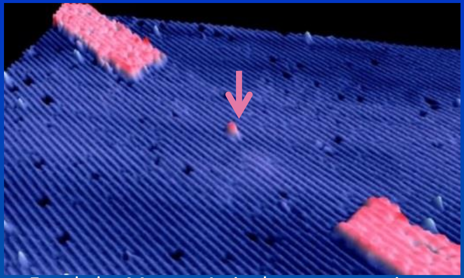
L:\internal\SET_team\Neil\Power Point\talks\17_3 FCMN

# Future Needs of Characterization and Metrology for Silicon Qubits in Quantum Computing


Neil Zimmerman, Rick Silver, Xiqiao Wang

NIST

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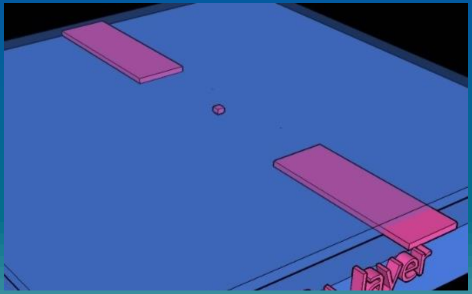
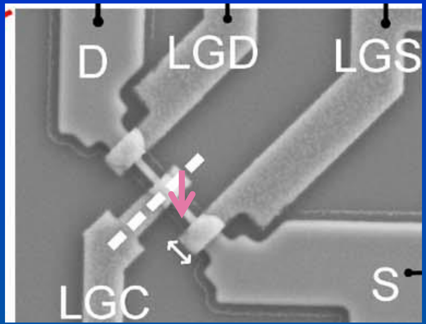
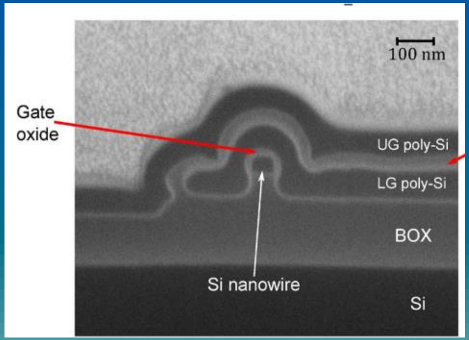


How do we

- Find and identify single atoms?
- Measure 500 000 000 coherence times?
- Quantify how strain produces devices?
- ….




Koppinen, Stewart, Zimmerman, IEEE TED 2013



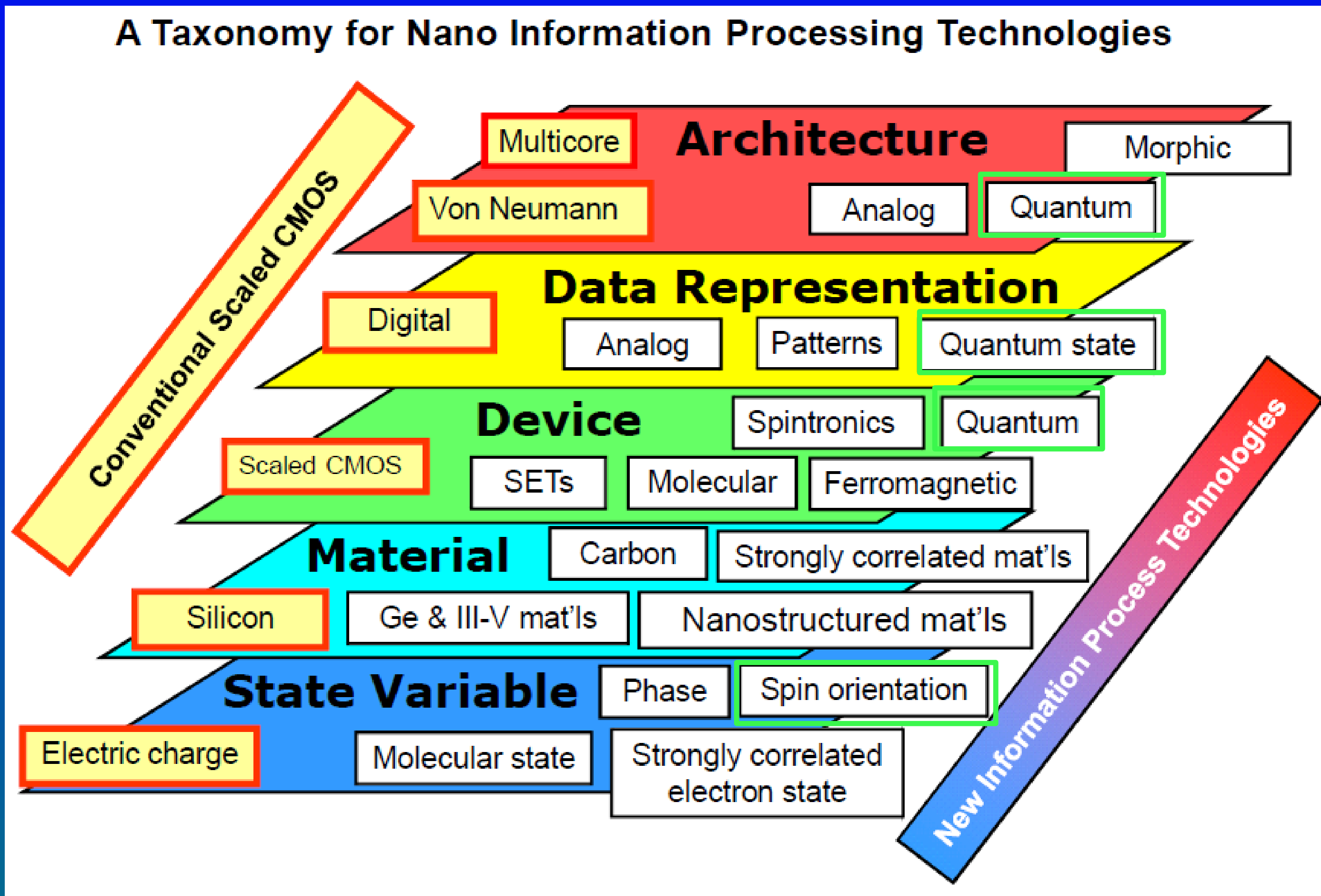

# "I'd rather uncover less than cover more"

- Please ask questions

# Outline

- Quantum Computing
  - Beyond CMOS
  - The potential of quantum computing: Quantum parallelism
- Characterization future needs of Si qubits
  - Structural
  - Electrical
- Summary of needs

