Electron Spin Qubits

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- Review of quantum dots (mostly GaAs/AlGaAs), with many references:

  Hanson, Kouwenhoven, Petta, Tarucha, Vandersypen,
  Rev. Mod. Phys. **79**, 1217 (2007).

- Overview of older silicon spin qubit work:

  Morton, McCamey, Eriksson, Lyon, Nature, **479**, 345 (2011).

Outline

- Background on Si and electrons
- Spin resonance measurements of spin coherence in Si
- GaAs quantum dot spin experiments
- Si quantum dot spin experiments
- Si donor spin experiments
- Other schemes (electrons on helium, …)

Why Electron Spins?

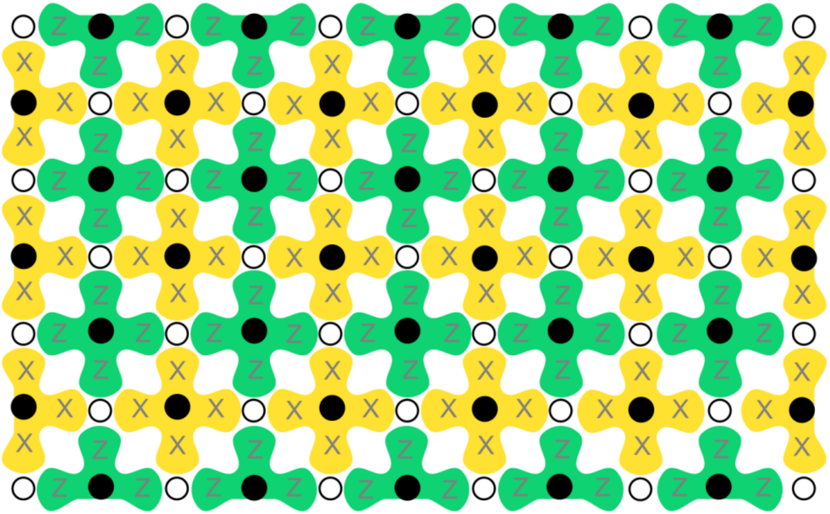
$\underline{\sim 10^9 \text{ Qubits}}$

for full-scale Quantum Computer

- Need small qubits
- Need fast qubits
- Recent Ion Trap proposal (shuttle ions)
  - 100 x 100 m^2 [Lekitsch, Sci. Adv. **3,** e1601540 (2017).]

    = 2.5 acres

Surface Code (Error Correction)



- Every cycle
  1. CNOT gates between the black dots and 4 neighbor white dots colored yellow
  2. Measure state of black dot
  3. Repeat 1 & 2 for green colored regions
- Turn off these operations in regions to define logical qubits
- Move (braid) these logical qubits to perform logical gates

Fowler, Phys. Rev. A 86, 032324 (2012)

Electron spins as quantum bits

- Natural 2-level system (for S = ½)
- Spins interact weakly (magnetic dipole)

  ⇒ long coherence (in principle)

  - But, weak interaction

  ⇒ difficult to manipulate spin

  ⇒ difficult to measure spin

  ⇒ difficult to make 2-qubit gates

Energies and transitions

- Zeeman Hamiltonian
  - – $H = g\mu_B \mathbf{B}\cdot\mathbf{S} = E_Z$
  - – Often g ~ 2, and S = ½

  ⇒ E_Z

  ~ 10 GHz at B=0.35T

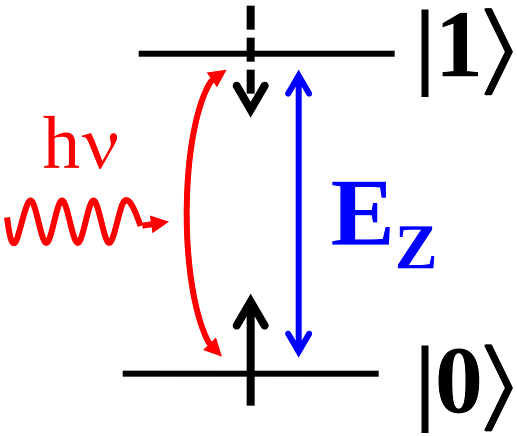
  ~ 0.5K

  ⇒ Drive spins with microwaves

  Typically 5 – 50 GHz

  Driven by magnetic field of microwaves (weak)

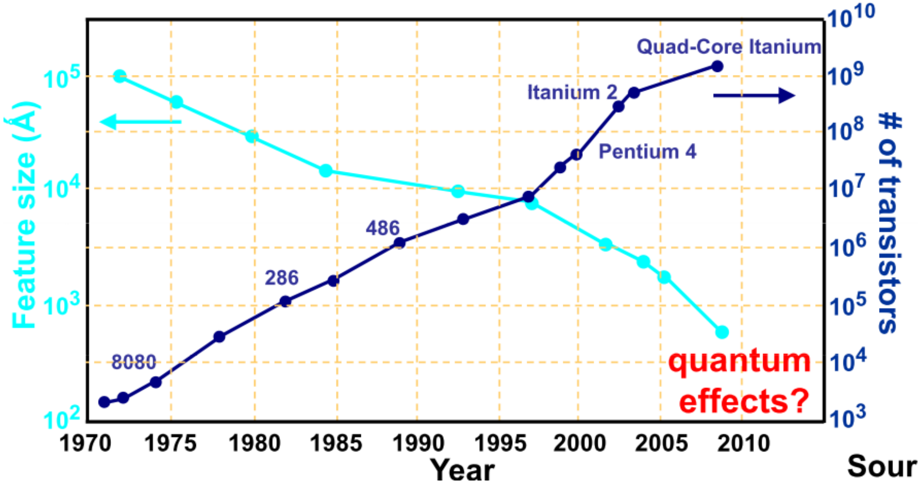
  ⇒Can initialize by cooling to mK



➢Conversions: 10 GHz ~ 450 mK ~ 41 μeV

Electron spins in semiconductors

- Why semiconductors?
  - Electrons readily moved and controlled in semiconductors
  - Huge industry exists which can manufacture chips with > 10^{11} devices



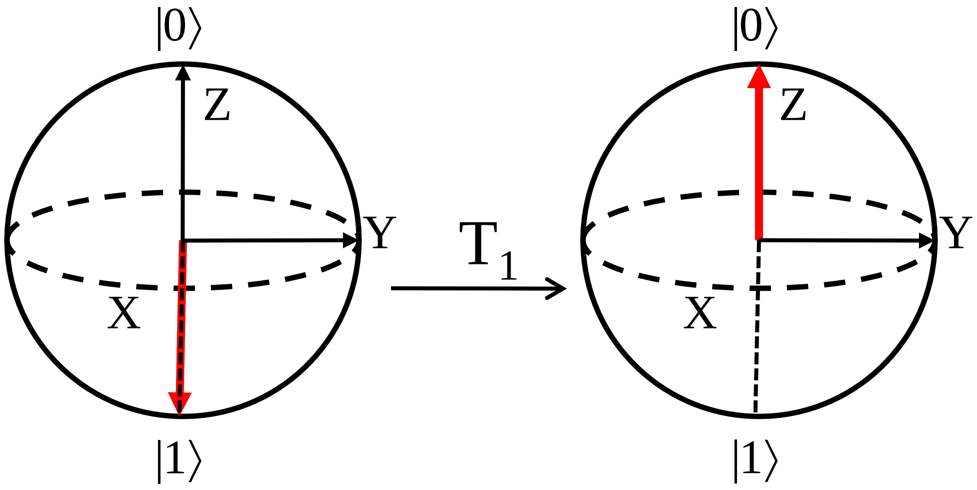
Source: Intel

  - Data from 1950's showed long spin lifetimes (T_1)
  - Semiconductors can be extremely pure
    - So, maybe long spin coherence (T_2)

Decoherence on the Bloch Sphere

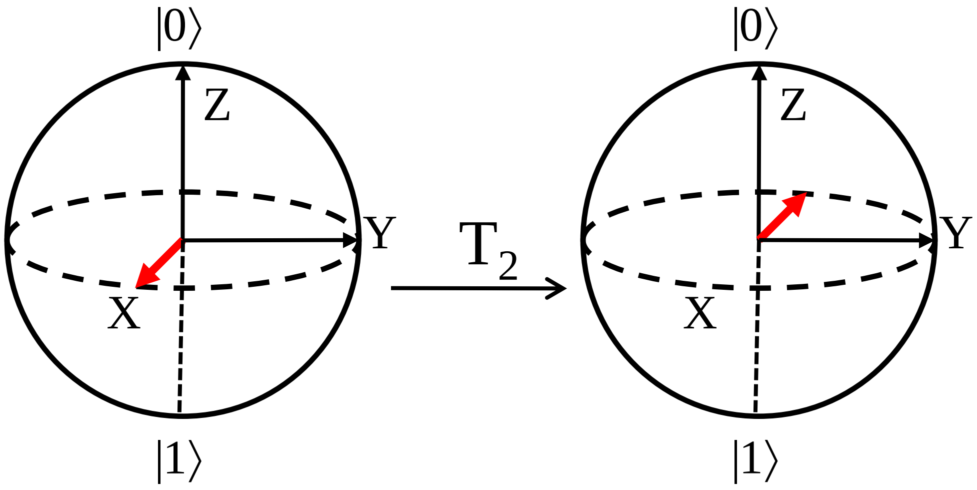
- T_1 = bit flip time

$$|1\rangle \xrightarrow{T_1} |0\rangle$$



- T_2 = phase flip time

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} \xrightarrow{T_2} \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$



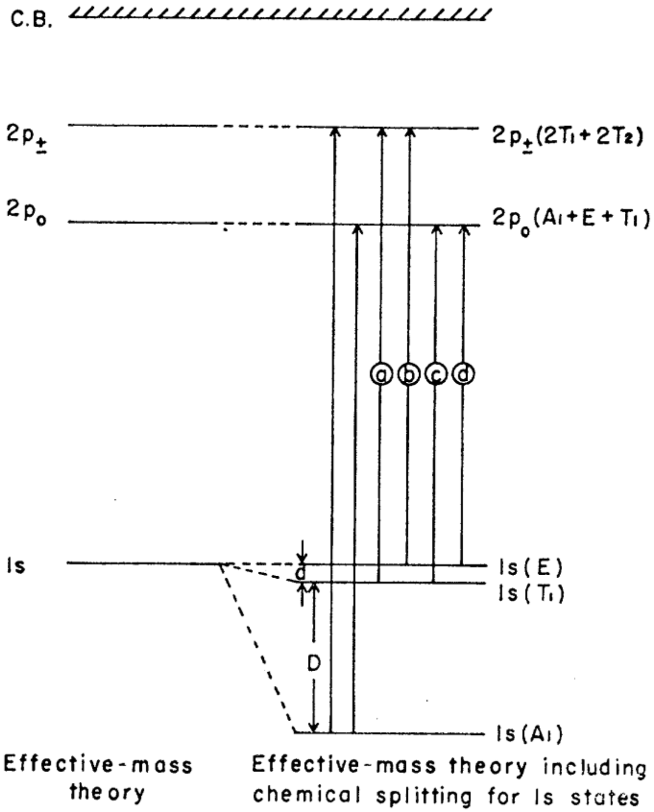
What do we know about electron spin coherence in Si?

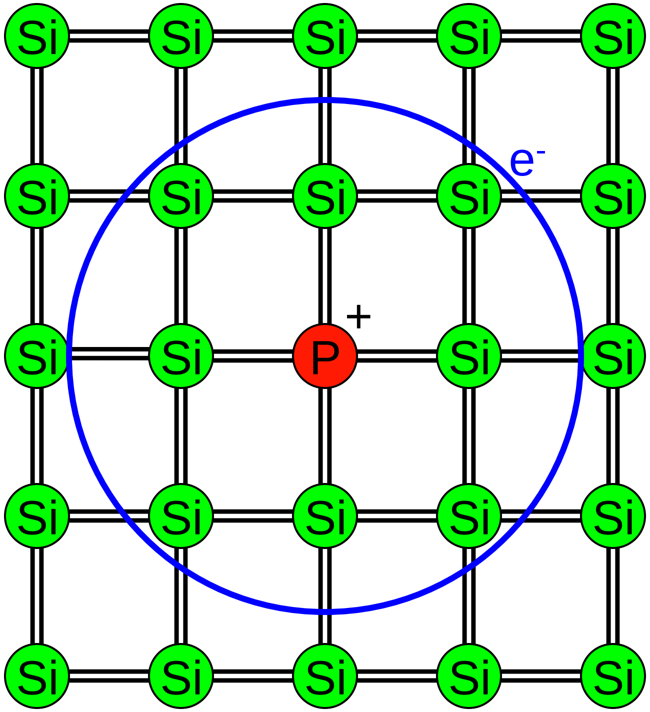
(in ~2000 assumed maximum coherence ~ 1 ms)

Pulsed electron spin resonance (ESR = EPR)

- Ensemble technique (measure ~10^8 – 10^{13}) spins at once – a spatial ensemble
  - Need many spins for enough signal
  - Often will not do time ensemble
  - Some sort of ensemble required for coherence
- Often simpler sample preparation than devices (sometimes just cutting to the right size)

Donor impurities in silicon





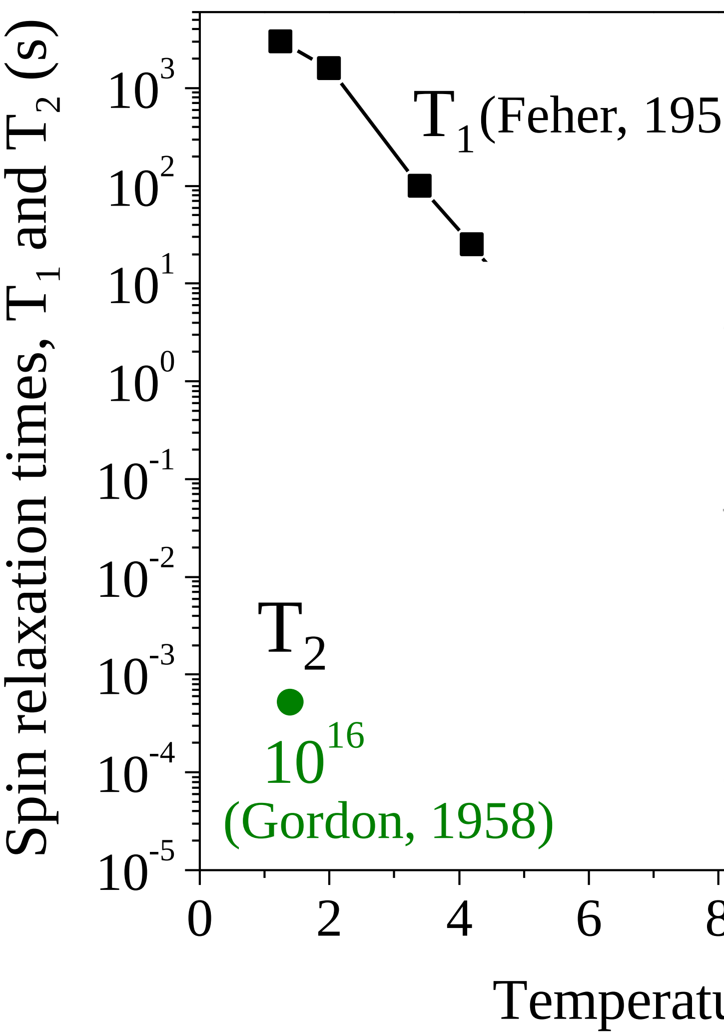
Ionization energy (phosphorus) ~ 50 meV

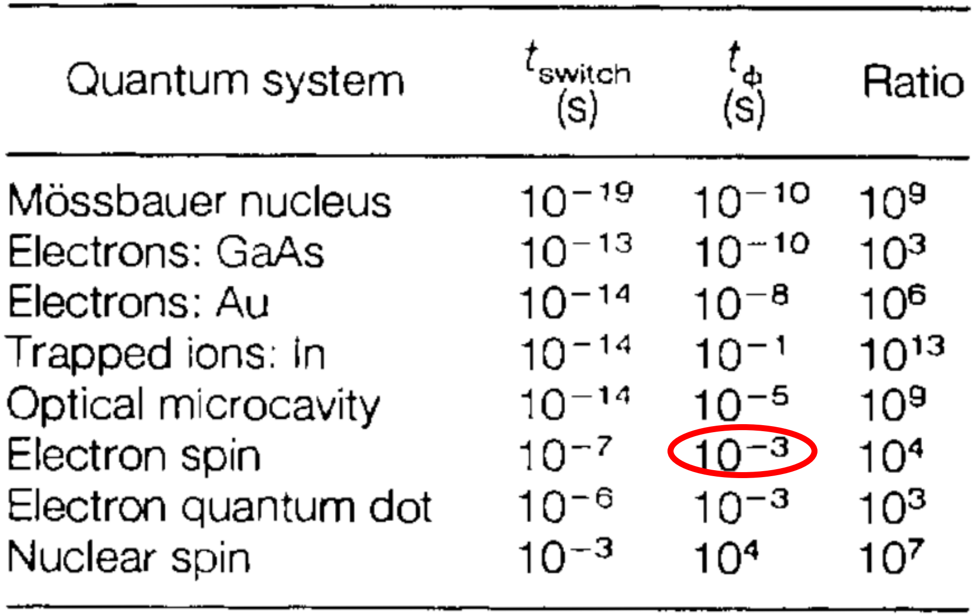
Impurity Bohr radius ~ 2 nm

Lowest excited state ~ 10 meV (not hydrogenic)

Nuclear spin (phosphorus) = ½

Spin qubits

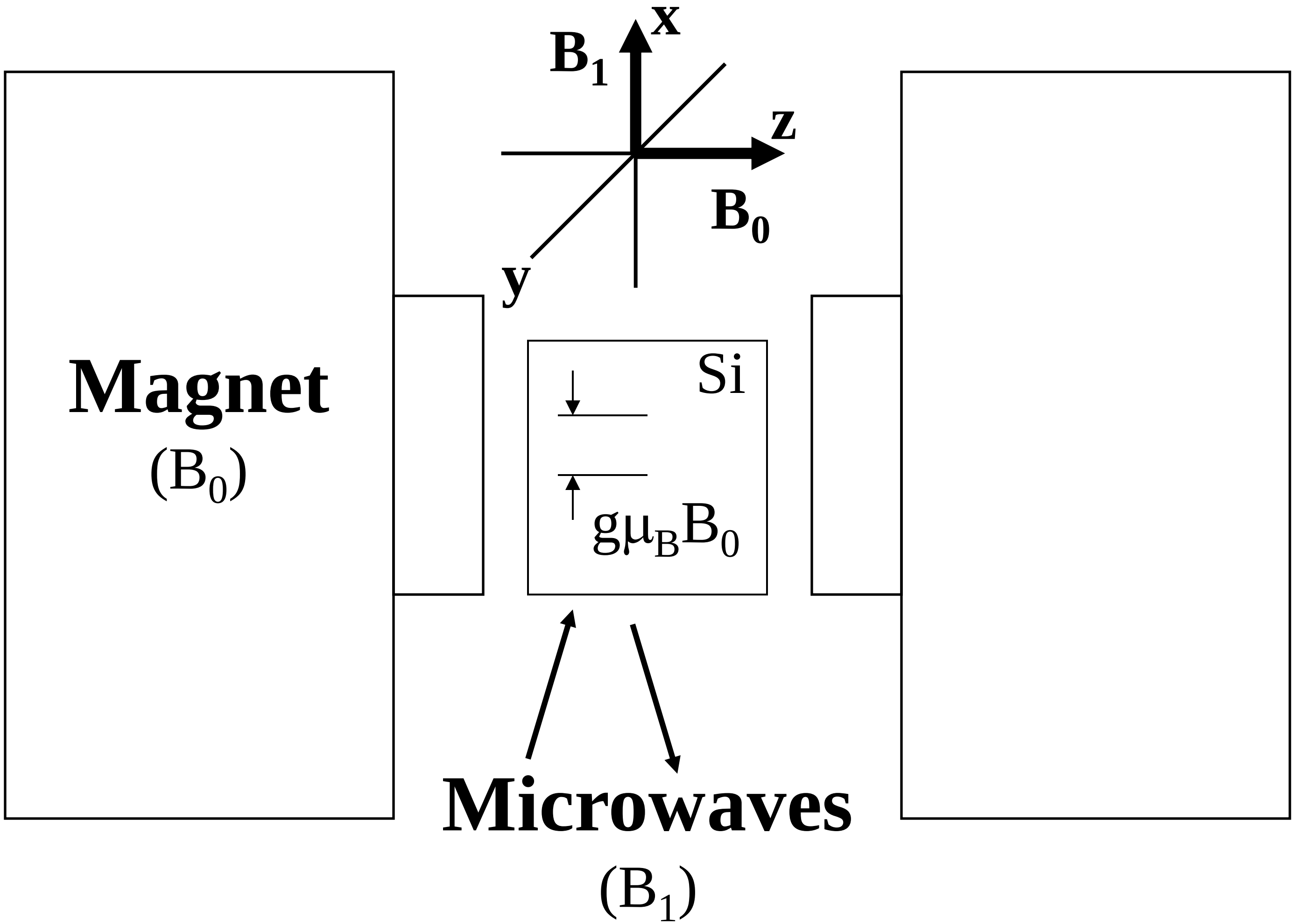




Quantum system	t_{switch} (s)	t_ϕ (s)	Ratio
Mössbauer nucleus	10^{-19}	10^{-10}	10^9
Electrons: GaAs	10^{-13}	10^{-10}	10^3
Electrons: Au	10^{-14}	10^{-8}	10^6
Trapped ions: In	10^{-14}	10^{-1}	10^{13}
Optical microcavity	10^{-14}	10^{-5}	10^9
Electron spin	10^{-7}	10^{-3}	10^4
Electron quantum dot	10^{-6}	10^{-3}	10^3
Nuclear spin	10^{-3}	10^4	10^7

DiVincenzo, Science **270,** 255 (1995)

Electron Spin Resonance (ESR) – the Laboratory Frame



Magnet

(B_0)

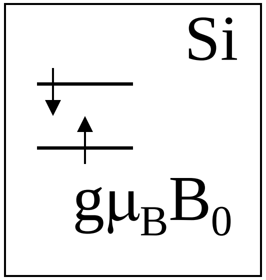
Microwaves

(B_1)

Adjust magnetic field (B_0) so that $g\mu_B B_0 \sim h\nu$ and measure microwave absorption and emission.

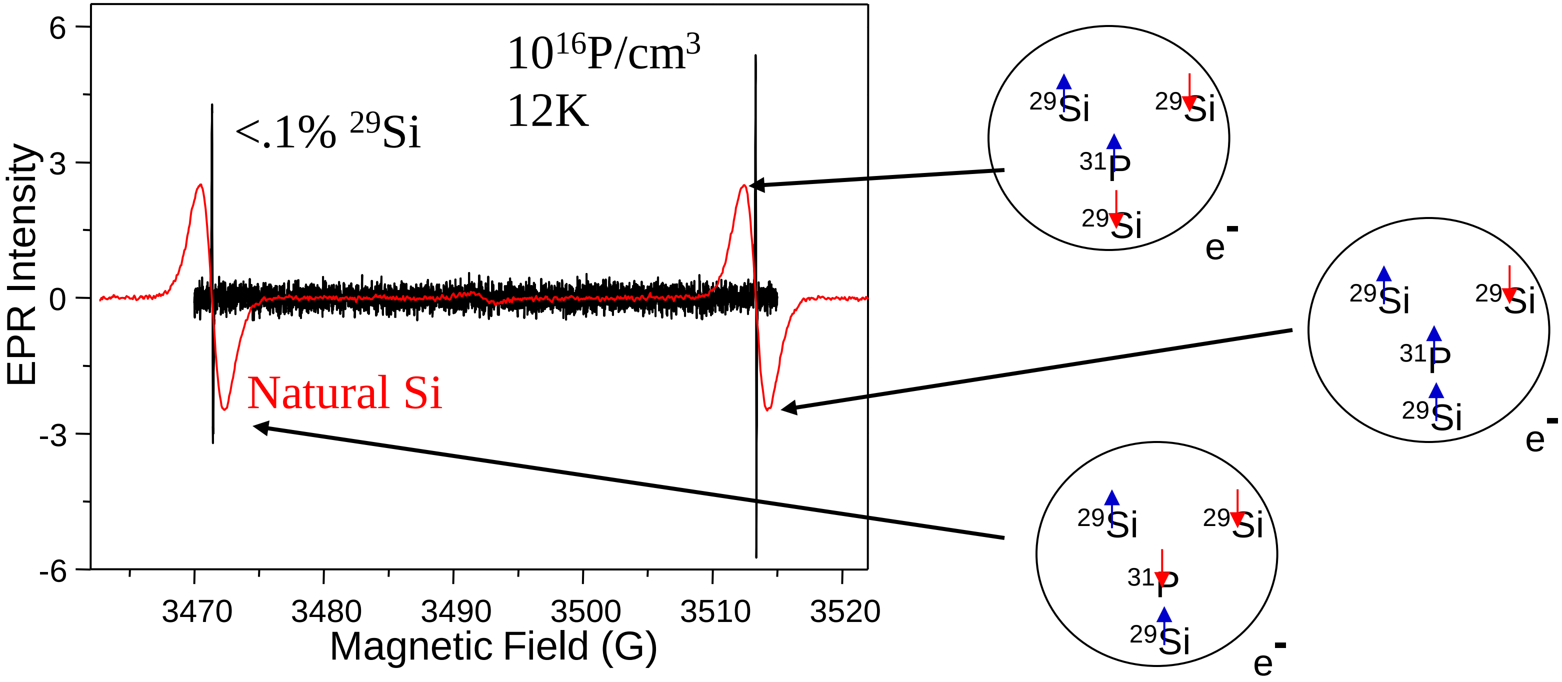
Electron Spin Resonance (ESR)

