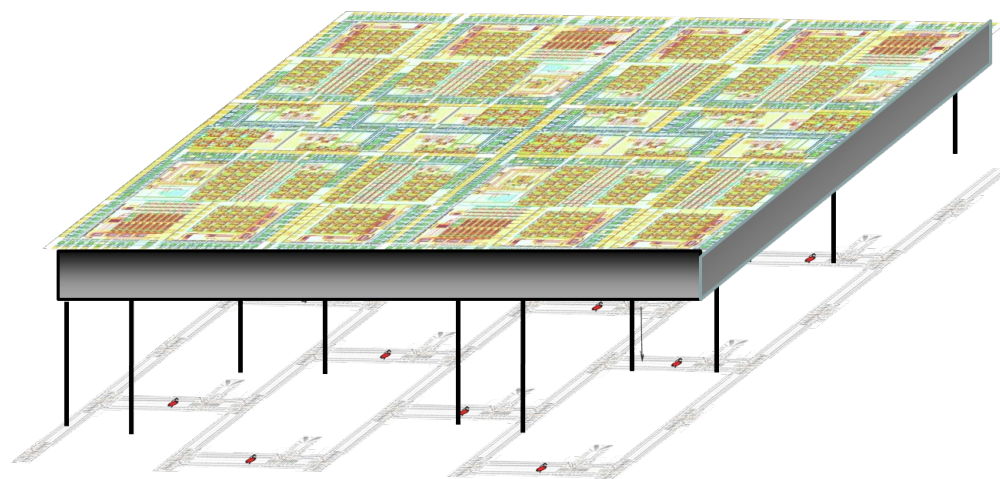
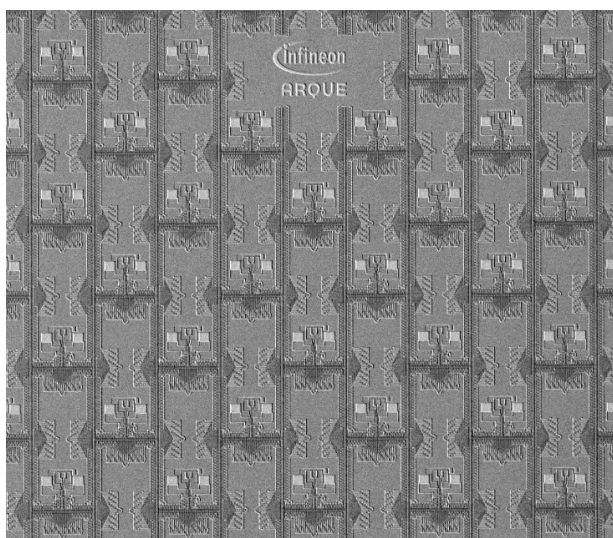


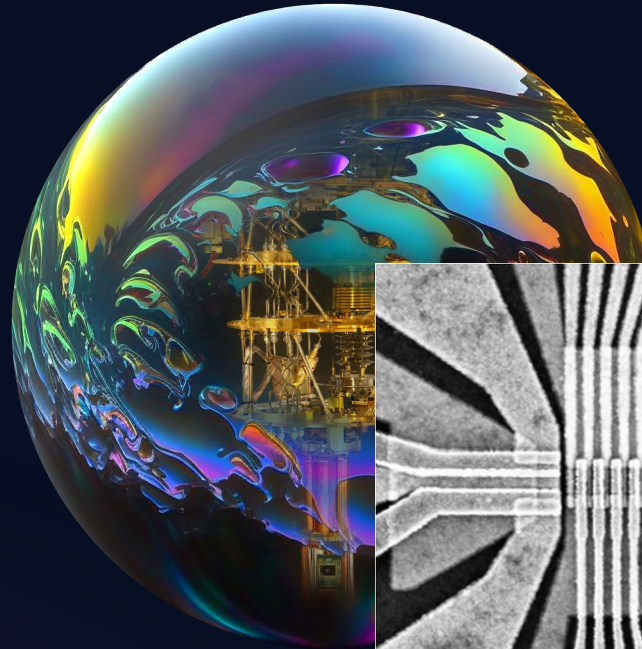
Towards utility-scale Si/SiGe-based quantum computers “Made in EU”

Hendrik Bluhm



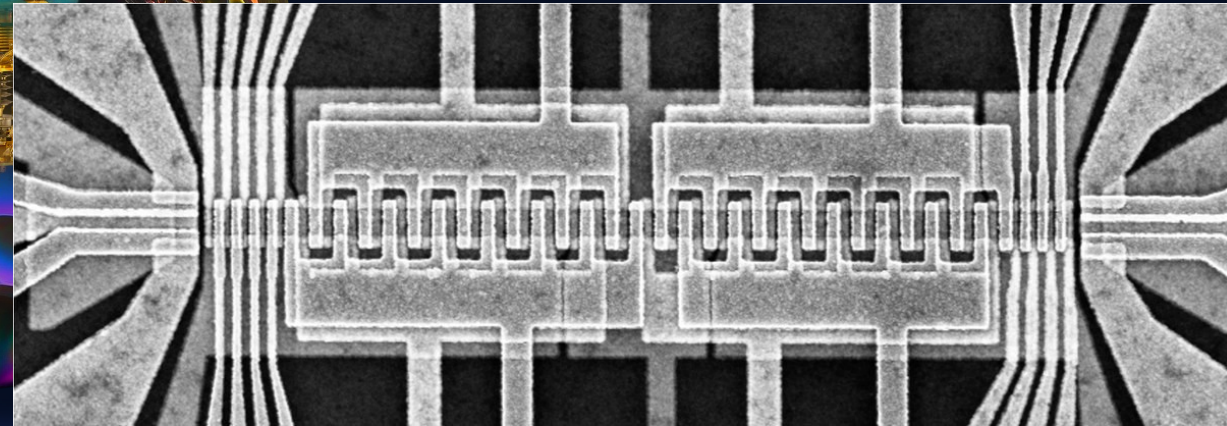
ARQUE





First 5-qubit system sold !

<https://www.fz-juelich.de/en/news/archive/announcements/2024/a-new-quantum-computer-for-juniq>



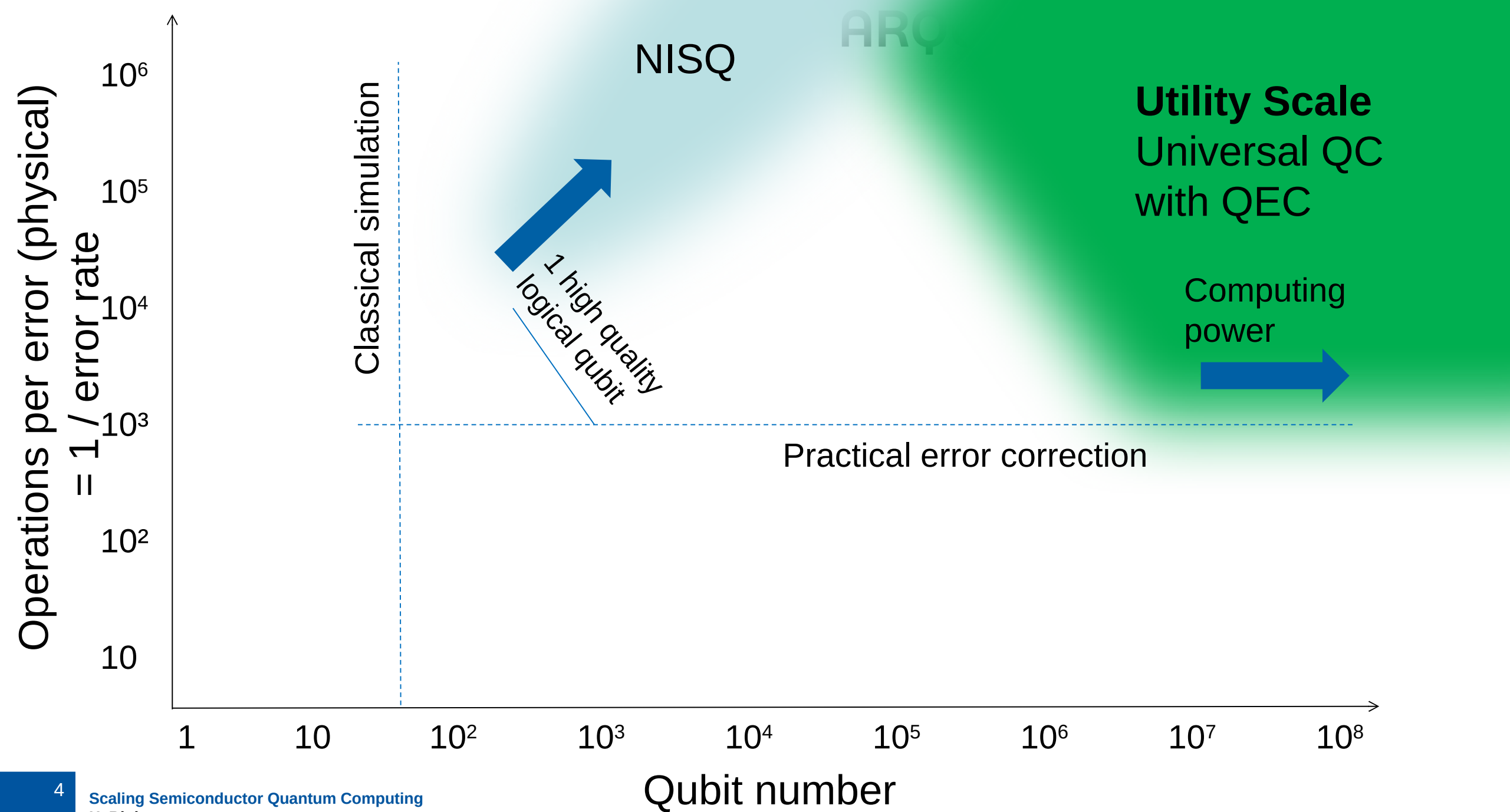
ARQUE Systems GmbH

A spinoff of RWTH and Forschungszentrum Jülich

Mission: Scalable semiconductor quantum computer

... and tools to develop it.

- Semiconductor qubits are now reaching outstanding performance and reproducibility.
- EU is (still) in a strong position.
- We have a concrete technical plan how to reach utility scale.



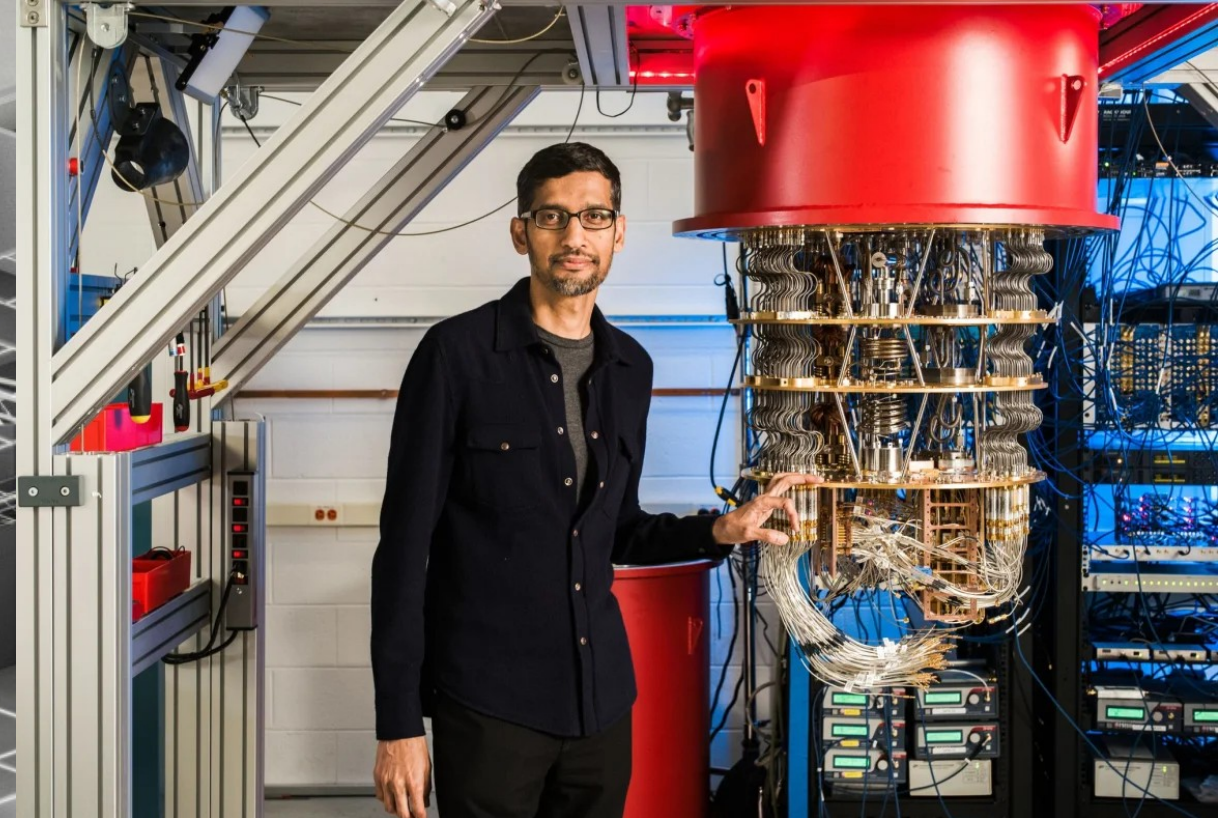
IBM Quantum Starling

200 logical qubits

100 million quantum gates

—

2029



<https://quantumcomputingreport.com/ibm-reveals-more-details-about-its-quantum-error-correction-roadmap/>