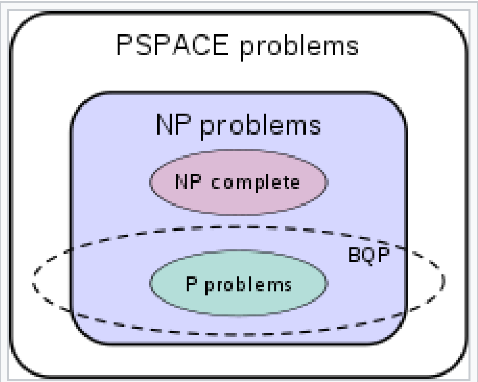
# Quantum Computing in Beyond CMOS



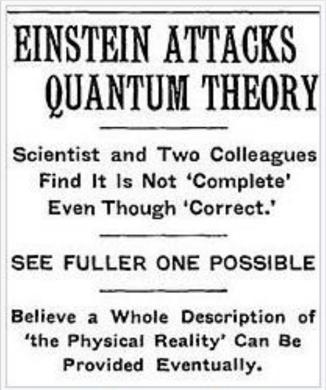


(most recent BC full chapter, IRDS 2016 similar)

# The Potential of a Quantum Computer (QC)




The suspected relationship of BQP to other problem spaces.[89]



EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

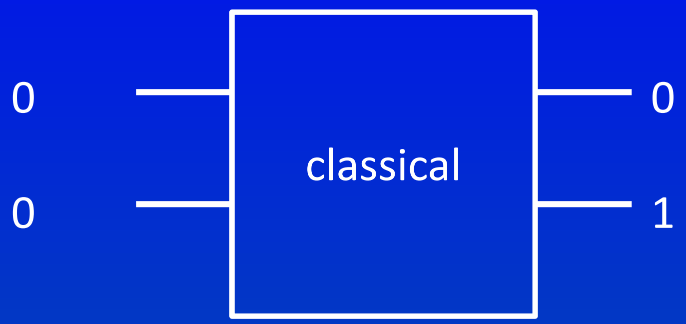
SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

May 4, 1935 *New York Times* article headline regarding the imminent EPR paper

- Computer science: QC can solve problems not possible with any classical computer
  - Eg, factorizing large integers aka cracking passwords
- Why is this?
  - "Superposition" means all possible iterations are solved at the same time!

# The Potential of a Quantum Computer (QC)

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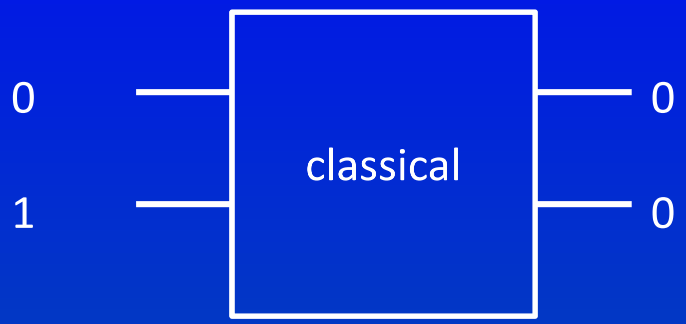


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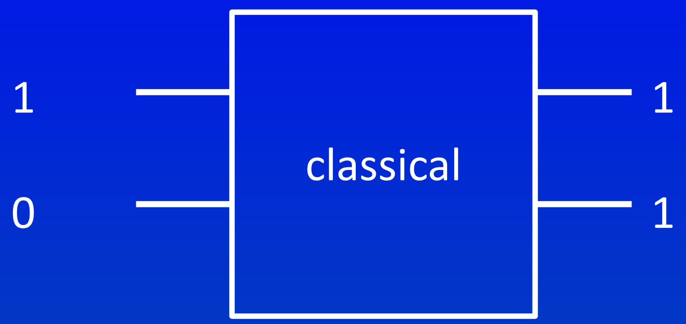


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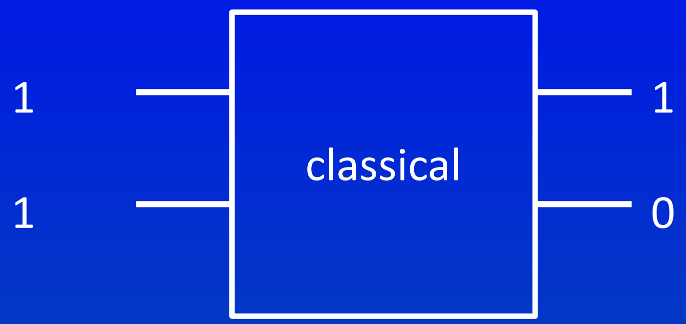
# The Potential of a Quantum Computer (QC)




- Computer science: QC can solve problems not possible with any classical computer
  - Eg, factorizing large integers aka cracking passwords
- Why is this?
  - “Superposition” means all possible iterations are solved at the same time!

# The Potential of a Quantum Computer (QC)


"quantum parallelism"

- Computer science: QC can solve problems not possible with any classical computer
  - Eg, factorizing large integers aka cracking passwords
- Why is this?
  - "Superposition" means all possible iterations are solved at the same time!
- Decoherence destroys superposition (bad).

# Some necessary items for a QC

- Si qubits with electron spin as the state variable (cf charge on the gate of a MOSFET switch)
  - Need $T_{coherence}/T_{switch} > 10^3$ (assumes QEC).
    - Eg, switching time 1 ns
    - No decoherence for 1 μs
  - Need up to 500 million qubits all operating correctly
    - No decoherence
    - No drift or other gross problems
  - Need up to 3 X $10^{13}$ (30 Tb) of classical bits
- Other candidates:
  - Atoms and ions
  - Superconducting qubits
  - …

# Outline

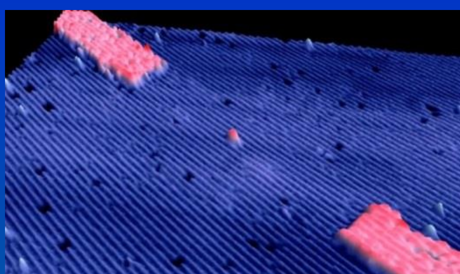
- Quantum Computing
  - Beyond CMOS
  - The potential of quantum computing: Quantum parallelism
- Characterization future needs of Si qubits
  - Structural
  - Electrical
- Summary of needs