- Put spins into magnetic field, B_0



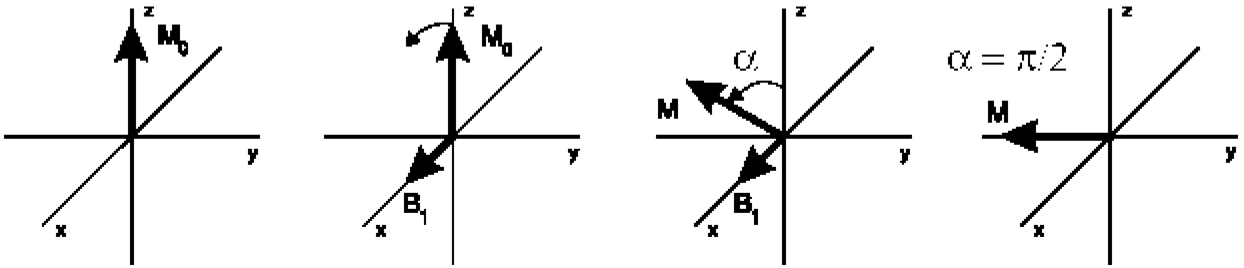
↔

Microwaves at $h\nu = g\mu_B B_0$



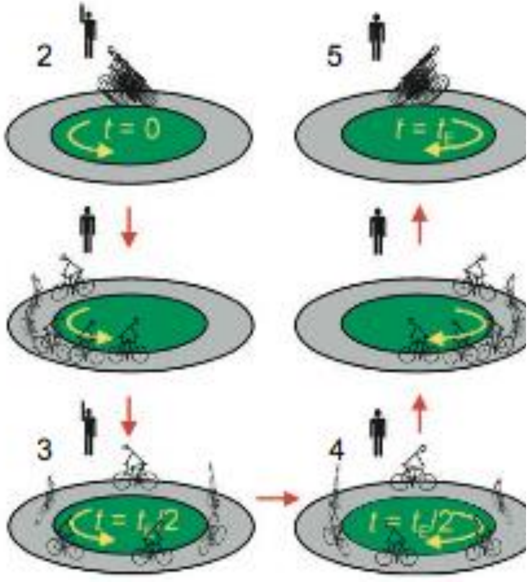
The Rotating Frame and a π/2 Pulse

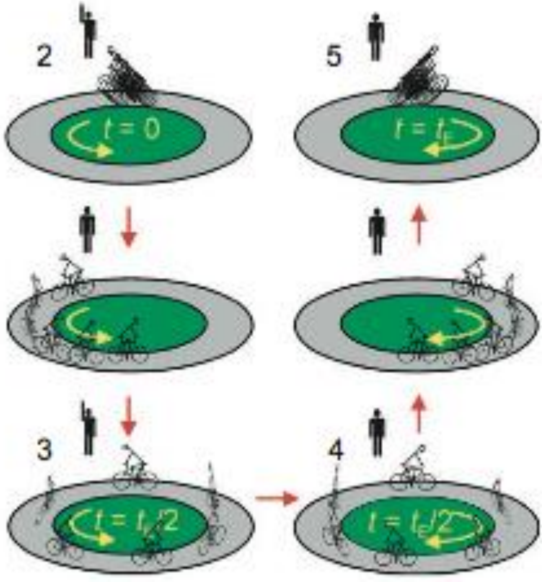
- The electrons’ magnetic moment is precessing about B_0 at the Larmor frequency (~10GHz)
- Reference frame rotating at $g\mu_B B_0 \Rightarrow$ spins nearly stationary
- In rotating frame a π/2-pulse (B_1) rotates the magnetization 90° around the x or y axis.
    - The B_1 pulse must “rotate” at the Larmor frequency



Spin echo (Hahn echo)

idents happen
lax (thermalize)
se phase information

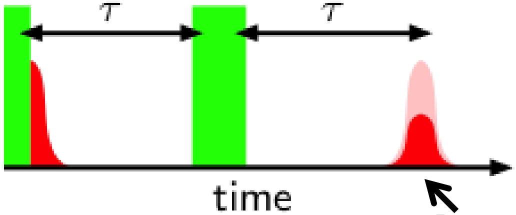




Microwave pulses

$\pi/2$ pulse
= “start”

π pulse
= “reverse”

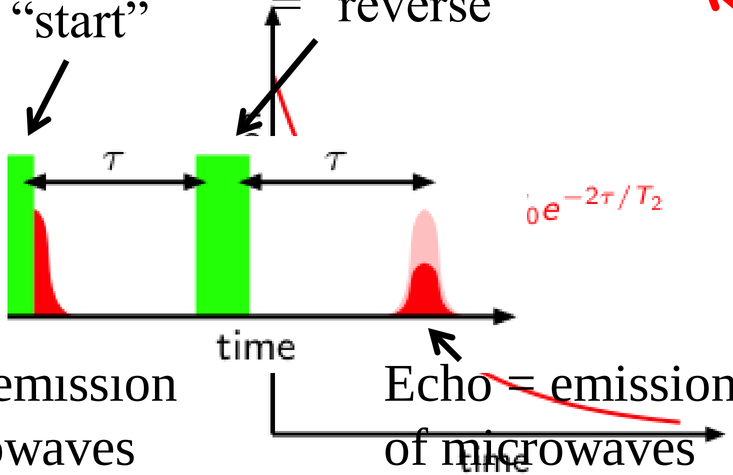


Echo = emission
of microwaves

Microwave pulses

$\pi/2$ pulse
= “start”

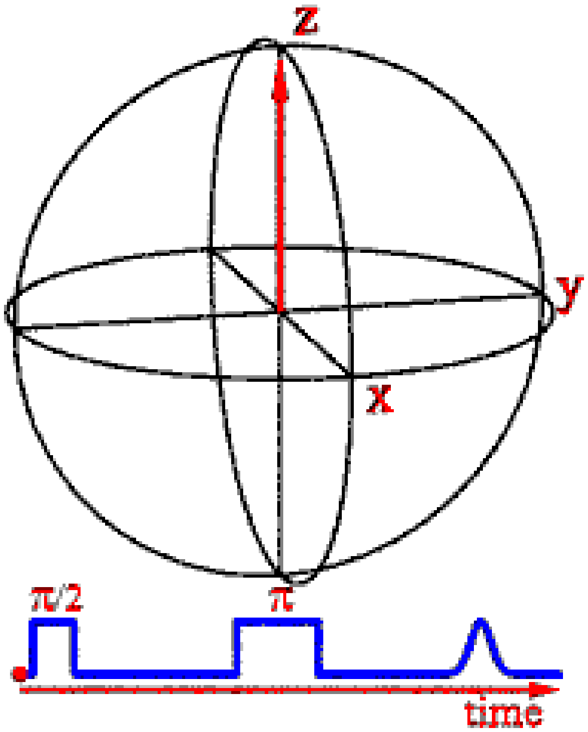
π pulse
= “reverse”



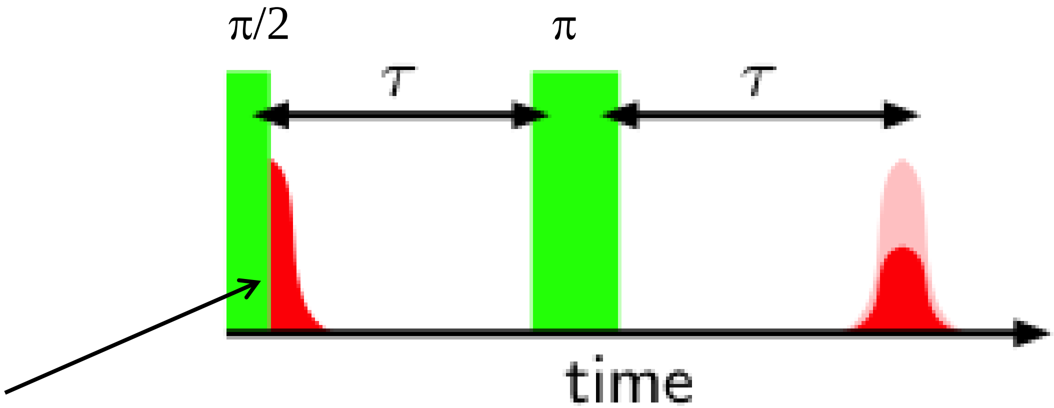
Echo = emission
of microwaves

T_1

Spin Echo Animation

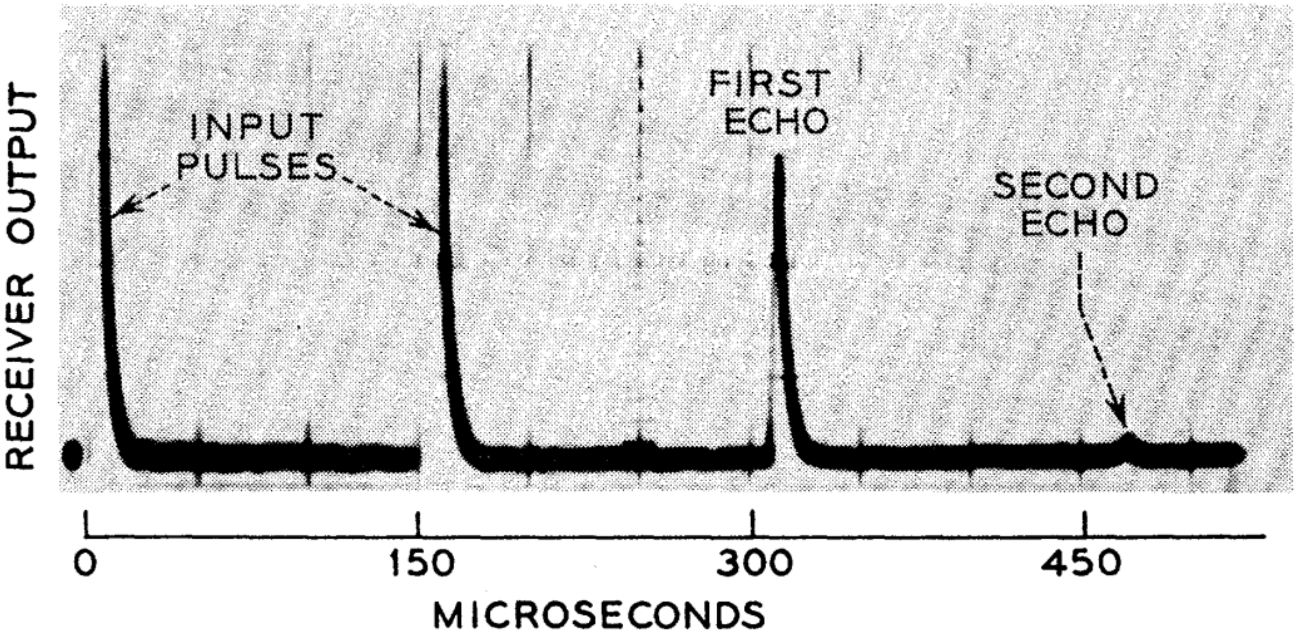


Magnetic Resonance Jargon



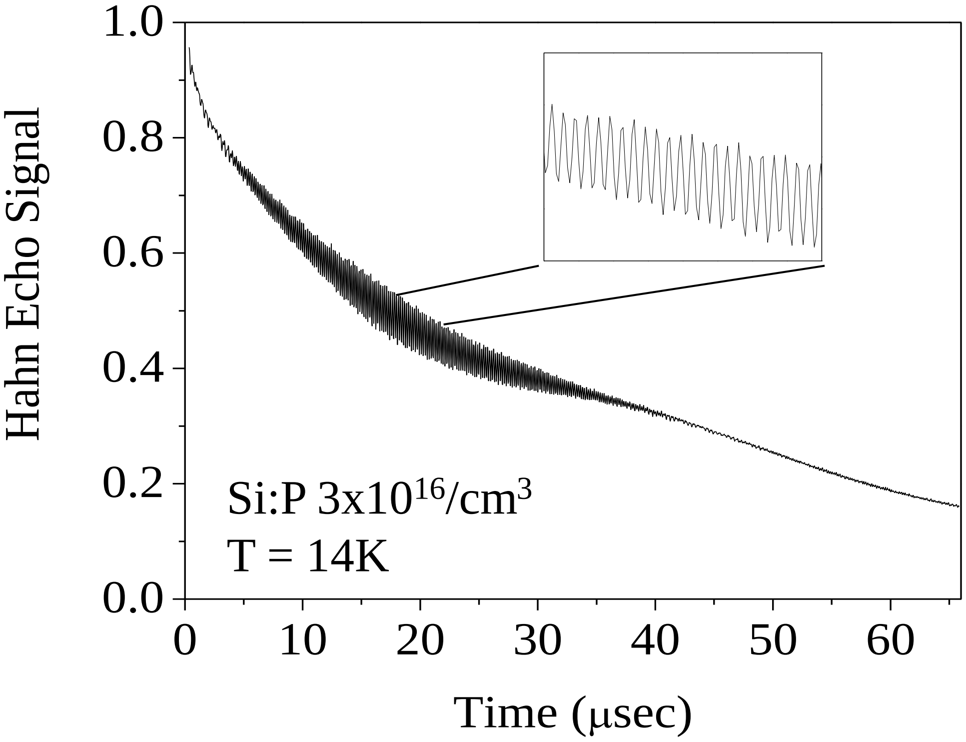
- FID = Free Induction Decay = initial emisson
- T_2^* = “Dephasing Time” = time for different spins to go out of phase with one another in FID
- “Refocusing pulse” = the π-pulse
- T_2 = decay time of the echo = “coherence time” = “spin-spin relaxation time”
- T_1 = “Relaxation time” = “Spin flip time” = “spin-lattice relaxation time”

First Microwave Spin Echo Experiment Si:P

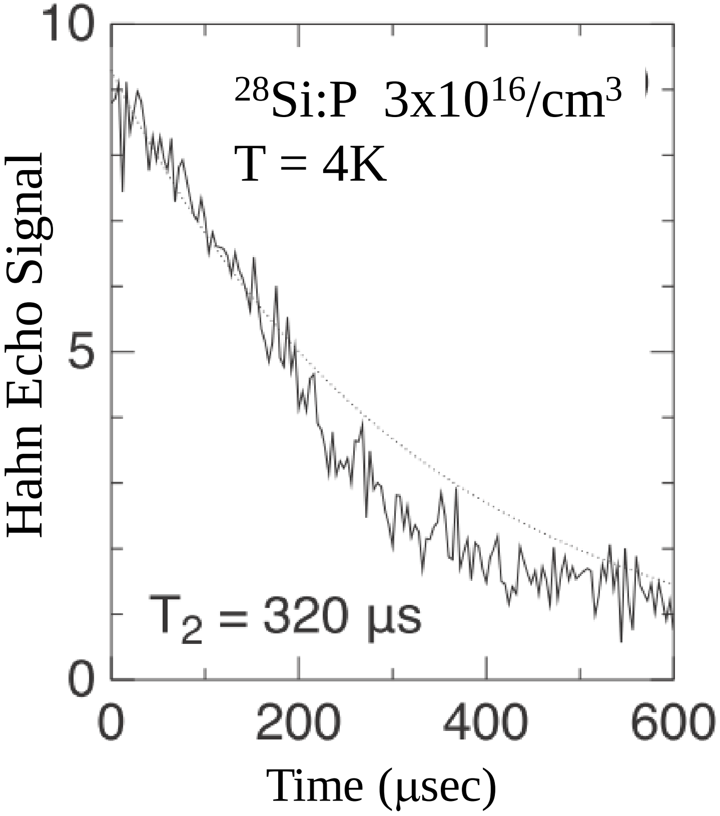


- Gordon & Bowers, Phys. Rev. Lett. **1**, 369 (1958)
- Measured T_2 ~ 520 μs with ^{28}Si:P
  - Longest electron spin T_2 until ~2003 (?)

Electron Spin Echoes from Donors in Silicon



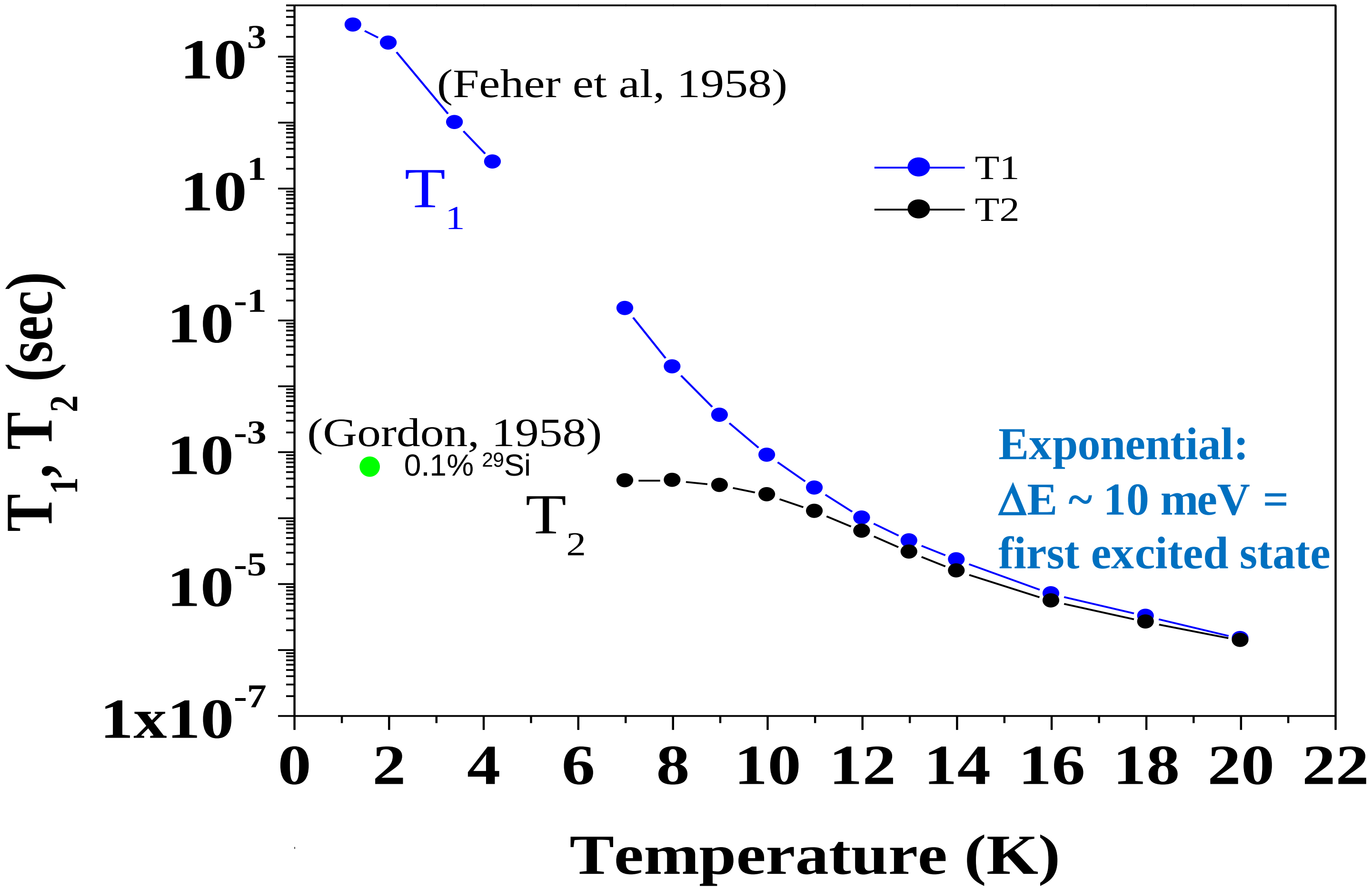
Natural silicon



Isotopically enriched silicon

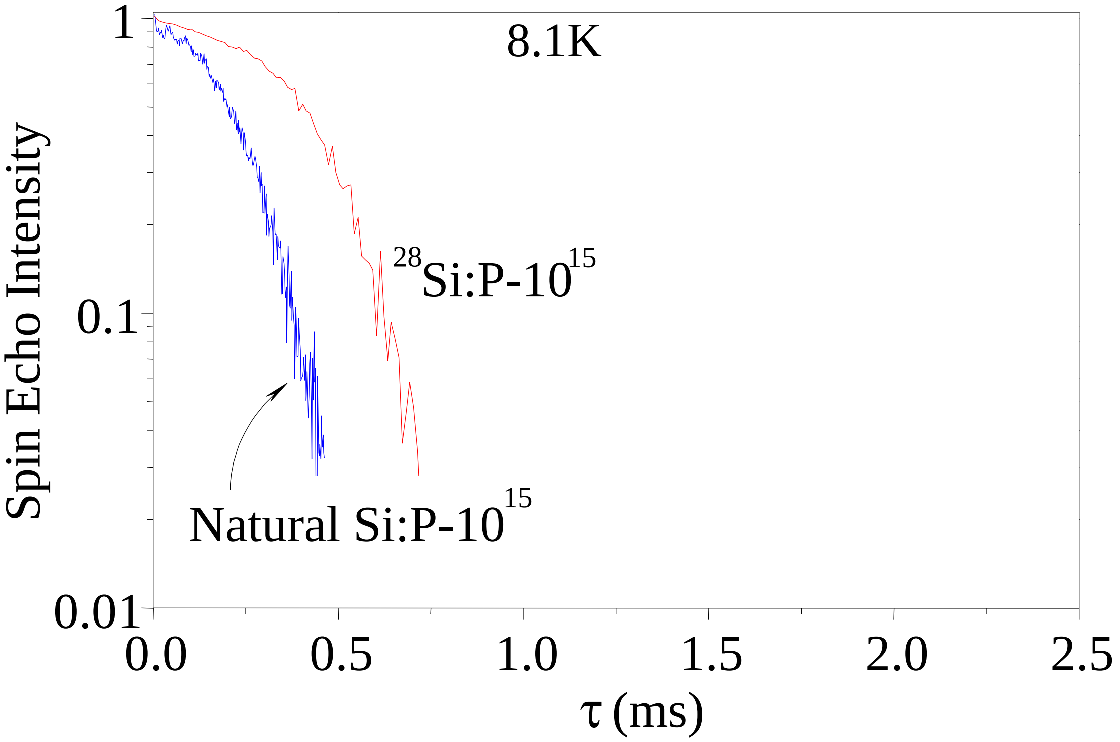
Donor electron spin qubits

- Doping ~10^{16}/cm^3
- Isotopically purified ^{28}Si:P (800ppm ^{29}Si)



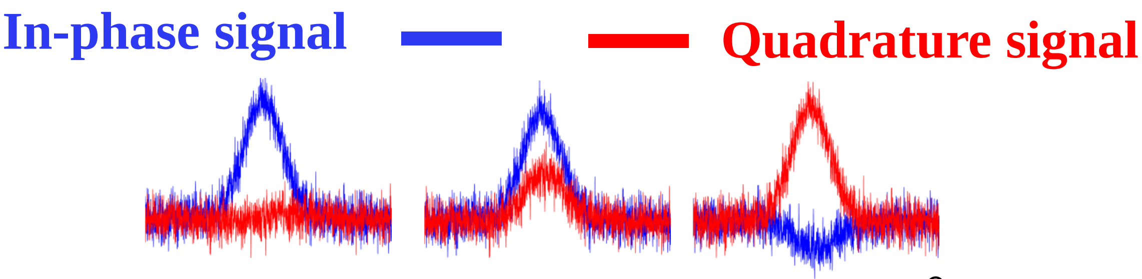
Gordon & Bowers measured T_2 ~ 520 μs with ^{28}Si:P

- Now measured it with fancier (= more expensive) equipment and get a similar T_2
- What was limiting T_2?



