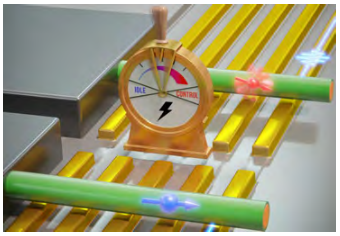
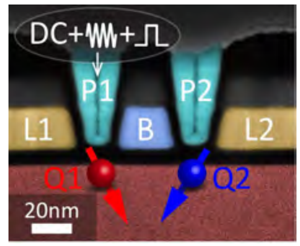
Quantum Computing with Silicon Spins

Dominik Zumbühl
University of Basel and **NCCR SPIN**

Quantum Computing Devices, Cryogenic Electronics and Packaging
IEEE Santa Clara, Tue, Oct 24, 2023



Ge/Si nanowire hole spin qubits



Si finFET hole spin qubits

Swiss National Science Foundation

NCCR SPIN

UNI BASEL

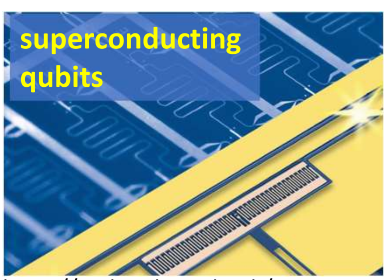
1

Qubit front runners

large and slow

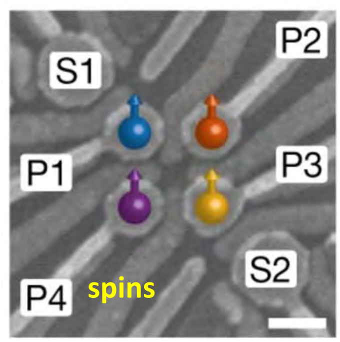
advanced, but...

https://quantumoptics.at/



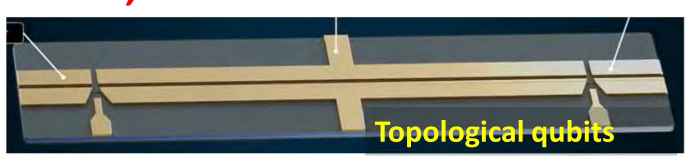
https://qudev.phys.ethz.ch/

small and fast, but...



https://qutech.nl/lab/

exotic, but...



https://www.microsoft.com/

3

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The Quantum *Computing Race*

UCSB + **Google**
sc Qubits

IBM
sc Qubits

Copenhagen+Delft+...
+**Microsoft**: Majoranas

Delft + **Intel**
Si Spins

Amazon + Caltech
sc Qubits

UNSW Sydney
Si spins

Basel + ETHs + **IBM**
Si Spins (2020)

Grenoble + **LETI**
Si spins

RIKEN
Si spins

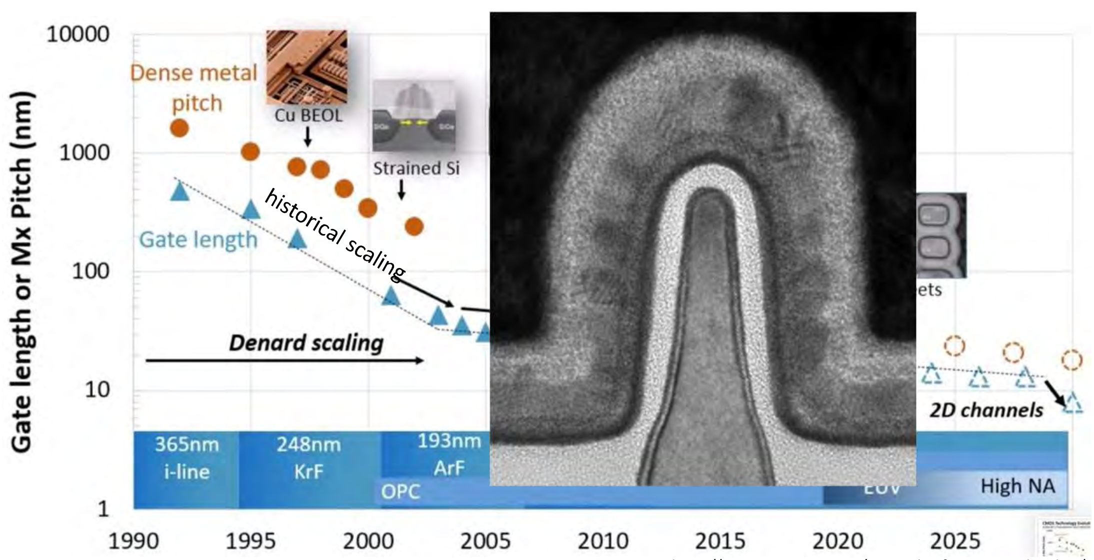
and many more, plus numerous startups...
and counting!

road maps to 10’000+ qubits...

4

4

Scaling transistors…



https://semiengineering.com/imecs-plan-for-continued-scaling/

Zumbühl, page 5

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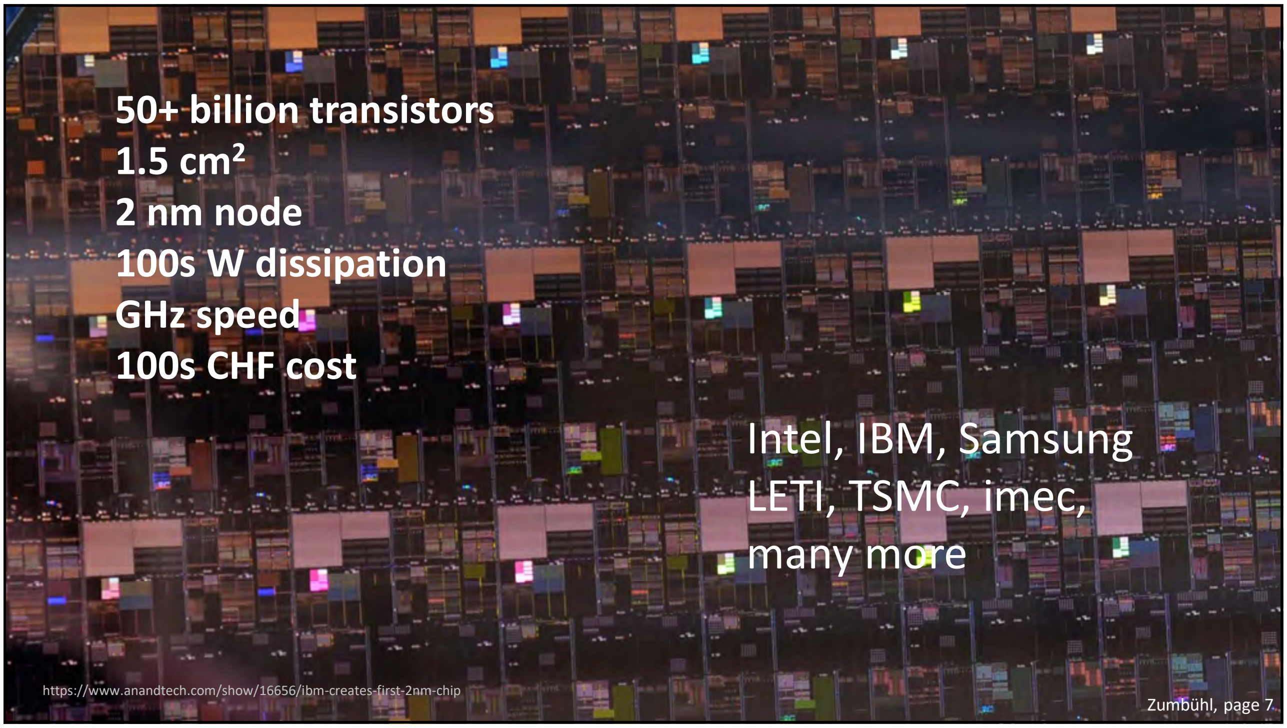

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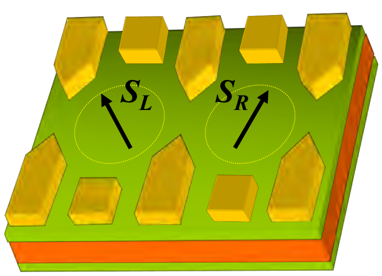
Loss-DiVincenzo Qubit

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]
[1]*Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106-4030*
[2]*Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*
[3]*IBM Research Division, T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*



spins in quantum dots
electrical control of spin qubit

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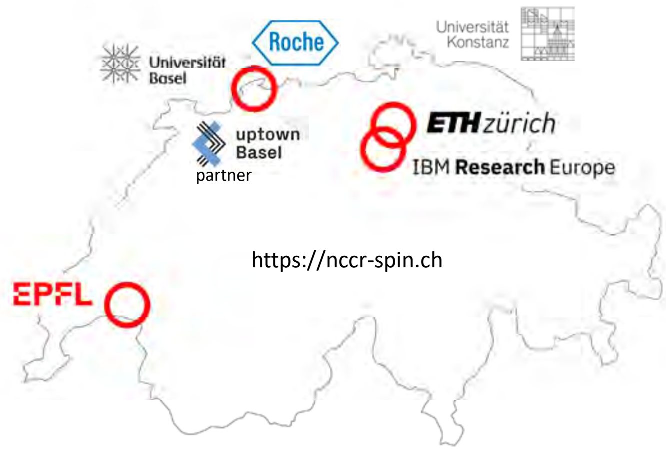
NCCR SPIN: Spin Qubits in Silicon

NCCR SPIN

- **NCCR SPIN** is developing a spin quantum computer in silicon and/or germanium
- **Main objective:** to develop fast, compact and scalable electron and hole spin qubits
- **Interdisciplinary team** from quantum physics, materials science, engineering and computer science



UNI BASEL

- Swiss network with **ETH Zurich, EPF Lausanne,** and **University of Basel** as home institution, and industrial partner **IBM Research Zurich**

Swiss National Science Foundation

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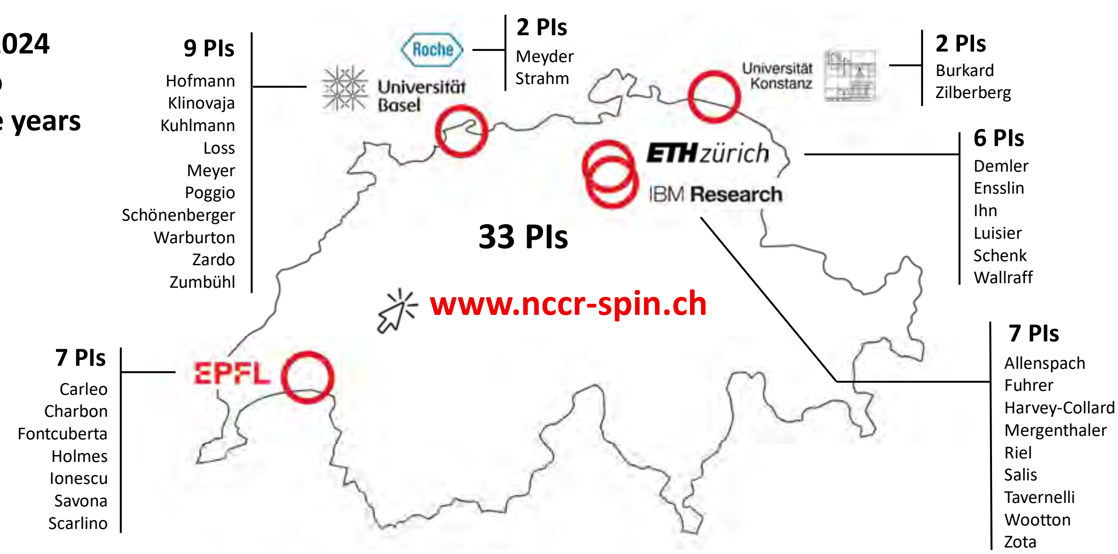
9

NCCR SPIN: Swiss Quantum Computing

2020-2024
+ up to
8 more years



04.11.2023 SPIN Swiss National Science Foundation 10

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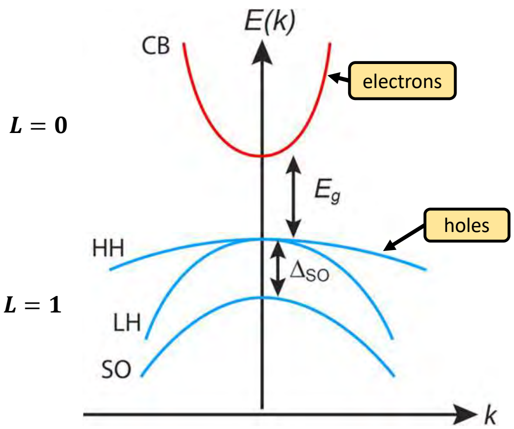
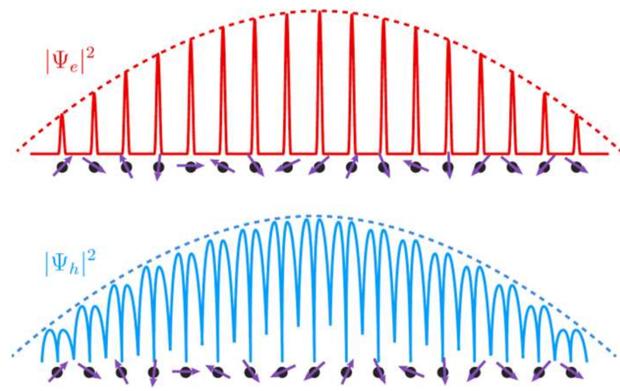
Hole spin qubits? Pros (and cons)





Adapted from Prechtel *et al.*, Nat. Mat. **15** (2016).

