SAND 2010-5992 C

Quantum Information Processing: Science & Technology

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Sandia National Laboratories (SNL)

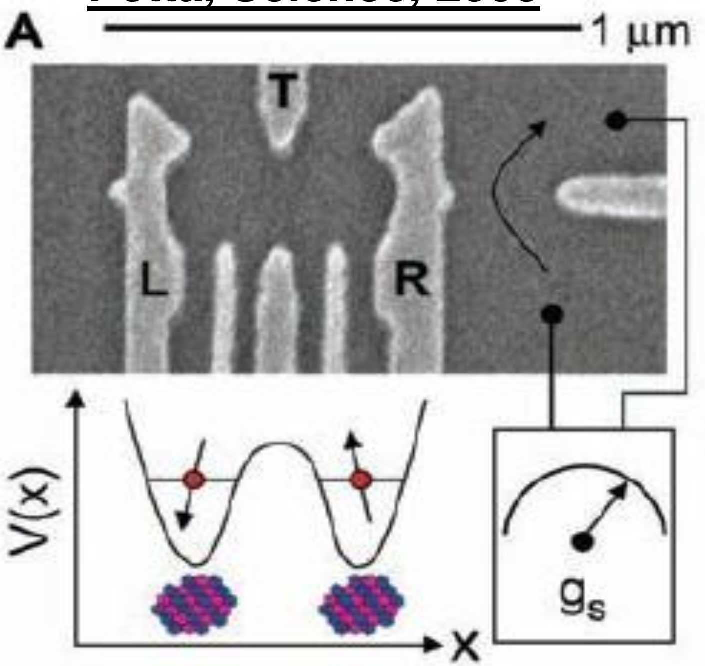
September 9, 2010

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.

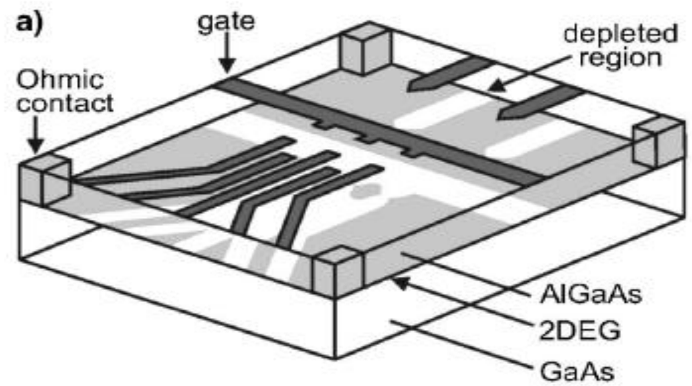
Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000

Solid-State Spin Qubit

Petta, Science, 2005



Hanson, Rev. Mod. Phys. 2007

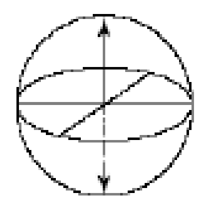


- Qubits demonstrated using GaAs double quantum dots (DQD) [Petta, Science 2005]
- The qubit basis states are the (1) singlet and (2) triplet stationary states
- Long spin decoherence times in silicon spurs translation of GaAs qubit in to silicon

Bloch Sphere (2 electron spins)

$|1\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

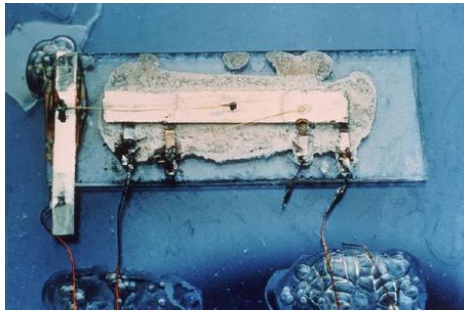
$|\downarrow\uparrow\rangle$



$|\uparrow\downarrow\rangle$

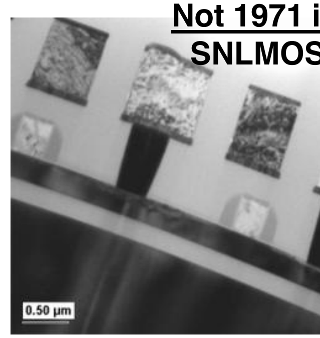
$|0\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Ge BJT(1947)
Nobel Prize
*MOSFET patent (1928)