Global Magnetic Field Noise

Single-shot Hahn echo, quadrature detection,
3 different 1-shot experiments

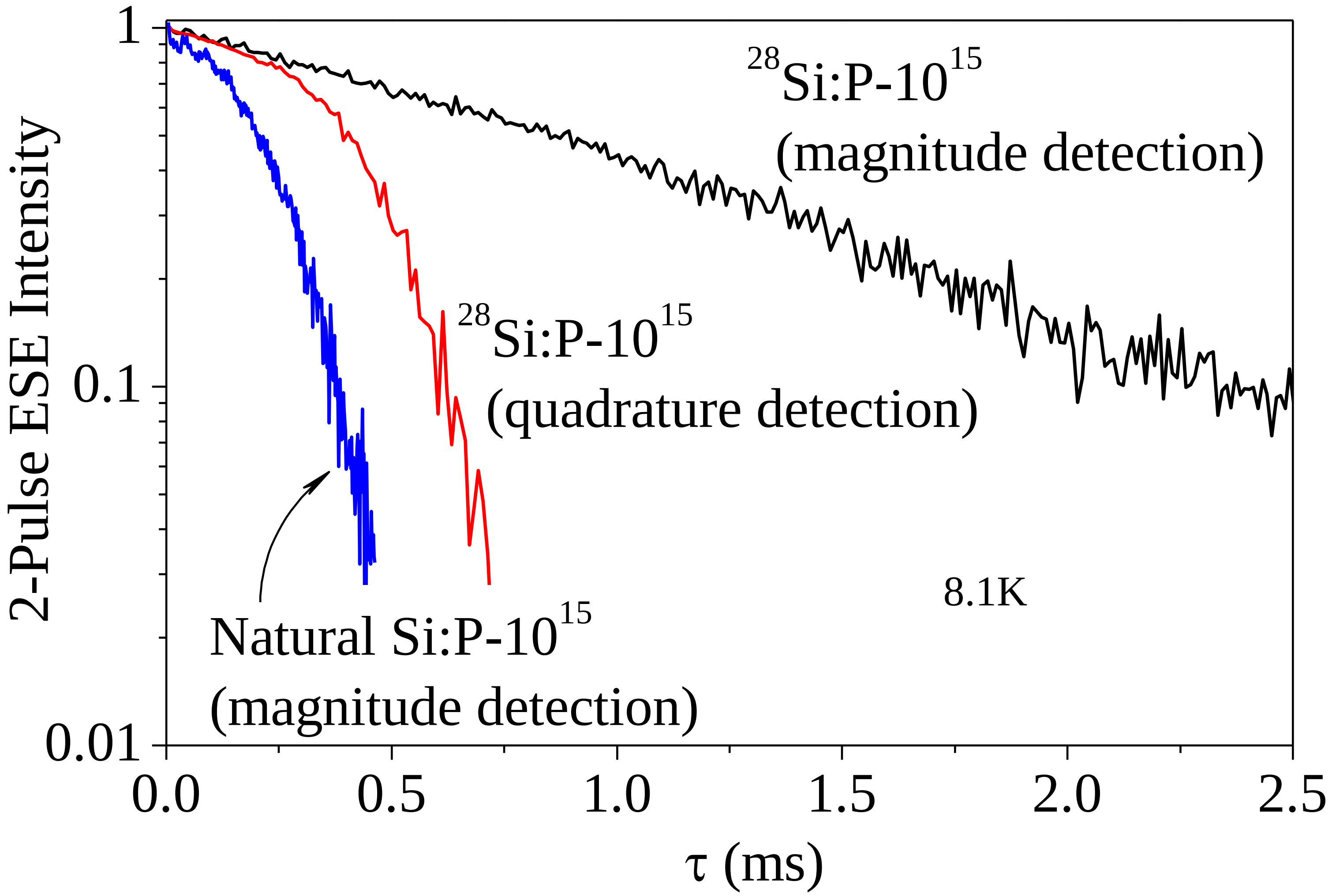


$\phi = 0^\circ$ $\phi = 23^\circ$ $\phi = 102^\circ$

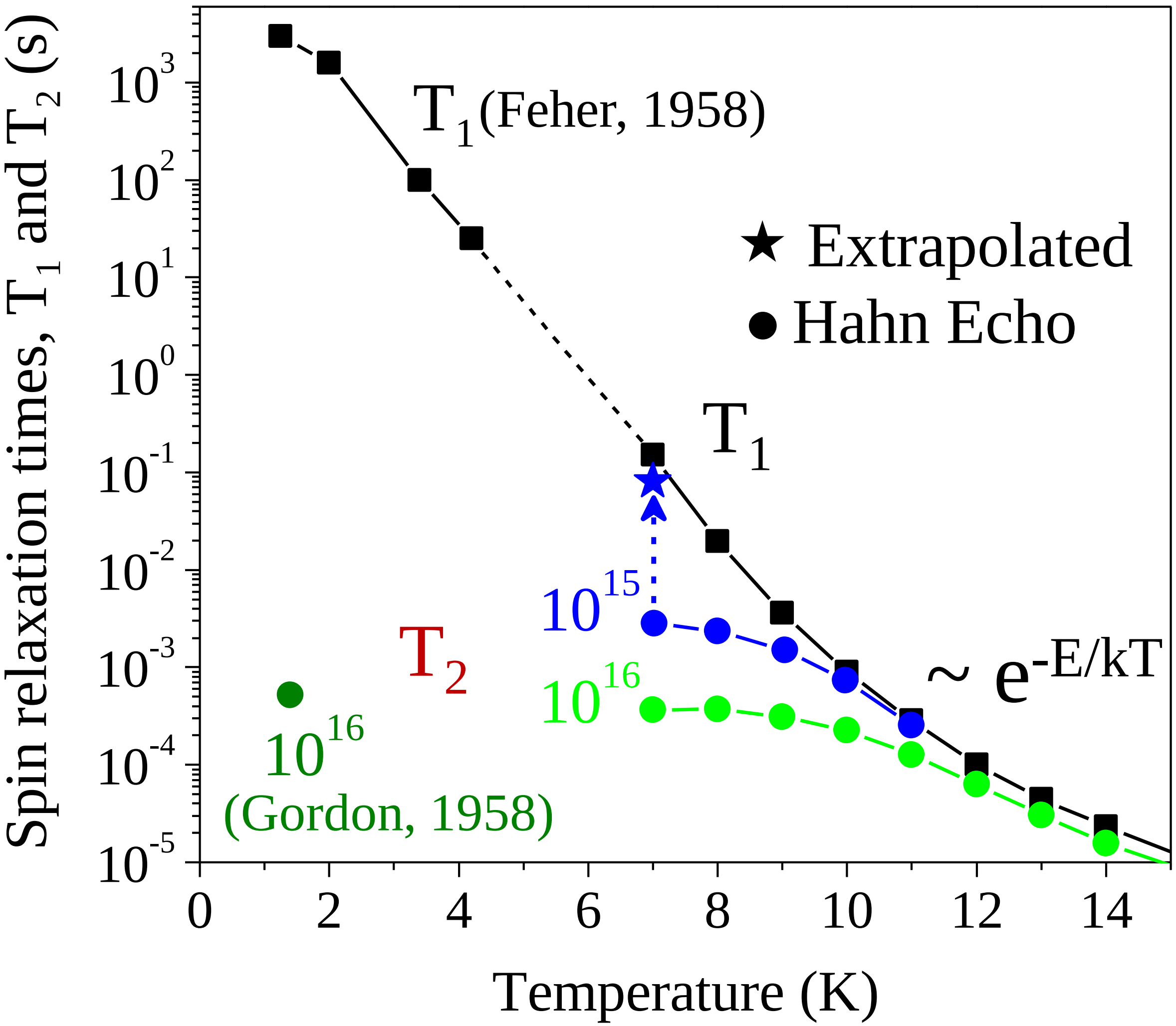
Strong echo signals ⇒ Spins stay in phase with one another

Global magnetic field fluctuations ⇒ Randomized echo phase

Magnitude Detection

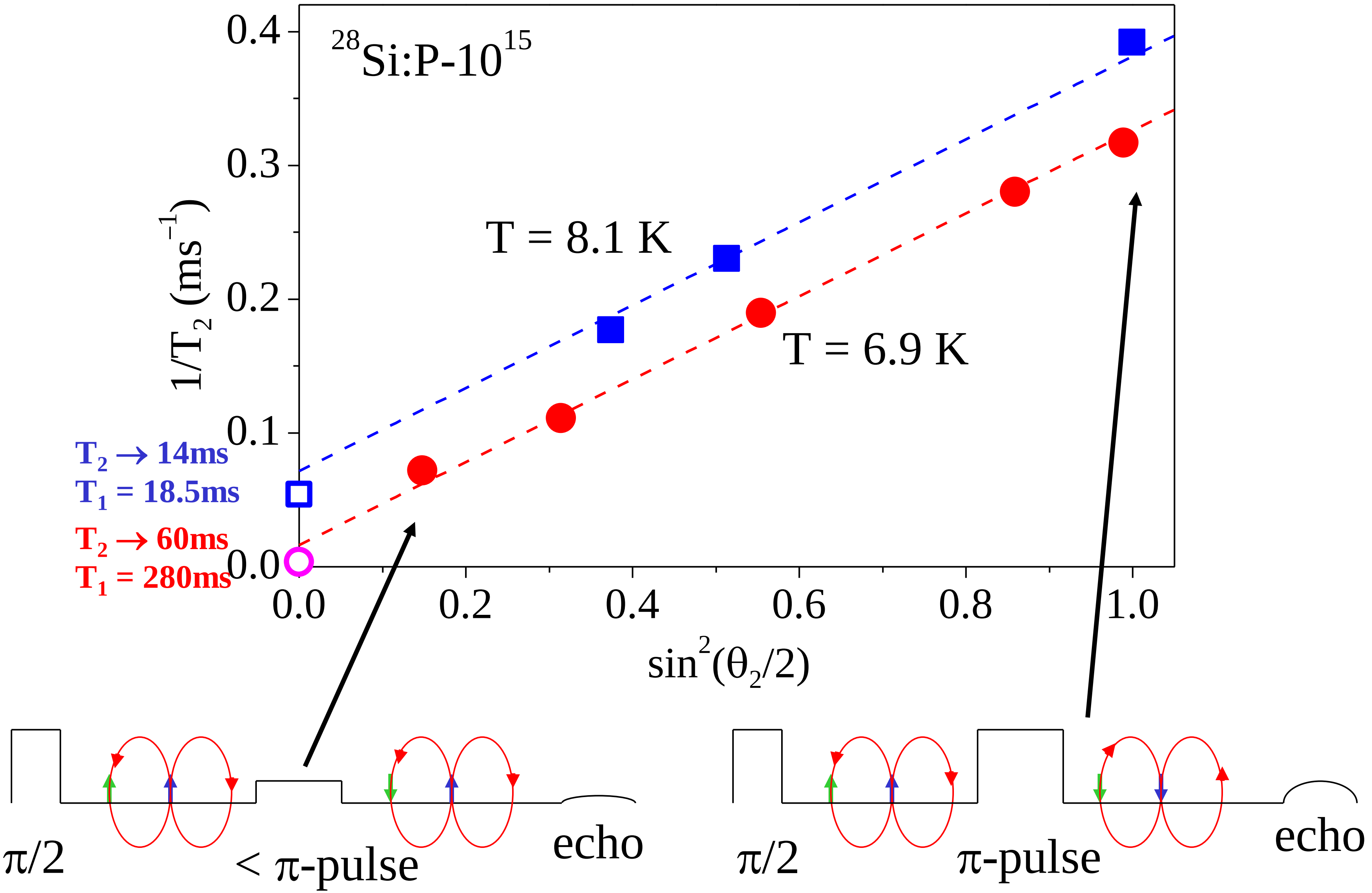


Coherence without Instantaneous Diffusion



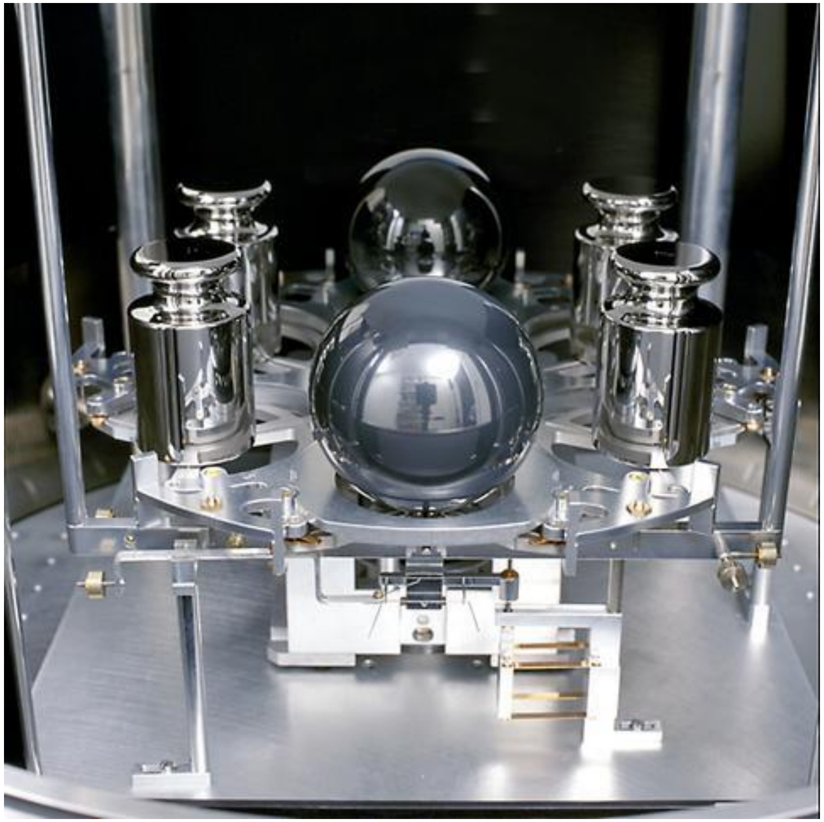
Eliminating Instantaneous Diffusion

Vary power of second pulse ⇒ probability to flip spin without flipping neighbors



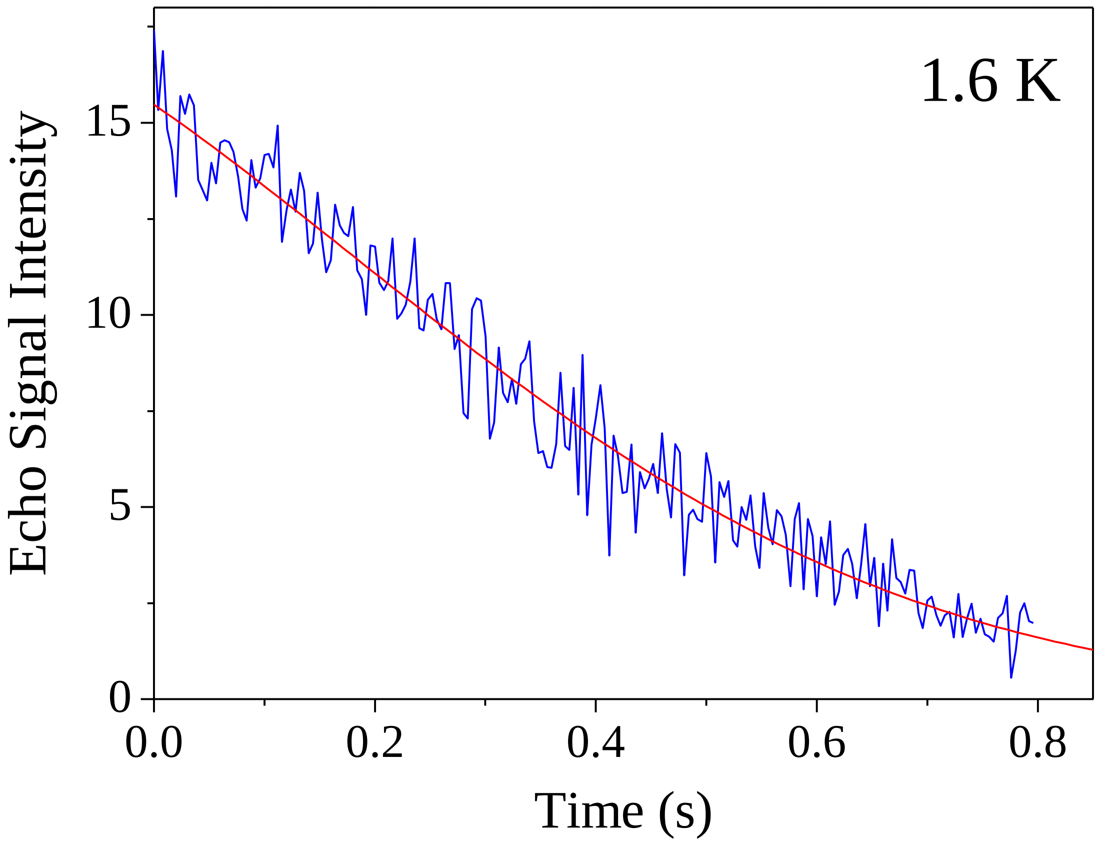
Avogadro Project Silicon

- Very highly enriched (~50ppm ^{29}Si)
- Very high chemical purity (boron, phosphorus ~$10^{12}/cm^3$)
- Large pieces of bulk Si



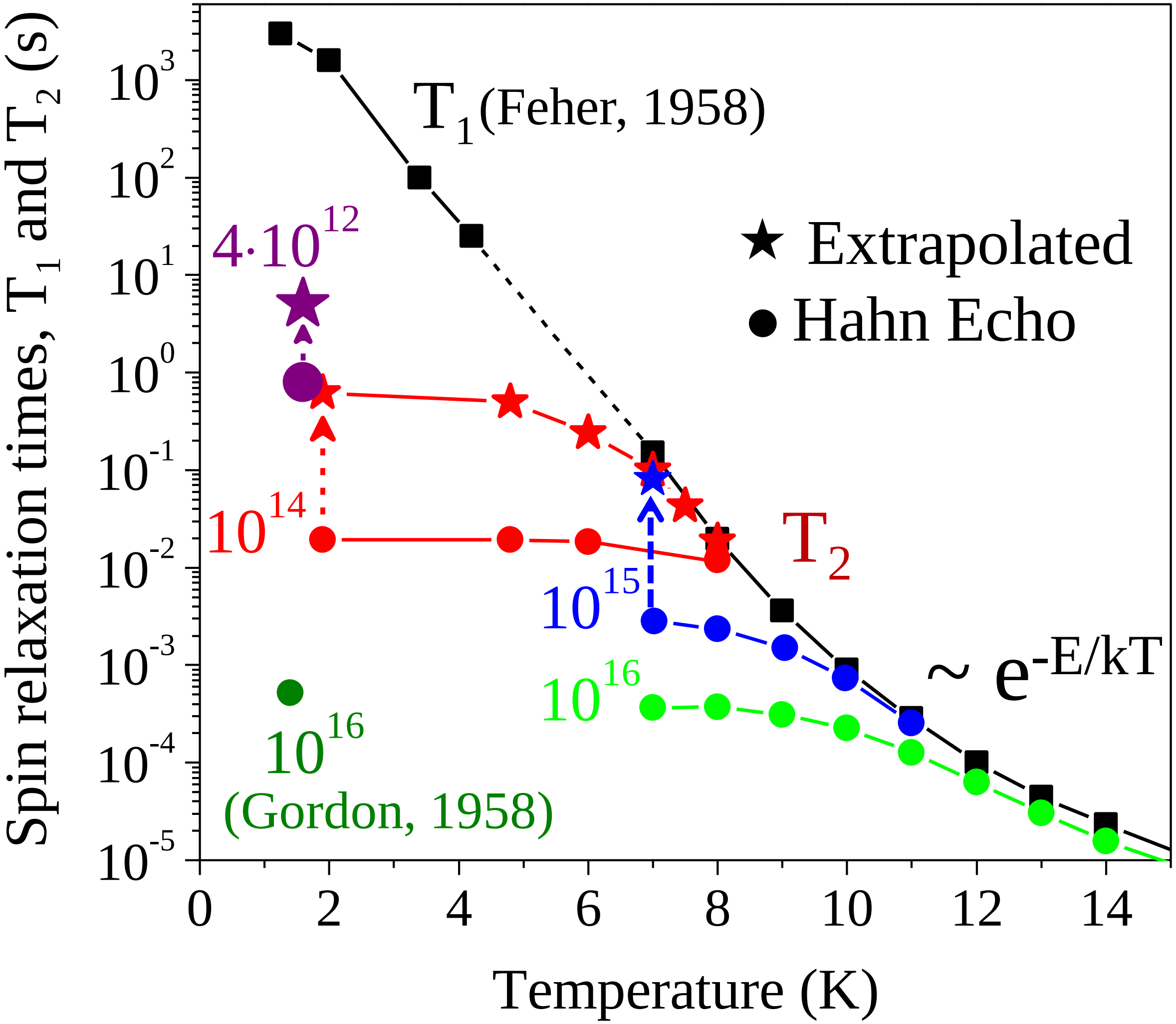
30x More Lightly Doped ^{28}Si:P

$4\text{x}10^{12}$ P/cm^3, $8\text{x}10^{12}$ B/cm^3 , 100 ppm ^{29}Si

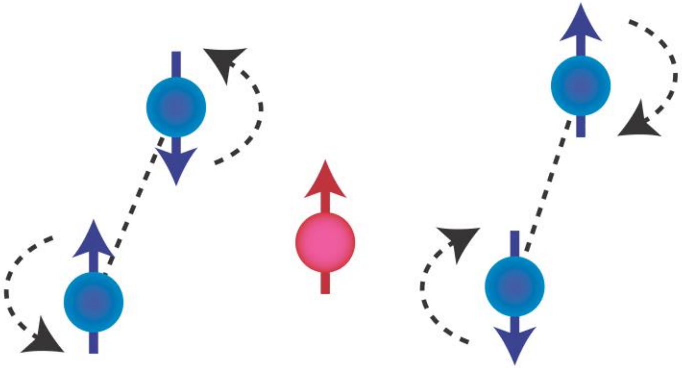


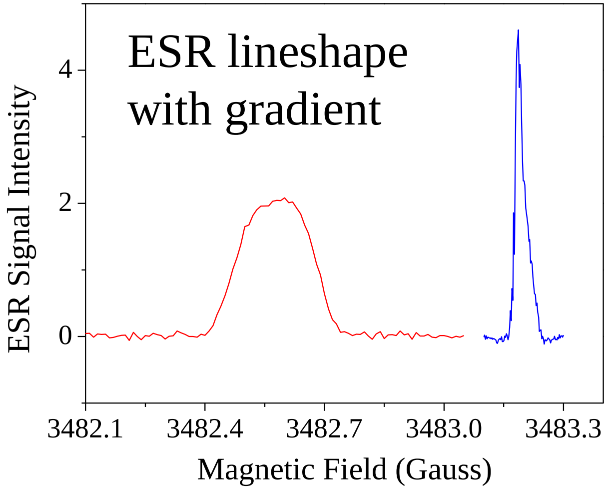
$$Echo \propto e^{-t/T_2} e^{-(t/T_{SD})^n}$$

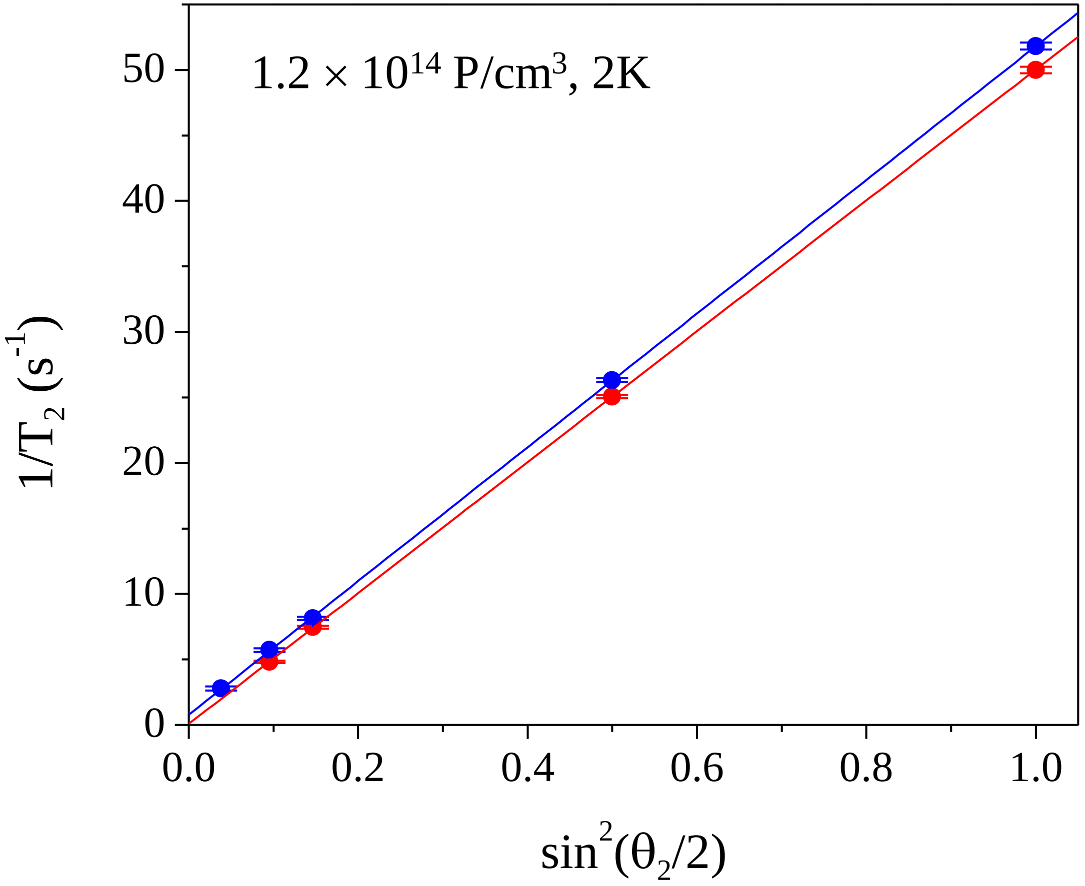
- T_{SD} = 0.7 sec; n = 2
- T_2 = 0.8 sec


Spin relaxation times, T_1 and T_2 (s)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
2
4
6
8
10
12
14
Temperature (K)
T_1(Feher, 1958)
★ Extrapolated
● Hahn Echo
$4 \cdot 10^{12}$
10^{14}
10^{15}
10^{16}
T_2
$\sim e^{-E/kT}$
10^{16}
(Gordon, 1958)

Suppressing Donor Flip-Flops with a Magnetic Field Gradient – take 4



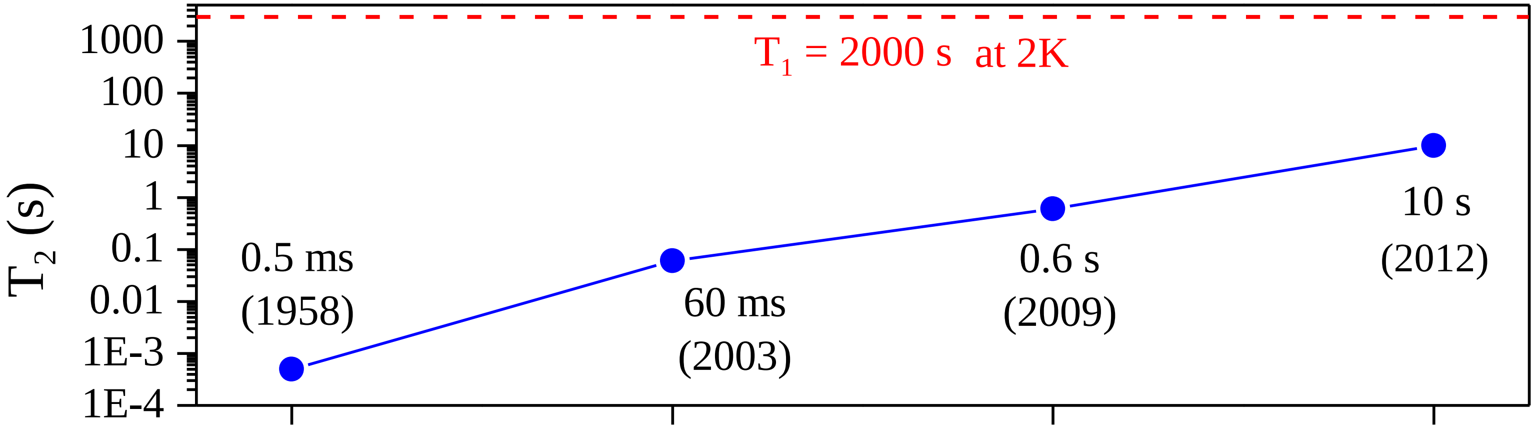




No gradient ⇒ $T_2 = 1.3 \pm 0.1$ sec

Gradient (0.3Hz/nm) ⇒ $T_2 = 12 \pm 7$ sec

Electron Spin Coherence in Ultra-pure Silicon - Isolated Donor T_2 in ^{28}Si



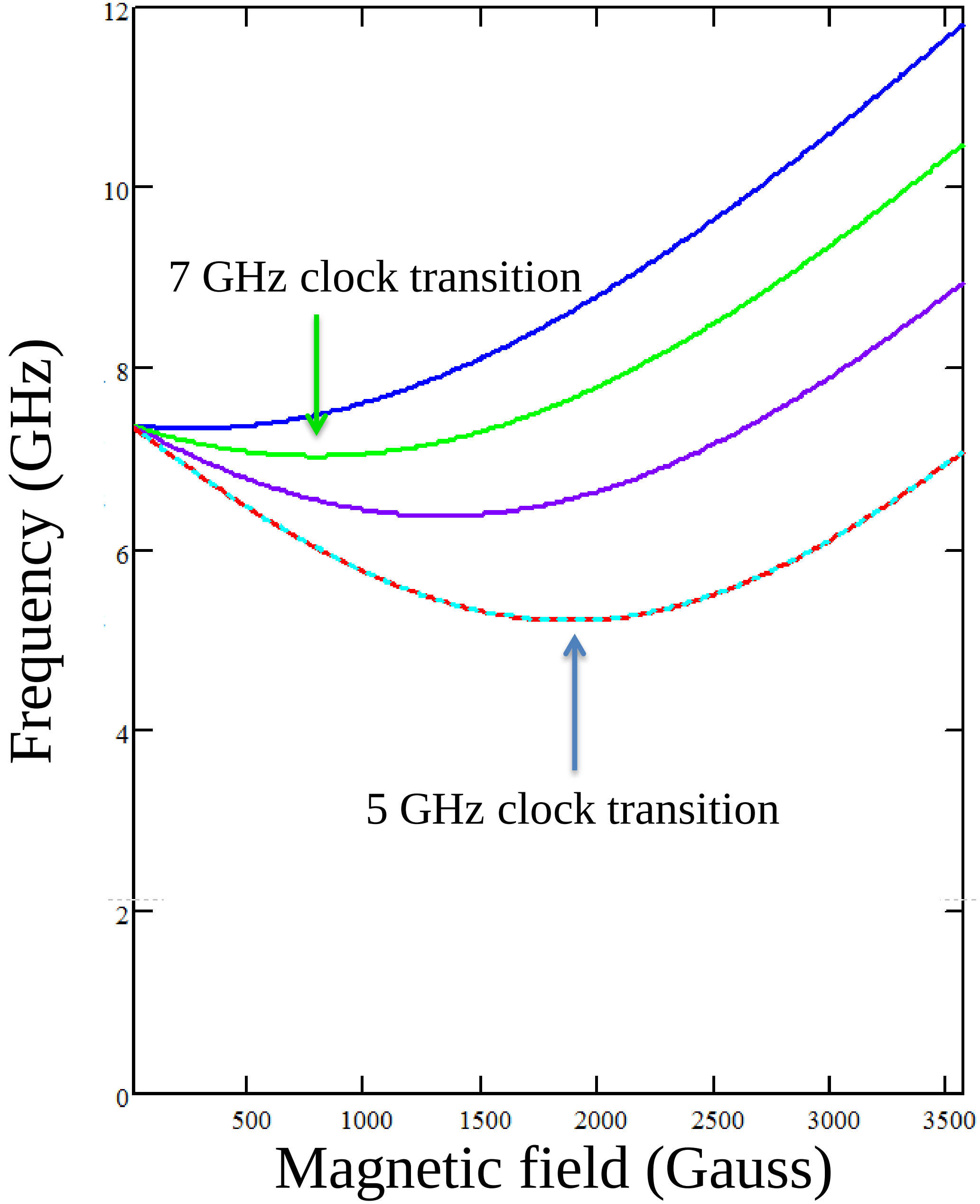
Physical process ⇒ Instantaneous diffusion | Donor T_1-flips | Donor flip-flops

Material ⇒

1000ppm ^{29}Si $4x10^{16}$/cm^3	800ppm ^{29}Si $1x10^{15}$/cm^3	100ppm ^{29}Si $1.4x10^{14}$/cm^3	100ppm ^{29}Si $1.2x10^{14}$/cm^3

A.M. Tyryshkin, *et al*., *Nature Materials*, **11**, 143 (2012).