Spin orbit interaction: $H_{SO} \sim \boldsymbol{L} \cdot \boldsymbol{S}$
→ **fast** (all-electrical) qubits
charge noise coupling
BUT: sweet spots

No contact hyperfine-interaction
no valleys
→ **longer coherence**

Zumbühl, page 11

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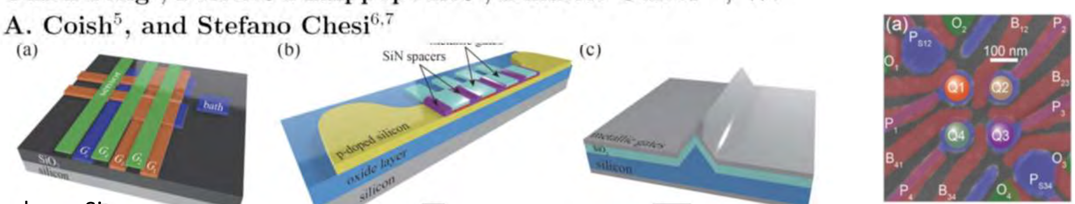
Recent advances in hole-spin qubits

Yinan Fang[1], Pericles Philippopoulos[2], Dimitrie Culcer[3,4], W. A. Coish[5], and Stefano Chesi[6,7]

arXiv:2210.13725v1 25 Oct 2022



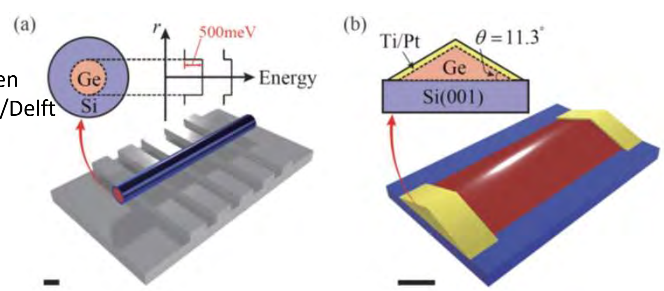
planar Si
Sydney

FD-SOI Si nanowire
Grenoble-LETI

Si FinFET
IBM - Basel

planar Ge
Delft
IST Austria

Basel
Copenhagen
Eindhoven/Delft
Grenoble
Harvard
Hefei
Pittsburgh
RIKEN
Twente



Bejing
Hefei CAS
Grenoble
IST Austria

and others…

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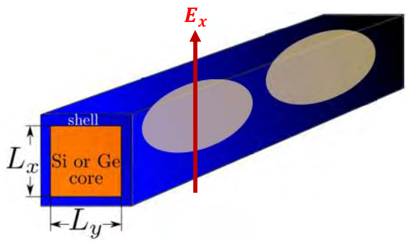
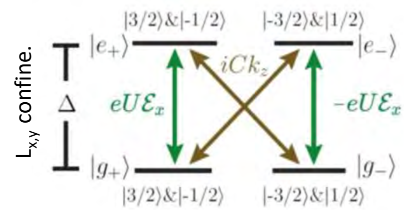
Holes in 1D: direct-Rashba SOI

Holes in 1D
strong transverse confinement
heavy-hole / light-hole mixing

→ **direct Rashba spin-orbit interaction**



Kloeffel *et al.*, Phys. Rev. B **84** (2011).
Maier *et al.*, Phys. Rev. B **87** (2013).
Kloeffel *et al.*, Phys. Rev. B **97** (2018).



strong SOI → Ultra fast qubits **1.**

$$H_R \sim \alpha\,(\boldsymbol{\sigma} \times \boldsymbol{k})$$

Traditional Rashba: $\alpha_R \propto e/E_g$ with $E_g \approx 0.9$ eV (band-gap)

Direct Rashba: $\alpha_{DR} \propto eCU/\Delta$ with $\Delta \approx 20$ meV (subband)
very strong term

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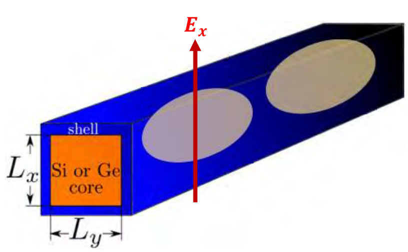
Holes in 1D: direct-Rashba SOI

Holes in 1D

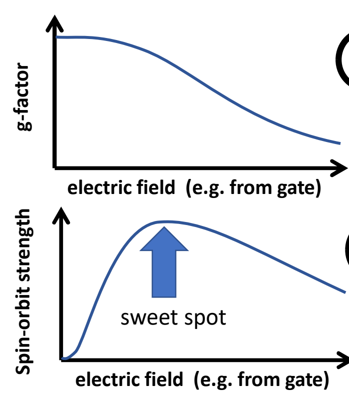
Heavy-hole / light-hole mixing

→ **direct Rashba spin-orbit interaction**



Kloeffel *et al.*, Phys. Rev. B **84** (2011).
Maier *et al.*, Phys. Rev. B **87** (2013).
Kloeffel *et al.*, Phys. Rev. B **97** (2018).

Strong **coupling** to **electric fields** → **electrical control**



2. **Qubit energy**

3. **Qubit speed**

(curves adapted from Kloeffel et al., PRB **88** (2013).)
Bosco, Hetenyi, and Loss, PRXQ **2** (2021)

Zumbühl, page 14

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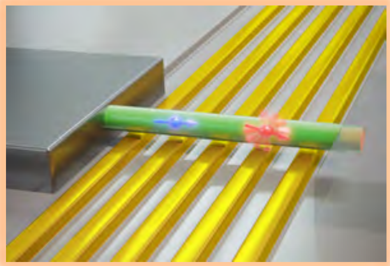
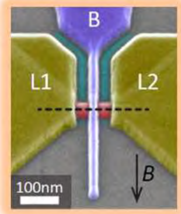
Ge/Si nanowires and Si finFETs

Germanium/Silicon core-shell NW



Kloeffel *et al.*, Phys. Rev. B **84** (2011)
Maier *et al.*, Phys. Rev. B **87** (2013)
Froning *et al.*, Appl. Phys. Lett. **113** (2018)
Froning *et al.*, Phys. Rev. Research **3** (2021)
Froning *et al.*, Nature Nano. **16** (2021)
Ungerer, Chervalier et al., Mat. QTech. 3, 031001 (2023)
Eggli, Svab et al., arXiv:2303.02933 (2023)

Silicon finFET



Kloeffel *et al.,* Phys. Rev. B **97** (2018)
Kuhlmann et al., Appl. Phys. Lett. **113** (2018)
Geyer et al., Appl. Phys. Lett. **118** (2021)
Camenzind, Geyer *et al.*, Nature Electr. **5** (2022)
Bosco *et al.*, PRX Quantum **2** (2021)
Geyer et al, arXiv:2212.02308 (2022)
Bosco, Geyer et al., Phys. Rev. Lett. in press (2023)

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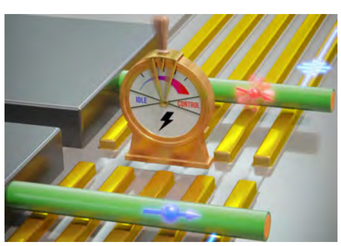
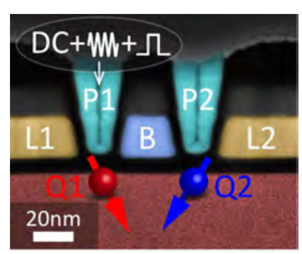
IEEE Santa Clara, Tue, Oct 24, 2023



Ge/Si nanowire hole spin qubits



Si finFET hole spin qubits

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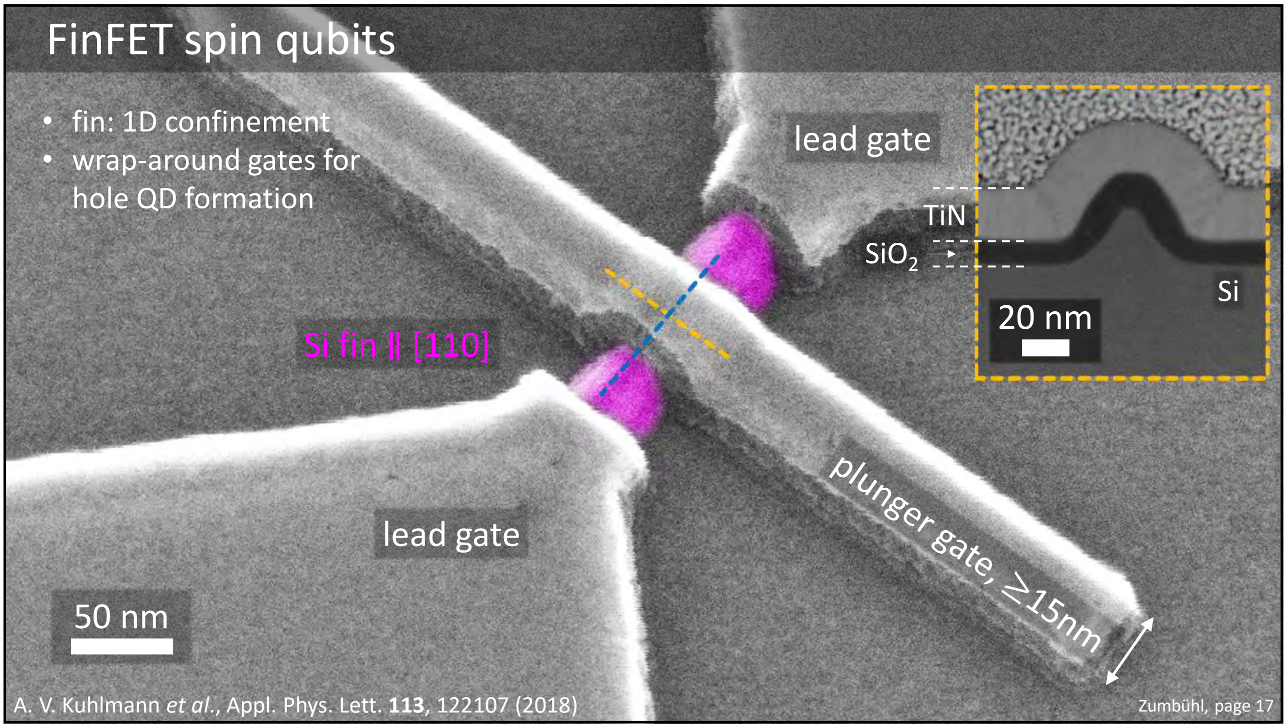
FinFET spin qubits
• fin: 1D confinement
• wrap-around gates for hole QD formation
lead gate
TiN
SiO2
Si
20 nm
Si fin ∥ [110]
lead gate
plunger gate, ≥15nm
50 nm
A. V. Kuhlmann et al., Appl. Phys. Lett. 113, 122107 (2018)
Zumbühl, page 17

