A spin qubit to interface semi and superconducting technologies

A. Crippa[1], D. Jirovec[1], K. Aggarwal[1], A. Hofmann[1], A. Ballabio[2], P. M. Mutter[3], G. Tavani[2], M. Botifoll[4], J. Kukucka[1], O. Sagi[1], F. Martins[1], J. Saez-Mollejo[1], I. Prieto[1], M. Borovkov[1], J. Arbiol[4,5], D. Chrastina[2], G. Isella[2], and G. Katsaros[1]

1 Institute of Science and Technology Austria, Am Campus 1, 3400 Klosterneuburg, Austria
2 L-NESS, Physics Department, Politecnico di Milano, via Anzani 42, 22100, Como, Italy
3 Department of Physics, University of Konstanz, D-78457 Konstanz, Germany
4 Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus UAB, Bellaterra, Barcelona, Catalonia, Spain
5 ICREA, Passeig de Llus Companys 23, 08010 Barcelona, Catalonia, Spain

alessandro.crippa@ist.ac.at

The route to Universal Quantum Computing

Goals

- Medium-term: 10^3 physical qubits with QEC
- Long-term: 10^6 - 10^8 qubits

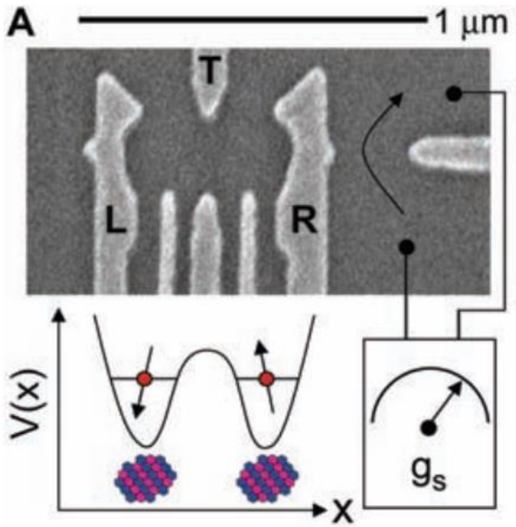
… (also) a matter of footprint!

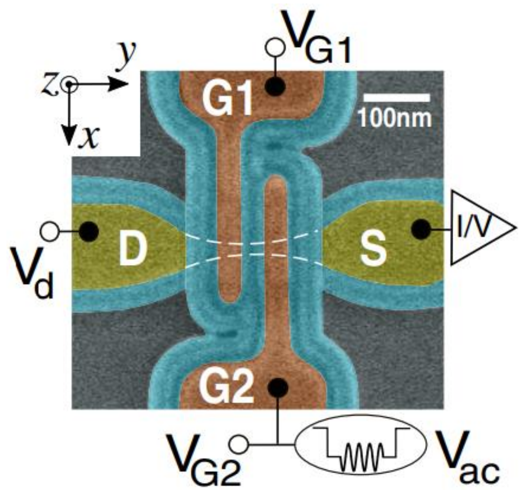
	Semiconductor Single-Spin qubit	Superconductor Flux qubit (DWave like)	Superconductor Transmon qubit (IBM like)	Trapped Ion qubit
# qubits [10^6/cm^2]	8000	8×10^{-4}	10^{-5}	2×10^{-5}
chip area [mm^2]	25	25×10^{7}	2×10^{10}	10^{10}

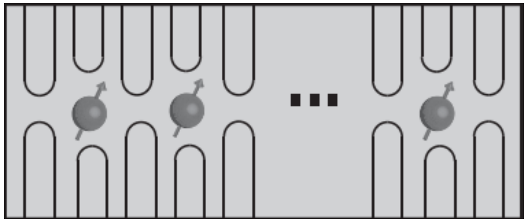
Ferraro and Prati, *Physics Letters A* 126352 (2020)

Spin qubits on the way

Academia ⇨ Pre-industrial facilities (IMEC, Leti) ⇨ CMOS factory (Intel)







Petta et al., Science **309**, 2180 (2005)

Crippa et al., Phys. Rev. Lett. **120**, 137702 (2018)

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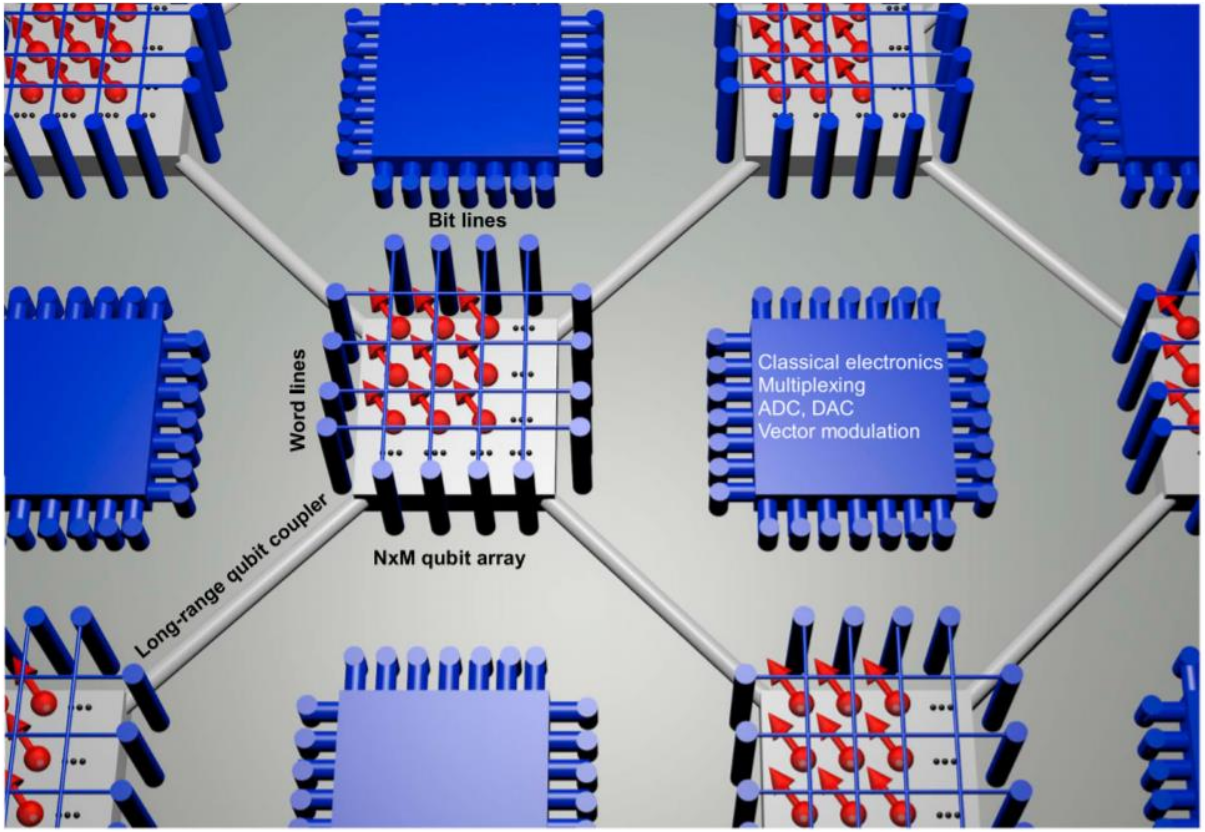

Vandersypen et al., npj Q. Info. **3**, 34 (2017)

A solid-state platform for QIP

First demonstration of quantum supremacy

superconductors

Google, Nature **574**, 505–510 (2019)

Know-how of the CMOS industry to address the scaling challenge

semiconductors

Crippa et al., Nature Comm. **10**, 2776 (2019)

Long range connectivity

optics

Ursin et al., Nature Phys. **3**, 481 (2007)