Clock Transitions for Si:Bi

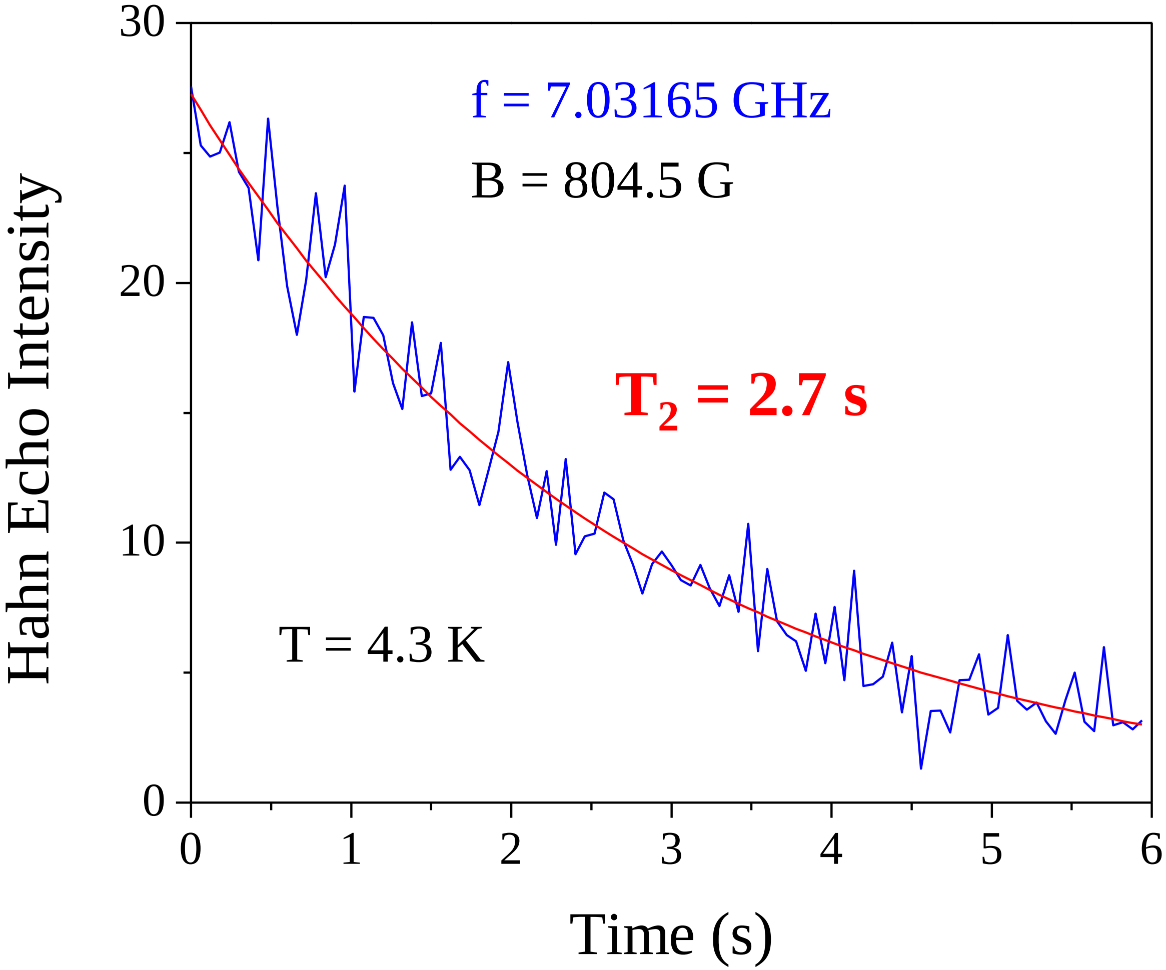


7 GHz clock transition

5 GHz clock transition

Electron T_2 for ^{28}Si

$4{\cdot}10^{14}$ Bi/cm^3, 50 ppm ^{29}Si



Dynamical Decoupling

- Hahn Echo ($\pi/2$ - τ - π - τ - echo) removes static and slow phase decoherence (frequencies $< 1/\tau$)
- So, just repeat
  - Carr-Purcell = $\pi/2$ - τ - π - τ - π -…- π - τ - echo
  - Filters noise, only allowing noise at $\omega \sim 1/\tau$

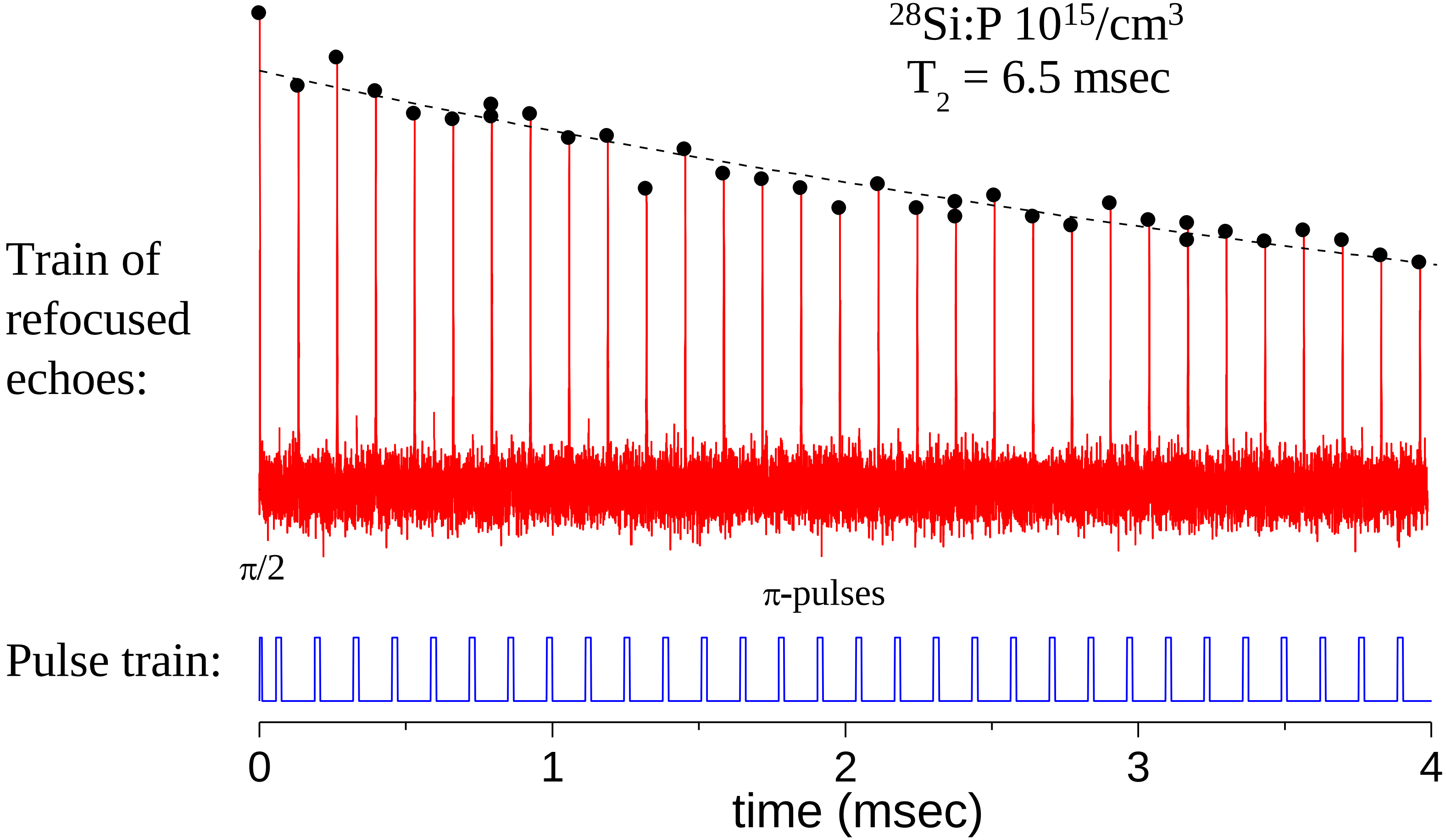
    [Biercuk J.Phys.B. 44,154002 (2011)]
- But, need to worry about pulse errors
  - CP = $\pi_x/2$ - τ - π_x - τ - π_x -…- π_x - τ - echo
    - Pulse errors ⇒ echo dies off quickly
  - CPMG = Carr-Purcell-Meiboom-Gill (fix some errors)

    = $\pi_x/2$ - τ - π_y - τ - π_y -…- π_y - τ - echo

Carr-Purcell-Meiboom-Gill Sequence

Refocus spins every 130μs (train of π-pulses) – decouples B-noise

⇒ retain coherence for > 6 msec

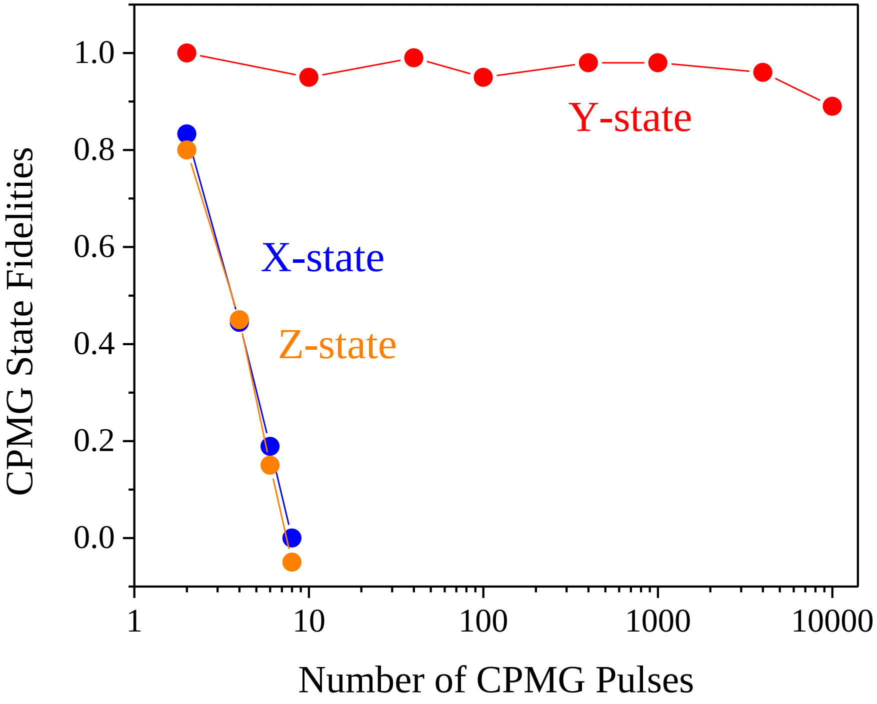


^{28}Si:P 10^{15}/cm^3

T_2 = 6.5 msec

Dynamical Decoupling with CPMG?

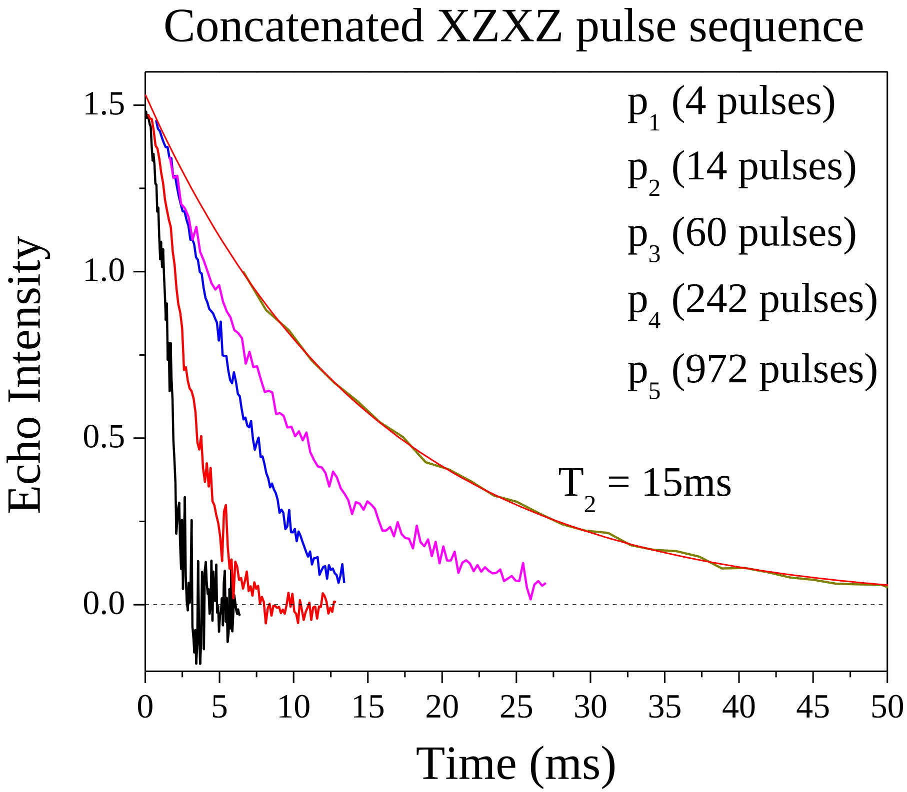
- Easy, just decouple noise with CPMG?
  - – No, there's no free lunch
- CPMG preserves only one state

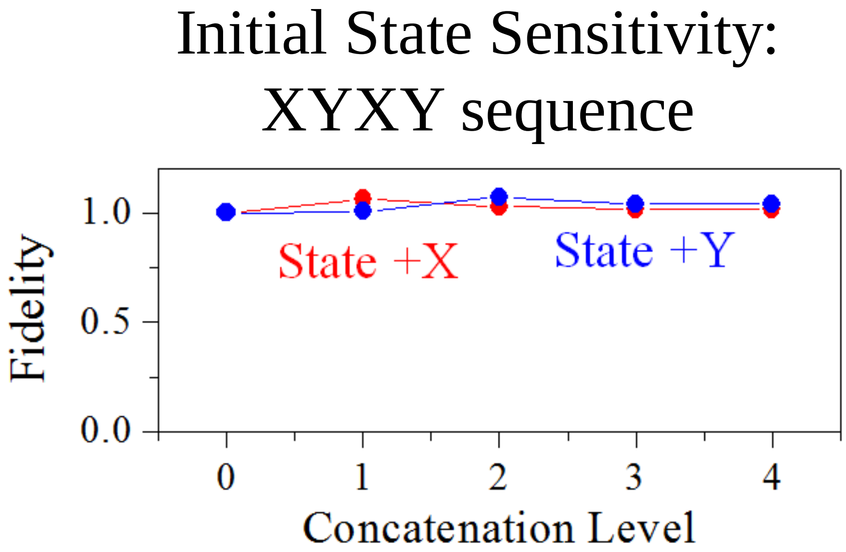


Better Dynamical Decoupling Sequences

- Sequences made from XYXY are "good" (for spins):
  - Especially "concatenated" versions:

K. Khodjasteh, PRL **95**, 180501 (2005) &Wang, PRB **85**, 085206 (2012)





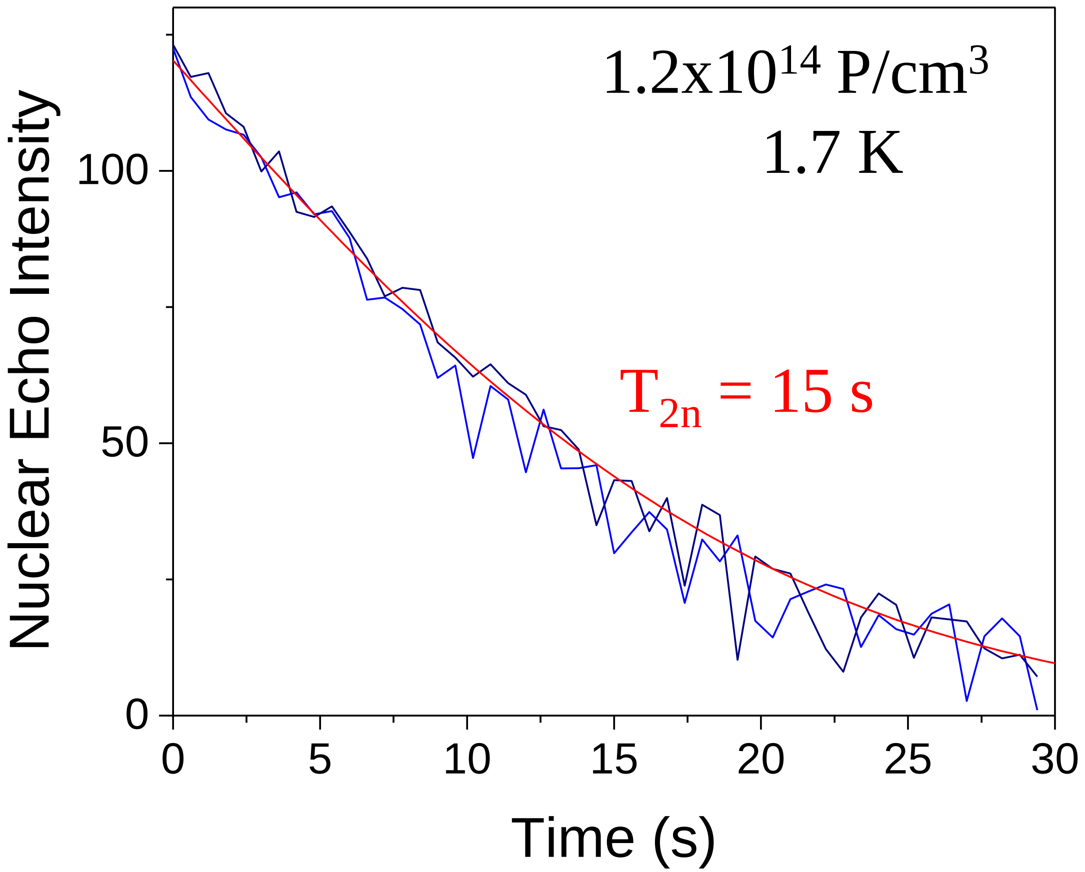
Dynamical Decoupling – Where are we?

- Dynamical decoupling is good for non-Markovian noise
  - Like 1/f noise
  - Errors that standard quantum error correction is bad at
- Dynamically makes a decoherence-free subspace
  - If spin is up and down half the time ⇒ insensitive to B_0
- Not known, in general, how to interleave DD and gates
  - Gates can be performed between repetitions of sequences
  - Must wait until concatenated sequence is complete
- CPMG is <u>not</u> useful dynamical decoupling for qubits
  - Does not protect general state
  - Pulse errors + dipolar interactions cause odd effects
  - Is useful for extending coherence of single QB's, but unclear what physics is being averaged out

What is the limit for donor electron spin T_2 in Si?

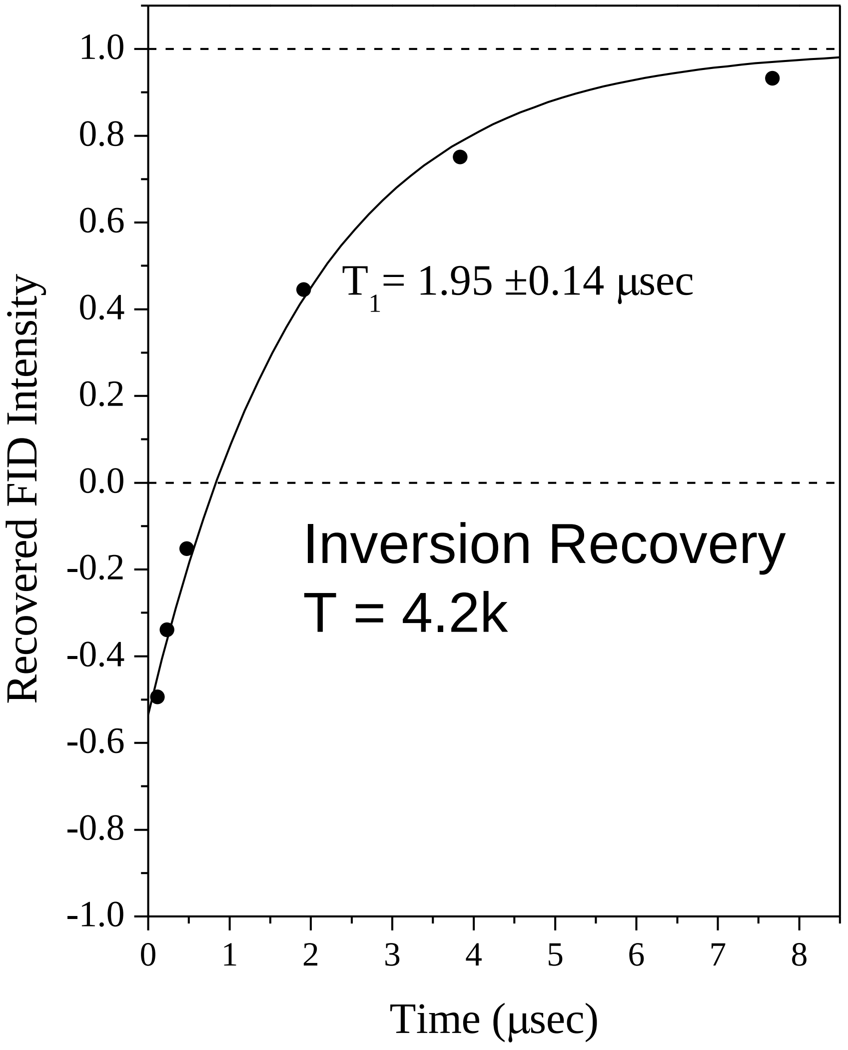
- We don't know
  - Our measurements are still limited by donor-donor interactions and residual ^{29}Si.
  - In most QC architectures, the donor-donor disance would be larger than we have
  - Expect $T_2 >> 10$ s.
- Do we need it longer?
  - Bigger is better?
  - Many other effects in devices – surfaces and interfaces, gate voltages, …

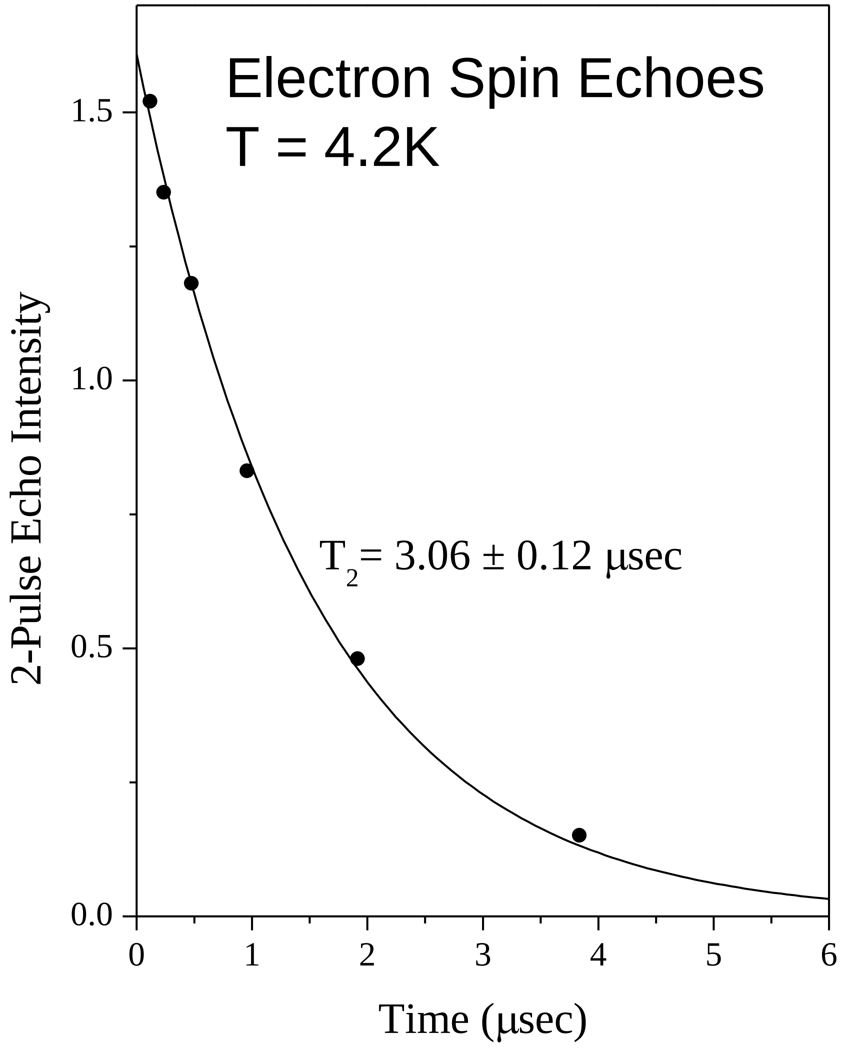
Nuclear T_2 in highly enriched silicon (~100 ppm ^{29}Si)



T_{2n} is limited by electron spin flip-flops.
Ionized donor nuclei ⇒ T_{2n} ~ 3 hr. Useful? Bigger is better?

