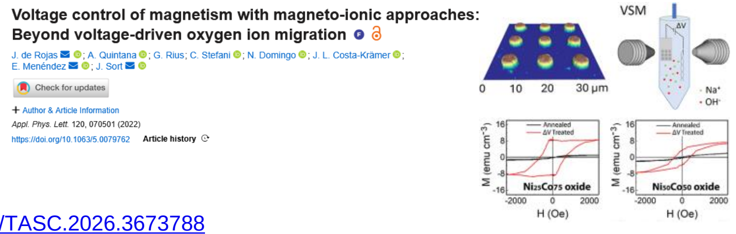
Hybrid and Emerging Systems.
Novel Fabrication Methods

Junctions: SIS, SNS, SScS…



Quantum-grade Sc-S junctions Manuscript in Prep.

Molecular or Quantum Materials Integration



Applications
TES
KICS
SQUIDs
Qubits
SNSPD
KID

Features
Multiplexing
Readout
Control
Operation
Range

Methods
Design
Fabrication
Simulation
Integration
Scalability

Collaborations
Characterization
Testing
Theory and Software
PTOLEMY experiment

Micro – Nano Technologies for the realization of Quantum Materials and Devices

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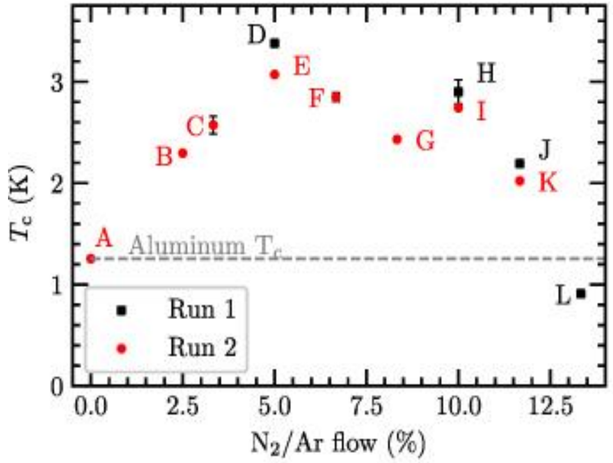
Superconducting & Hybrid Quantum Chips Research Line

Customized or Advanced Superconducting Thin films



Nitridized Aluminum

***2024** Supercond. Sci. Technol. 37* 035017

***2026** J Low Temp Phys* 222, 55
doi.org/10.1007/s10909-026-03390-y

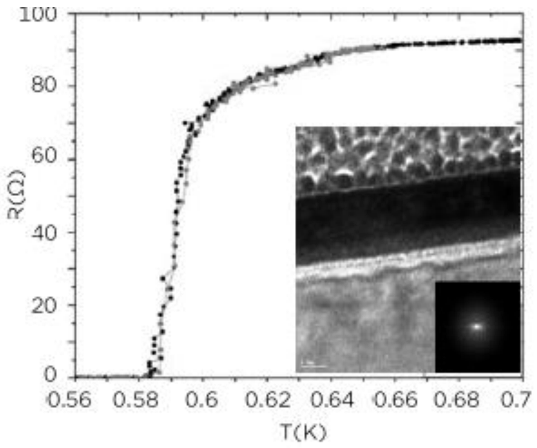
- ✓ Design of tuned or novel superconductivity features
- ✓ Developing methods and deposition conditions
- ✓ Fabrication, morphostructural characterization and functional/operational testing

Tools and Methods:

- ○ Sputtering & Evaporation, Ion irradiation (std implantation or FIB)
- ○ Micro and Nano Patterning of devices
- ○ SRIM/TRIM, Tridyn

Ultrathin Amorphous WSix

***2026** IEEE Trans. Appl. Superconductivity* 36, 5, 1-5 doi.org/10.1109/TASC.2026.3673788



- ❖ Intended for Quantum sensing applications, e.g. direct DM detection
- ❖ Realization of (ultra) thin films and devices or circuits with specifics in Tc, Lk
- ❖ Application-oriented design of materials and devices

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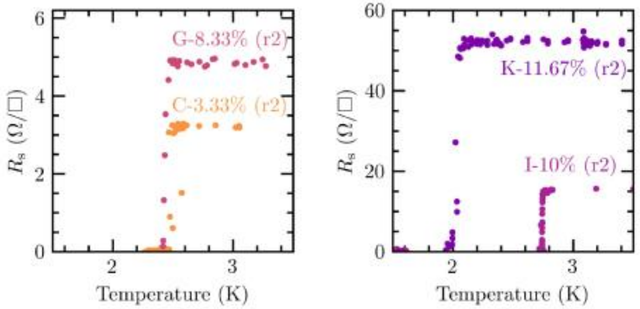
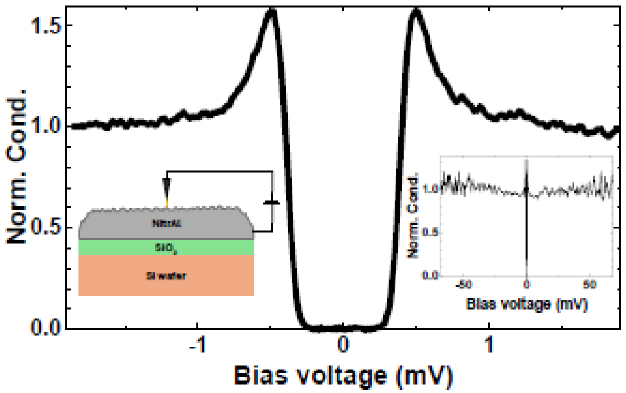
Superconducting & Hybrid Quantum Chips Team - Overview