June 2025

IBM Quantum Blue Jay

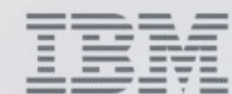
2000 logical qubits

1 billion quantum gates

—

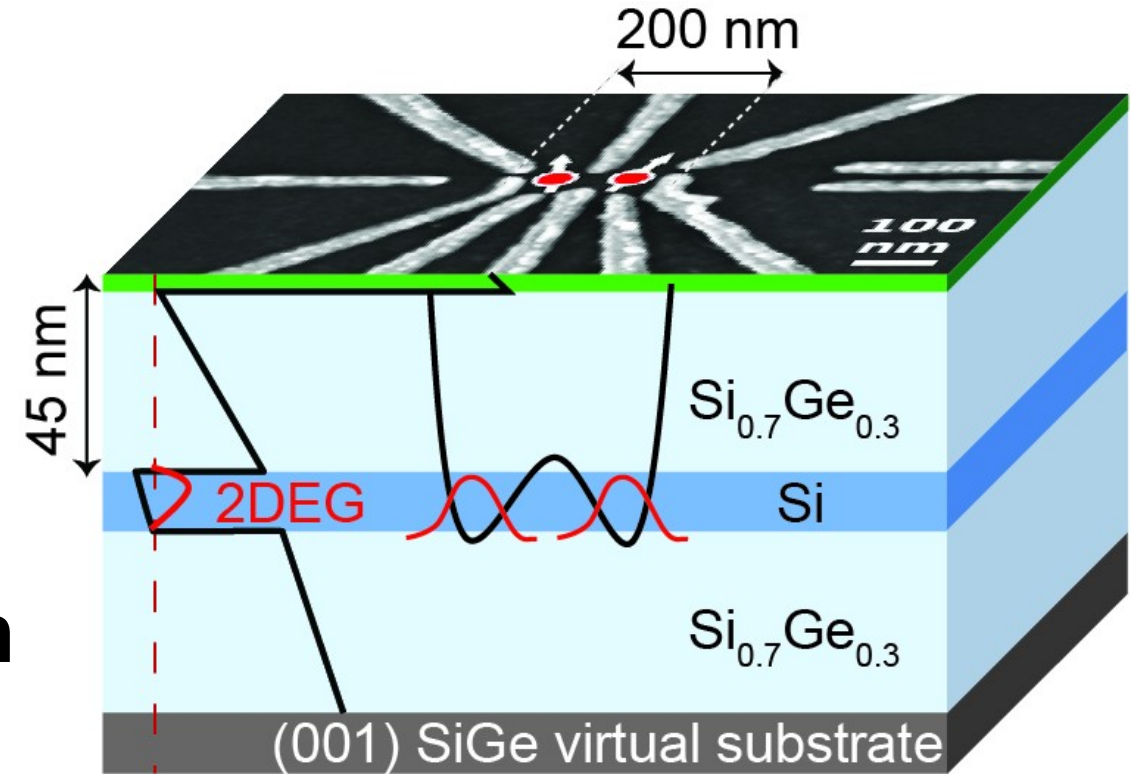
2033+

IBM Quantum Data Center
Poughkeepsie, New York



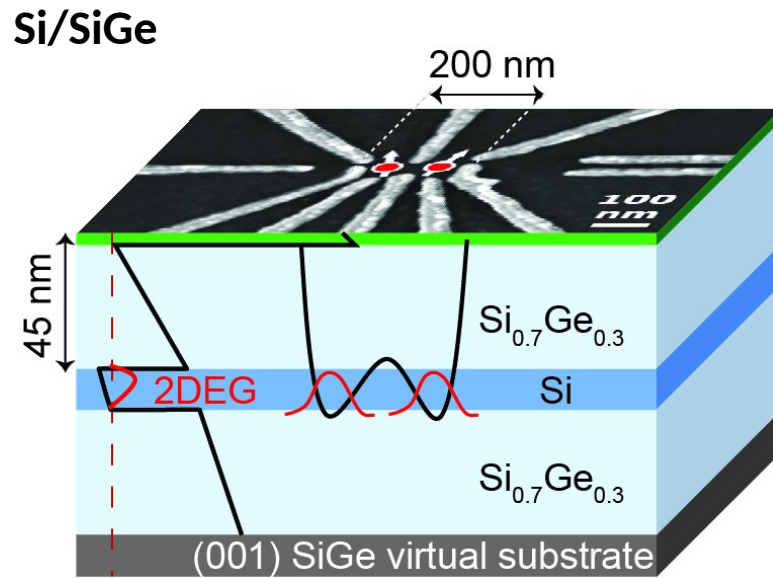
... use spin of carriers in transistor-like structures

- ⇒ **Small size**
- ⇒ **Very good coherence**
- ⇒ **CMOS-compatible production**
- + Fast operation**



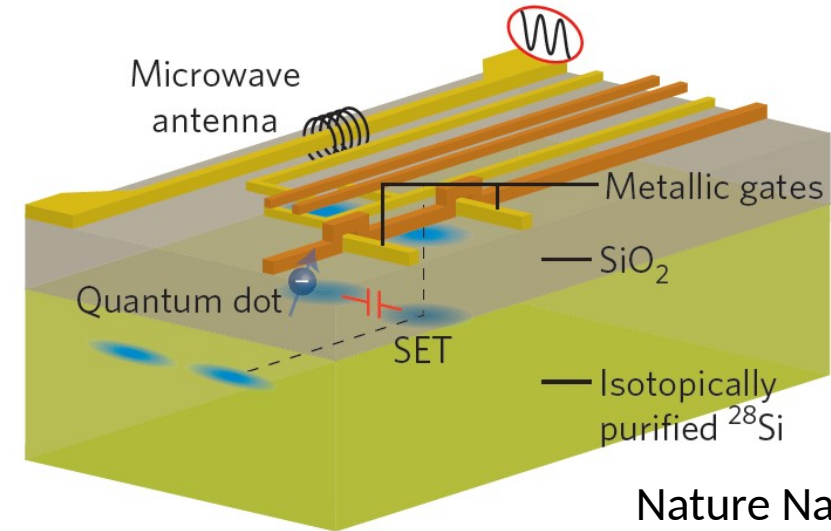
Excellent, reproducible in-system error rates

Complementary platforms



- + Crystalline qubit environment
- + Spatial separation from interface defects
- (-) Lower valley splitting
- (-) Standard CMOS-processes with adaptation

MOS



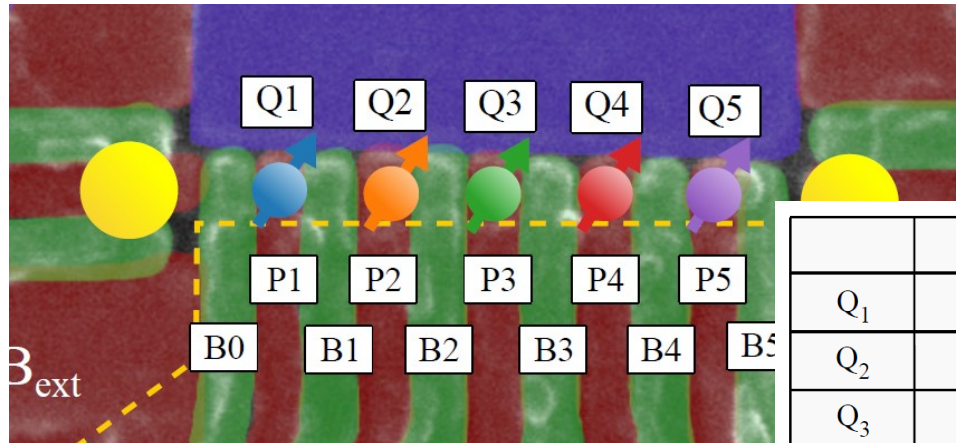
Nature Nano 2014

- Qubits at oxide interface
- Strong disorder effects
- + Higher valley splitting
- + Standard CMOS-processes
- Smaller feature size needed

Qubit fidelity and coherence

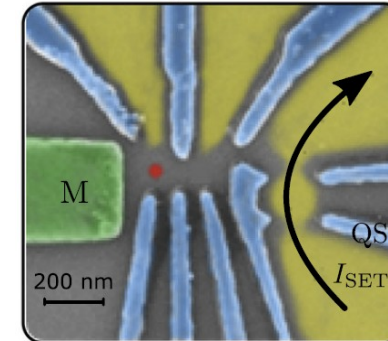
Best fidelity

10^{-5} (reported at conference)



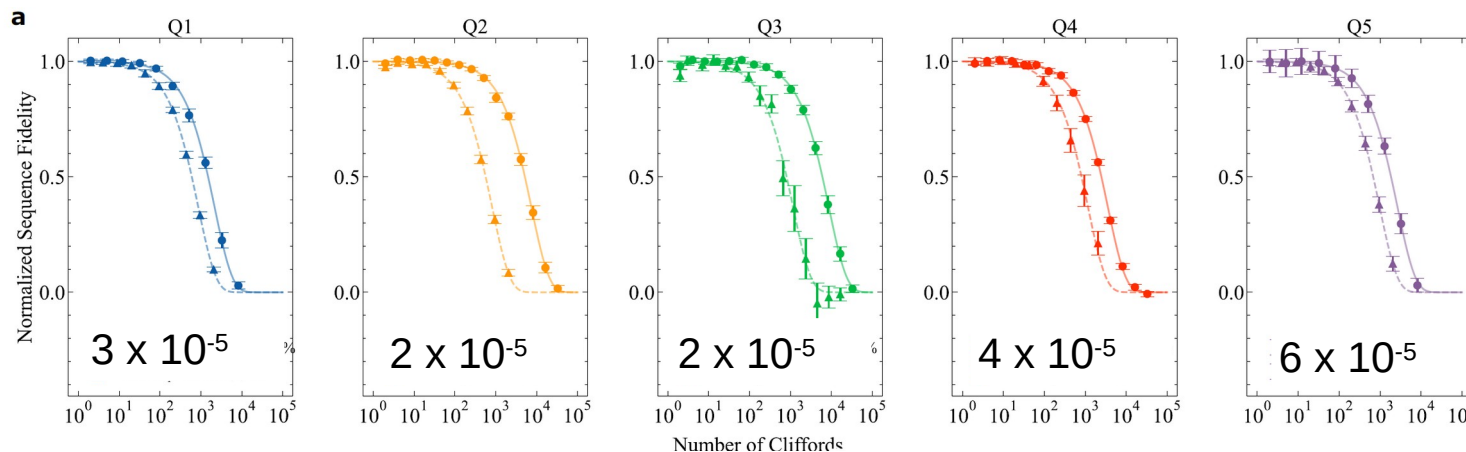
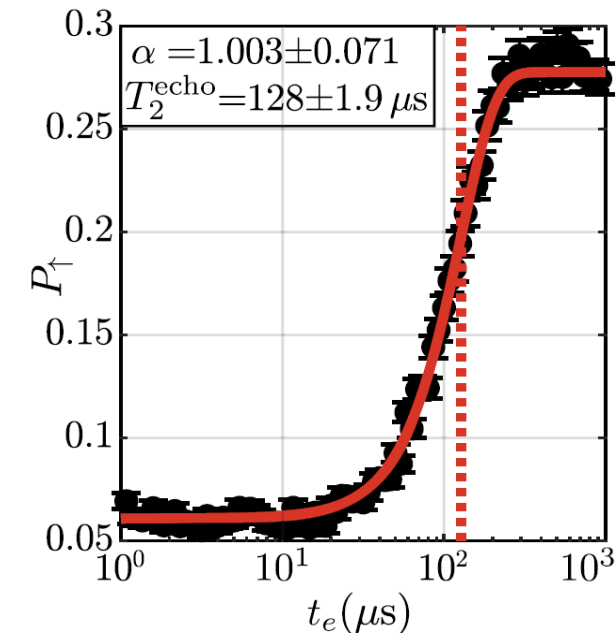
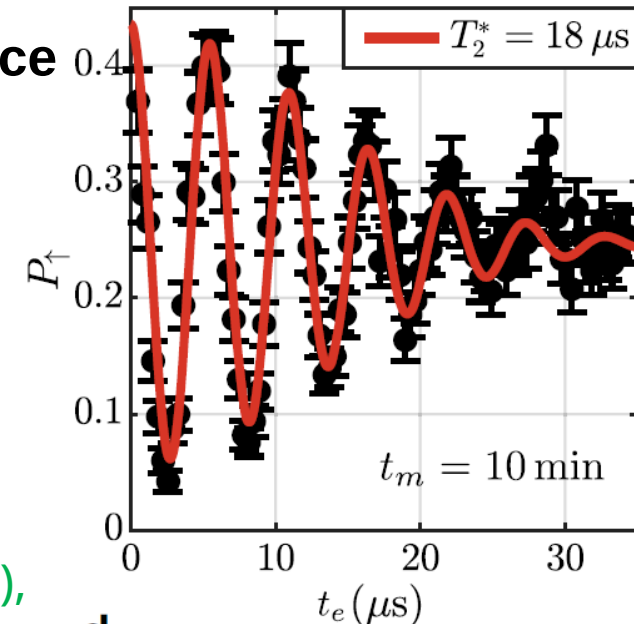
	$T_2^* (\mu s)$	$T_2^{\text{Hahn}} (\mu s)$
Q ₁	16.7(4)	60(2)
Q ₂	7.8(2)	36(1)
Q ₃	7.5(3)	63(3)
Q ₄	12.9(3)	97(5)
Q ₅	6.6(2)	44(2)

Better coherence



Lower ^{29}Si content.

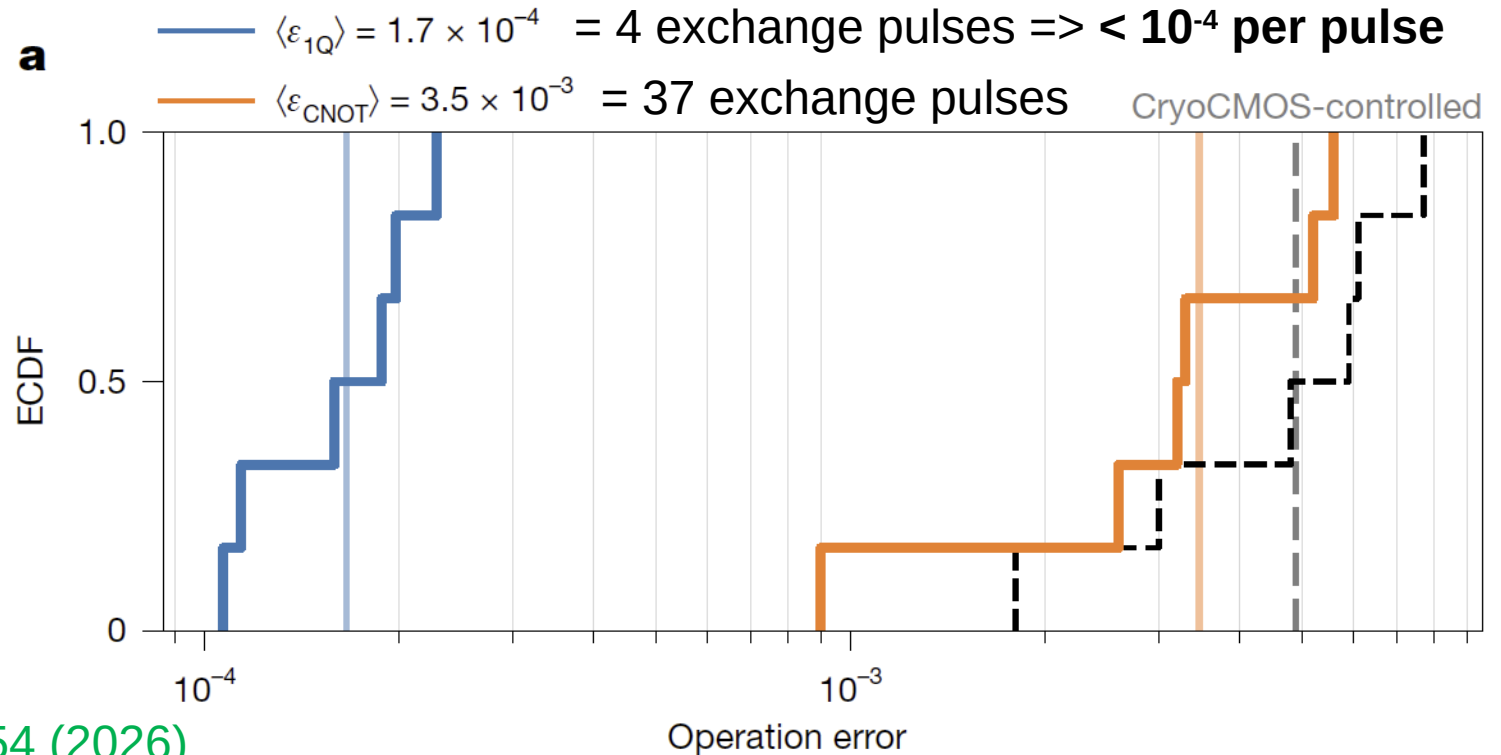
npjQI 6, 40 (2020),
AC

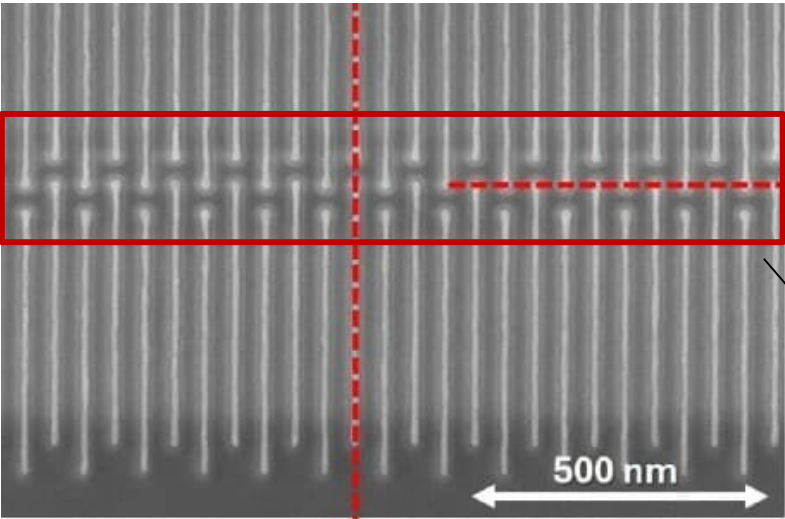


arxiv:2507.11918 (Tokyo)