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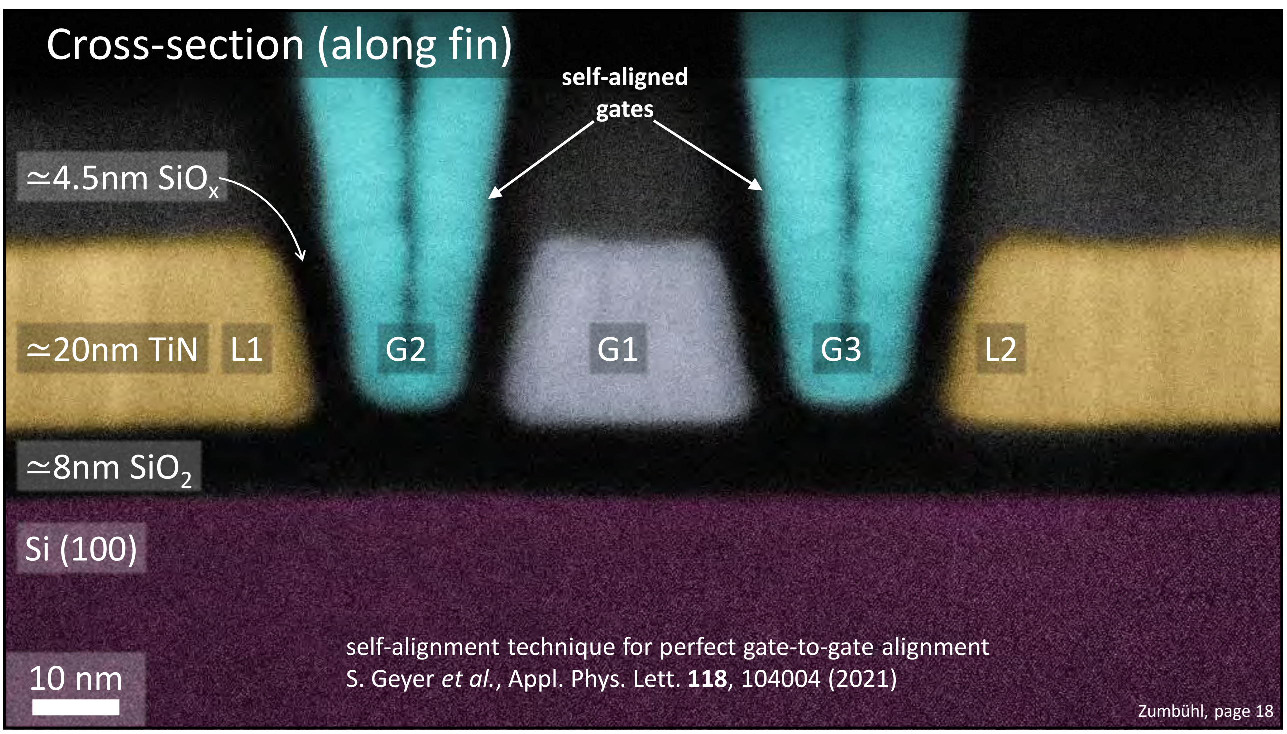
Cross-section (along fin)
self-aligned gates
≃4.5nm SiOx
≃20nm TiN
L1
G2
G1
G3
L2
≃8nm SiO2
Si (100)
10 nm
self-alignment technique for perfect gate-to-gate alignment
S. Geyer et al., Appl. Phys. Lett. 118, 104004 (2021)
Zumbühl, page 18

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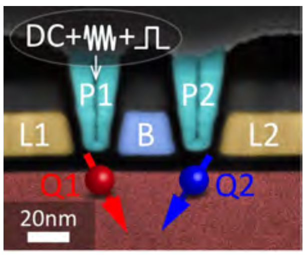
IBM Binnig Rohrer Nanotechnology Center (BRNC)

State-of-the-art mixed-use / exploratory clean room

- expertise in Si technology
- high quality devices
- fast and flexible processes



Close collaboration with team IBM
Fuhrer, Salis, Harvey-Collard

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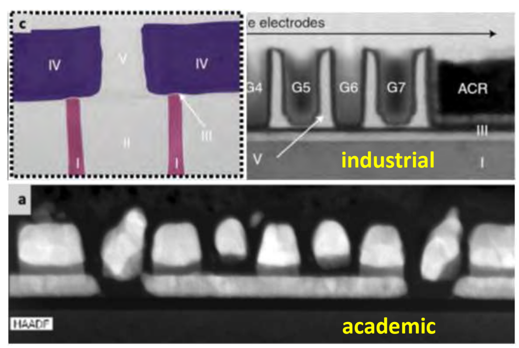
ARTICLES
https://doi.org/10.1038/s41928-022-00727-9
nature electronics

OPEN

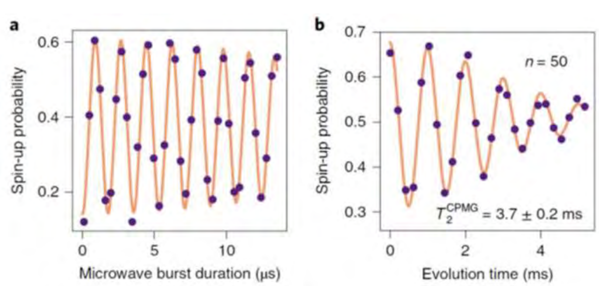
Qubits made by advanced semiconductor manufacturing

A. M. J. Zwerver[1], T. Krähenmann[1], T. F. Watson[2], L. Lampert[2], H. C. George[2], R. Pillarisetty[2], S. A. Bojarski[2], P. Amin[2], S. V. Amitonov[1], J. M. Boter[1], R. Caudillo[2], D. Correas-Serrano[2], J. P. Dehollain[1], G. Droulers[1], E. M. Henry[2], R. Kotlyar[2], M. Lodari[1], F. Lüthi[2], D. J. Michalak[2], B. K. Mueller[2], S. Neyens[2], J. Roberts[2], N. Samkharadze[1], G. Zheng[1], O. K. Zietz[2], G. Scappucci[1], M. Veldhorst[1], L. M. K. Vandersypen[1] and J. S. Clarke[2] **Delft - Intel**



- gate length 50 nm
- large aspect ratio fins
- trenches filled with oxide
- electrons (vs holes)
- full industrial all-optical process 300 mm Intel

micromagnets for spin manipulation



Nature Electronics **5**, 184 (March 2022)

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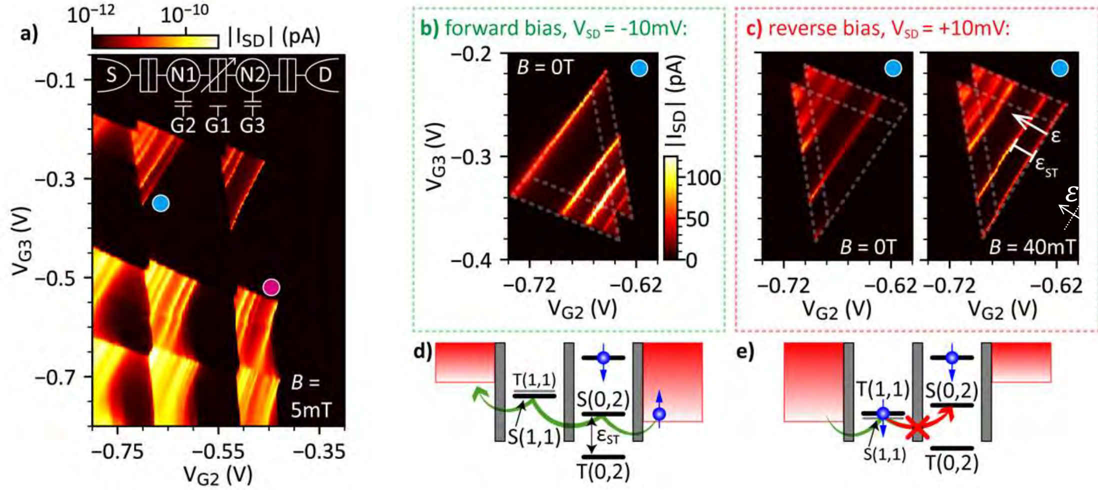
Spin blockade readout

Double dot



[1]S. Geyer *et al.*, Appl. Phys. Lett. **118**, 104004 (2021)

Zumbühl, page 22

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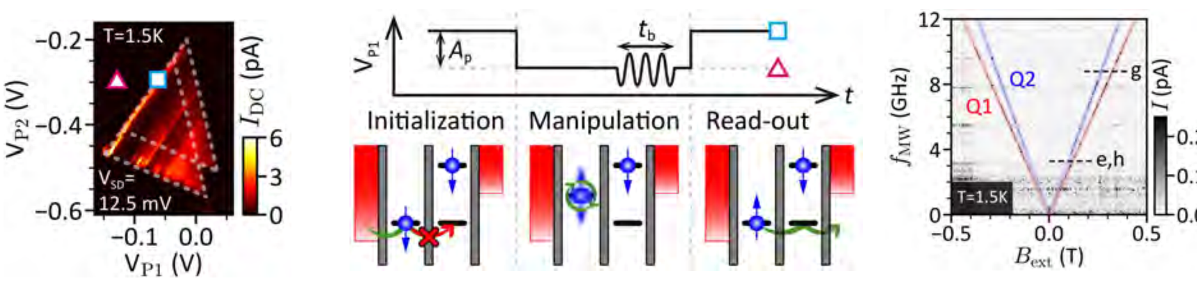
Qubit operation scheme



two qubits:
g^*_{Q1} = 1.94
g^*_{Q2} = 2.35

[1]L. C. Camenzind, S. Geyer *et al.*, **Nature Electronics** (2022)

Zumbühl, page 23

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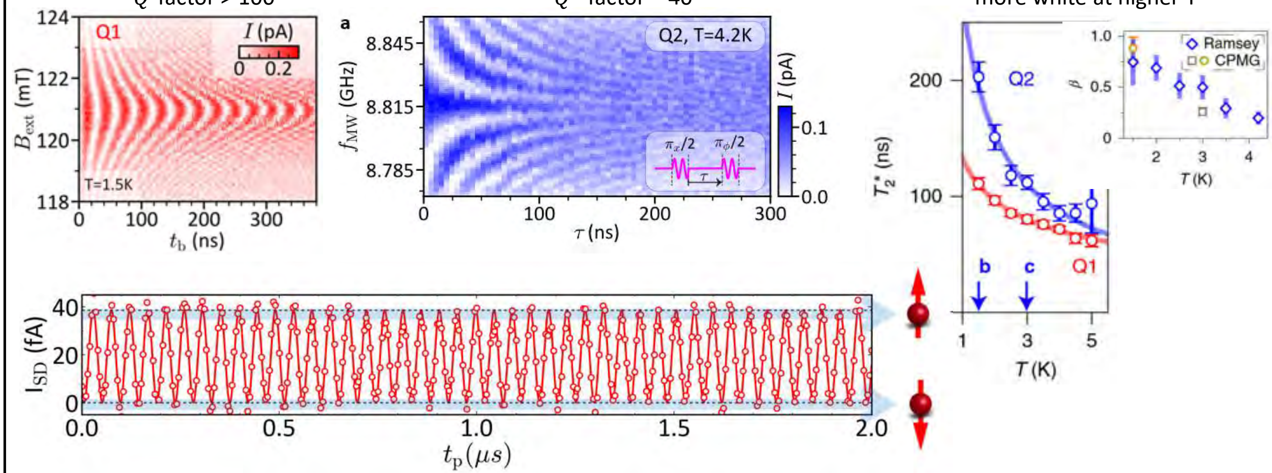
finFET qubits above 4 K