Mobile qubits? Free 2D Electron Spin Relaxation Times in Si/SiGe Heterostructure

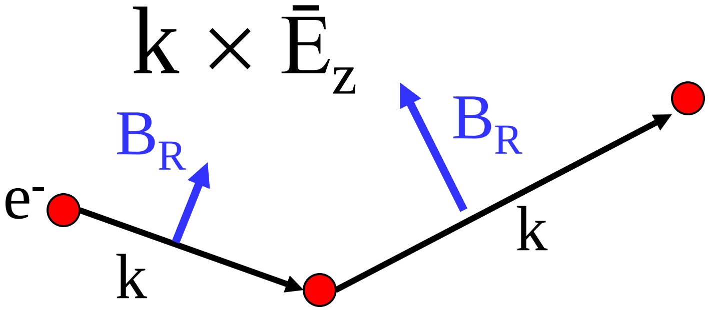




Origin of the Spin Relaxation in 2D

- $T_2 > T_1$ requires anisotropic relaxation mechanism
- Abstractly, fluctuating B-fields cause relaxation
- Appears that fluctuating fields arise from Rashba effect (spin-orbit interaction from broken symmetry at interface):

$$H_R = \underbrace{\alpha(\bar{k}\times\bar{E})}_{B_R}\cdot\hat{S}$$



- Use correlation time, τ_c = 10 psec (from mobility)
  - In-plane fields (B_x, B_y) = 10 Gauss
  - Perpendicular (B_z) = 5 Gauss

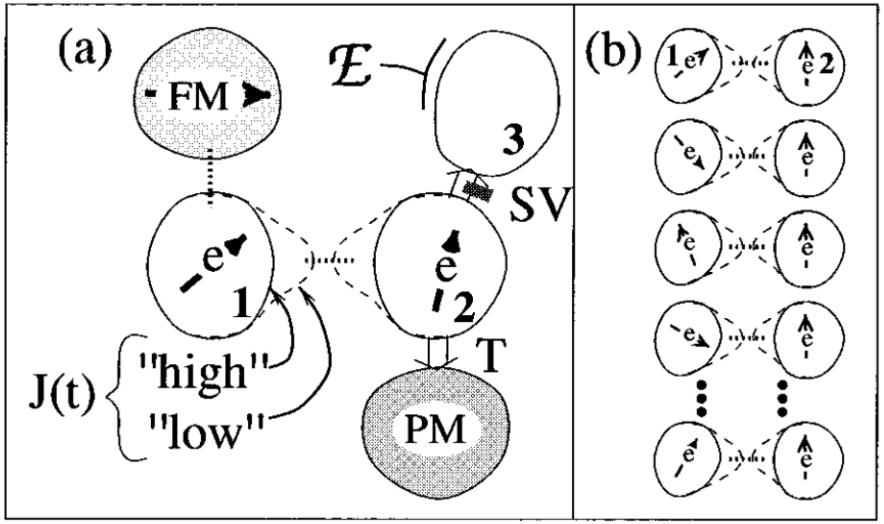
Outline

- Background on Si and electrons
- Spin resonance measurements of spin coherence in Si
- GaAs quantum dot spin experiments
- Si quantum dot spin experiments
- Si donor spin experiments
- Other schemes (electrons on helium, …)

1998: Two proposals

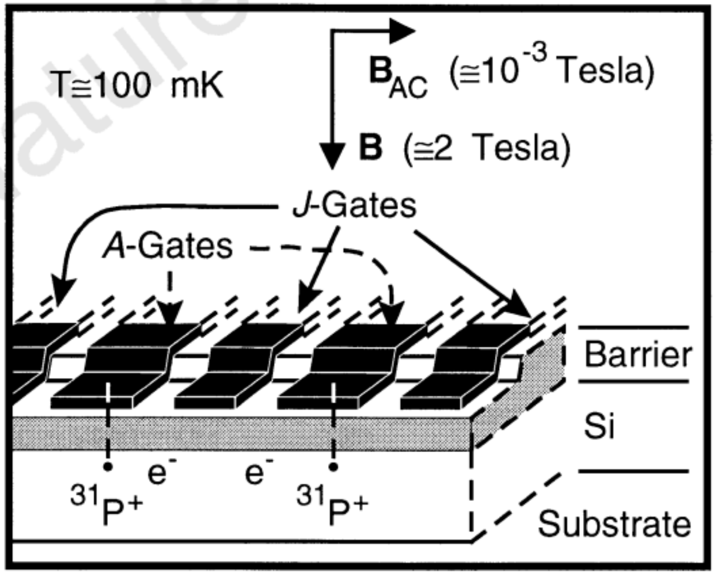
1. Loss & DiVincenzo, PRA **57,** 120 (1998)

   - Quantum dots



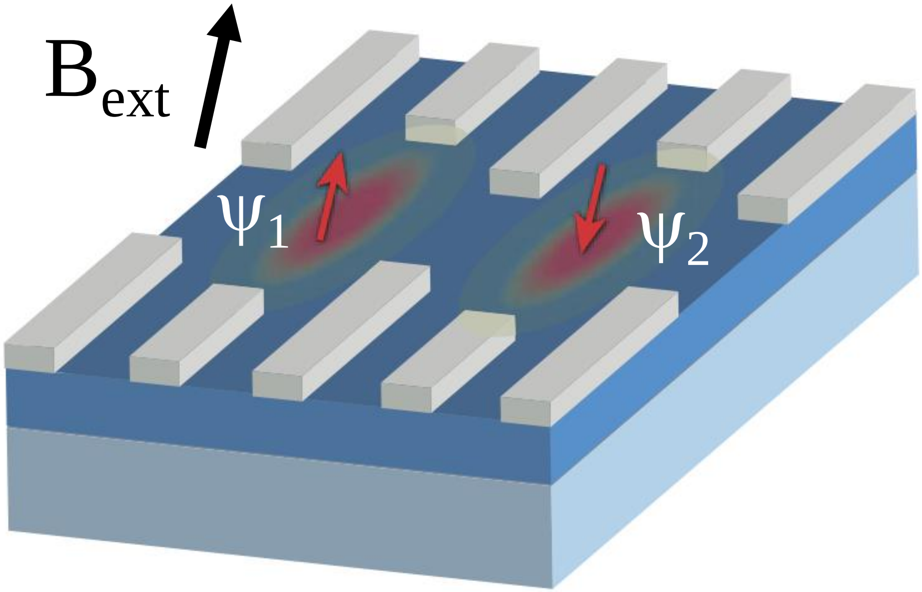
2. Kane, Nature **393**, 133 (1998)

   - Donor impurities in Si

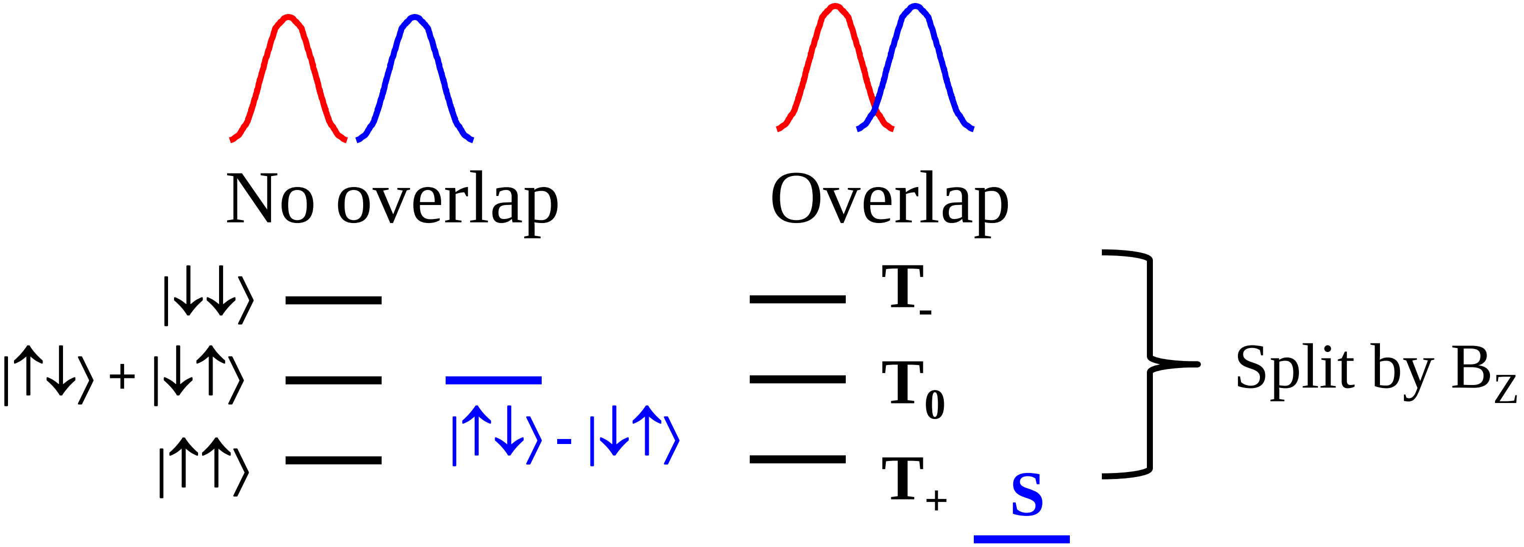


Electrons in quantum dots

- Gates (white) hold electrons (red) in dots
- Electrons assumed to be held at interface between light and dark materials (unspecified)
- Use gate voltages to cause ψ_1 and ψ_2 to overlap ⇒ exchange interaction (J)



Exchange gates



No overlap

Overlap

$|\downarrow\downarrow\rangle$

$|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

$|\uparrow\uparrow\rangle$

$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

$\mathbf{T_-}$

$\mathbf{T_0}$

$\mathbf{T_+}$

S

Split by B_Z

- $H_J \sim J\mathbf{S_1}\cdot\mathbf{S_2}$
- In $B_Z \Rightarrow S_X, S_Y$ mix $|0\rangle$ & $|1\rangle$
  - – Mixture oscillates at ω_Z
- $\Rightarrow H_J \sim J\mathbf{S_{1z}}\cdot\mathbf{S_{2z}}$

Exchange → CPHASE

- $H_J \sim J\mathbf{S}_{1z}\cdot\mathbf{S}_{2z}$

$$\Rightarrow \; H_J(\alpha) = \begin{pmatrix} e^{-i\alpha} & 0 & 0 & 0 \\ 0 & e^{i\alpha} & 0 & 0 \\ 0 & 0 & e^{i\alpha} & 0 \\ 0 & 0 & 0 & e^{-i\alpha} \end{pmatrix}$$

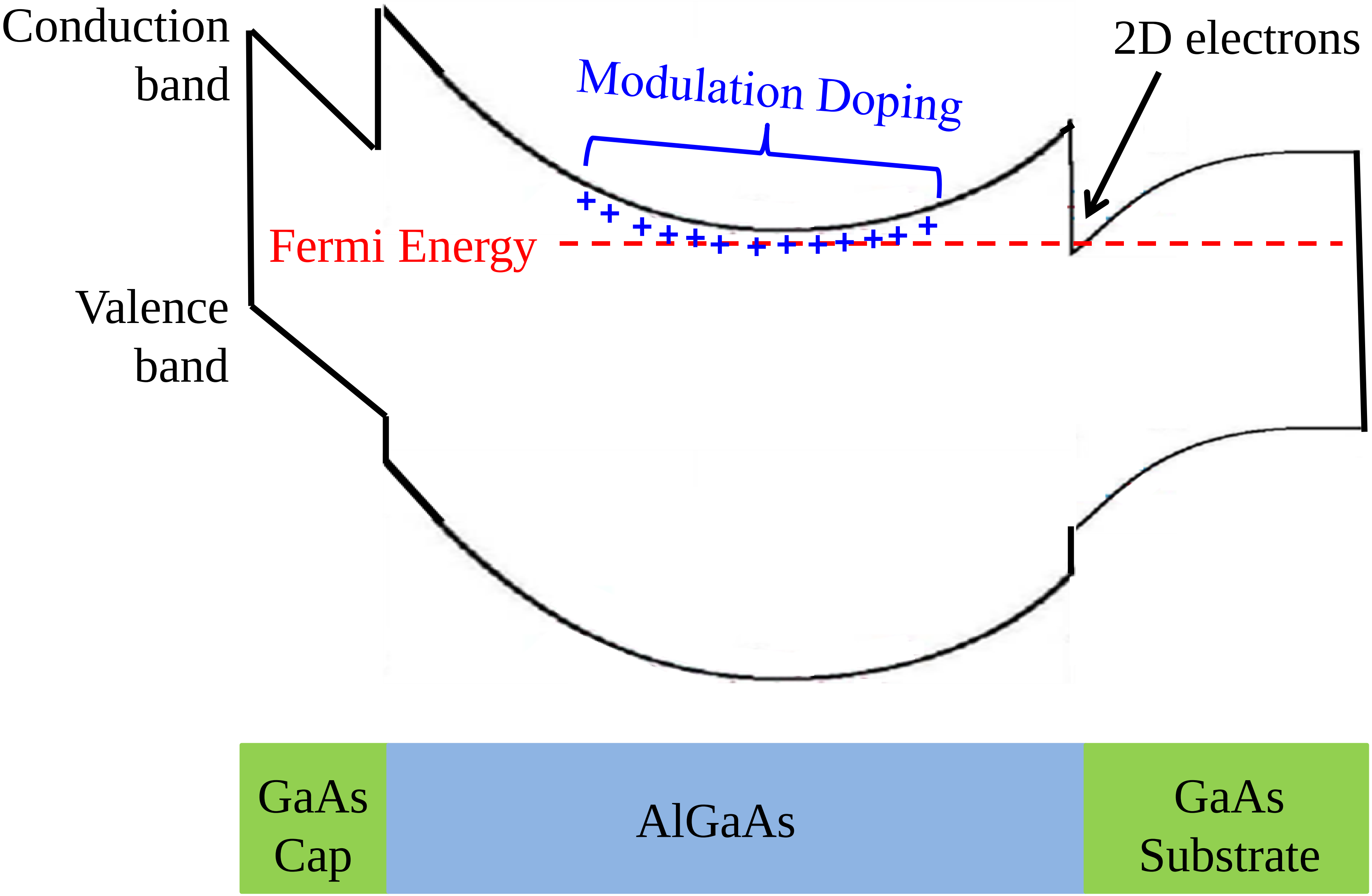
$$R_{1z}(2\alpha) = \begin{pmatrix} e^{i\alpha} & 0 & 0 & 0 \\ 0 & e^{i\alpha} & 0 & 0 \\ 0 & 0 & e^{-i\alpha} & 0 \\ 0 & 0 & 0 & e^{-i\alpha} \end{pmatrix} \qquad R_{2z}(2\alpha) = \begin{pmatrix} e^{i\alpha} & 0 & 0 & 0 \\ 0 & e^{i\alpha} & 0 & 0 \\ 0 & 0 & e^{-i\alpha} & 0 \\ 0 & 0 & 0 & e^{-i\alpha} \end{pmatrix}$$

$$H_J(\pi/4)\; R_{1z}(\pi/2)\; R_{2z}(\pi/2) = e^{i\pi/4} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \text{CPHASE}$$

Quantum dot jargon

- Solution-grown nanocrystal quantum dots
  - Typically less than 10 nm in size
  - Coated with organic ligands
- Self-assembled quantum dots
  - Typically less than 20 nm across, and a few nm thick
  - Formed during growth by Molecular Beam Epitaxy
- Vertical quantum dots
  - Few x 100 nm pillars etched into multilayer GaAs/AlGaAs
  - Have been used to study electron spins
- Lateral or gate-defined quantum dots
  - Typically 100’s of nm across
  - Start with 2D electron heterostructure
  - These are the main dots we want to use

GaAs/AlGaAs Heterostructures



Conduction band

Modulation Doping

2D electrons

Fermi Energy

Valence band

GaAs Cap

AlGaAs

GaAs Substrate

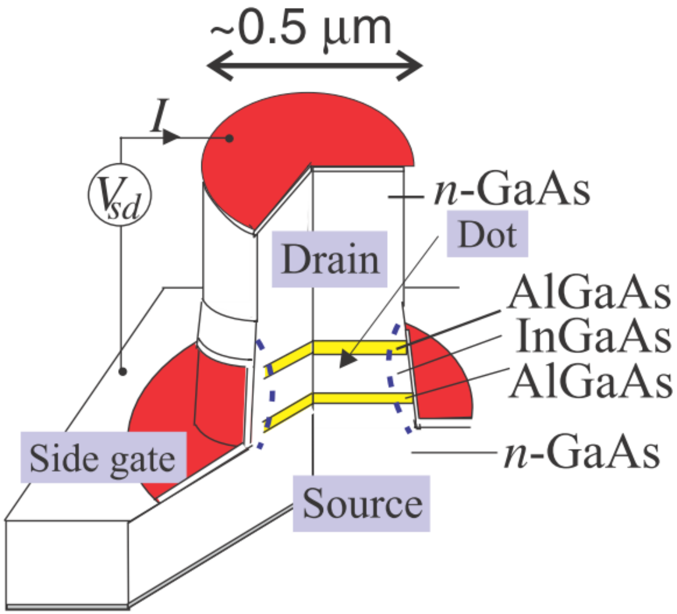
Properties of GaAs/AlGaAs

- Nearly defect-free interfaces
  - Reduce electron density to $\sim 10^{10}/\text{cm}^2$ before charges trap ($\Rightarrow$ 100nm between electrons)
- Single conduction band valley
- Small effective mass ($m^* \sim 0.07\ m_0$)
  - Small mass means large energy splitting (for spatial part of ψ), even in a large device
  - Approximately harmonic potential $\Rightarrow \Delta E \sim 1/\sqrt{m^*}$
- Little leakage for Au gates on GaAs cap

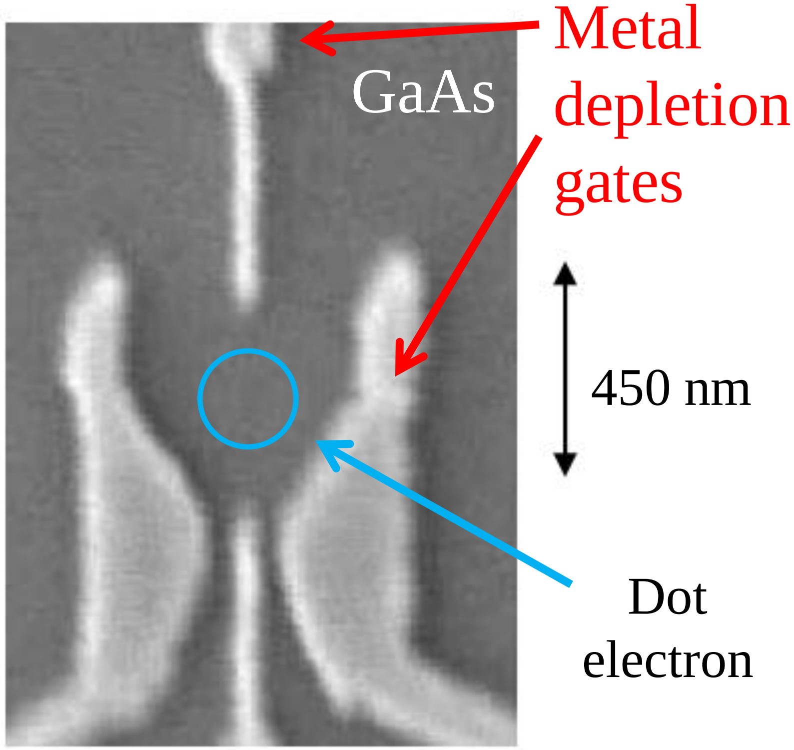
- Charge motion in doping layer can cause noise
- No stable isotopes with zero nuclear spin
  - As: 100% ^{75}As; Ga: 60% ^{69}Ga, 40% ^{71}Ga; all with $I = 3/2$

Single quantum dot structures

Vertical dot



Kouwenhoven, Rep. Prog. Phys. **64**, 701 (2001)

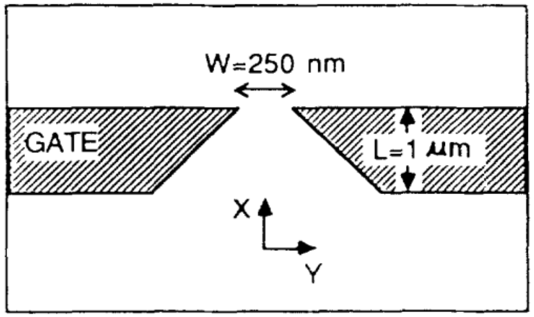


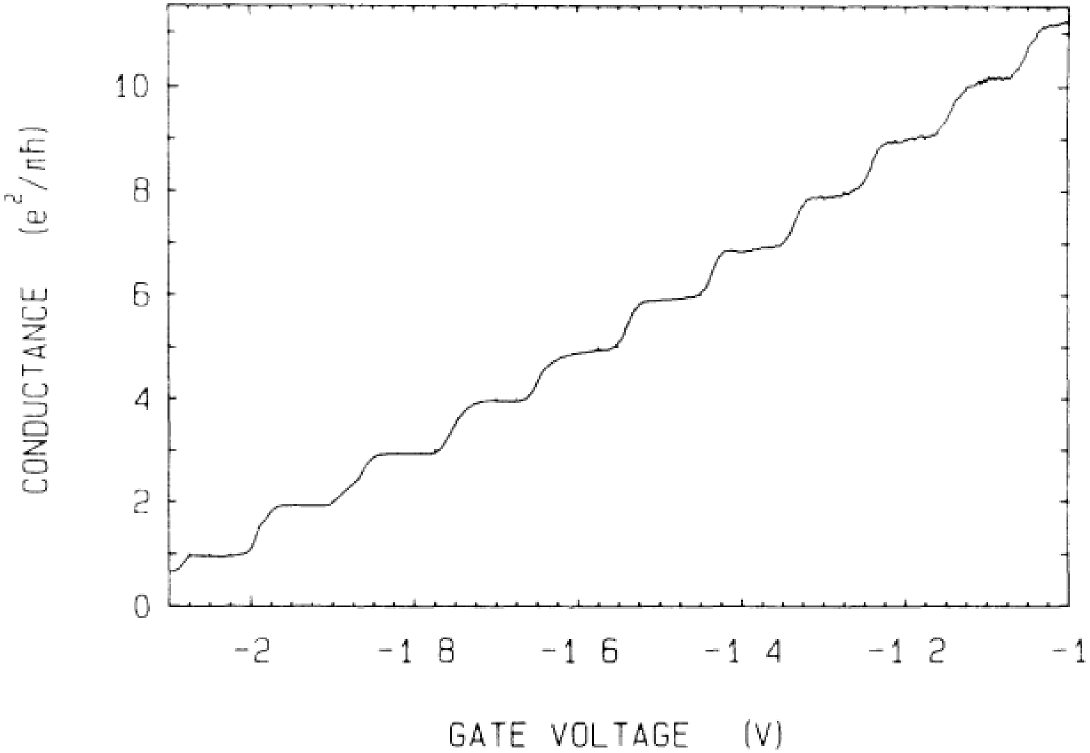
Ciorga, PRB **61**, 16315 (2000)

For Both

- Size of dot can be controlled by side gate(s)
- Must pass current through dots to measure

Quantum point contacts (QPC)



