Semiconductor Devices for Quantum Computing

Bruce Kane

Laboratory for Physical Sciences, University of Maryland

ICPS 27 Tutorial Session #3

Semiconductor Devices and Quantum Computing

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www.lps.umd.edu

Outline

1. Why QC?
2. Requirements for a quantum computer
3. Picking a good qubit (charge, spin, etc.)
4. Picking the right materials (silicon, GaAs, etc.)
5. Proposals for QC in semiconductors
6. Recent Experimental work
7. Picking the right interactions between qubits
8. Prognosis: The formidable obstacles to scaling and the need to develop atom-scale devices

Computer Science in a Nutshell

There are two types of problems in the world:

Easy & **Hard**

Solutions to easy problems can be found in a number of steps that is a polynomial function of the size of the input.

Example: Multiplication

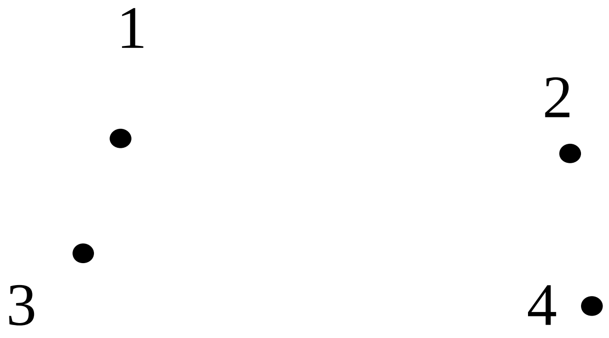
$$8\times5=40$$

$$78\times45=5\times8+5\times70+40\times8+40\times70=3510$$

Multiplication of digits of length n requires
n^2 references to a times table

Solutions to hard problems can be found in a number of steps that is a exponential function of the size of the input.

Example: Traveling Salesman Problem:



1→2→3→4→1 : Bad

1→3→4→2→1 : Good

Number of possible routes goes as (*n*-1)!, where *n* is the number of cities visited.

15 cities: 10^{11} routes

30 cities: 10^{31} routes

Is a problem that is hard on one computer
hard on *all* computers?

Yes, if the differences are in software
(Windows v. Linux v. Mac).

What if the difference is hardware?

Ultimately, the process of computation must be a physical process, and the question cannot be answered without reference to physics.

Feynman first noted that the problem of simulating a quantum mechanical system is hard in the computer science sense:

Consider a system of spin ½ particles:

The number of terms needed to determine the wave function grows Exponentially with the number of spins:

1 spin: $\Psi=\alpha_1|0> + \alpha_2|1>$

2 spins: $\Psi=\alpha_1|00> + \alpha_2|01> + \alpha_3|10> + \alpha_4|11>$

3 spins: $\Psi= \alpha_1|000> + \alpha_2|001> + \alpha_3|010> + \alpha_4|011> + \alpha_5|100> + \alpha_6|101> + \alpha_7|110> + \alpha_8|111>$

A quantum system “doing what comes naturally” is performing a calculation which is exponentially hard to emulate on a classical computer.

Note: for 1000 spins Ψ contains $2^{1000} \approx 10^{300}$ terms!

Can a quantum mechanical system “doing what comes naturally” be used to solve any other hard problems?

Answer (Peter Shor, 1994): Yes!

This result has spurred tremendous interest in the development of a “quantum computer”.

Shor’s algorithm determines the prime factors of large composite numbers.

$$15=3\times5$$

$$221=13\times17$$

RSA-200 =
27997833911221327870829467638722601621070446786955428537560009929326128400107609
34567105295536085606182235191095136578863710595448200657677509858055761357909873
4950144178863178946295187237869221823983 = ? × ?

Public key cryptography relies on the difficulty of this problem.

Classical computation time is exponential in the number of digits.

A quantum computer using Shor’s algorithm can factor in a number of steps quadratic in the number of digits.

→***A PC-sized quantum computer could compromise the security of all public key cryptography data (internet, bank transactions, etc.)***

Quantum Logic

<table>
<tr><th>Classical Computer</th><th>Quantum Computer</th></tr>
<tr><td>0,1</td><td>|0>,|1></td></tr>
<tr><td>Bits</td><td>"Qubits":
Quantum state of a two level system such as spin 1/2</td></tr>
</table>

Important Differences between quantum and conventional computers:

1. Superposition: $|\phi> = \alpha|0> + \beta|1>$

2. Entanglement: $|\phi> = |01> + |10>$

3. Measurement outcomes consistent with quantum mechanics (always 0 or 1).

Why quantum computation is so difficult

Even if measurements of single quantum states can be made reliably:

- quantum phase is a continuous variable and errors will be cumulativ (like analog computer).

- Quantum systems inevitably interact with their surrounding environment, leading to the destruction of the coherent state upon whi quantum algorithms rely.

Quantum computation ruined by decoherence unless errors can be corrected.

Consensus until 1995: thinking about quantum computation is entirely an academic exercise.

Quantum error correction, discovered in the late 1990’s means that ‘perfect’ quantum computation can be performed despite errors and imperfections in the computer.

Accuracy threshold for continuous quantum computation ≈ 1 error every 10,000 steps.

Consensus in today: building a quantum computer may still be a difficult (or impossible) enterprise, but the issue can only be resolved by doing experiments on real systems that may be capable of doing quantum computation.

Things necessary for a spin quantum computer:

1. Long lived spin states

2. Single spin operations (Q NOT)
controlled spin interactions with an external field

3. Two spin operations (Q CNOT)
controlled interactions between spins

4. Single spin preparation and detection
controlled interactions with external reservoirs

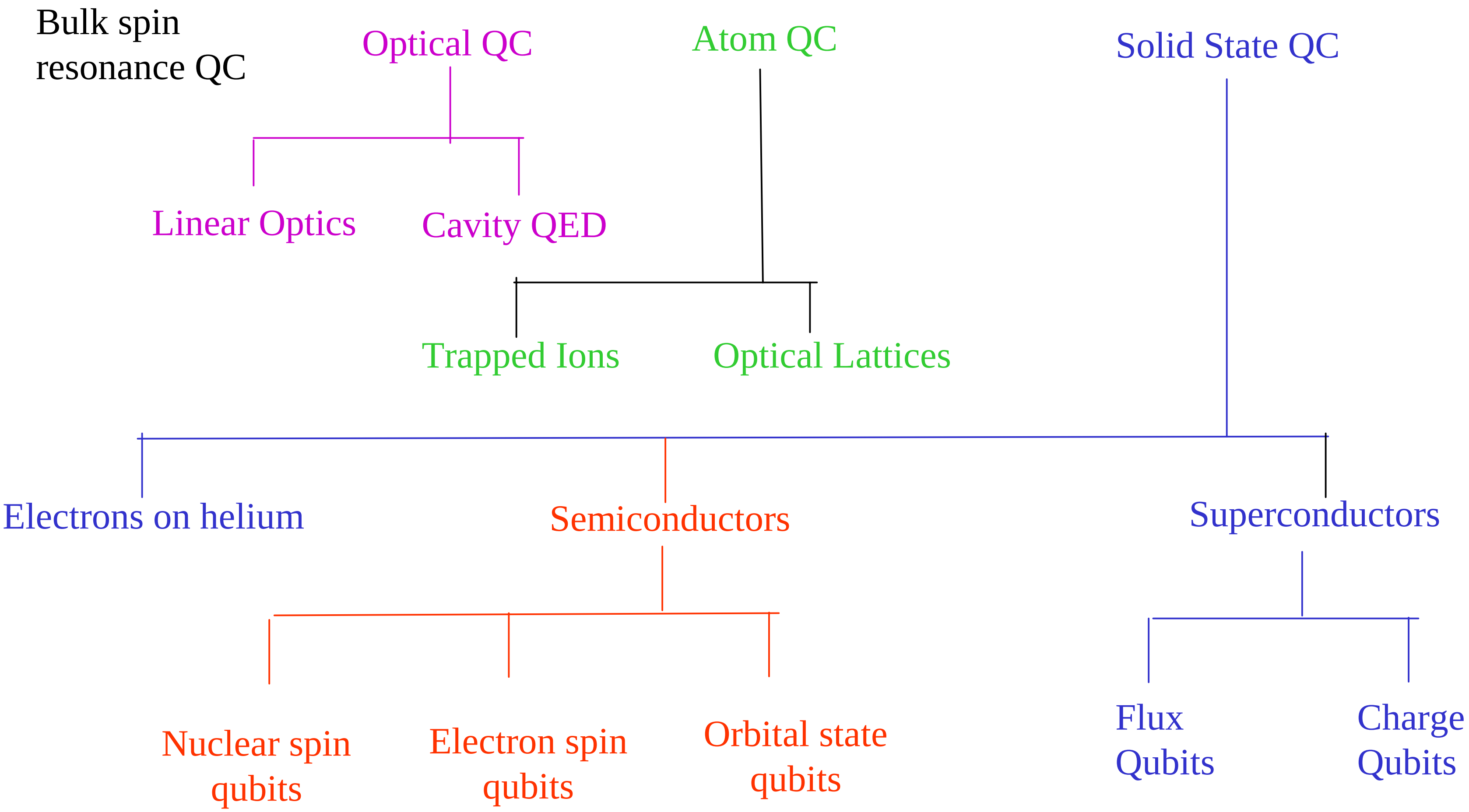
Grand Challenge Quantum Computing Poses to Physicists and Engineers:

1. Identify systems in which single quantum states (qubits) may be accurately measured and manipulated.

2. Learn to control interactions between quantum states in a complex, many-qubit system.

Note: State of the art for solid state quantum computing
~2 qubits
What we need for Shor's algorithm
~10,000 qubits