Customized or Advanced Superconducting Thin films

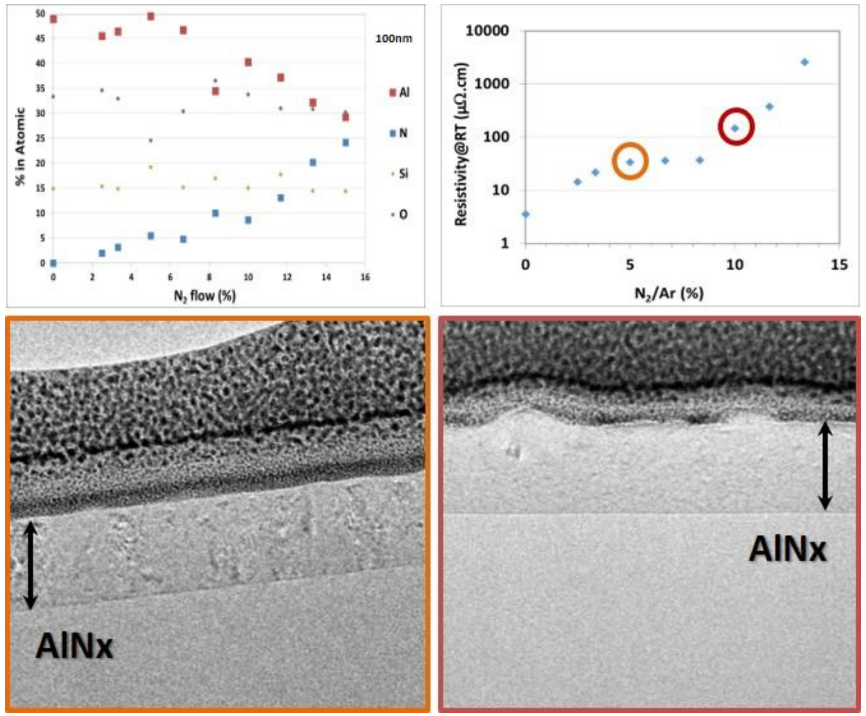


[*2024* *Supercond. Sci. Technol.* ***37*** 035017]

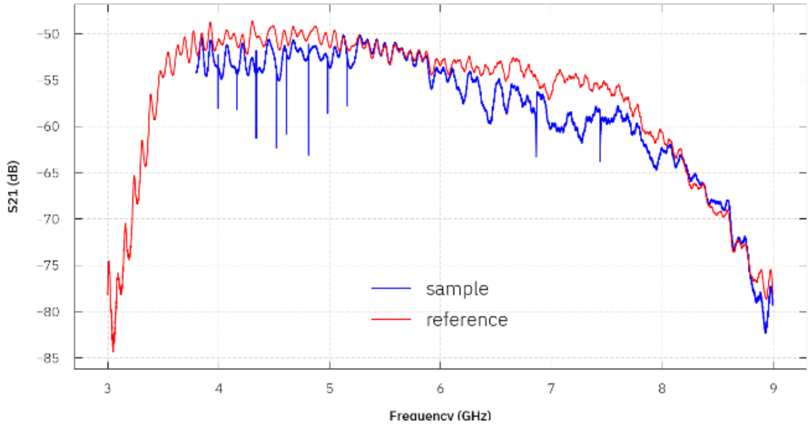


2026 *J Low Temp Phys* 222, 55 doi.org/10.1007/s10909-026-03390-y

Nitridized Aluminum



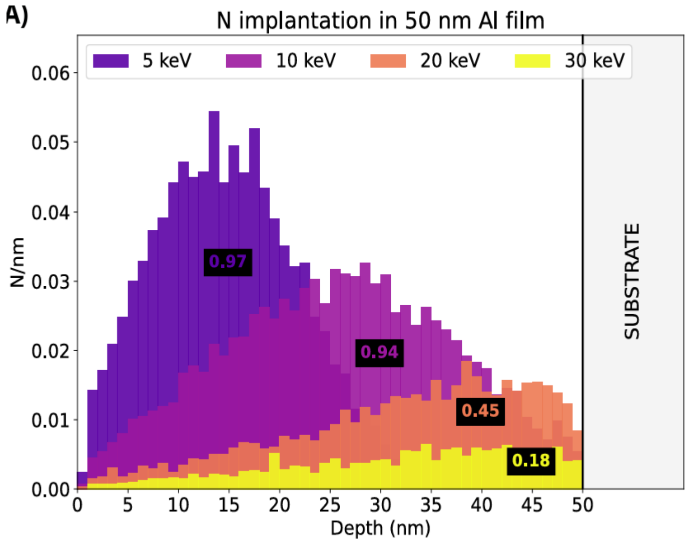
First array of Microwave Resonators made out of nitridized Al



Superconducting & Hybrid Quantum Chips Team - Overview

Customized or Advanced Superconducting Thin films

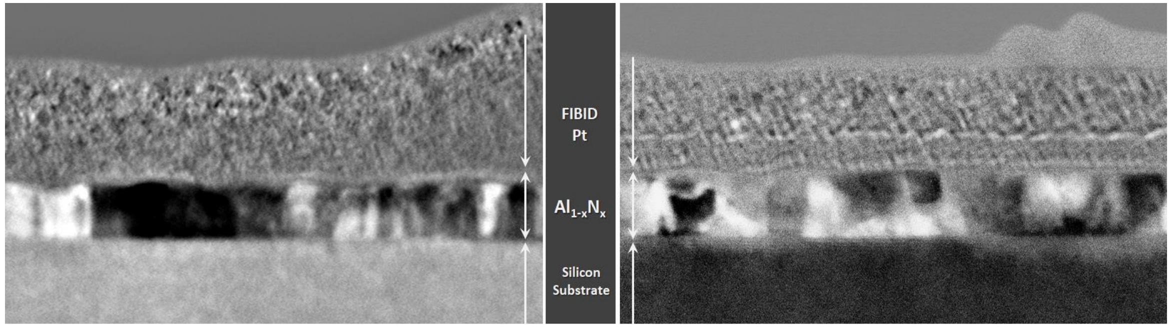
Ion Irradiation for Thin Film Tuning
AlNx



Sample	Dose (ions/cm^2)
ID-1	10^{13}
ID-2	10^{14}
ID-3	10^{15}
ID-4	10^{16}

Tc=1.5 K

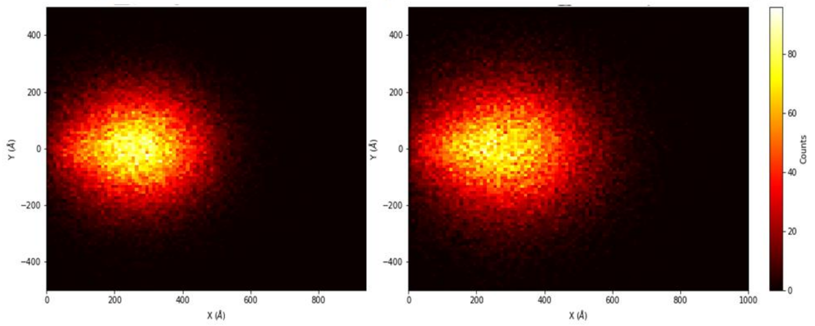
Sample	RRR
ID-0	4.448
ID-2	3.010
ID-4	1.589



Feature	TRIM	TRIDYN
Interaction potential	ZBL universal potential	Kr-C potential
Cutoff energy	$E_F \approx$ 1-3 eV	Lowest surface binding energy
Weak collisions	Not processed simultaneously	Processed simultaneously

MC Simulations of Depth & Straggle

Estimation of composition for ID-4, $Al_{0.97}N_{0.03}$



QUTE Project Ref. CNS2023-145234

Ion Irradiation for Advanced Control of Superconductivity in Thin Films

Standard

Proximity effect:

Tc adjust based on ratio between **Superconductor** + **Normal** metal
TiAu, **MoCu**, **MoAu**, ...