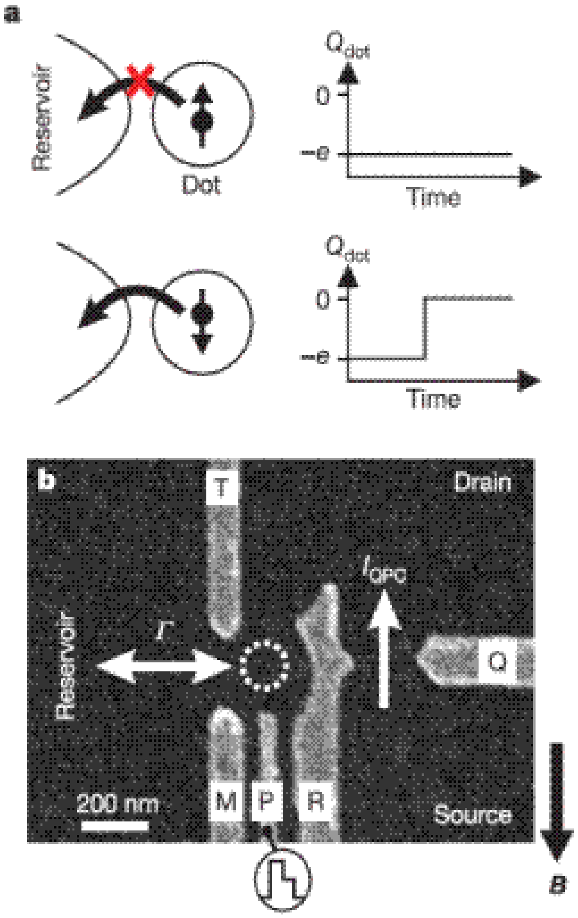


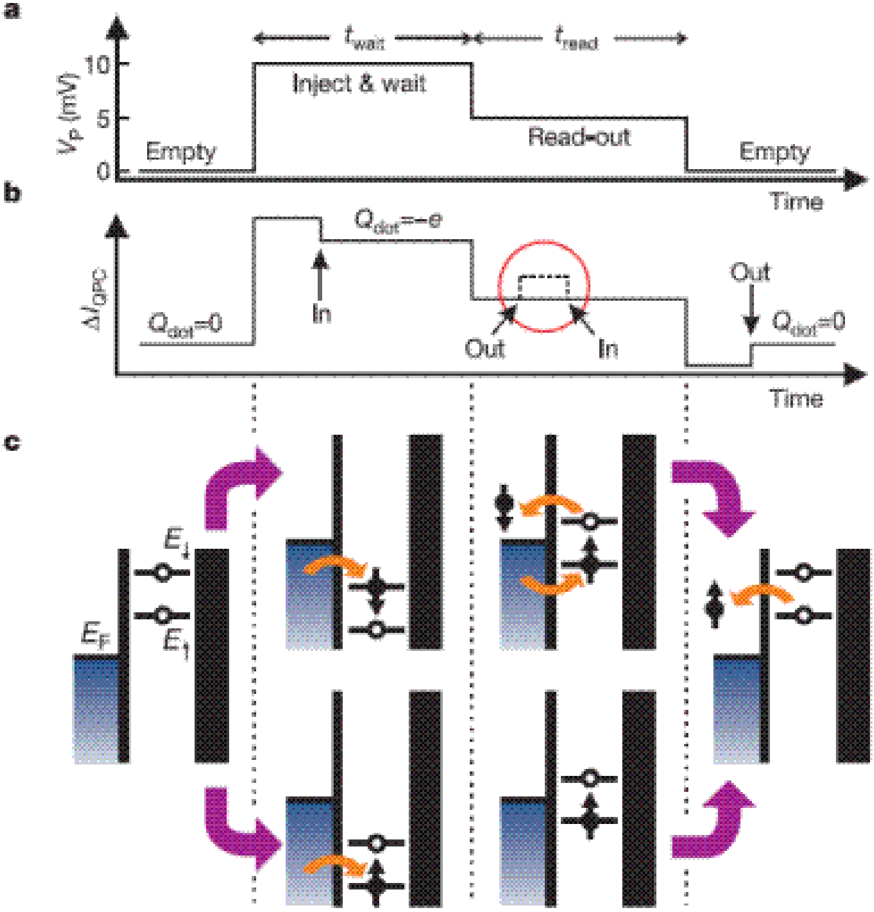
Narrow channel acts as electron waveguide. Step increase in current when new mode becomes available

van Wees, PRL **60**, 848 (1988)

A QPC forms a very high-gain detector of electric fields (or charge). M. Field showed that single electrons can be detected - Field, PRL **70**, 1311 (1993)

Single dot spin measurement

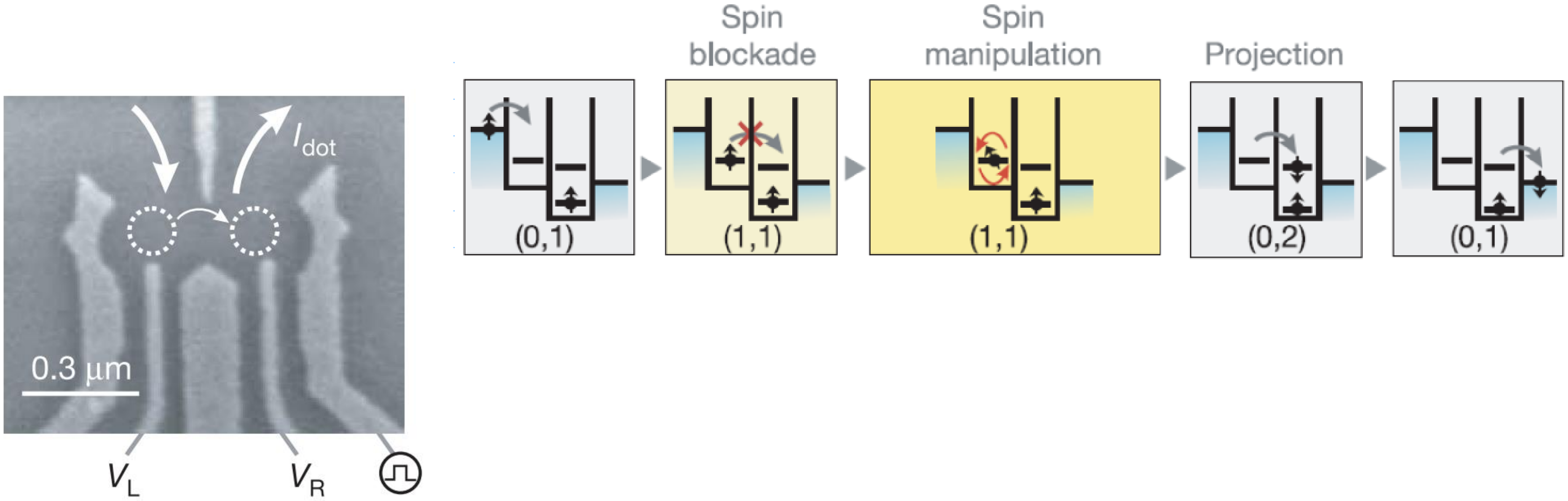




Need large spin splitting ($g\mu_B B >> kT_e$)

Elzerman, Nature **430**, 431 (2004)

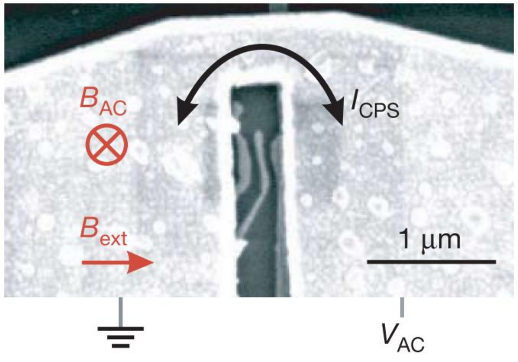
Spin blockade in double quantum dot



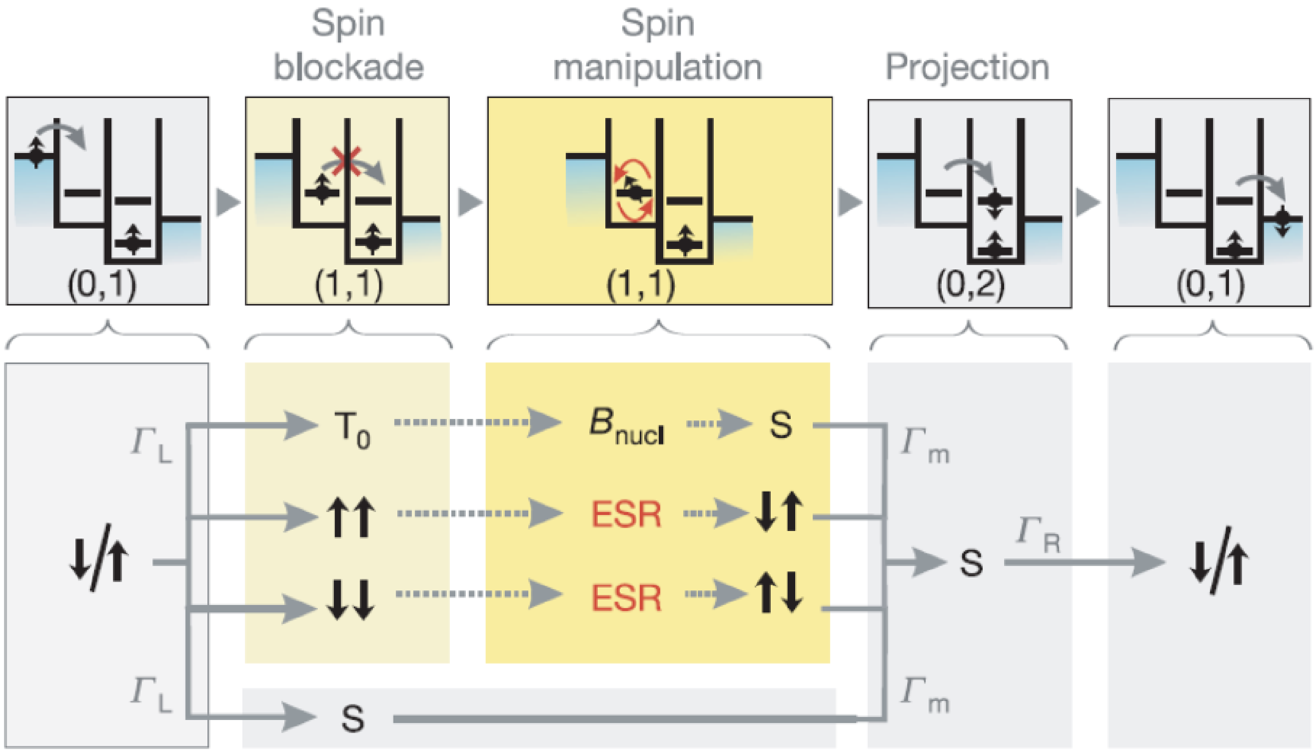
Singlet-Triplet splitting can be >> kT, meaning electron can only move from left to right dot if the two form a singlet

Koppens, et *al*. Nature **442**, 766 (2006)

Single spin electron spin resonance (ESR)



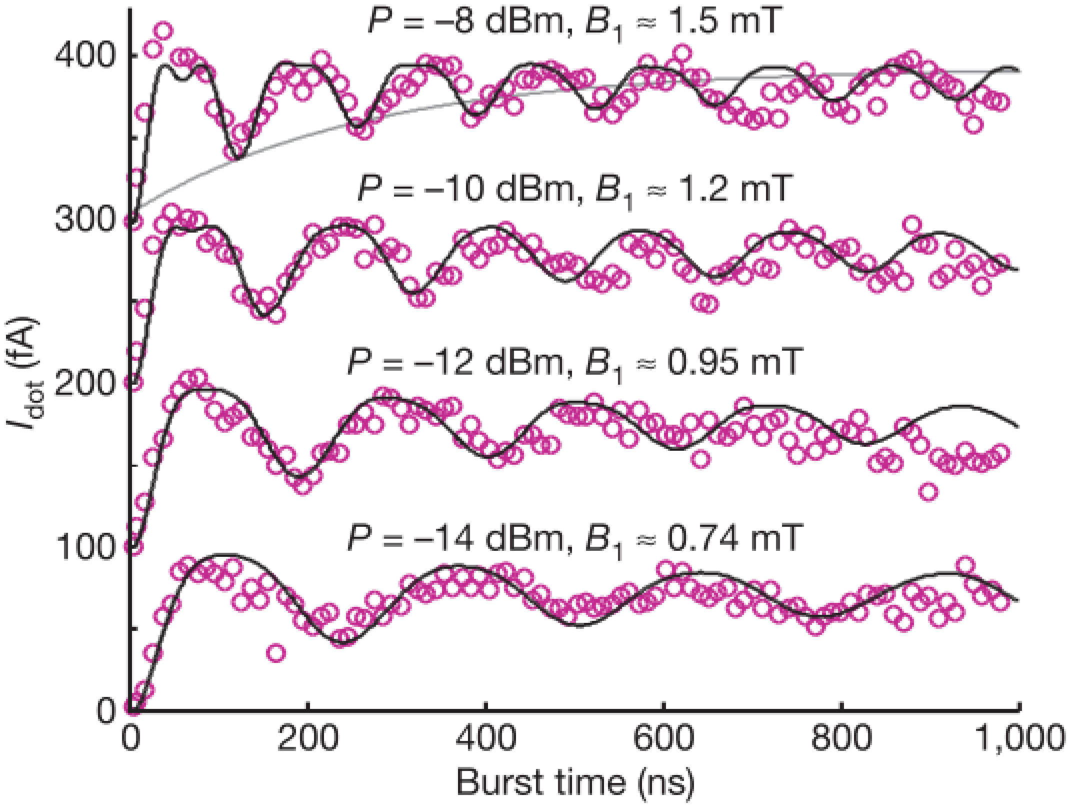
Quantum dot covered with large co-planar strip microwave guide. Shorting waveguide gives maximum B and mininum E at the dots.



Rotating a spin with the microwaves can lift the blockade by converting triplets into singlets (middle two lines)

Koppens, et *al*. Nature **442**, 766 (2006)

Single spin coherence

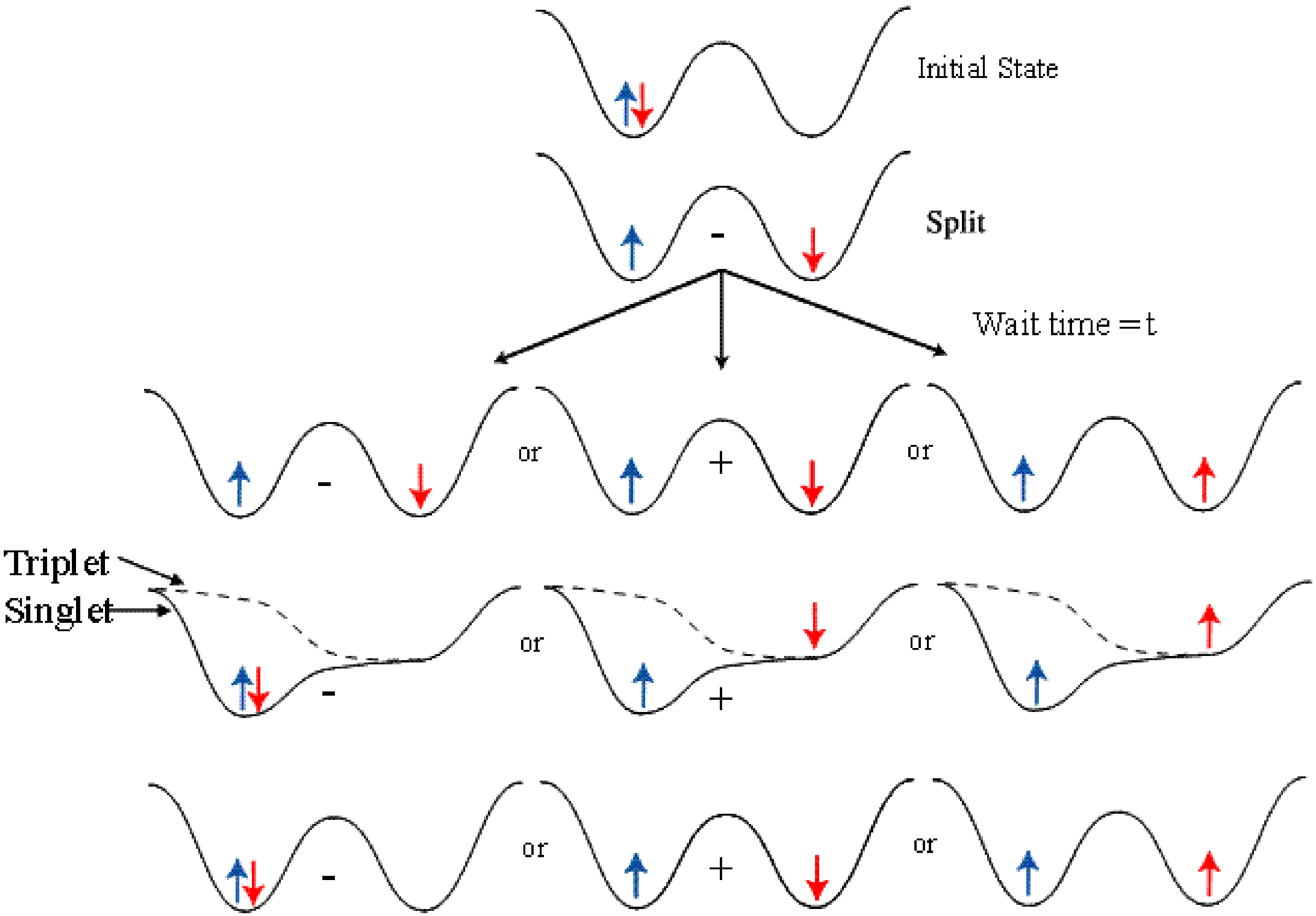


Current increases, as triplet probability increases, then decreases as spin rotates past the optimal point to form singlets. Oscillations decay non-exponentially, but conclude T_2 ~ 500 ns.

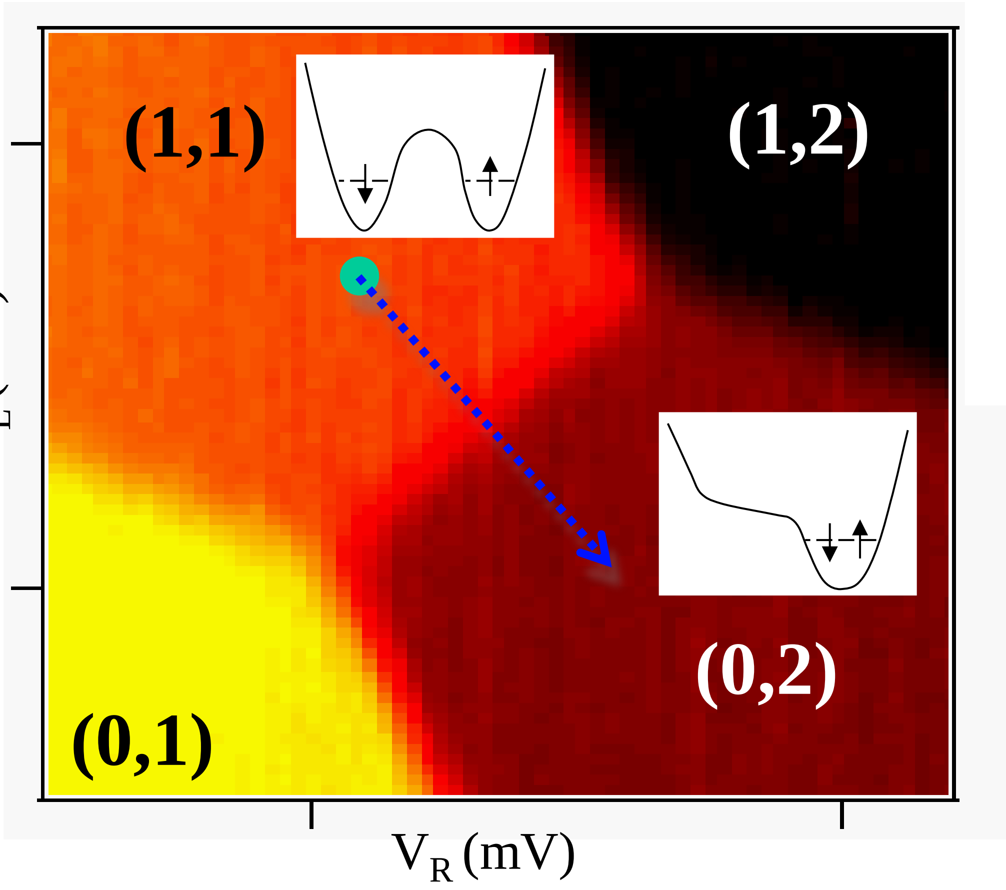
Koppens, et *al*. Nature **442**, 766 (2006)

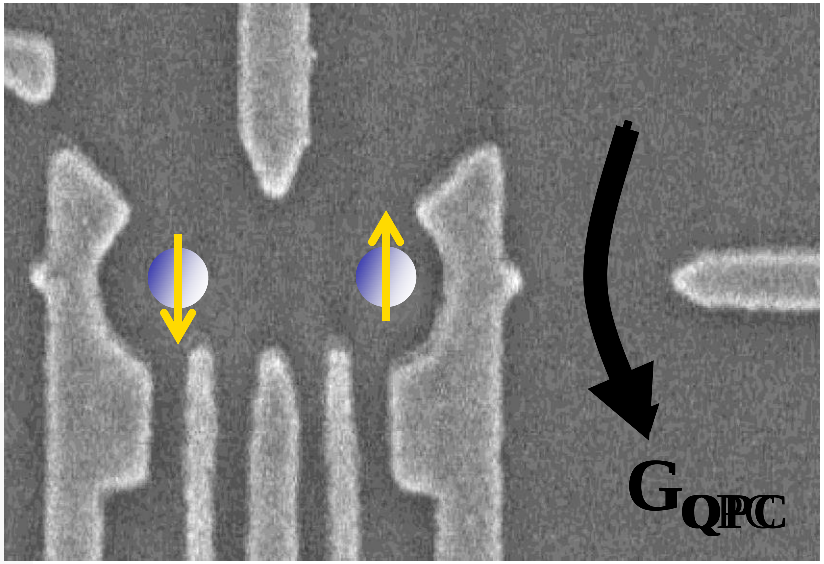
Double Dot Spin "Coherence"

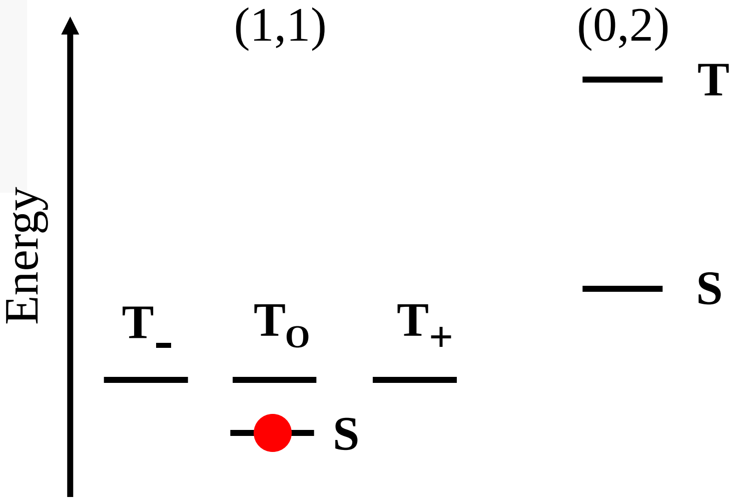
nonlocal, since two electrons are in different dots



Spin state measurement (spin-to-charge conversion)



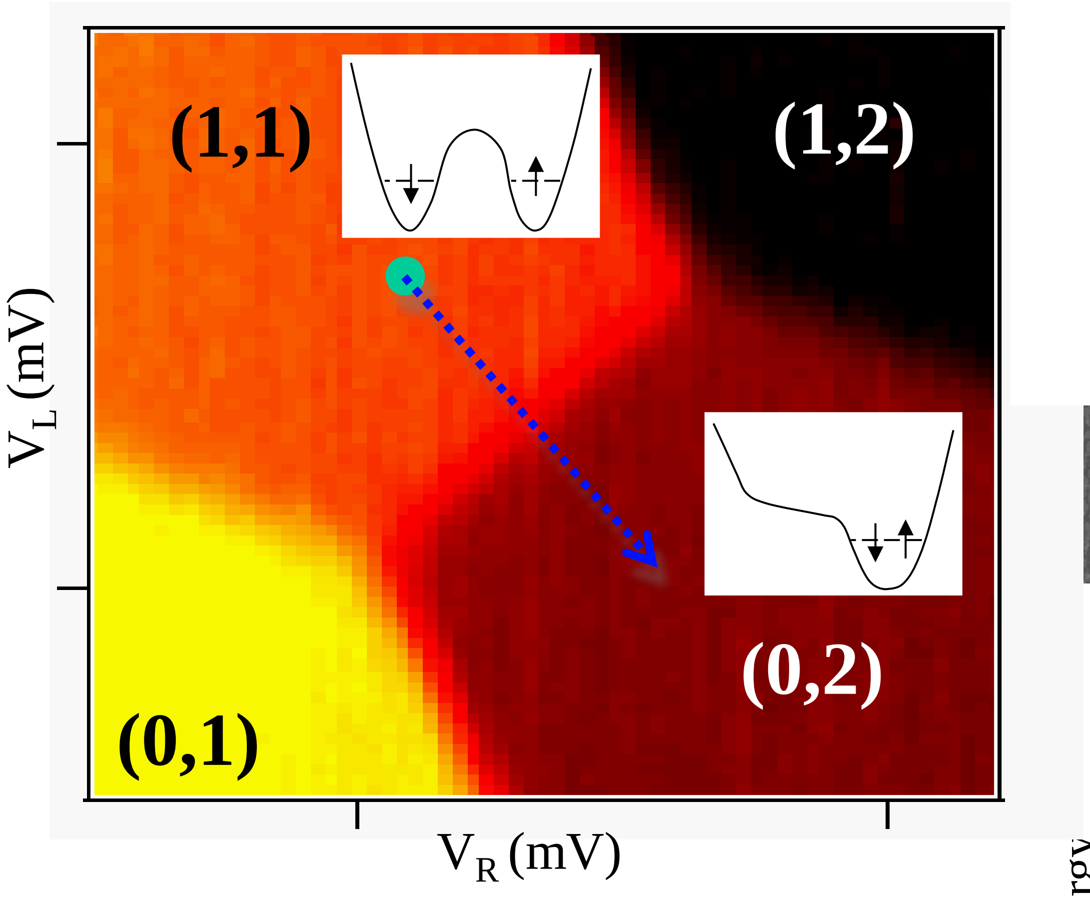




Singlet measurement

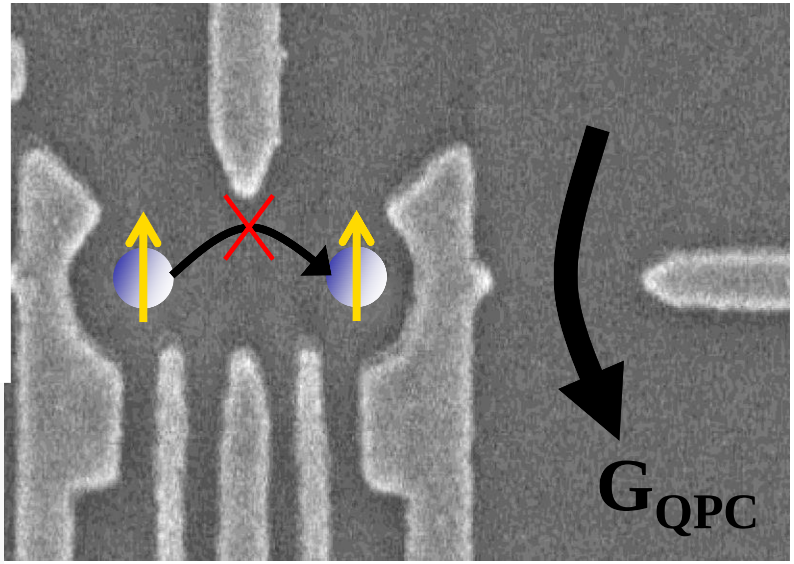
Petta, Science **309**, 2180 (2005)