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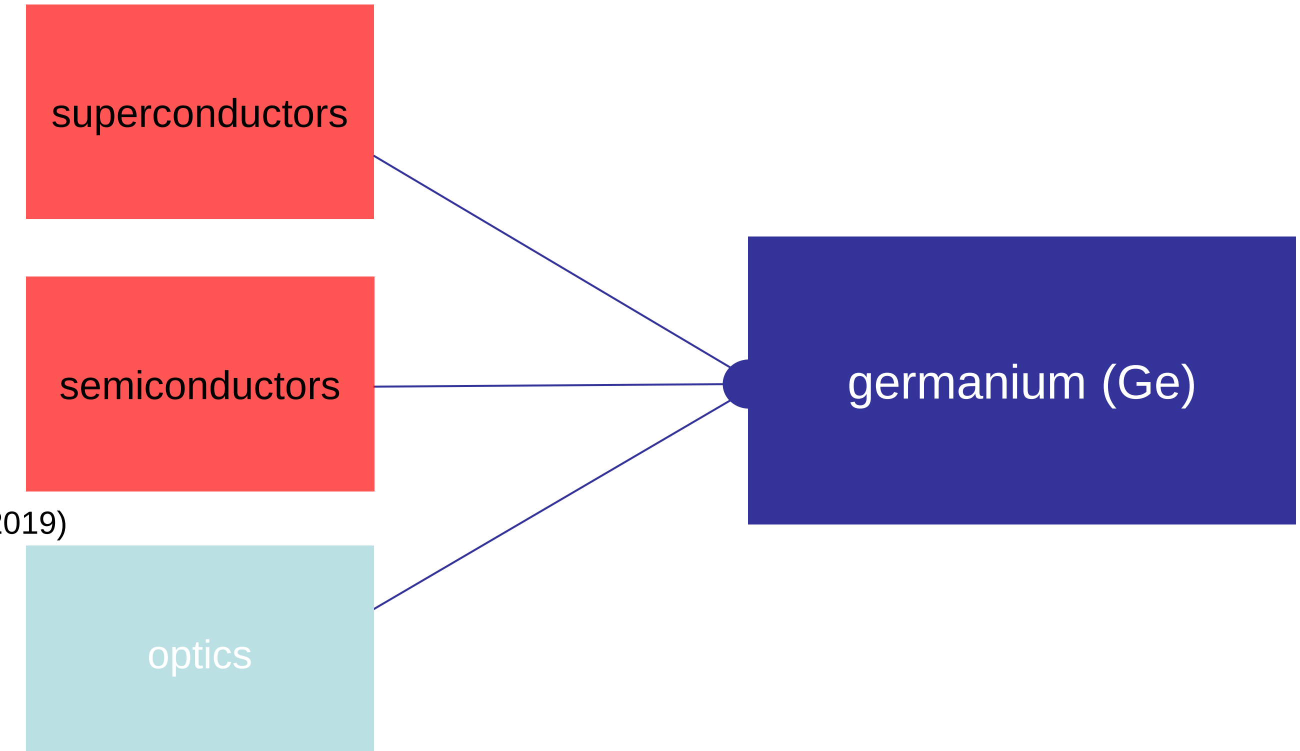
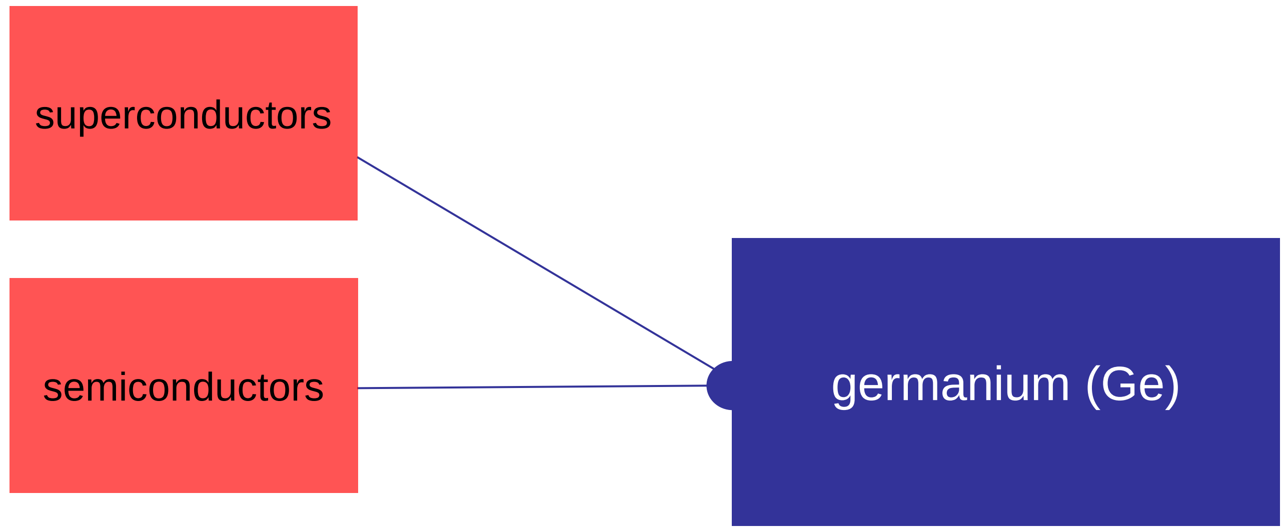


Outline

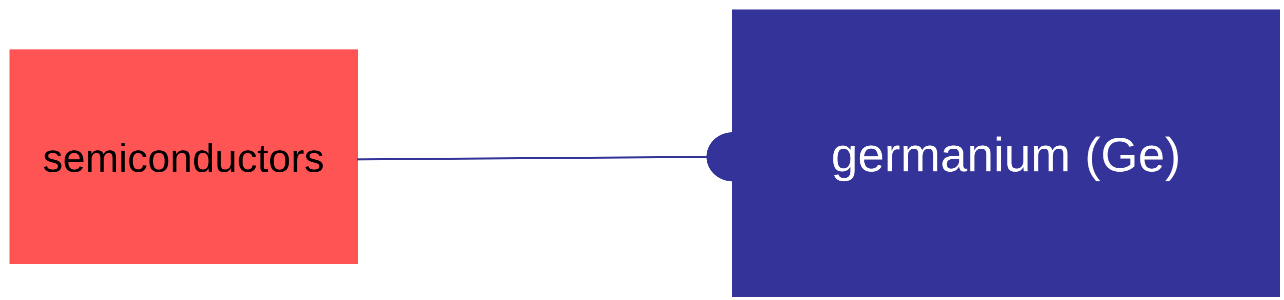
Proximity-induced superconductivity on Ge