Crystalline Phases:

Tc adjust based on mixture of element phase
α/β/a-W, α/β Ta

Compound:

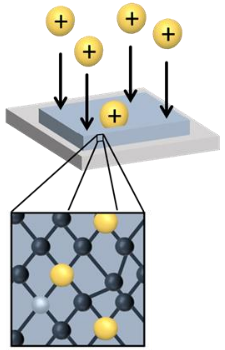
Tc adjust based on element concentrations.
NbN, TiN, TaN, NbTiN, ...

QUTE approach:

Deposition
+
Post processing:

Ion Irradiation:

Post deposition tuning by modifying the material via ion irradiation



2023 *Appl. Phys. Rev.* 10, 041311
https://doi.org/10.1063/5.0162597

Superconducting thin film & processing By G Rius Team	Material(s)	Evap	Sputt	CMOS
Pure Element / Target	Nb	x		
	Ta		x	
	Al	x	x	x
	$Al_{95}Cu_5$	x		
	Ti	x		
	W		x	
Proximitized layers or Stacks	EG-SiC-Al	x	x	
	EG-SiC-Ti/Au	x		
	Al-Ti	x		
	Al-Ti-Au	x		
	Nb-Au	x		
	Ti-Au	x		
	W-Au	x	x	
Compounds & Alloys	AlN_x	x	x	x
	$AlAu_x$	x	x	
	AlAl	x	x	x
	$AlHe_x$	x	x	
	$AlGa_x$	x	x	
	$AlSi_x$	x	x	x
	WSi_x		x	
	WGe_x		x	
	NbN_x	x		
	$NbSi_x$	x		
	TaN_x		x	
	$TaSi_x$		x	
	TiNx		x	

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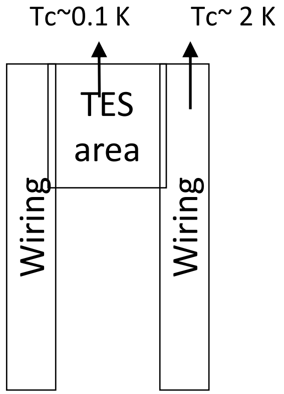
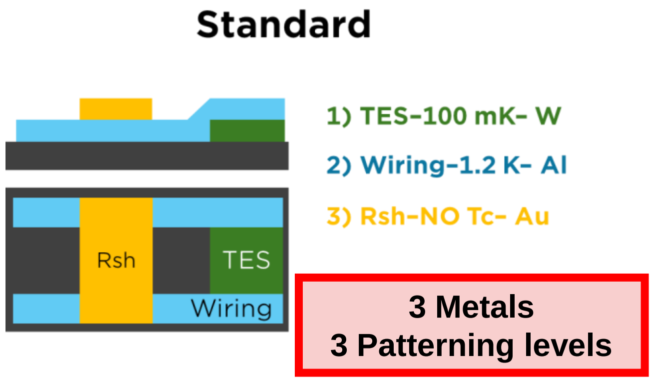
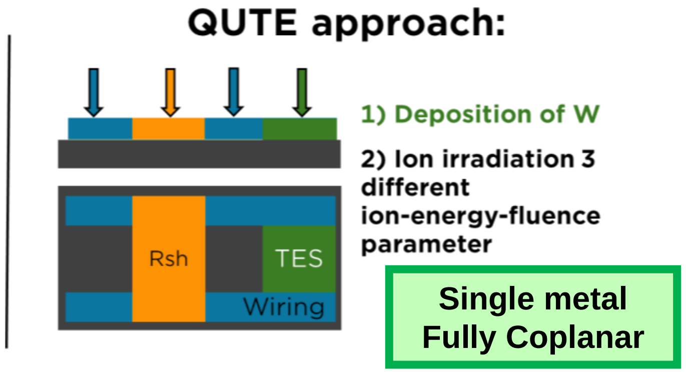
Application of Ion-based SC Thin Films - Transition Edge Sensor







INRiM Carlo Pepe's software tes.inrim.it/

TES Area	Tc
α-Tungsten	200mK
Titanium	400 mK
Titanium + gold	Thickness-ratio tunable

- **Selection of superconducting material(s)**
- **Functional and operational requirements**

Wiring	Tc (K)
Aluminum	1.2
Tantalum	4.2-4.4
Niobium	~ 4.5
Tungsten implanted	> 1.5

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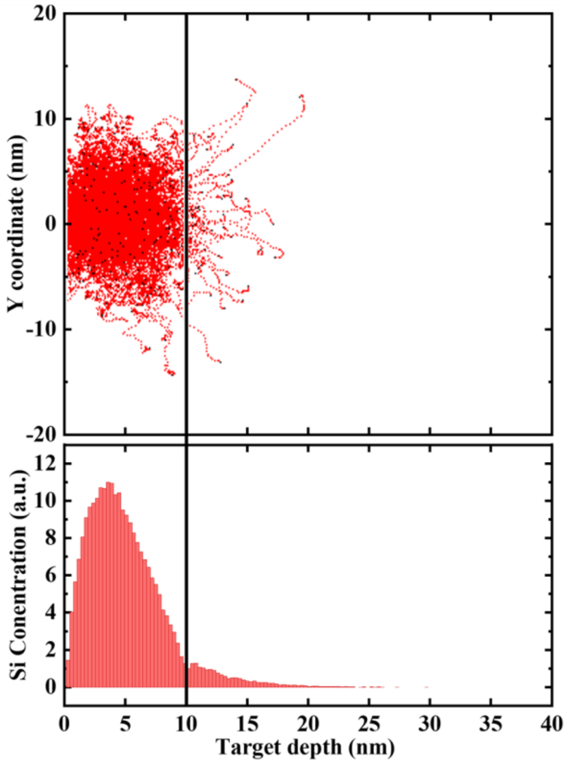
Quantum environment