# Two prototypes of Si qubits

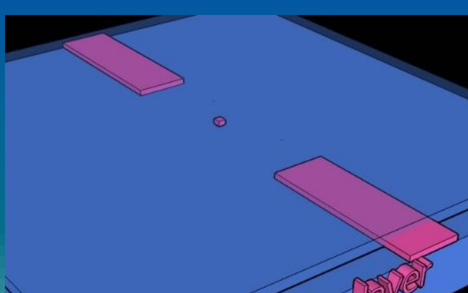
“single atom”

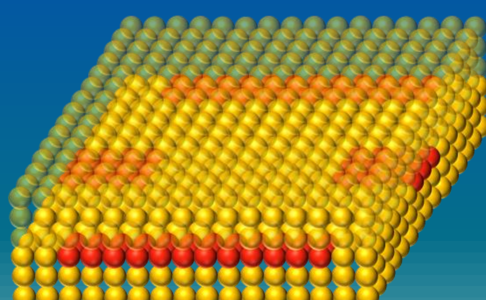
Patterned P atoms

encased in Si



Fuechsle, M, etc., A single-atom transistor. *Nat Nano* **2012,** 7, (4), 242-246.

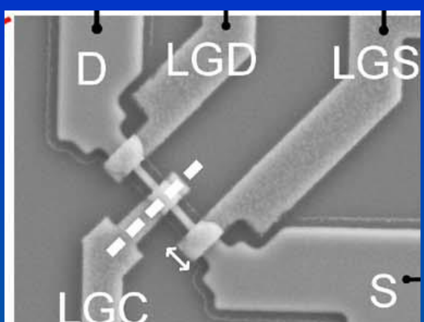




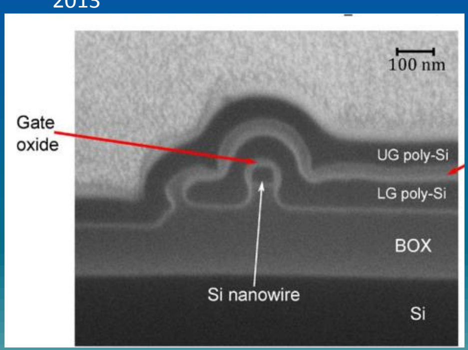
“quantum dot”

Si/SiO2 multi-gate

multi-layer MOSFET



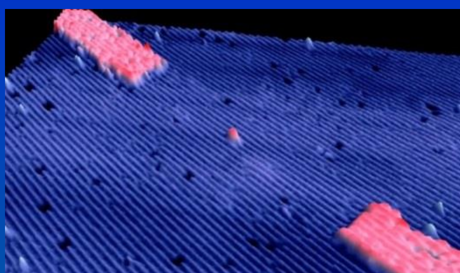

Koppinen, Stewart, Zimmerman, IEEE TED 2013



# A smattering of metrology and characterization needs



- Just illustrative, not exhaustive



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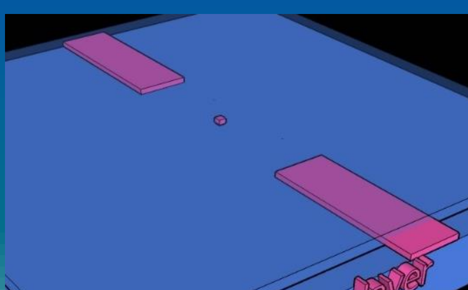
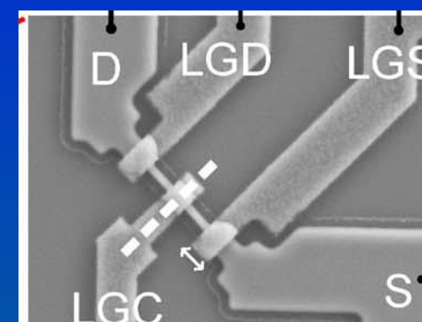
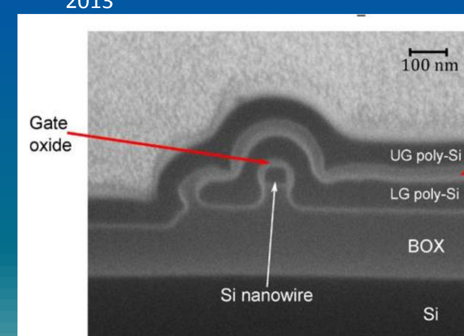


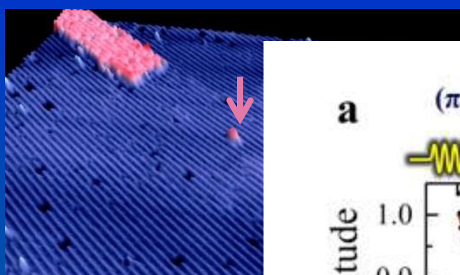



Koppinen, Stewart, Zimmerman, IEEE TED 2013

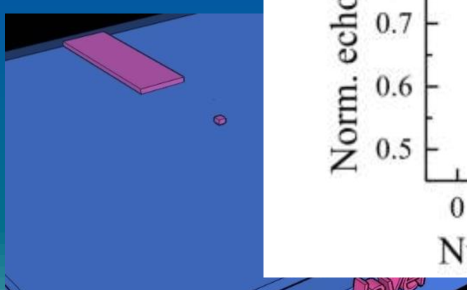


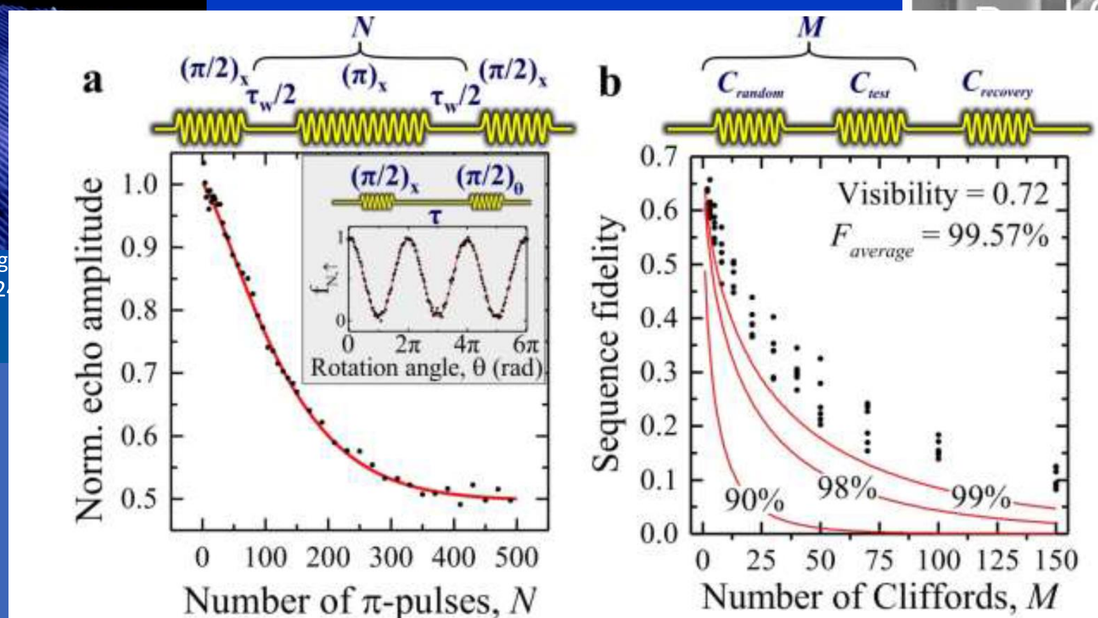
# A smattering of needs: Decoherence measurements

