Introduction to Nanotechnology in the Solid State

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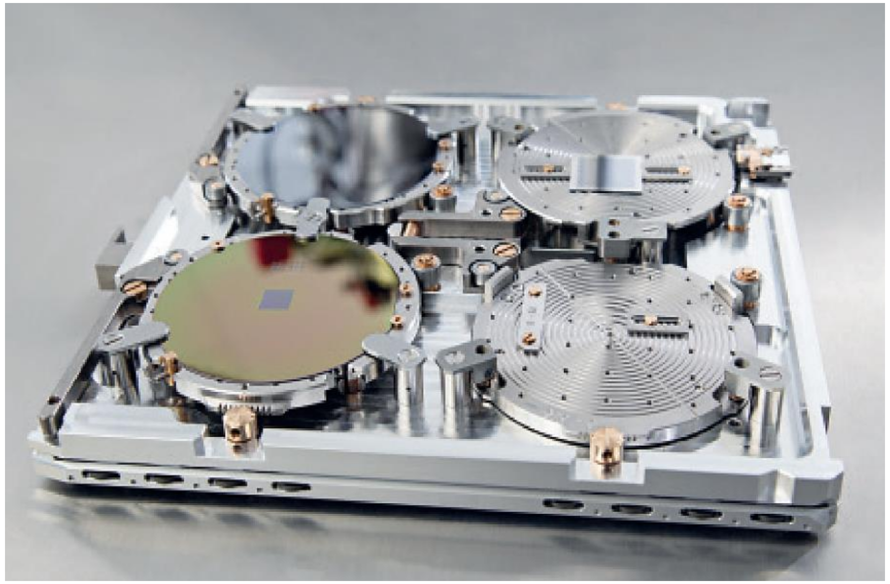

Raith Nanofabrication, *Multi-Sample Holder* (2022)

Quick Notes

- This presentation/ lecture series will involve extensive use of **metaphors** & **analogies** to illustrate key ideas 💯 .
- QuantumGrad is part of a recent effort **dedicated** to providing **quantum resources & relative content** that can be accessed on a single website.
  - Recent news
  - Journal publications
  - Jobs/ workforce
  - Articles
  - Books
  - Conferences
  - Hackathons
  - Tutorials/ public lecture series

Quantum Grad

Generated with artificial intelligence from Microsoft Bing AI

Biography

- Originally from Oak Springs (Tsé Ch'il Yaa Tó), Arizona, on the Navaho Nation
  - Largest Native American tribe in the United States 💯 [Diné Bikéyah]
- Came to Minnesota in **2017** on a nanotechnology research fellowship
  - Before I started my B.S. program
- Doctoral researcher & quantum hardware team leader in
- Department of Electrical and Computer Engineering
  Nano Magnetism and Quantum Spintronics Lab
- Electrical Engineering Ph.D. program
- My primary area of work is **nanofabrication** & **quantum hardware development**
- **IBM Quantum Provider Administrator** & **Quantum Developer**
- Member of Quantum Grad & IEEE Quantum

GREAT SEAL OF THE NAVAJO NATION

materials research science + engineering center
MRSEC
UNIVERSITY OF MINNESOTA

IBM
Associate Certified
Developer
Quantum Computation using Qiskit v0.2X

Roof Butte, Arizona 86556

Elevation above sea level:
≈ 3,000 m or < 10,000 ft

Home

Roof Butte

4.8 ★★★★★ 5 reviews

Mountain peak

Directions | Saved | Nearby | Send to phone | Share

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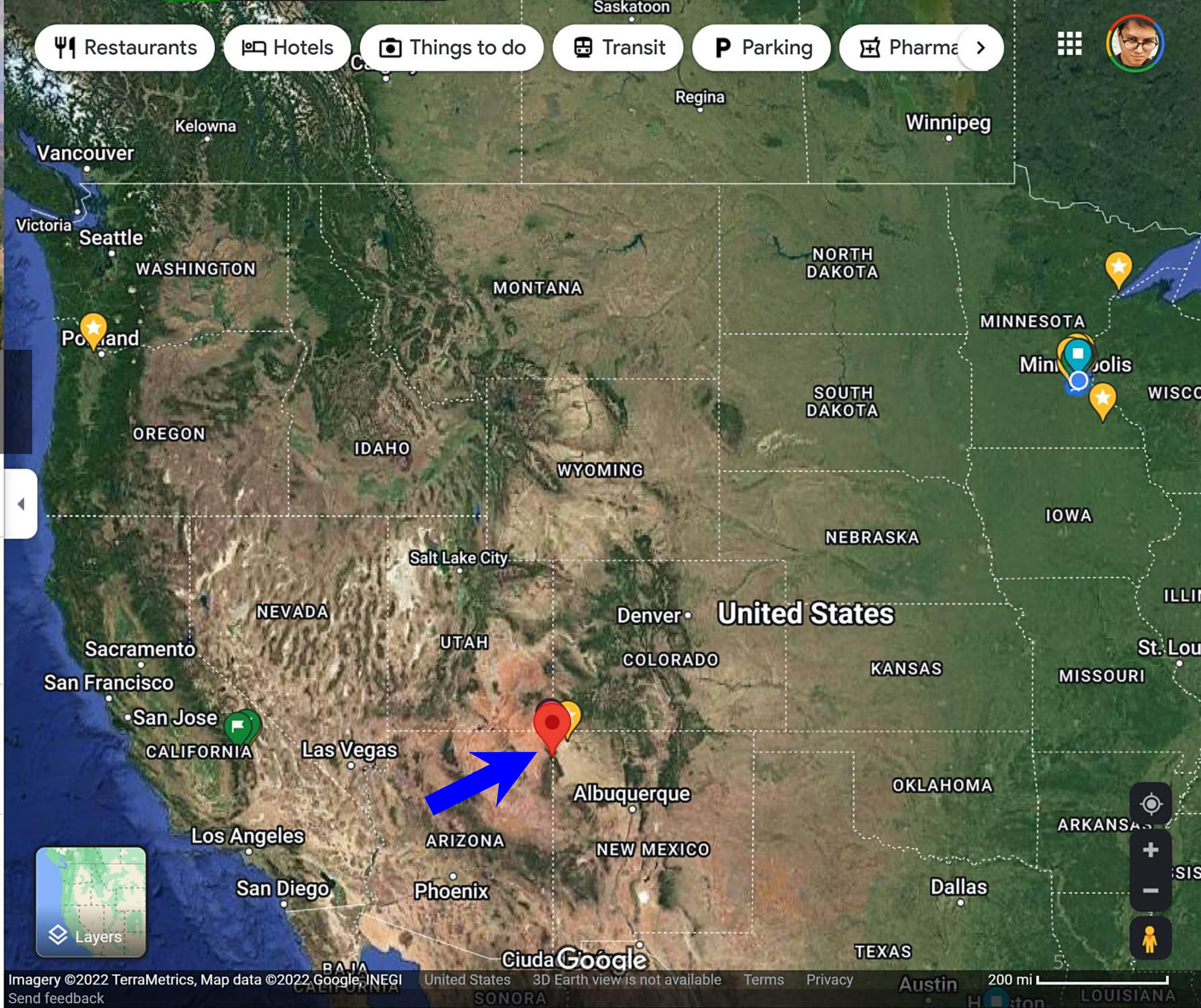
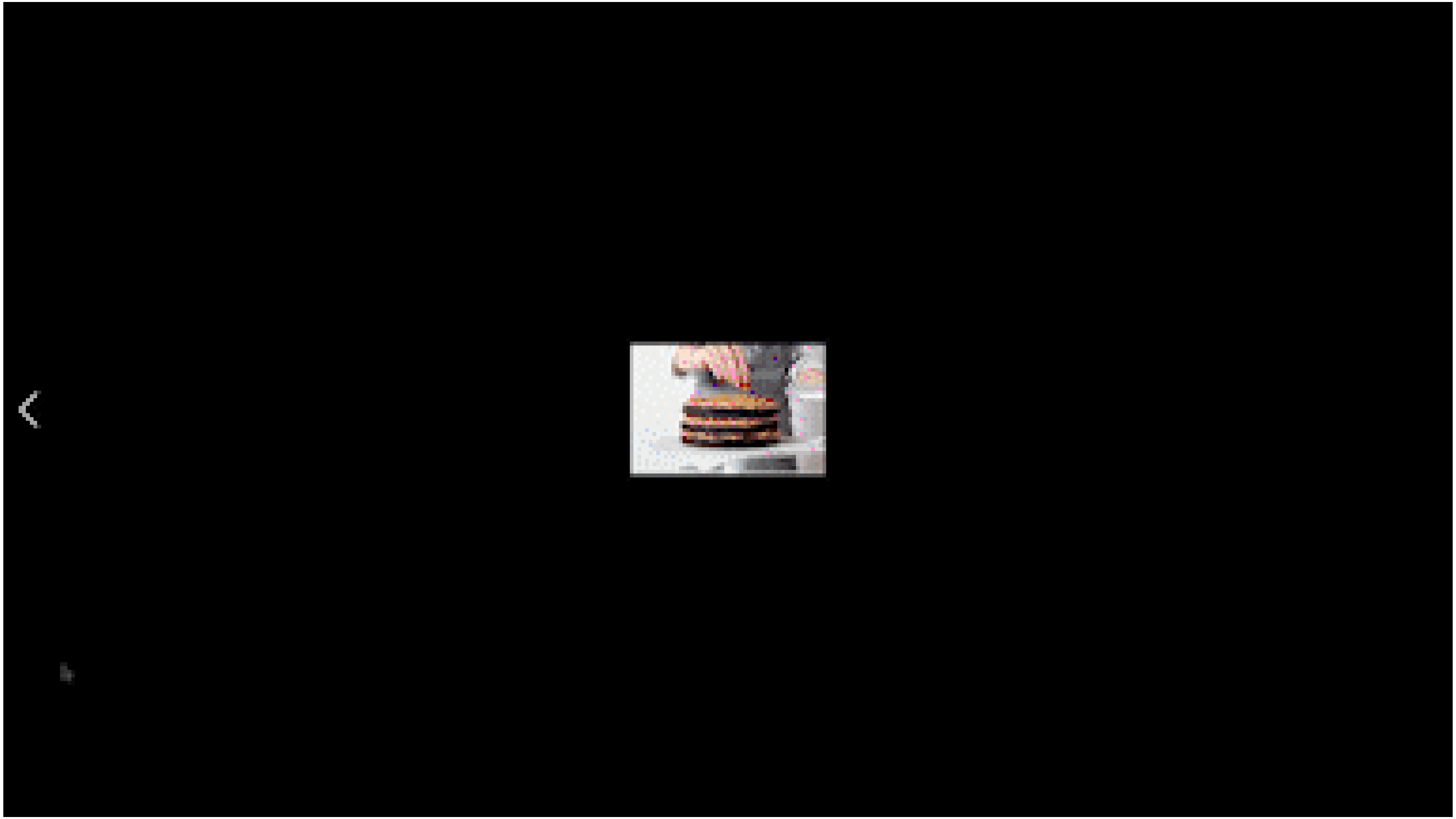
Arizona 86556