An ultra-low magnetic field spin qubit on Ge

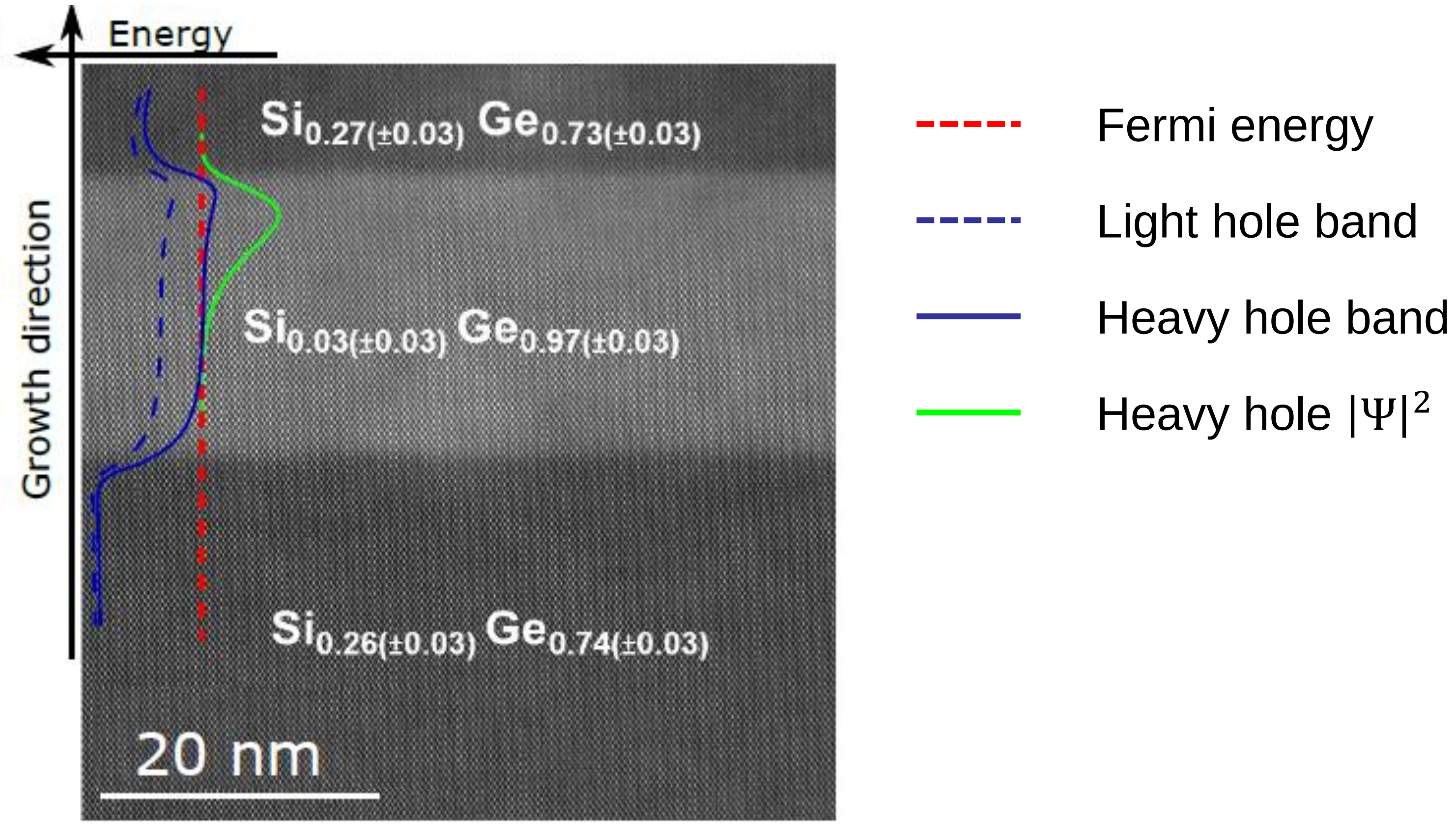


Section 1

An ultra-low magnetic field spin qubit on Ge

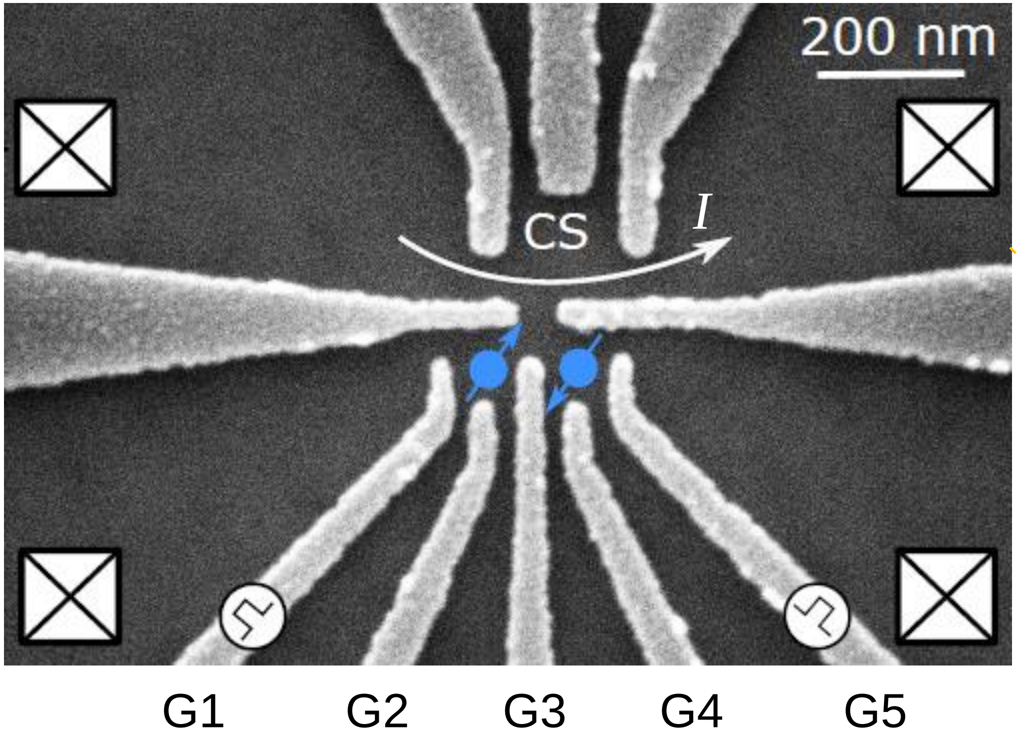


Ge/SiGe structure



L-NESS, Physics Department, Politecnico di Milano

Spin qubit device



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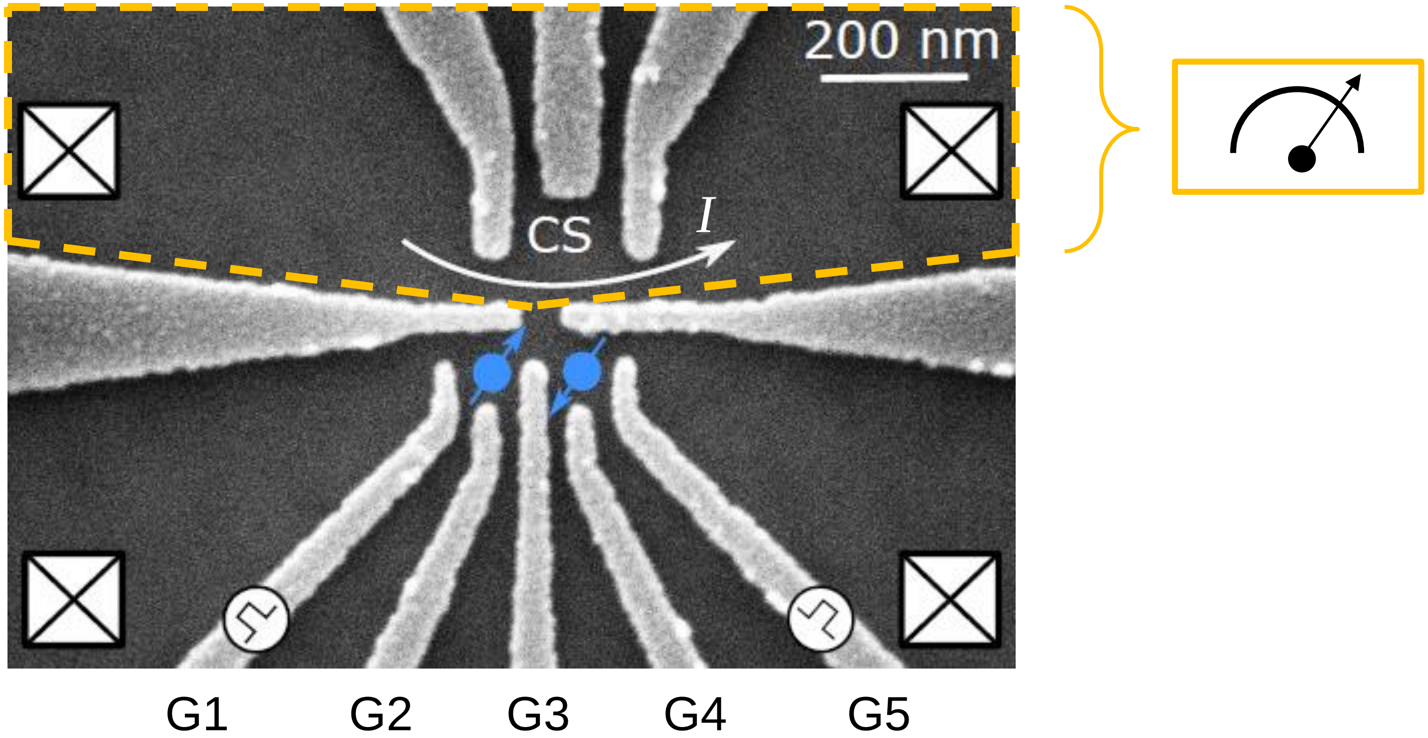