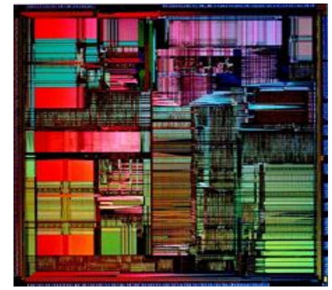


First Integration in ***Ge*** (1959)
Nobel Prize
*Integration in ***Si*** (1960)

Not 1971 image
SNLMOSFET

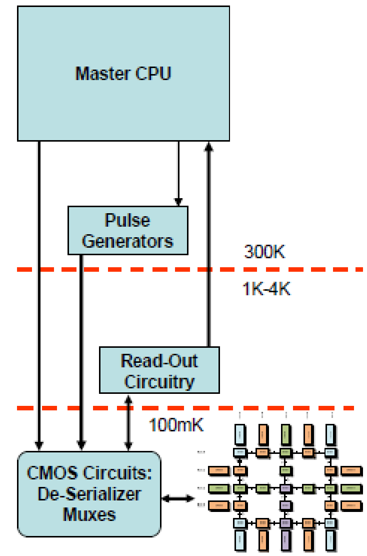


23 Si FET oscillator (1971)

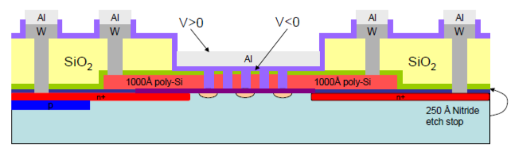


Modern CPU

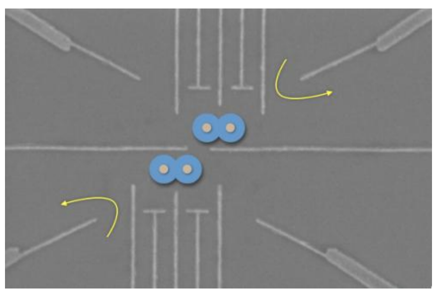
Quantum Circuit (>2010)



Si Qubit (2010?)

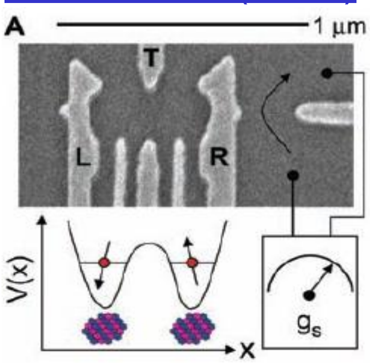


GaAs 2 Qubit Gate (2010?)



Marcus, Vienna, VA 2009

GaAs Qubit (2005)



Quantum Information Science & Technology (QIST) Grand Challenge (3 years)

1. Demonstrate Si qubit (longer decoherence time)
2. Design error corrected logical qubit (quantum memory circuit)
   - Understand requirements for quantum circuit