Rabi:
- f_{Rabi} ~ 150MHz
- Q-factor > 100

Ramsey:
- T_2^* ~ 440ns
- Q^*-factor ~ 40

High T > 4 K
- readout contrast vanishes
- more white at higher T



[1]L.C. Camenzind, S. Geyer *et al.*, Nature Electronics **5**, 178 (2022)

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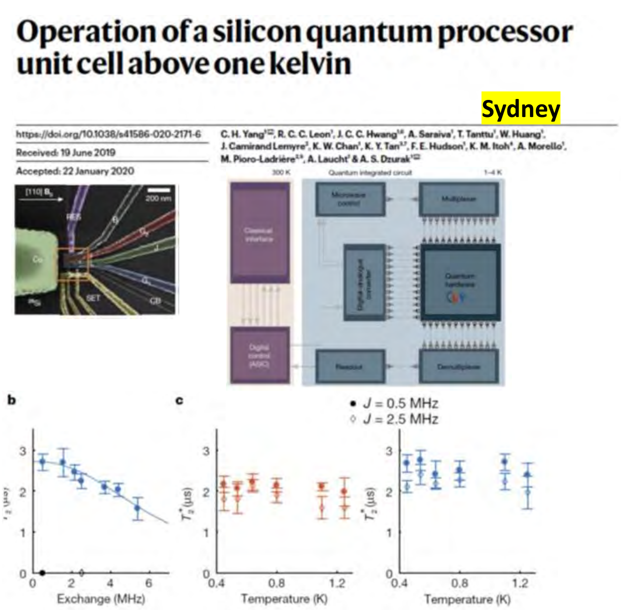
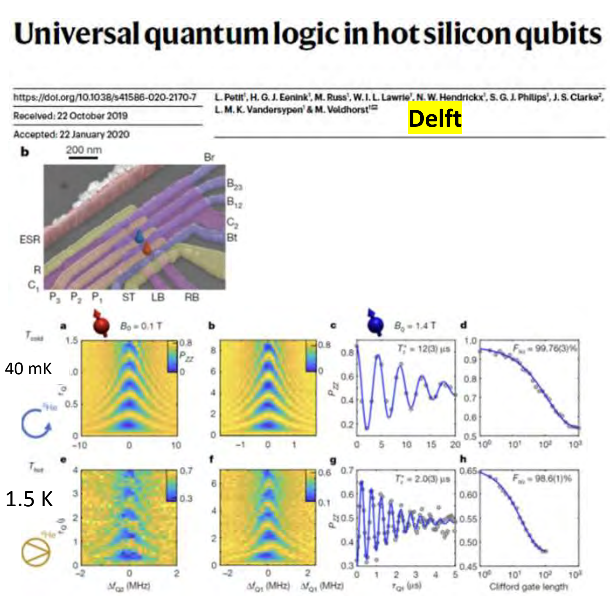


Nature **580**, 350 (Apr 2020)



Nature **580**, 355 (Apr 2020)

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Basel Precision Instruments GmbH

IV converter
low noise, floating, bias V
2 nV, 6 fA/rHz @ 10 Hz

Voltage preamp
low noise, low drift
1.8 nV/rHz @ 10 Hz

Basel Precision Instruments

https://baspi.ch
Spin-off

Basel Precision Instruments GmbH

New DC voltage source: fast scans, low noise

LNHR DAC II
12/24 DAC channels 24-bit resolution
1.2 µV step-size < 0.3 µV noise (100 Hz) ppm stability
100 Hz/ 100 kHz BW AWG functioanlity

Basel Precision Instruments

https://baspi.ch
Spin-off

Basel Precision Instruments GmbH

Microwave Filters and Thermalizers (MFT)

LNHR DAC II
12/24 DAC channels 24-bit resolution
1.2 µV step-size < 0.3 µV noise (100 Hz) ppm stability
100 Hz/ 100 kHz BW AWG functioanlity

Basel Precision Instruments

https://baspi.ch
Spin-off

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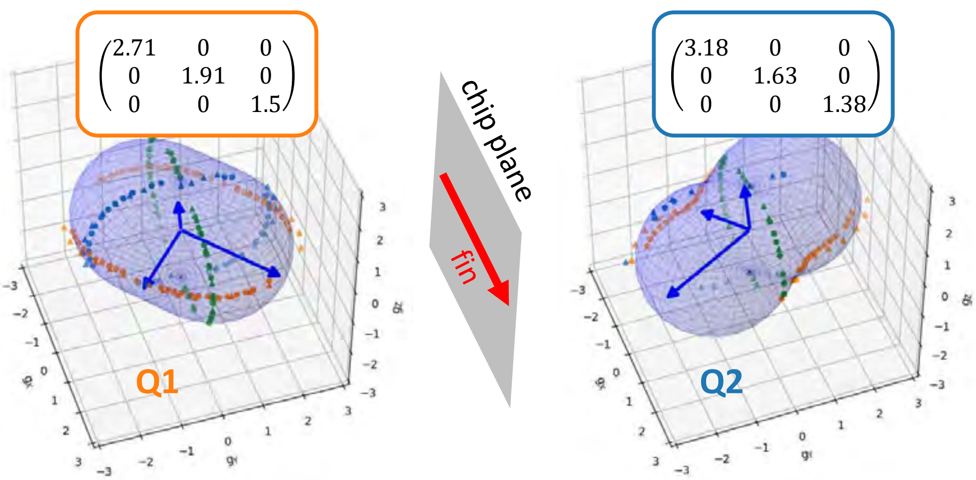
g-factor anisotropy



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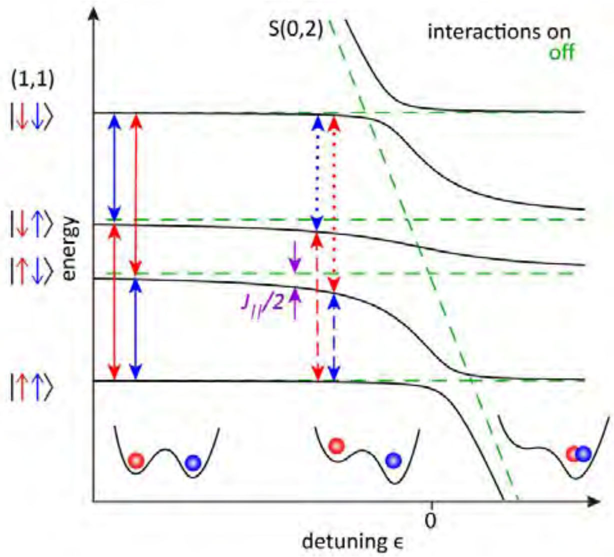
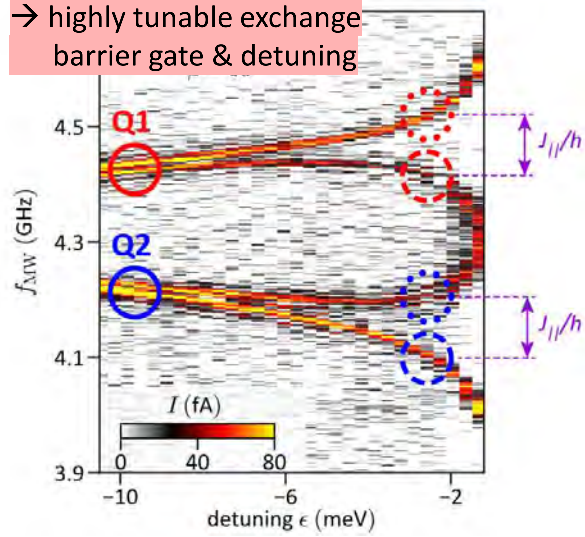
Highly tunable exchange and 2Q gate



→ highly tunable exchange barrier gate & detuning



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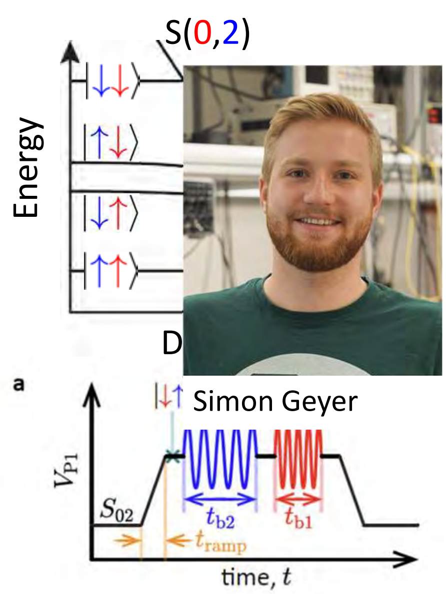
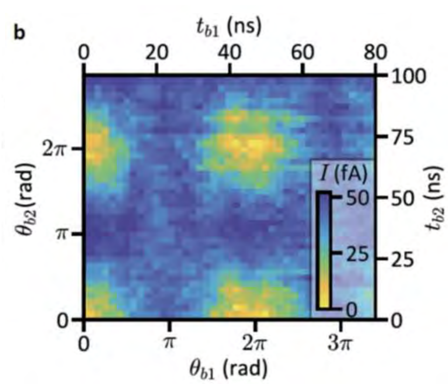
First CROT for hole spins in silicon



Coherent 2-qubit controlled rotations



Fast controlled-X (CX) gate within

$$t_{\mathrm{CX,Q2}} \simeq 27\,\mathrm{ns}$$

see also Noiri *et al.*, Nature **601**, 338 (2022)

→ First CROT for hole spins in silicon

Zumbühl, page 35

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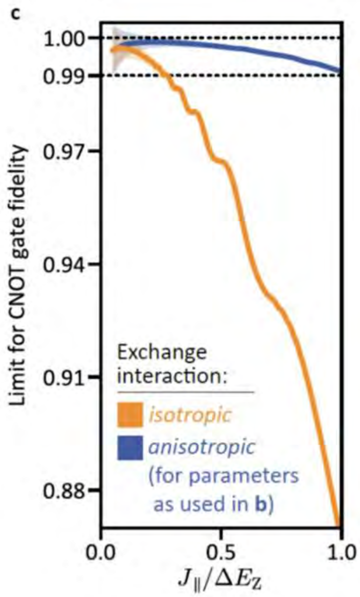
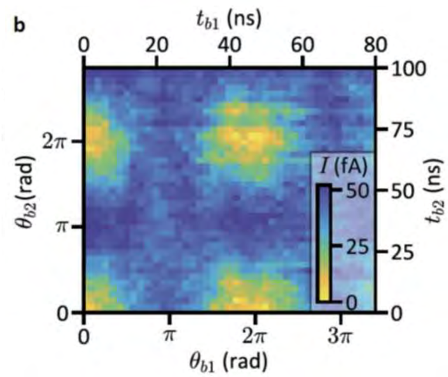
High fidelity 2Q gates



Coherent 2-qubit controlled rotations



Fast controlled-X (CX) gate within

$$t_{\mathrm{CX,Q2}} \simeq 27\,\mathrm{ns}$$

→ First CROT for hole spins in silicon

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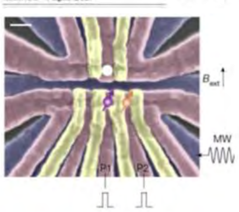
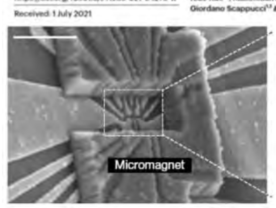
Fast universal quantum gate above the fault-tolerance threshold in silicon



Nature **601**, 338 (Jan 2022)