- Decoherence measurements – need 99.9% fidelity
  - For a <u>single</u> qubit, need to repeat 100's of microwave pulses 1000's of times
  - For 500 000 000 qubits?!?

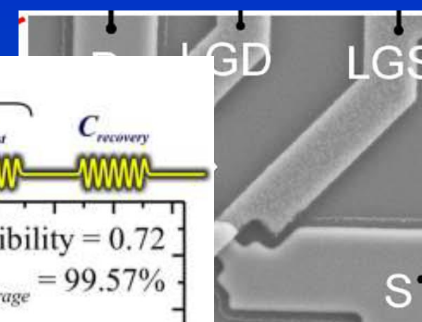


Fuechsle, M, etc., A sing... *Nat Nano* **2012,** 7, (4), 2...

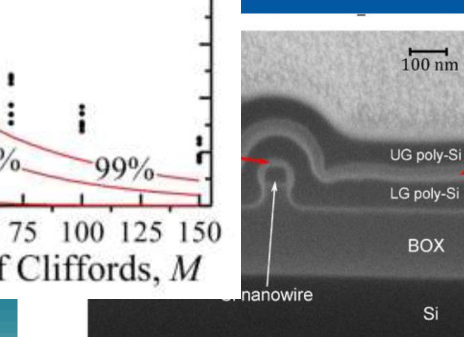





Veldhorst et al, Nature Nanotech 2014

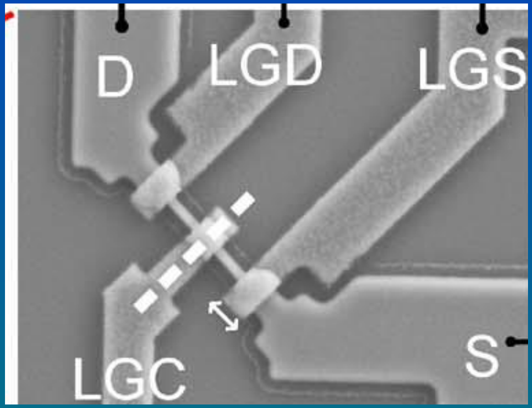



..., Zimmerman, IEEE TED



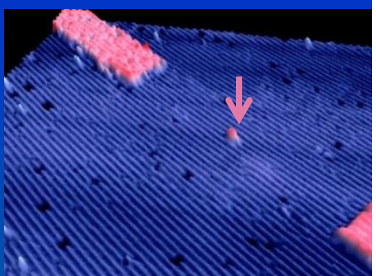
# Aside: Everything is harder at low temperatures

- Many of the measurements we discuss must be done at low temperatures.
  - Limited number of leads
  - Can't see inside dewar
  - Power < 1 mW $\Rightarrow$ current < 1 $\mu$A!




# A smattering of needs: $^{28}$Si isotopic enrichment

- Spin qubits were in GaAs, but nuclear spins cause decoherence
- In Si, isotope 5% $^{29}$Si (bad)
- Want << $10^{-4}$ $^{29}$Si – this SIMS measurement down to 1 ppm!



Fuechsle, M, etc., A single-atom tra
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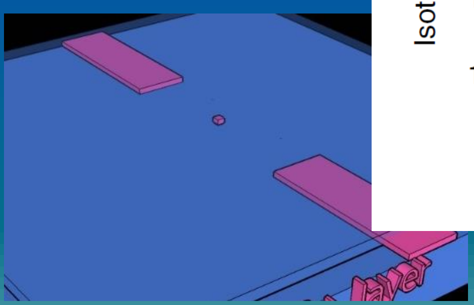
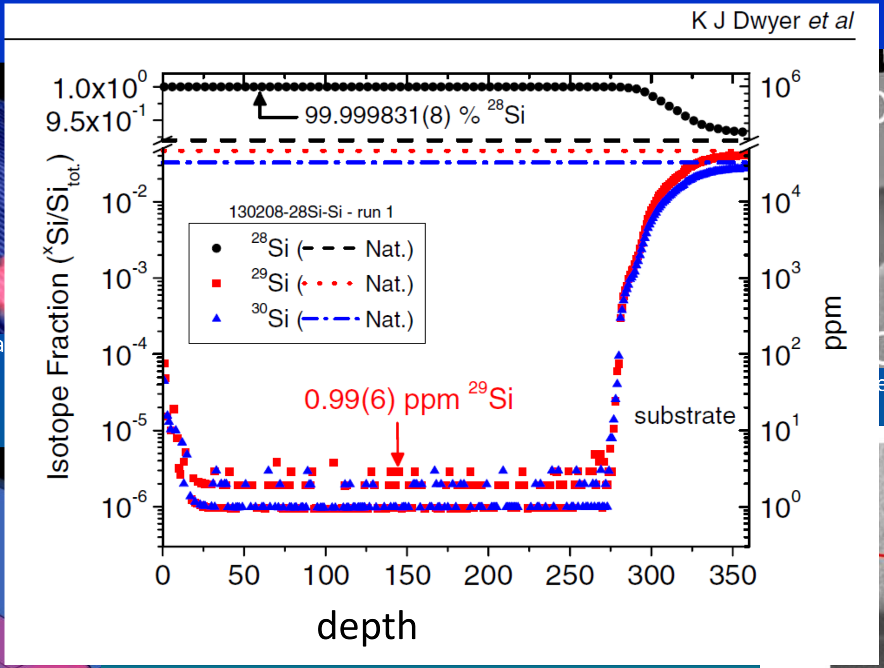
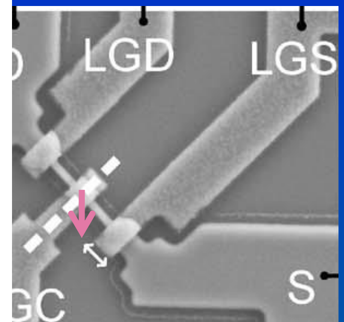
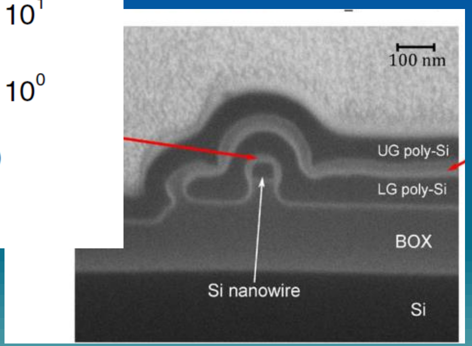