QC implementation proposals



Bulk spin
resonance QC

Optical QC

Atom QC

Solid State QC

Linear Optics

Cavity QED

Trapped Ions

Optical Lattices

Electrons on helium

Semiconductors

Superconductors

Nuclear spin
qubits

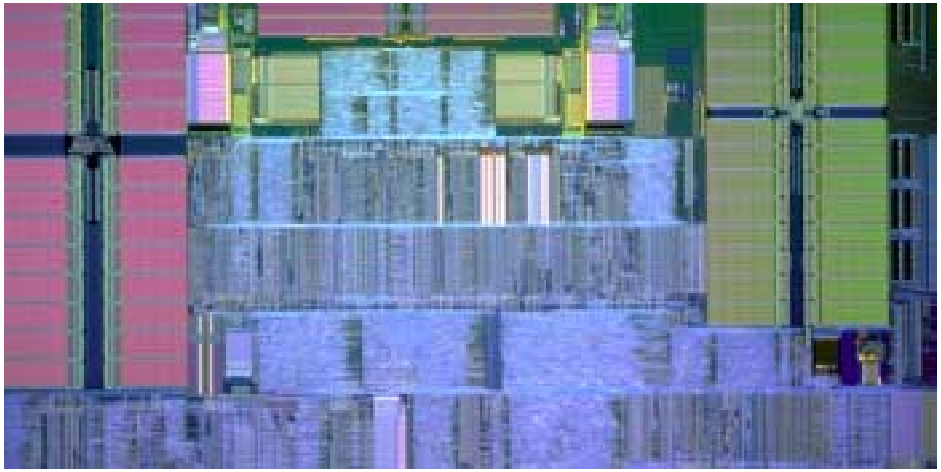
Electron spin
qubits

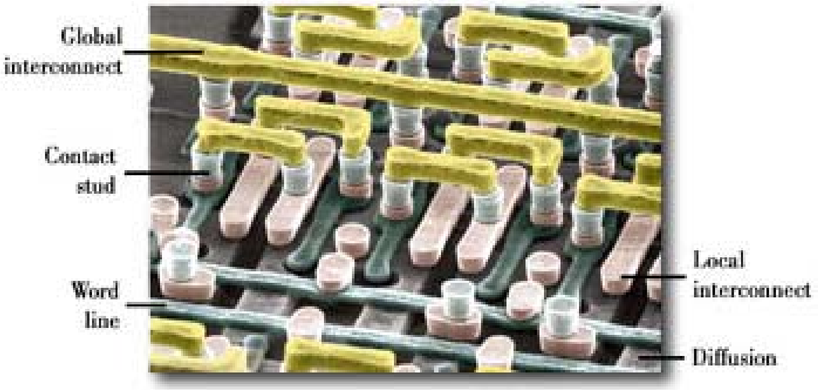
Orbital state
qubits

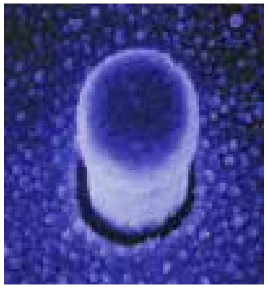
Flux
Qubits

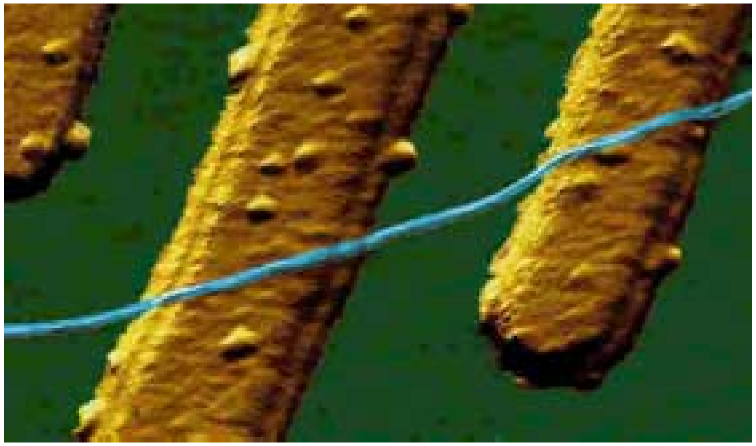
Charge
Qubits

Good news: Semiconductor fabrication technology is advancing at a rapid rate.









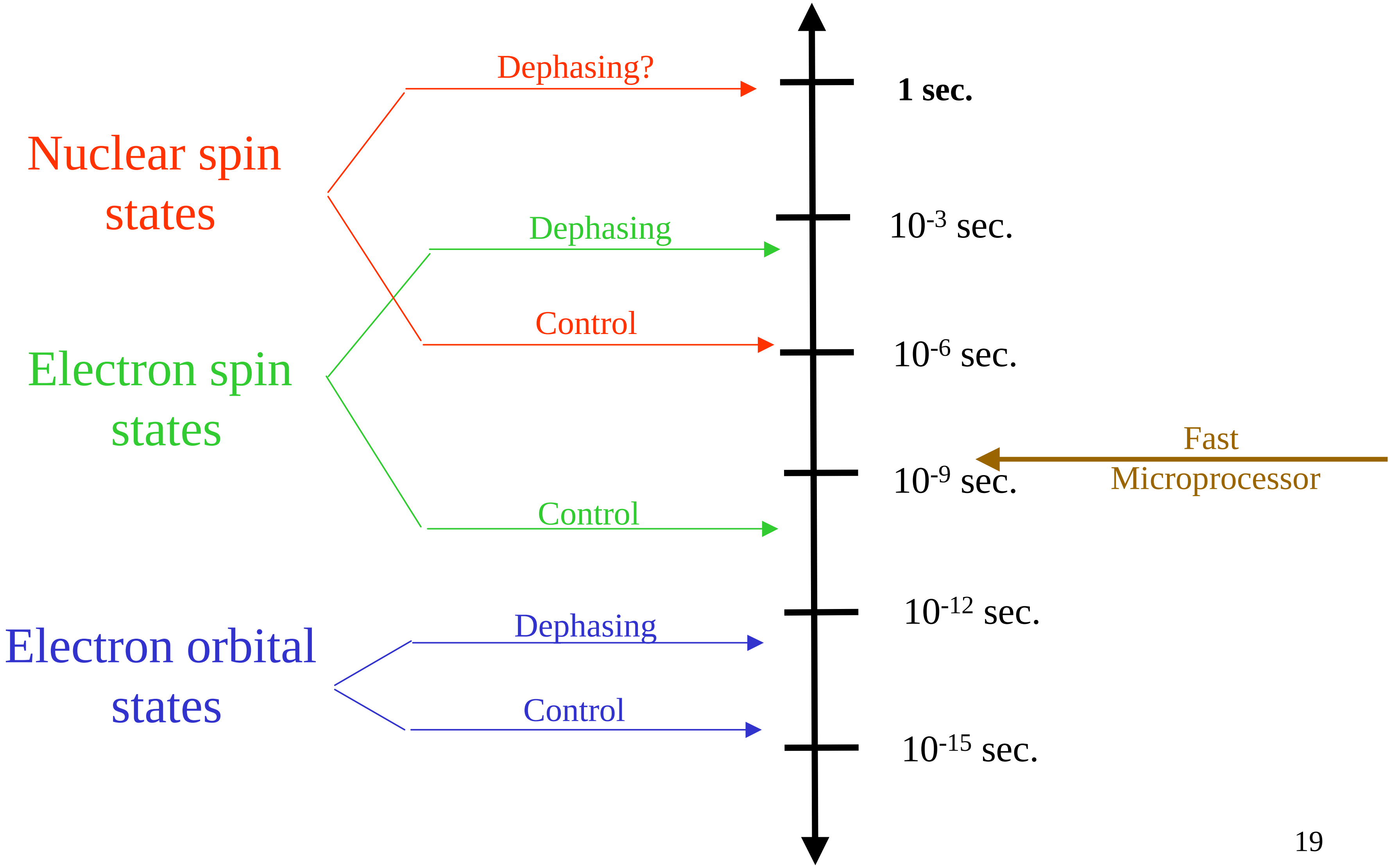
Photos
Top: IBM
Bottom: TU Delft

Bad News: In semiconductors many quantum degrees of freedom are present, and all tend to interact with each other.

Semiconductor qubits may *decohere* rapidly.

Many quantum logic operations must be performed on a qubit before decoherence occurs.

We would like $t_{\mathrm{dephasing}} / t_{\mathrm{control}} \geq 10^4$



Nuclear spin states

Dephasing?

Control

Electron spin states

Dephasing

Control

Electron orbital states

Dephasing

Control

1 sec.

10^{-3} sec.

10^{-6} sec.

10^{-9} sec.

10^{-12} sec.

