intel

HOT CHIPS

Towards A Large Scale Quantum Computer Using Silicon Spin Qubits

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Intel Corporation

16 August 2020

Quantum Computing: Key Concepts

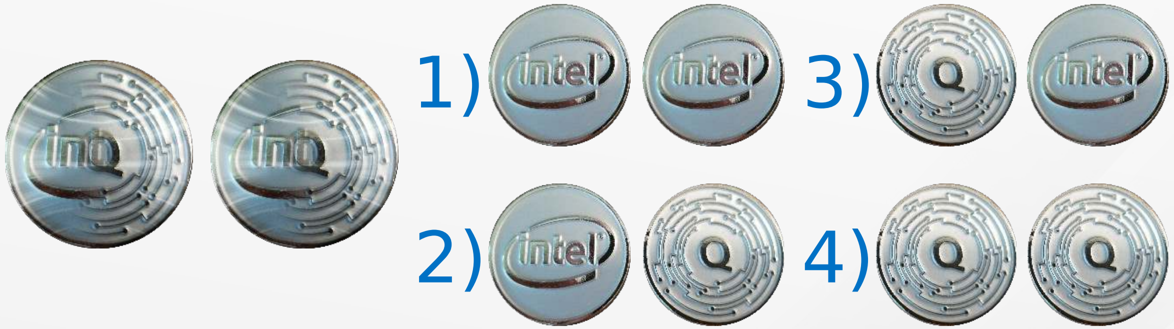
Superposition

Classical Physics | Quantum Physics

Heads or Tails | Heads and Tails

- 50 Entangled Qubits = more states than any possible supercomputer
- 300 Entangled Qubits = more states than atoms in the universe
- Fragility will require error correction and likely millions of qubits

Entanglement

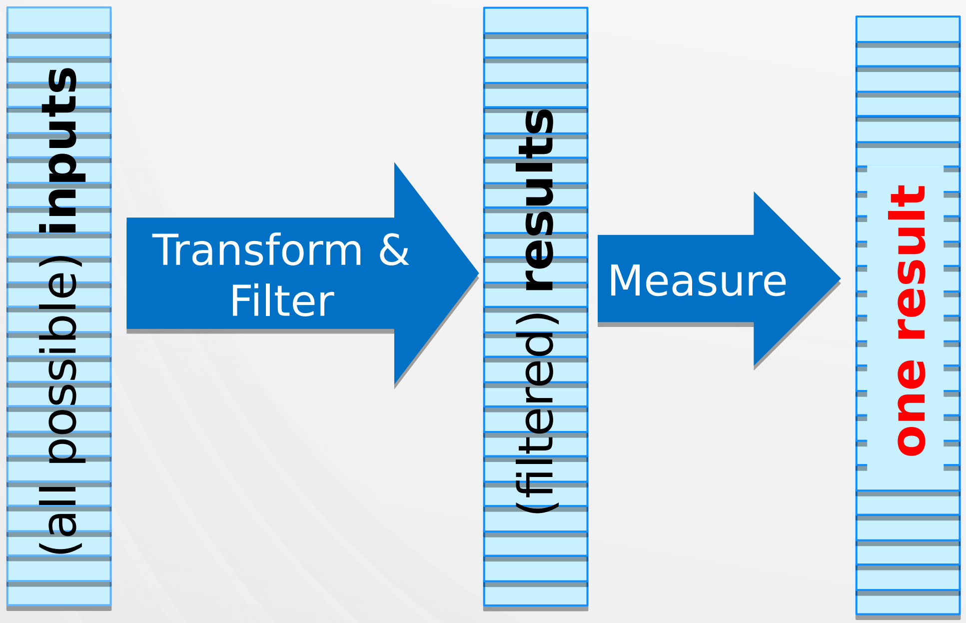


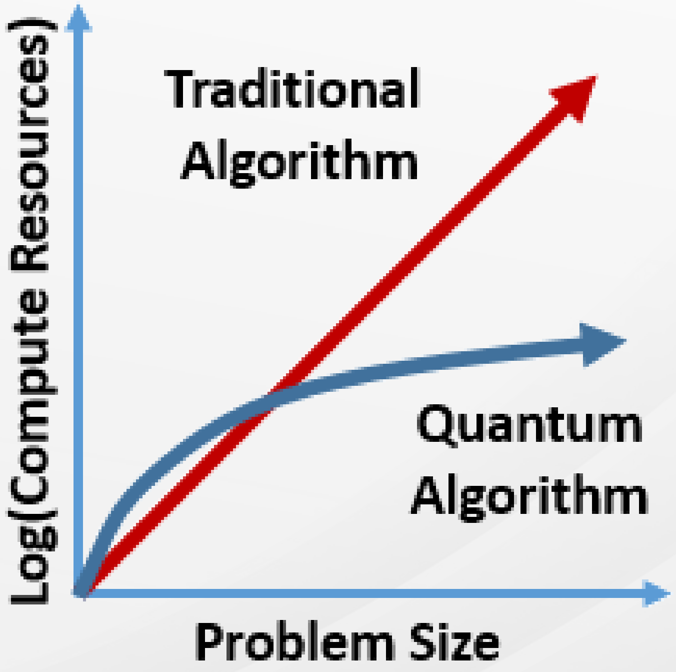
N Quantum Bits or **Qubits** = 2^N States

Fragility

Observation or Noise Causes Loss of Information

The Promise of Quantum Computing

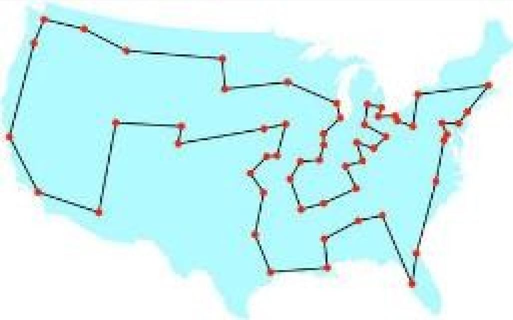




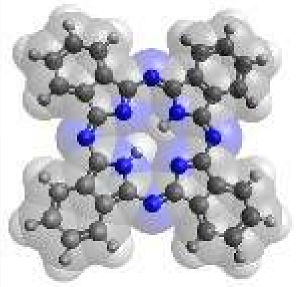
Exponential Speedup Surpassing The Limits Of Traditional Scaling

The Demand for Quantum Computing

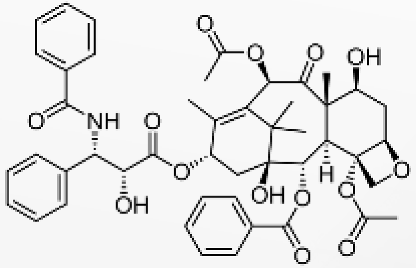
TIME
“Quantum Will Change Everything”



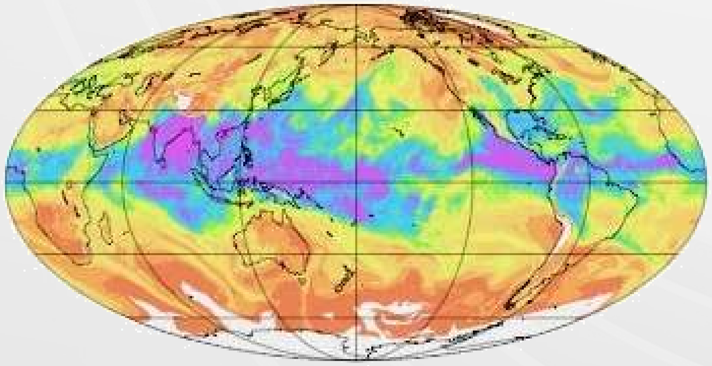
Travel & Logistics



Chemistry



Pharmacology



Climate Modeling

Financial Analysis

Cryptography

Relevant System Sizes

Brute Force Limit

Quantum co-processor: augmenting, not replacing, traditional HPC systems

~50+ Qubits: Proof of concept

- Computational power exceeds supercomputers
- Learning test bed for quantum "system"

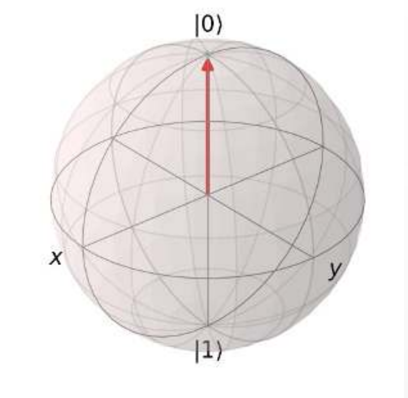
~1000+ Qubits: Small problems

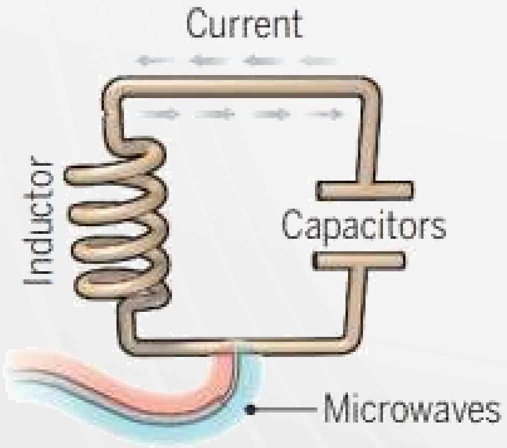
- Limited error correction
- Chemistry, materials design
- Optimization