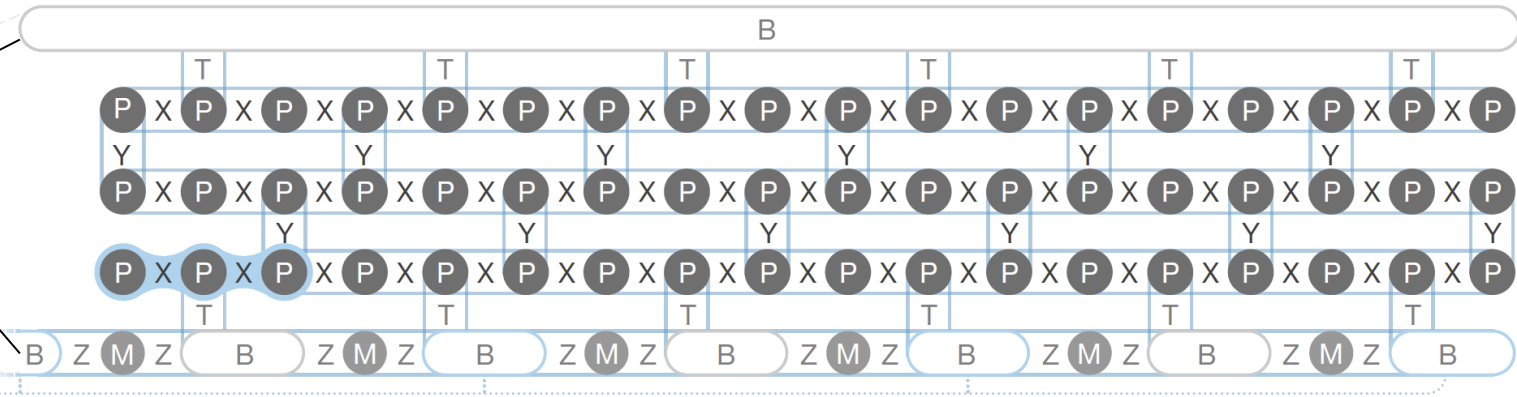
Michael Abraham¹, Edwin Acuna¹, Tower S. Adams¹, Moonmoon Akmal¹, Matthew R. Alfaro¹, I. Alvarado¹, Jacob Amontree¹, Carter Andrews¹, Reed W. Andrews¹, Michael Antcliff¹, André R. Asencio¹, Ryan M. Avila Batres¹, Cynthia D. Baringer¹, David W. Barnes¹, Katherine M. Beech¹, Russell G. Blakey¹, Zachery T. Bloom¹, Aaron J. Bluestone¹, Jacob Z. Blumoff¹, Matthew G. Borselli¹, Koel A. Bose², Brydon Boyd¹, Jacob T. Boyer¹, Teresa L. Brecht¹, Christopher C. Brough¹, Rex A. Brown¹, Steven L. Brown¹, Tyler A. Cain¹, John B. Carpenter¹, Stephen Carr¹, Faustini W. Carter¹, Mitchell Casanova¹, Jacob L. Chambers¹, Matthew D. Chambers¹, Khamsorn L. Chanthavong¹, James M. Chappell¹, Rhian Chavez¹, Kevin C. Chen¹, Peter S. Chen¹, Maxwell D. Choi¹, Krishna Choudhary¹, Matthew N. H. Chow¹, Justin E. Christensen¹, Aaron M. Chronister¹, Andrew M. Clapper¹, Abigail A. Coker¹, Michael D. Cornelius¹, Albert E. Cosand¹, Ian T. Counts¹, Edward T. Croke¹, Gregory M. Crosswhite¹, Adam Dally¹, Erik S. Daniel¹, Tuan A. Dao², Dominic Daprano¹, Tiffany Davis¹, Neha Deshpande², Rachel S. Dey¹, D. Scott Diamond¹, Claire E. Dickerson¹, J. P. Dodson¹, James B. Dragan¹, Marc Dvorak¹, Lisa F. Edge¹, Charles R. Elliott¹, Kenneth R. Elliott¹, Kevin Eng¹, Jacob Fast¹, Colin P. Feeney¹, David J. Fialkow¹, Dylan H. Finestone¹, Micha N. Fireman¹, Bryan H. Fong¹, Trevor M. Fowler¹, Sean Frazier¹, Kiera L. Fuller¹, Christina A. C. Garcia¹, Kacy L. Garstka¹, Kara C. Garvey¹, Zachary A. Geiger¹, Galen R. Gledhill¹, Caleigh M. Goodwin-Schoen¹, Joseph L. Goralka², Bradley W. Greene², Hrayr K. Gurgenian¹, Sieu D. Ha¹, Wonill Ha¹, Nathaniel R. Hapeman¹, Brooke M. Hardesty¹, Jim W. Harrington¹, Patrick M. Harrington¹, Thomas R. B. Harris¹, Ben M. Harrison¹, Anthony T. Hatke¹, Robert R. Hayes¹, Kevin He¹, Raul Hernandez Garcia¹, Ryan M. Hickey¹, Jocelyn Hicks-Garner¹, Alex Hirman¹, Donald A. Hitko¹, David Ho¹, Holland Y. Ho², Vinh S. Ho¹, Nathan Holman¹, Adam Holmes¹, Nerys Huffman¹, Daniel R. Hulbert¹, Eric B. Isaacs¹, Clayton A. C. Jackson¹, Logan Jaeger¹, Ian Jenkins¹, Cameron Jennings¹, Paul C. Jerger¹, B. Johnson¹, Aaron M. Jones¹, Michael P. Jura¹, Adour Y. Kabakian¹, Raj M. Katti¹, Tyler Keating¹, Joseph Kerckhoff¹, Joseph D. Kern¹, Isaac Khalaf¹, Aditya Kher¹, Jake J. Kim², Erich W. Kinder¹, Andrey A. Kiselev¹, William F. Koehl¹, Patrick W. Krantz¹, Thaddeus D. Ladd¹, Pierce G. Laing¹, Sanaaya Lakdawala¹, Nathan J. Lang¹, Robert Lanza¹, Elias Lawson-Fox¹, Dustin Le¹, Kangmu Lee¹, Nathan R. A. Lee¹, Jaime Lerma², Mark P. Levendorf¹, Alwina R. Liu¹, Henry Lizarraga², Aurelio Lopez¹, Hoa C. Ly¹, Torrey T. Lyons¹, Theodore K. Macioce¹, Matthew M. Mackey¹, John K. Maeda¹, Ryan M. Martin¹, Daniel S. Matic¹, Justine W. Matten¹, Gavin C. Mazur¹, Max S. McCready¹, Olivia Means¹, Kevin E. Millner¹, Ivan Milosavljevic¹, Matthew Morris¹, Susan L. Morton¹, Samuel Mumford¹, Bryce D. Murley¹, Robert G. Nagele¹, Taro A. Naoi¹, Cameron R. Nelson¹, Georgia A. Newman¹, David B. Nguyen¹, Tina Niknejad¹, Rebecca N. Nishide¹, Liam C. O'Brien¹, Colin B. E. O'Keefe¹, Riley P. O'Neil¹, Andrew E. Orian¹, Anthony F. Ortiz¹, John J. Ottusch¹, Andrew Pan¹, Pamela R. Patterson¹, Uttam Paudel¹, Julius C. Perez¹, Christi A. Peterson¹, Vu T. Phan¹, Nickolas H. Pilgram¹, Clifford E. Plesha¹, Winston Pouse¹, Eric M. Prophet¹, Daniel R. Queen¹, Nicholas Quirk¹, Kate Raach¹, Matthew T. Rakher¹, Matthew D. Reed¹, Brandon D. Reynolds¹, Luke D. Robertson¹, Zechariah Rogers¹, Yakov Royter¹, Matthew J. Ruiz¹, Golam Sabbir¹, Roshan Sajjad¹, Christopher D. Sanborn¹, Rachel H. Sarmiento¹, Christian J. Schnaible¹, Cole Scott¹, Nicholas M. Sebastiani¹, Eric M. Segall², Alen Senanian¹, Adalberto Sicairos¹, Shariq Siddiqui², Kartik Singh¹, Aaron Smith¹, Daniel E. Smith¹, Robert S. Smith¹, Sarah F. Sontag², Emilio A. Sovero¹, Kevin C. Staley¹, Andrea Su¹, June Suh¹, Bo Sun¹, Danny Sun¹, Christopher M. Swank¹, Noah Swimmer¹, Mariano J. Taboada¹, Bryan J. Thomas¹, Yessica Torres¹, Jeremy W. Touve¹, Alan Tran¹, Ivan Tran¹, Chantang Tsen¹, Skylar Turner¹, Miguel Valencia¹, Irma Valles¹, James R. van Meter¹, Nicholas D. VanRensselaer², Franklin Vartanian¹, Daniel Volya¹, Zachary J. Vrba¹, Phuong Hong Vu¹, Annette L. Wagner¹, John Wallner¹, Michael P. Walsh¹, Shuoqin Wang¹, Tong Wang¹, Daniel R. Ward¹, Aaron J. Weinstein¹, Terry B. Welch¹, Thomas V. Westrick¹, Evan T. White¹, Randall M. White¹, Samuel J. Whiteley¹, Gananath Wijeratne¹, Parker Williams¹, Jack T. Wilson¹, Courtney P. Wilt¹, Deborah E. Winkler¹, Onnik Yaglioglu¹, Daniel Yap¹, Clifford S. YoungSciortino¹, Daniel Zehnder¹ & Andrew Ziegler¹

- $\sim 10^{-4}$ in system 2Q gate-fidelity (atomic 2-spin exchange)
- **Reproducible** qubit properties with industry-style fabrication
- Fidelity retained with **cryoelectronic control**

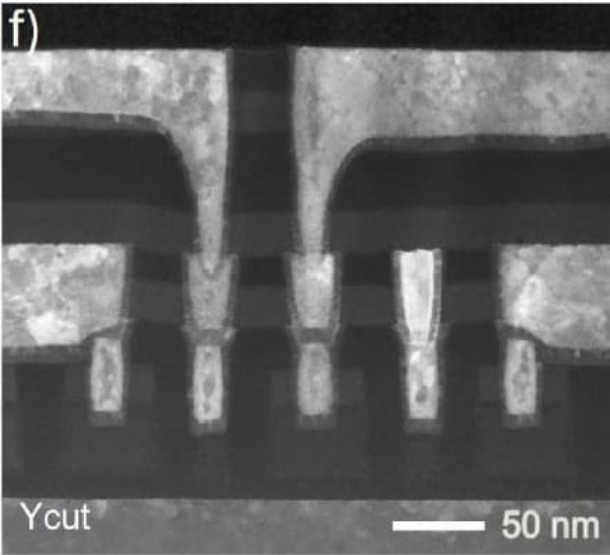




54-dot device topology



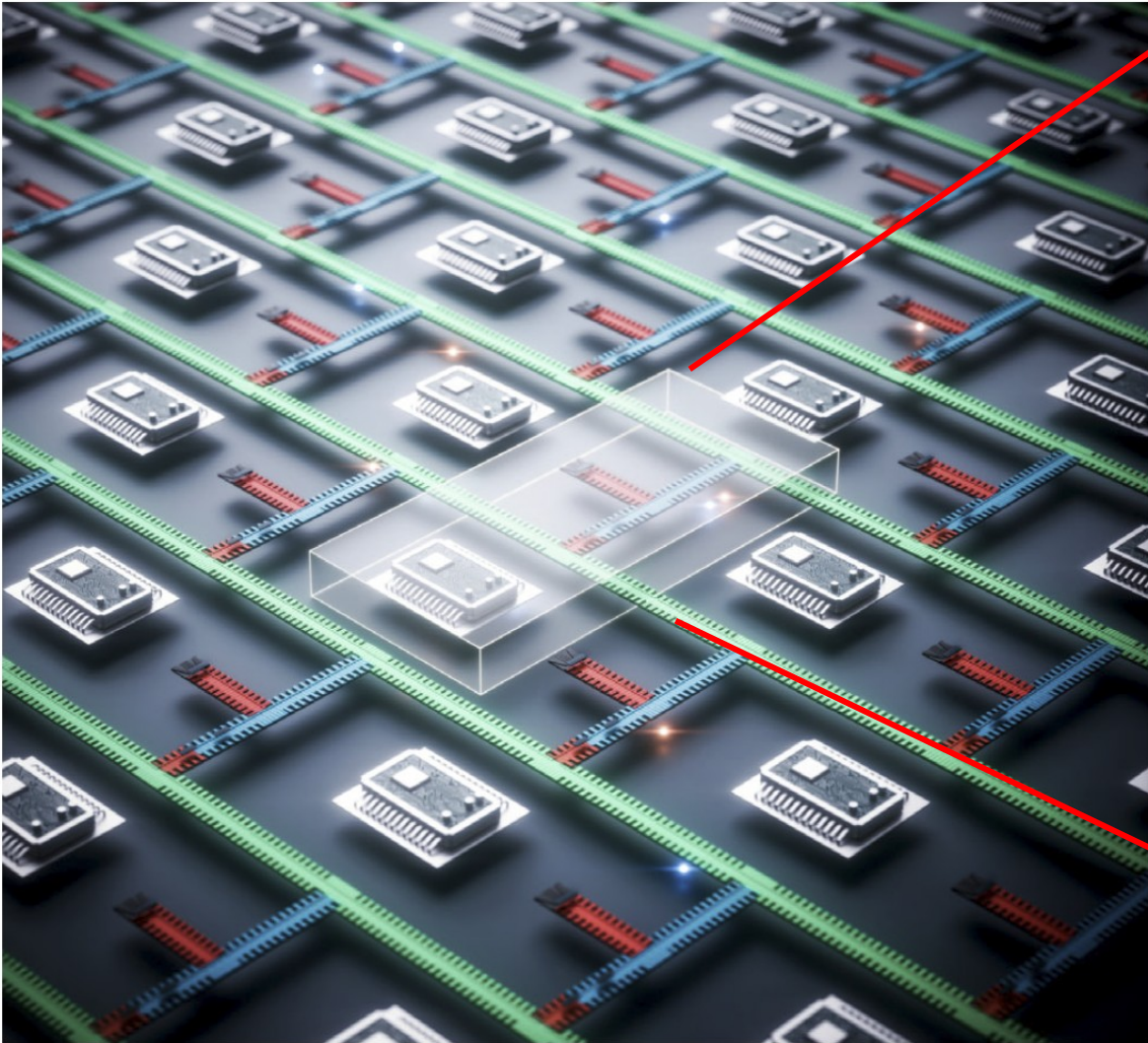
Nature **655**, 1154 (2026)