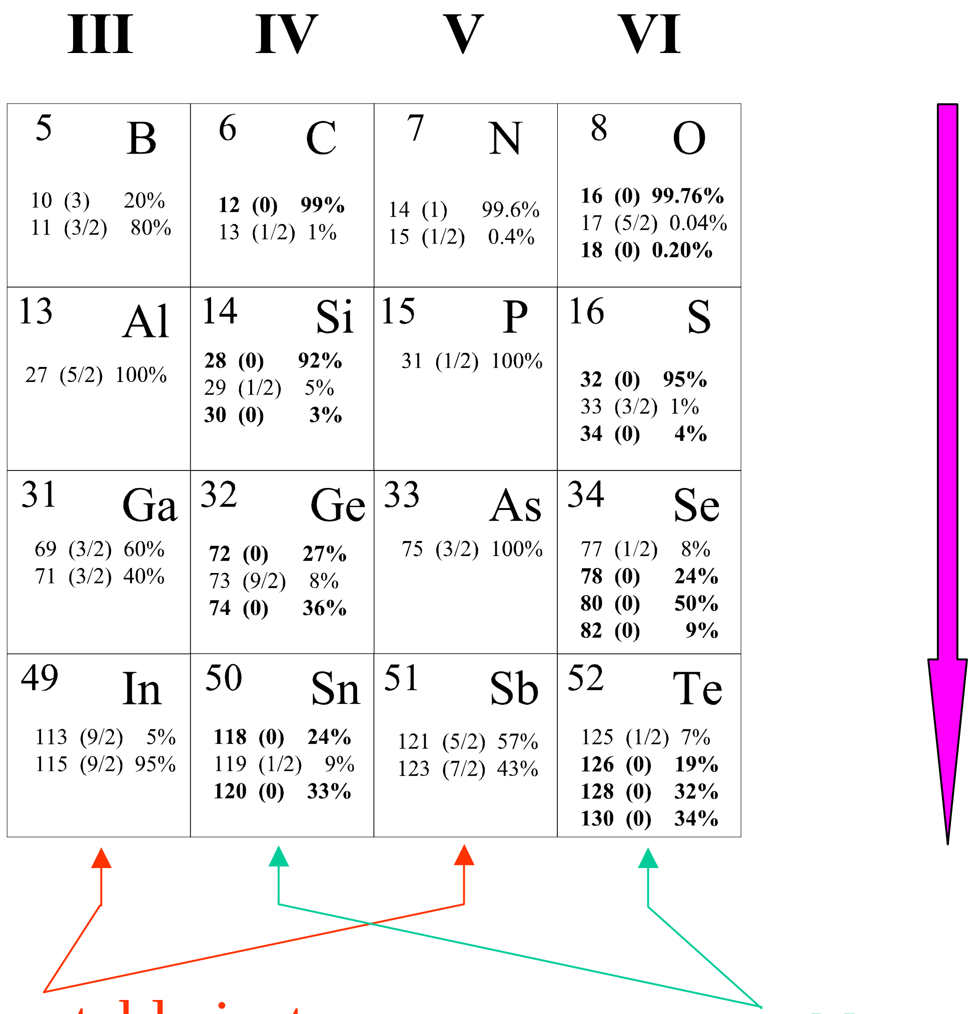
10^{-15} sec.

Fast Microprocessor

Spin qubits

- Qubit stored on a *single* electron or nuclear spin
- Extremely well isolated and localized
- Quantum transport via electrons (or photons over the long haul)
- Rapid logic and measurement operations possible in principle
- But *devices must be engineered at or near the atomic level*

Decoherence times of spins inevitably will depend on what materials they are situated in.



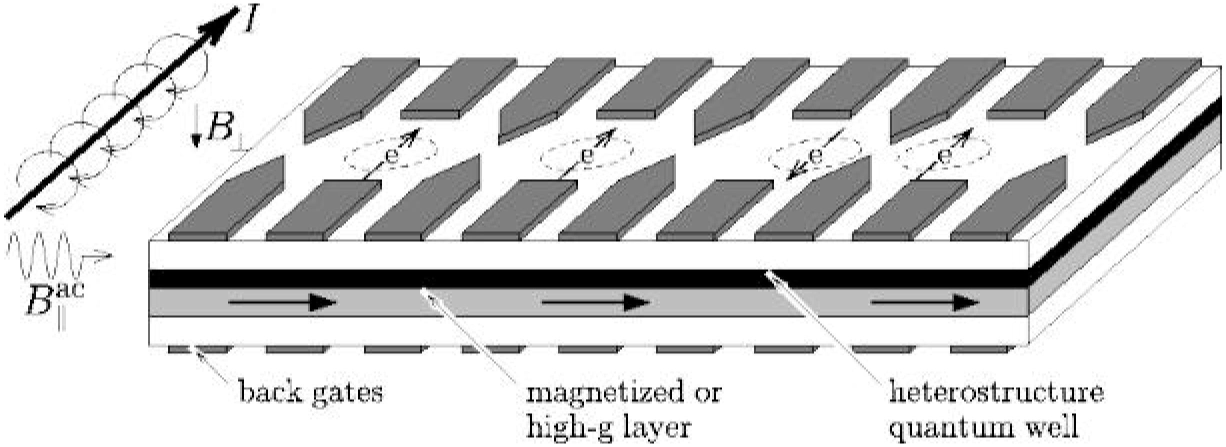
III	IV	V	VI
5 B 10 (3) 20% 11 (3/2) 80%	6 C **12 (0) 99%** 13 (1/2) 1%	7 N 14 (1) 99.6% 15 (1/2) 0.4%	8 O **16 (0) 99.76%** 17 (5/2) 0.04% **18 (0) 0.20%**
13 Al 27 (5/2) 100%	14 Si **28 (0) 92%** 29 (1/2) 5% **30 (0) 3%**	15 P 31 (1/2) 100%	16 S **32 (0) 95%** 33 (3/2) 1% **34 (0) 4%**
31 Ga 69 (3/2) 60% 71 (3/2) 40%	32 Ge **72 (0) 27%** 73 (9/2) 8% **74 (0) 36%**	33 As 75 (3/2) 100%	34 Se 77 (1/2) 8% **78 (0) 24%** **80 (0) 50%** **82 (0) 9%**
49 In 113 (9/2) 5% 115 (9/2) 95%	50 Sn **118 (0) 24%** 119 (1/2) 9% **120 (0) 33%**	51 Sb 121 (5/2) 57% 123 (7/2) 43%	52 Te 125 (1/2) 7% **126 (0) 19%** **128 (0) 32%** **130 (0) 34%**

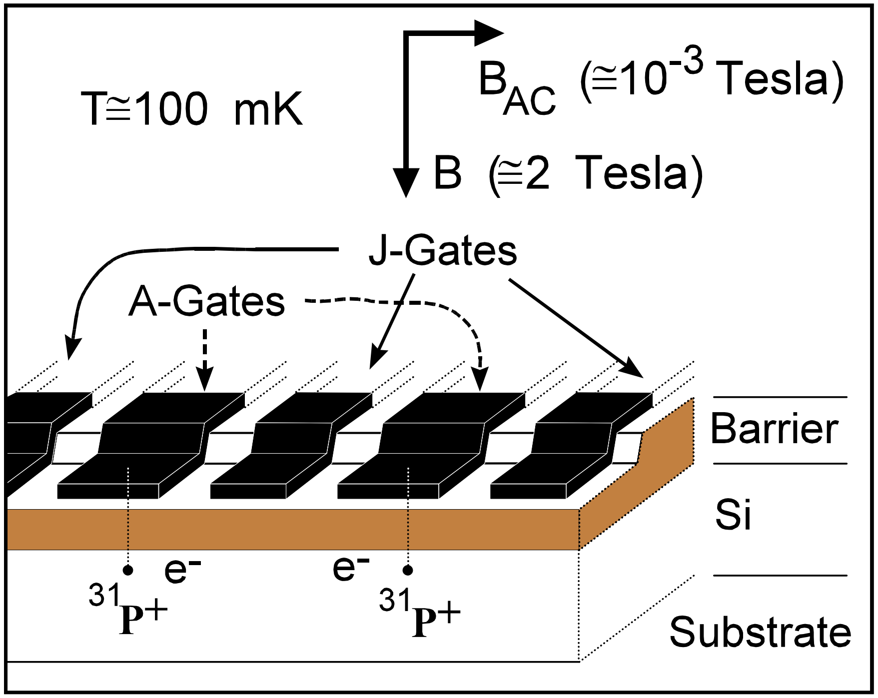
Spin-orbit interaction increases with larger atomic number

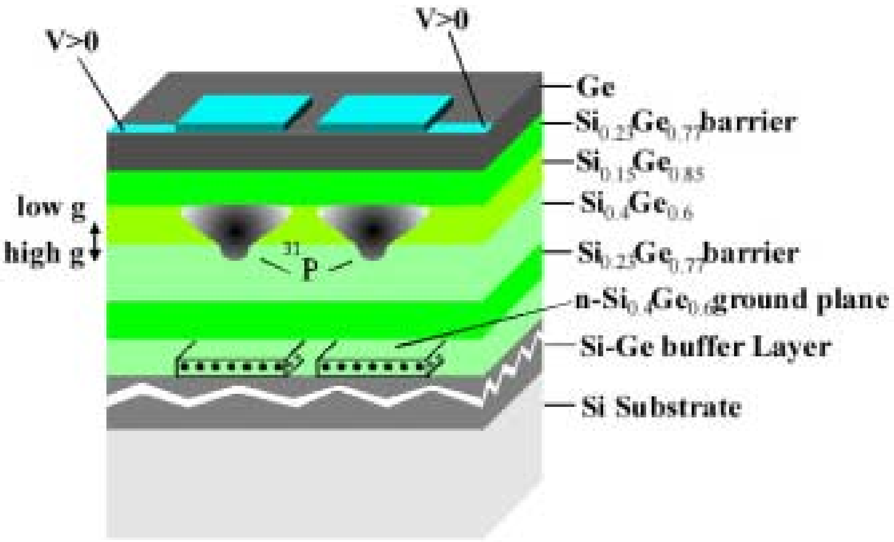
III-V’s: *no* stable isotopes with nuclear spin =0

IV,VI: stable isotopes with nuclear spin =0 *and* ≠0

QC Models


I
$B_\perp$
e
$B_\parallel^{ac}$
back gates
magnetized or high-g layer
heterostructure quantum well


T≅100 mK
B_{AC} (≅10^{-3} Tesla)
B (≅2 Tesla)
J-Gates
A-Gates
Barrier
Si
Substrate
e-
e-
$^{31}P^+$
$^{31}P^+$


V>0
V>0
low g
high g
^{31}P
Ge
$Si_{0.23}Ge_{0.77}$ barrier
$Si_{0.15}Ge_{0.85}$
$Si_{0.4}Ge_{0.6}$
$Si_{0.23}Ge_{0.77}$ barrier
n-$Si_{0.4}Ge_{0.6}$ ground plane
Si-Ge buffer Layer
Si Substrate

Experimental Focus of Current Research:

What are decoherence times and mechanisms in semiconductor materials?