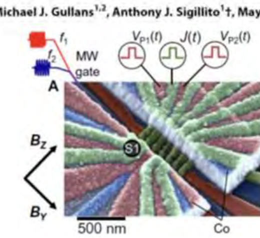
Quantum logic with spin qubits crossing the surface code threshold



Nature **601**, 343 (Jan 2022)

Two-qubit silicon quantum processor with operation fidelity exceeding 99%

Adam R. Mills[1], Charles R. Guinn[1], Michael J. Gullans[1,2], Anthony J. Sigillito[1]†, Mayer M. Feldman[1], Erik Nielsen[3], Jason R. Petta[1]*



Science Adv. **8**, (Apr 2022)

Precision tomography of a three-qubit donor quantum processor in silicon

Mateusz T. Mądzik[1,9,12], Serwan Asaad[1,10,12], Akram Youssry[2,3], Benjamin Joecker[1], Kenneth M. Rudinger[4], Erik Nielsen[4], Kevin C. Young[5], Timothy J. Proctor[5], Andrew D. Baczewski[6], Arne Laucht[1,2], Vivien Schmitt[1,11], Fay E. Hudson[1], Kohei M. Itoh[7], Alexander M. Jakob[8], Brett C. Johnson[8], David N. Jamieson[8], Andrew S. Dzurak[1], Christopher Ferrie[2], Robin Blume-Kohout[4] & Andrea Morello[1]

Nature **601**, 348 (Jan 2022)

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Qubits with Machine Learning

Identifying Pauli spin blockade using deep learning

J. Schuff, D. T. Lennon, S. Geyer, D. L. Craig, F. Fedele, F. Vigneau, L. C. Camenzind, A. V. Kuhlmann, G. A. D. Briggs, D. M. Zumbühl, D. Sejdinovic, N. Ares, › arXiv:2202.00574 (Feb 1, 2022), manuscript › pdf

Bridging the reality gap in quantum devices with physics-aware machine learning

D. L. Craig, H. Moon, F. Fedele, D. T. Lennon, B. Van Straaten, F. Vigneau, L. C. Camenzind, D. M. Zumbühl, G. A. D. Bri Sejdinovic, N. Ares, › arXiv:2111.11285 (Nov 22, 2021), manuscript › pdf

Natalia Ares, Oxford

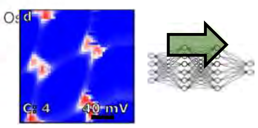
Efficiently measuring a quantum device using machine learning

D. T. Lennon, H. Moon, L. C. Camenzind, Liuqi Yu, D. M. Zumbühl, G. A. D. Briggs, M. A. Osborne, E. A. Laird, N. Ares
› npj Quantum Information 5, 79 (Sept 26, 2019), manuscript › pdf, supporting materials › pdf, arXiv: › 1810.10042
› SNI-News "Machine Learning at the Quantum Lab"

Machine learning enables completely automatic tuning of a quantum device faster than human experts

H. Moon*, D.T. Lennon*, J. Kirkpatrick, N.M. van Esbroeck, L.C. Camenzind, Liuqi Yu, F. Vigneau, D.M. Zumbühl, G.A.D. Briggs, M.A Os D. Sejdinovic, E.A. Laird, N. Ares
› Nature Communications 11, 4161 (Aug 20, 2020), manuscript › pdf, supplementary › pdf, peer review file › pdf, › arXiv:2001.02589
› Oxford University press release "AI automatic tuning delivers step forward in quantum computing"

Qubit



Zumbühl, page 45

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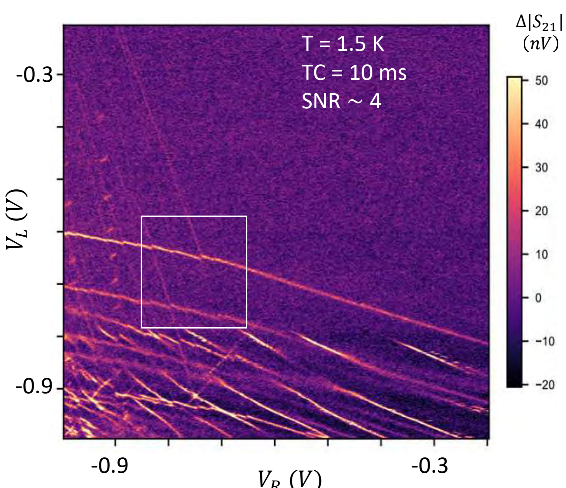
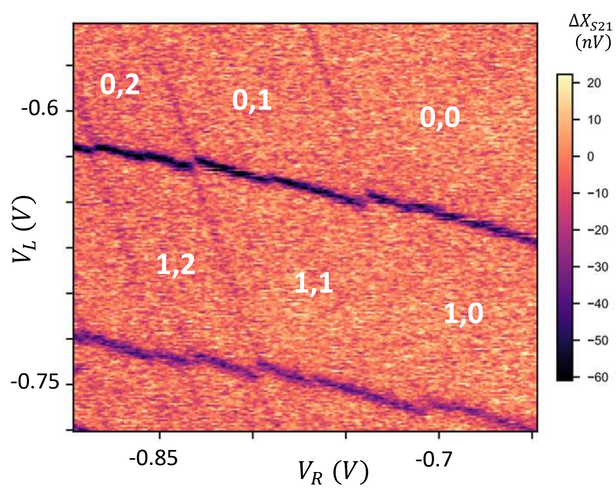
Single holes dots at 1.5 K





- Last hole regime:
  - Lead transitions continue without interruption
  - Change of slope
- No interdot transition visible in reflectometry:

Zumbühl, page 46

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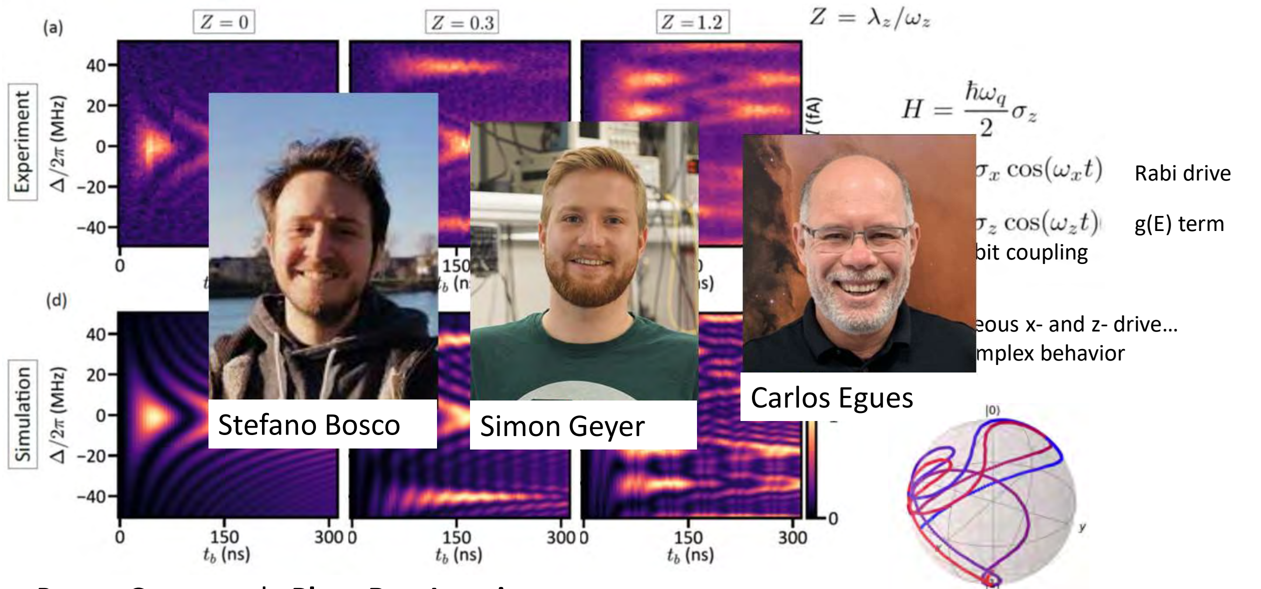
Phase driving of a hole spin qubit



Bosco, Geyer et al., **Phys. Rev. Lett. in press**

Zumbühl, page 47

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FinFET qubits: summary and outlook

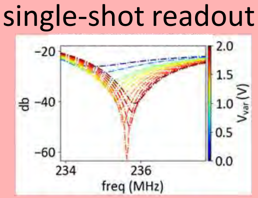
Summary

- silicon FinFET qubit at 99% 1Q
- fast all-electrical driving up to 150MHz
- record coherence T_2^* ~ 440ns (for h in Si)
- **qubit operation up to 5K**
- anisotropy and driving mechanism
- **fast 2Q logic with Si holes, anisotropic J**
- **phase drive of qubit**

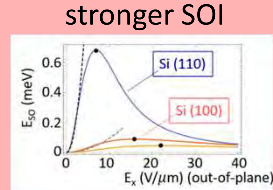
[1] Simon Geyer *et al.,* Appl. Phys. Lett. **118**, 104004 (2021)
[2] Leon C. Camenzind *et al.*, Nat. Electron. (2022).
[3] Geyer et al, arXiv:2212.02308 (2022)
[4] Bosco, Geyer et al., **Phys. Rev. Lett. in press** (2023)

In the future

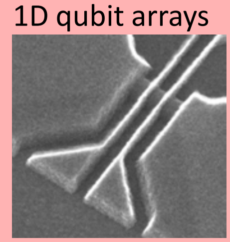
single-shot readout



stronger SOI



1D qubit arrays



Zumbühl, page 48

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FinFET team at Uni Basel and IBM

BRNC

Spin Qubits in Silicon
National Centre of Competence in Research

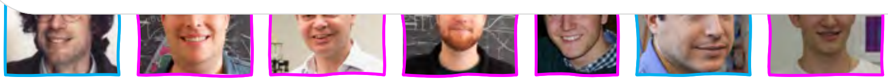
ghe GEORG H. ENDRESS STIFTUNG

Swiss National Science Foundation

Universität Basel

EMPA

SNI SWISS NANOSCIENCE INSTITUTE



Peter Müller | Rafael Eggli | Richard Warburton | Simon Geyer | Stefano Bosco | Stephan Paredes | Taras Patlatiuk

Zumbühl, page 49

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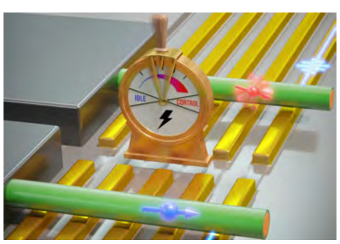
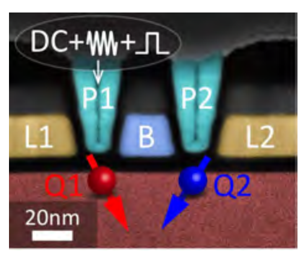
Quantum Computing with Silicon Spins

Dominik Zumbühl
University of Basel and **NCCR SPIN**

Quantum Computing Devices, Cryogenic Electronics and Packaging
IEEE Santa Clara, Tue, Oct 24, 2023



Ge/Si nanowire hole spin qubits



Si finFET hole spin qubits

Swiss National Science Foundation

NCCR SPIN

UNI BASEL

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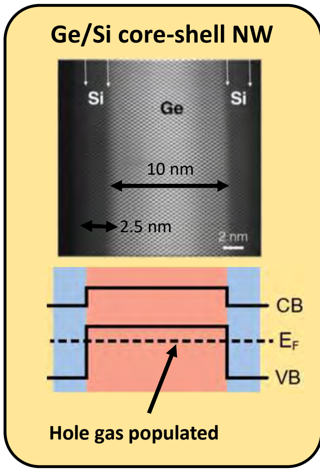
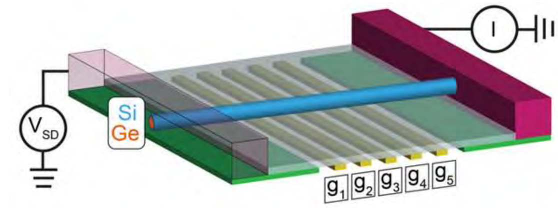
Ge/Si core/shell nanowires

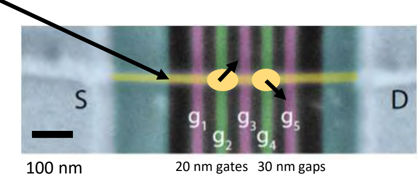


Grown by **Erik Bakkers**, TU Eindhoven

Conesa-Boj et al., Nano Lett. **17** (2017).