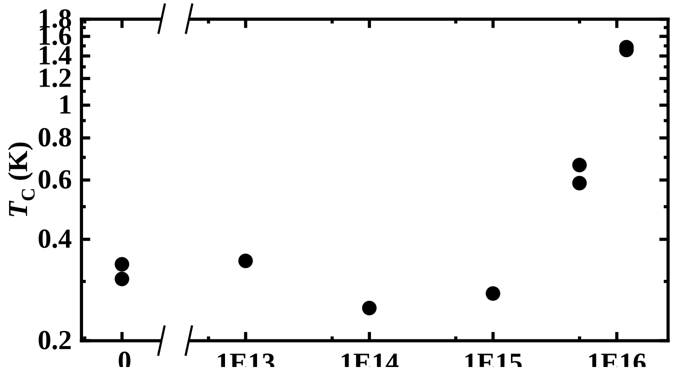
IMB-CNM Research

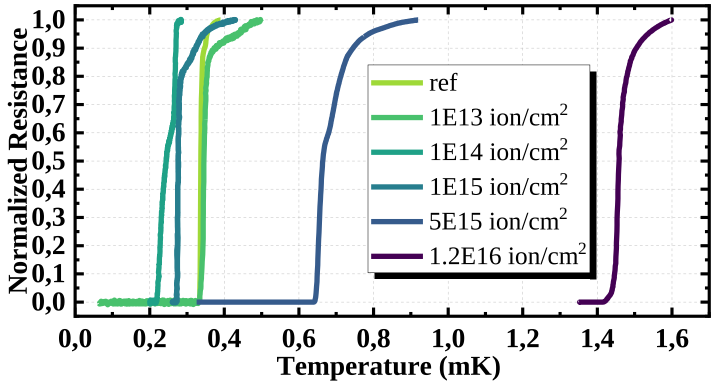
Application of Ion-based SC Thin Films - TES

Ion Irradiation for Advanced Control of Superconductivity in Thin Films

Ultra thin W Tc Tuning via Ion irradiation with Si ions







2026 *IEEE Trans. Appl. Superconductivity* 36, 5, 1-5
doi.org/10.1109/TASC.2026.3673788

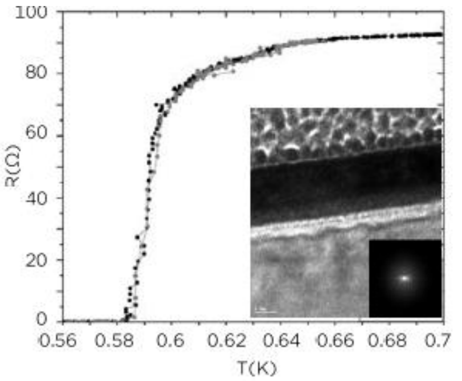


TABLE II

DESIGN PARAMETERS AND SIMULATED PERFORMANCE FOR THE PROPOSED TES. THE T_C VALUES REFER TO THE ACTIVE AREA AND THE WIRING, TUNED VIA SELECTIVE ION IRRADIATION.

Parameter	Value	Units
Capacitance C	0.42	fJ/K
Conductance G	87	pW/K
Active area T_C	220	mK
Wiring T_C	585	mK
Temperature sensitivity α	200	
Current sensitivity β	1	
Energy resolution ΔE	0.17	eV
Recovery time τ_{ETF}	233	ns

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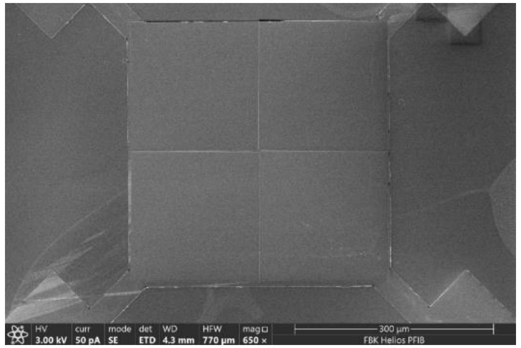
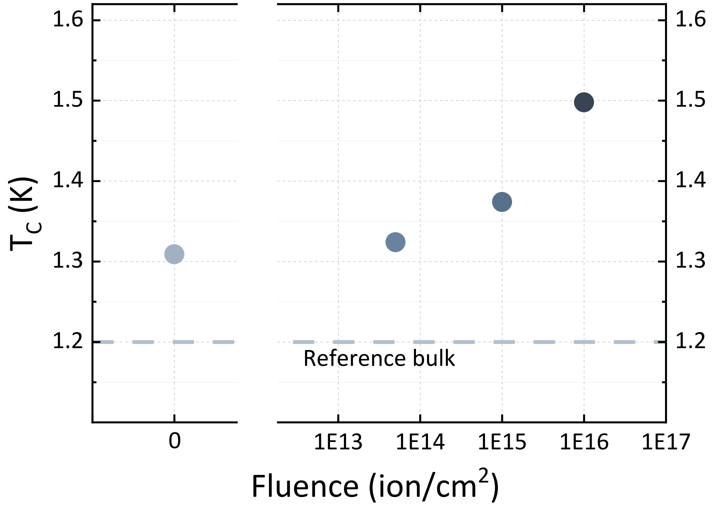
Ongoing Developments and Achievements on Customized superconducting Thin films & Operational Devices

Local/area selective Ion Irradiation (FIB)

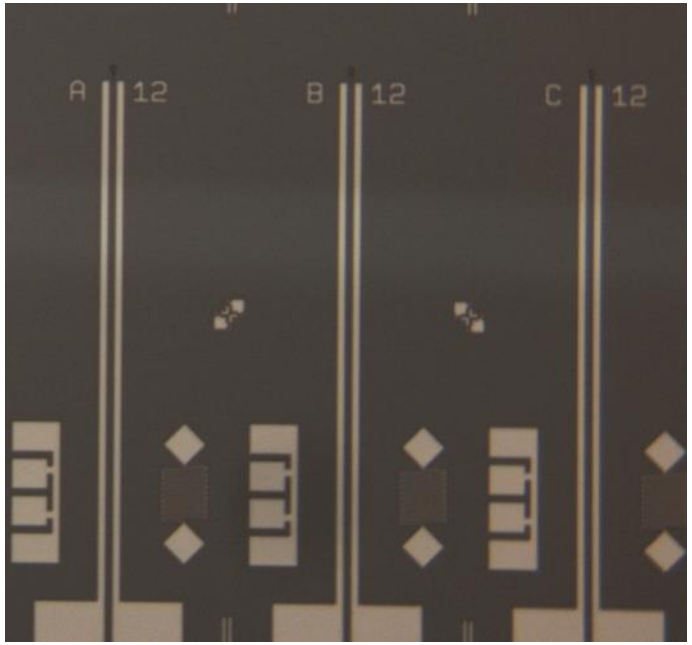
Au++ on Al thin films

Test structures:
VdPauw
Strips

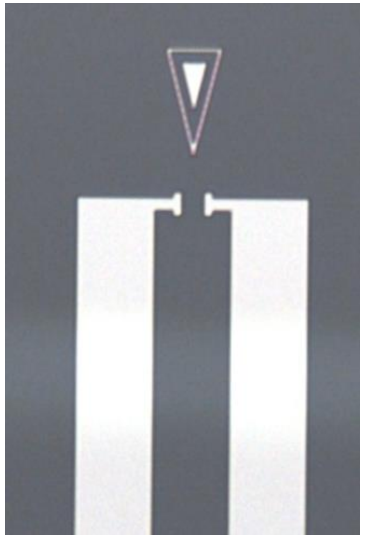




Design and Fab Preliminary Trials. DC and TES Test structures



New test structures
mask tested



- **Quantum-grade interfaces and junctions**
- **Design for experimental validation and callibration**