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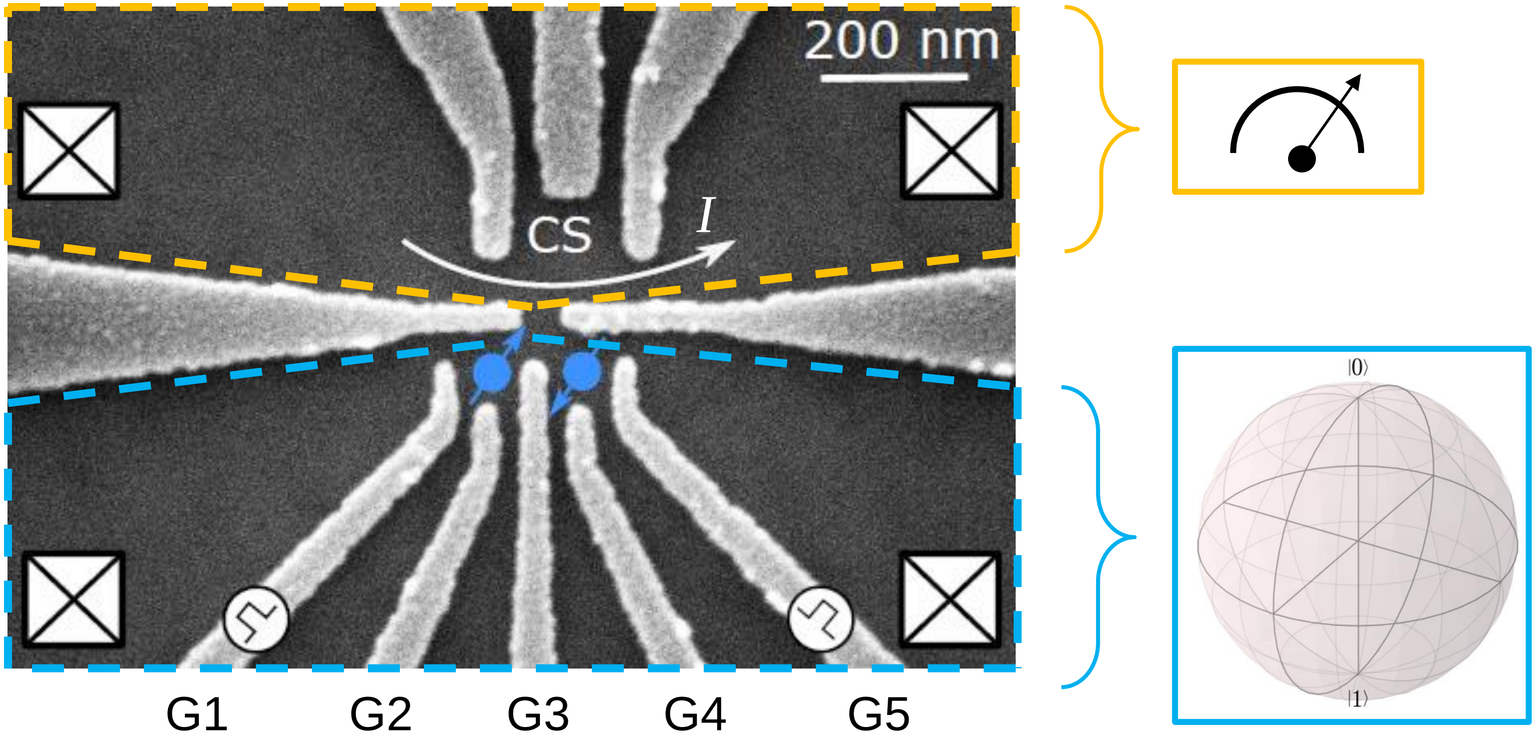
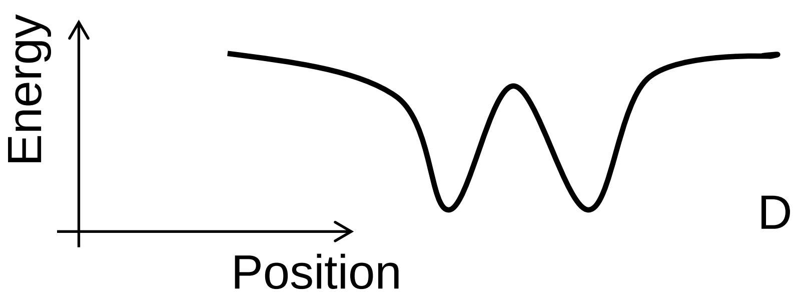
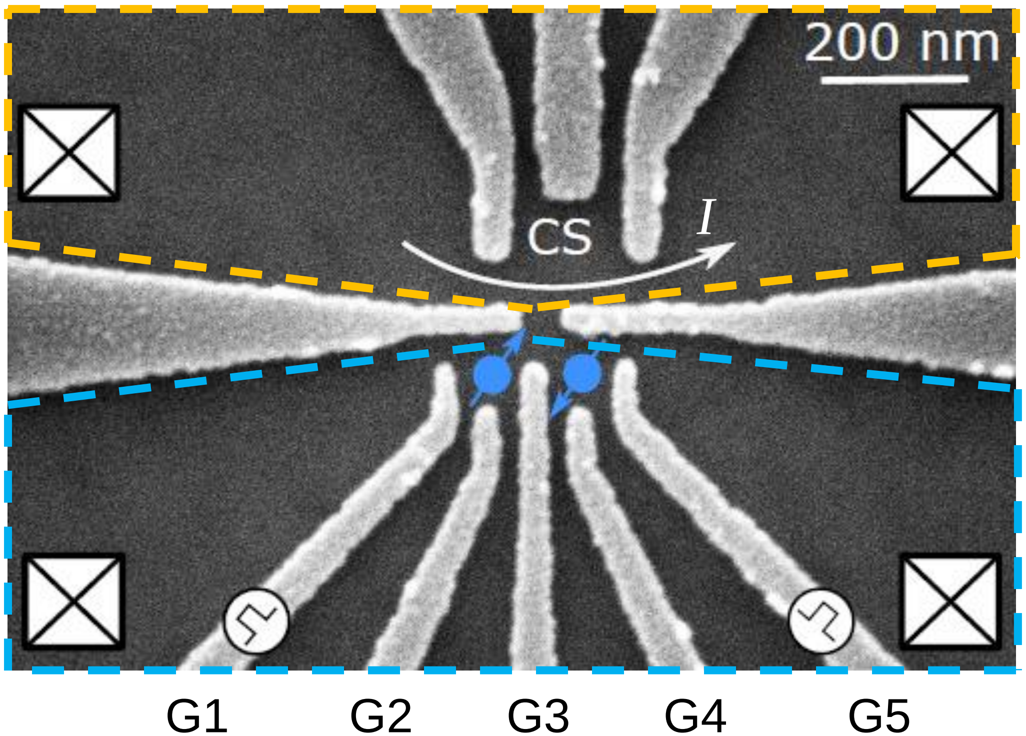
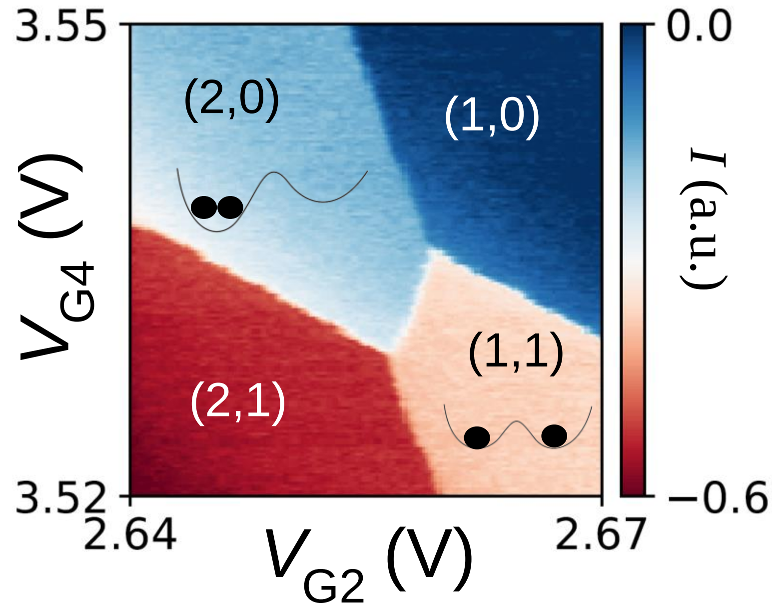




Double quantum dot

Double quantum dot





Hole:

Charge ●, ○

Spin ↑, ↓

Qubit’s basis

Two spins ½ :

$\vec{B} = 0$

Triplets

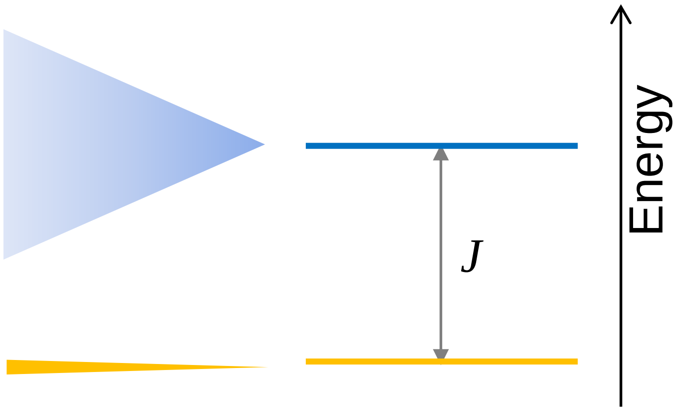
$T_- = |\downarrow\downarrow\rangle$ $\quad m_s = +1$

$T_0 = \frac{|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle}{\sqrt{2}}$ $\quad m_s = 0$

$T_+ = |\uparrow\uparrow\rangle$ $\quad m_s = -1$

Singlet

$S = \frac{|\uparrow\downarrow\rangle - |\uparrow\downarrow\rangle}{\sqrt{2}}$ $\quad m_s = 0$



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$m_s = +1$

$m_s = 0$

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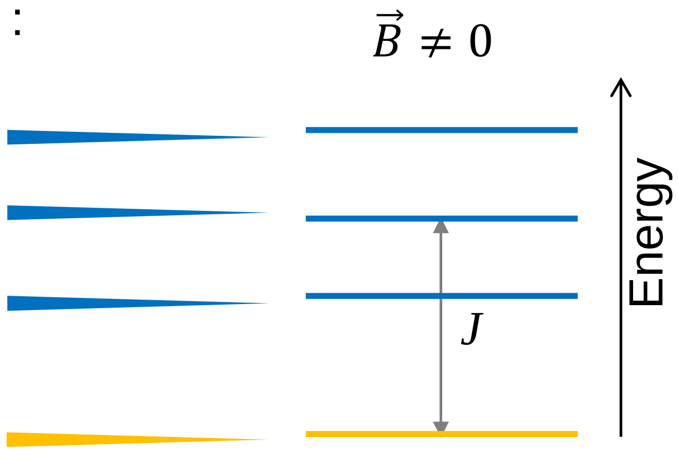
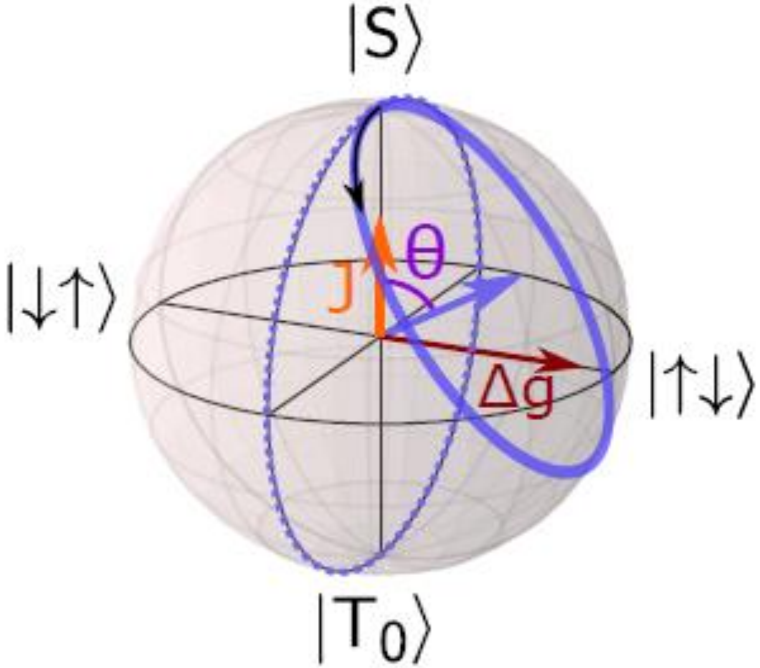