Dwyer et al, J Phys D 2014

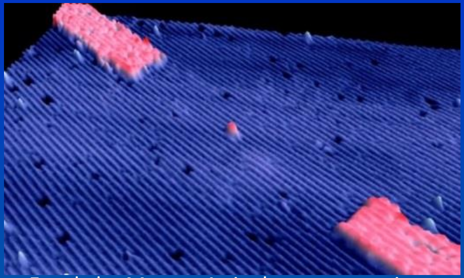



en, Stewart, Zimmerman, IEEE TED



# A smattering of needs: dopant “monolayer” thickness

- How do we measure the thickness of an epitaxial 1 nm layer?



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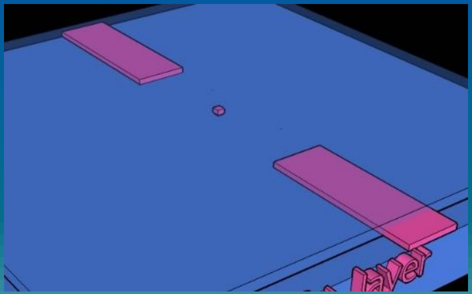
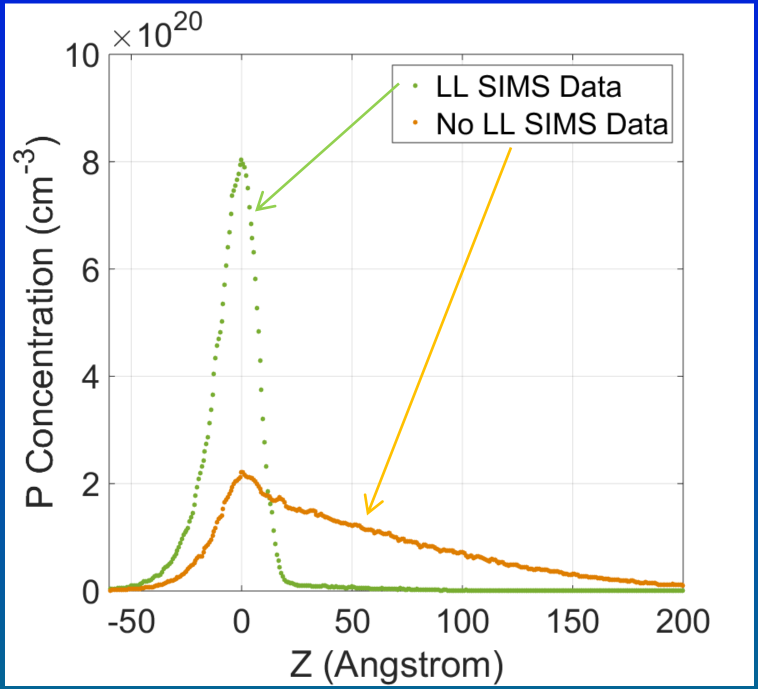




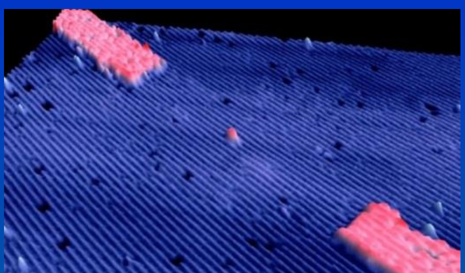

We believe the monolayer (green curve) is about

5 Å thick.

# A smattering of needs: single atom overgrowth thickness, etc.

- We would like to characterize the Si overlayer
  - Thickness
  - Purity
  - Crystallinity, …

But we don't know exactly where the overlayer starts!



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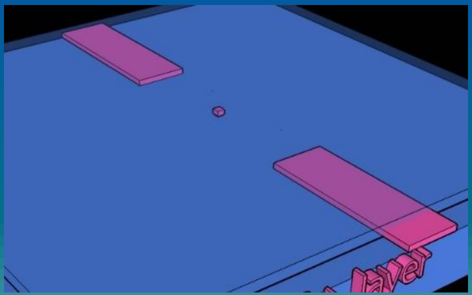
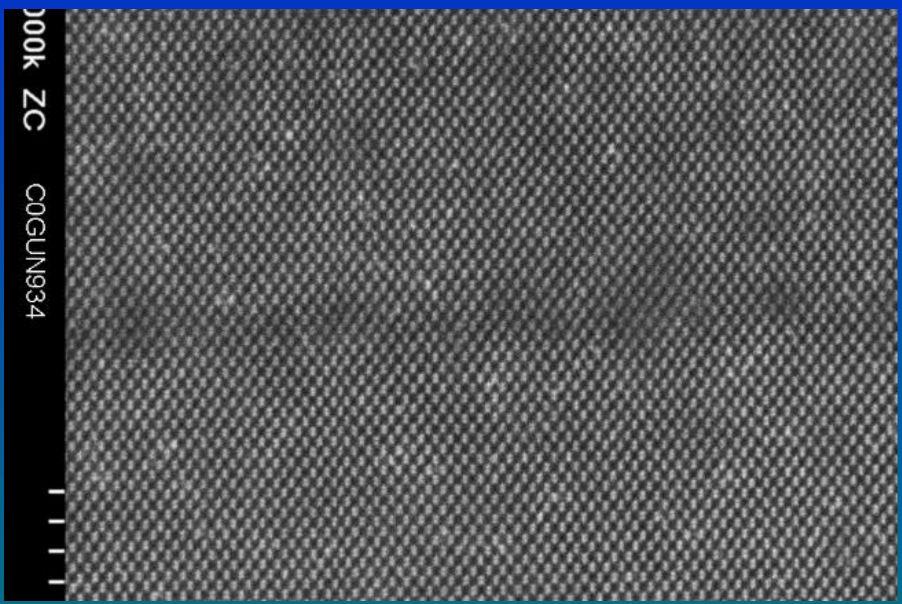
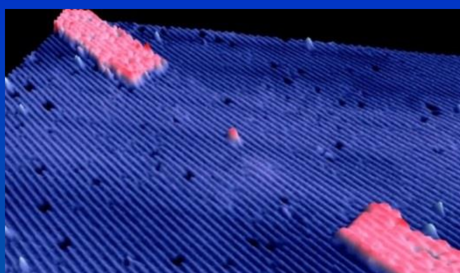