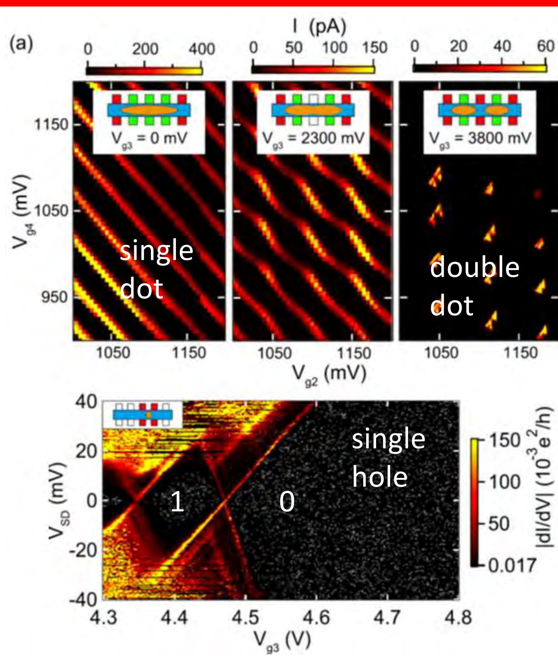
Froning *et al.,* Appl. Phys. Lett. **113** (2018).

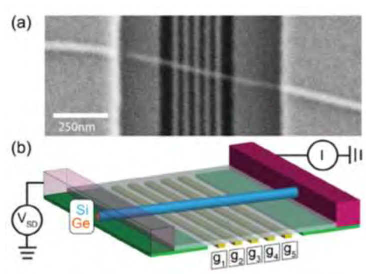


More recently: nanowires grown by Zardo group, Basel

Selective area growth (SAG) for scalability

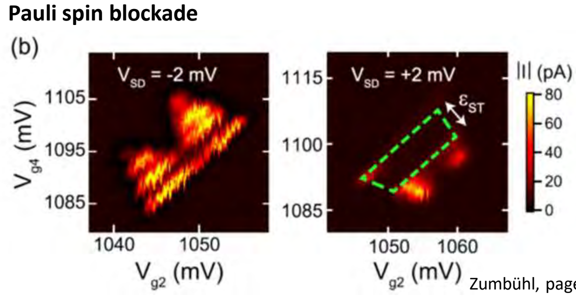
Highly tunable Ge/Si nanowire quantum dots



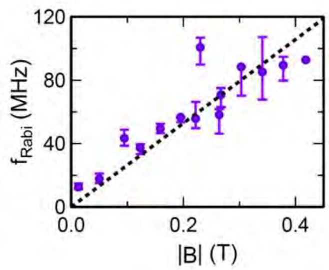


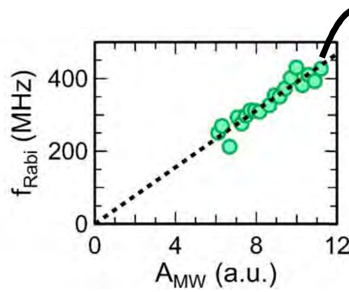
Froning et al, APL **113**, 073102 (2018)

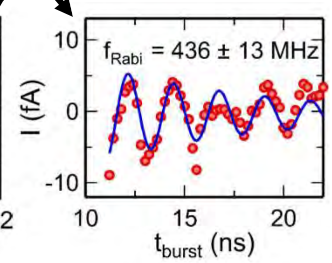
Pauli spin blockade



Ultrafast spins: coherent flips in ~1 ns!







[3]

spin-flip $T_\pi \approx$1 ns!

$l_{so} \approx$ 4 nm

(Si finFET $\approx$ 4 ns & 50 nm)

EDSR: $|f_{Rabi}| \propto |\boldsymbol{B}| \cdot \boldsymbol{A_{MW}} \cdot \frac{1}{E_{orb}^2 \cdot l_{so}}$ [1,2]

1. Ultra fast qubit

Froning *et al.*, Nature Nano (2021).

*[1] Nowack et al., Science **318** (2007). [2] Golovach et al., Phys. Rev. B. **74** (2006).*

[3] 540 MHz in (Ge hut wires): Wang et al., Nature Communications 13, 2022

Zumbühl, page 56

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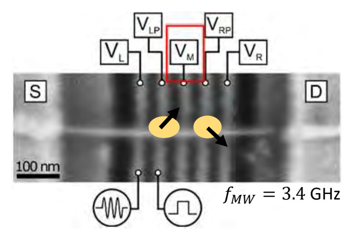
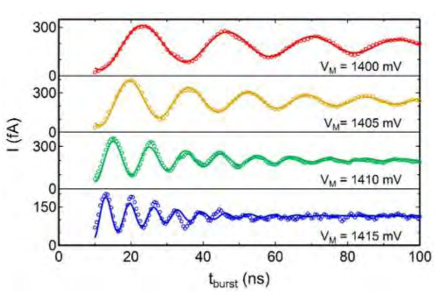
Gate voltage control of qubit: *spin-orbit switch*



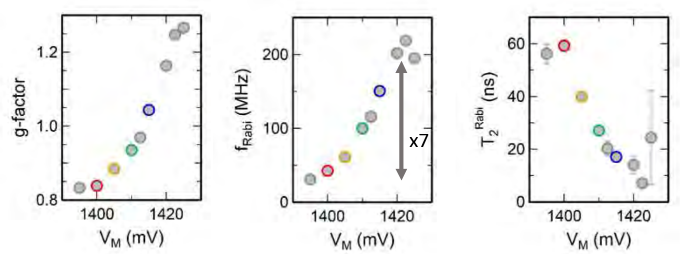
Coherent Rabi oscillations



2. **Qubit energy**

3. **Qubit speed**

Coherence



stronger DR-SOI → faster qubit

stronger coupling to charge noise

Froning *et al.*, Nature Nano (2021).

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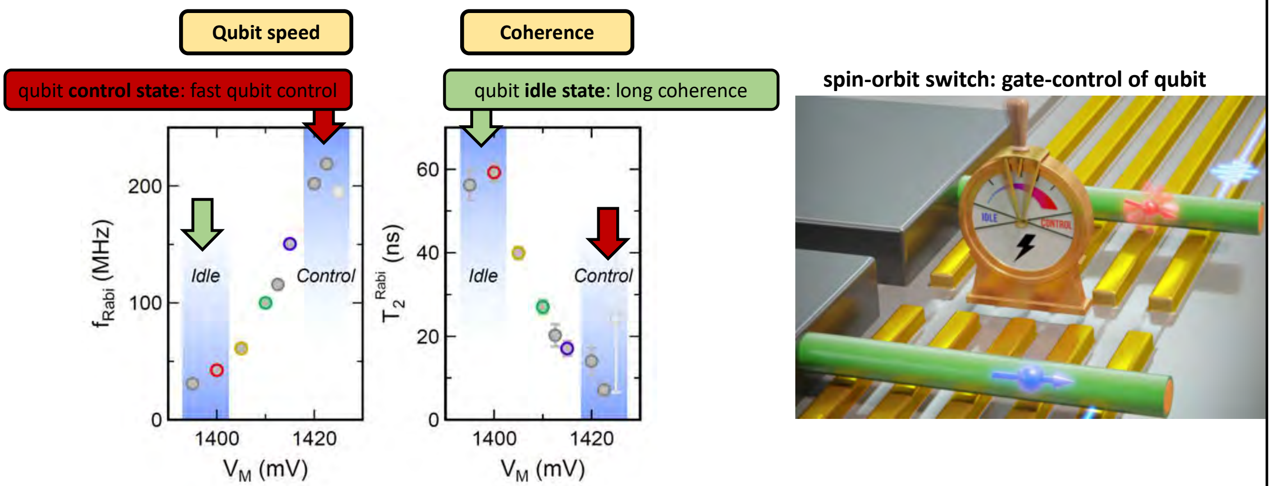
The spin-orbit switch



Froning *et al.*, Nature Nano (2021).

Zumbühl, page 59

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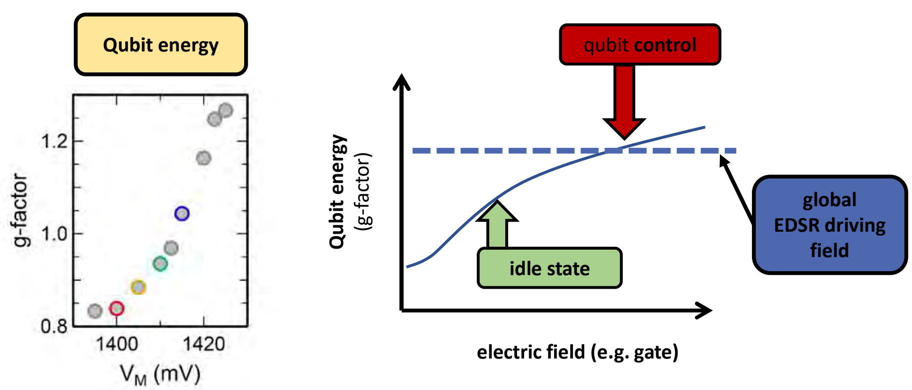
The spin-orbit switch: qubit energy



theory curve adapted from Kloeffel *et al.*, PRB 88 (2013).

Zumbühl, page 60

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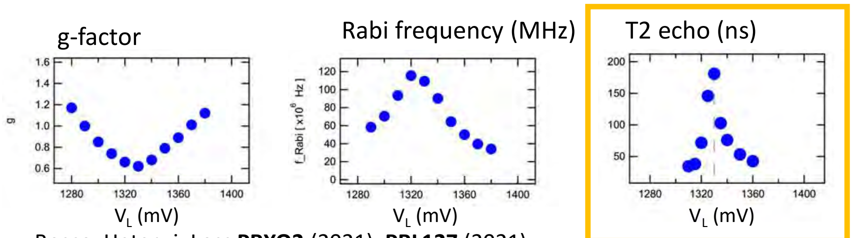
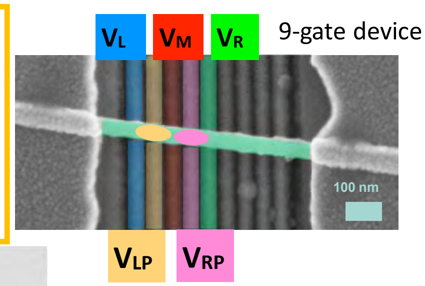
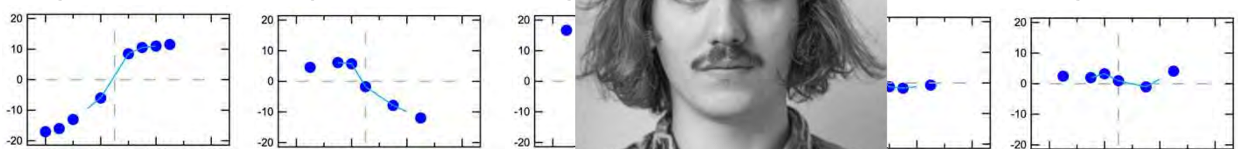
Double sweet-spot: maximizing qubit coherence and speed