Development and demonstration of single spin measurement devices

We'll look at recent work in Si, diamond and GaAs

III	IV	V	VI
5 B 10 (3) 20% 11 (3/2) 80%	6 C **12 (0) 99%** 13 (1/2) 1%	7 N 14 (1) 99.6% 15 (1/2) 0.4%	8 O **16 (0) 99.76%** 17 (5/2) 0.04% **18 (0) 0.20%**
13 Al 27 (5/2) 100%	14 Si **28 (0) 92%** 29 (1/2) 5% **30 (0) 3%**	15 P 31 (1/2) 100%	
31 Ga 69 (3/2) 60% 71 (3/2) 40%	32 Ge **70 (0) 21%** **72 (0) 27%** 73 (9/2) 8% **74 (0) 36%** **76 (0) 8%**	33 As 75 (3/2) 100%	
49 In 113 (9/2) 5% 115 (9/2) 95%	50 Sn **116 (0) 15%** 117 (1/2) 8% **118 (0) 24%** 119 (1/2) 9% **120 (0) 33%**	51 Sb 121 (5/2) 57% 123 (7/2) 43%	

G. Feher c. 1956
(ENDOR)

In Si:P at Temperature (*T*)=1K:

electron relaxation time (T_1) = 1 hour

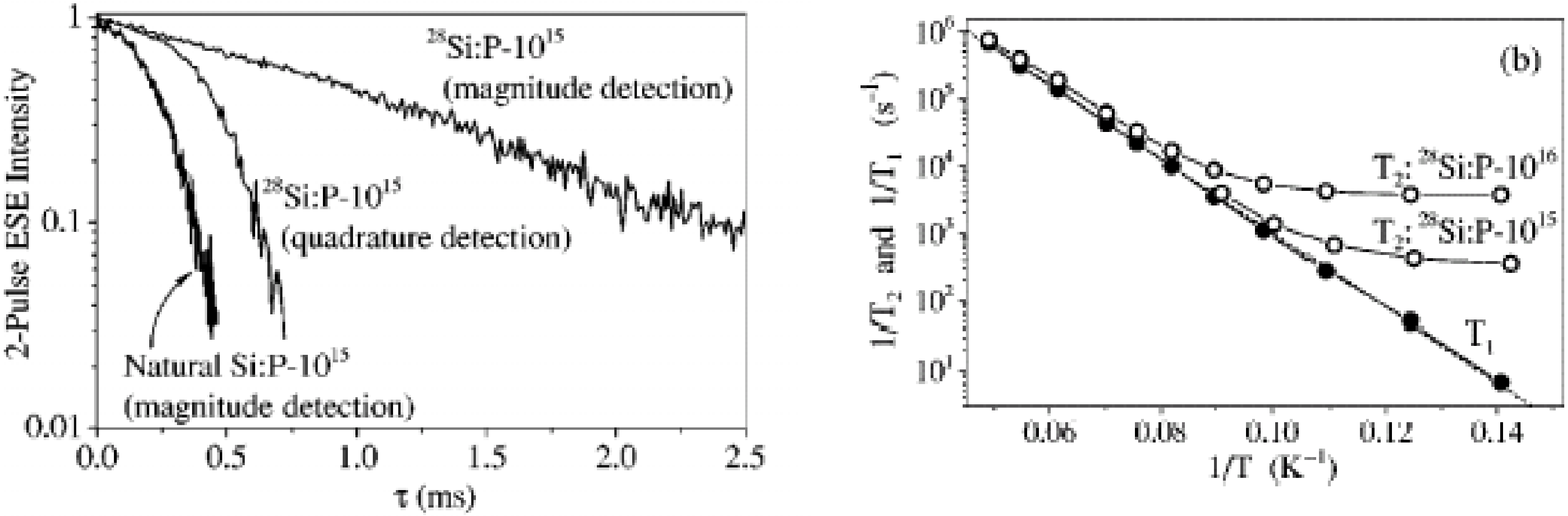
PHYSICAL REVIEW B **68**, 193207 (2003)

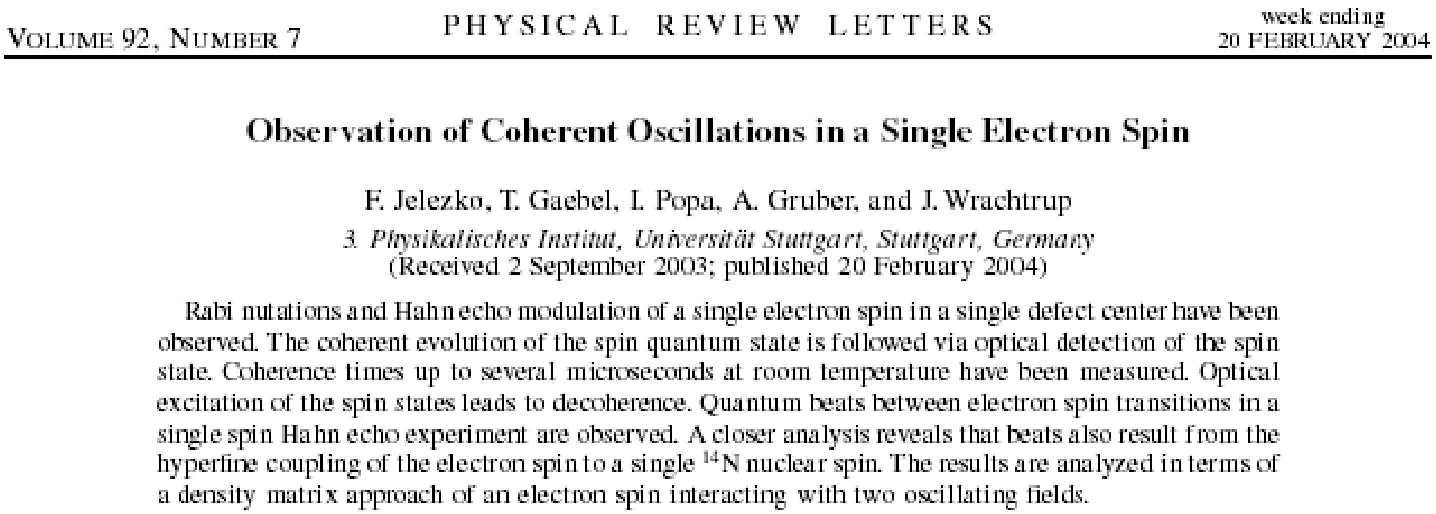
Electron spin relaxation times of phosphorus donors in silicon

A. M. Tyryshkin,[1] S. A. Lyon,[1,*] A. V. Astashkin,[2] and A. M. Raitsimring[2]
[1]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*
[2]*Department of Chemistry, University of Arizona, Tucson, Arizona 85721, USA*

(Received 6 August 2003; published 20 November 2003)

Donor electron spins in phosphorus-doped silicon (Si:P) are a candidate two-level system (qubit) for quantum information processing. Spin echo measurements of isotopically purified ^{28}Si:P are presented that show exceptionally long transverse relaxation (decoherence) times, T_2, at low temperature. Below ~10 K the spin decoherence is shown to be controlled by instantaneous diffusion and at higher temperatures by an Orbach process. T_2 for small pulse turning angles is 14 ms at 7 K and extrapolates to ~60 ms for an isolated spin, over 2 orders of magnitude longer than previously demonstrated.





VOLUME 92, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 20 FEBRUARY 2004

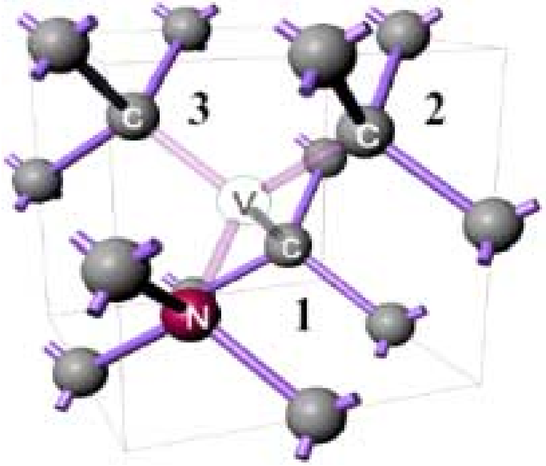
Observation of Coherent Oscillations in a Single Electron Spin

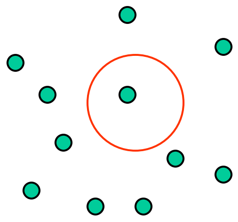
F. Jelezko, T. Gaebel, I. Popa, A. Gruber, and J. Wrachtrup

3. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany

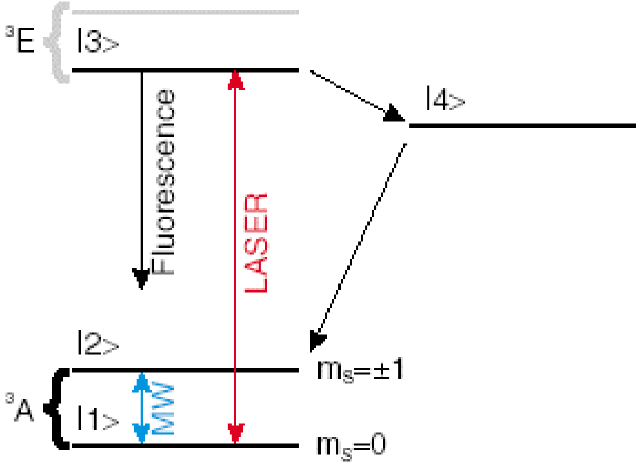
(Received 2 September 2003; published 20 February 2004)