# A smattering of needs: single atom locations

- For CMOS now, and even more for single atom devices, knowledge of the location of every individual dopant is crucial



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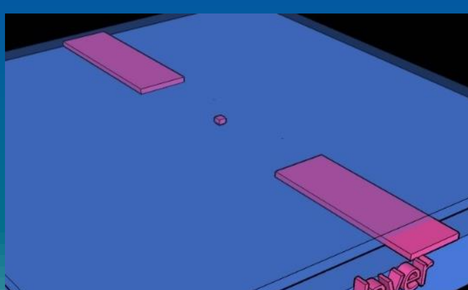
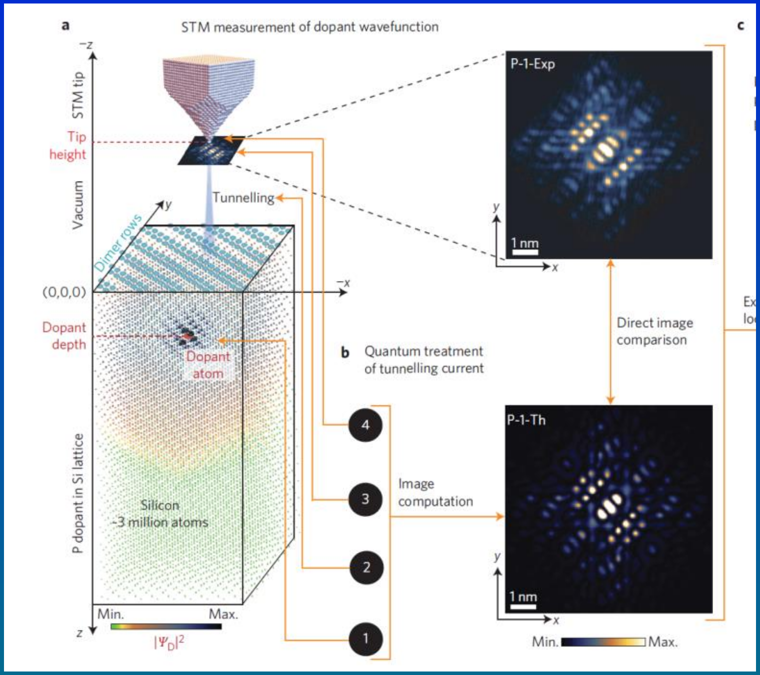


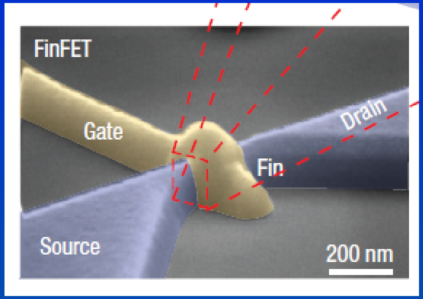



Usman et al, Nature Nanotech 2016

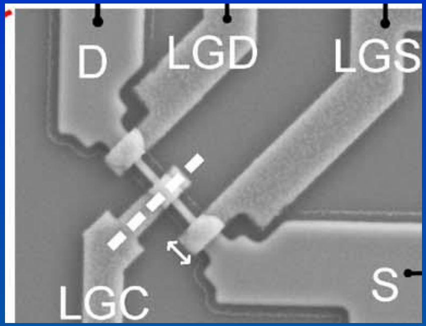
- STM imaging (slow)
- No deeper than 5 nm
- Required isolated dopant

# A smattering of needs: dopant identification

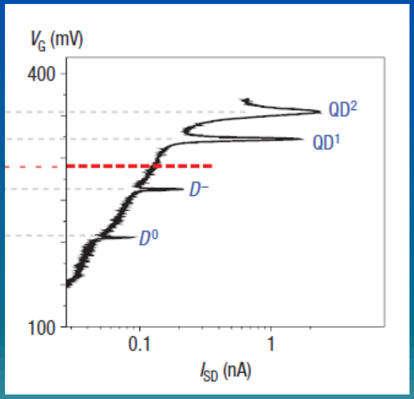
- Given background doping of wafers, we need to identify the species
- Can be done by comparing I(V) and modelling