Bosco, Hetenyi, Loss **PRXQ2** (2021), **PRL127** (2021)
Michal, Niquet et al. **PRB107** (2023)

g-factor gate-derivatives ***vanish***



Miguel Carballido

Zumbühl, page 70

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ARTICLES
https://doi.org/10.1038/s41565-022-01196-z

nature nanotechnology

OPEN

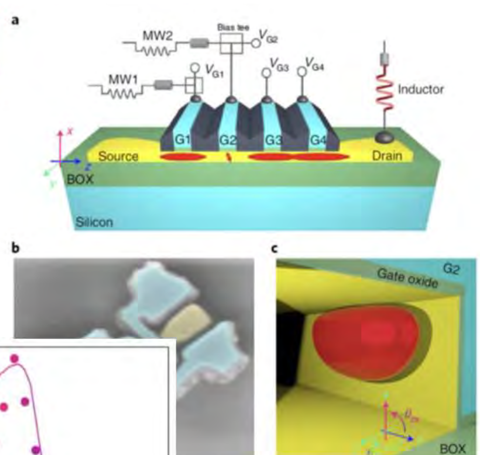
A single hole spin with enhanced coherence in natural silicon

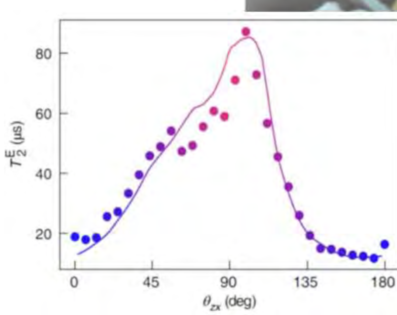
N. Piot[1,5], B. Brun[1,5], V. Schmitt[1], S. Zihlmann[1], V. P. Michal[2], A. Apra[1], J. C. Abadillo-Uriel[2], X. Jehl[1], B. Bertrand[3], H. Niebojewski[3], L. Hutin[3], M. Vinet[3], M. Urdampilleta[4], T. Meunier[4], Y.-M. Niquet[2], R. Maurand[1] and S. De Franceschi[1] **Grenoble**

- undoped Si [110] nanowire
- 17 nm and thick 100 nm wide rectangular
- wrapping gates 40 nm spaced by 40 nm
- gaps filled by Si_3N_4
- corner/wall dots, boron doped source-drain pads
- full industrial all-optical process 300 mm LETI

sweet spots with excellent coherence!

Nature Nanotechnology **17**, 1072 (Oct 2022)





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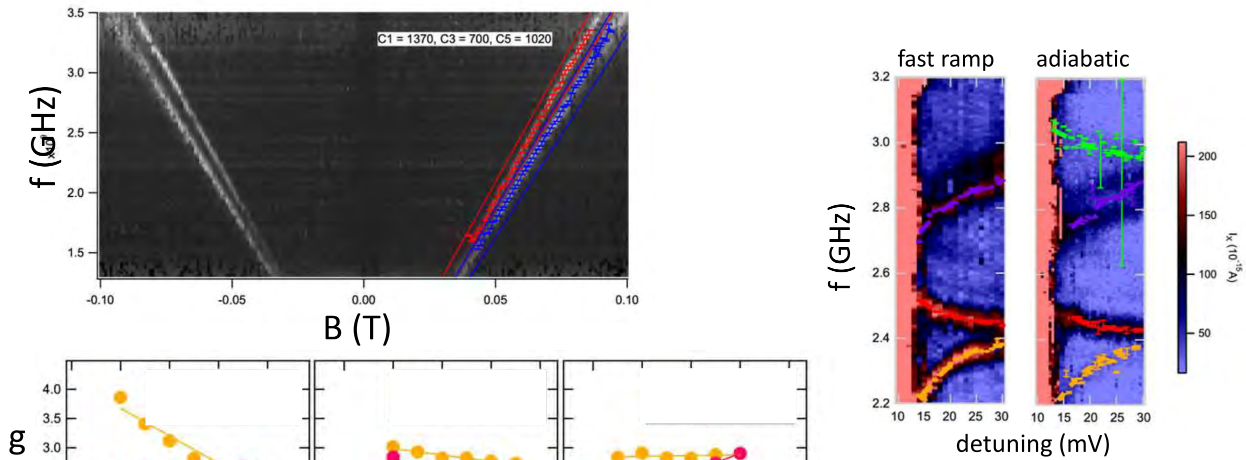
2 Qubit exchange coupling J



left gate affects
left qubit

right gate affects
right qubit

Exchange J
up to 300 MHz !

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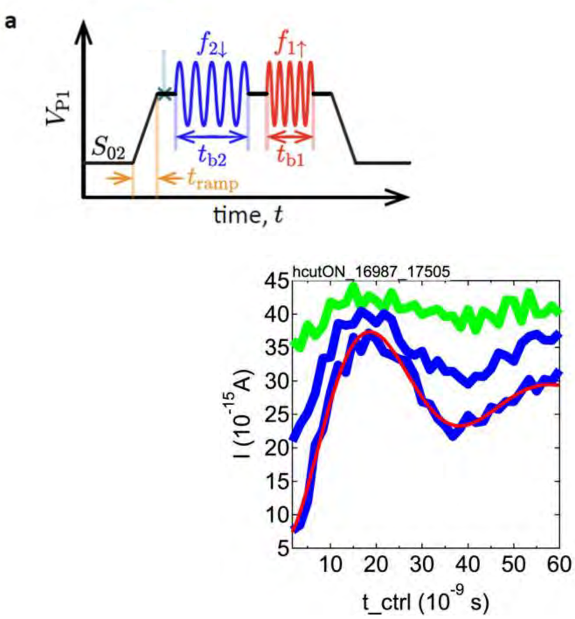
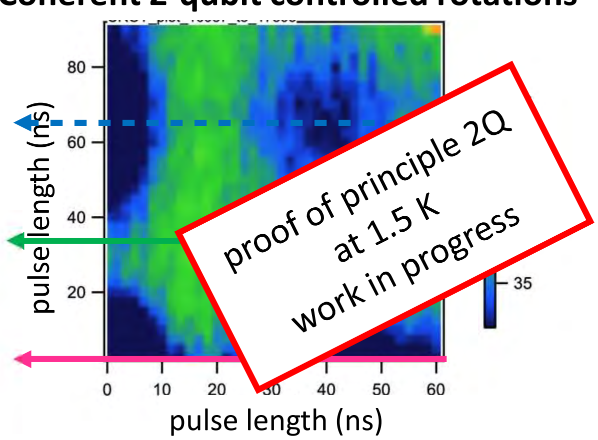
controlled-ROT gate 1.5 K



Coherent 2-qubit controlled rotations



Fast controlled-X (CX) gate 18 ns
(J ~ 40 MHz)

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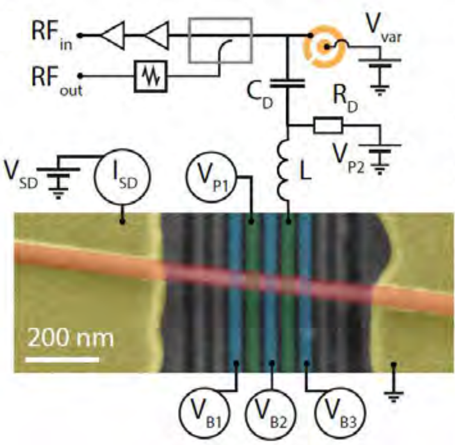
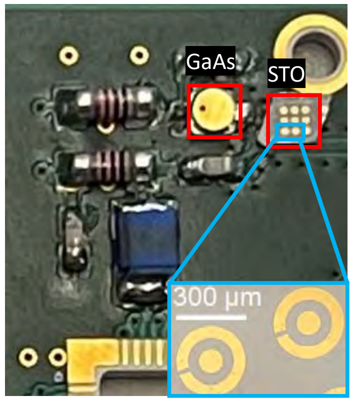
SrTiO Varactors: Impedance matching at 15 mK





Ge/Si core/shell nanowire quantum dot device[1,2]

Eggli, Svab et al., arXiv:2303.02933 (Mar 6, 2023)

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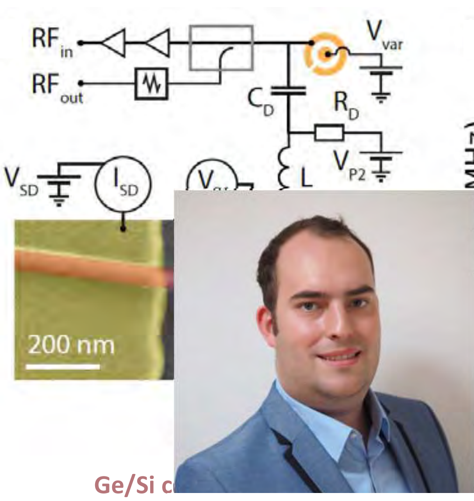
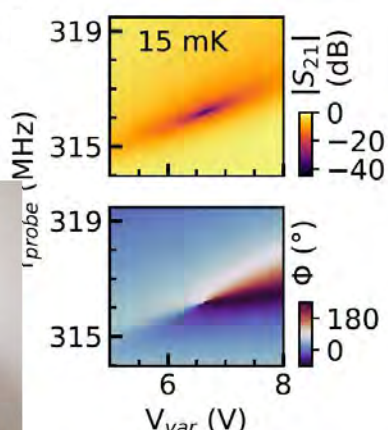
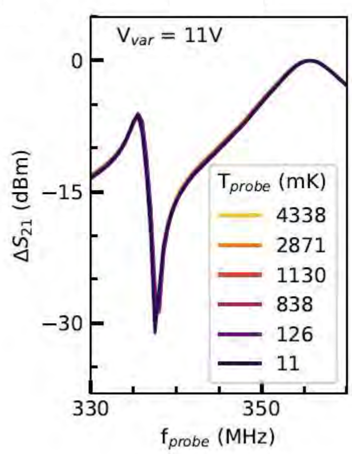
SrTiO Varactors: Impedance matching at 15 mK



Ge/Si c
quantu **Rafael Eggli**



Perfect impedance matching:
- moderate V_{var}
- only 1 varactor



Highly resilient to temperature-changes

Eggli, Svab et al., arXiv:2303.02933 (Mar 6, 2023)

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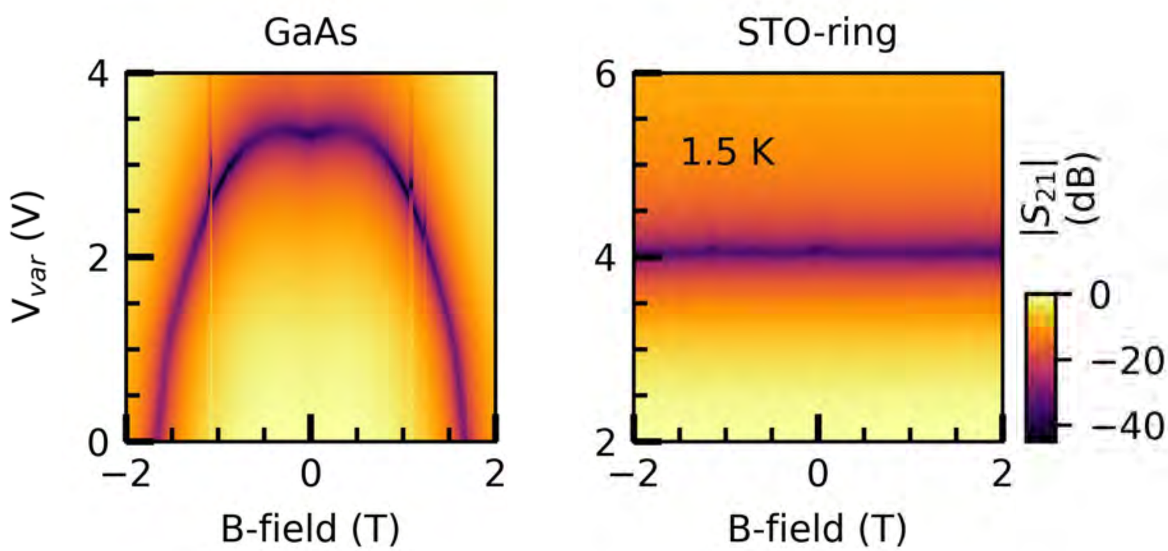
STO Varactors: B-field resilient