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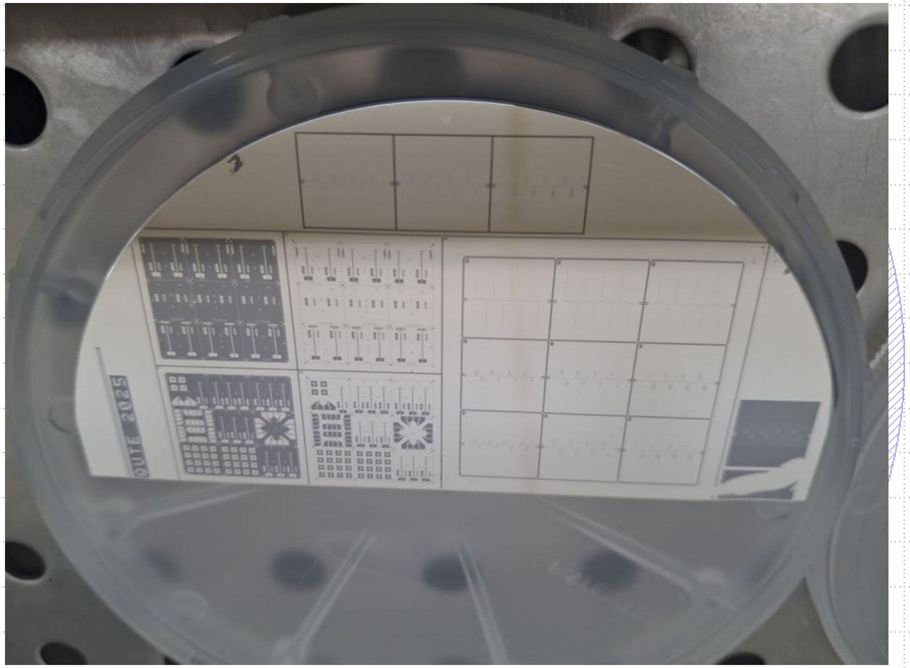
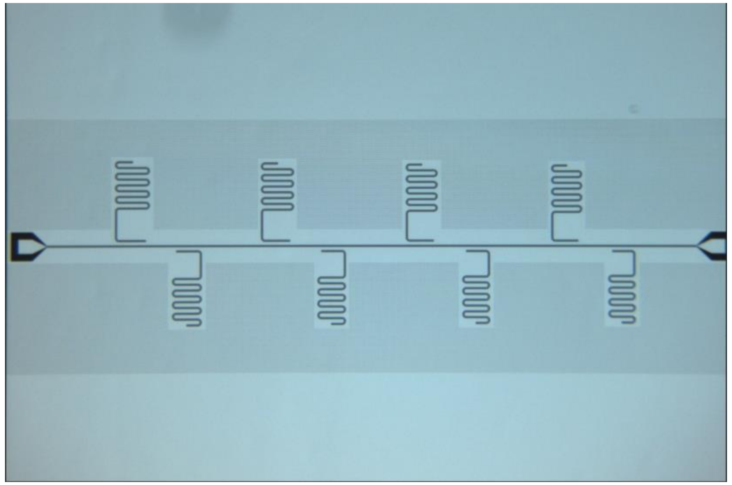
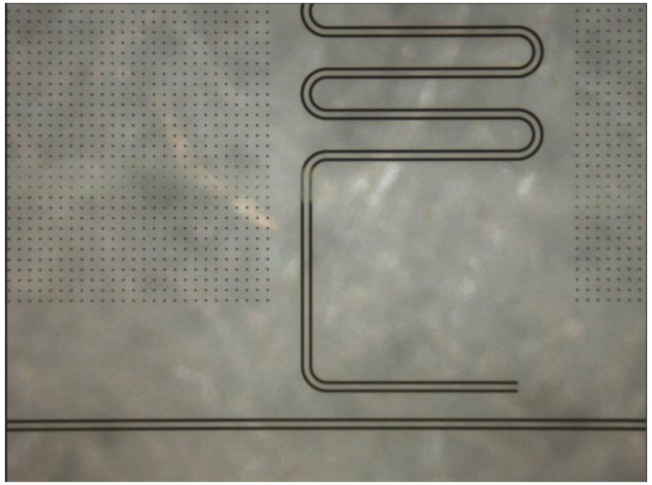
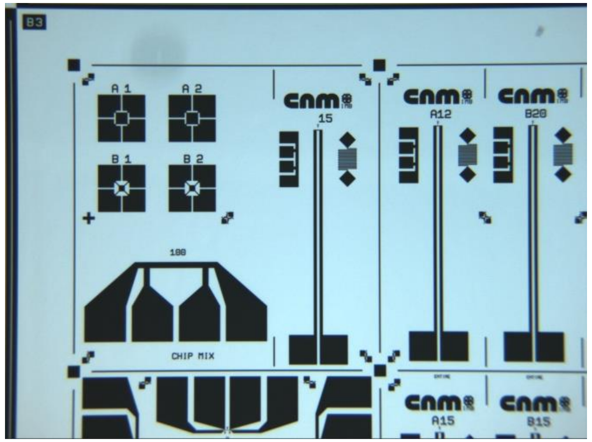
Materials and Devices Design and Technology Developments

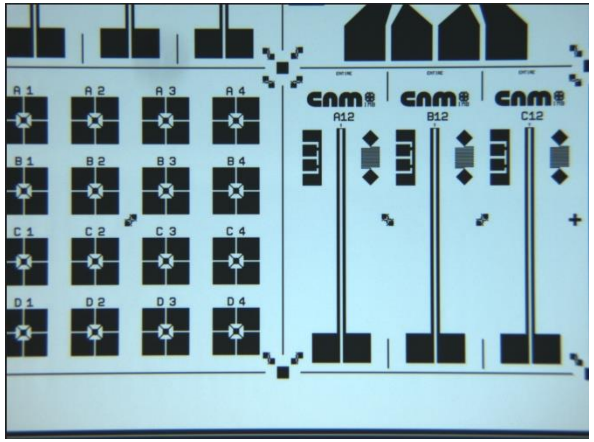
- GDS Mask v.2 MINARE-QUTE











- Multiple possibilities on micro/nanofab processing, thin films, device architectures