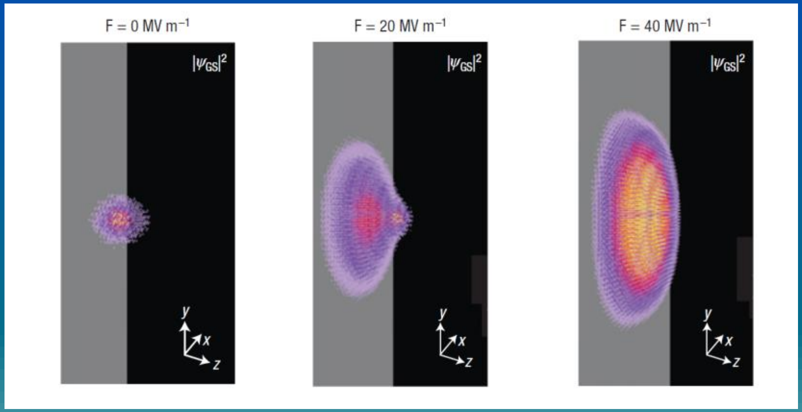


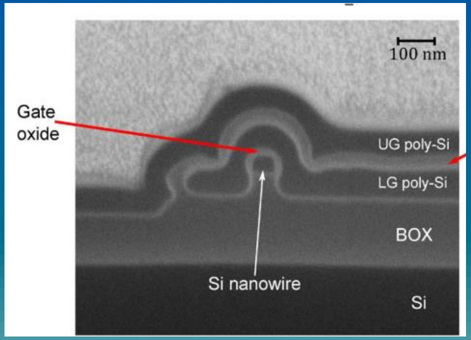

Lansbergen et al, Nature Phys 2008




Koppinen, Stewart, Zimmerman, IEEE TED 2013

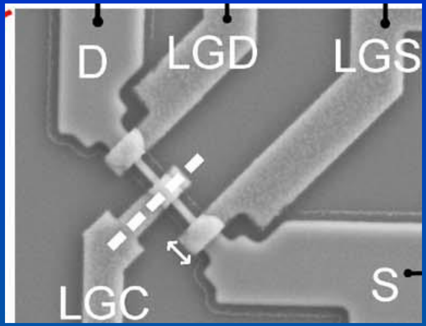


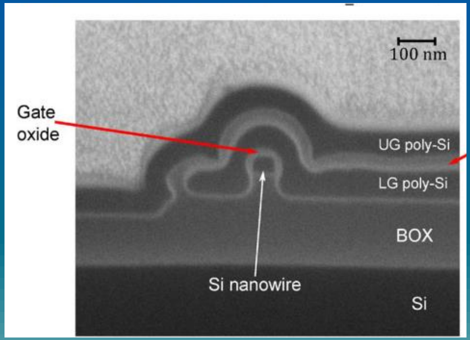



# A smattering of needs: strain-induced quantum dots

- Stress and strain are very important in CMOS, for enhancing mobility

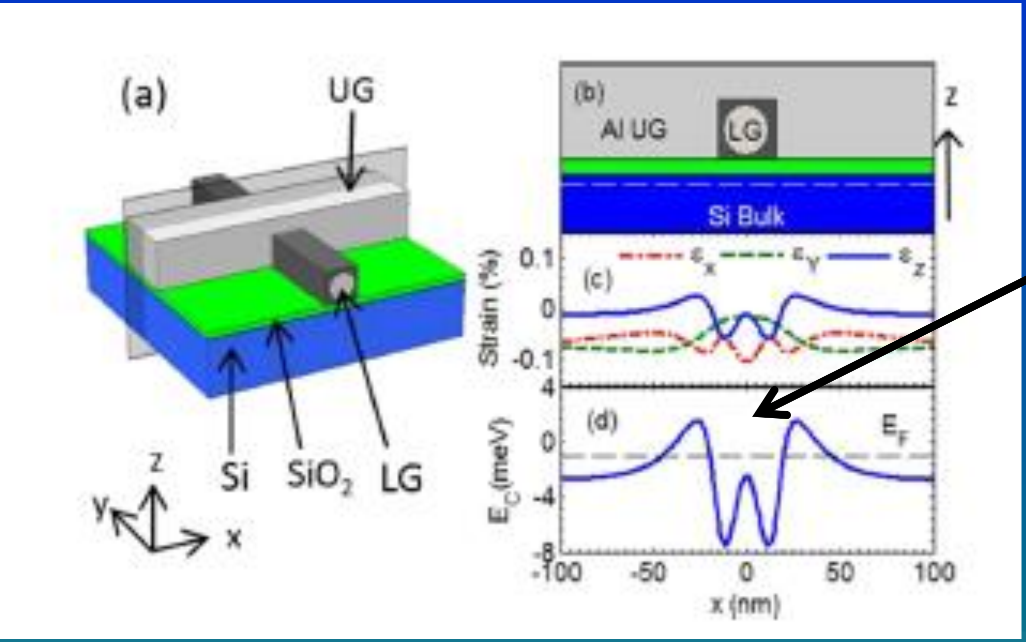



Koppinen, Stewart, Zimmerman, IEEE TED 2013



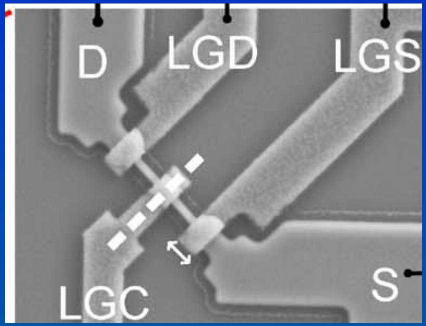
# A smattering of needs: strain-induced quantum dots

- Stress and strain are very important in CMOS, for enhancing mobility
- We have discovered that they also can change the device electrical geometry completely!