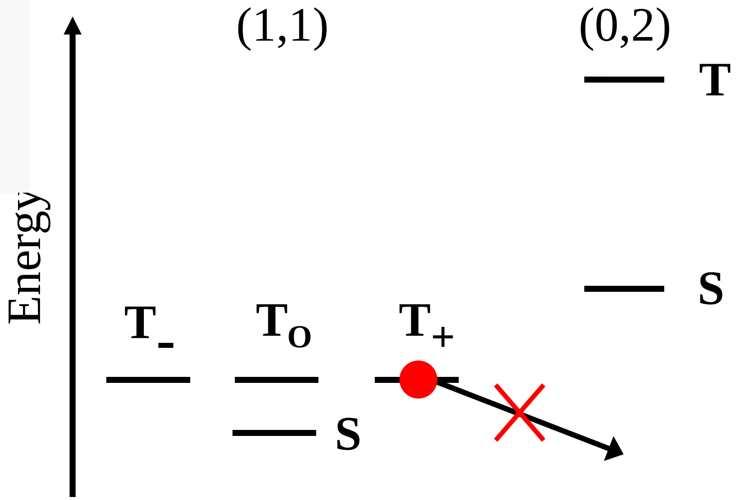
Spin state measurement (spin-to-charge conversion)



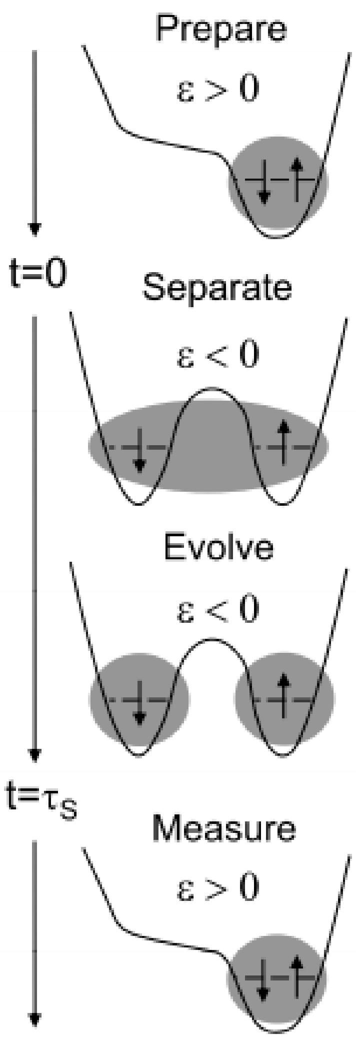
Triplet measurement

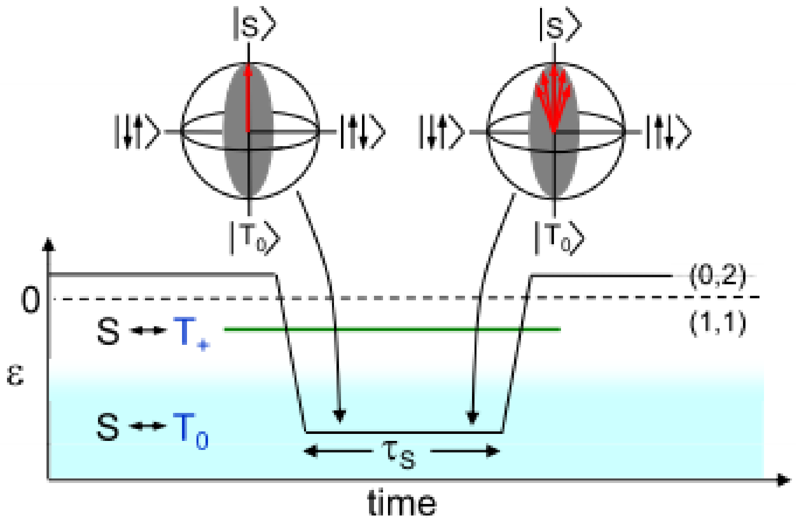
Petta, Science **309**, 2180 (2005)

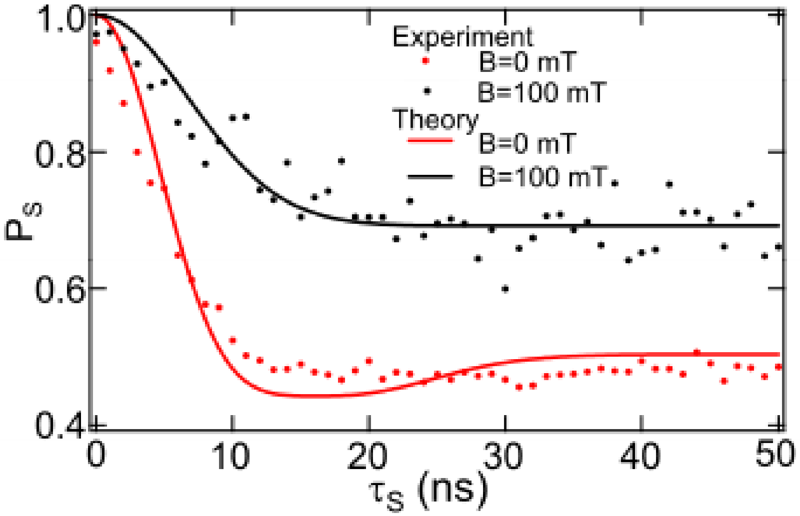




Dephasing of the singlet spin state: T_2^* measurement







Petta *et al.*, Science **309**, 2180 (2005).

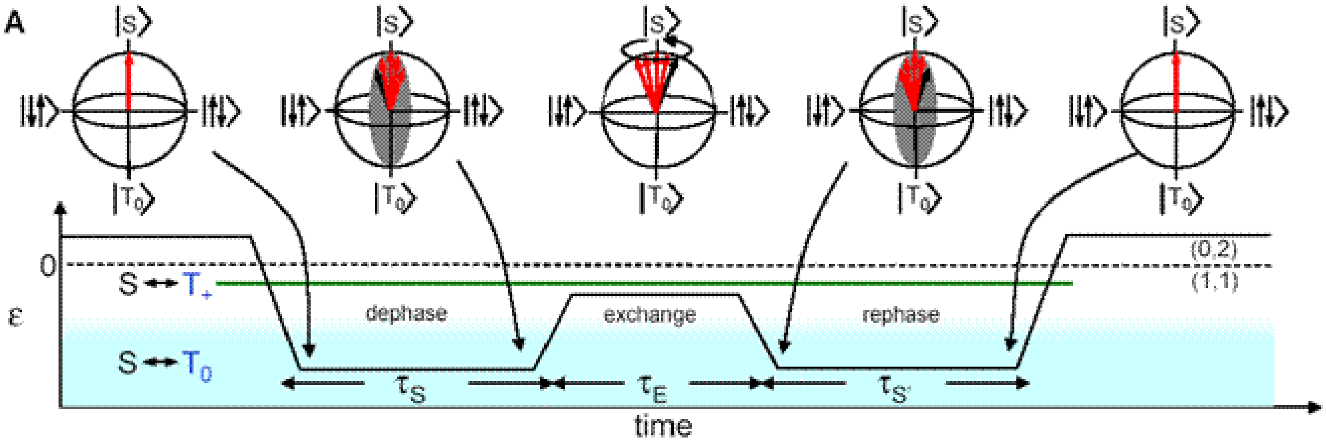
B_{nuc}=2.3 mT and T_2^*=10 ns

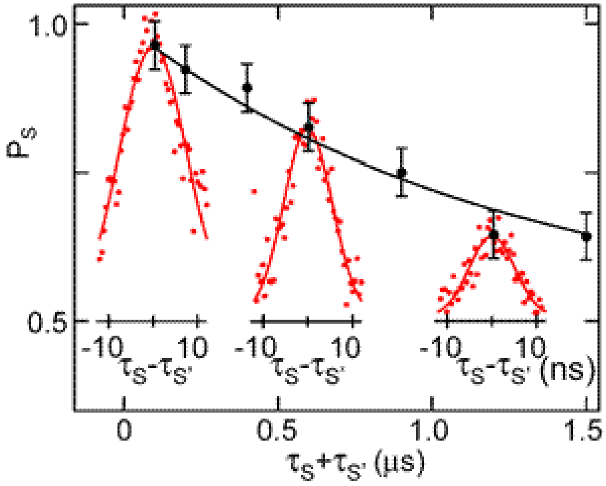
Different effective nuclear fields in the two dots (T_2^* not T_2)

Singlet/Triplet Qubits

use 2 electrons to make 1 qubit

"Spin echo" $\Rightarrow$ T_2 (decoherence)



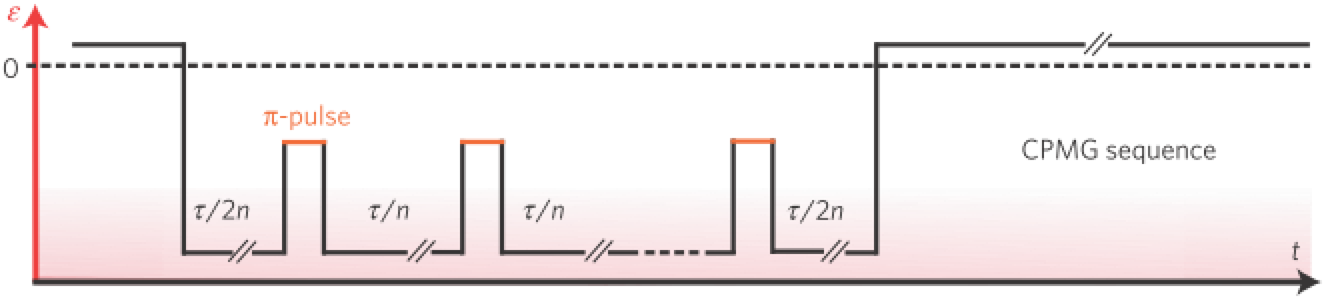


$\Rightarrow$ $T_2 \sim 1\mu s$

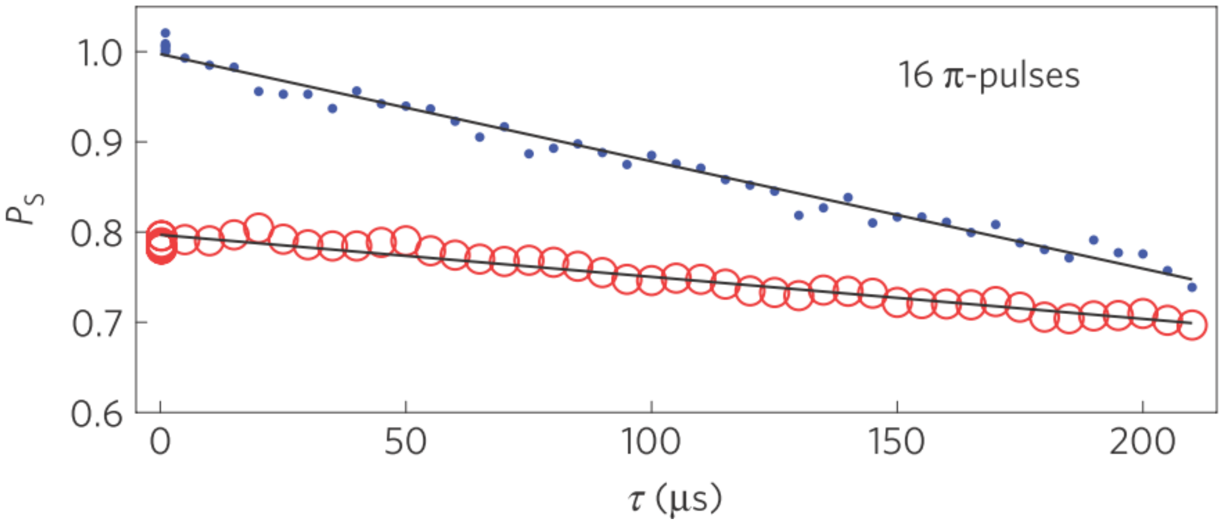
Note: All done at < 100mK, but tried it at 300mK and works just as well

Petta et *al*. Science **309**, 2180 (2005)

Extending coherence – dynamical decoupling



Red is reference. Difference represents the loss of coherence



Coherence can be extended to > 200 μs with CPMG

Bluhm, Nat. Phys. **7**, 109 (2011)

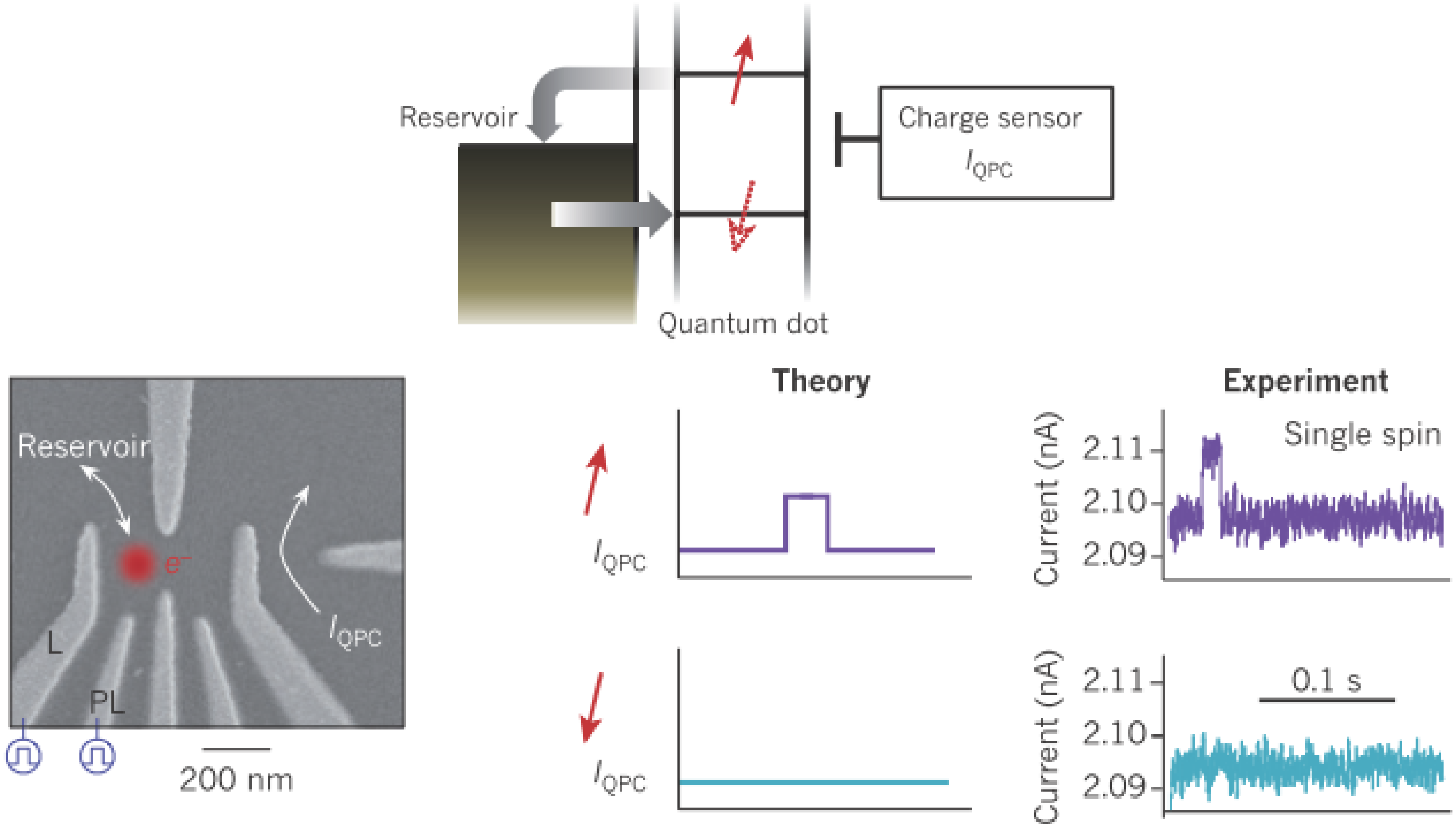
Where are GaAs/AlGaAs dots?

• Qubits	• Singlet-Triplet pairs in double QD (DQD)
• 1 and 2 qubit gates	• Two DQD’s dots have been coupled
• Decoherence	• ~200 μs with decoupling
• Initialization	• Just freeze into ground state
• Measurement	• Use QPC and spin blockade

What about Si QD’s?

- Low density of non-zero spin nuclei (4.75% ^{29}Si), and isotopically enriched ^{28}Si is available
- Medium $m^* \sim 0.2 \Rightarrow$ need smaller dots than for GaAs
- Multiple conduction band valleys could cause complications
- Si/SiGe heterostructures are analogous to GaAs/AlGaAs structures, but more difficult to grow and still somewhat lower mobility (if that matters?)

Spin measurement with Si/SiGe QD



Here the spin was measured “single shot” rather than signal averaging over many electrons

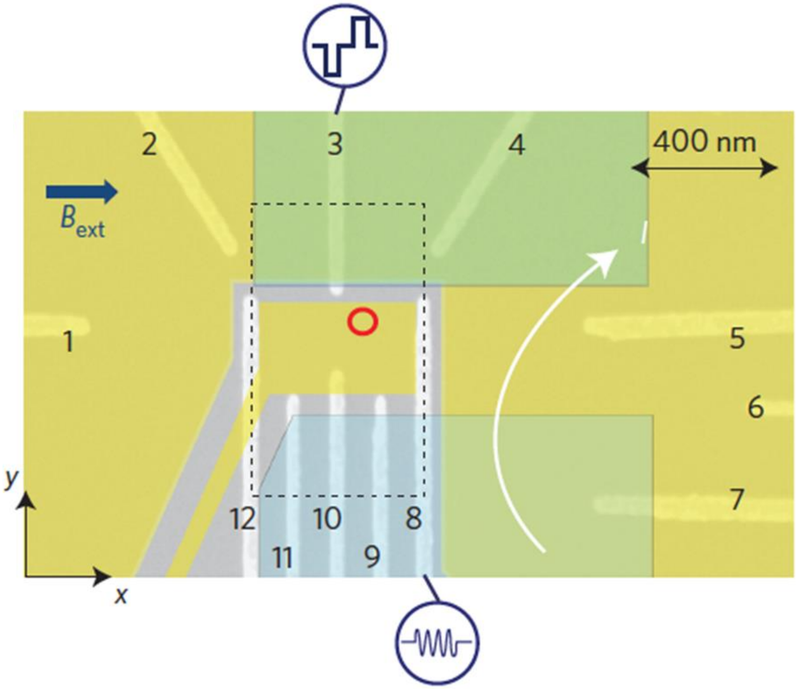
Simmons, PRL **106**, 156804 (2011)

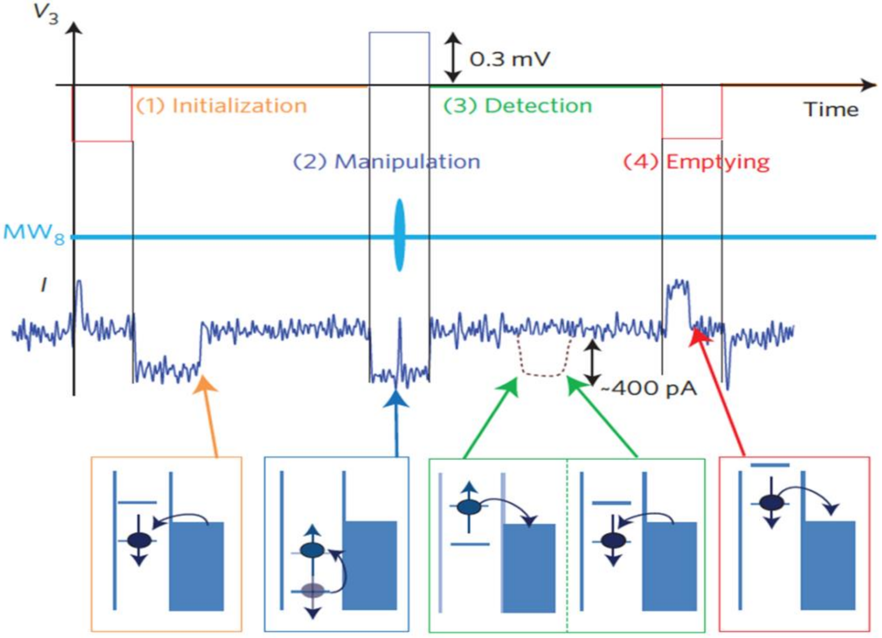
Driving Spin Electrically in ^{nat}Si/SiGe

- Microwave B-fields often (low-power) spead out ~ λ
- Electric fields better confined

⇒ Address individual dot/electron

  - Results: T_2^{Hahn} ~ 70μs, T_2^{XY8x16} ~ 400μs (extra charge noise)
  - Gate fidelity ~ 98 – 99%

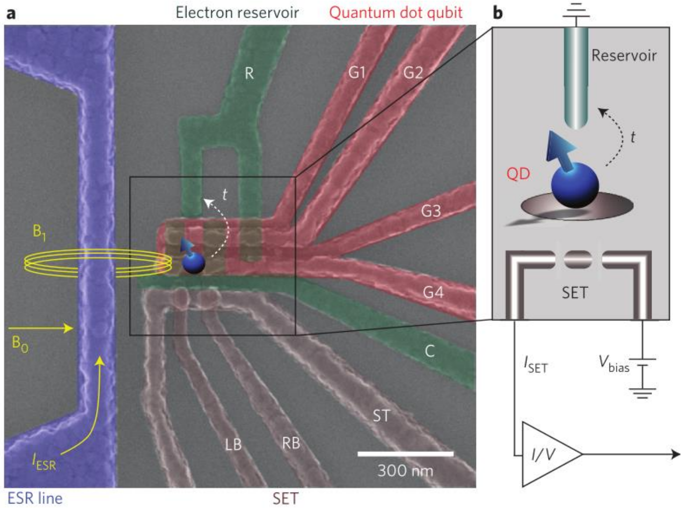




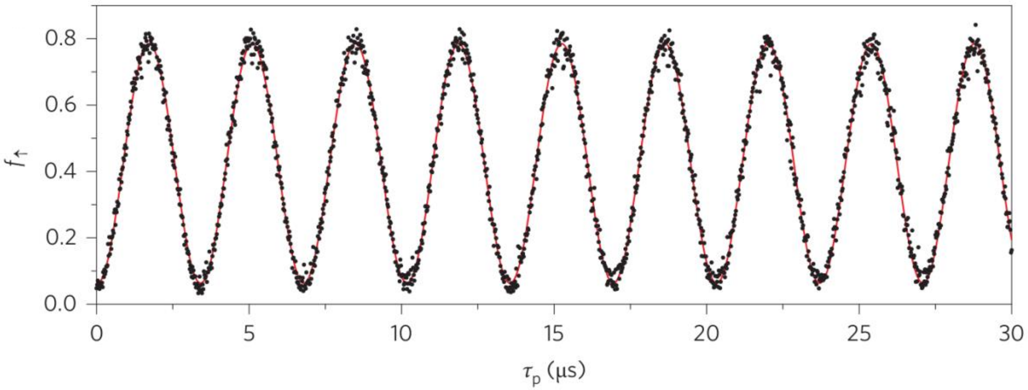
Kawakami, PNAS 113, 11738 (2016)

^{28}Si MOS Quantum Dots

- Metal-oxide-Si (MOS) is close to Si industry
- ^{28}Si eliminates decoherence from nuclear spins