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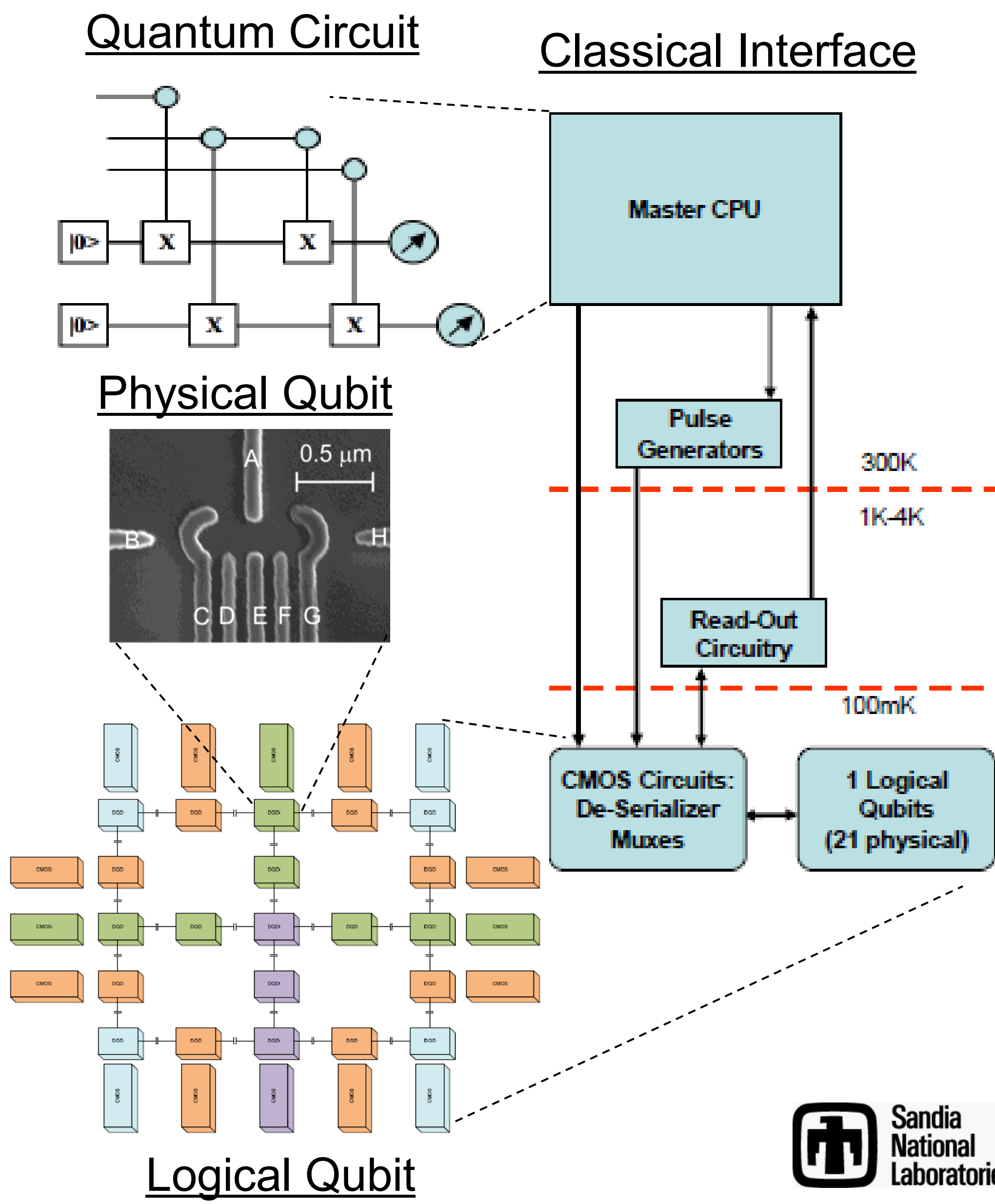
Multidisciplinary Grand Challenge

- Focus Areas
  - Physical Qubit (Si fab)
  - Electronics (Si CMOS)
  - Error Correction
  - Modeling
  - Second Generation Qubit