Possible Contributions to PTOLEMY working packages

***PTOLEMY detection principle*:**
Cosmic Neutrino Background captured on a beta-unstable target.
Emission of mono-energetic e-

The PTOLEMY Collaboration | Media | LNGS-Wiki (private)

- **Physics Studies**
- **Graphene Studies**
- **High Voltage and Calibration methods**
- **Multiplexed readout and Cryogenics**
- **TES Calorimeter**
- **EM Filter design**

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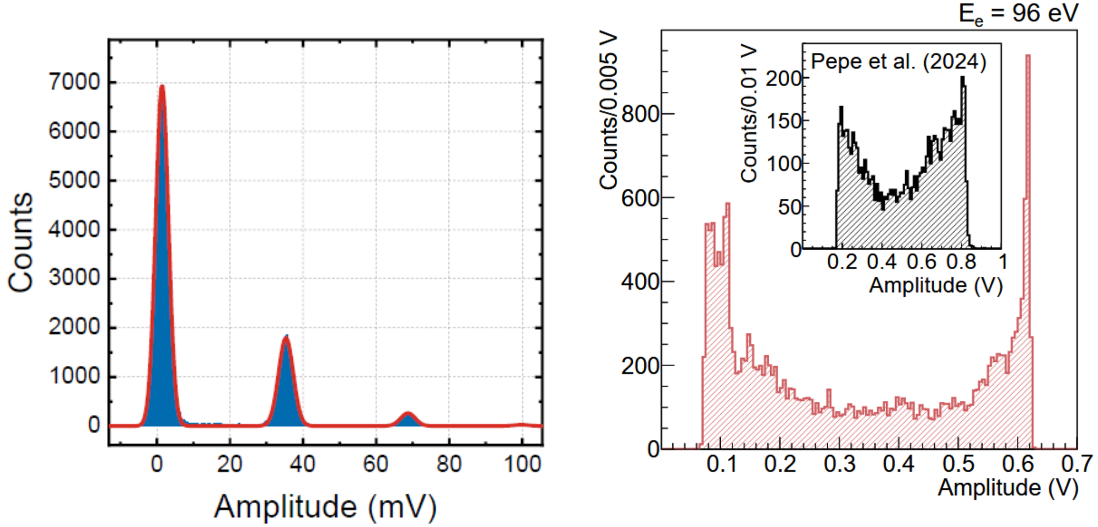
Proposed Contribution of IMB to PTOLEMY

If PTOLEMY were to ultimately adopt a TES array, where do we currently stand?

1. TES energy resolution → ✓ Achieved for photon
2. Single-electron detection → ✓ Demonstrated
3. Combining 1 and 2 → Ongoing
4. Large TES optical arrays → Critical bottleneck



SQUID Multiplexing Limits

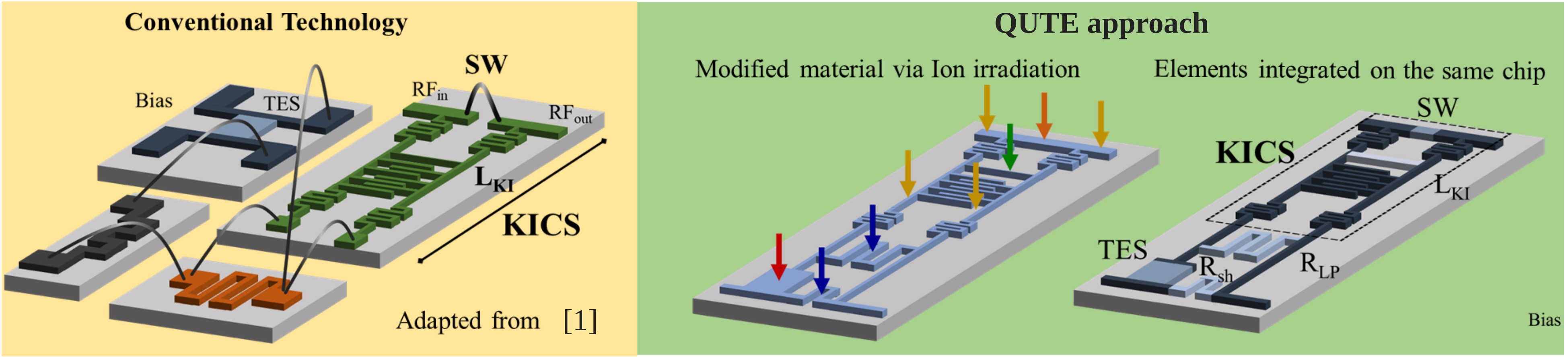
- Bandwidth: 10-100 kHz/channel
- Scalable to tens of pixels only

Possible Solution: KINETIC INDUCTANCE CURRENT SENSORs

Demonstrated by:

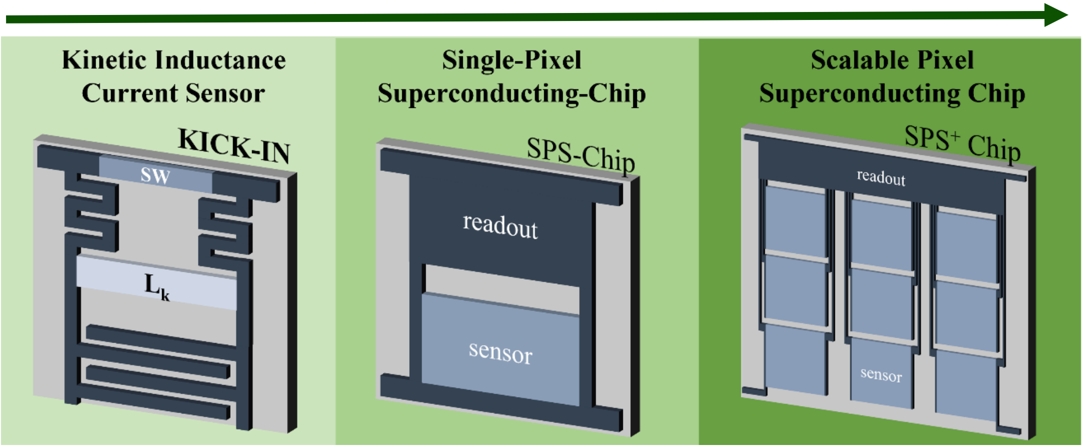
Szypryt, Paul, et al. "Kinetic inductance current sensor for visible to near-infrared wavelength transition-edge sensor readout." *Communications Engineering* 3.1 (2024): 160.