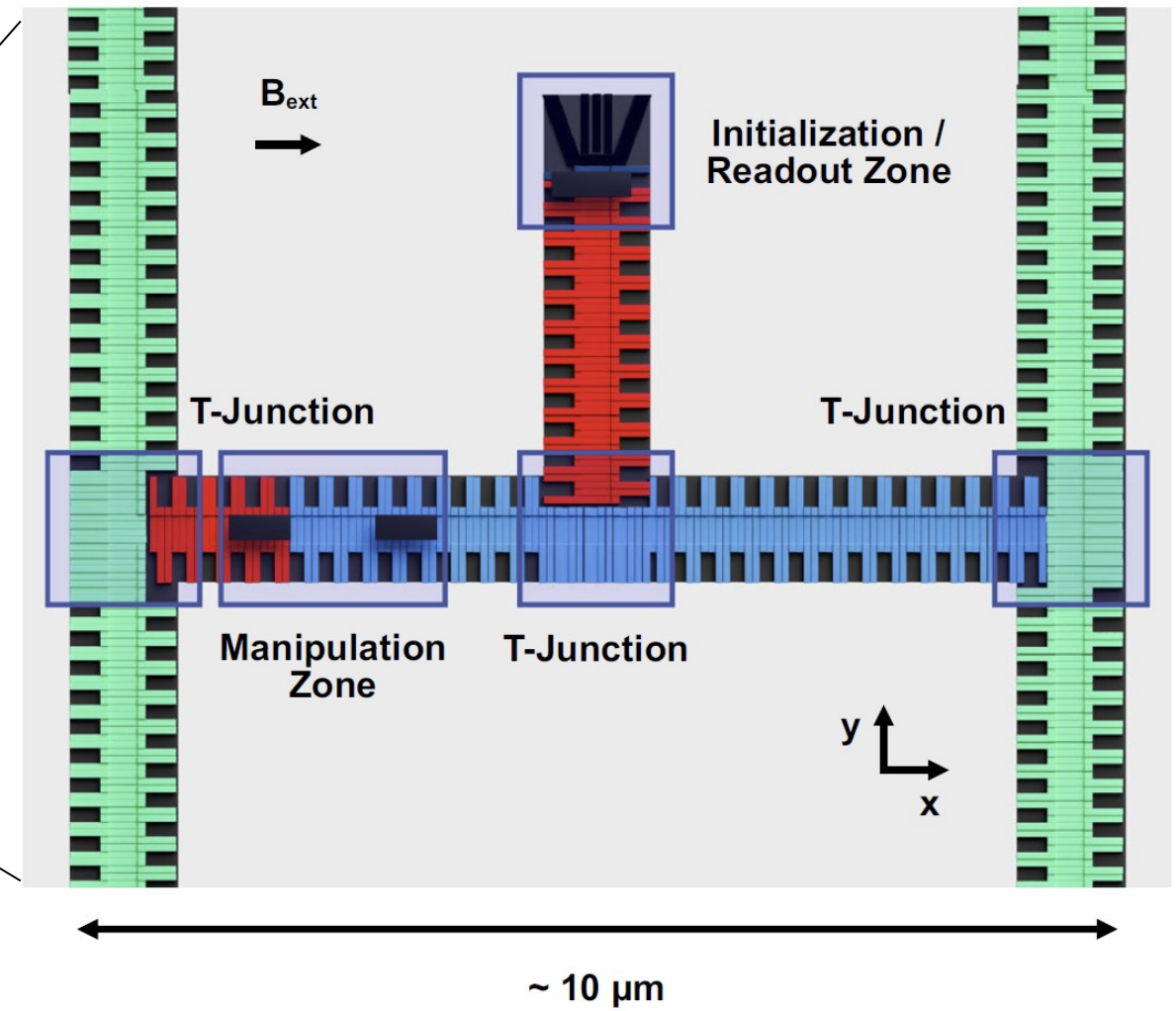
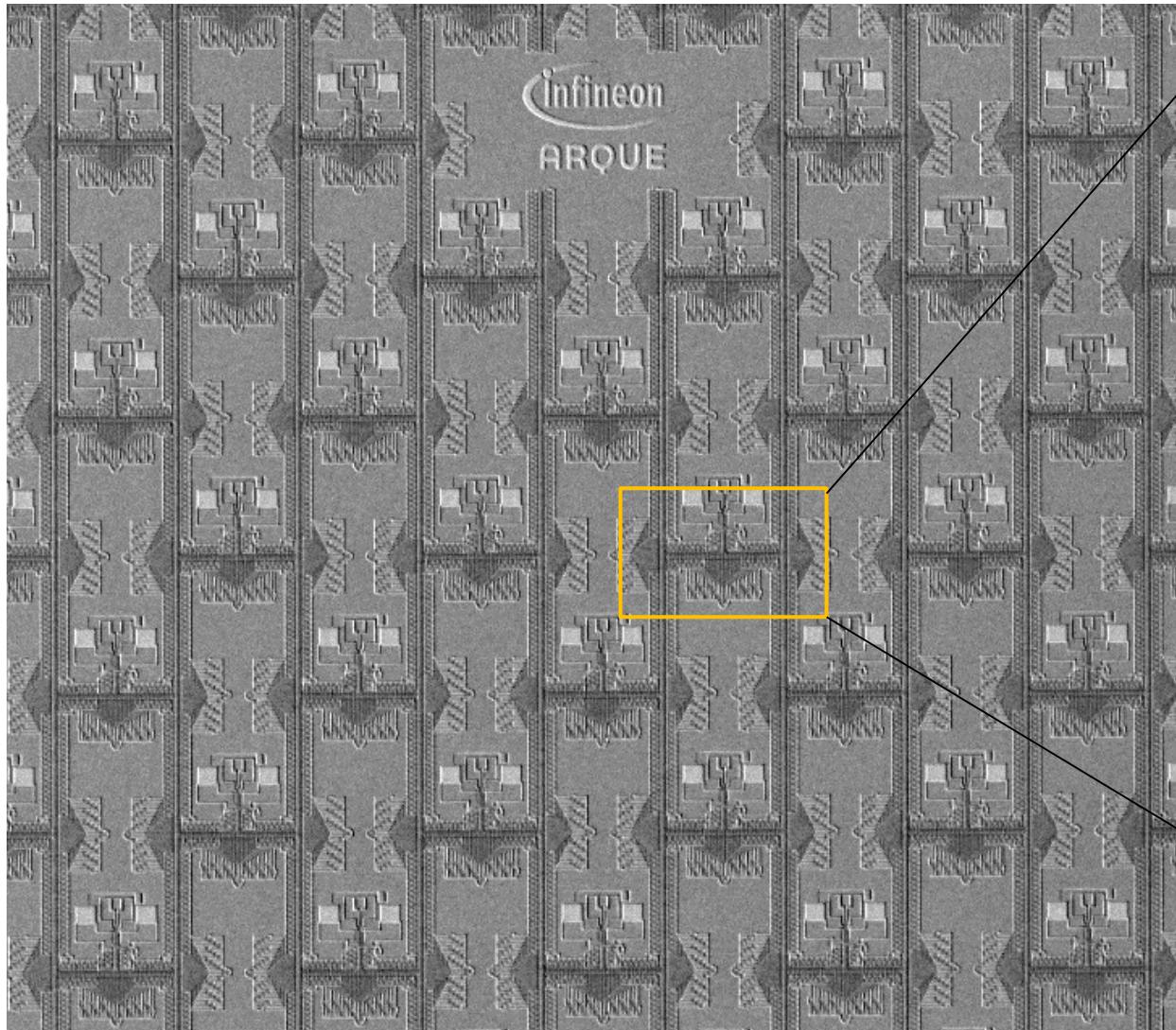
IEDM
2025
(IMEC)

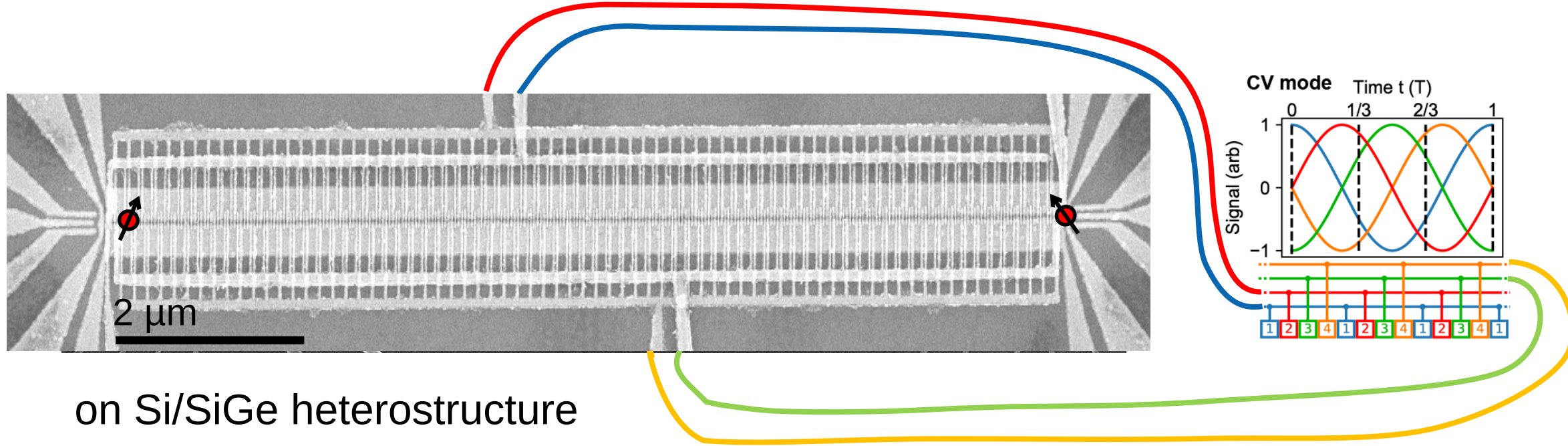
Packing too dense for (2D) scaling.

Dilute array with cryoelectronics



Architecture – Unit Cell





Key features

- 4 input signals, independent of length
- No calibration needed (ideally ...)

Charge shuttling

- 99.4...100 % fidelity over 10 μm ([Nature Commun. 15 2296 \(2024\)](#), AC)
- $\leq 10^{-8}$ infidelity in T junction ([arXiv:2601.03942](#), AC)
- Speed-distance record in industrial devices ([IEDM 2025](#), AC/Infineon)

Coherent spin shuttling

- With fully shared control ([Nat. Commun. 15, 1325 \(2024\)](#), AC)
- 99.5 % over 10 μm (total, with tuned potential) ([Nature Nano 20, 866–872 \(2025\)](#), Delft)
- > 98 % over 10 μm (full conveyor mode) ([unpublished](#), Delft)
- Distributed entanglement in Ge ([arxiv:2510.26860](#), Delft)