~1M+ Qubits: Commercial scale

- Fault tolerant operation

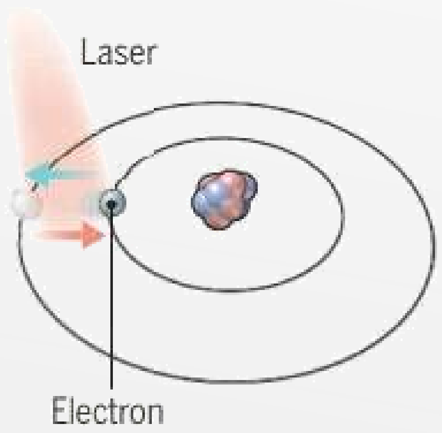
Qubit = A Quantum Bit





Superconducting loops

Google, IBM, Rigetti, DWave

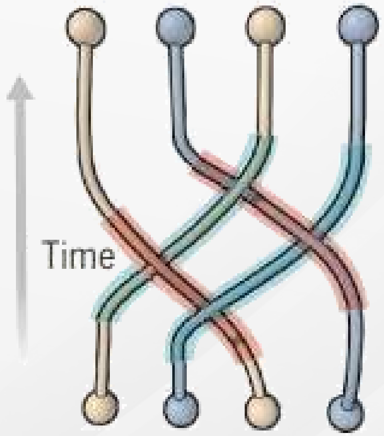


Trapped ions

Honeywell, IonQ

Silicon quantum dots

Intel Corporation, HRL

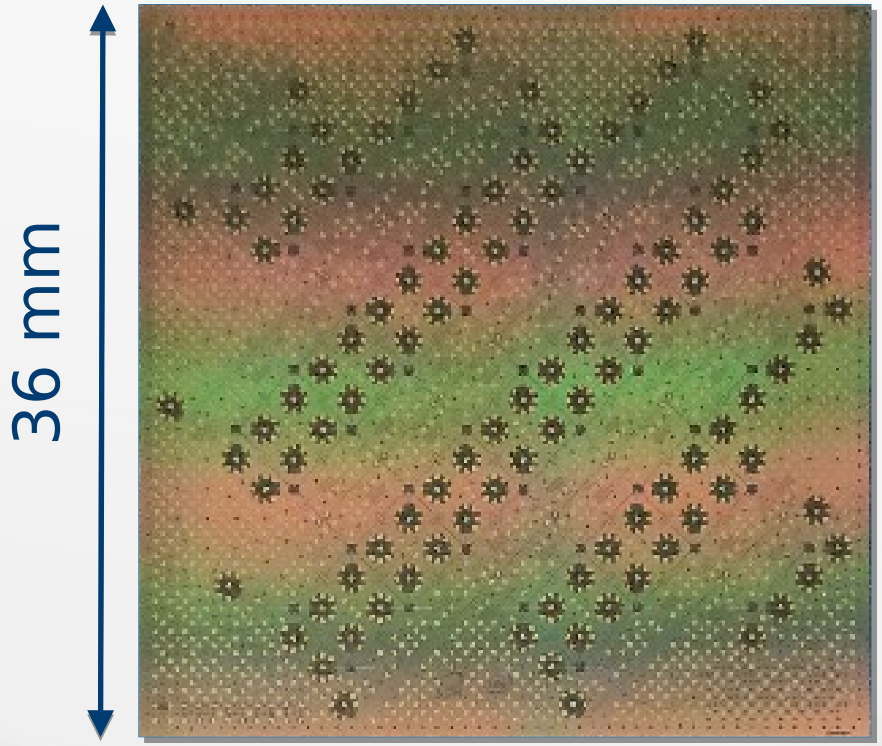


Topological qubits

Microsoft

DOI: 10.1126/science.354.6316.1090

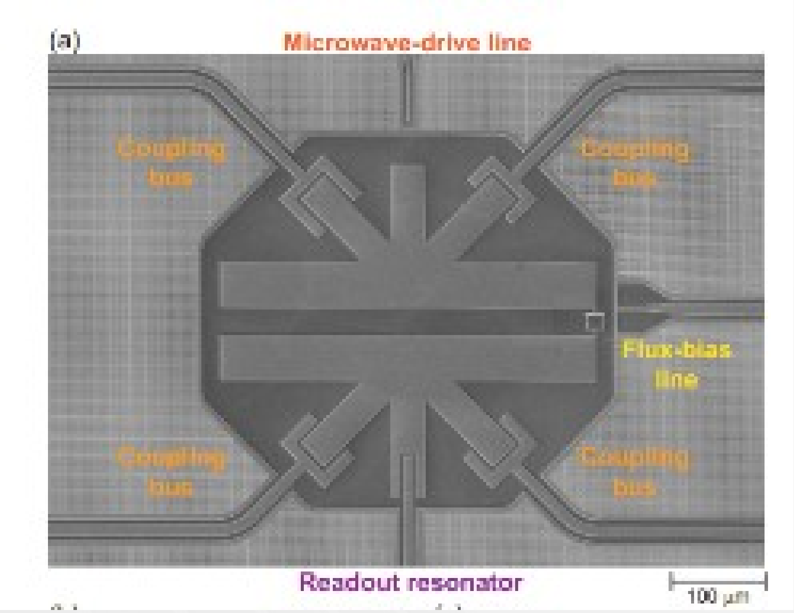
Why Not Superconducting Qubits?



Transmon Test Chip
49 qubits

Larger Than an Advanced Processor with Billions of Transistors

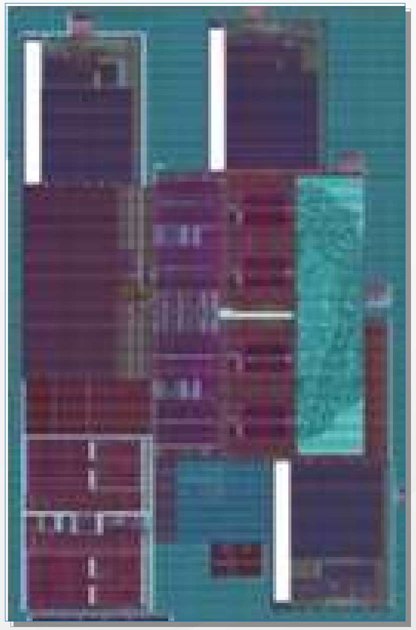
Another View



Starmon Qubit
[R. Versluis et al., arXiv:1612.08208v1]

Same Scale

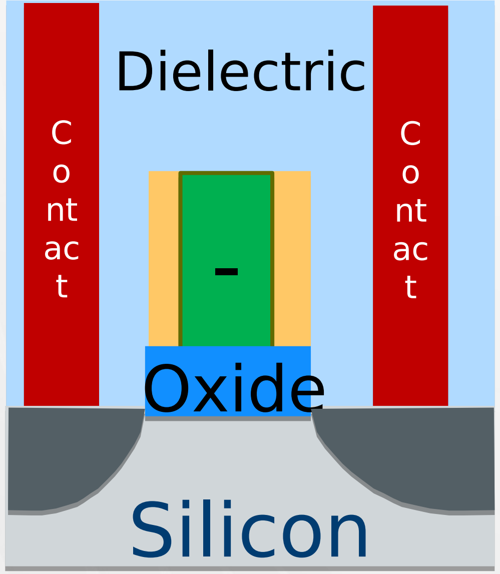
420µm

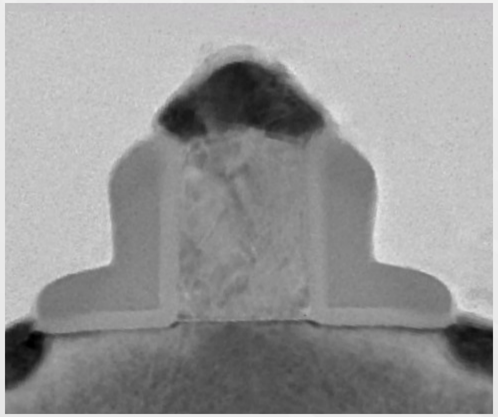


Bluetooth Low-Energy Transceiver in 14nm

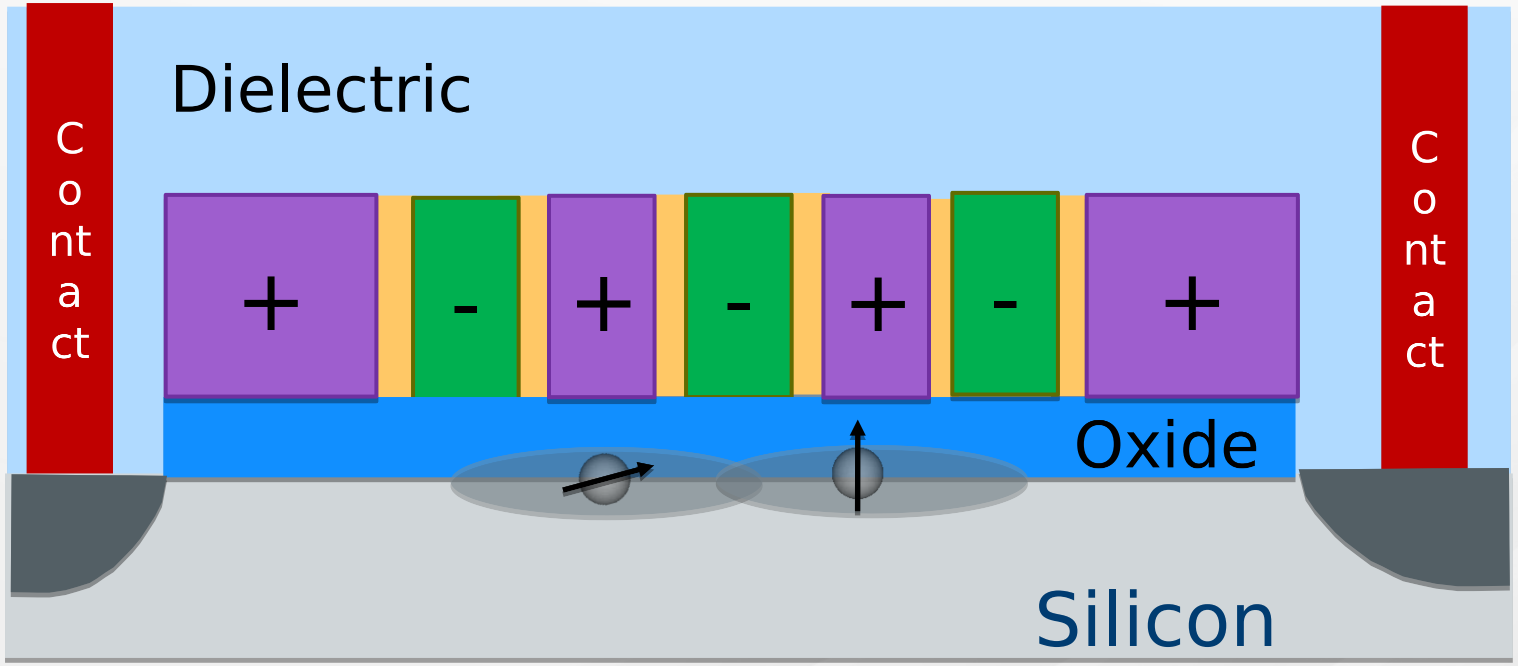
Commercial CMOS Circuits Are Smaller Than Individual Superconducting Qubits