FW63+HG Lukachukai, Arizona

Send to your phone



Collection of My Work



Quick Summary of Familiar Devices

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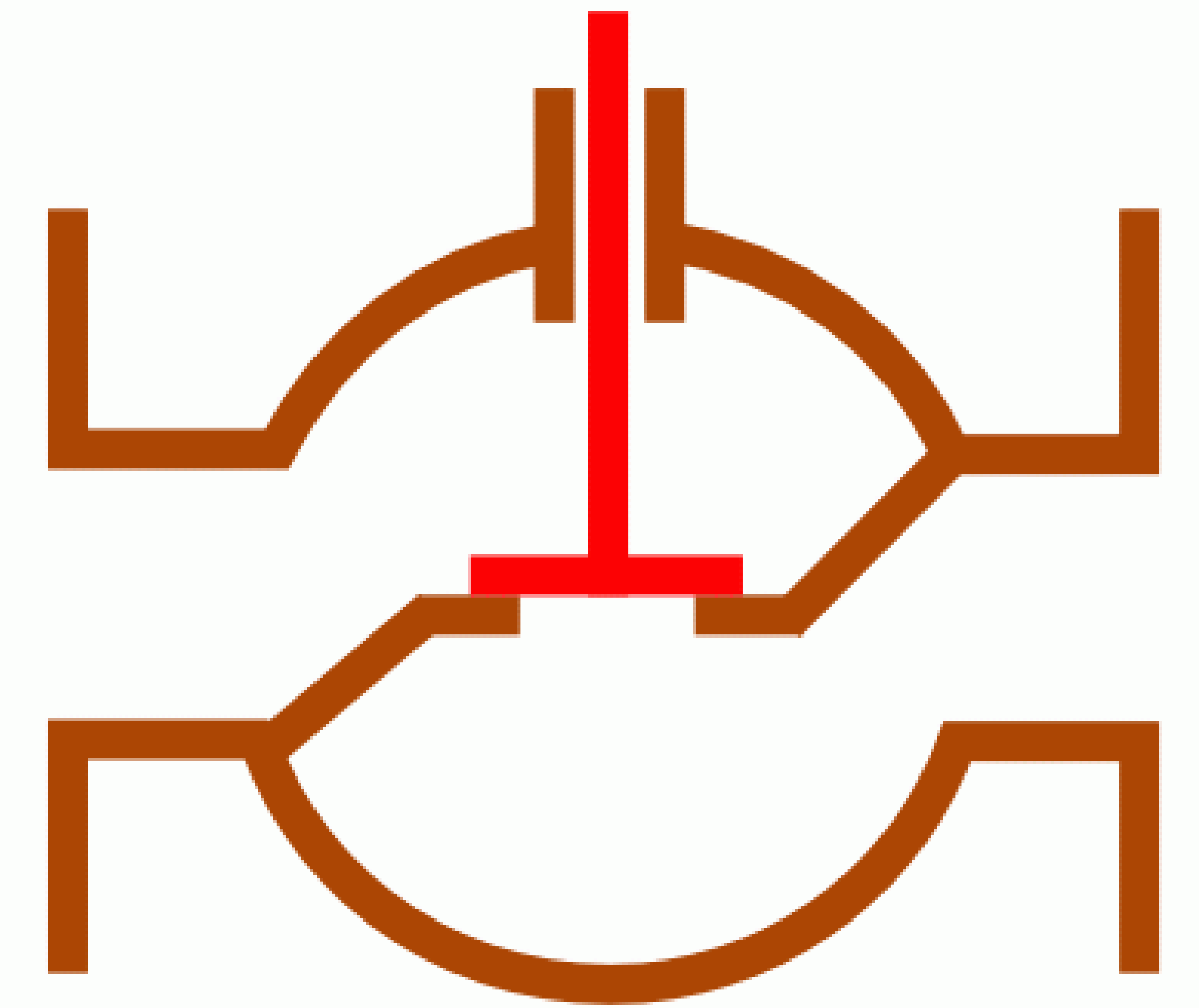
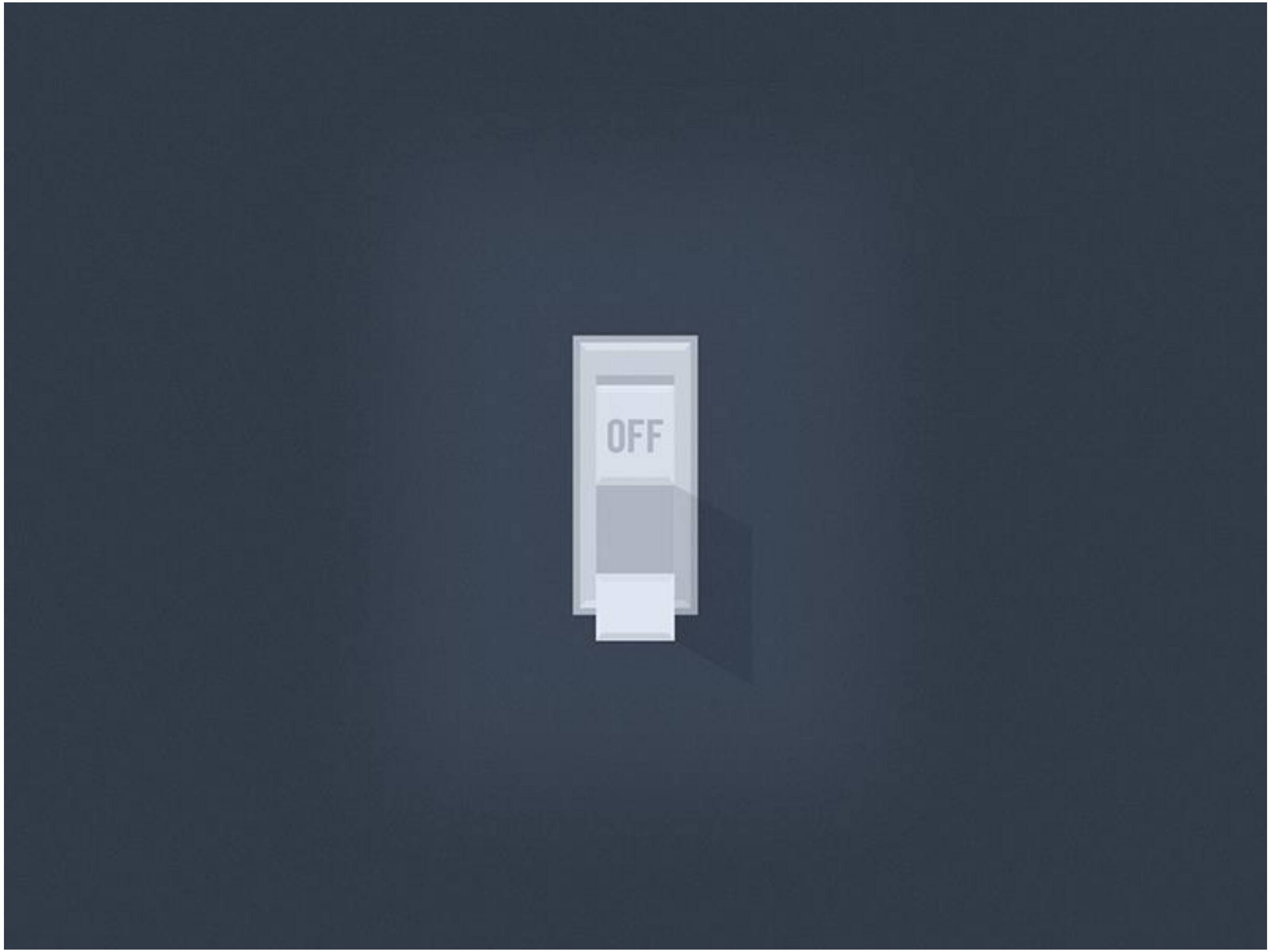
1. Taken from: Wikimedia Commons