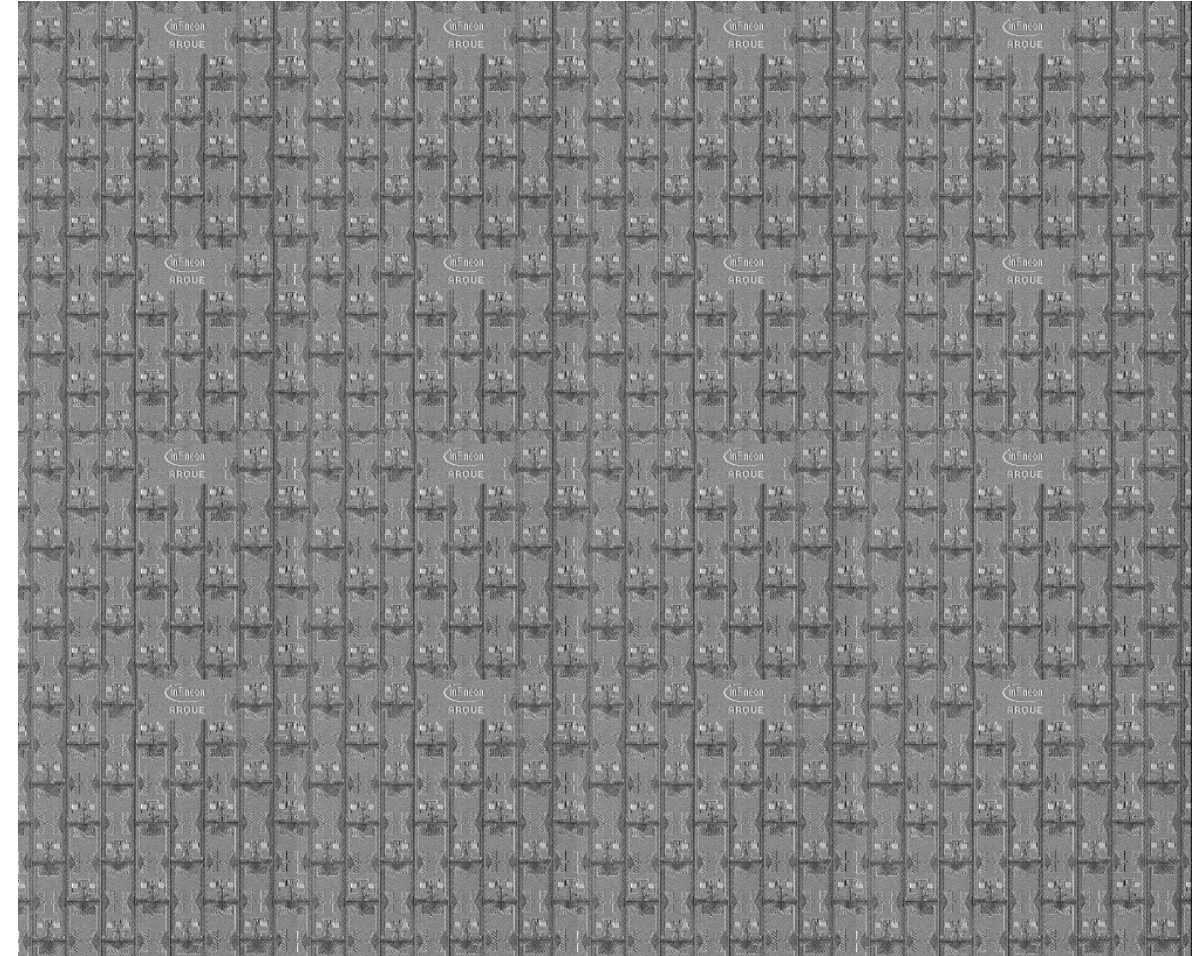
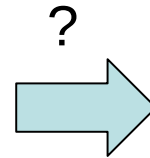
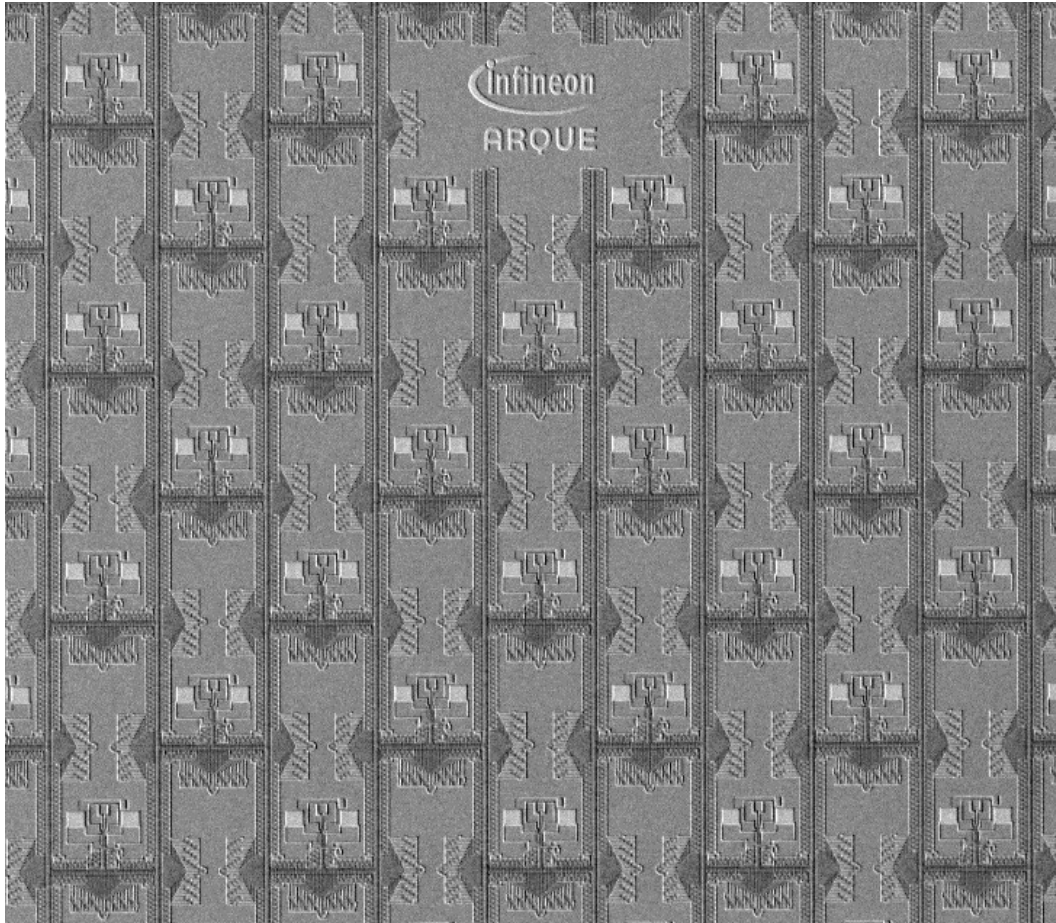
Avoidance and elimination of valley hot spots

- Theory for 99.9 % with high yield ([PRX Quantum 5, 040322 \(2024\)](#), AC/Wisconsin)
- Experimental proof of concept ([arXiv:2510.03773](#), AC)
- Strain and heterostructure design predicted to remove them ([arxiv:2310.18879](#), Wisconsin)

Multi-qubit aspects

- 99% 2Q gates in shuttling channels ([arXiv:2503.15434](#), Delft)
- Shuttling based QEC syndrome computation ([arXiv:2601.23267](#), Delft)
- Reachable surface code fidelity requirements ([arxiv:2503.10601](#), AC)

Industrial fab for reproducibility



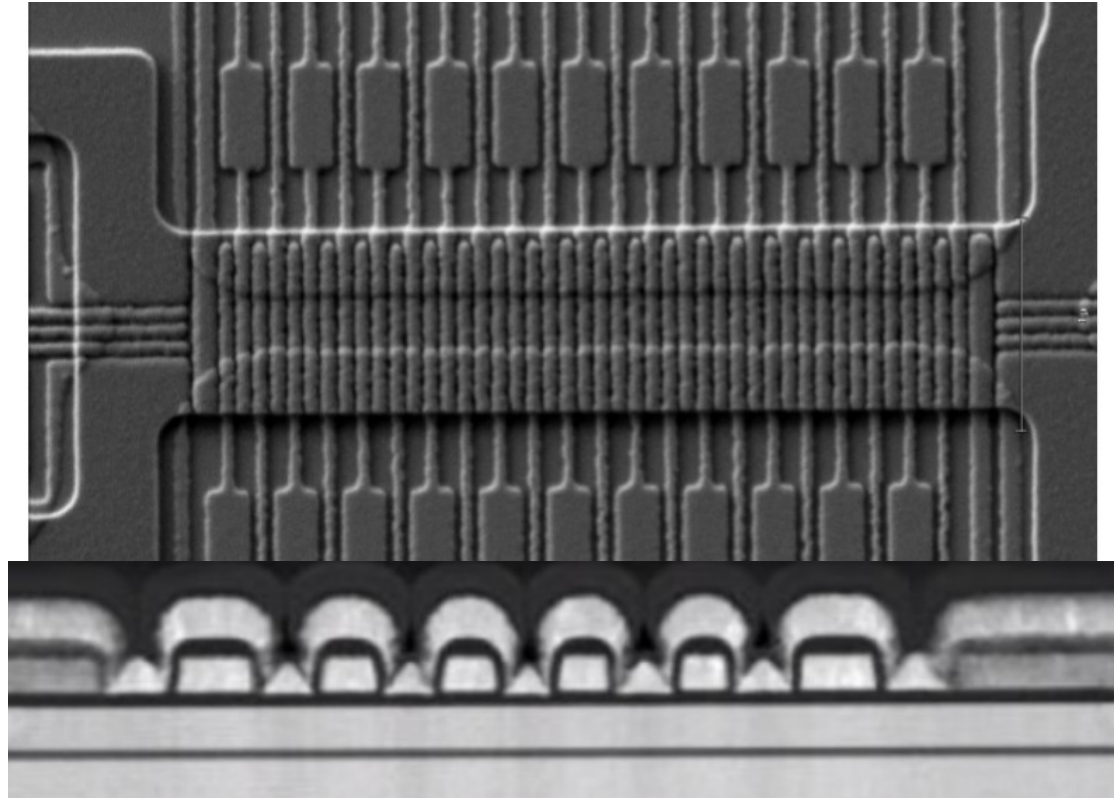
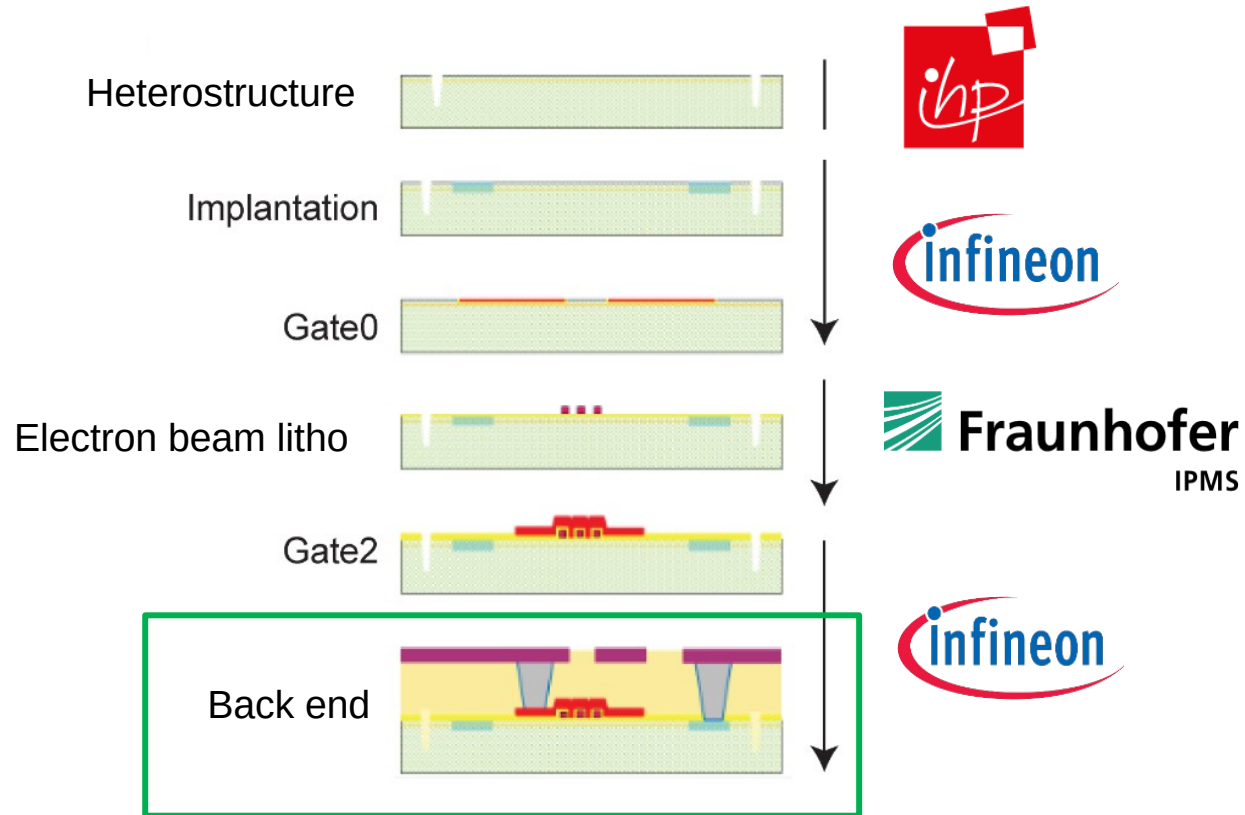
In Silico design study

2 x 2 cm²

10⁷ qubits

Distributed process flow

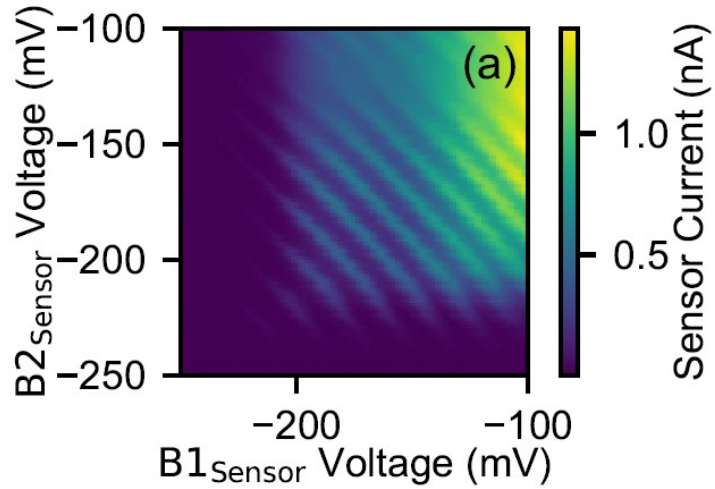
=> Shuttling devices



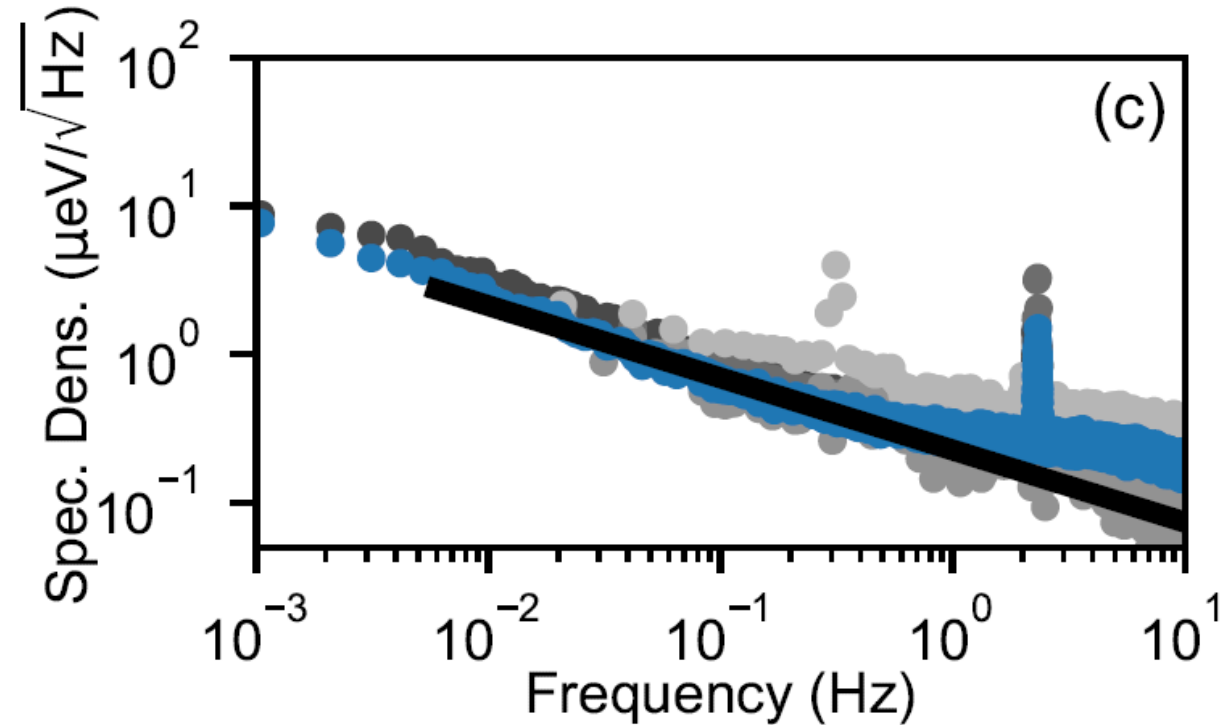
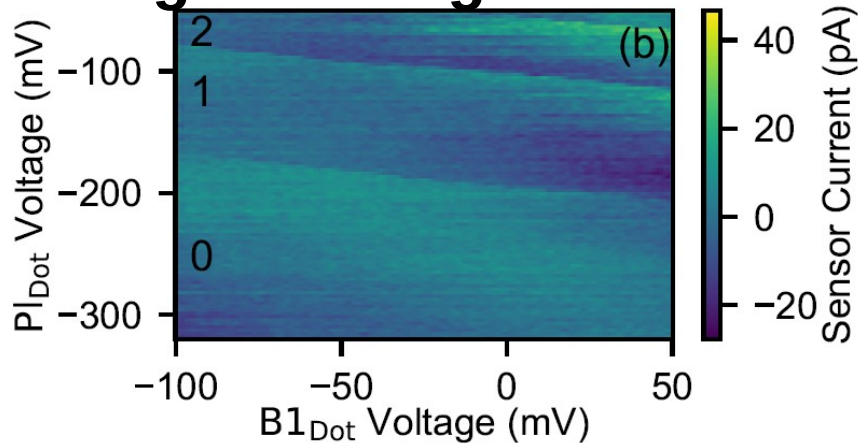
IEDM 2025, AC/Infineon+