Conceptual Proposition



[1] Szypryt, Paul, et al. "Kinetic inductance current sensor for visible to near-infrared wavelength transition-edge sensor readout." *Communications Engineering* 3.1 (2024): 160

Platform evolution

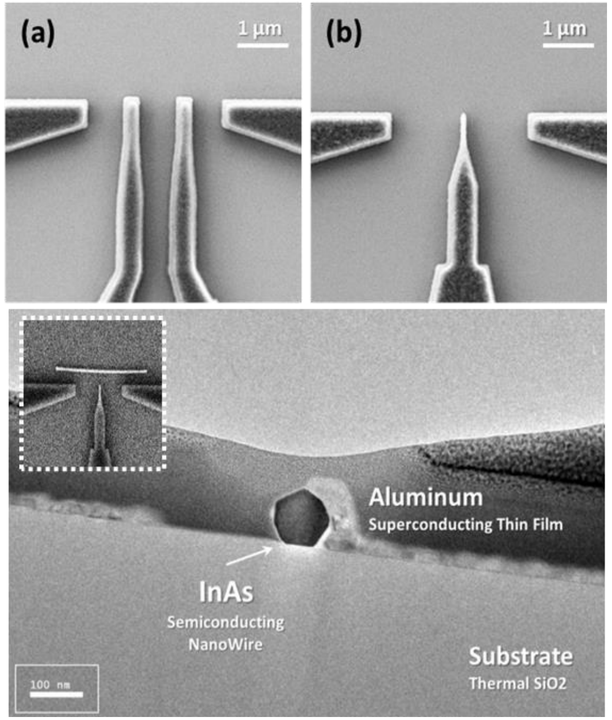


Hybrid Devices and Unconventional Systems

Semiconductor-Superconductor
Magnetic-Superconductor

HyFab and IKUR Projects

HyBound and I-QUMA Proposals



Manuscript in Prep.

- ✓ Innovative developments of fabrication technology/sequences
- ✓ Realization of quantum grade interfaces and hybrid integration
- ✓ Fabrication, morphostructural characterization and functional testing

Methodologies:

- Shadow Wall patterning, e.g. single step EBL
- Epitaxial NWs, selective materials growth, local patterning, mix and match
- Coordinated processing and characterization in multiple sites

- ❖ Assessment and demonstrators of compatible fabrication sequences and device operation
- ❖ Realization of (ultra) thin films and devices or circuits with specifics in Tc, Lk
- ❖ Oriented to quantum physics studies and novel quantum computing/sensing applications

➢ **Unconventional Approaches and Research on Quantum Technologies**

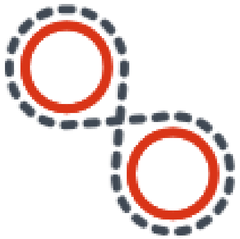
NeuroQ: Quantum Inspired Brain emulation
Biomimetics **2025**, *10*(8), 516;
https://doi.org/10.3390/biomimetics10080516

Quantum Principles push/pull Quantum Techmologies

<u>**Framework**</u>**:** to deliver **useful devices and processes** that are based on **quantum principles**

SUPERPOSITION & WAVE-PARTICLE DUALITY

Quantum particles, like electrons and photons, exhibit both particle and wave-like behaviour. They also exist in multiple states simultaneously, a property called superposition. Superposition lets particles explore many possibilities at once, and their wave-like nature causes these possibilities to add up or cancel out – called quantum interference – which shapes measurement outcomes (Nielsen & Chuang, 2010).

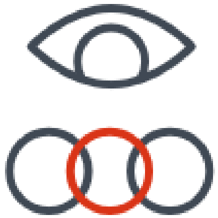


QUANTUM ENTANGLEMENT

Two quantum particles can become intricately linked, forming a single shared quantum state in which measuring one instantly reveals information about the other, regardless of distance. The states of entangled particles are correlated in ways that have no counterpart in classical physics and can be used to influence other systems in ways that would be impossible classically (Gisin, Ribordy, Tittel, & Zbinden, 2002).

Quantum Principles push/pull Quantum Techmologies

Framework: to deliver **useful devices and processes** that are based on **quantum principles**



THE UNCERTAINTY PRINCIPLE[4]

It is impossible to simultaneously know complementary properties of a particle, like its exact position and momentum, with perfect accuracy (Griffiths & Schroeter, 2018).

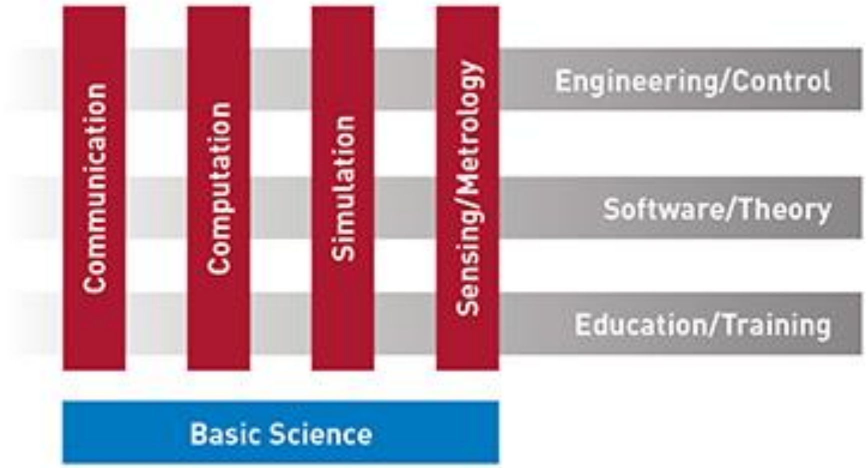
QUANTUM TUNNELLING

A particle can pass through an energy barrier that it classically should not have enough energy to overcome. This allows nuclear fusion by enabling atomic centres to jump their electrostatic barrier, even when their energy is not enough to classically do so (Sze & Ng, 2006).

QUANTISATION

At the quantum level, properties like energy, charge and spin (magnetic orientation) can only exist in discrete, specific amounts, rather than as continuous values. Electrons can only occupy specific orbits, and they can “jump” between these levels by absorbing or emitting exact amounts of energy (i.e. photons) (Ludlow, Boyd, Ye, Peik, & Schmidt, 2015).