Quick Summary of Familiar Devices



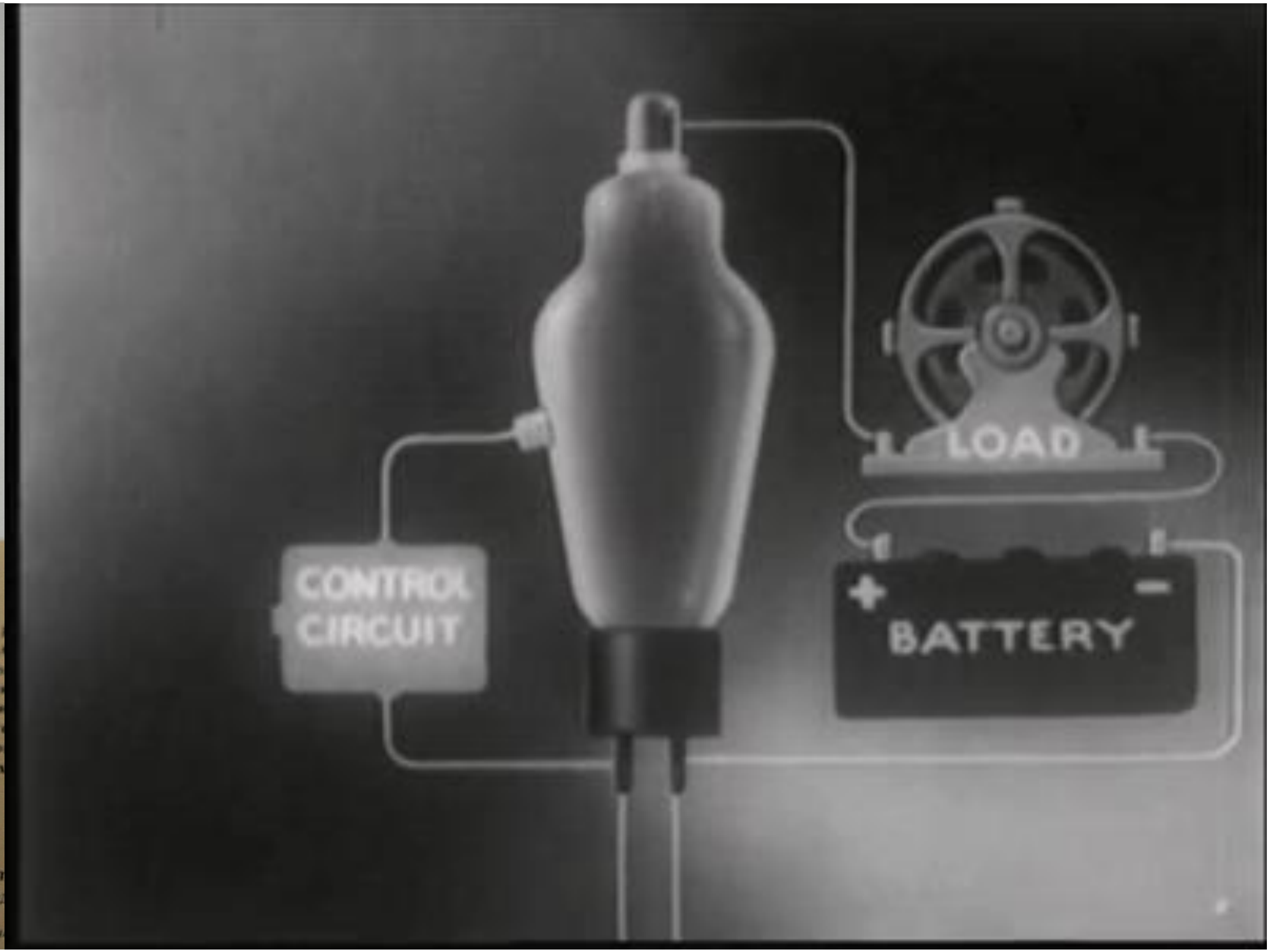
1. Taken from: Wikimedia Commons

Quick Summary of Familiar Devices



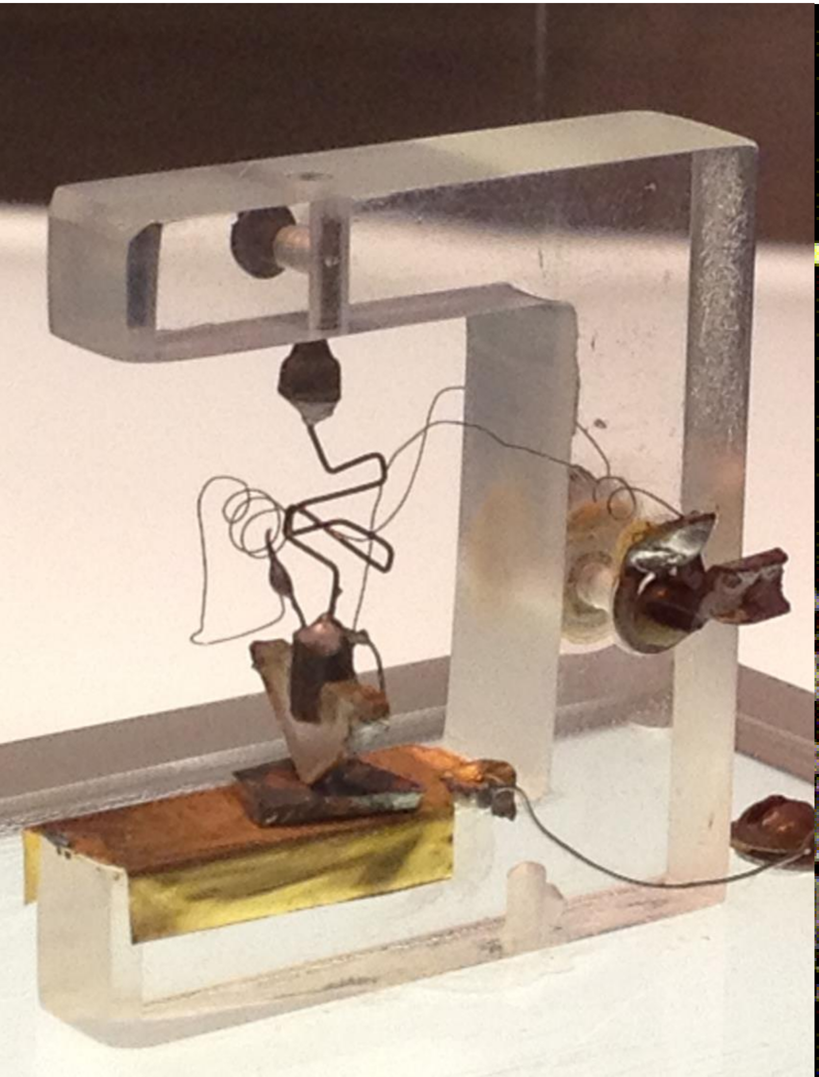
1. Taken from: dribbble.com

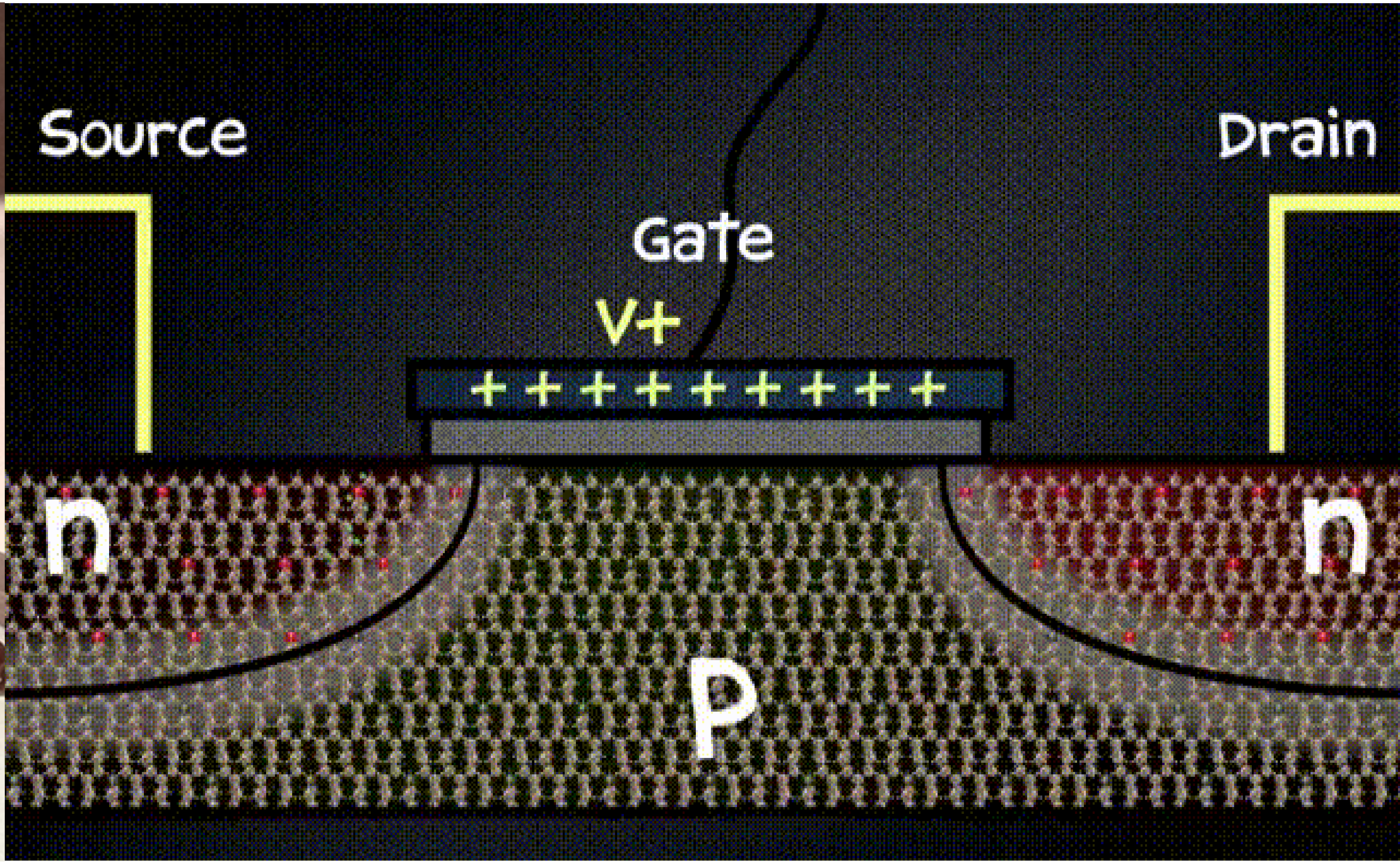
Quick Summary of Familiar Devices



1. Taken from: Wikimedia Commons
2. Taken from: thomann.de

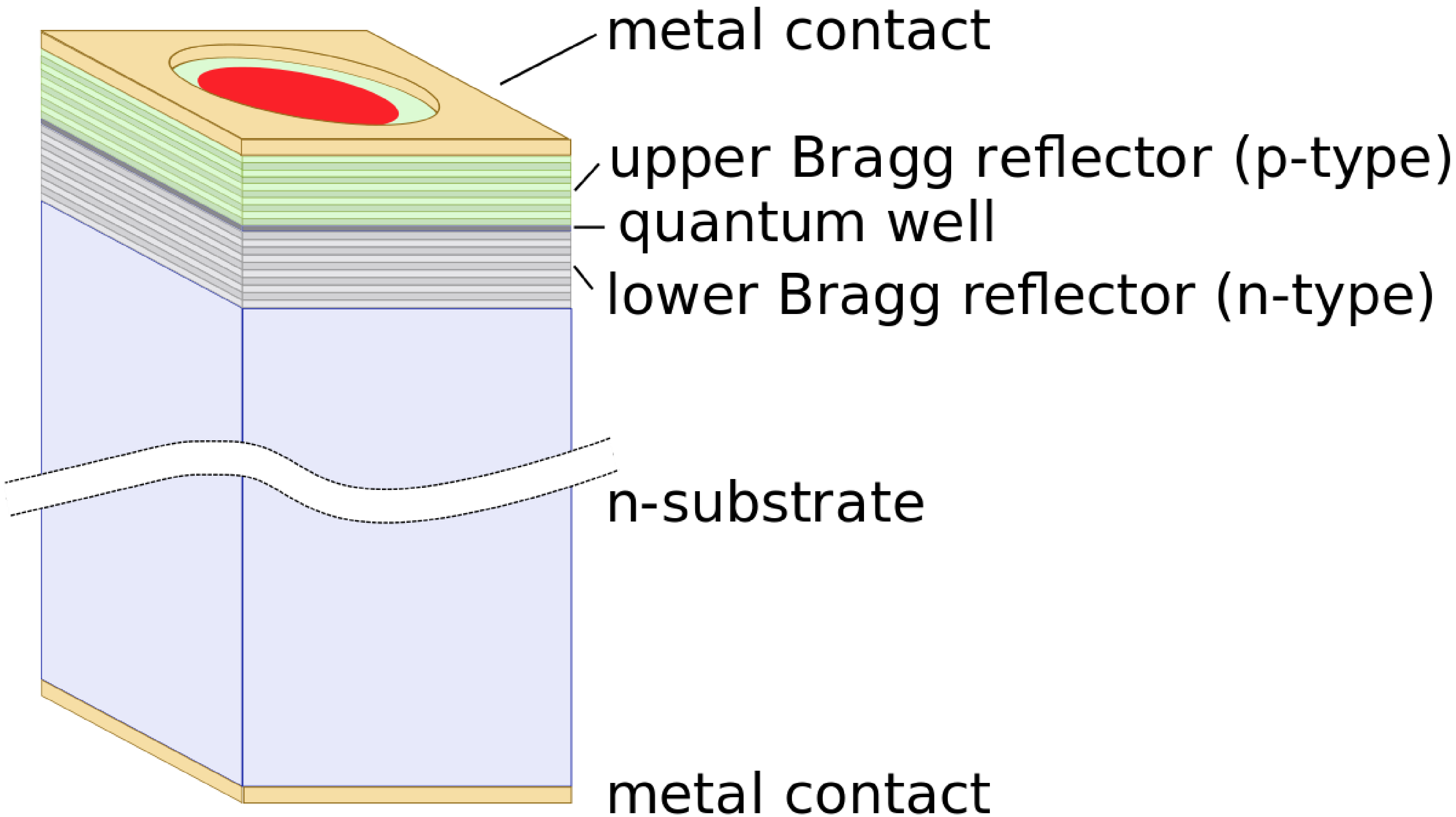
Quick Summary of Familiar Devices

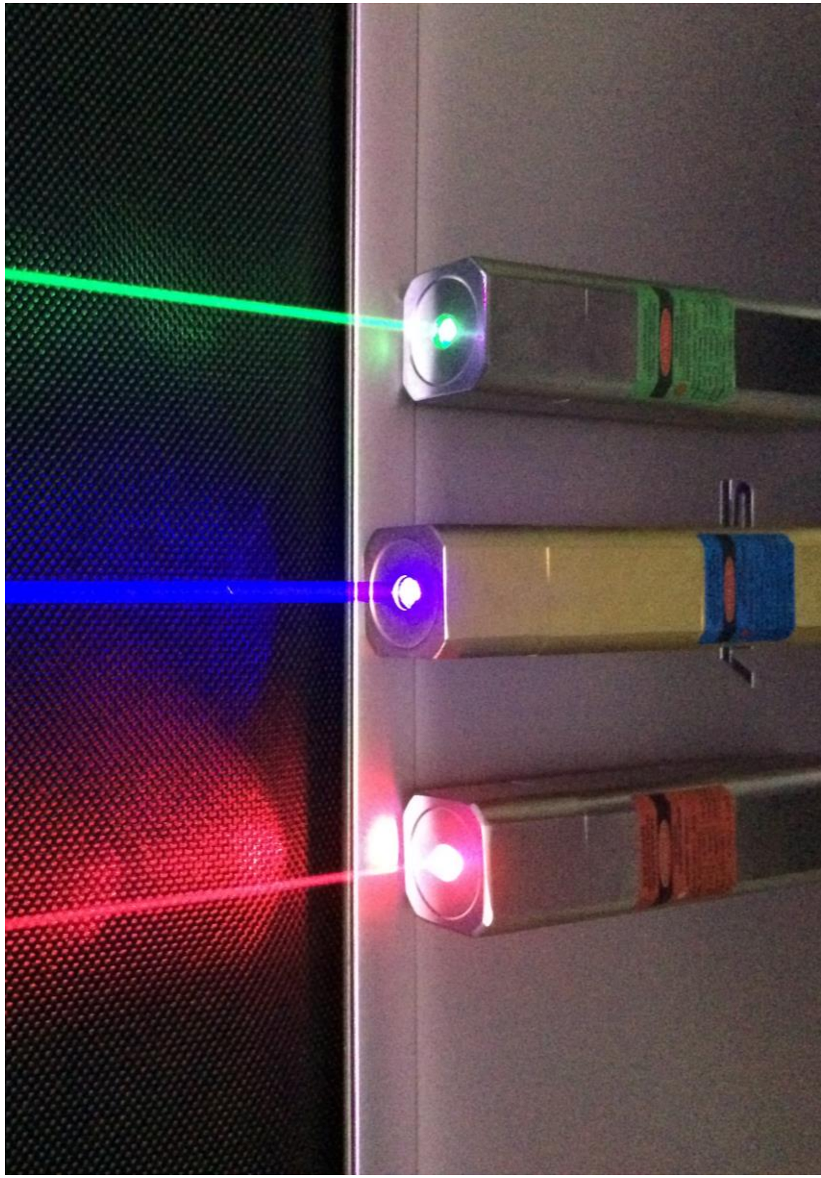




1. Taken from: Wikimedia Commons