A Spin Qubit Looks Like a Transistor





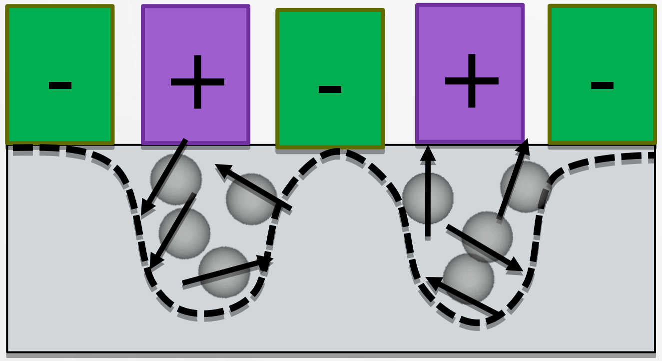
Transistor



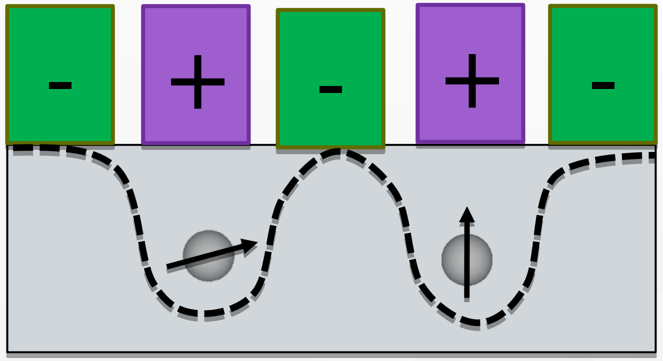
Linear Quantum Device

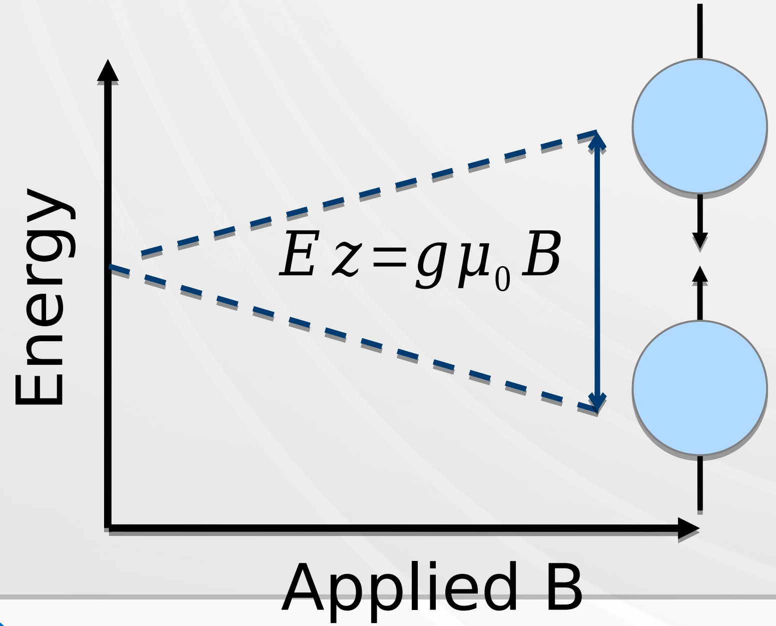
Requires Single Electron Control

From Quantum Dots to Qubits

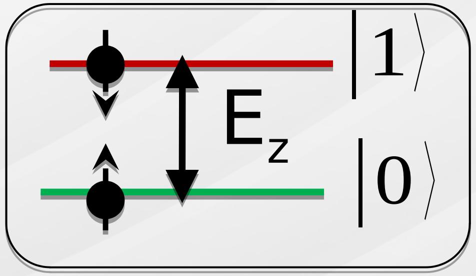


Single/Few Electrons



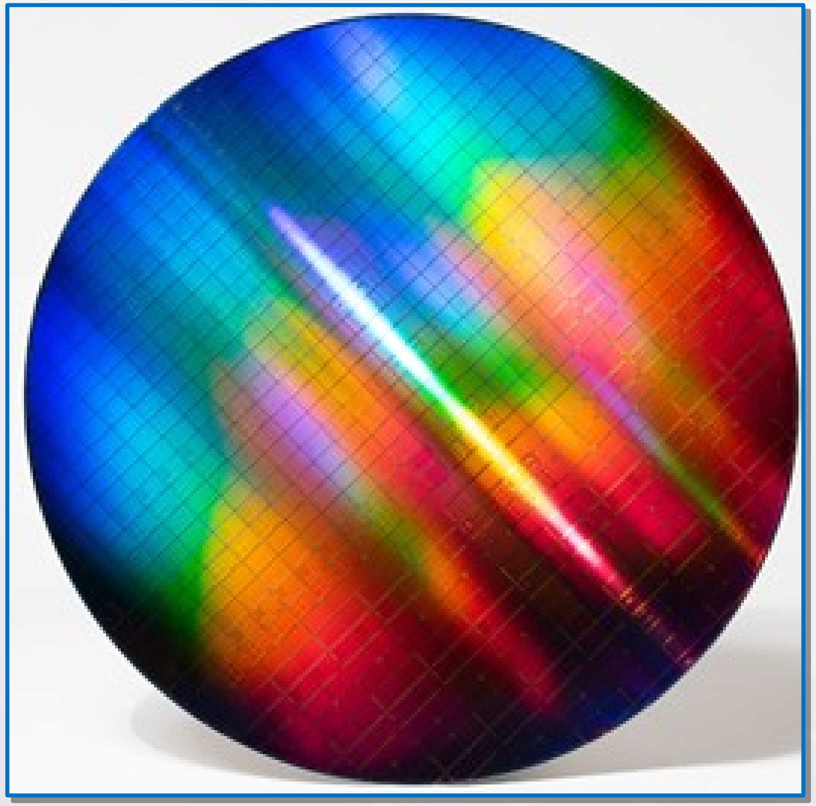


Apply Magnetic Field

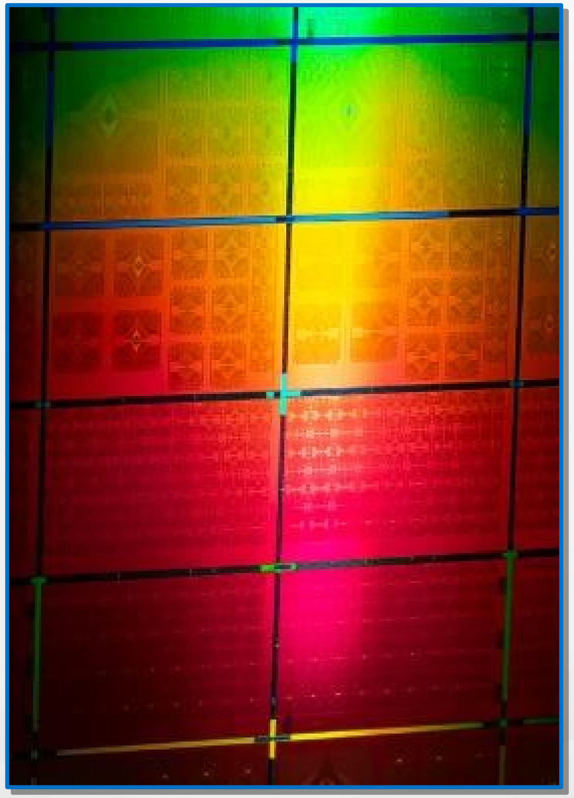


Customized Testchip for Spin Qubits

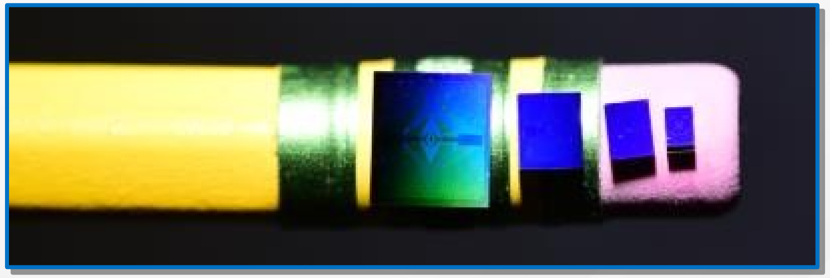
Full 300mm Wafer



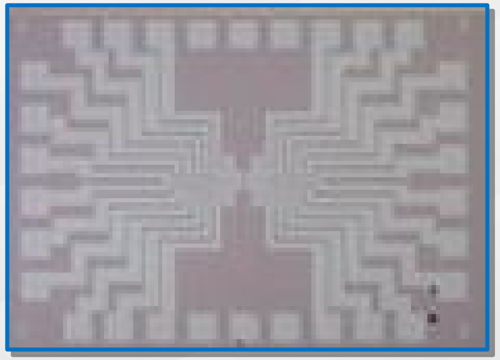
Full Reticle