$$H = \begin{pmatrix} -J(\epsilon) & \frac{\Delta g \mu_B B}{2} \\ \frac{\Delta g \mu_B B}{2} & 0 \end{pmatrix}$$

Δg: g factor difference

μ_B: Bohr magneton

B: external magnetic field



Why Ge?

Planar Ge:

- Low *m**
- Intrinsic high g factor (compared to GaAs and Si) → Δg
- Excellent electrostatic control → J

Low magnetic field operability

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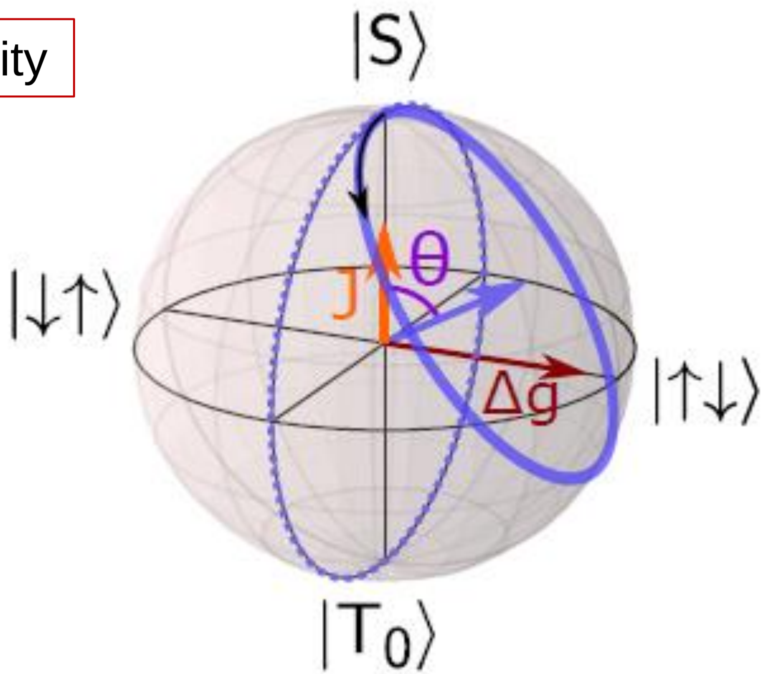
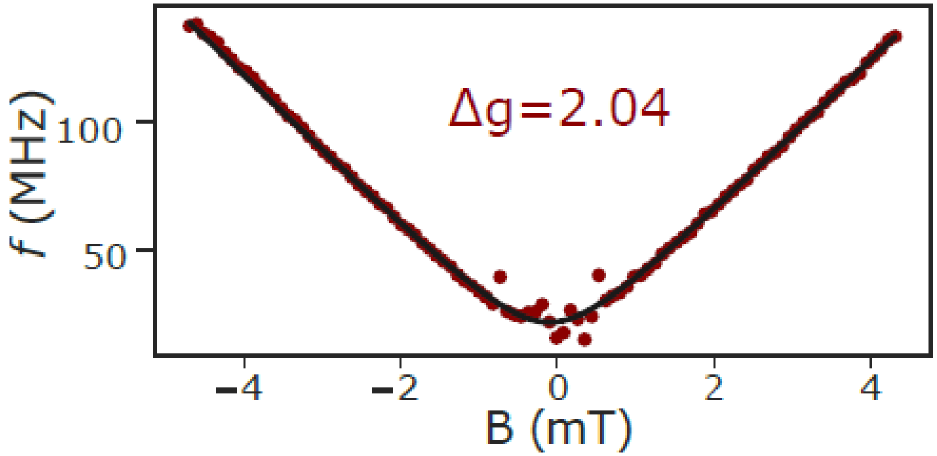
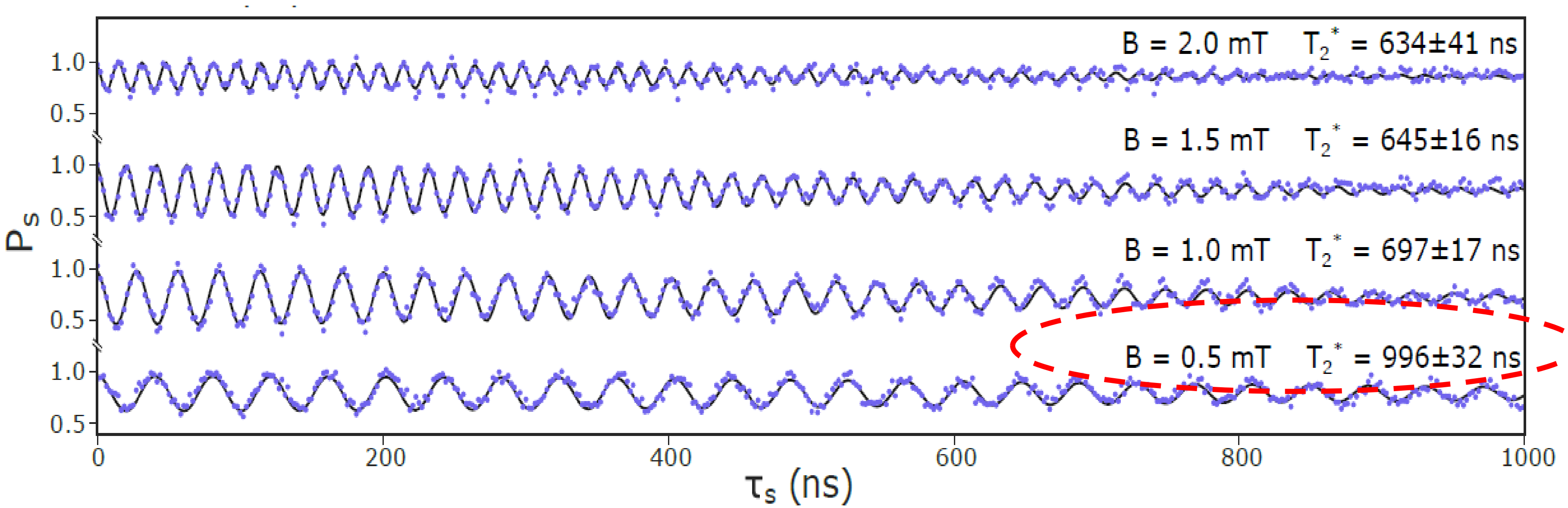


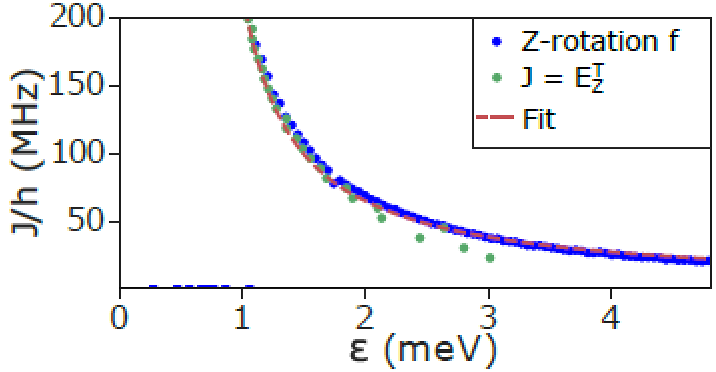
X gate (Rabi oscillations)



<10ns to perform a X gate



Z gate (exchange oscillations)