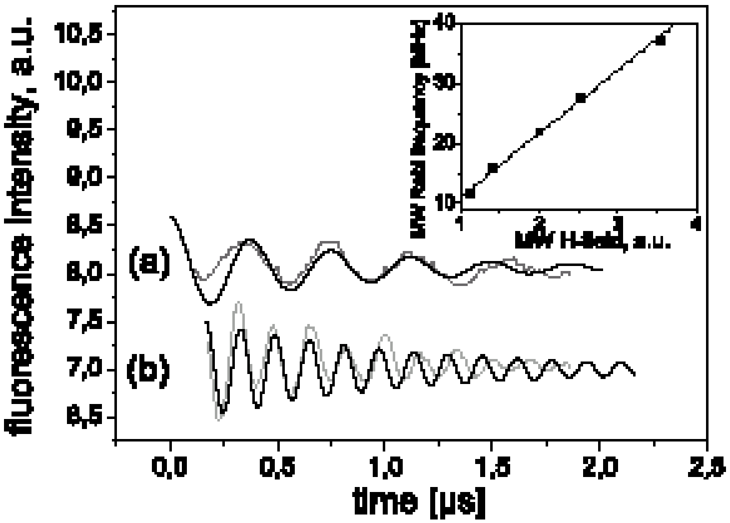
Rabi nutations and Hahn echo modulation of a single electron spin in a single defect center have been observed. The coherent evolution of the spin quantum state is followed via optical detection of the spin state. Coherence times up to several microseconds at room temperature have been measured. Optical excitation of the spin states leads to decoherence. Quantum beats between electron spin transitions in a single spin Hahn echo experiment are observed. A closer analysis reveals that beats also result from the hyperfine coupling of the electron spin to a single ^{14}N nuclear spin. The results are analyzed in terms of a density matrix approach of an electron spin interacting with two oscillating fields.

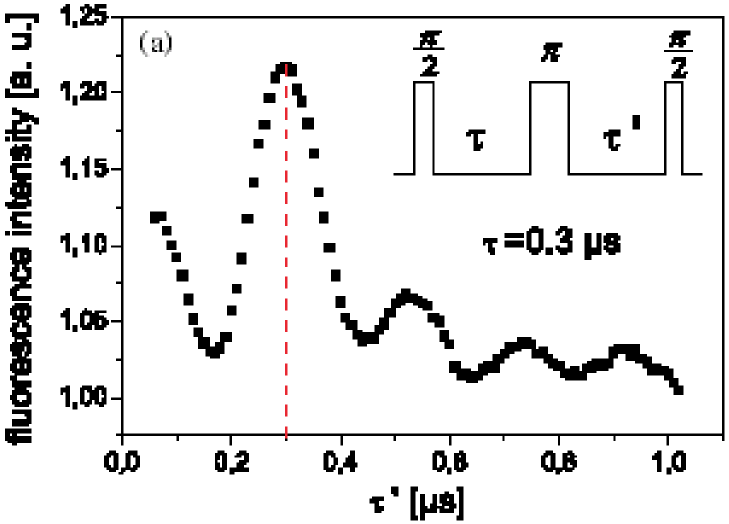




Use confocal microscope to focus on a single NV center







Observation of coherent oscillation of a single nuclear spin and realization of a two-qubit conditional quantum gate

quant-ph/0402087

F. Jelezko, T. Gaebel, I. Popa, M. Domhan, A. Gruber, J. Wrachtrup

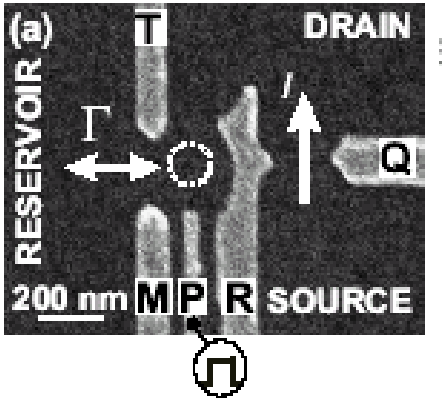
University of Stuttgart, 3. Physical Institute, Stuttgart, Germany

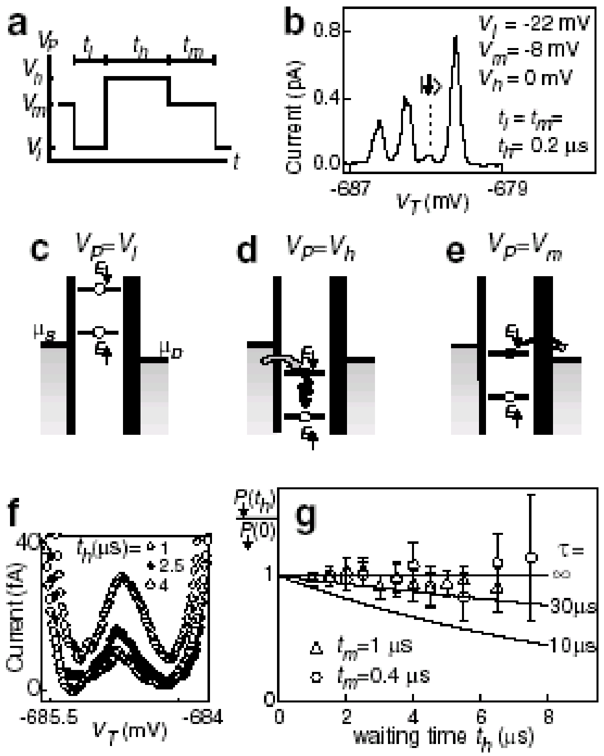
VOLUME 91, NUMBER 19 PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2003

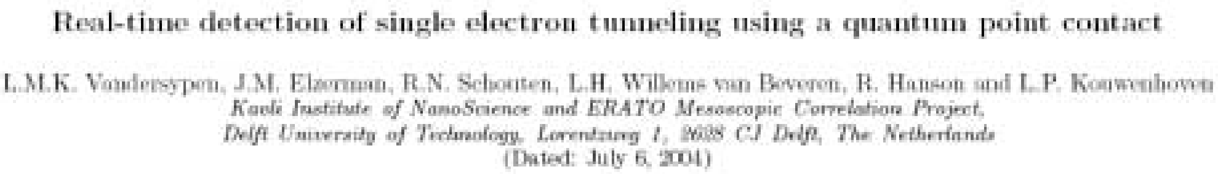
Zeeman Energy and Spin Relaxation in a One-Electron Quantum Dot

R. Hanson, B. Witkamp, L. M. K. Vandersypen, L. H. Willems van Beveren, J. M. Elzerman, and L. P. Kouwenhoven
Department of NanoScience and ERATO Mesoscopic Correlation Project, Delft University of Technology,
P.O. Box 5046, 2600 GA Delft, The Netherlands

(Received 7 March 2003; published 7 November 2003)



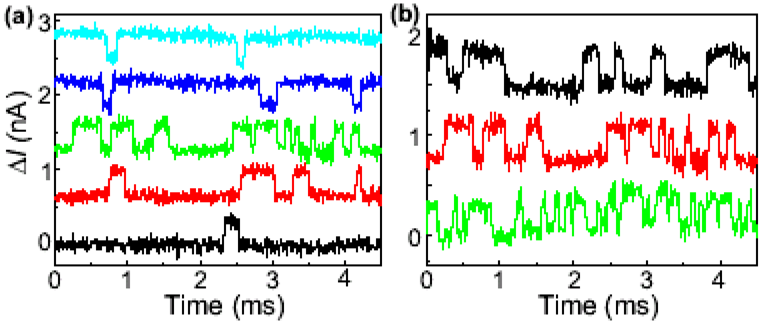




Real-time detection of single electron tunneling using a quantum point contact

L.M.K. Vandersypen, J.M. Elzerman, R.N. Schouten, L.H. Willems van Beveren, R. Hanson and L.P. Kouwenhoven
Kavli Institute of NanoScience and ERATO Mesoscopic Correlation Project,
Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

(Dated: July 6, 2004)



Quantum Logic

Quantum logical devices will have to control the interaction of single spins with their environment and with their neighbors with extraordinary precision.