Overview of most important Hardware Platforms for Quantum Technologies

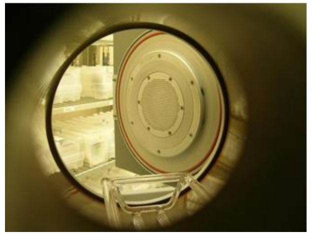


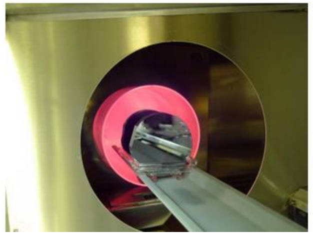
Platform	Vacuum (UHV)	Cryo (millikelvin)	What is being manipulated	How it works	Communication	Computing	Computing-Simulation	Sensing
Optical traps	✓		Neutral-atom internal states	Focused laser light forms tiny traps confining single neutral atoms in vacuum.	1	2	3	2
Magnetic traps	✓		Neutral-atom internal states	Precisely shaped magnetic fields create low-energy regions that hold selected atoms in place.	0	1	2	3
Electromagnetic traps	✓		Trapped-ion internal states	Oscillating electric fields generate a stable potential well that suspends individual ions.	2	3	2	2
Superconducting circuits		✓	Superconducting current (loop state)	Cryogenic superconducting loops create controllable microwave circuits that act as quantum bits.	1	3	2	2
Quantum dots		✓	Single-electron spin (magnetic orientation)	Nanoscale semiconductor islands isolate one electron whose energy or spin can be individually controlled.	2	2	1	1
Diamond NV centres			Defect electron spin	A nitrogen-vacancy defect in diamond hosts a spin that can be set and read optically, even at room temperature.	2	1	1	3
Diamond SiV centres		✓	Defect electron spin	Silicon-vacancy defects in diamond emit ultra-pure photons for linking distant quantum nodes.	3	1	0	1
Silicon carbide defects			Defect electron spin	Crystal defects in silicon carbide provide long-lived spins on wafers compatible with standard chip processes.	2	1	0	3
Topological materials		✓	Majorana quasiparticle states	Engineered materials encode information in protected quantum states resistant to many local errors.	0	1	1	0
Optical cavities			Single photons	Highly reflective mirrors trap light between them, boosting its interaction with atoms or solid-state emitters.	3	2	1	2
Optical waveguides/ networks			Single photons	On-chip glass or silicon channels route single photons with minimal loss to build scalable light-based circuits.	3	2	1	1
Molecular magnets/ complexes			Molecular-electron spin	Tailored molecules lock an electron's magnetic orientation, forming customisable quantum units at moderate temperatures.	0	1	2	2

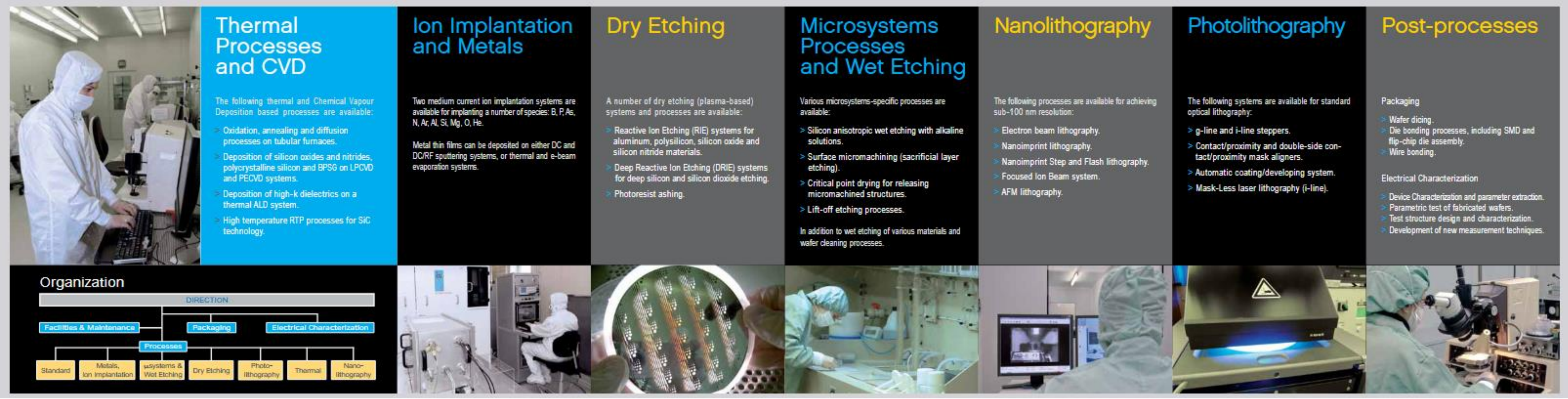
Integrated Clean Room for Micro/Nanotechnologies

KEY FIGURES

1500	190	2000	5-7
m2 surface	process equipments	wafers/year	ISO class (100-10,000)







Thermal Processes and CVD

The following thermal and Chemical Vapour Deposition based processes are available:

- Oxidation, annealing and diffusion processes on tubular furnaces.
- Deposition of silicon oxides and nitrides, polycrystalline silicon and BPSG on LPCVD and PECVD systems.
- Deposition of high-k dielectrics on a thermal ALD system.
- High temperature RTP processes for SiC technology.

Ion Implantation and Metals

Two medium current ion implantation systems are available for implanting a number of species: B, P, As, N, Ar, Al, Si, Mg, O, He.

Metal thin films can be deposited on either DC and DC/RF sputtering systems, or thermal and e-beam evaporation systems.

Dry Etching

A number of dry etching (plasma-based) systems and processes are available:

- Reactive Ion Etching (RIE) systems for aluminum, polysilicon, silicon oxide and silicon nitride materials.
- Deep Reactive Ion Etching (DRIE) systems for deep silicon and silicon dioxide etching.
- Photoresist ashing.

Microsystems Processes and Wet Etching

Various microsystems-specific processes are available:

- Silicon anisotropic wet etching with alkaline solutions.
- Surface micromachining (sacrificial layer etching).
- Critical point drying for releasing micromachined structures.
- Lift-off etching processes.

In addition to wet etching of various materials and wafer cleaning processes.

Nanolithography

The following processes are available for achieving sub-100 nm resolution:

- Electron beam lithography.
- Nanoimprint lithography.
- Nanoimprint Step and Flash lithography.
- Focused Ion Beam system.
- AFM lithography.

Photolithography

The following systems are available for standard optical lithography:

- g-line and i-line steppers.
- Contact/proximity and double-side contact/proximity mask aligners.
- Automatic coating/developing system.
- Mask-Less laser lithography (i-line).

Post-processes

Packaging

- Wafer dicing.
- Die bonding processes, including SMD and flip-chip die assembly.
- Wire bonding.

Electrical Characterization

- Device Characterization and parameter extraction.
- Parametric test of fabricated wafers.
- Test structure design and characterization.
- Development of new measurement techniques.

Organization

DIRECTION

Facilities & Maintenance | Packaging | Electrical Characterization

Processes

Standard | Metals, Ion Implantation | µsystems & Wet Etching | Dry Etching | Photo-lithography | Thermal | Nano-lithography anys fent grans les coses petites

CNM

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EXCELENCIA MARÍA DE MAEZTU

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