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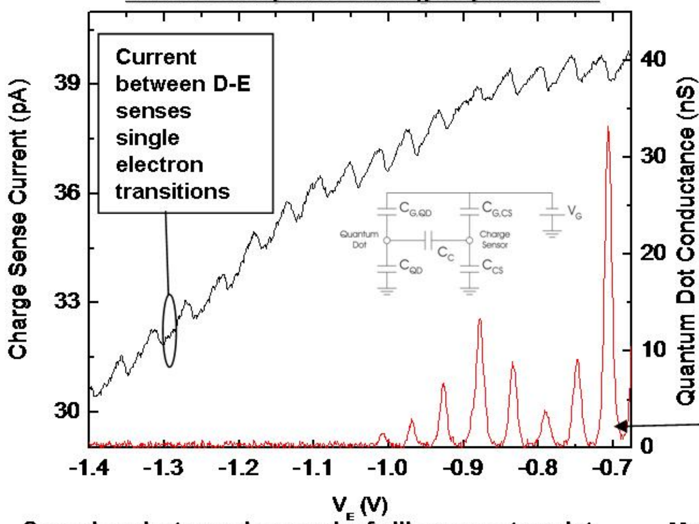
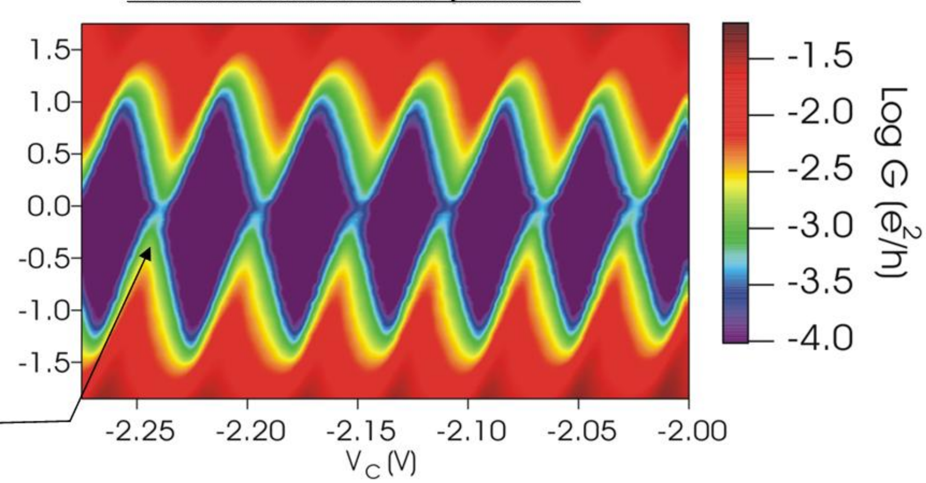
Quantum Information S&T

Single Charge Sensitive Sensor for Silicon Double Quantum Dot Qubit State Read-out

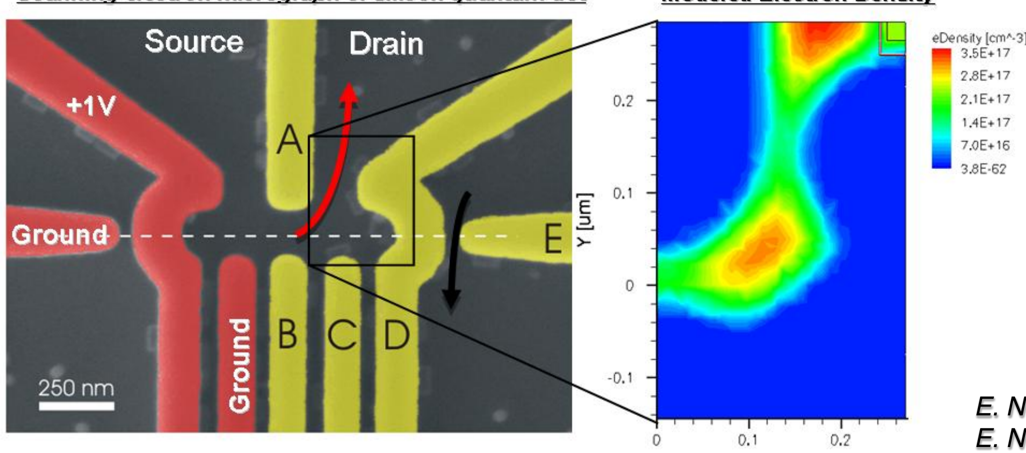
Electron occupation sensing of quantum dot



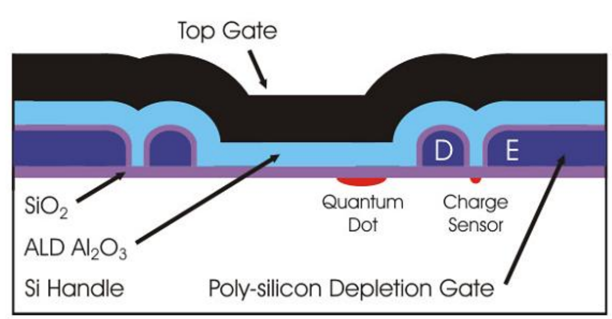
Coulomb blockade in Si MOS quantum dot



Scanning electron micrograph of silicon quantum dot ***Modeled Electron Density***