2. Muller., *Veritasium: How Does a Transistor Work?* (2013)

Quick Summary of Familiar Devices





1. Taken from: Wikimedia Commons

Quick Summary of Familiar Devices

- From: fire starters to basic plugs/valves >> electrical switches >> vacuum tubes (thermionic valves) >> transistors >> LASERs >> integrated computer chips/touch displays made of **melted sand**/**metal**.

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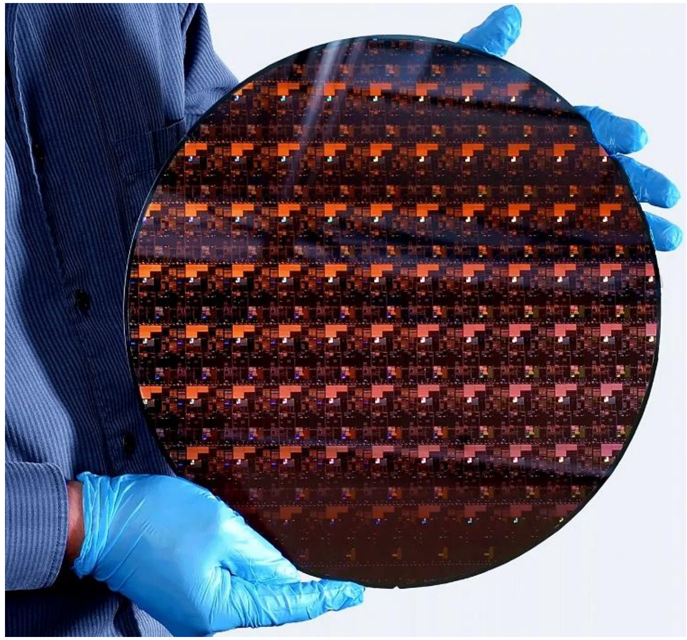
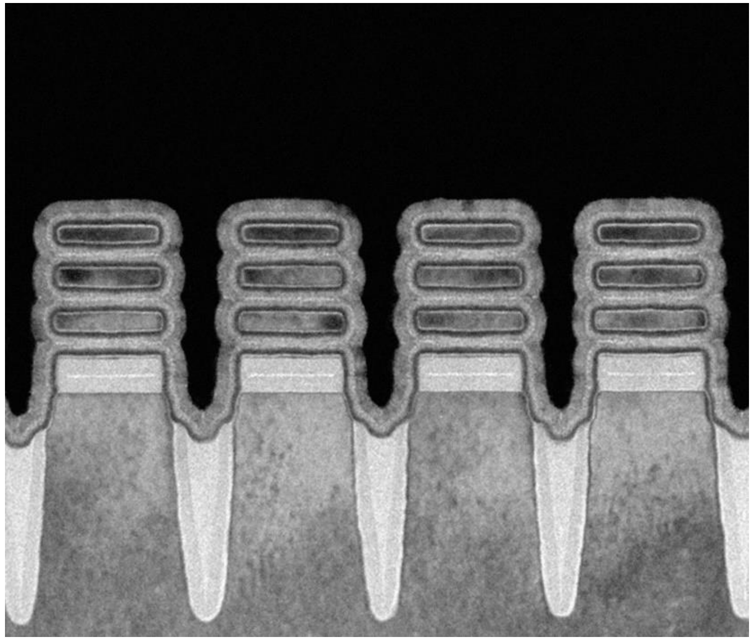
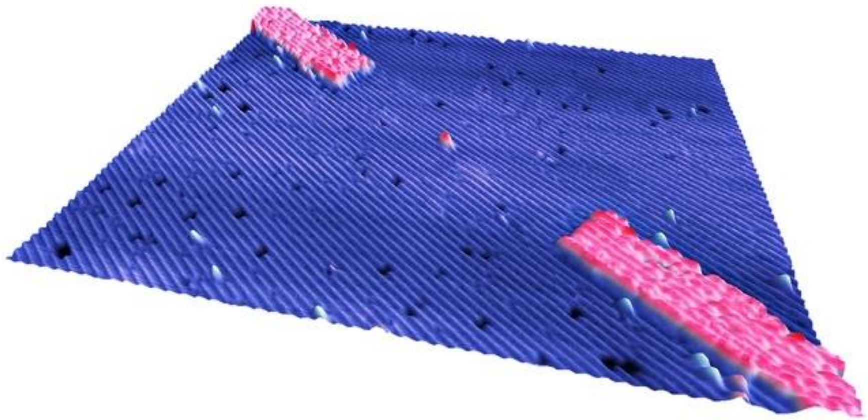