Speed-distance record in charge shuttling

High quality Industrial Si/SiGe dots

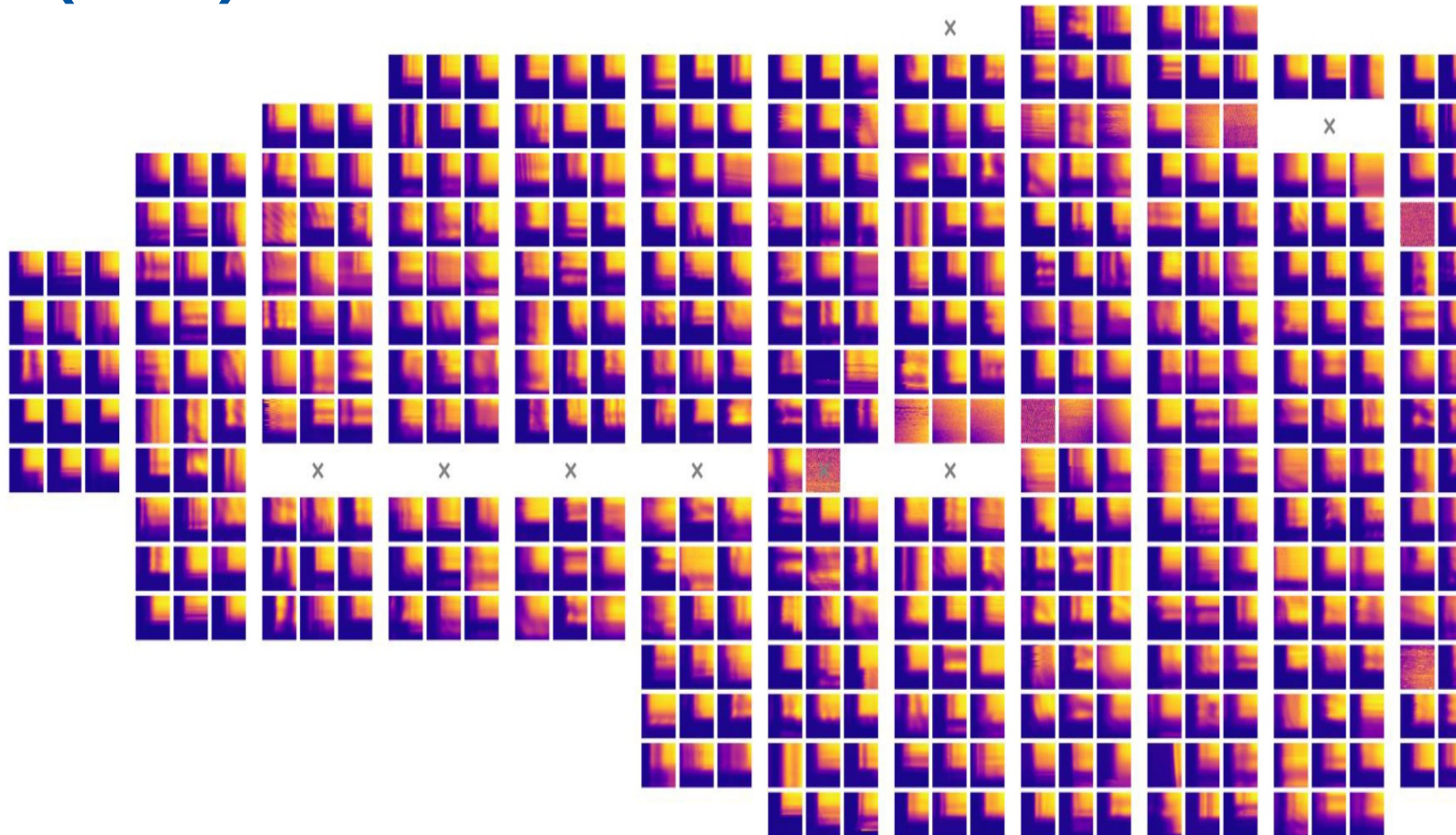


Charge sensing



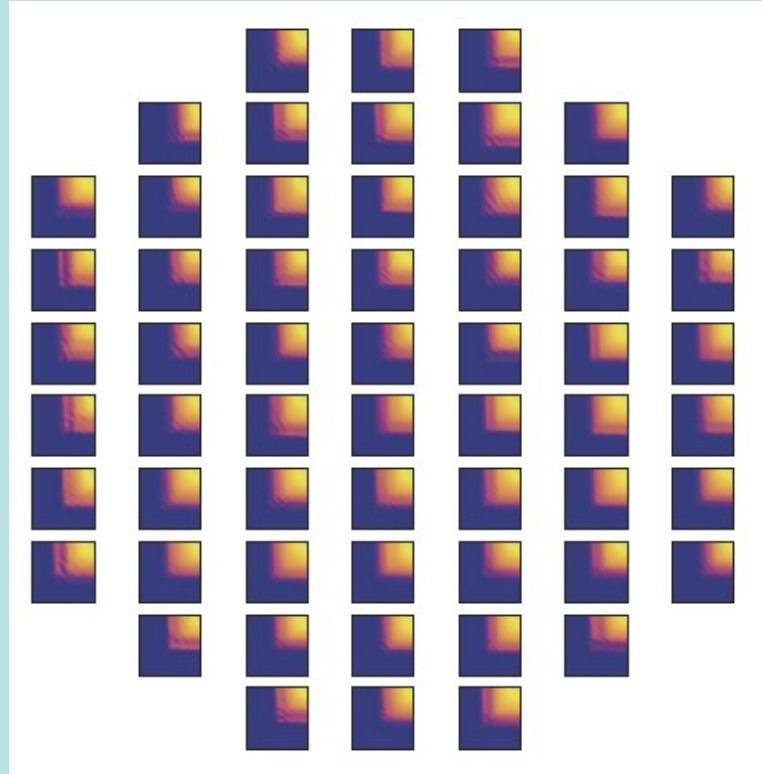
Performance competitive with very good academic devices.

Wafer scale yield demonstration (2025)



Intel:

99.8% Quantum dot yield,
> 91 % charge sensing yield



Nature **629**, 80 (2024)

~85 % automated tuning to charge sensor operating regime

A semiconductor approach for millions of qubits

Fully integrated quantum processor

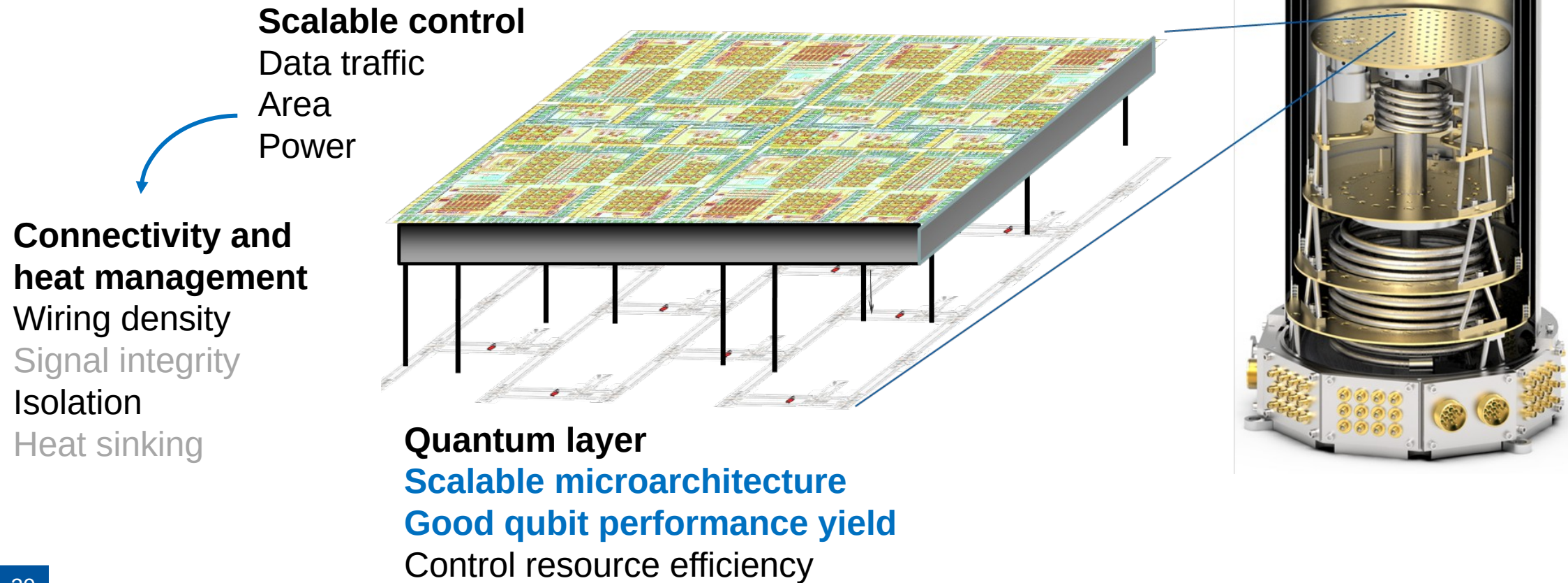
... with low-power cryogenic control circuits

Quantum layer

... in a rack-sized refrigerator

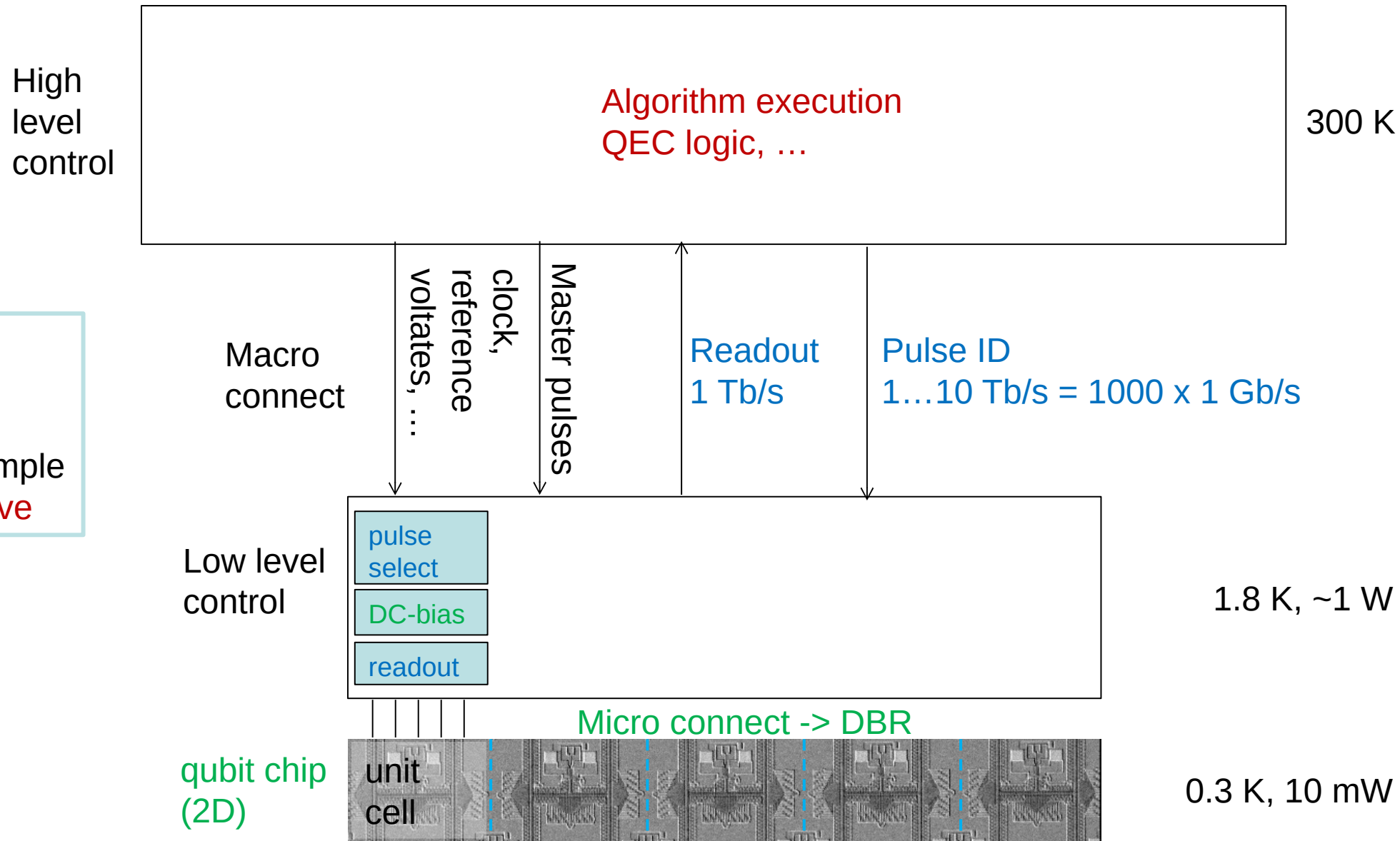
SIONLUDI L
Qinu GmbH
qinu.de

System scaling



System concept

Legend
Encouraging progress
Looks feasible
Should be relatively simple
Leave for others to solve



