Towards A Large Scale Quantum Computer Using Silicon Spin Qubits

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Quantum Computing: Key Concepts

Superposition

Classical Physics

Heads or Tails

Quantum Physics

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

1)

2)

3)

4)
The Promise of Quantum Computing

Exponential Speedup — Surpassing The Limits Of Traditional Scaling
The Demand for Quantum Computing

"Quantum Will Change Everything"

Travel & Logistics
Chemistry
Pharmacology

Climate Modeling
Financial Analysis
Cryptography
Quantum co-processor: augmenting, not replacing, traditional HPC systems

Relevant System Sizes

~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]

Commercial CMOS Circuits Are Smaller Than Individual Superconducting Qubits

Same Scale

Bluetooth Low-Energy Transceiver in 14nm

420µm
A Spin Qubit Looks Like a Transistor

Linear Quantum Device

Requires Single Electron Control
From Quantum Dots to Qubits

Single/Few Electrons

Energy $E_z = g \mu_0 B$

Apply Magnetic Field

$|0\rangle$

$|1\rangle$

$E_z$
Customized Testchip for Spin Qubits

- Full 300mm Wafer
- Full Reticle
- Individually diced 7, 15, 23, and 55 gate arrays

300mm Device Integration: Each Wafer Has Over 10,000 Arrays
28Si Fin Based Quantum Dots

Fins: Strong Confinement $\Rightarrow$ 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)

T1 ~800ms
ESR Line and Rabi Oscillations

Demonstration of Coherent Control of a Qubit Made In Intel Fab!
How good is a qubit if you can’t scale?

7 Gate Device

55 Gate Device

Large 2D Arrays

7 Qubit Gates

55 Qubit Gates

Crawl: Studying today

Walk: Larger Devices on Same Chip

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!

Fridges

Qubits (~50)

[Bardin, ISSCC 2019]
Highly Integrated Cryogenic Qubit Control

Main Controller (Firmware/Software)

Fridge

300k

4k

20mk

Qubit Chip

Qubit Board/Package

Control Chip Board/Package

High-speed Digital Interface

Requires Several Attenuators, Filters, etc..., For Each Line

Control Electronics

Main Controller (Firmware/Software)

Fridge

300k

4k

20mk

Qubit Chip

Qubit Board/Package

Control Chip Board/Package

Horse Ridge

High-speed Digital Interface
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 qubit
- Matched to discrete electronics
- Execute 2-qubit algorithm

- Demonstrate frequency multiplexing in progress
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
Thank you!