2-nm Node (Wafer)



2-nm Node (Nanosheet Cross Section)



Single Atom Transistor

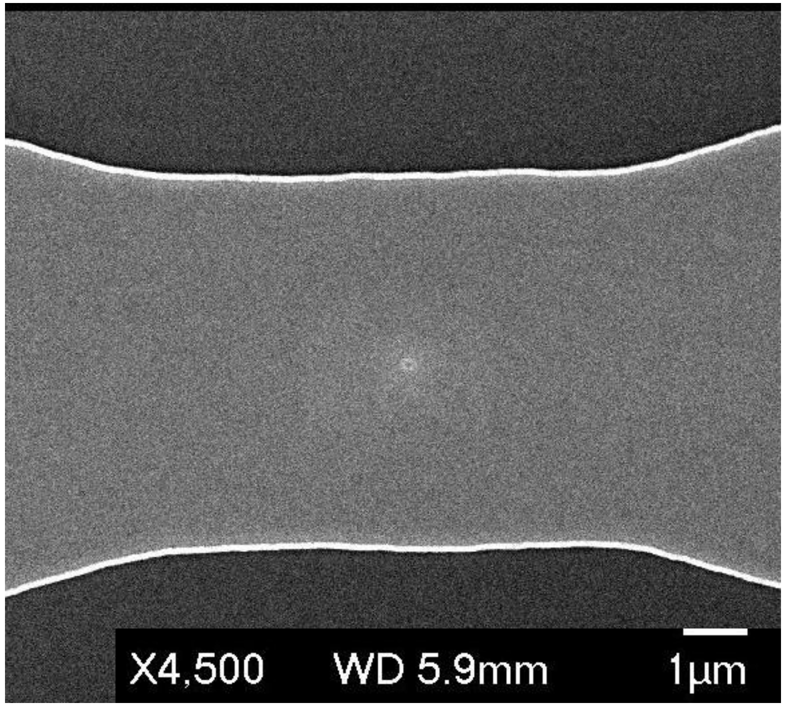
1. IBM Research, *2-nm Node* (2022)
2. Fuechsle et al., *Nature Nanotechnology* (2012)
3. Taken from: cdegroup.com
4. Taken from: coremarkmetals.com

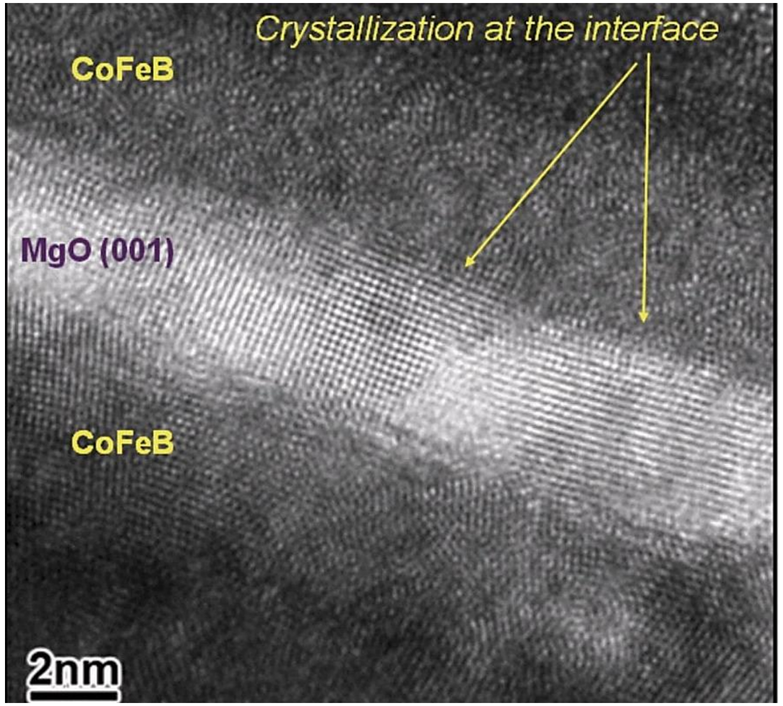
Quantum Effects vs. Scale

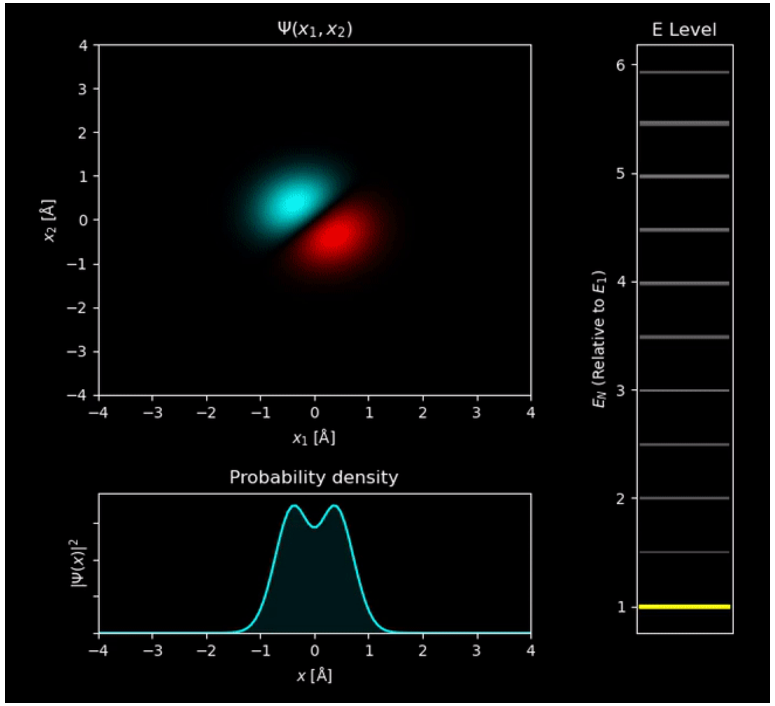
- We acknowledge 6 quantum postulates*. It turns out that the **smaller** objects become, they behave **more like waves**.
- According to the De Broglie wavelength, you can relate Planck's constant to an object's momentum.
  - Ex: a person with a mass of 70 kg moving at 5 m/s has a wavelength of 1.89×10^{-36} m.
    (Short wavelength = virtually impossible quantum tunneling!)
- We can build **nanostructures**, which have **larger wavelengths** that can allow for > likely quantum.

Lower wavelength = more particle-like behavior

Higher wavelength = more wave-like behavior





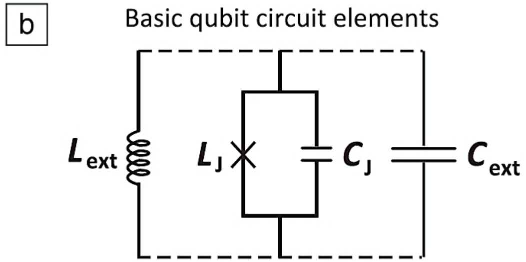


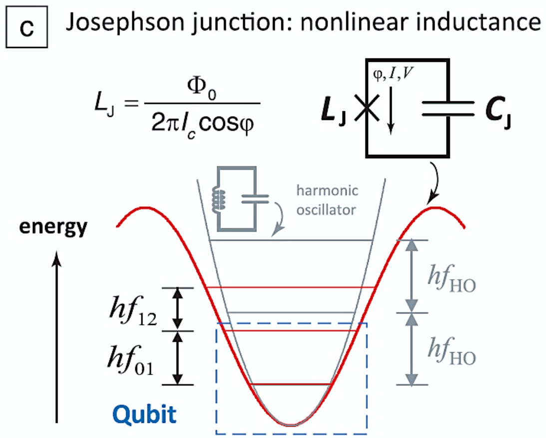
* Postulates: assumption used as a basis for mathematical reasoning.