Power and area budget

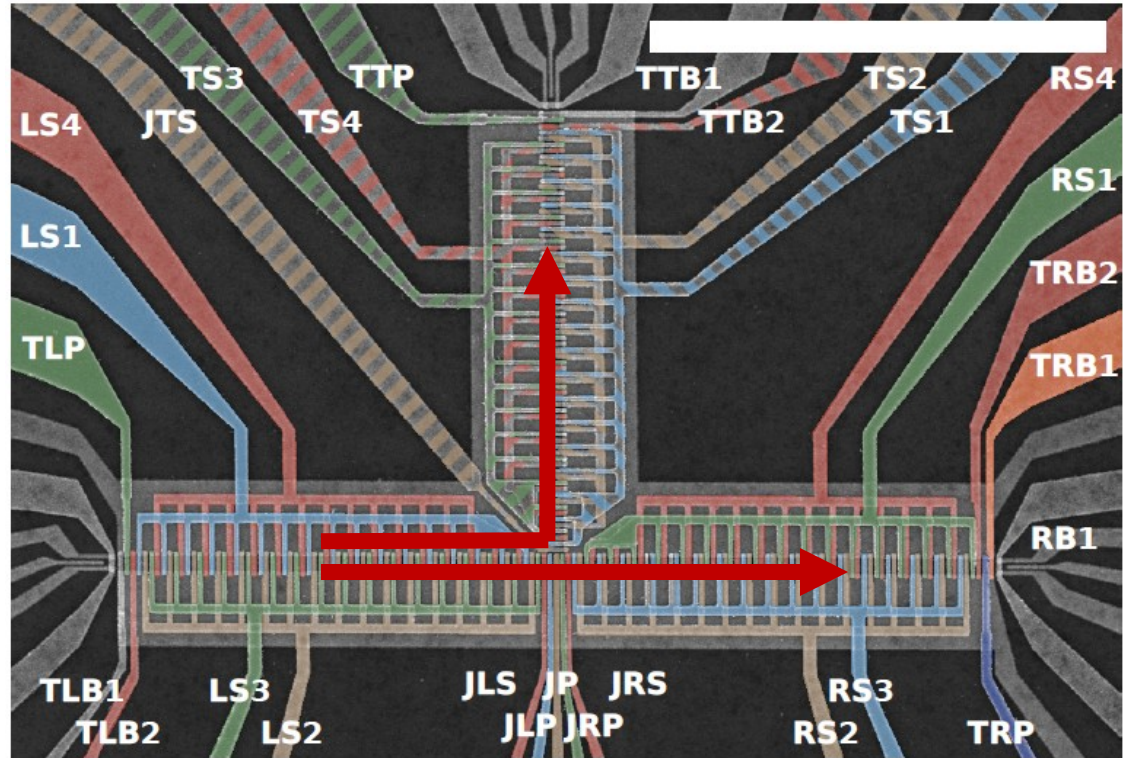
Function	Power/channel	Area/channel	Innovation/Assumption
DC bias	60 pW	30 μm^2	high-k deep trench caps
Pulse switching	Not a lot		Voltage-tunable qubit parameters
Dynamical qubit tuning	< 100 nW/MHz	Similar to DC	Extrapolation from experiment
Readout	~ 100 nW	Few μm^2	Novel readout sensor. Estimate from experiments.
Signal transmission	< 100 nW	~ 1 μm^2	Physicist's trickbox + Physicist's estimate.
Signal multiplexing	100 nW		Brainstorming estimate
Budget for 10⁶ qubits	1 μW	~100 μm^2	Broadband DBRs. Heat removal to be demonstrated.

Scaling concept.

Looks promising to match connectivity, area and power budget.

- Semiconductor qubits are now reaching outstanding performance and reproducibility.
- EU is (still) in a strong position.
- We have a concrete technical plan how to reach utility scale.

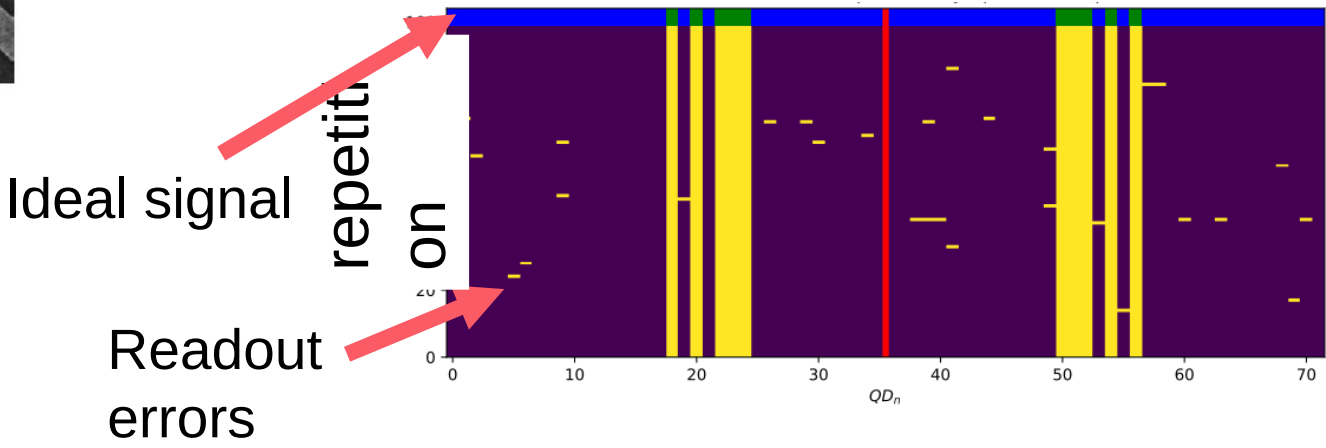
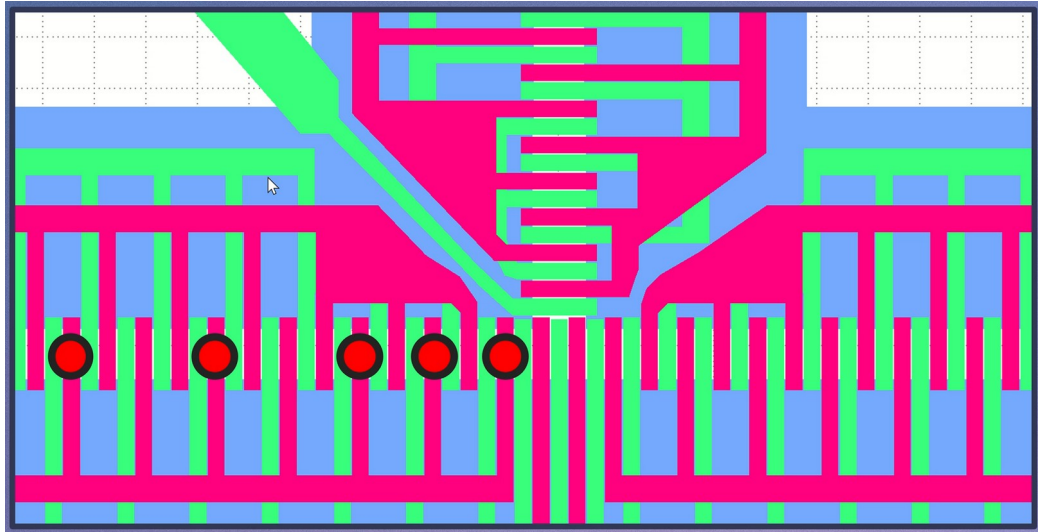
T-Junction enabling 2D connectivity



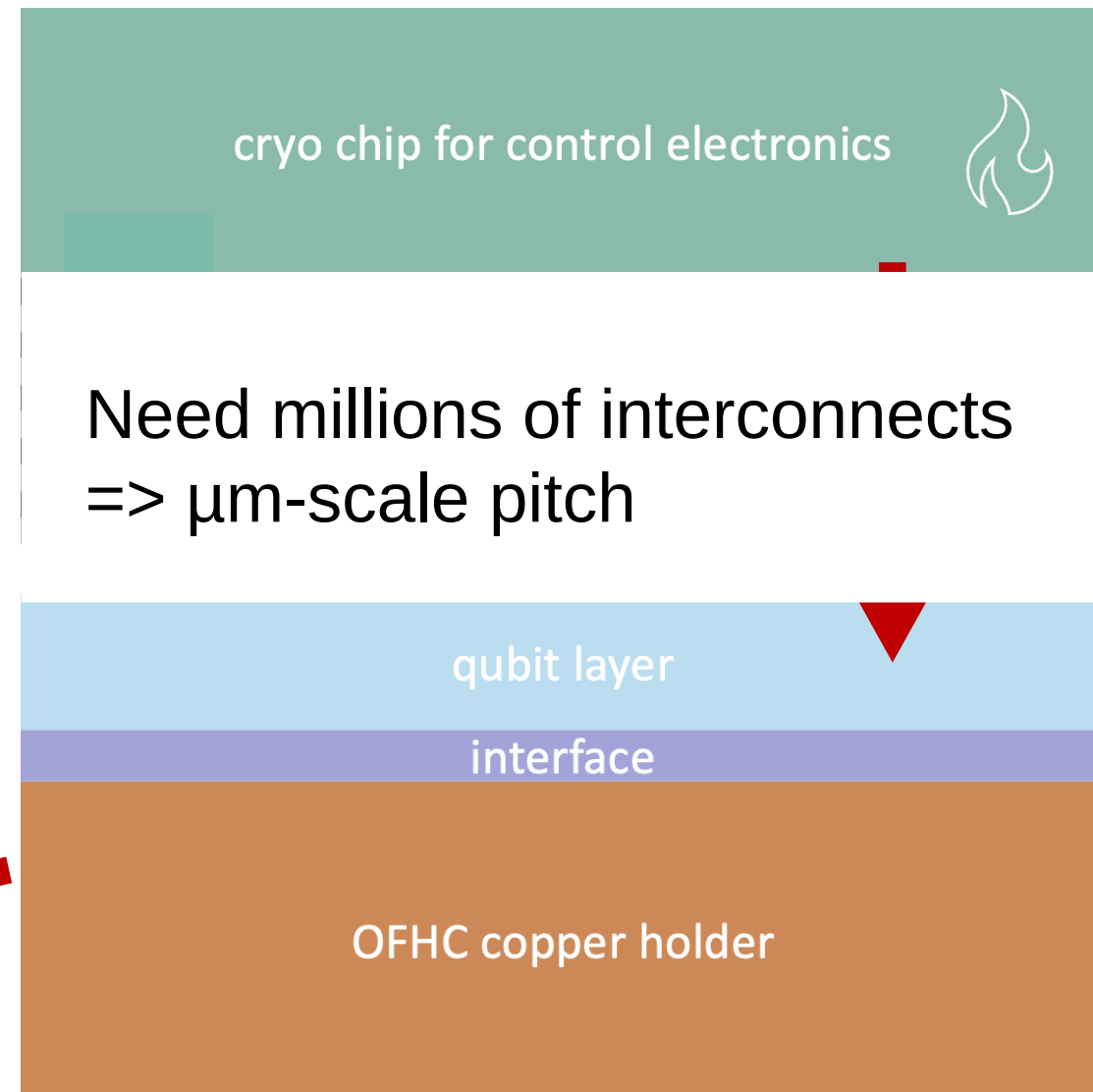
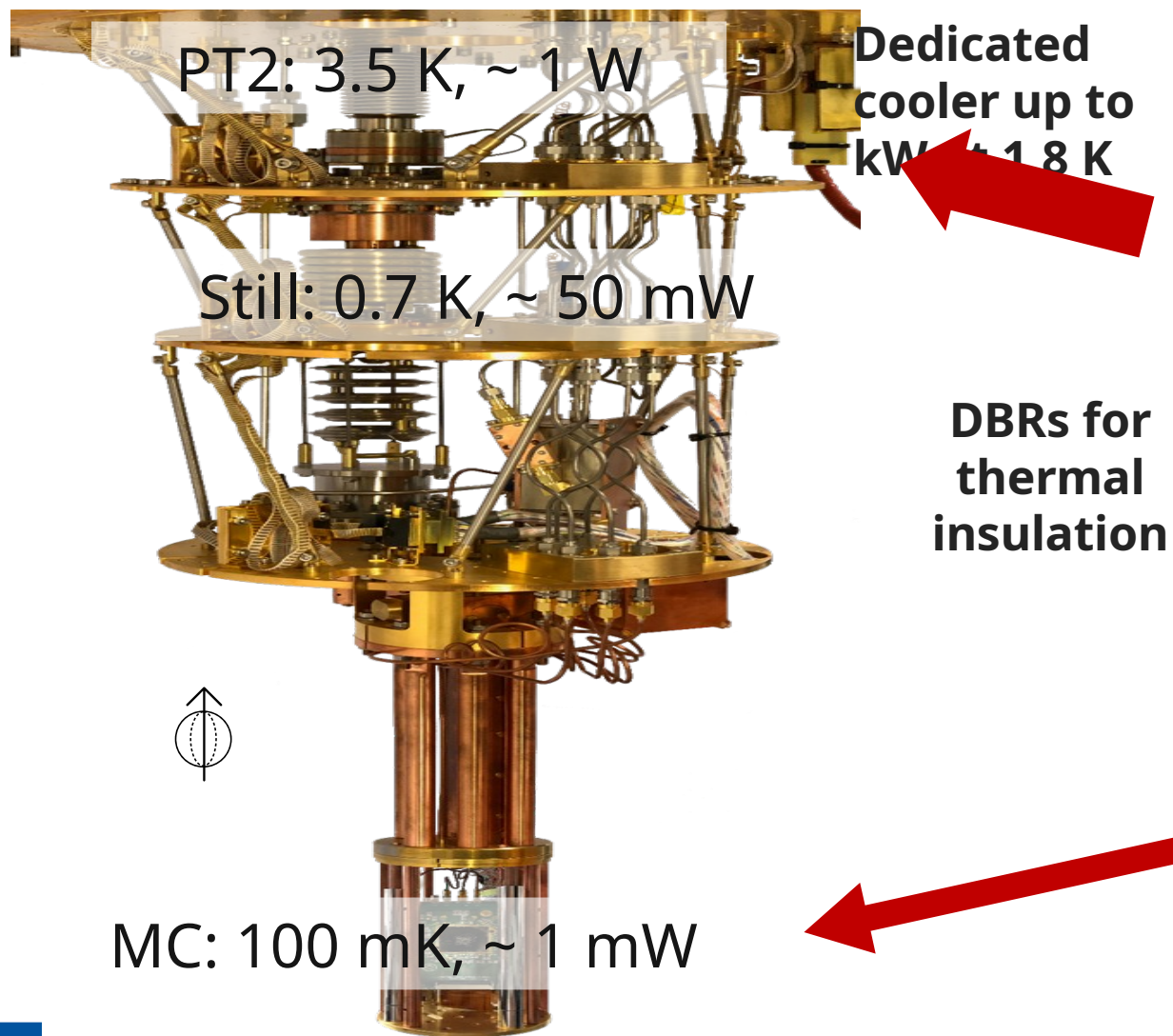
< 10⁻⁸ charge transfer error rate

[arXiv:2601.03942](#)