Cross section of silicon quantum dot



E. Nordberg et al., PRB 2009
E. Nordberg et al. APL 2009
H. Stalford et al., IEEE T. Nanotechnology 2010
L. Tracy et al., (in progress for APL) 2010

- *Single electron donor implants also under investigation*

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MOS DQD Qubit

Required steps

1. Develop low disorder tunnel barriers – point contacts
2. Develop low disorder stable quantum dots
3. Develop charge sensors (SET)
4. Couple MOS QD and charge sensor
5. Develop few electron dots (w/ charge sensor)
6. Develop few electron DQD (w/ charge sensor)
7. T1 : Initialization and read-out of singlet vs. triplet (pulsed w/ charge sensing)
8. Integrate external dB for singlet/triplet evolution (if necessary?)
9. T2* : Rabi oscillations
10. T2 : Hahn - echo

State-of-the-art

SNL starts QIST Oct. 2007

2006-7: NIST/NTT, CQCT & others

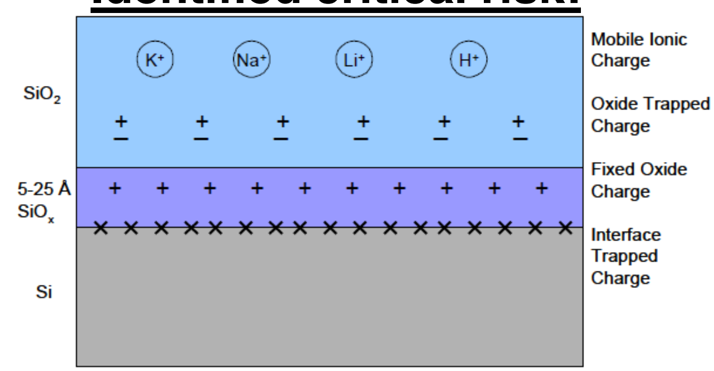
2008: CQCT

DQD 2008-10: NTT, CQCT, ***SNL***

2009: ***SNL***, UCLA & others in 2010

2009-2010: UCLA, CQCT (donors)

Identified critical risk:



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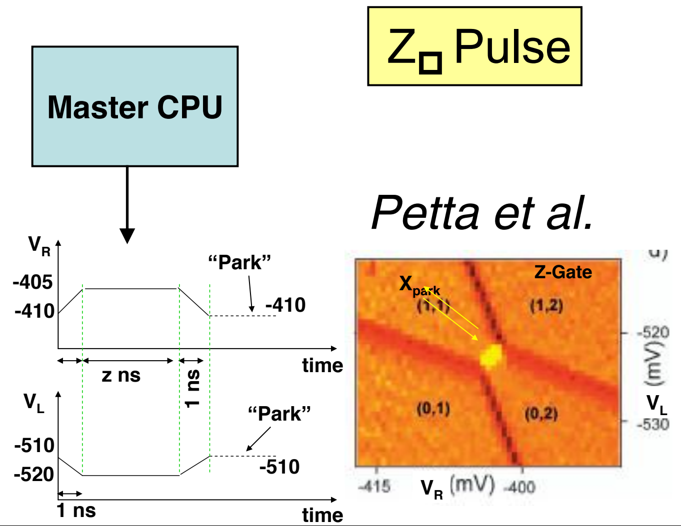
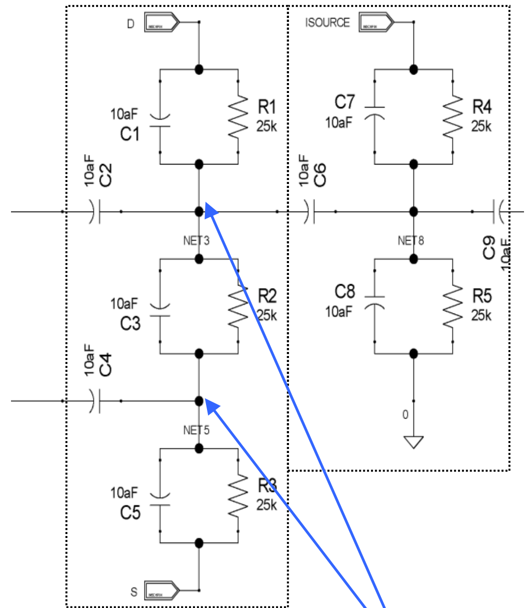
"Circuit Designer Meets QIP"