Spin interactions in a semiconductor

Interaction	Extent	Strength
Electron spin exchange interaction	Size of Wave function	>> 1 GHz
Electron-nuclear hyperfine interaction	Contact	10 MHz- 1 GHz (donors)
Electron spin dipolar interaction	$\frac{\mu_B^2}{r^3}$	10 kHz (100 Å)
Nuclear spin dipolar interaction	$\frac{\mu_N^2}{r^3}$	10 mHz (100 Å)
Anisotropic Exchange		Large in some materials

Exchange Interaction

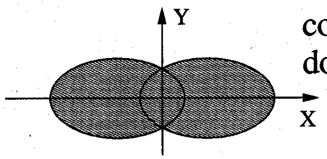
Well suited to implementing quantum logic via $\sqrt{\text{SWAP}}$

PHYSICAL REVIEW A, VOLUME 61, 062301

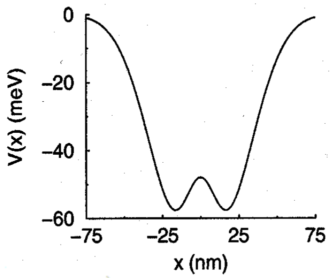
Hilbert-space structure of a solid-state quantum computer: Two-electron states of a double-quantum-dot artificial molecule

Xuedong Hu and S. Das Sarma
Department of Physics, University of Maryland, College Park, Maryland 20742-4111

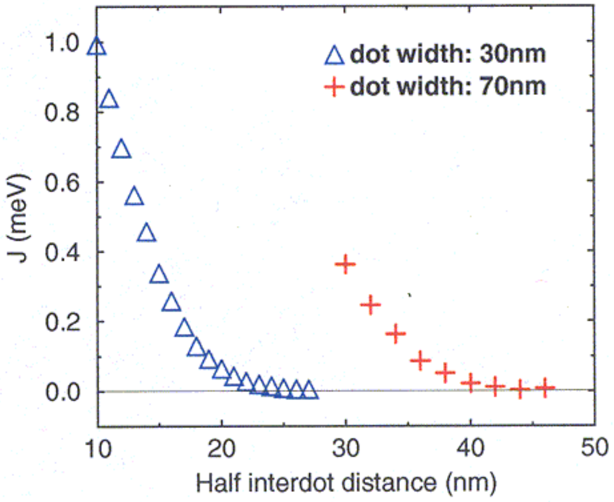
(Received 17 November 1999; revised manuscript received 26 January 2000; published 3 May 2000)

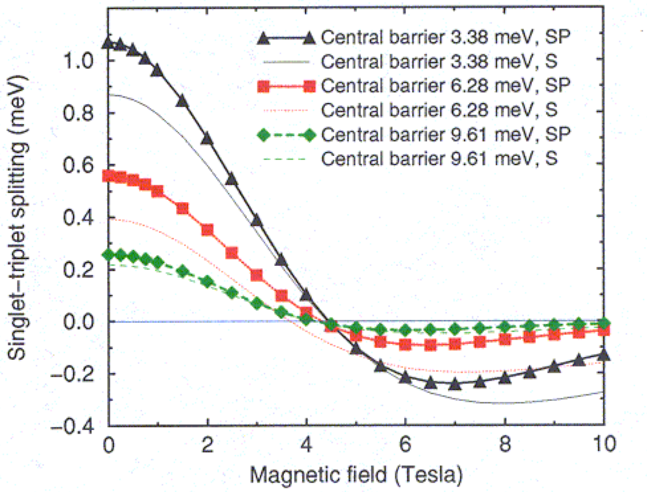


coupled 2-d double-dot



confinement potential profile





It will be difficult to know the exchange interaction spins in quantum dots with any precision.

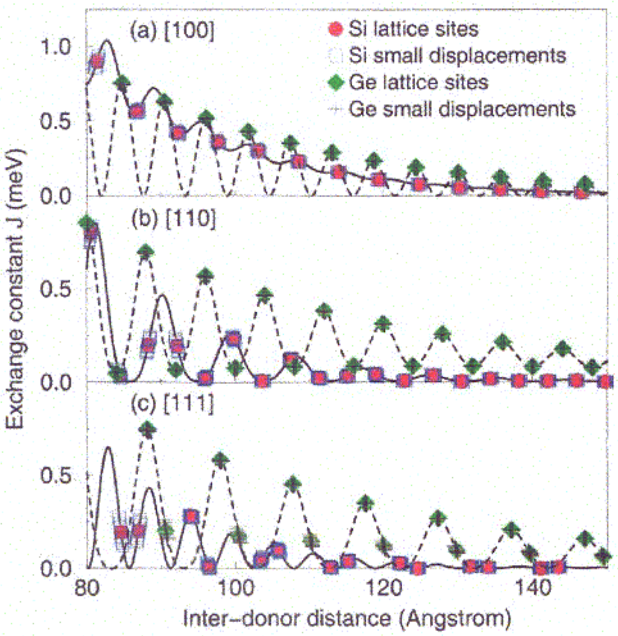
This problem can be even worse in silicon because of its band structure.

VOLUME 88, NUMBER 2 PHYSICAL REVIEW LETTERS 14 JANUARY 2002

Exchange in Silicon-Based Quantum Computer Architecture

Belita Koiller,[1,2] Xuedong Hu,[1] and S. Das Sarma[1]
[1]*Department of Physics, University of Maryland, College Park, Maryland 20742-4111*
[2]*Instituto de Física, Universidade Federal do Rio de Janeiro, 21945 Rio de Janeiro, Brazil*

(Received 13 June 2001; published 28 December 2001)



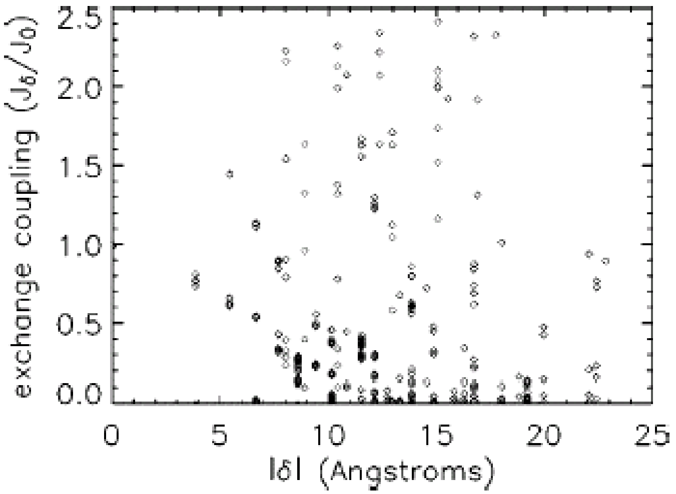
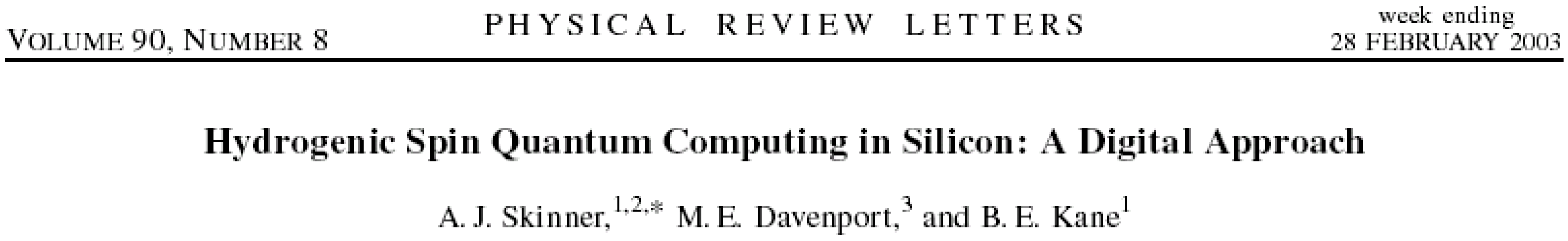


FIG. 4. Calculated exchange couplings for donors at fcc lattice sites that are displaced by a vector $\boldsymbol{\delta}$ from their ideal separation of 200.91 Å in the [100] direction. The couplings are plotted as a fraction of the expected exchange coupling $J(200.91\ \text{Å}) = 0.18\ \mu\text{eV}$.

Wellard et al. Phys. Rev. B 68 195209 (2003).

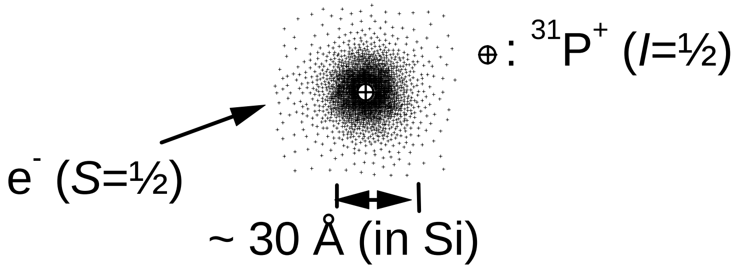
One way out: Use hyperfine coupling instead of Exchange



VOLUME 90, NUMBER 8 PHYSICAL REVIEW LETTERS week ending 28 FEBRUARY 2003

Hydrogenic Spin Quantum Computing in Silicon: A Digital Approach

A. J. Skinner,[1,2,*] M. E. Davenport,[3] and B. E. Kane[1]



⊕: $^{31}P^+$ (I=½)

e^- (S=½)

~ 30 Å (in Si)

$$H = A\,\boldsymbol{I}\cdot\boldsymbol{S}$$

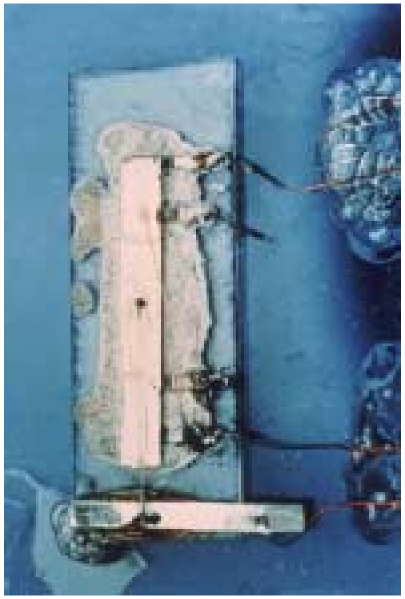
In *unstrained* pure Si, A=117.53±0.02 MHz (Feher)

Electron-nuclear interaction is very close to pure Heisenberg, probably better than for two electrons.

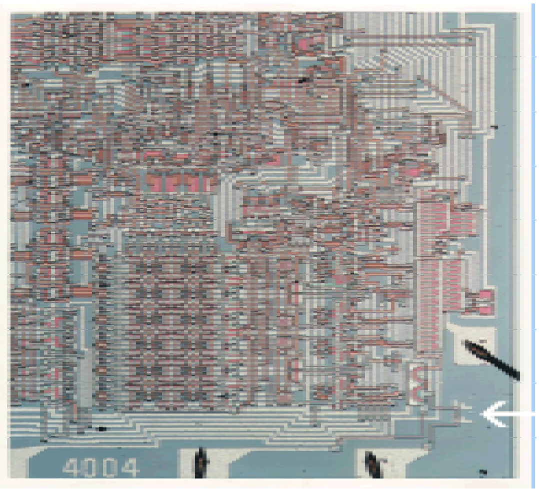
Status of Semiconductor QC

- Single spin manipulation and measurement, while difficult, appear to be in reach.
- But can will large scale quantum computing be possible?