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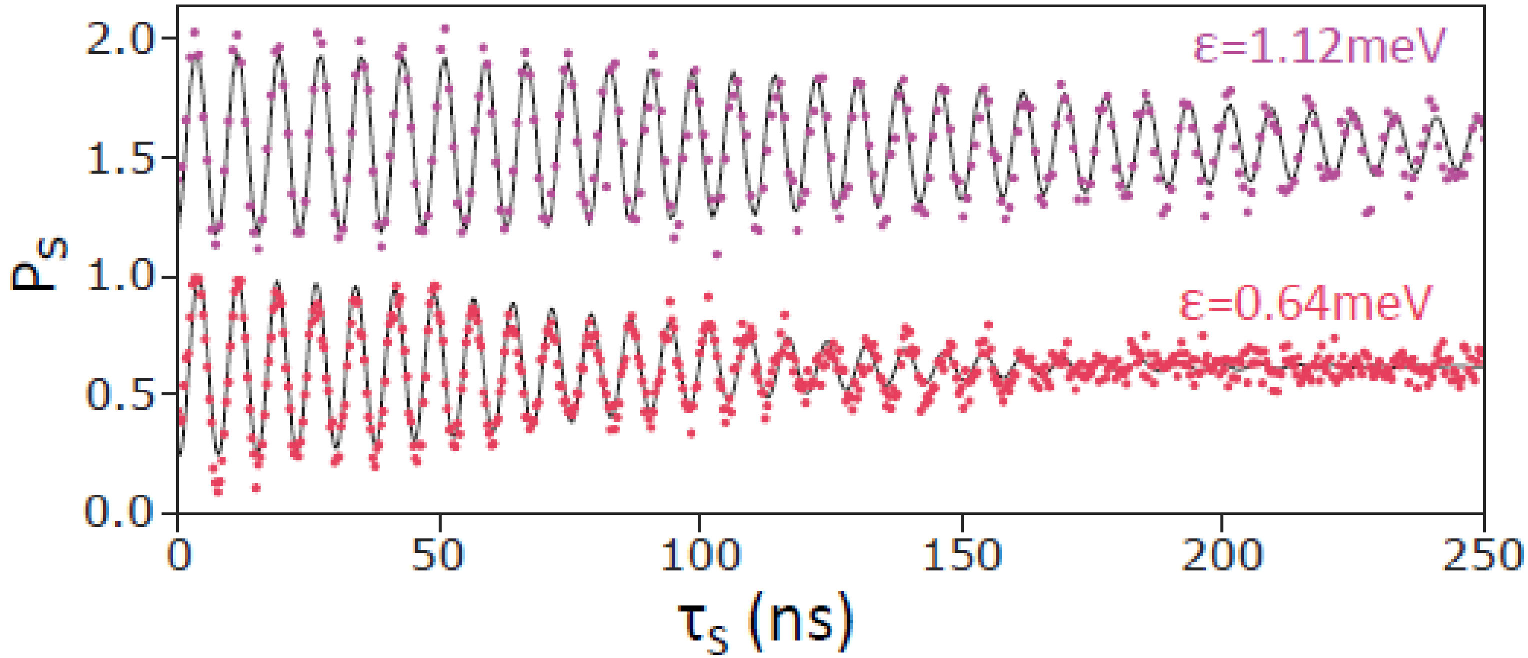
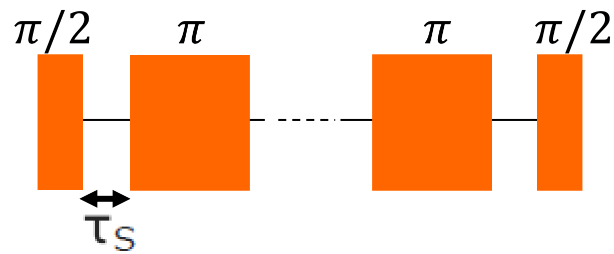
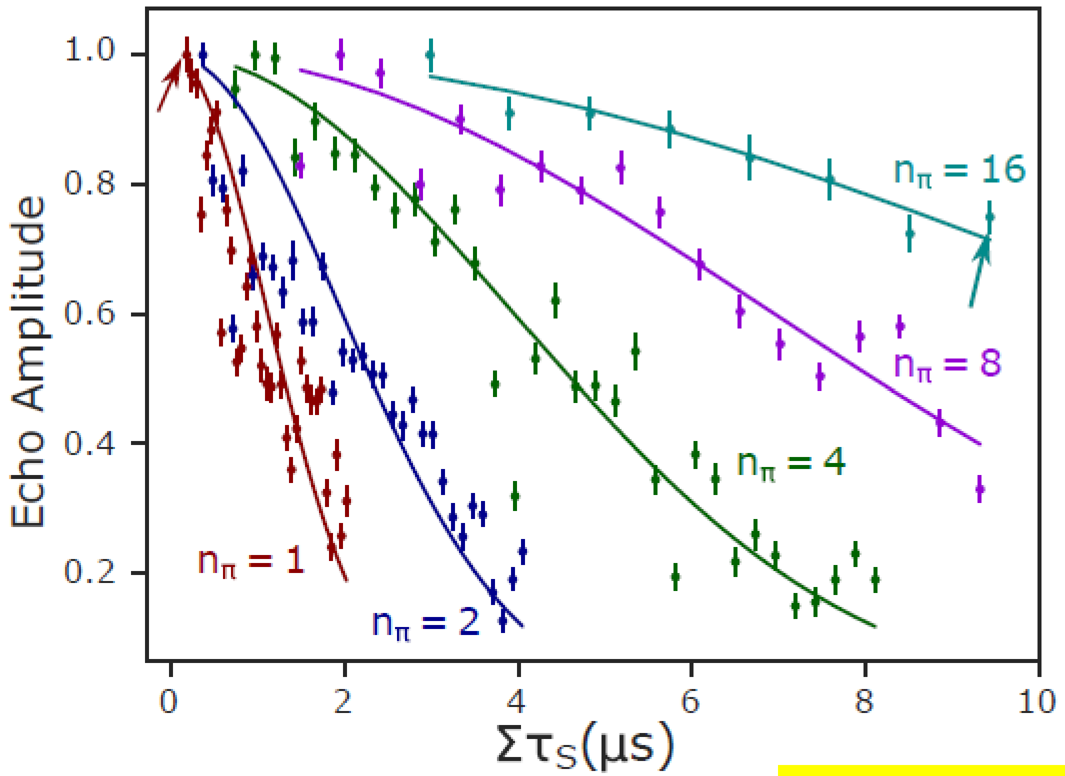


Coherence (Echo)



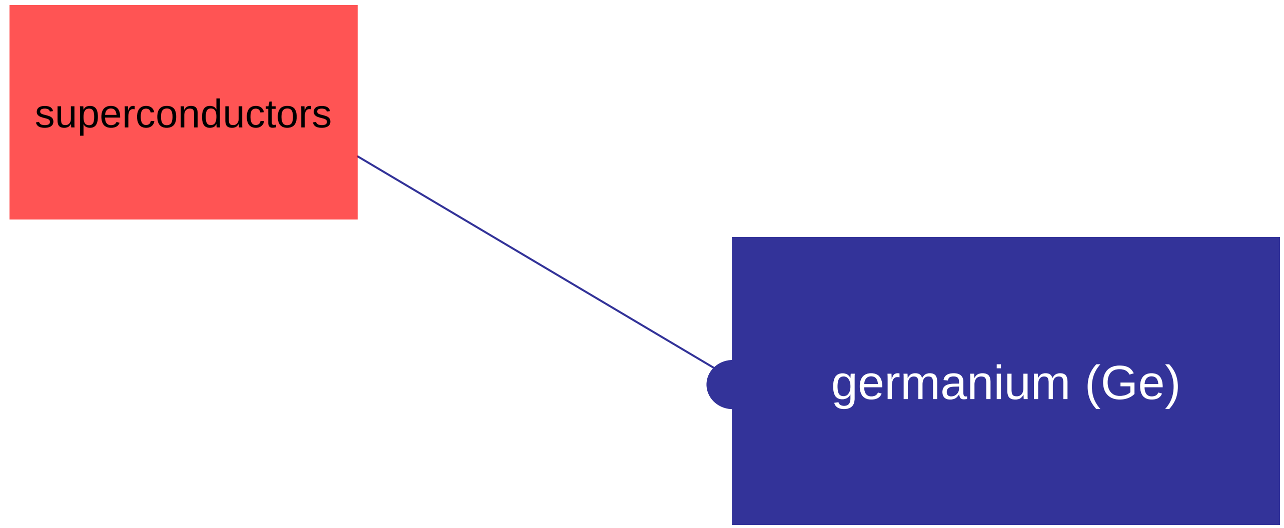


Jirovec et al., arXiv 2011.13755 (2020)