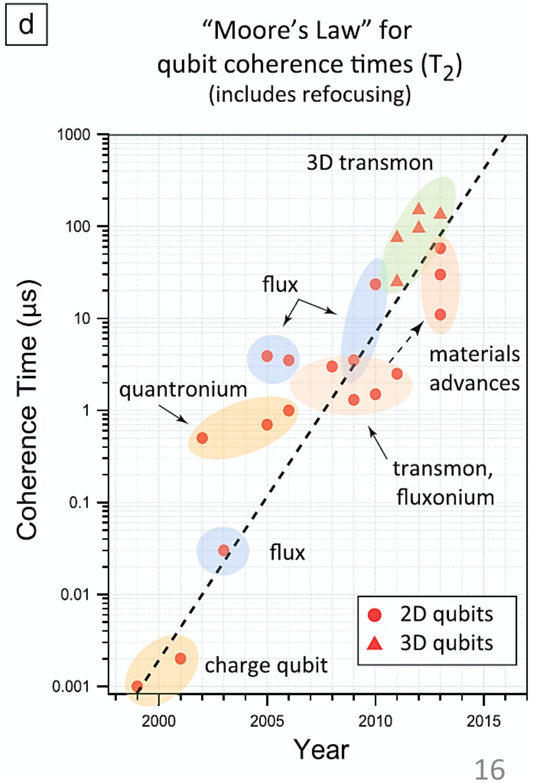
1. Miyajima et al., *Applied Physics Letters* (2009)

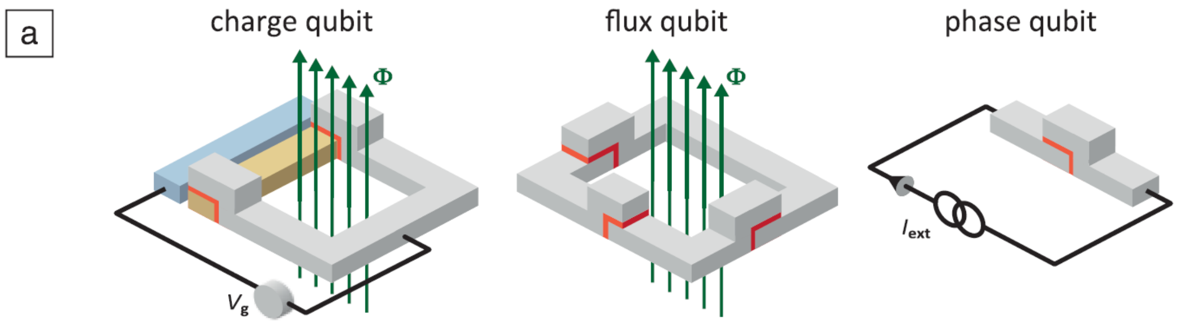
More Background & Motivation

- In 1982, Richard Feynman described an idea of creating quantum simulators, which would need physical devices that use quantum mechanical effects, rather than logic alone.
- Quantum bits = qubits (anharmonic oscillator).
- Qubits can either function as artificial atoms or be made of natural atoms.
- Quantum states created by qubits can be thought of as vectors, which can be modified by matrices.
    - Quantum state = vector
    - Qubit = matrix









1. Feynman, *Int. J. Theor. Phys.* (1981)
2. Oliver et al., *Materials Research Society* (2013)

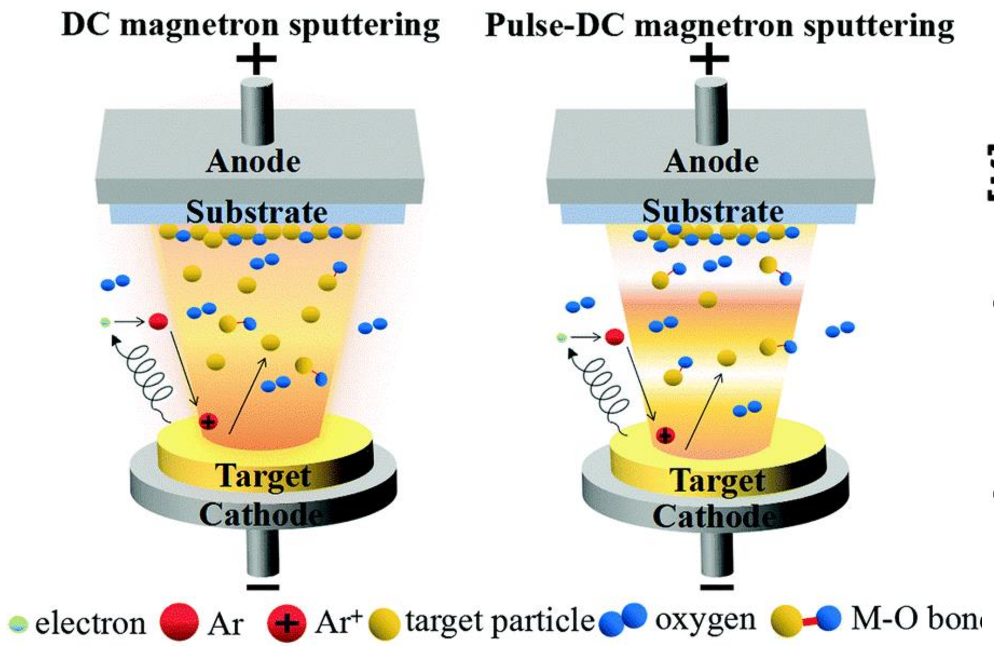
List of Physical Qubits

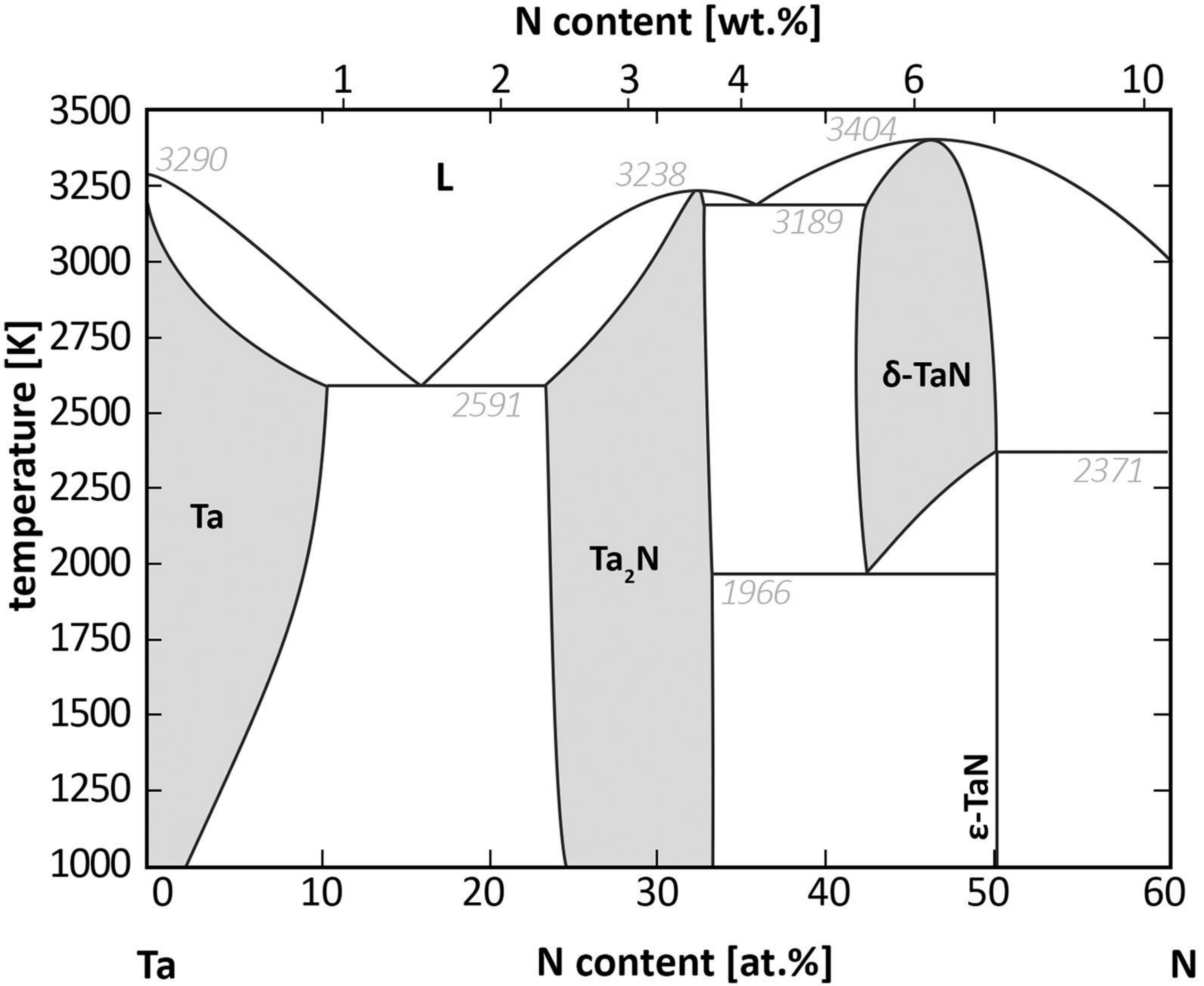
- 2 flavors exist: solid-state qubits & non-solid-state qubits (photonic or similar).
- A key challenge for solid-state systems is to realize a spin coherence time that is much longer than the time for quantum spin manipulation protocols.