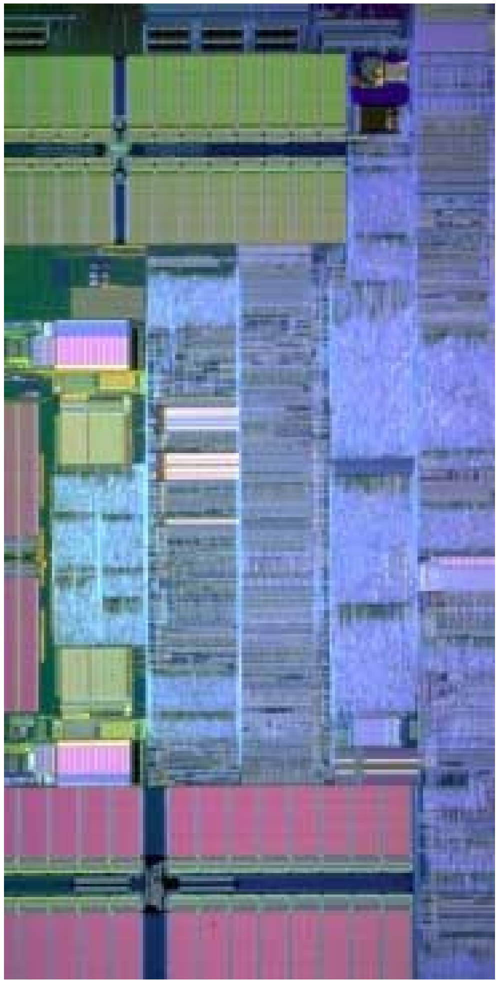
Most Technologies aren't scaleable!



1958



1970



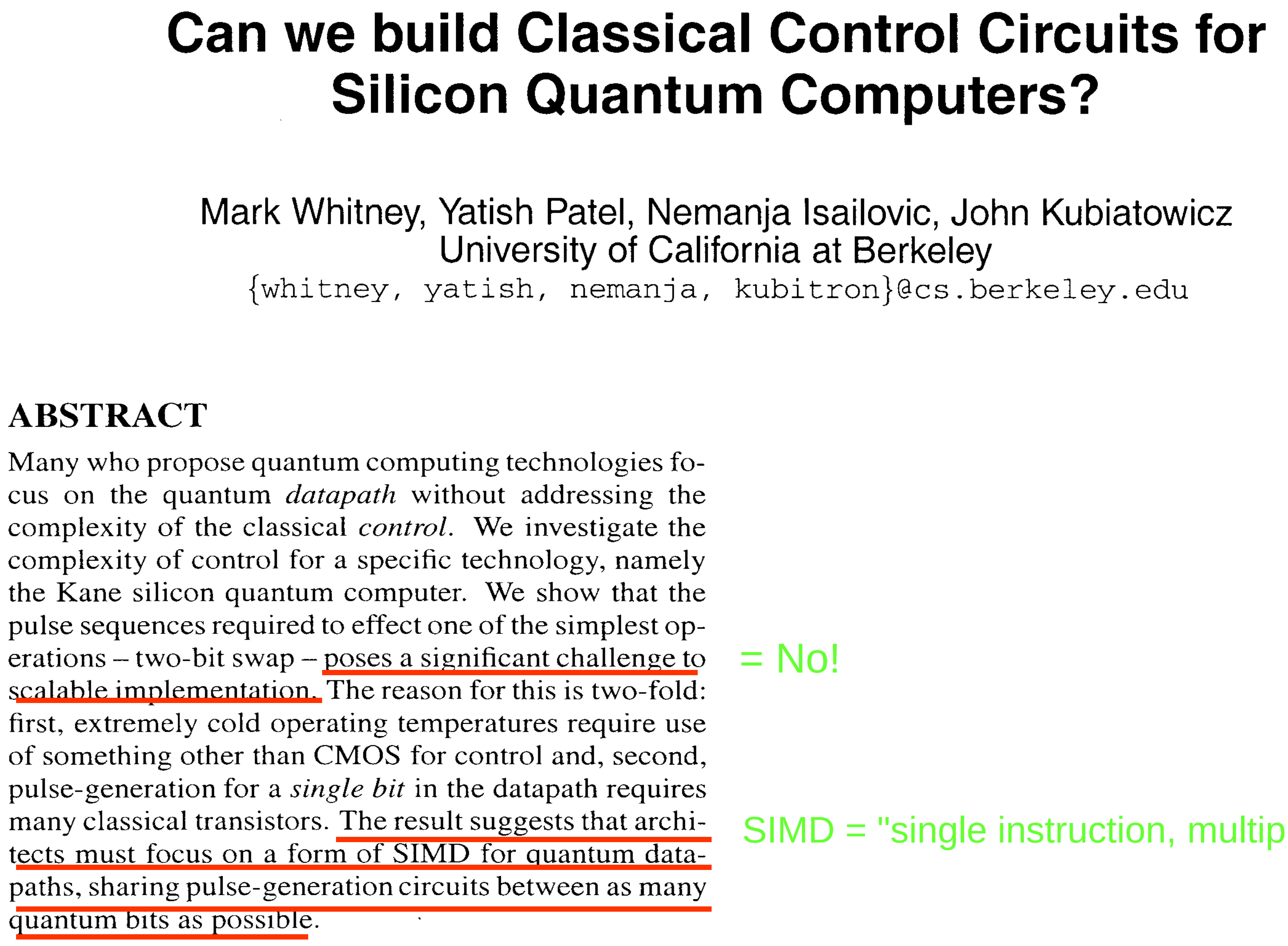
Today

Imperatives of large-scale QC

- *Parallel operations* (measurement and logic)
- Efficient quantum information *transport*
- Manageable classical control, preferably facilitated by *nearly identical devices*

Scaling and Classical Control

- In most proposed quantum computer architectures, quantum logic and measurement are performed using classical logic circuitry to control gate voltages, laser pulses, or other means used to determine the quantum state of the system. *Does the complexity of this classical control "blow up" as the size of the quantum computer increases?*



Can we build Classical Control Circuits for Silicon Quantum Computers?

Mark Whitney, Yatish Patel, Nemanja Isailovic, John Kubiatowicz
University of California at Berkeley
`{whitney, yatish, nemanja, kubitron}@cs.berkeley.edu`

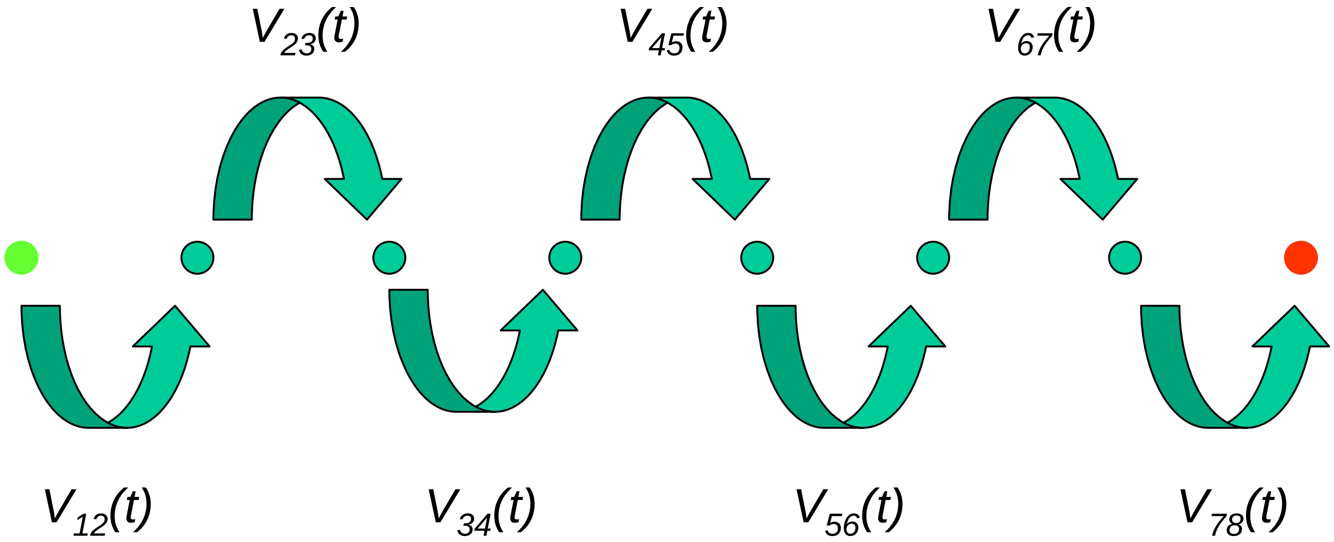
ABSTRACT

Many who propose quantum computing technologies focus on the quantum *datapath* without addressing the complexity of the classical *control*. We investigate the complexity of control for a specific technology, namely the Kane silicon quantum computer. We show that the pulse sequences required to effect one of the simplest operations – two-bit swap – poses a significant challenge to scalable implementation. The reason for this is two-fold: first, extremely cold operating temperatures require use of something other than CMOS for control and, second, pulse-generation for a *single bit* in the datapath requires many classical transistors. The result suggests that architects must focus on a form of SIMD for quantum datapaths, sharing pulse-generation circuits between as many quantum bits as possible.