Individually diced 7, 15, 23, and 55 gate arrays

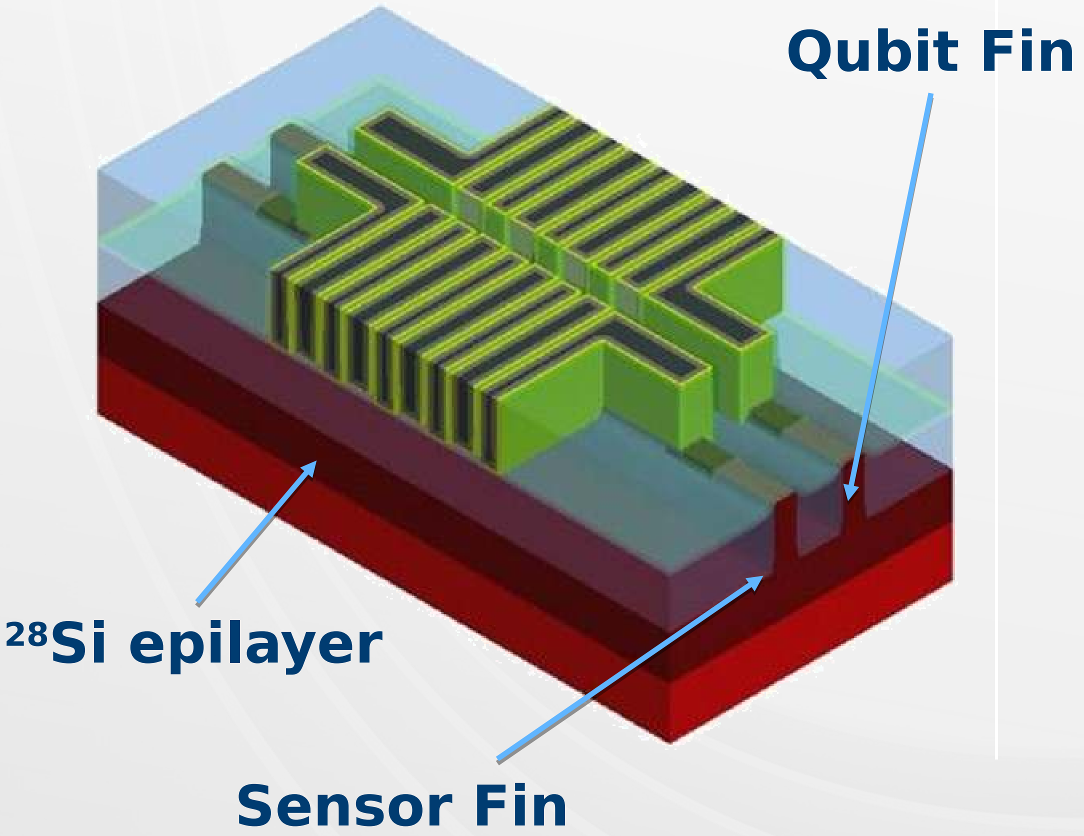


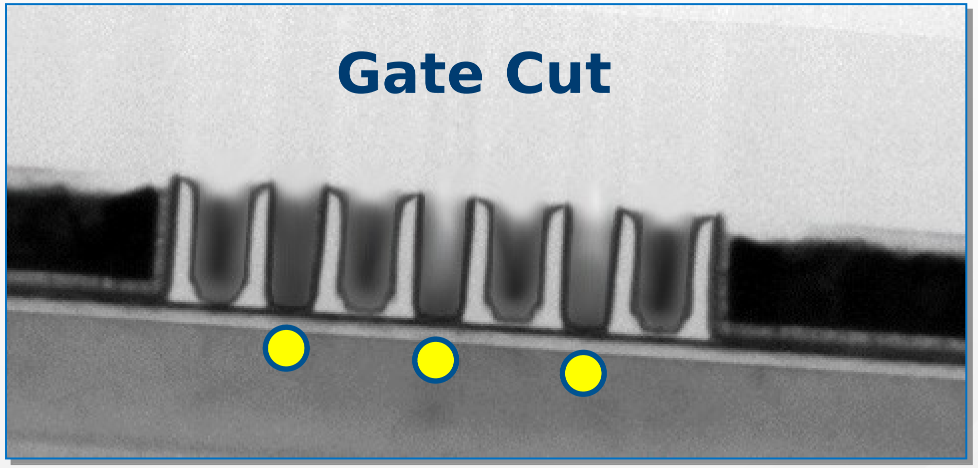
7 gate array

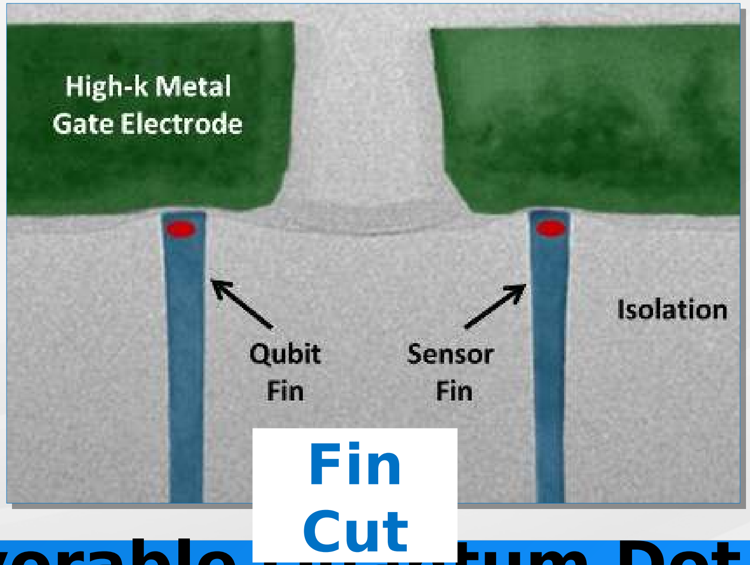


300mm Device Integration: Each Wafer Has Over 10,000 Arrays

^{28}Si Fin Based Quantum Dots



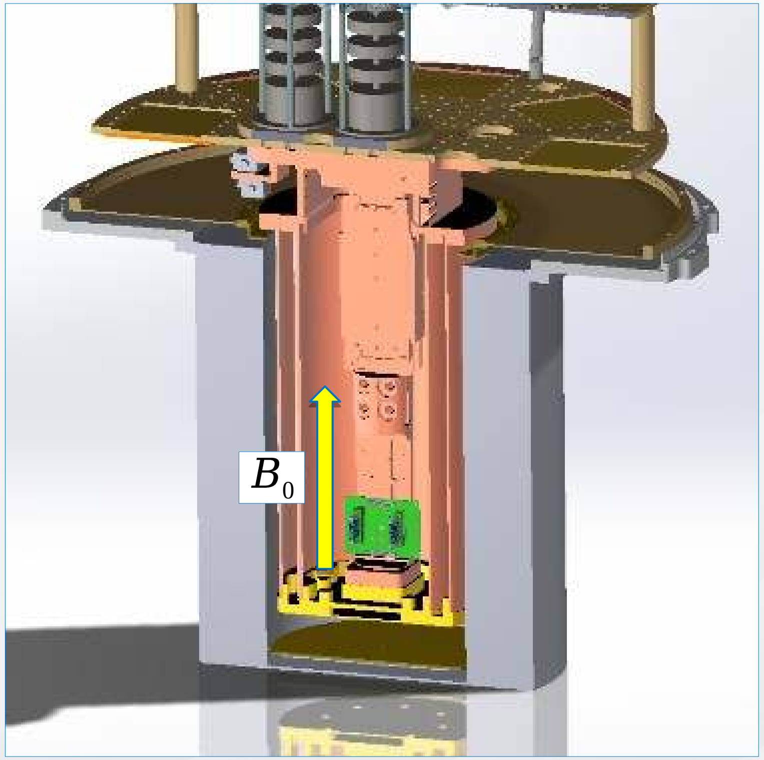




Fins: Strong Confinement ⇒ Favorable Quantum Dot Energetics

Quantum Measurements Capability

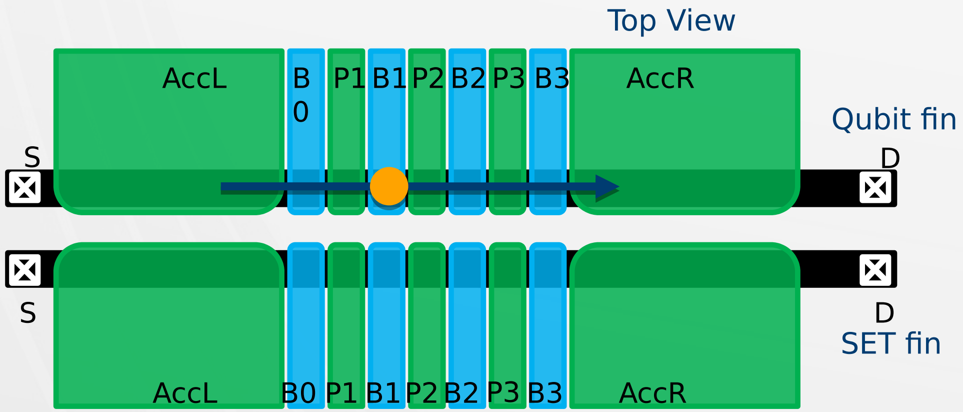
Series of dilution fridges

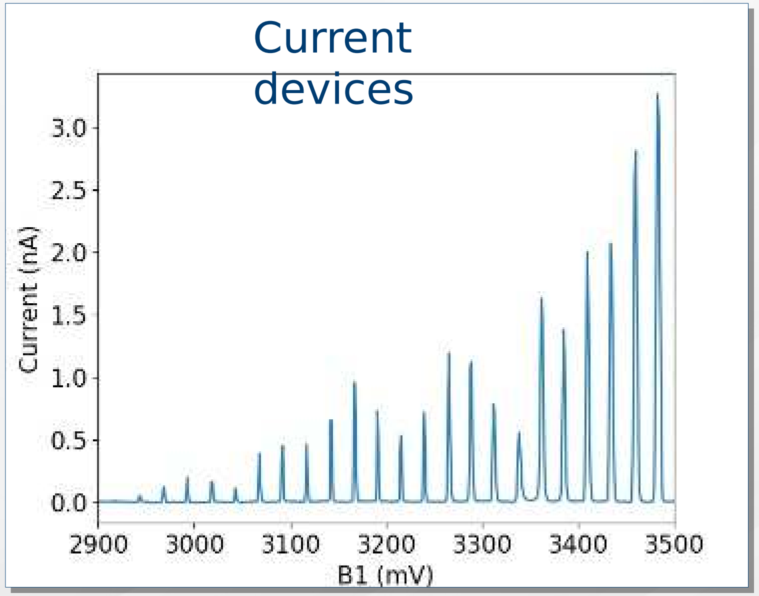


Samples kept inside superconducting magnet at 10mK

Competitive Quantum Measurement Facilities in US and Europe