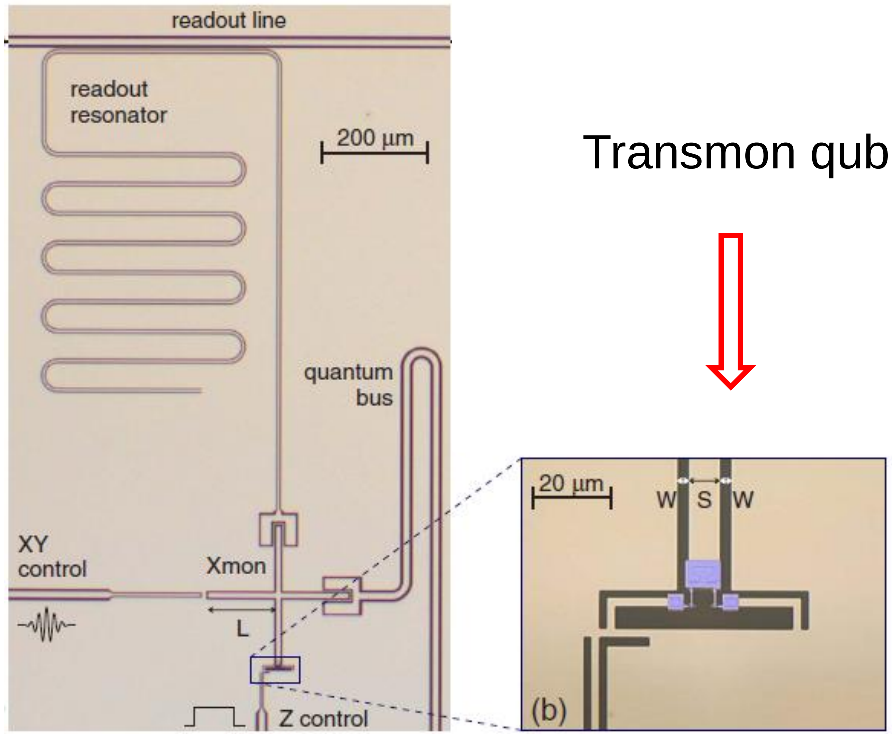
T2 > 15 μs with 16 refocusing pulses

Section 2

Proximity-induced superconductivity on Ge

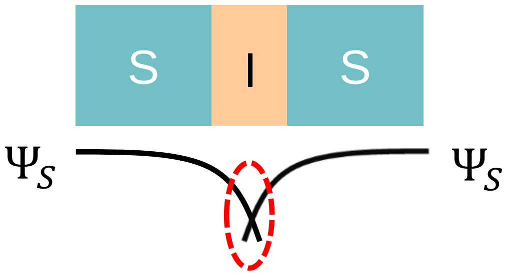


«Conventional» superconducting qubit



Transmon qubit

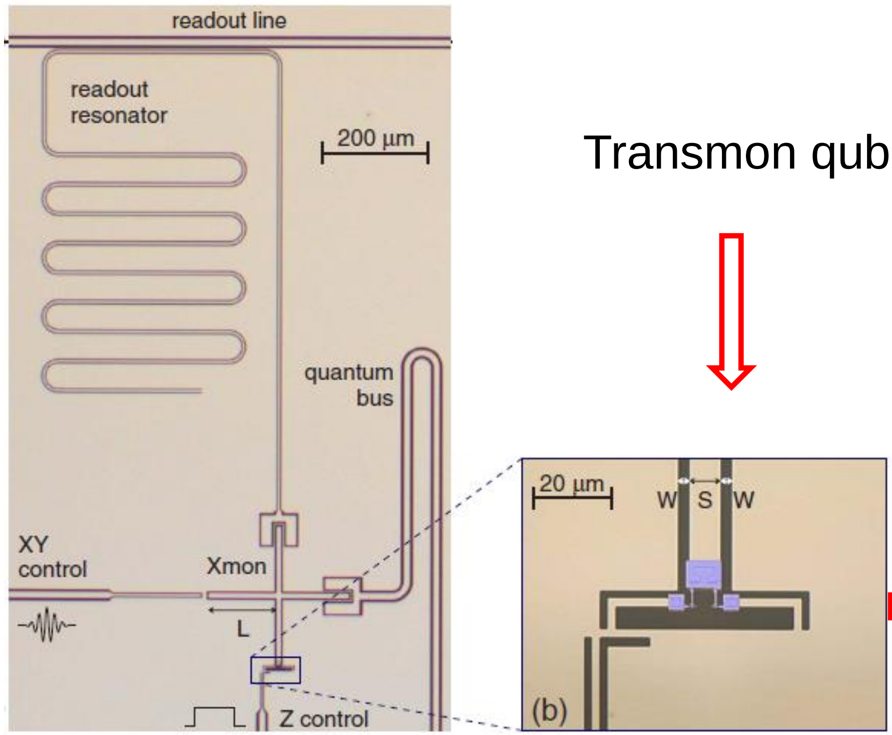
Josephon junction



Barends et al., PRL **111**, 080502 (2013)

«Super» superconducting qubit

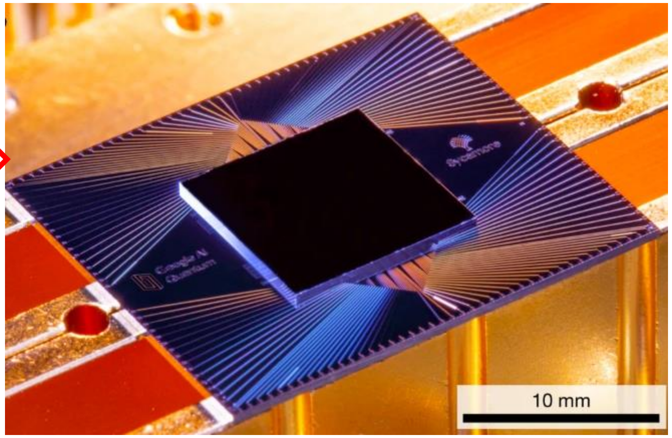
Transmon qubit



Barends et al., PRL **111**, 080502 (2013)

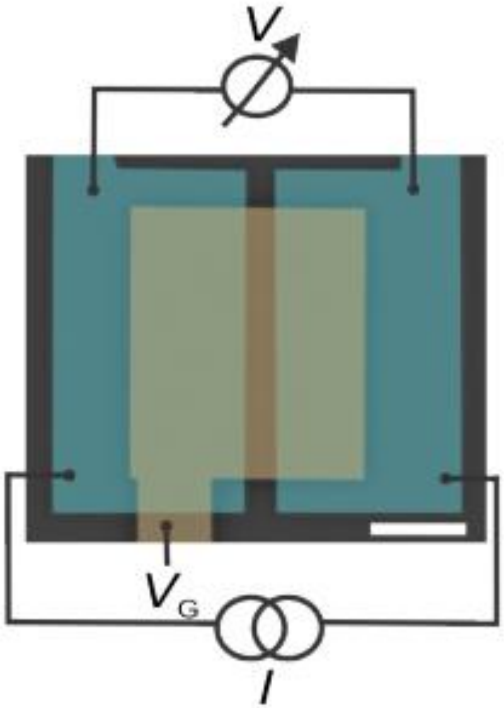
x53

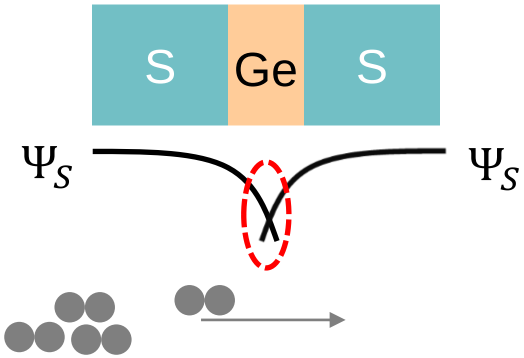
Sycamore processor

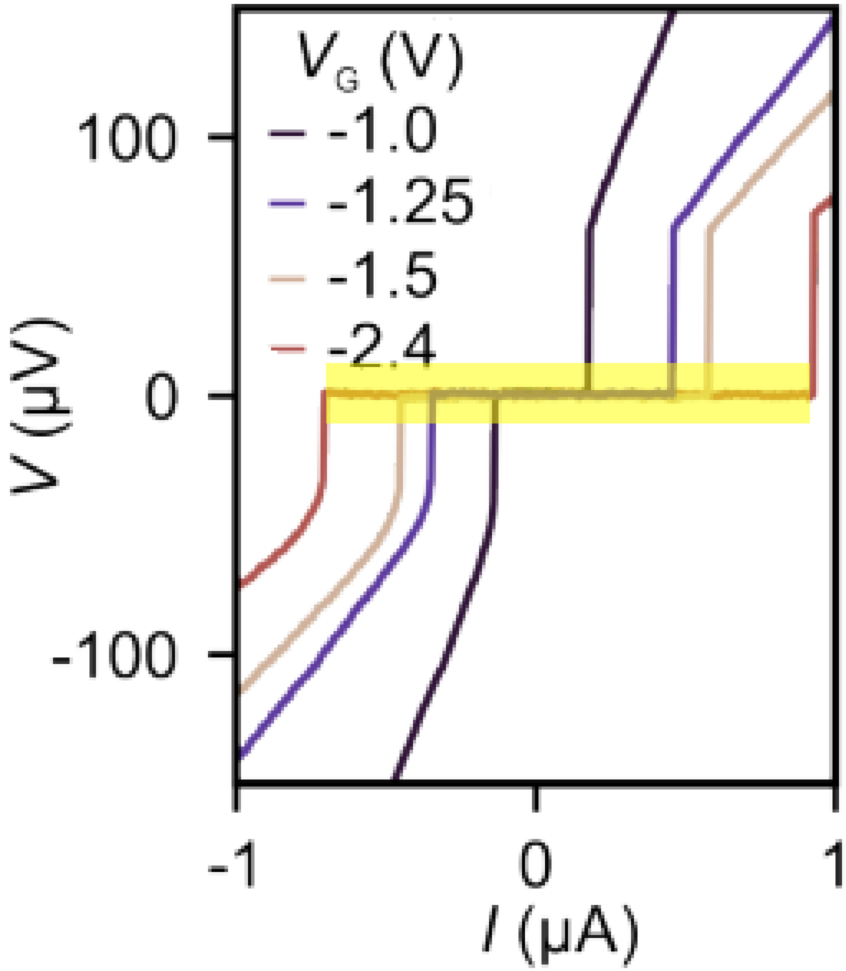


Google, Nature **574**, 505–510 (2019)