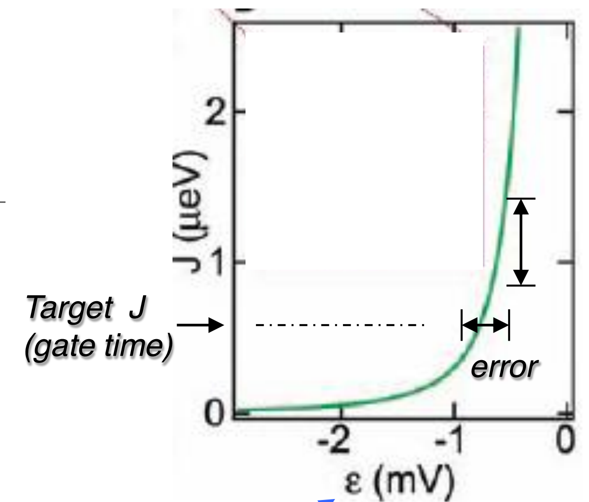


Electrometer

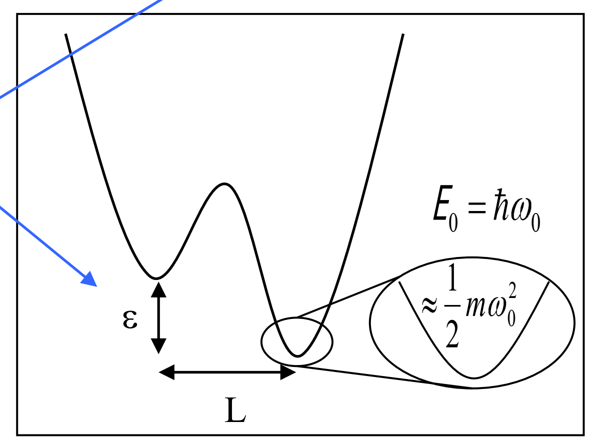


DQD

Petta, Science 2005



∇V

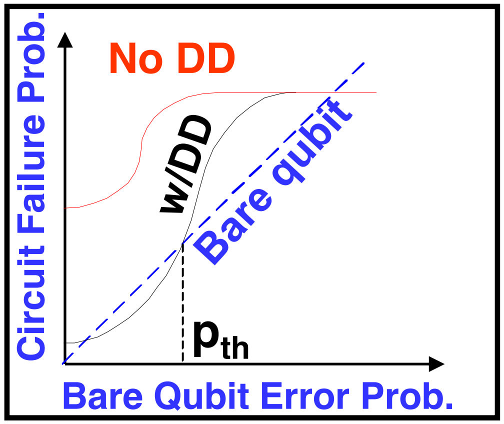


- Quantum algorithm calls for a Z-rotation of a qubit
- Accuracy & precision requirements produce clock constraints (3 ns not 120 ps)
  - Idle time is set relative to T2 (or T2*)
- Pulse shapes must be designed (will talk again about this later)
- Small signal model developed to bridge classical electronics and qubit physics
- Qubit design guidance is also suggested
  - Exchange flats [Nielsen et al. arXiv]