Physical Support	Name	Information Support	$\|0\rangle$	$\|1\rangle$
Photons	Polarization encoding	Light polarization	Horizontal	Vertical
	Number of photons	Fock state	Vacuum	Single photon state
	Time-bin encoding	Time of arrival	Early	Late
Coherent state of light	Squeezed light	Quadrature	Amplitude-squeezed state	Phase-squeezed state
Electron	Electron spin	Spin	Up	Down
	Electron number	Charge	No electron	One electron
Nucleus	Nuclear spin (NMR)	Spin	Up	Down
Optical lattices	Atomic spin	Spin	Up	Down
Josephson junction	Superconducting charge	Charge	Uncharged superconducting island	Charged superconducting island
	Superconducting flux	Current	Clockwise current	Counterclockwise current
	Superconducting phase	Energy	Ground state	First excited state
Single-charged quantum dot pair	Electron localization	Charge	Electron on left dot	Electron on right dot
Quantum dot	Dot spin	Spin	Down	Up
Gapped topological system	Non-abelian anyons	Excitation braiding	Topological system specific	Topological system specific
Phonon	Vibrational states	Phonon/ vibron	$\|01\rangle$ Superposition	$\|10\rangle$ Superposition
van der Waals heterostructure	Electron localization	Charge	Electron on bottom sheet	Electron on top sheet

1. Lucatto, *Phys. Rev. B* (2019) 2. Nielsen et al., *Quantum Computation & Quantum Information* (2010) 3. https://en.wikipedia.org/wiki/Qubit

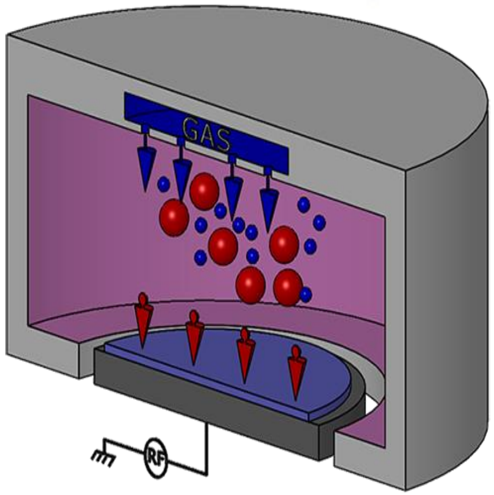
Phase Diagrams as Guiding Maps

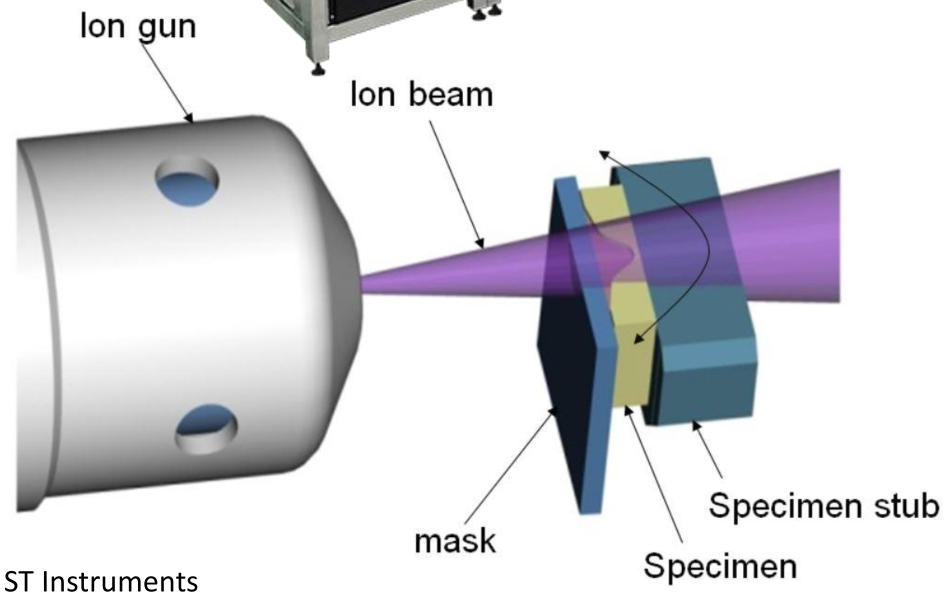




1. Koller, et al., *Surface & Coatings Technology (2018)*

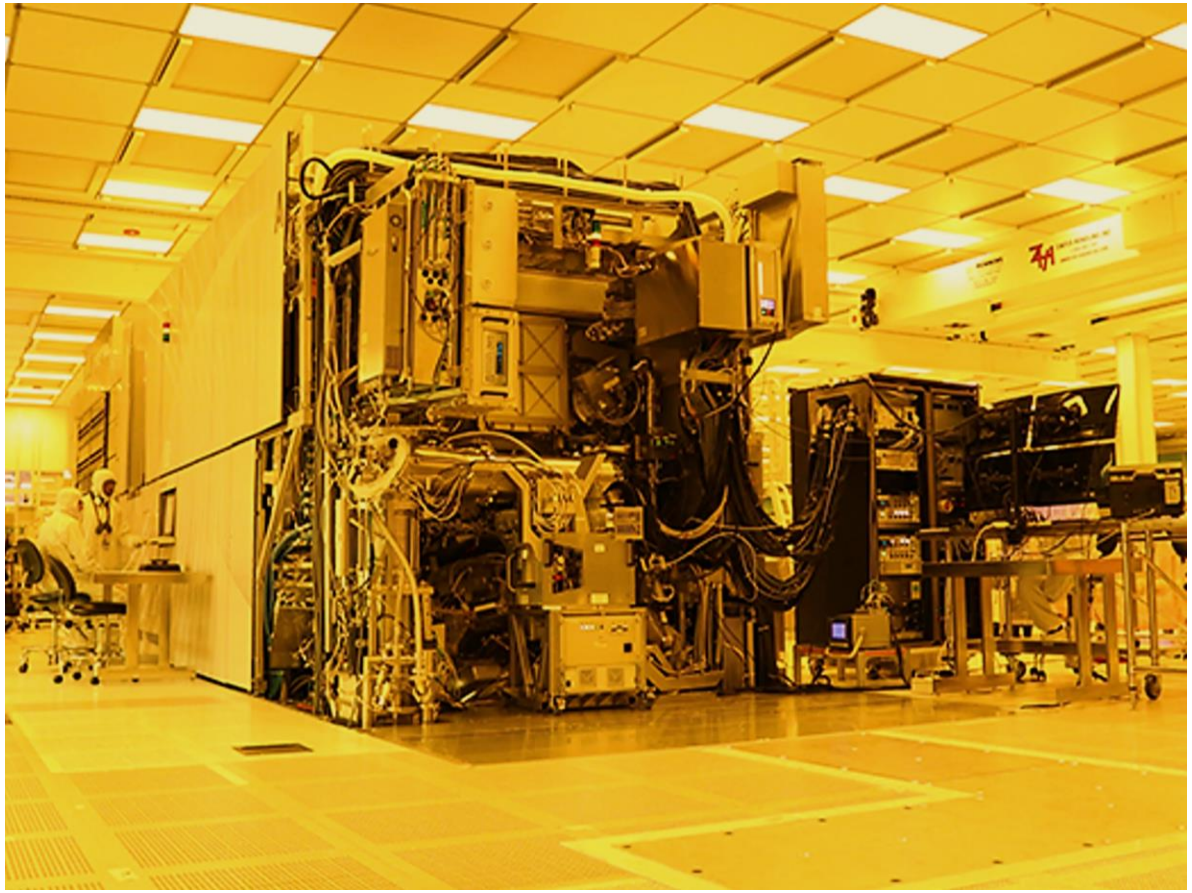
Reactive Ion Etching System vs. Ion Beam Etching System