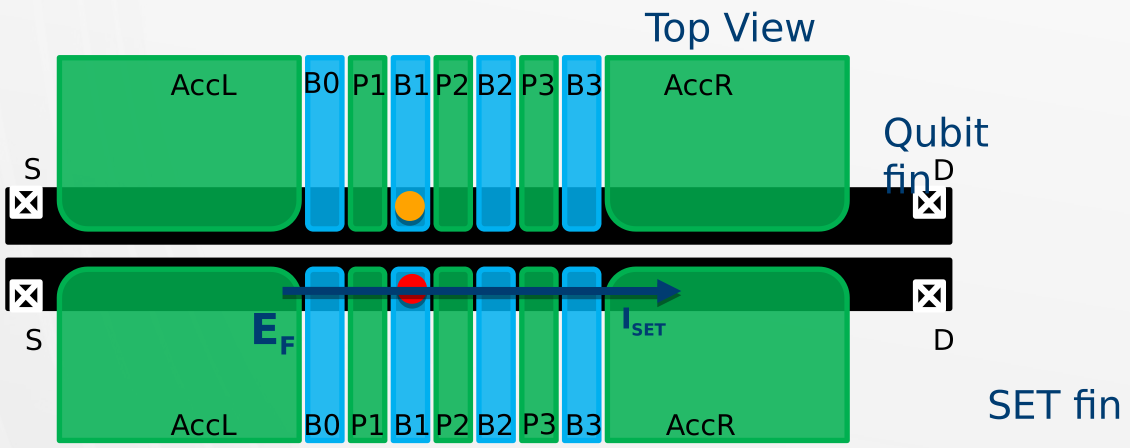
Defining a Quantum Dot



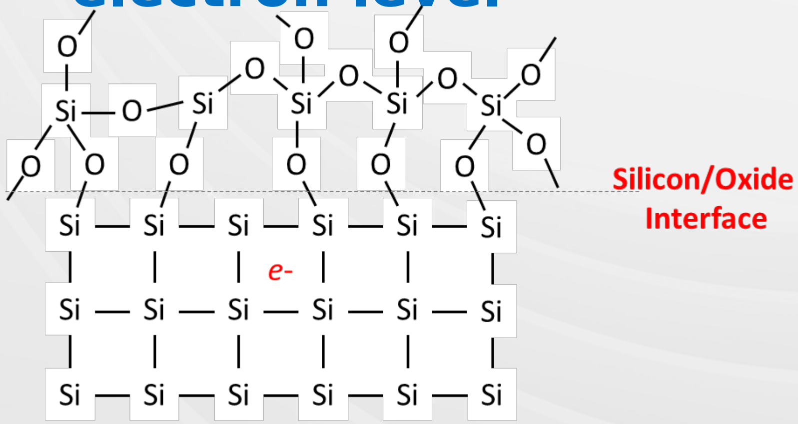


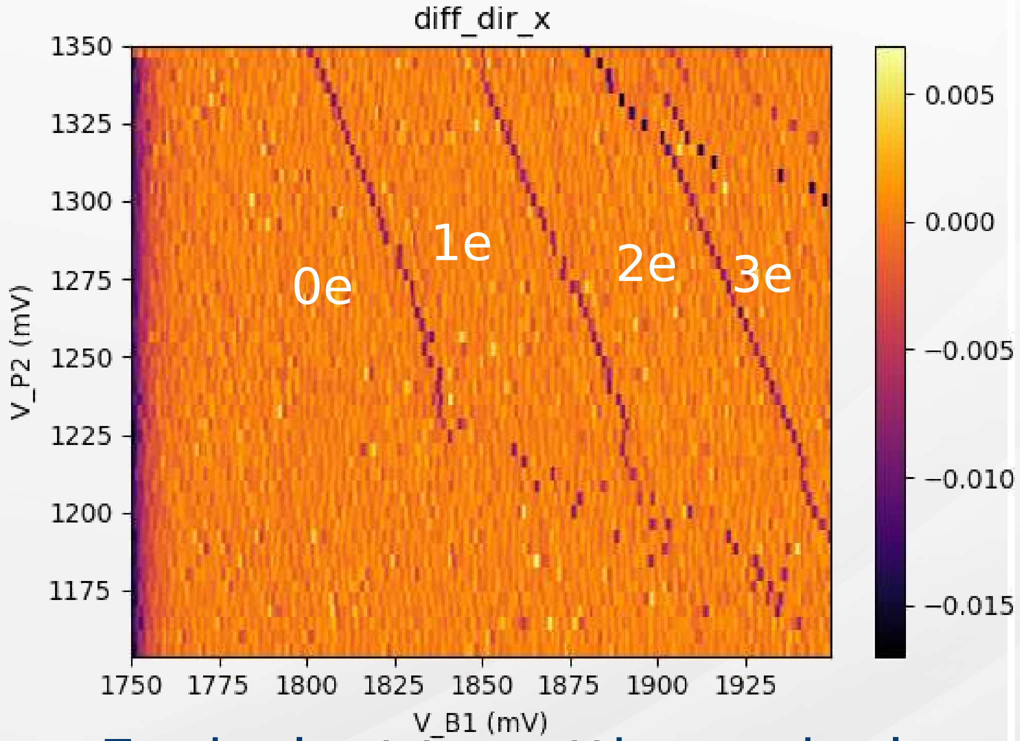
Ability to add individual electrons on a gate defined Quantum Dot

A Single Electron Quantum Dot



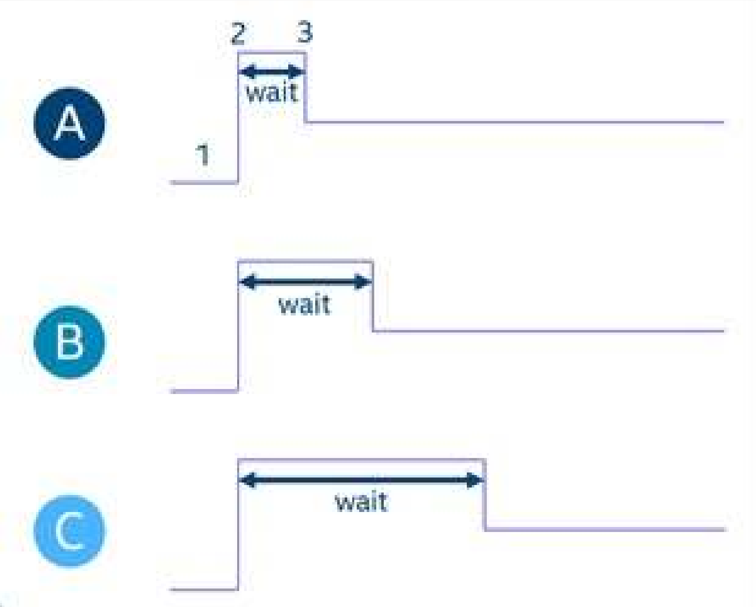
Use a Sensor Dot to detect at 1 electron level

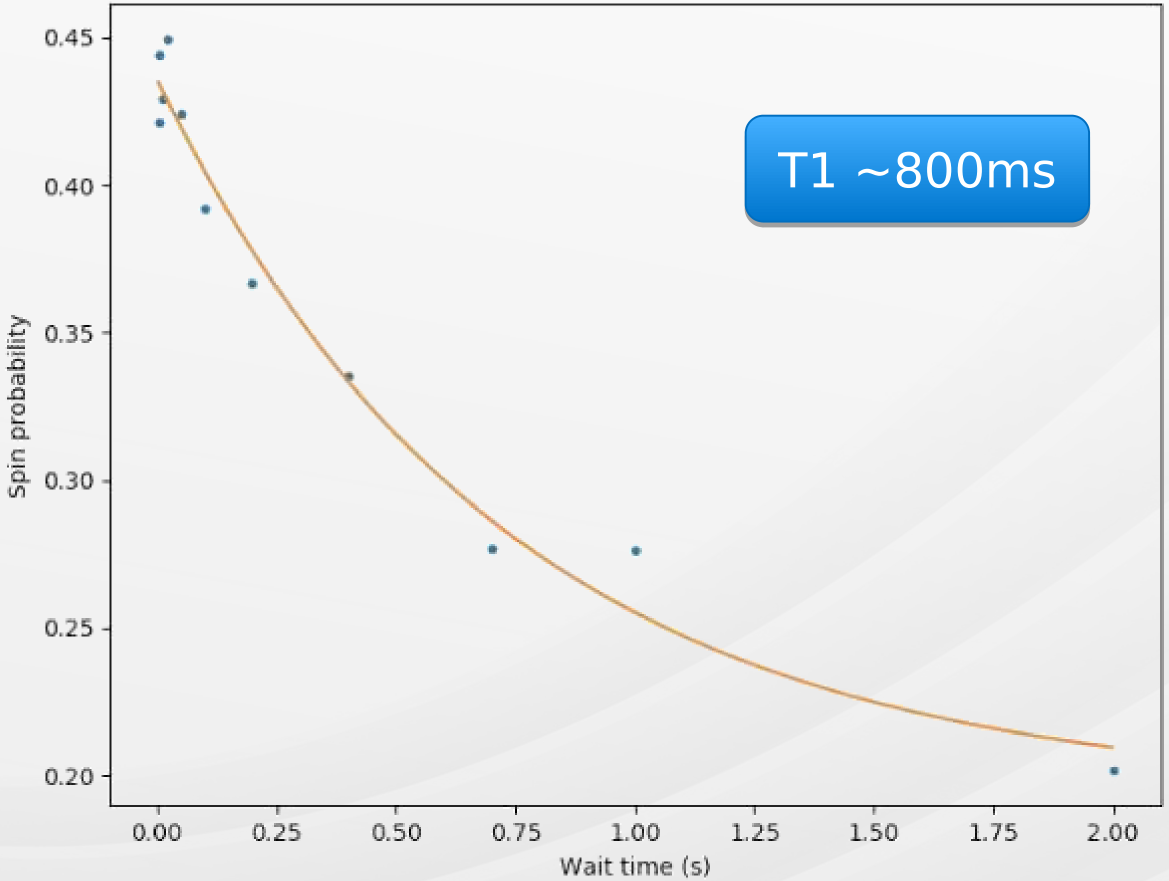




Equivalent to putting a single electron (Cleanly) into a sea of 100k silicon atoms. **Materials and Integration Focus**

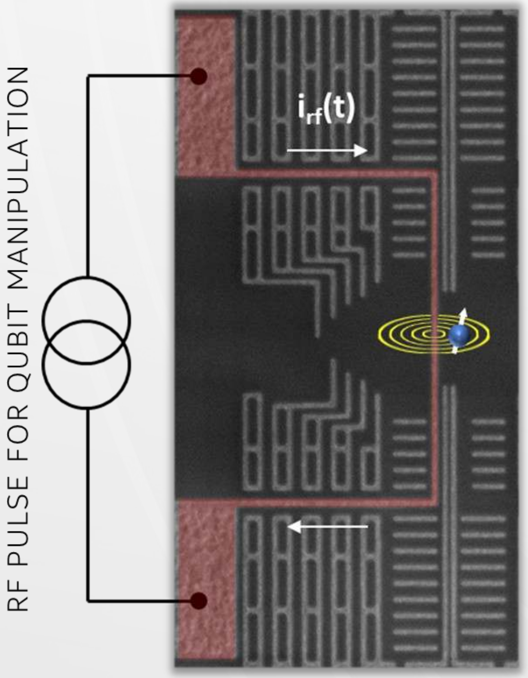
Single Electron Relaxation: T1 Measurement