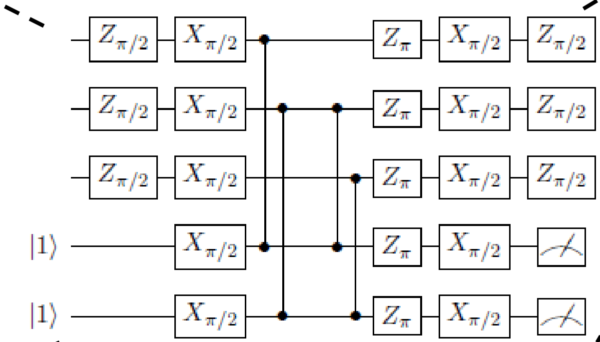
QIST Quantum Information S&T

Logical Qubit Design in a Cryostat

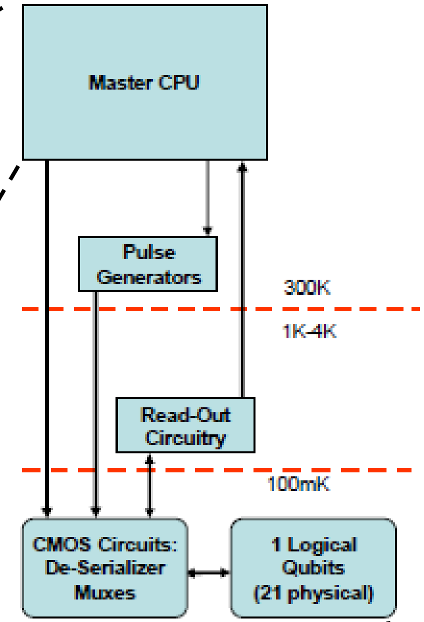
Quantum Circuit Performance



Quantum Error Correction



SNL Classical Electronics Interface



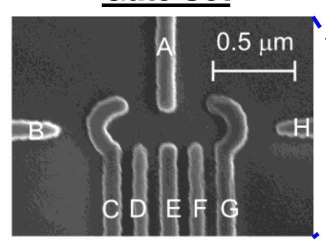
<u>Goal:</u> Can we design a beneficial error corrected memory (1st level) and for what range of T_2?

<u>Approach:</u>

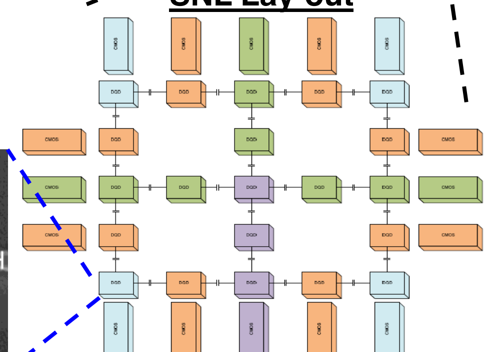
1. Choose hardware defined by qubit
2. Choose quantum error correction
3. Optimize constrained schedule
4. Determine gate requirements for QEC circuit to provide benefit
5. **improve & <u>iterate (if necessary)</u>**

<u>Result:</u> $p_{threshold}$ BS9(21) = 4.7×10^{-4}

SNL Physical Qubit & Native Gate Set



SNL Lay-out



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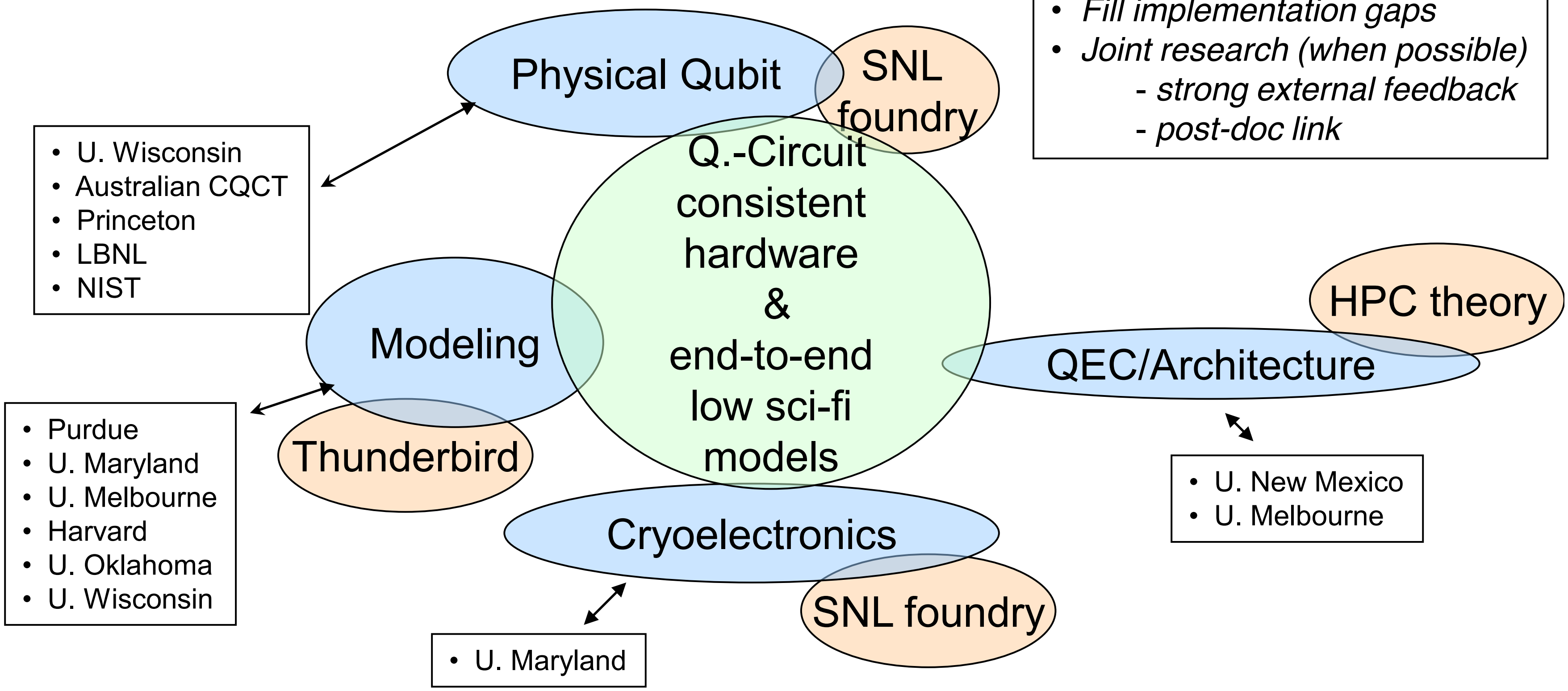
Team, Resources & External Ties