Towards a Ge-superconducting qubit

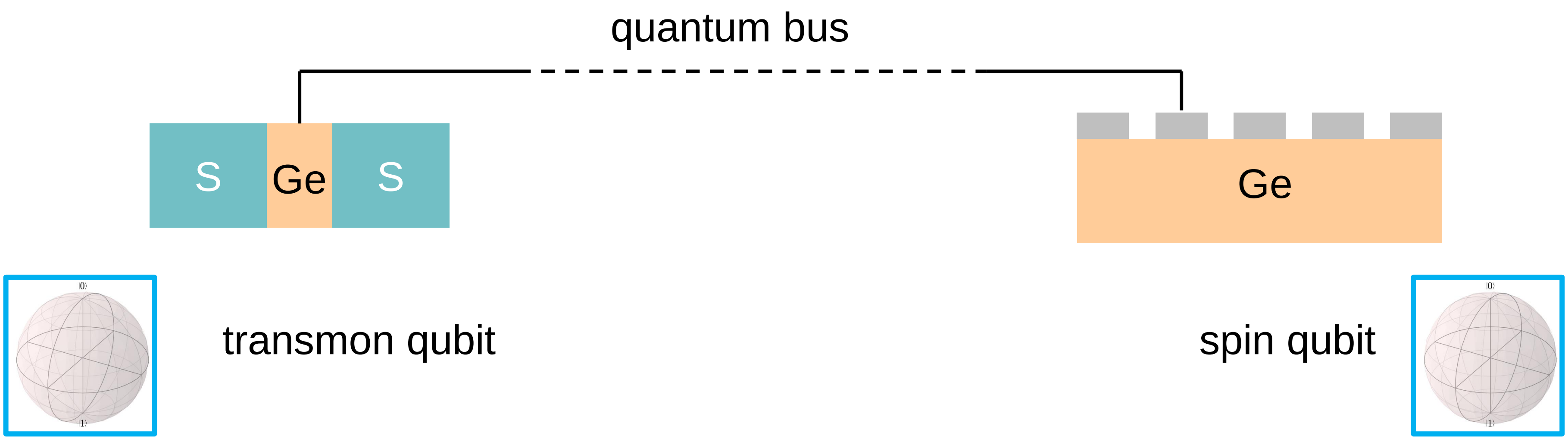




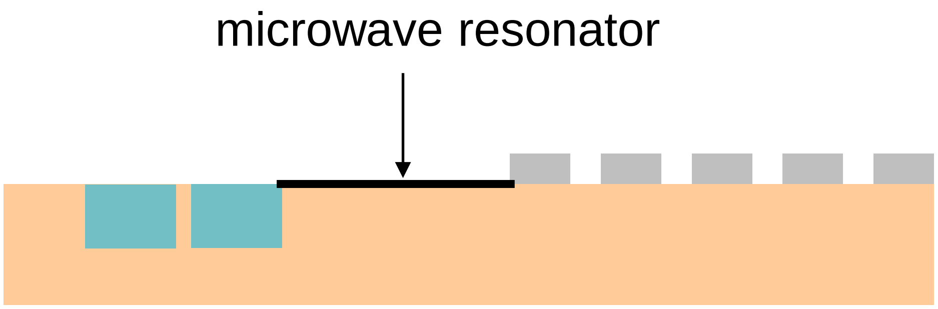


Aggarwal et al., arXiv 2012.00322 (2020)

Semi-super monolithic integration



BOTH qubits within a single material platform: germanium



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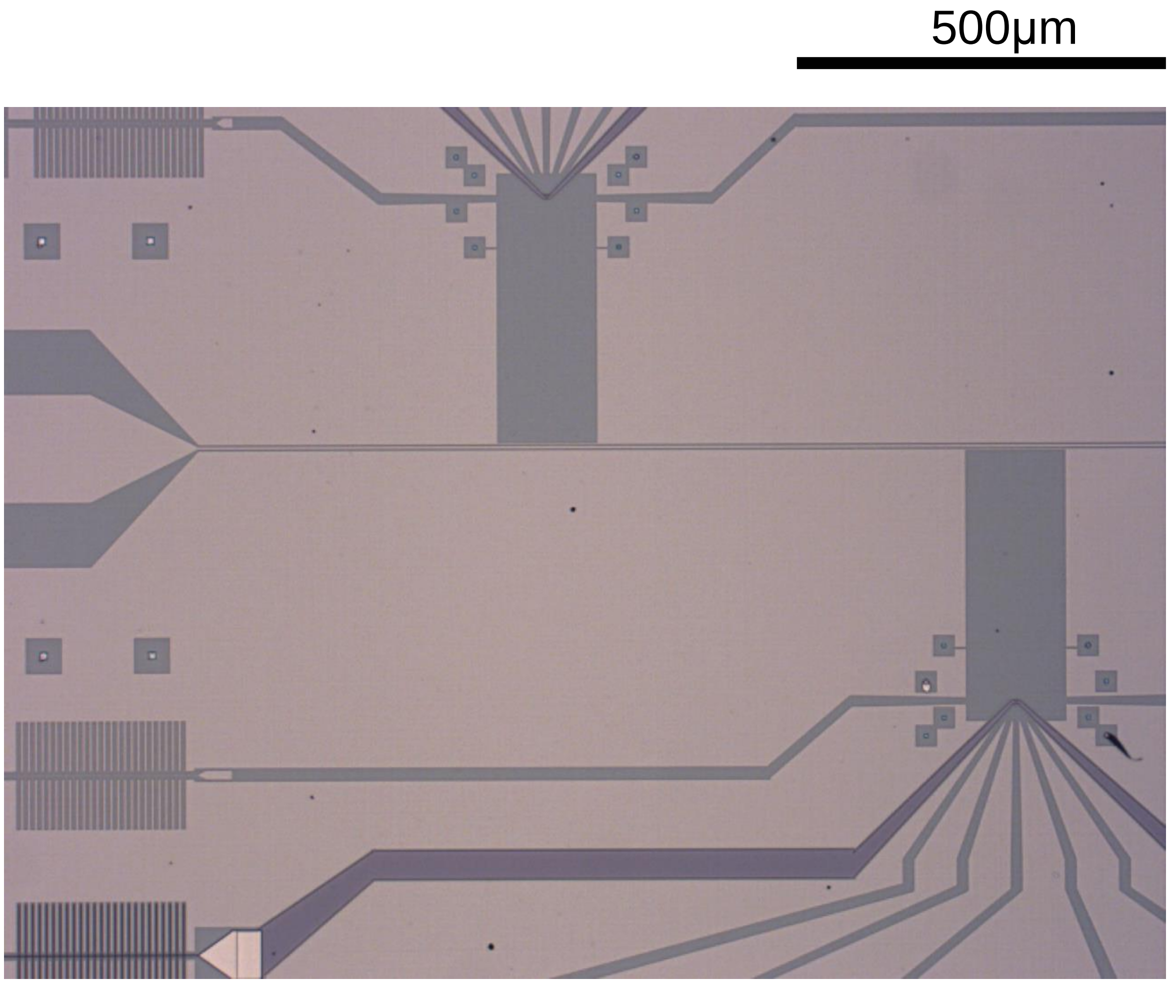

Conclusions & Outlooks

- Singlet-triplet Ge spin qubit:
  - Single-qubit gates in less than 10 ns, coherence > 15 μs
  - Tools for characterizing and mitigating errors
  - Low B field operability → cohexistence with superconducting classical & quantum electronics

Jirovec *et al.*, arXiv 2011.13755 (2020)

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Aggarwal *et al.*, arXiv 2012.00322 (2020)

on a CMOS-compatible substrate

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Thank you!

alessandro.crippa@ist.ac.at

IST AUSTRIA
Institute of Science and Technology

alessandro.crippa@nano.cnr.it

CNRNANO NEST PISA

Why holes?

Contacts: favorable work functions of many metals to inject carriers (fermi pinning)

Well: deeper than for electrons

Properties: low m* (~0.1m_e) → promotes the confinement by uniform potential landscapes

→ large extent of the wavefunction

electrical spin manipulation with no detrimental effects on coherence

ease in fab (gates pitch relaxed)