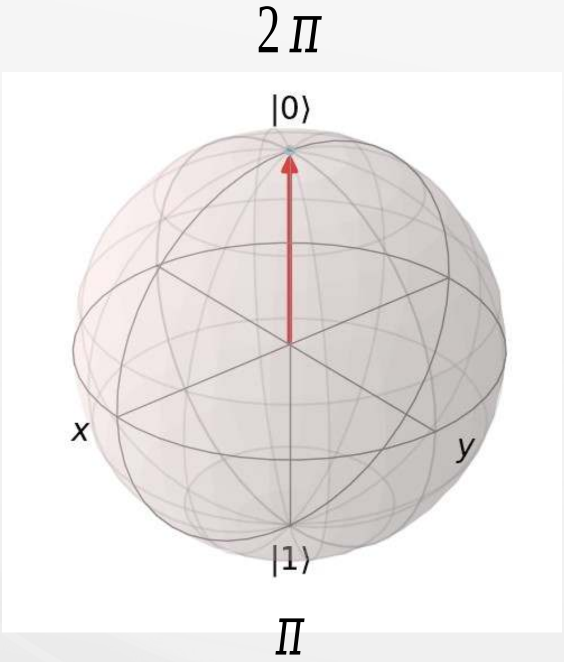


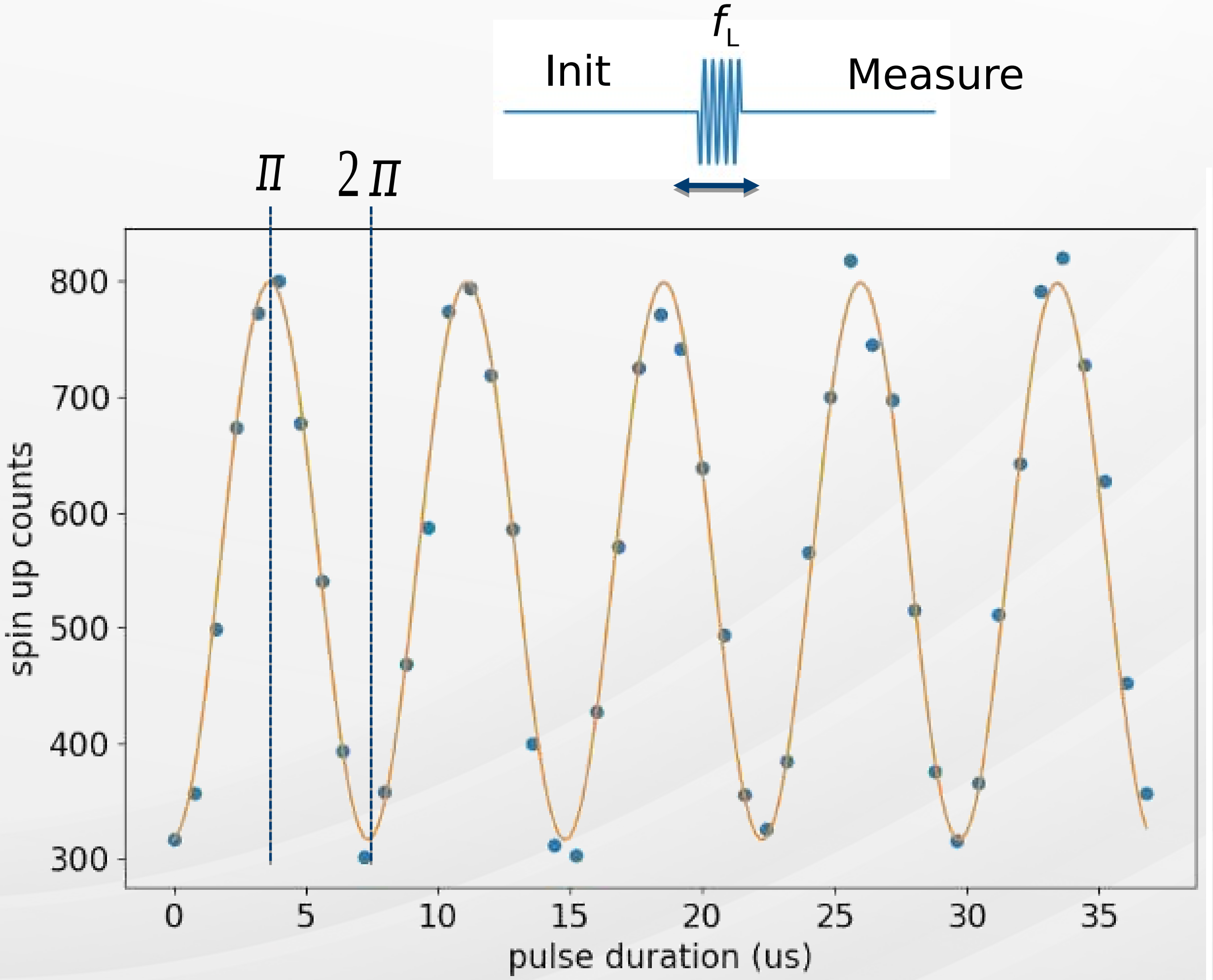
T1 Measures The Energy Decay Rate (Classical Information)

ESR Line and Rabi Oscillations



Microwave ESR Line
On Top Layer

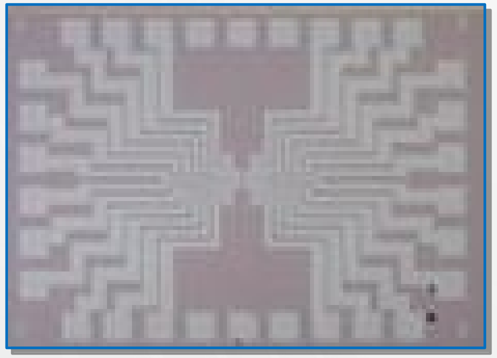


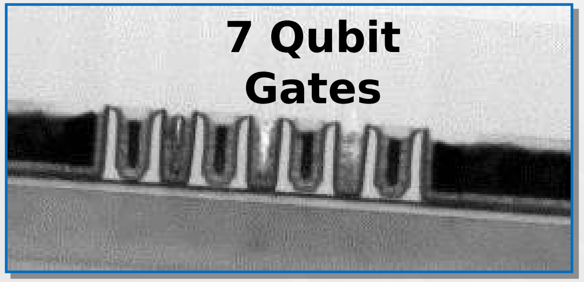


Demonstration of Coherent Control of a Qubit Made In Intel Fab!

How good is a qubit if you can't scale?

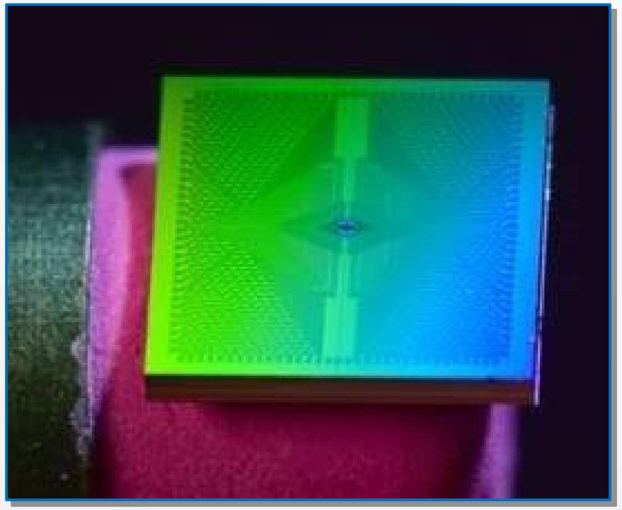
7 Gate Device

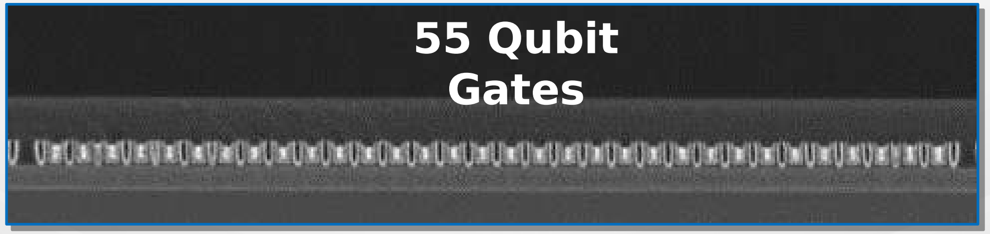




Crawl:
Studying today

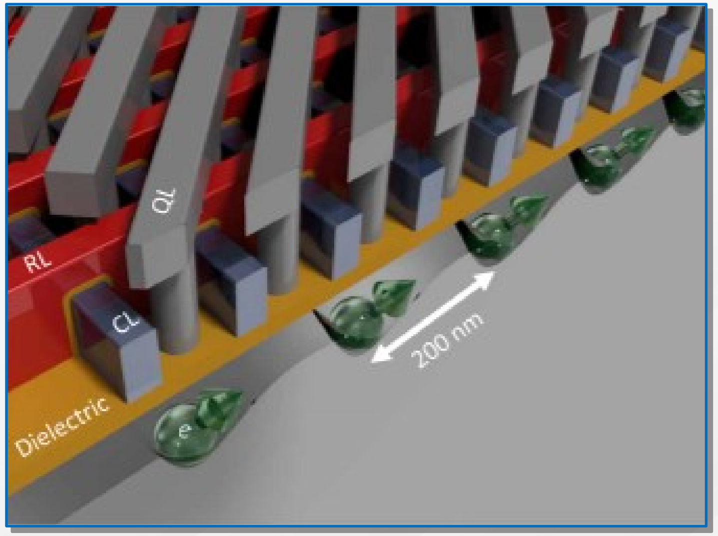
55 Gate Device





Walk:
Larger Devices on Same Chip

Large 2D Arrays



Run:
Extensible 2D Array

What about the Interconnects

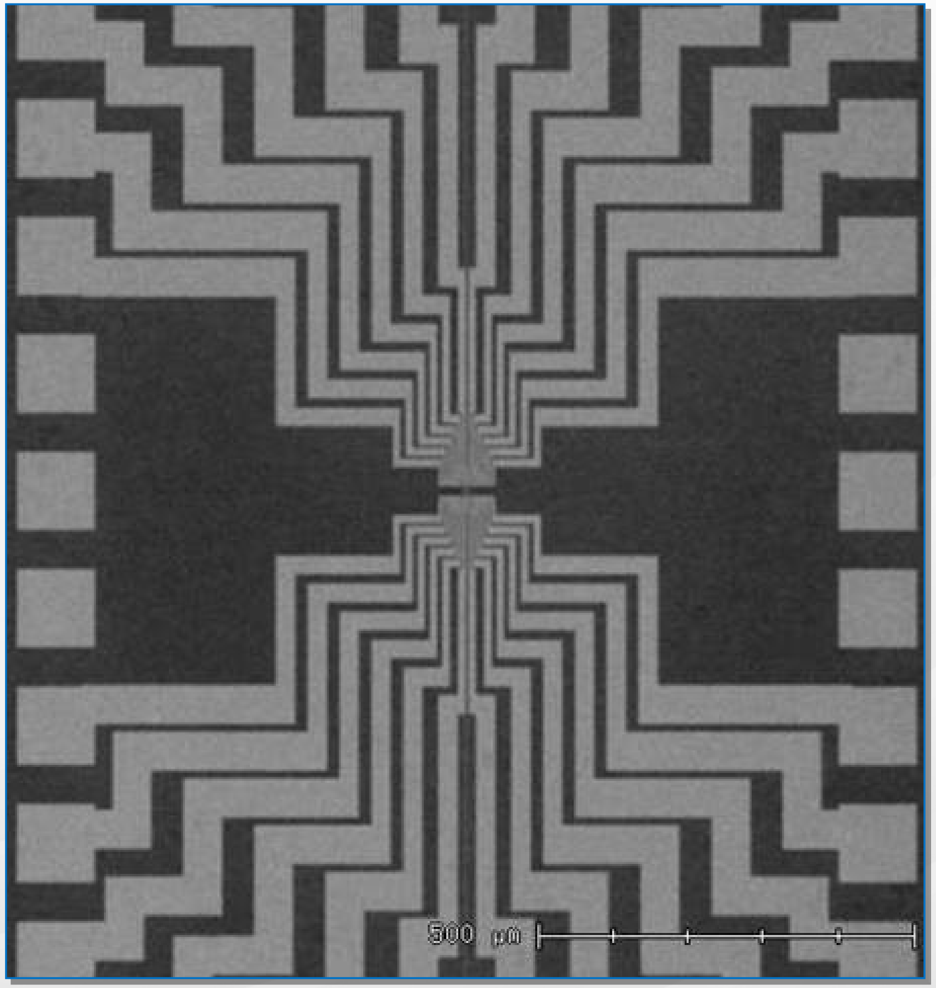
3 spin qubit chip requires:

- 1 RF ESR line
- >10 DC/AC gates for the qubits and Readout

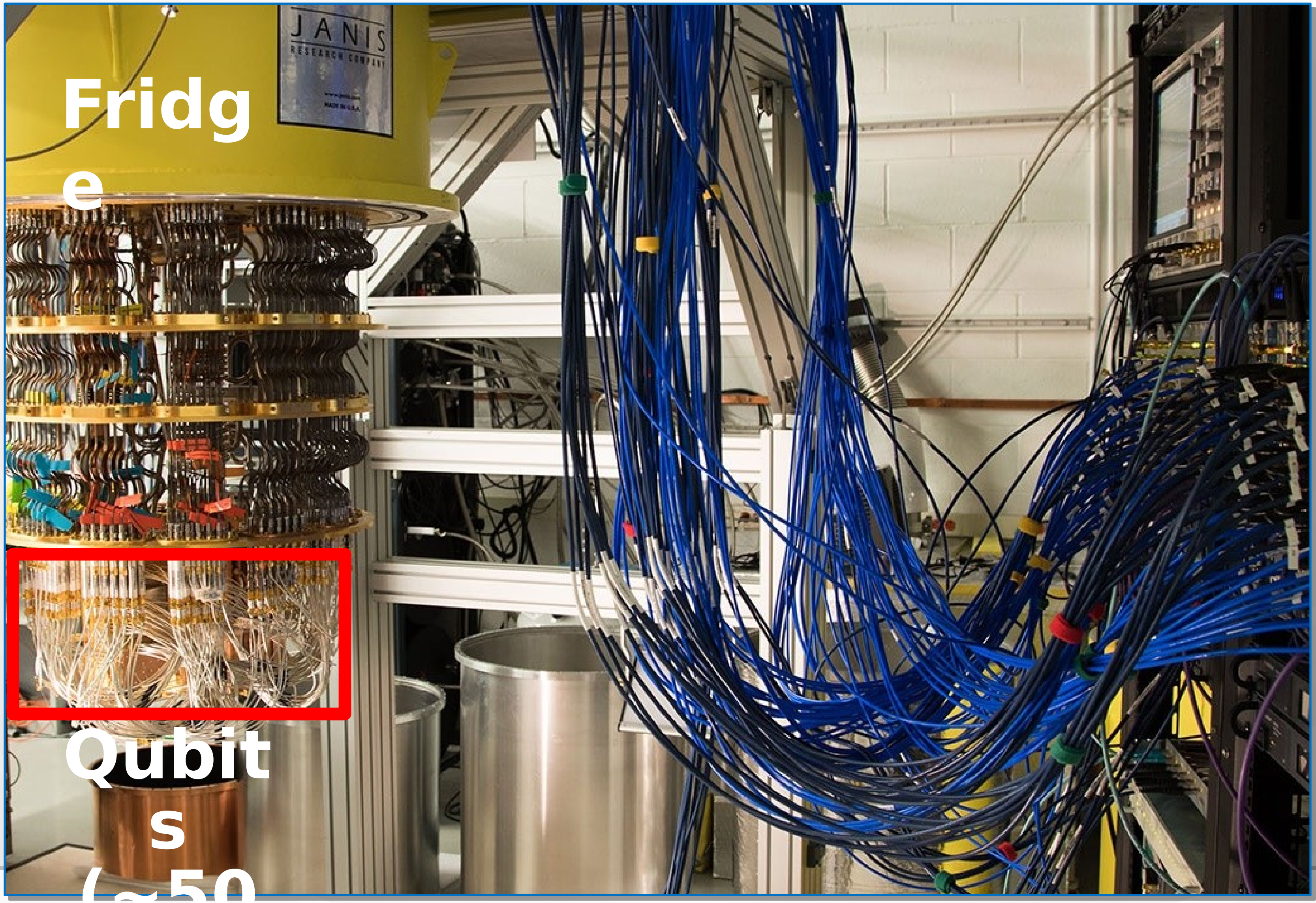
Scaling this to 1,000 qubits several *thousands* of coax lines

Current approach does not scale

- Form factor
- Thermal load on fridge (~1mW per cable)
- Power consumption

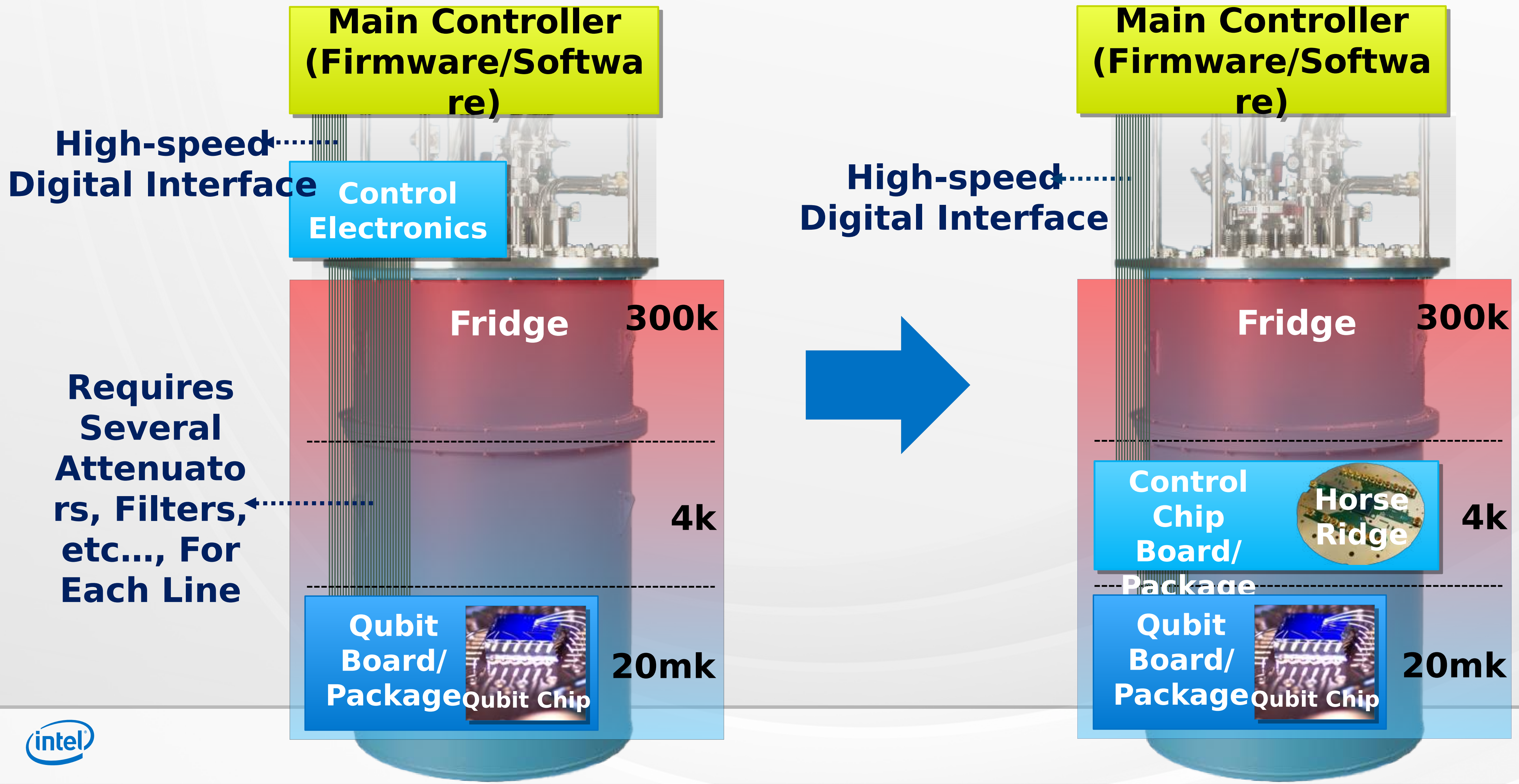


Too Many!



[Bardin, ISSCC

Highly Integrated Cryogenic Qubit Control

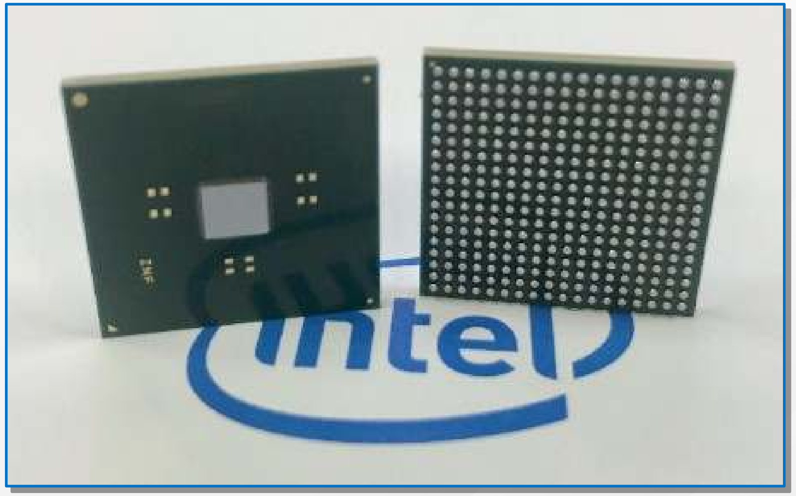


Cryogenic Controller Challenges

- Enable System-on-Chip (SoC) Design at Cryogenic Temperature
- Identify Signal Specifications
- Fully-Scalable Architecture
- Cryogenic Packaging
- Mechanical and Thermal Integration

Intel Competitive Advantage

- RFIC/mixed-signal/quantum core expertise
- Leverage communication theory DSP and algorithms
- Packaging and interconnect expertise
- Intel 22nm FinFET technology