Emphasis for QIST
- *Extend existing physics & QIS*
- *Fill implementation gaps*
- *Joint research (when possible)*
  - *strong external feedback*
  - *post-doc link*



The internal technical team

Physical qubit: M. Lilly, K. Childs, R. Grubbs, T. Lemp, J. Means, E. Nordberg*, B. Silva, J. Stevens, *G. Ten Eyck*, D. Tibbets, L. Tracy, J. Wendt, P. Hines, T. Pluym

2nd Generation: E. Bielejec, *N. Bishop*

Modeling: R. Muller, E. Nielsen, R. Rahman, *H. Stalford***, *W. Witzel*, *R. Young*

Electronics: T. Gurrieri, *J. Levy*, J. Hamlet

Logical qubit: A. Landahl, R. Carr, A. Ganti, *M. Grace*, U. Onunkwo, C. Phillips, T. Tarman

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Grand Challenge Summary

In the last 12 months:

21 invited talks
8 papers published
2 papers submitted
4 papers near submission
5 papers anticipated from recent results

- GC Vision:
  - *Develop silicon qubit hardware and develop the capability to assess the scalability to a logical qubit built with the hardware*

- Magnitude & Impact
  - Si DQDs offers an experimental platform to complement and advance current Si qubit technology
  - Classical electronics, theory, and QEC combined with experimental model validation is producing a world-class logical qubit assessment
  - Classical/quantum design experience and cryogenic CMOS is providing more general capability for QIP community
  - GC project will produce a more integrated systems understanding of quantum circuitry at Sandia National Laboratories

- Tools/Capabilities/Collaborations
  - SNL has lab wide expertise to cover all critical areas (QIS is a big lab problem)
  - Increased university & government lab collaboration being pursued

Moving Forward

Near term:

- Develop surface gate enhancement mode double quantum dots (MOS & **strained-Si/SiGe**) to:
  - Demonstrate few electrons & spin read-out
  - Examine impurity doped quantum-dots as an alternative architecture
- Use mobility, C-V, ESR, quantum dot performance & modeling to feedback and improve upon processing
  - Includes development of atomic precision fabrication at SNL
- Examine integrated electronics approaches to RF-SET
- Use combinations of numerical packages for multi-scale simulation of quantum dot systems (NEMO3D, EMT, TCAD, SPICE)
- Continue micro-architecture evaluation for different device and transport architectures

Long term:

- Experimental and modeling activities will continue under external funding
- Continuing strong interactions with universities and other national labs

QIST has established Sandia as a national and international resource in silicon quantum information science and technology.