Eggli, Svab et al., arXiv:2303.02933 (Mar 6, 2023)

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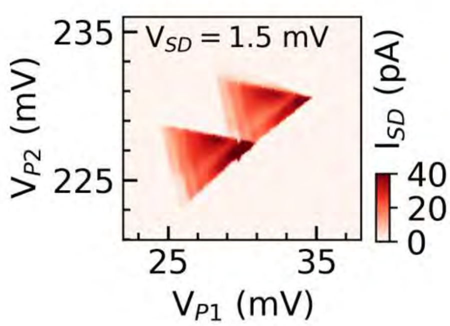
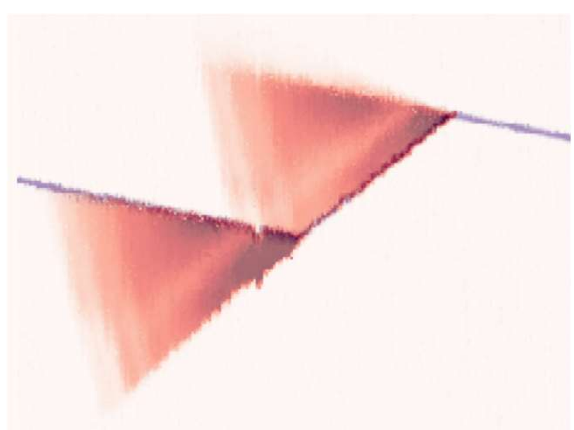
Dispersive charge sensing





Bias triangles in DC current: DQD

Eggli, Svab et al., arXiv:2303.02933 (Mar 6, 2023)

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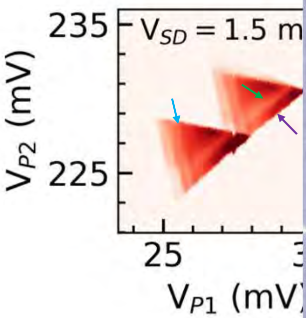
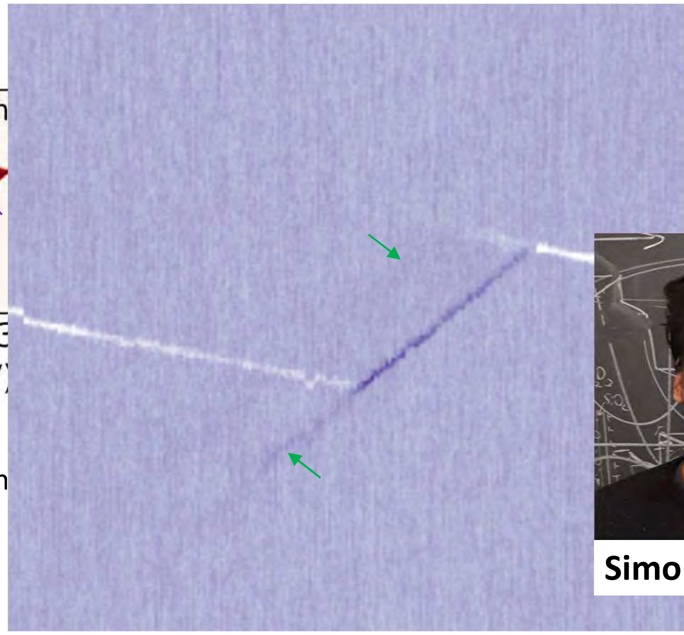
Dispersive charge sensing





ion

Simon Svab

Bias triangles in current: DQD

Eggli, Svab et al., arXiv:2303.02933 (Mar 6, 2023)

Zumbühl, page 79

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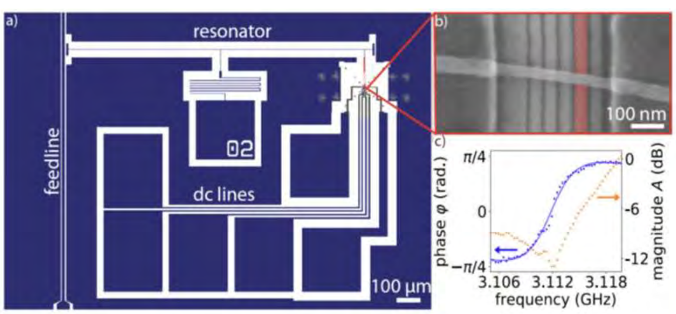
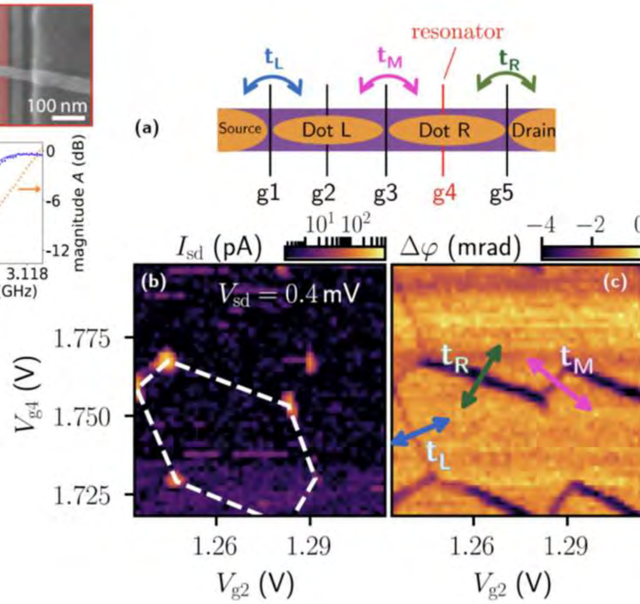
Dispersive charge sensing with a NbTiN resonator





Collaboration with Schönenberger, Baumgartner

Ungerer, Chervalier et al.,
Mat. QTech. **3**, 031001 (2023)

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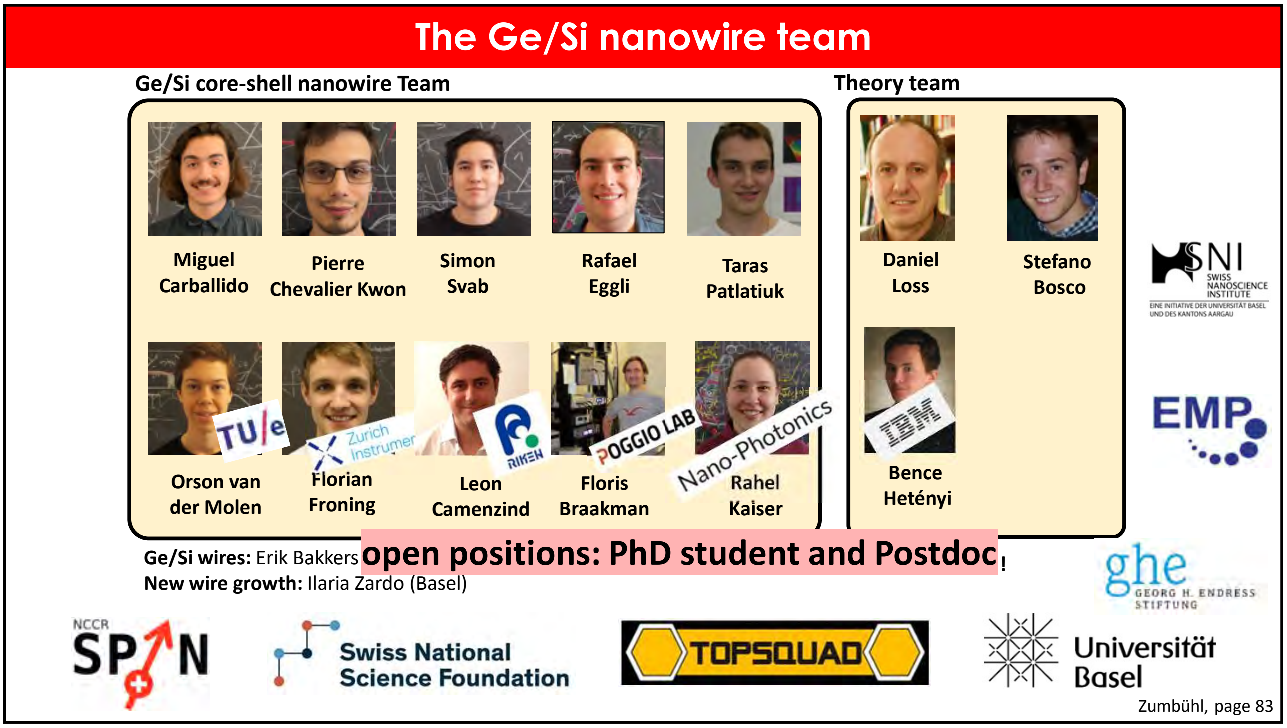

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Ge/Si nanowire qubit conclusions

- **Ge/Si core/shell nanowire qubits operating at 1.5 K**
- Dominant source of decoherence: Ge/Si nanowire / shell… (not ALD oxide)
- **Gate-voltage sweet spot**
- **Fast J-based CROT gate at 1.5 K**
- **STO varactors for dispersive readout**
  B-field resilient and operating at mK

Next steps

- Dispersive readout of a qubit device
- High-Z superconducting resonator coupling (Basel, EPFL and ETHZ)
- Improvement of nanowire growth: coherence and scaling

Zumbühl, page 84

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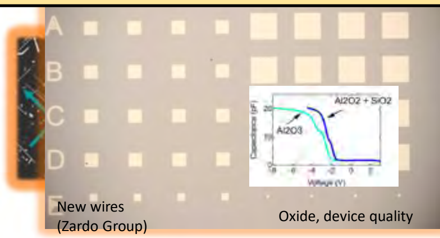
Outlook on Ge/Si hole spin qubits

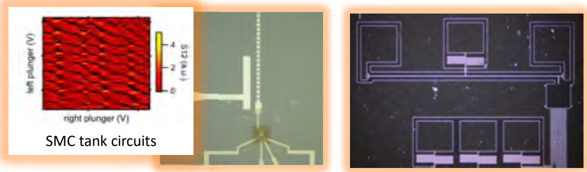
Improving coherence: wires & shells



New wires (Zardo Group)

Oxide, device quality

Charge sensing, resonator coupling

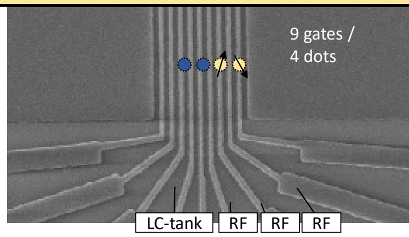


SMC tank circuits

SQUID array resonator (w. Wallraff Group)

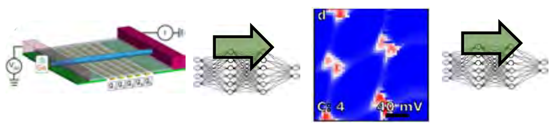
NbTiN resonator (w. Schönenberger Group)

More qubits, 2-Q gates RBM



Automated tuning, control & optimisation

Device QDs/ PSB Qubit



Machine learning Ares Group, Oxford
Severin *et al.*, arXiv:2107.12975 (2021).

Zumbühl, page 85

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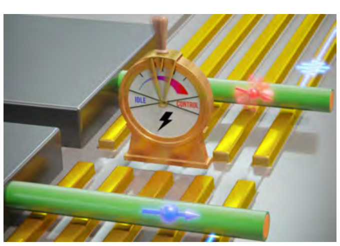
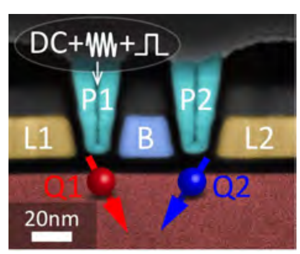
Quantum Computing with Silicon Spins

Dominik Zumbühl
University of Basel and **NCCR SPIN**

Quantum Computing Devices, Cryogenic Electronics and Packaging
IEEE Santa Clara, Tue, Oct 24, 2023



Ge/Si nanowire hole spin qubits



Si finFET hole spin qubits

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