HR1 IC Fabricated in Intel 22nm FinFet CMOS Technology

Horse Ridge

Controller capability

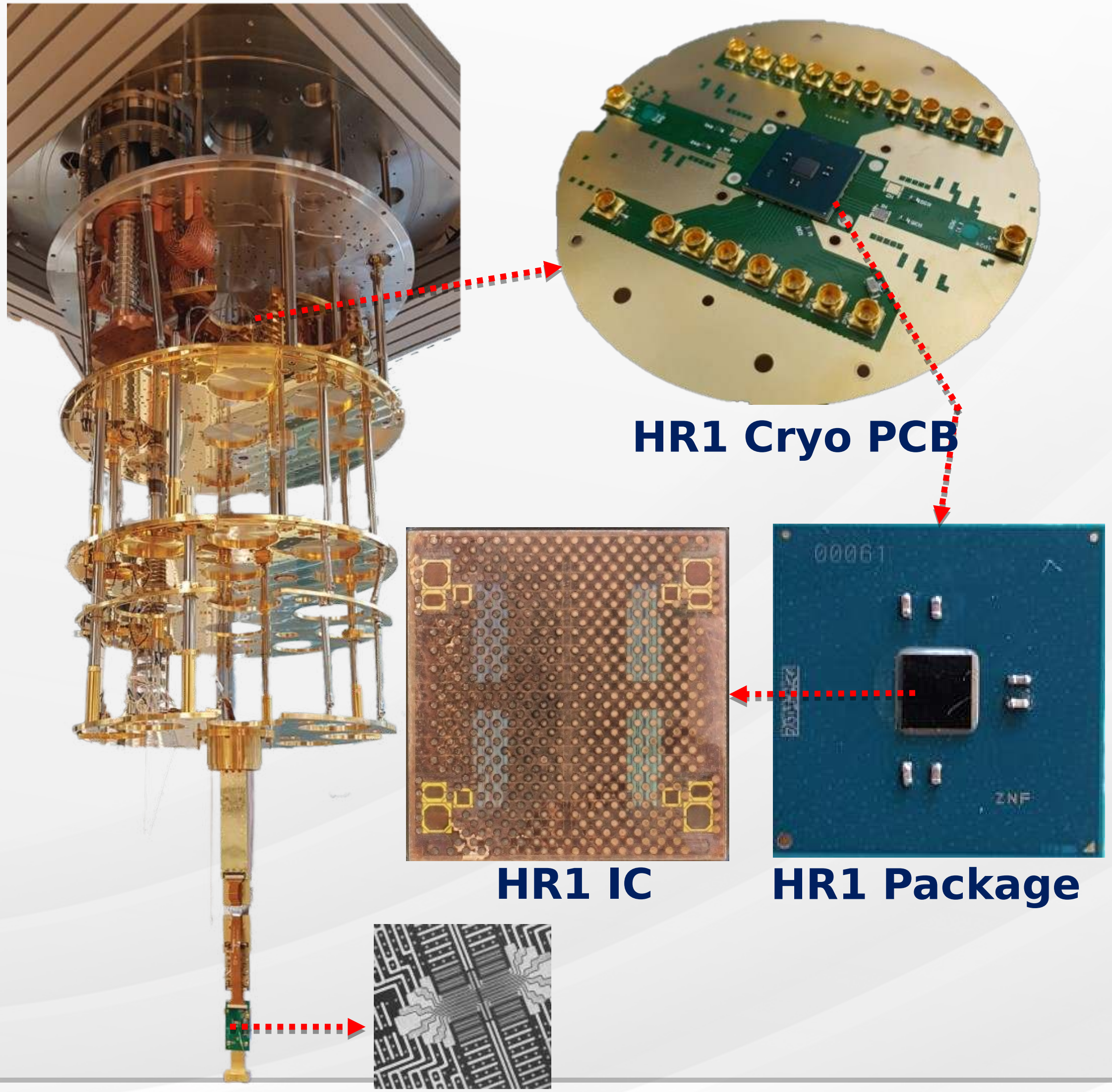
- Drive

Qubit type

- Superconducting and spin

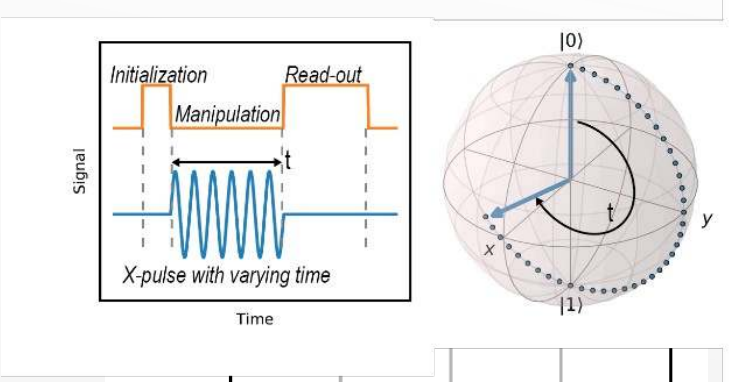
Main features

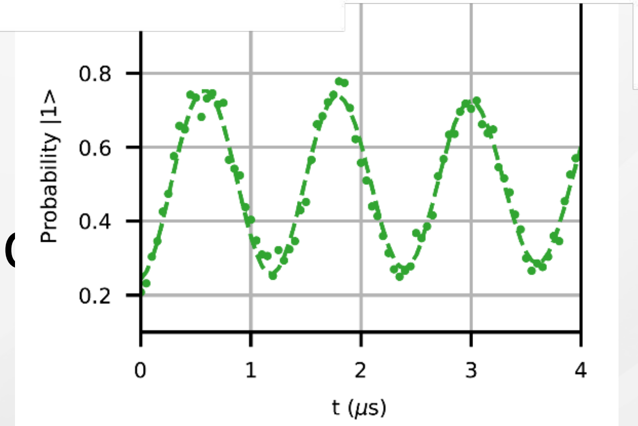
- Frequency Multiplexing (4x32 qubits)
- Arbitrary pulse envelope (SRAM based)
- Wideband frequency output (2-20GHz)



Horse Ridge – Key Objectives

- ✓ Transistor models an design methodology at 4K
- ✓ Benchmark Intel 22nm FFL process at 4K
- ✓ Validate fridge thermal and mechanical integration
- ✓ Demonstrate fundamental gate operation on single
- ✓ Matched to discrete electronics
- ✓ Execute 2-qubit algorithm
- ☐ Demonstrate frequency multiplexing **in progress**

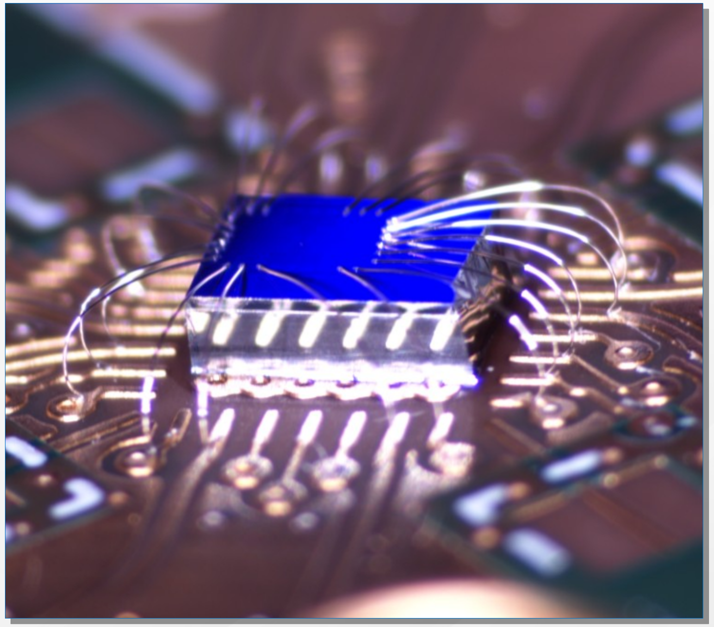




Measured Rabi oscillation on single spin qubit with HR1

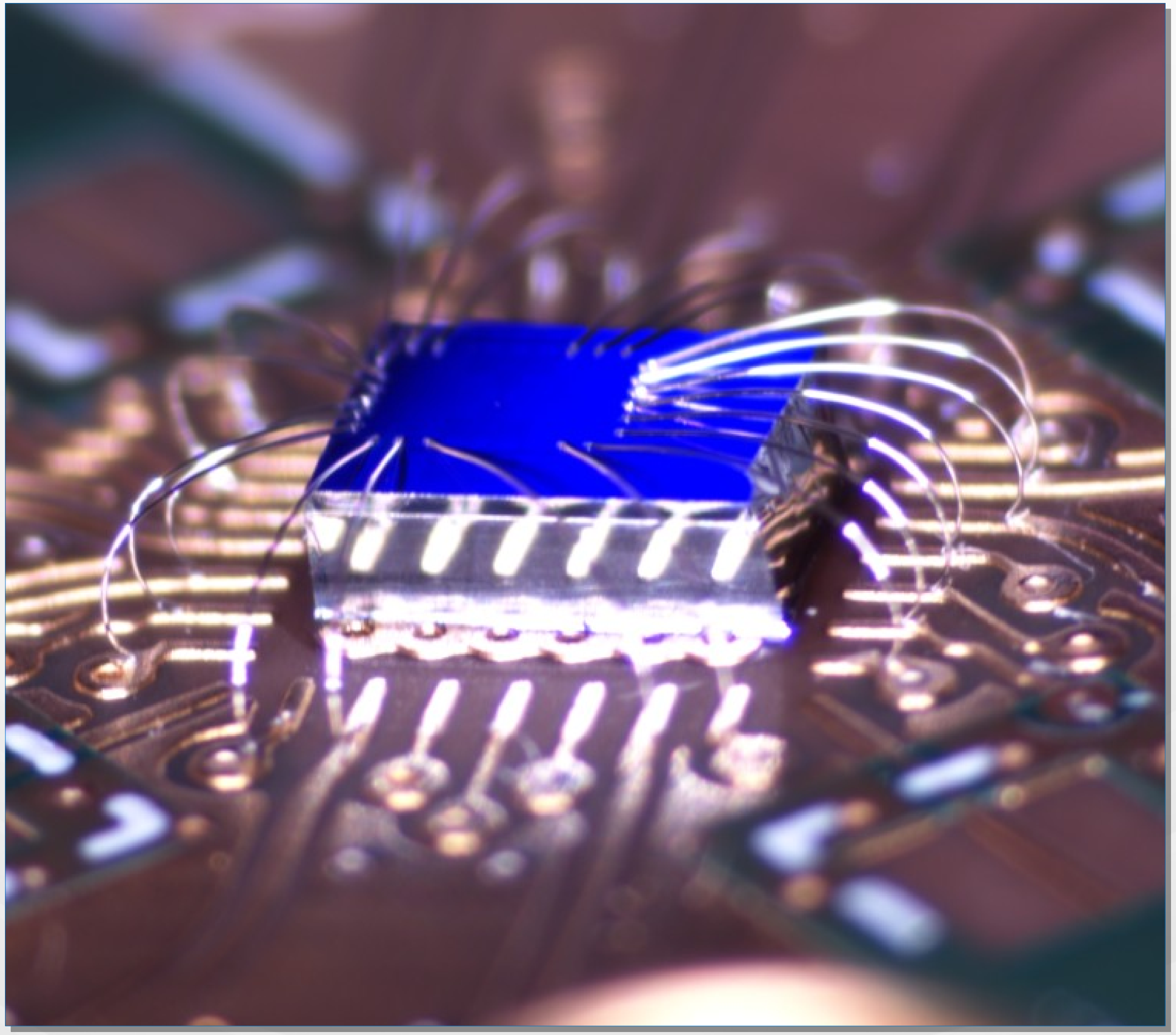
Conclusions

- Quantum will change the world
- But it will require millions of qubits
- Spin Qubits are built on the same technology as transistors and have compelling performance
- Quantum Computing won’t happen with brute force wiring and control



Intel Is Working On This

Thank you!



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