= No!

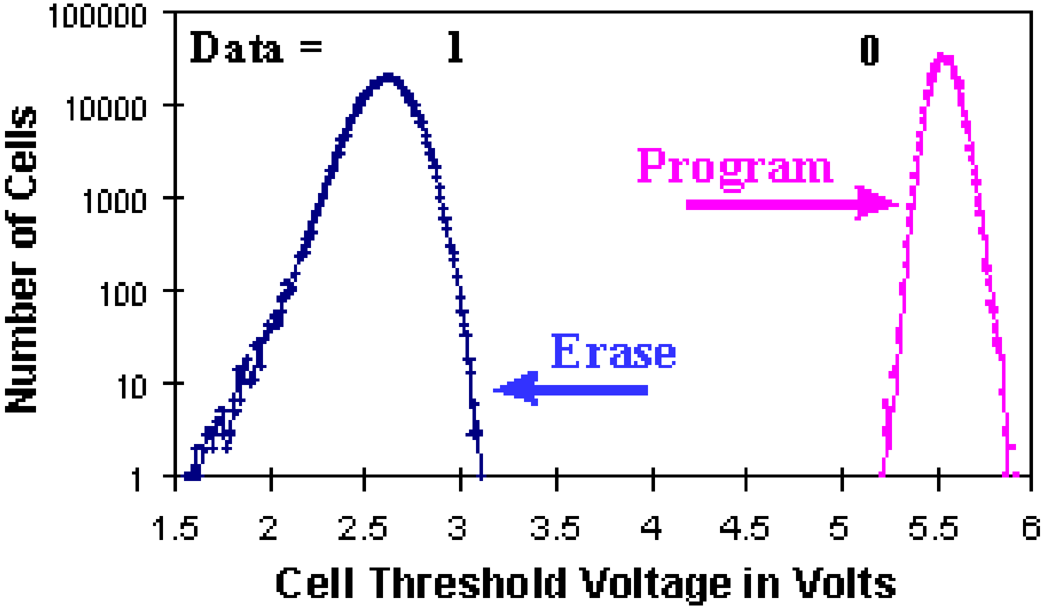
SIMD = "single instruction, multiple data"

Control of a “SWAP Wire” using applied gate voltages



A *tremendous* increase in scaling efficiency would result if single control lines could control multiple gates.

Making “identical devices” for scaling is much harder for QC than it is for CC.



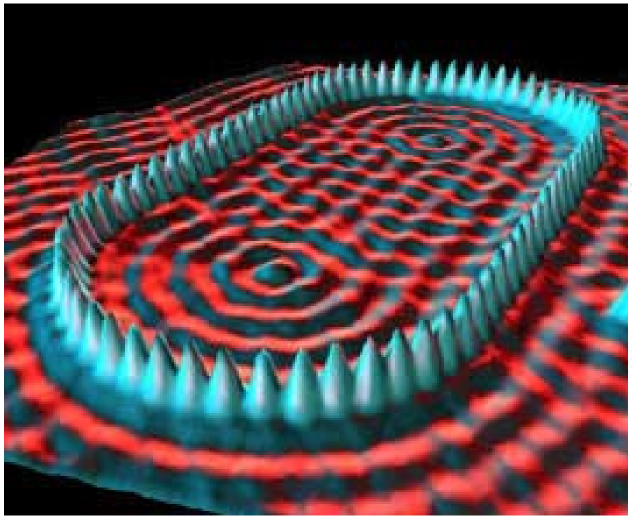
Intel Corp.

The materials science and nanofabrication communities need to start thinking about “monoclonal” (i.e. atomically identical) devices and how to implement them

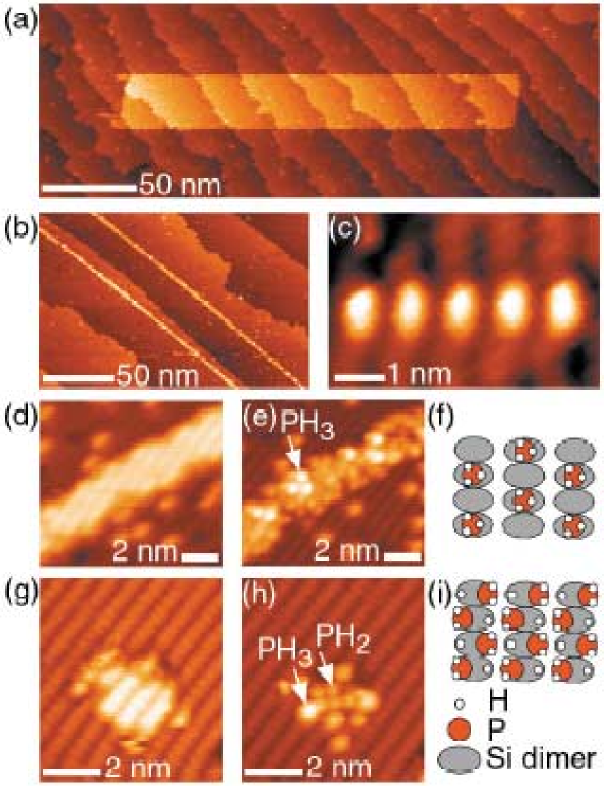
- Single donor devices (Australian QC group and many others working hard on this)

- Single atoms and molecules attached to semiconductor surfaces?

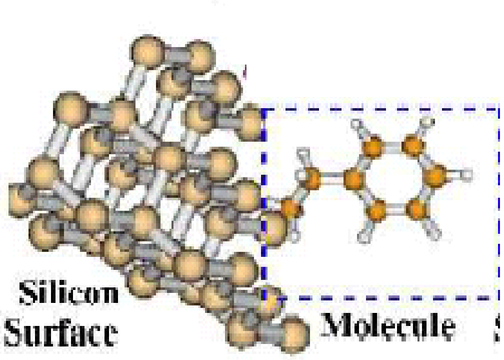
“Bottom up” Nanofabrication



Single atom Manipulation
using an STM.
(M. Crommie *et al.*)



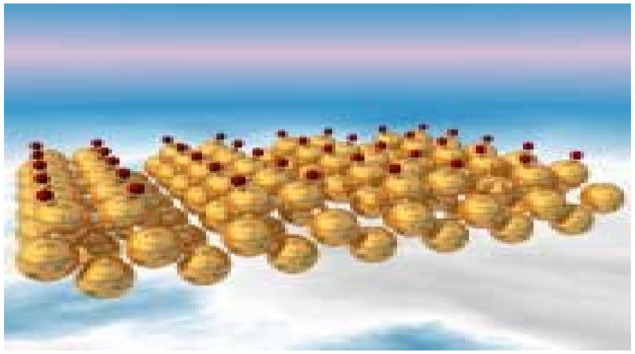
Schofield et al.: PRL
91 136104 (2003).

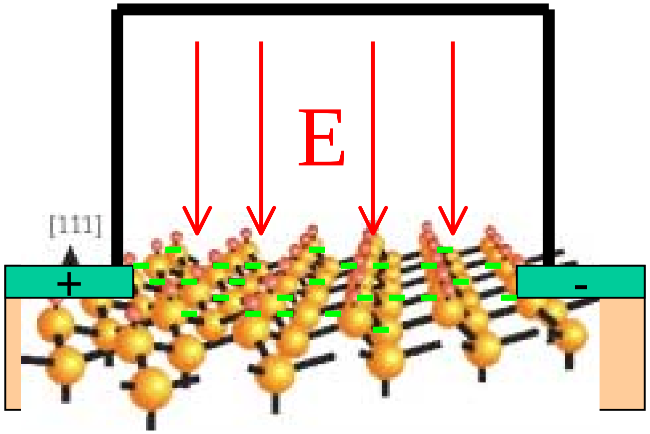


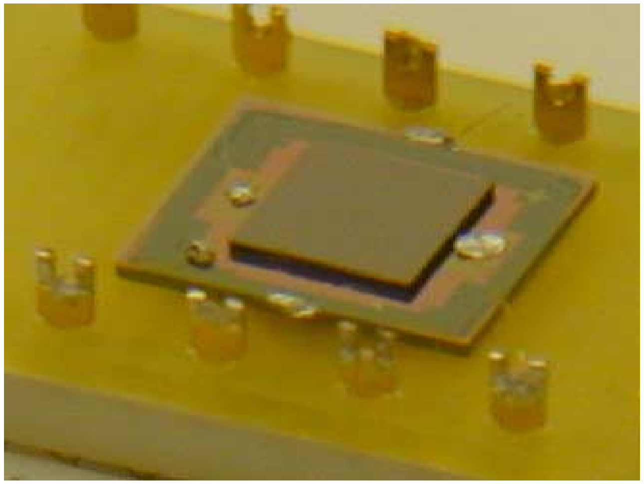
Taken from “Silicon-based
molecular electronics” S.
Datta et al.

- For future devices it would be desirable to couple surface atoms and molecules to conducting electrons within a silicon crystal.

Electron system on a hydrogen passivated silicon surface







[Q5.126] Electron Transport on Hydrogen-Passivated Silicon Surfaces

Kevin Eng, Robert McFarland, Bruce Kane

Conclusions

1. QC has the potential to revolutionize the way we solve a limited number of problems
2. Semiconductor QC implementations have important advantages (existing technological base, vast research effort in nanofabrication) and disadvantages (decoherence) compared to alternatives
3. Devices demonstrating single electron spin manipulation and measurement are difficult, but doable
4. Nonetheless, there are very serious doubts about the ability to scale simple quantum logical devices into a technologically relevant quantum computer
5. This (mildly) pessimistic outlook presents new opportunities for semiconductor physics research and nanofabrication at the end point of Moore’s Law scaling.