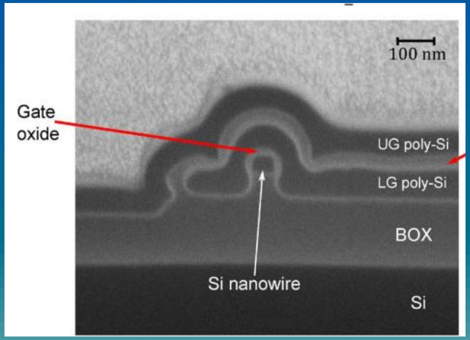



Thorbeck, Zimmerman, AIP Adv 2016

A quantum dot forms without voltages



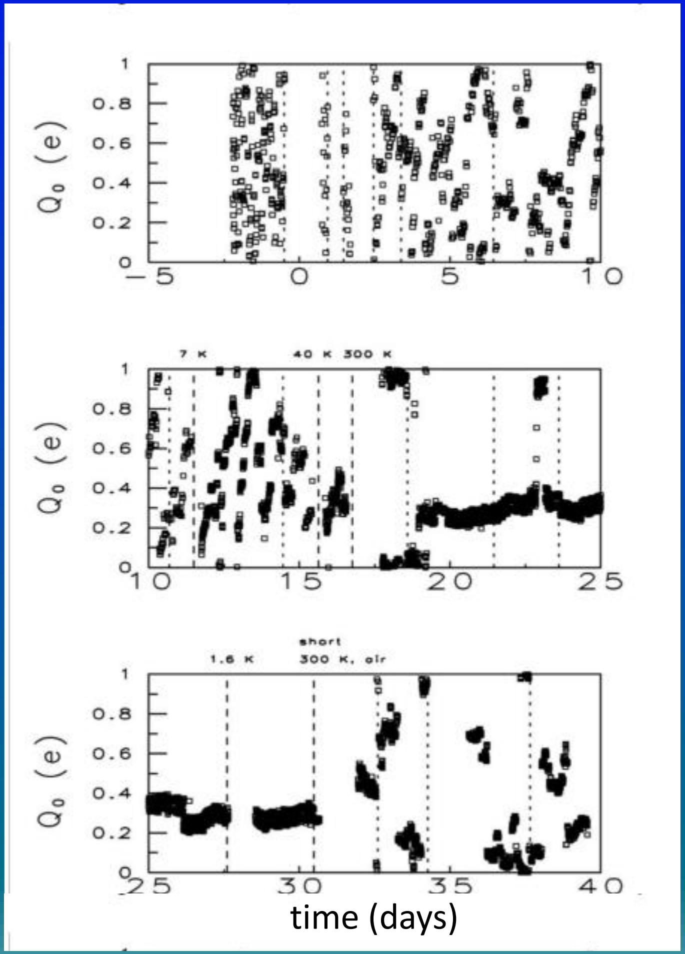

Koppinen, Stewart, Zimmerman, IEEE TED 2013



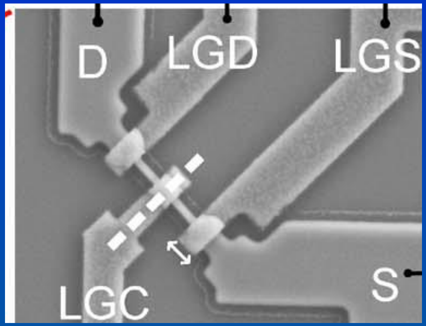
# A smattering of needs: defect-induced time instability



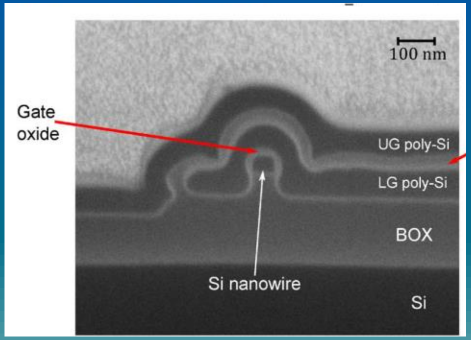
- "Charge offset drift" – similar to $V_T$ shift




Stewart, Zimmerman, Appl. Sci. 2016




Koppinen, Stewart, Zimmerman, IEEE TED 2013



# Outline

- Quantum Computing
  - Beyond CMOS
  - The potential of quantum computing: Quantum parallelism
- Characterization future needs of Si qubits
  - Structural
  - Electrical
- Summary of needs

# Summary of needs

| Need | Single atom or quantum dot | New or extension? | Challenge 1 | Challenge 2 | Known technique destructive? |
|---|---|---|---|---|---|
| 1 ppm isotopes | both | extension | SIMS? | Atom probe? | Yes |
| 1 nm monolayer thickness | Single atom | extension | Epitaxial - hard to find | Atom probe? | Yes? |
| Location of monolayer | Single atom | extension | Epitaxial - hard to find | STEM/EDS? | Yes |
| Strain-induced dots | Quantum dot | extension | Re-focus existing techniques | Deliberate design for tighter geometry? | yes |
| Coherence time | both | new | 99.9% | 500 000 000 qubits | No |
| Single atom location | Single atom | new | STM – slow | Low temperature | No |
| Dopant identification | Quantum dot | new | SET - slow | Low temperature | no |
| Charge offset drift | Quantum dot | new | SET - slow | Low temperature | no |

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Need to know strain at low T!
Need EBSD Power < 1 mW!

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| Location of monolayer | Single atom | extension | Epitaxial - hard | STEM? | Yes |
| Strain-induced dots | Quantum dot | extension | Re-focus existing techniques | Deliberate design for tighter geometry? | yes |
| Coherence time | both | new | 99.9% | 500 000 000 qubits | No |
| Single atom location | Single atom | new | STM - slow | Low temperature | No |
| Dopant identification | Quantum dot | new | SET - slow | Low temperature | no |
| Charge offset drift | Quantum dot | new | SET - slow | Low temperature | no |

Great new ideas needed!

Research performed in part at the NIST Center for Nanoscale Science and Technology

L:\internal\SET_team\Neil\Power Point\talks\

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

# Summary of needs

| Need | Single atom or quantum dot | New or extension? | Challenge 1 | Challenge 2 | Known technique destructive? |
|---|---|---|---|---|---|
| 1 ppm isotopes | both | extension | SIMS? | Atom probe? | Yes |
| 1 nm monolayer thickness | Single atom | extension | Epitaxial - hard to find | Atom probe? | Yes? |
| Location of monolayer | Single atom | extension | Epitaxial - hard | STEM? | Yes |
| Strain-induced dots | Quantum dot | | | | yes |
| Coherence time | both | | | | No |
| Single atom location | Single atom | | | | No |
| Dopant identification | Quantum dot | new | SET - slow | Low temperature | no |
| Charge offset drift | Quantum dot | new | SET - slow | Low temperature | no |

Great new ideas needed!

Josh Pomeroy, Michael Stewart, Curt Richter, NIST
Alan Seabaugh, UND
Jim Clarke, Intel

"1) Future Needs of Characterization and Metrology for Silico"
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"2) "
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"3) Outline"
""
"4) Quantum Computing in Beyond CMOS"
""
"5) The Potential of a Quantum Computer (QC)"
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"6) The Potential of a Quantum Computer (QC)"
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"7) The Potential of a Quantum Computer (QC)"
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"8) The Potential of a Quantum Computer (QC)"
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"9) The Potential of a Quantum Computer (QC)"
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"10) The Potential of a Quantum Computer (QC)"
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"11) Some necessary items for a QC"
""
"12) Outline"
""
"13) Two prototypes of Si qubits"
""
"14) A smattering of metrology and characterization needs"
""
"15) A smattering of needs: Decoherence measurements"
""
"16) Aside: Everything is harder at low temperatures"
""
"17) A smattering of needs: 28Si isotopic enrichment"
""
"18) A smattering of needs: dopant ‘monolayer’ thickness"
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"19) A smattering of needs: dopant ‘monolayer’ thickness [HID"
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"20) A smattering of needs: single atom overgrowth thickness,"
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"21) A smattering of needs: single atom locations"
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"22) A smattering of needs: dopant identification"
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"23) A smattering of needs: strain-induced quantum dots"
""
"24) A smattering of needs: strain-induced quantum dots"
""
"25) A smattering of needs: defect-induced time instability"
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"26) Outline"
""
"27) Summary of needs"
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"28) Summary of needs"
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"29) Summary of needs"
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"30) "
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"31) "
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"32) "
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"33) "
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|---|---|---|
| 25 | 25 | 229 |
| 25 | 25 | 229 |
| 19 | 62 | 199 |
| 19 | 79 | 177 |
| 45 | 97 | 155 |
| 46 | 130 | 168 |