1. Corial-Plasma-Therm.
2. Intl Vac
3. ST Instruments

Extreme Ultraviolet Lithography System vs. Electron-Beam Lithography System

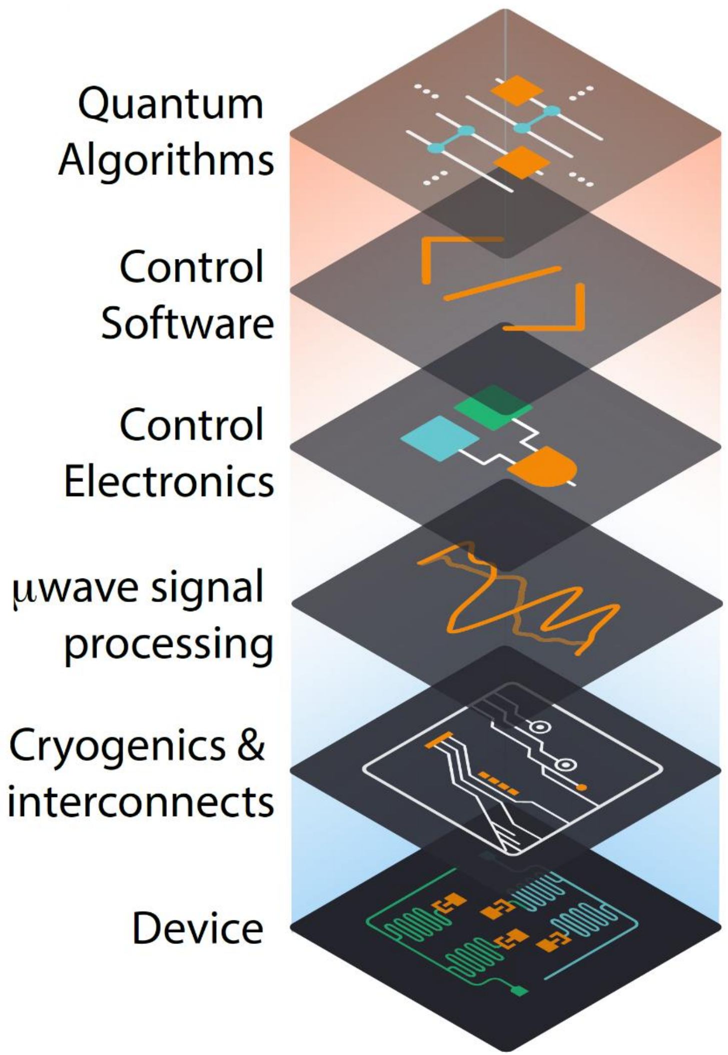


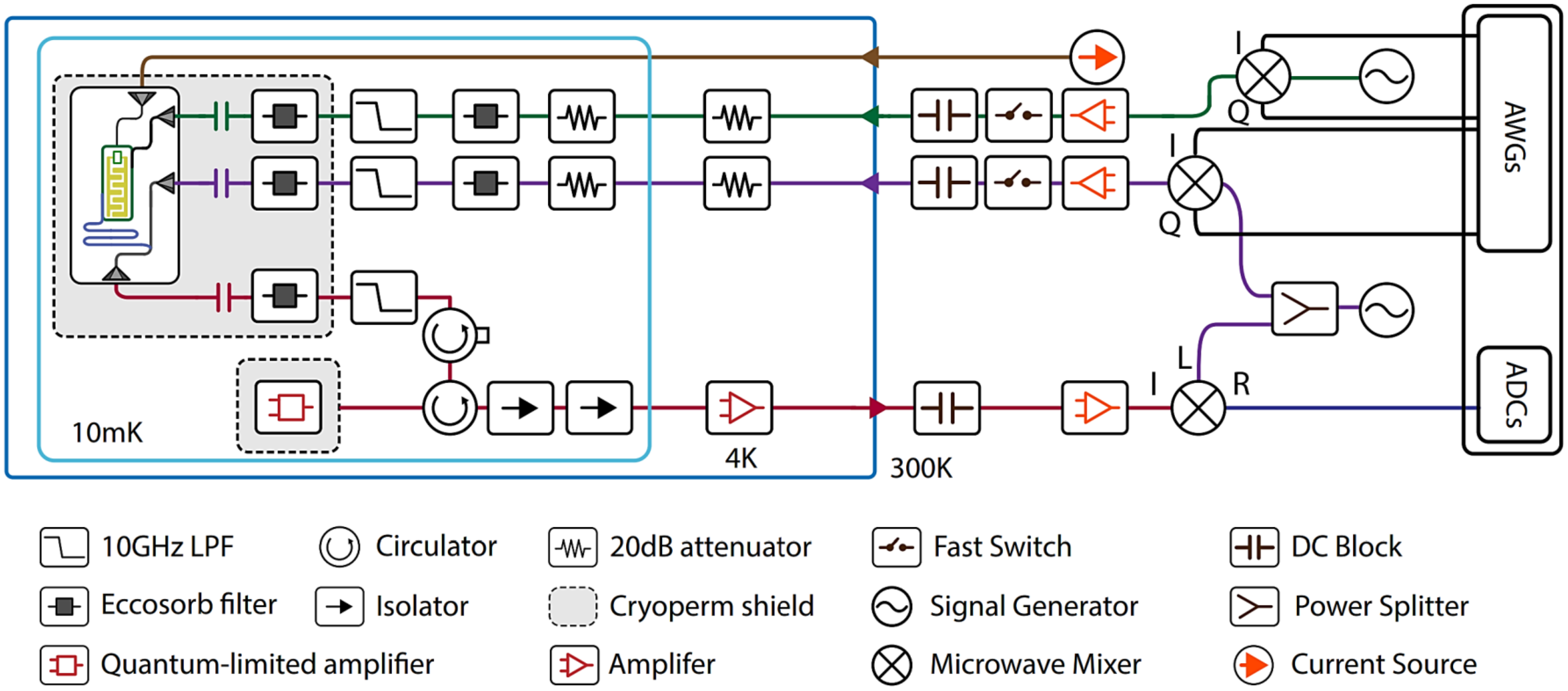
ASML NXE 3300B

Raith EBPG-5000+

1. ASML, *NXE:3300B*

Quantum Stack vs. Quantum Device Control Schematic

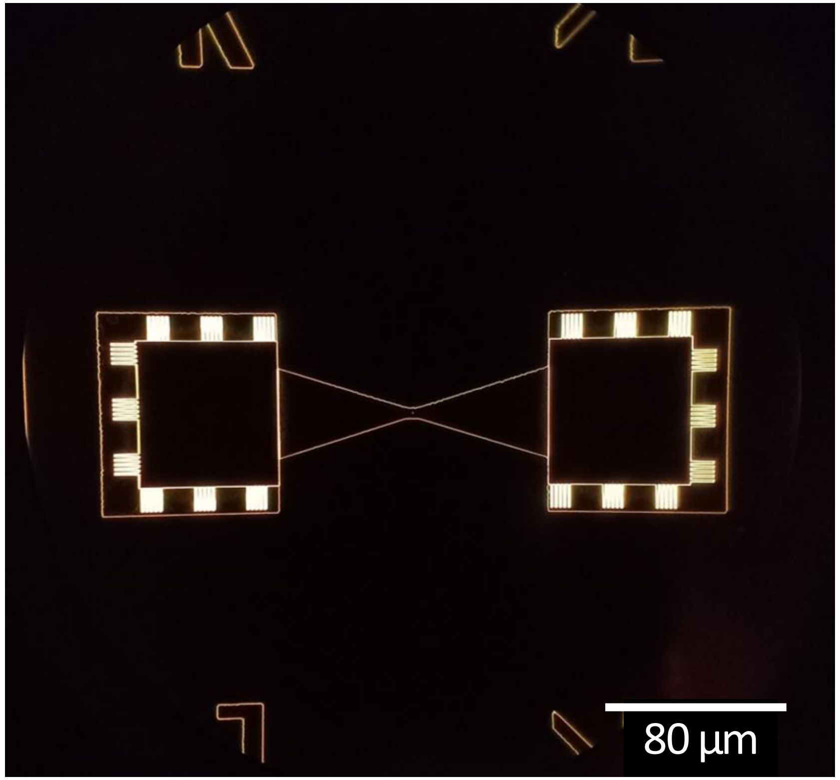


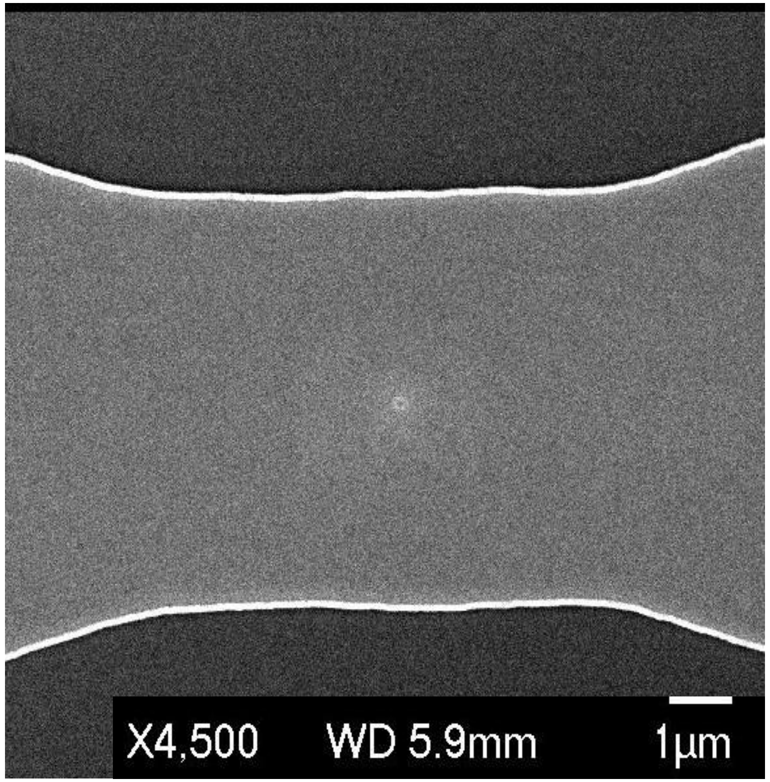


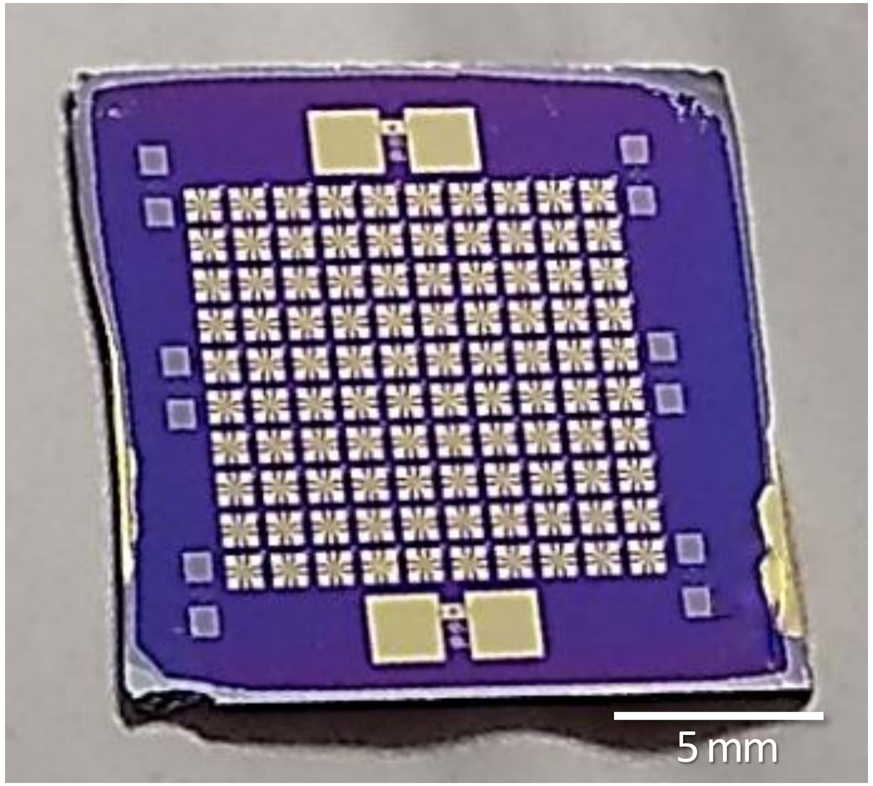
Hardware Footprint

1. Gao et al., *arXiv* (2021)

Example of Our Nano MTJ Chips







MTJ = Magnetic Tunnel Junction, a device that employs quantum effects for classical purposes.

Summary

- Physical devices used as qubits are a type of quantum anharmonic oscillator.
- One can treat **phase diagrams** as maps for growing materials that are needed to build a nano scale device.
- It is possible to pick from a number of fabrication methods widely available to develop critical features of devices.
- Multiple platforms of physical qubits can be fabricated with micro & nano.
  - The top-3 qubit systems are superconducting, trapped ion, & photonic.
- Quantum processor **chips** exist at bottom of the overall quantum stack.
  - This is where we place a fabricated set of devices for computing & memory.