Pattern swap

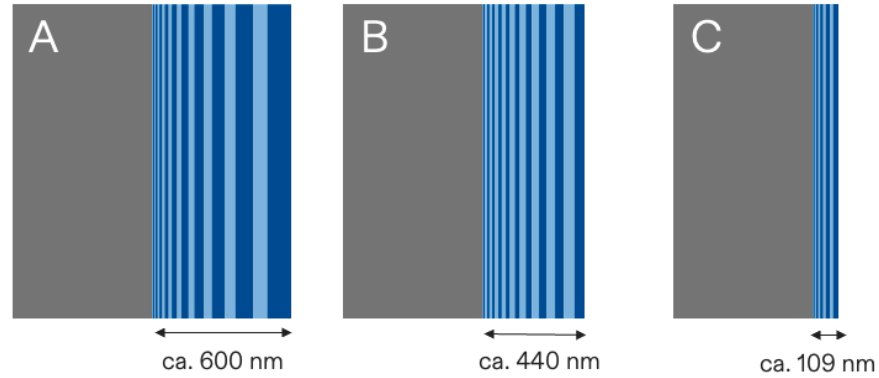


Heat management concept

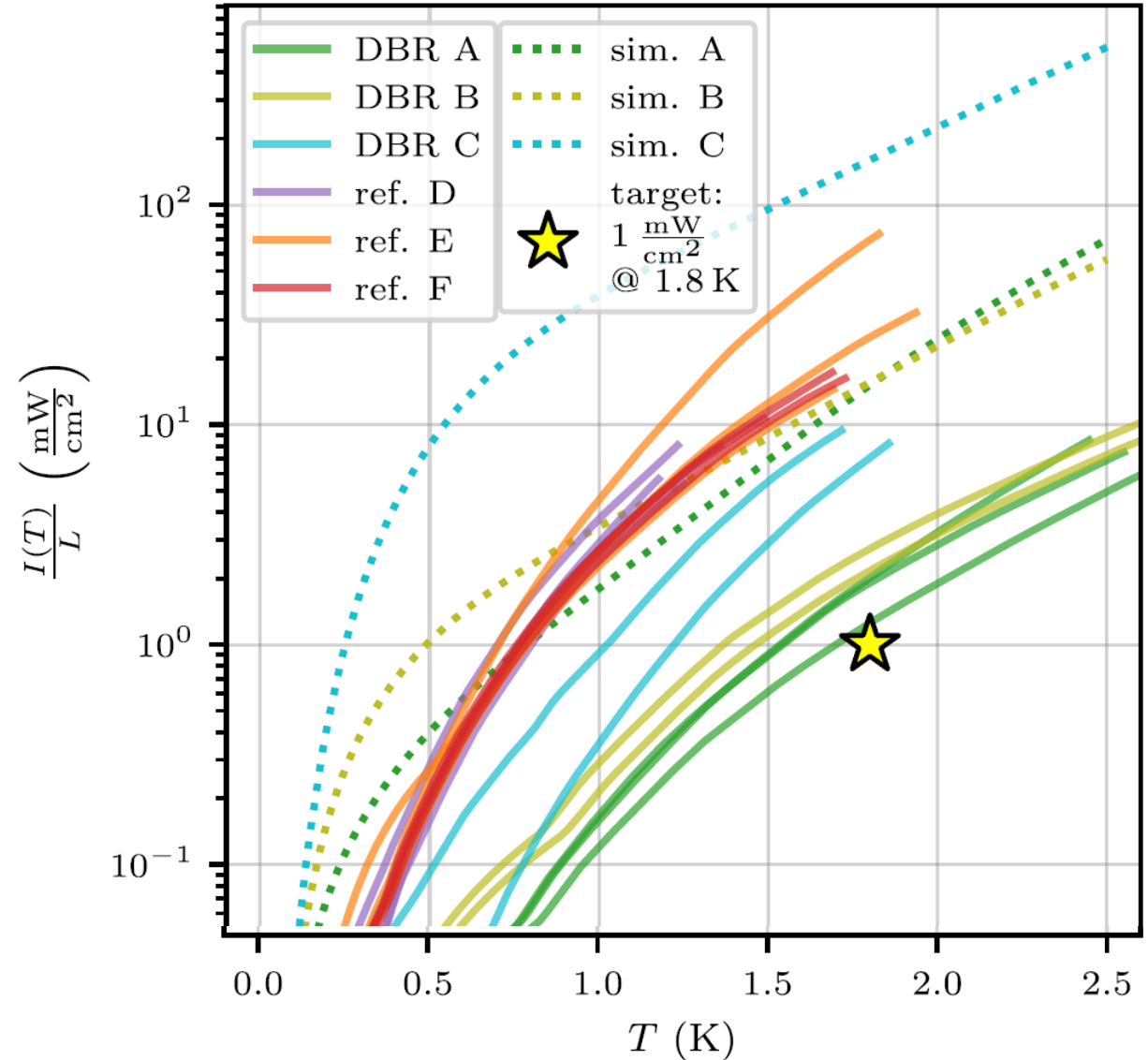
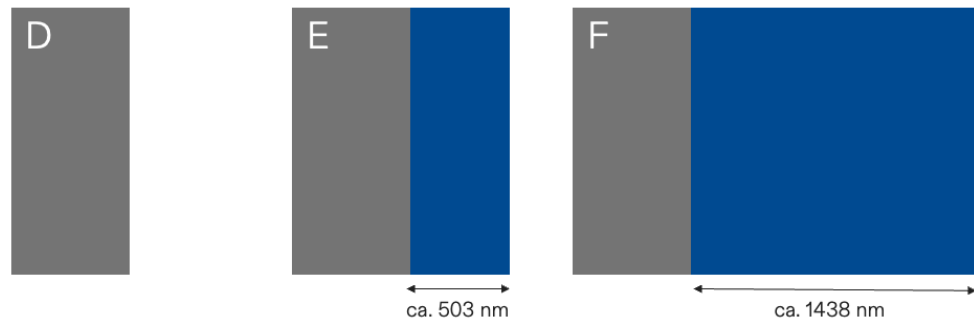


Validation experiment

DBRs of Ta & SiO₂ on Si

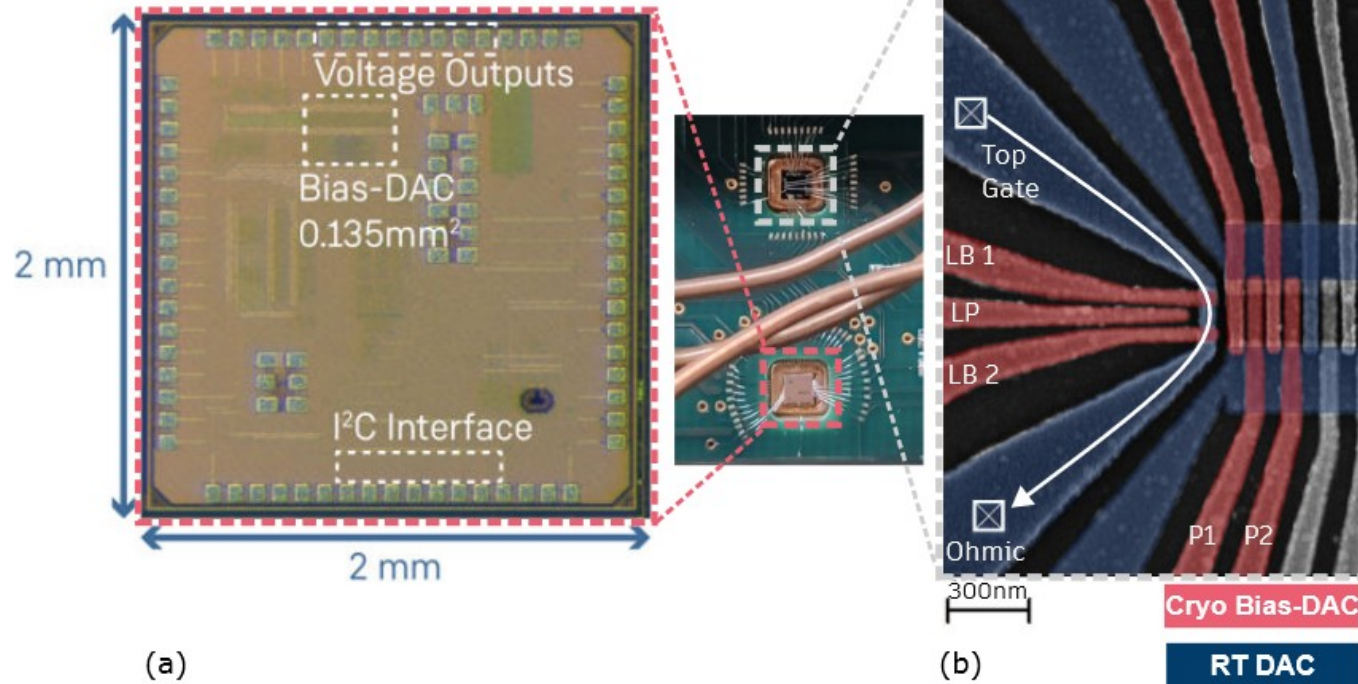


References: Si only and SiO₂ on Si

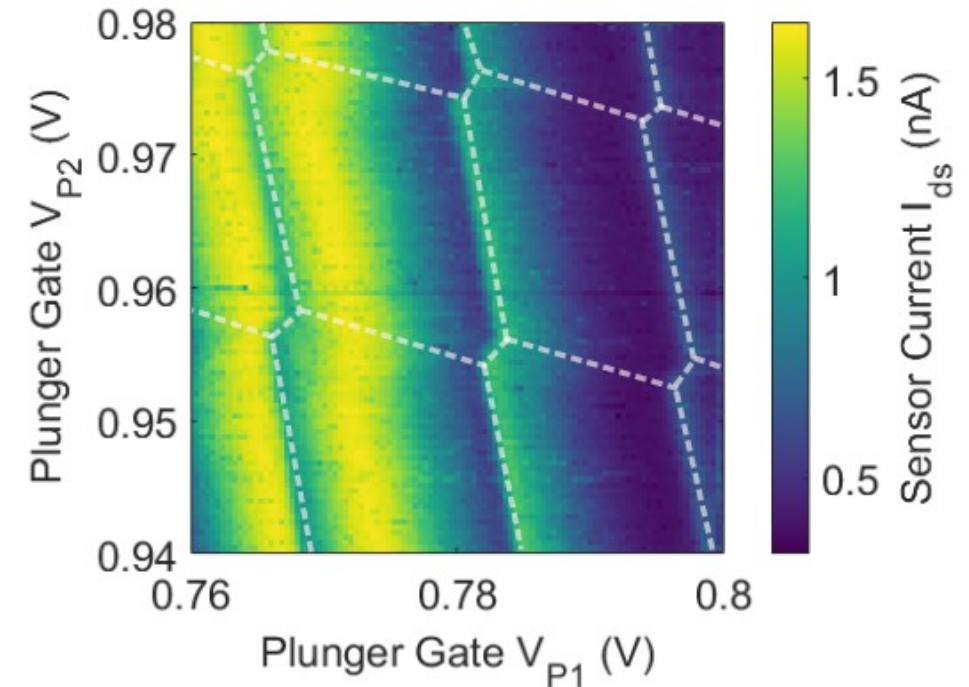


DC Bias with integrated Cryo DAC

Fully integrated DAC next to qubit device



Charge sensing of double-dot

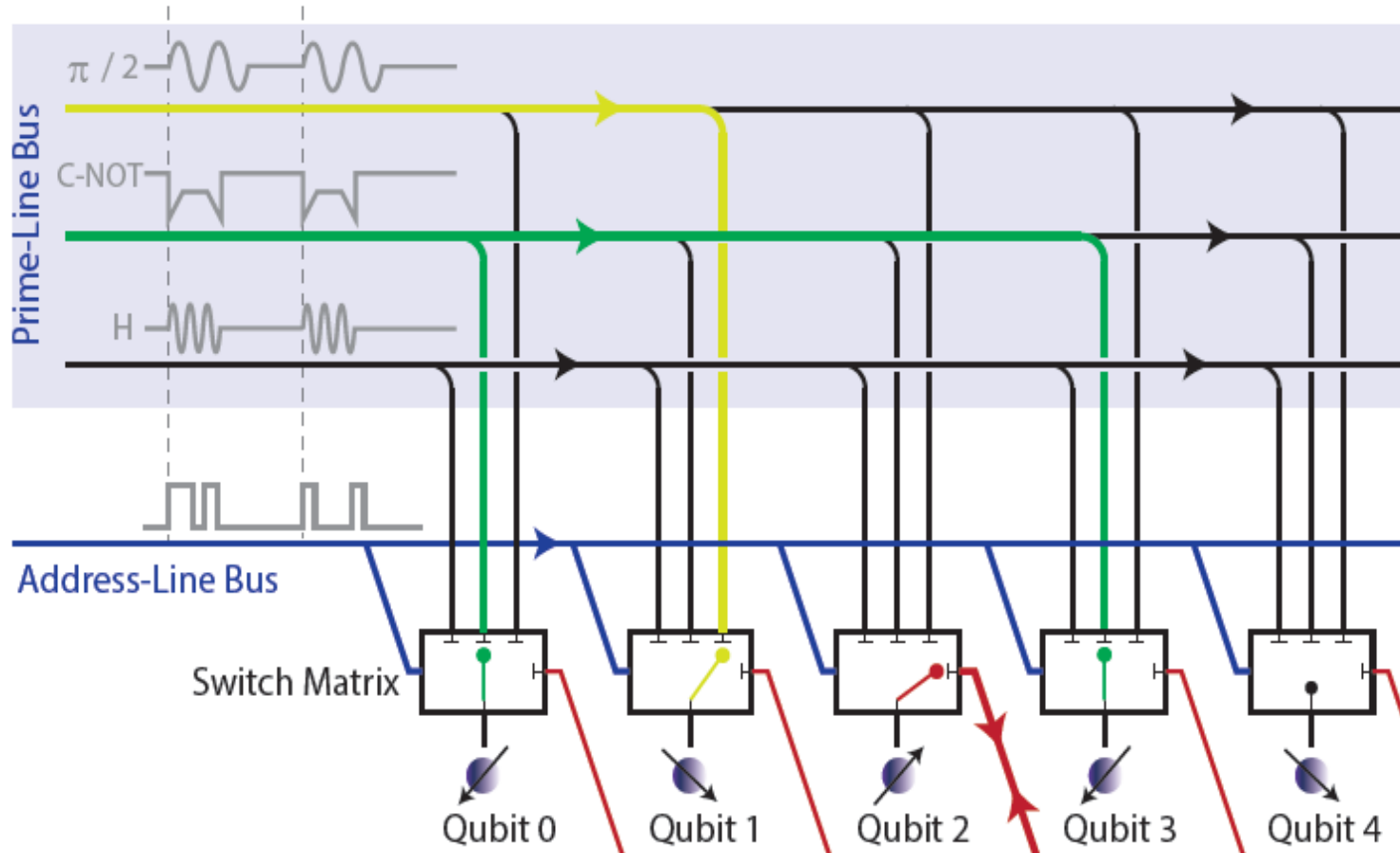


Dissipation extrapolates to 60 pW/channel.

ESSCIRC 2023, AC/FZJ

$T_{el} \sim 400$ mK
 $\Rightarrow$ Improve heat sinking
Noise/crosstalk?

Control: Switching external pulses



Reilly et al, Phys. Rev. Appl. 2015 (Sydney)

Challenge: requires „identical“ qubits

Solution: tune qubits