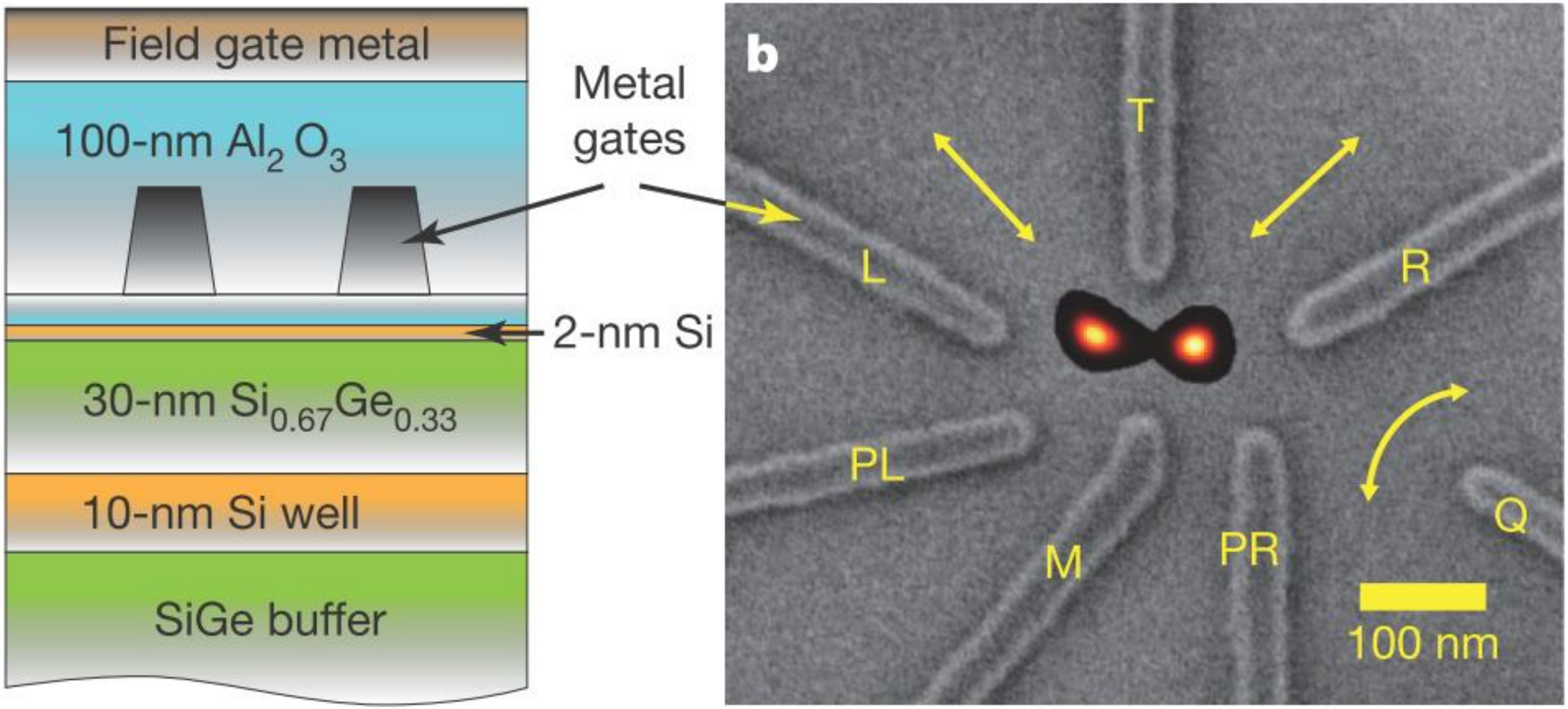
Rabi oscillations



- Results: $T_2^* \sim 120$ μs (Ramsey fringe)
  $T_2^{Hahn} \sim 1.2$ ms (Ramsey echo)
  $T_2^{CPMGx500} \sim 28$ ms
- Gate fidelities ~ 99.2% - 99.9%

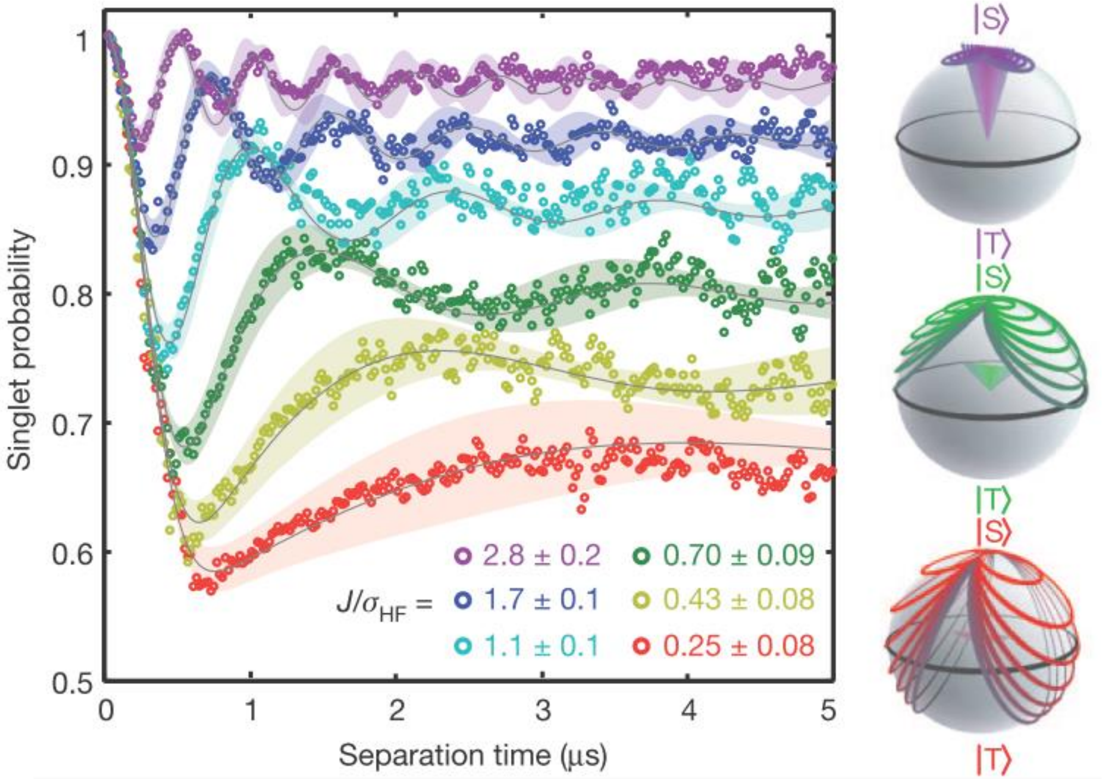
Veldhorst, Nat Nano **9**, 981 (2014)

Undoped Si/SiGe double quantum dot



Maune, Nature, **481**, 344 (2012)

T_2^* in ^{nat}Si double quantum dot



Find T_2^* ~ 350 ns

Couldn’t make J small enough for whole Bloch Sphere

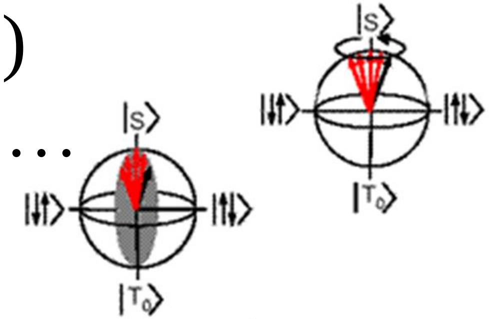
Do we need singlet-triplet qubits in Si?

- No
  - T_2 with just Hahn echo is longer than GaAs S-T qubit
  - World's best ^{28}Si (50 ppm) and similarly enriched Ge might make $T_2^* \sim 10\ \mu$s

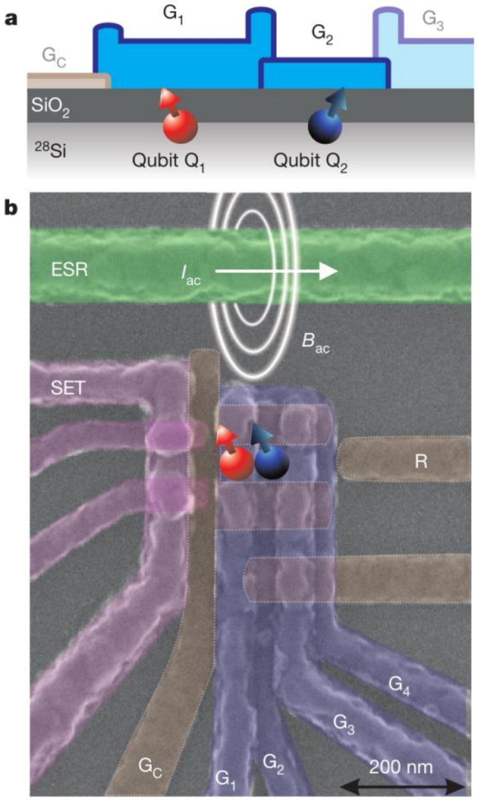
  $\Rightarrow$ need dynamical decoupling and limited by gate noise

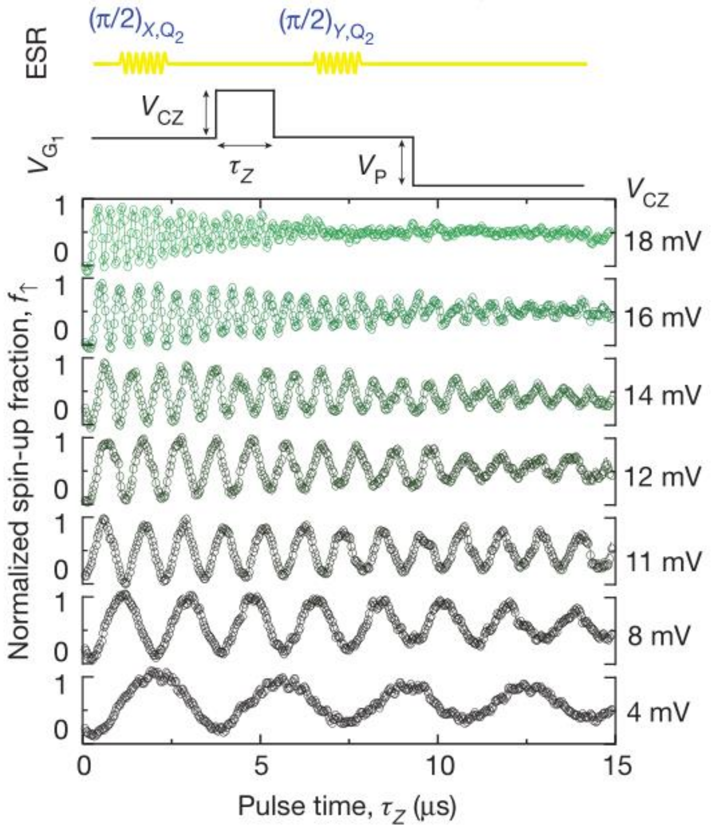
Do we want singlet-triplet qubits in Si?

- Maybe
  - Inherently insensitive to B (decoherence-free subspace)
  - One fast 1-qubit operation (exchange)
  - Other 1-qubit operation difficult, but …
    - Need micromagnet for ΔB?



^{28}Si-MOS 2-Electron Double Dot

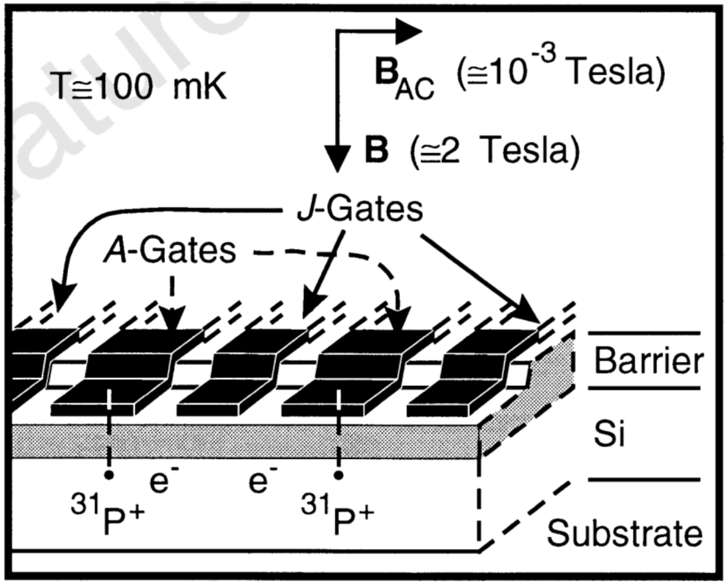




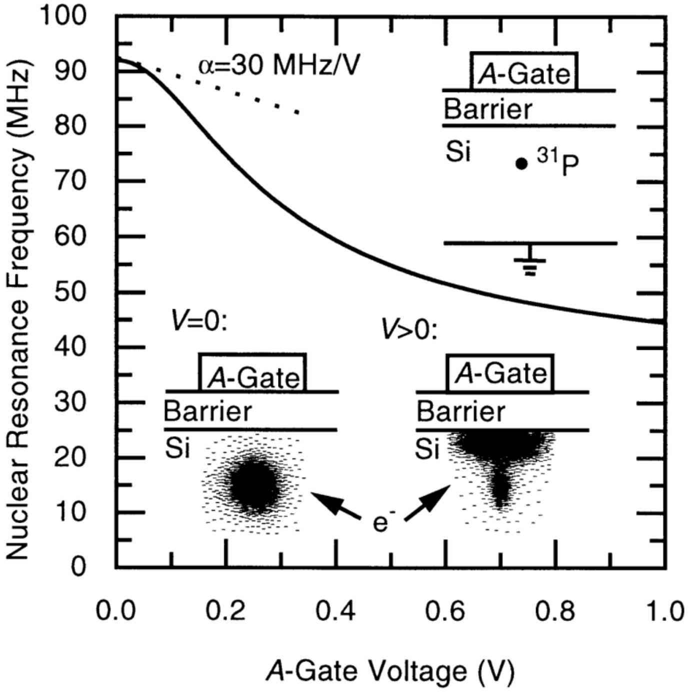
- CPHASE between 2 electrons → CNOT
- Now working on improving fidelity

Veldhorst, Nature **526**, 410 (2015)

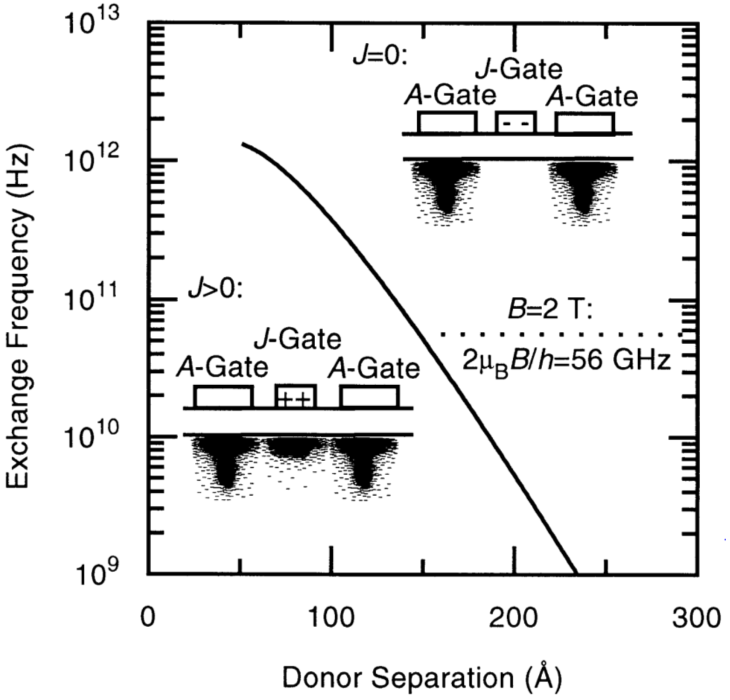
Donors in Si – the Kane Scheme



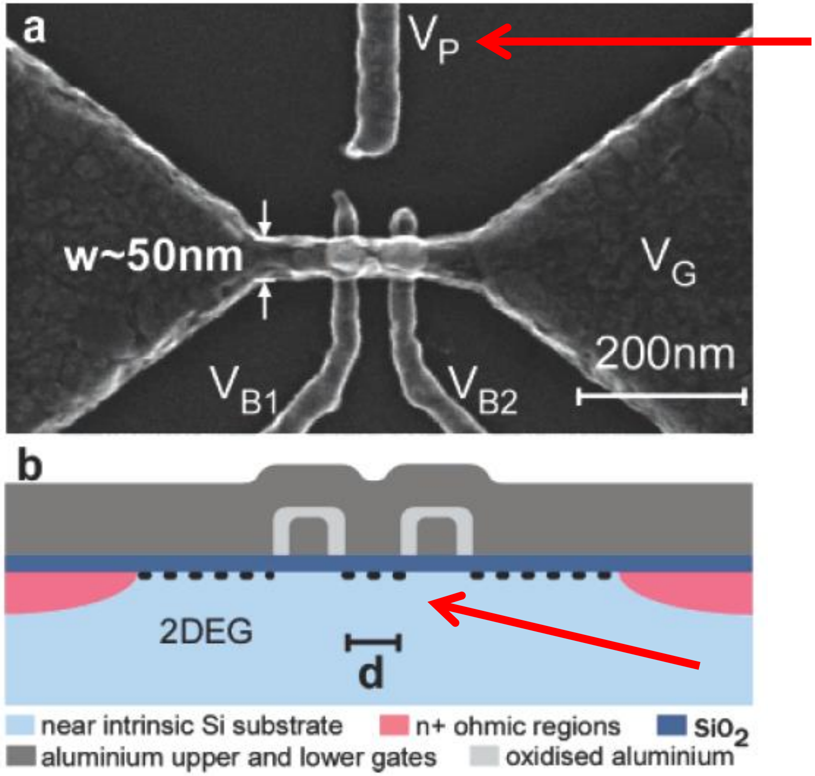
1-Qubit



2-Qubit



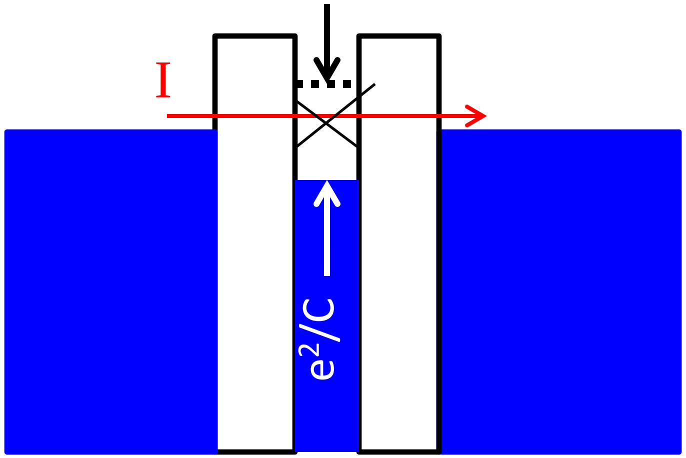
Single electron transistor (SET)

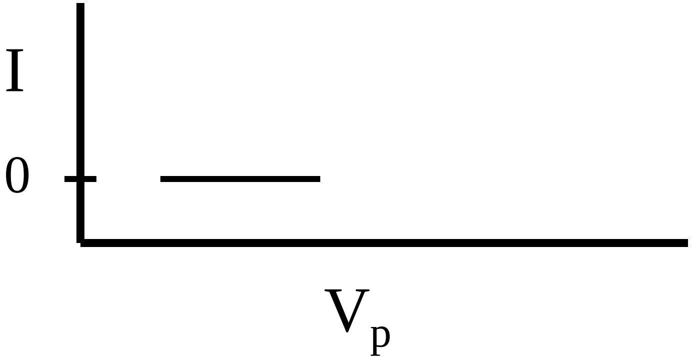


Plunger

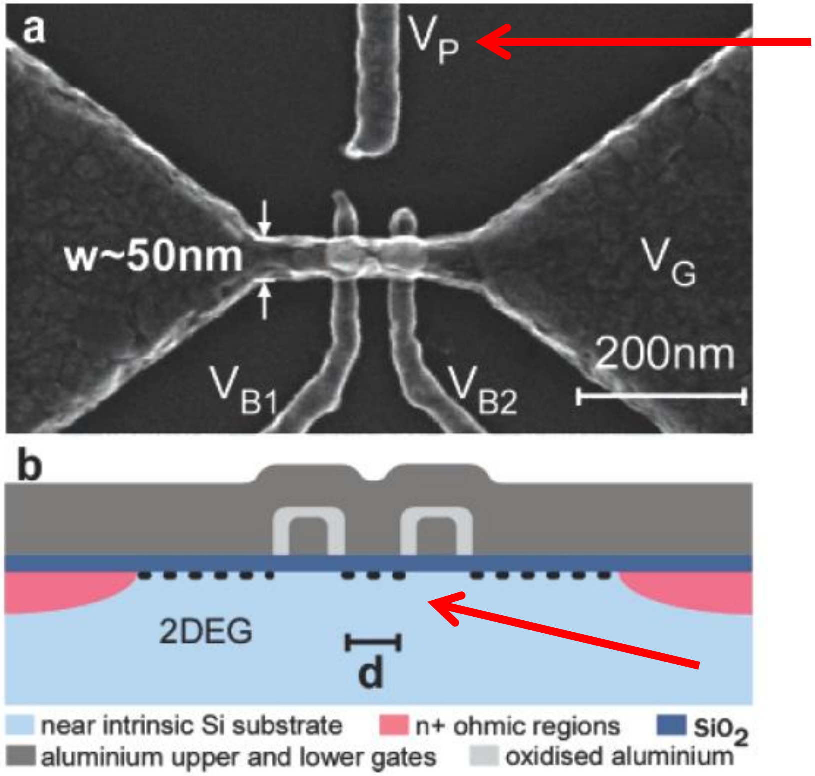
Angus, Nano Lett. **7**, 2051 (2007)

The “island”, length d, is small enough that the simple Coulomb energy to add an electron (½ e^2/C) is non-negligible. The current has spikes as a function of plunger-gate voltage, V_p.





Single electron transistor (SET)



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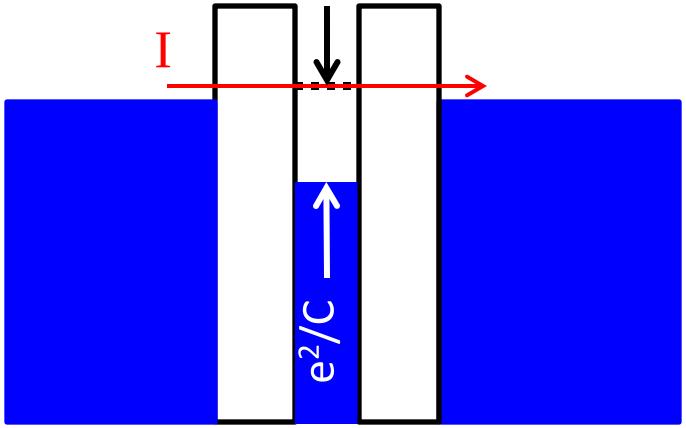
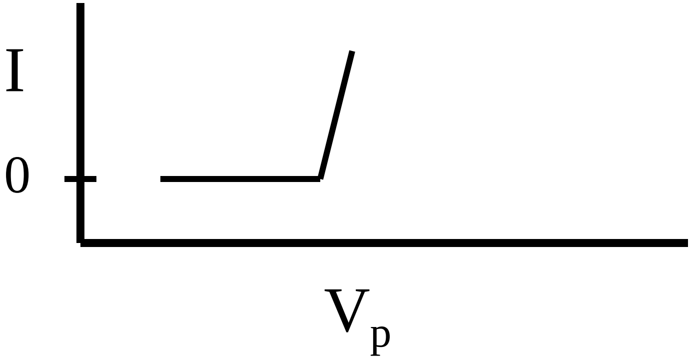
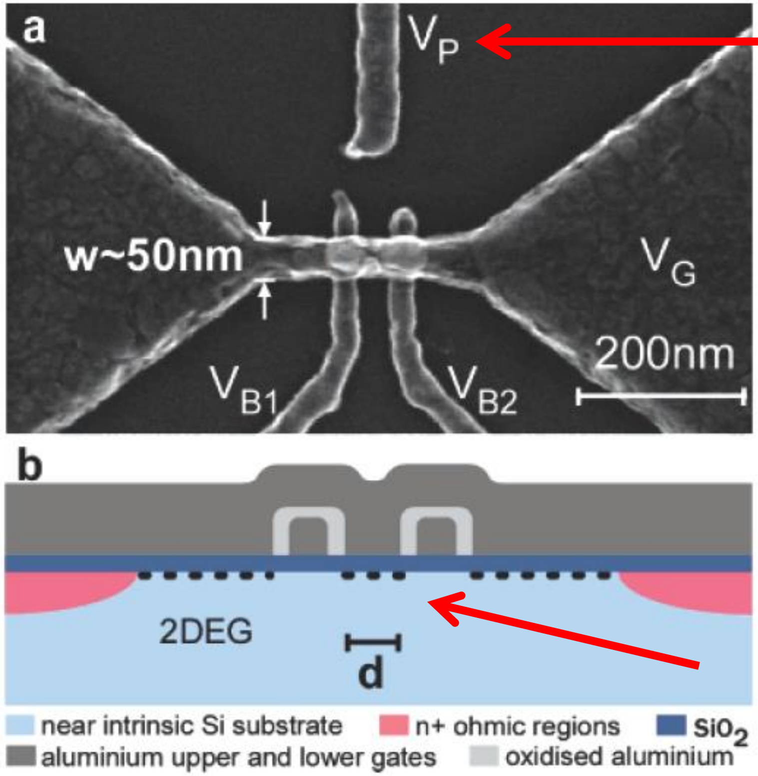




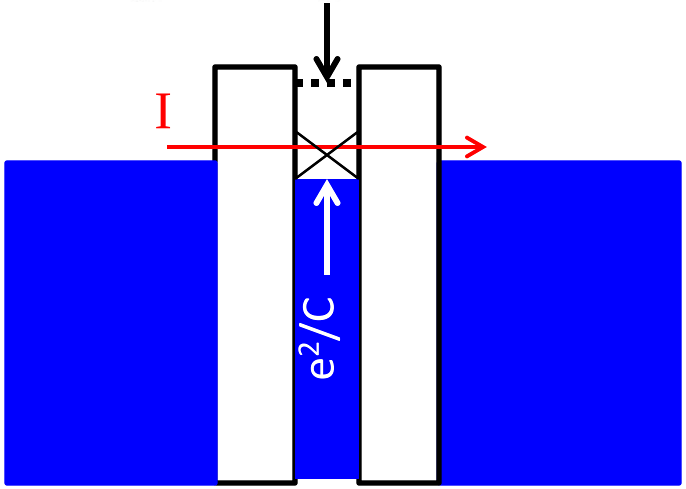
Single electron transistor (SET)

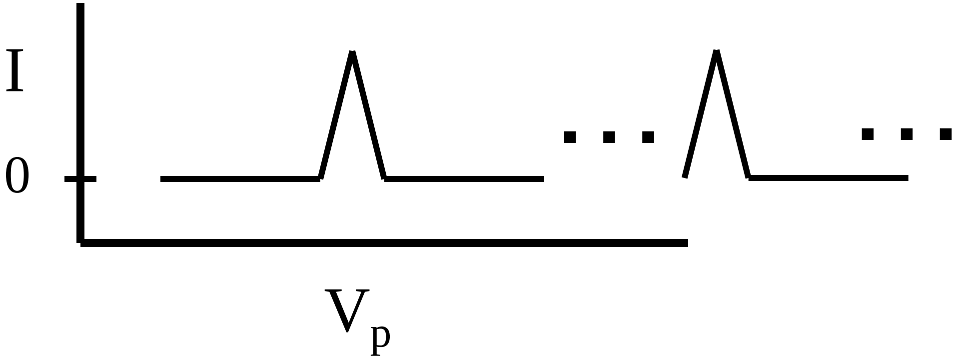


Plunger

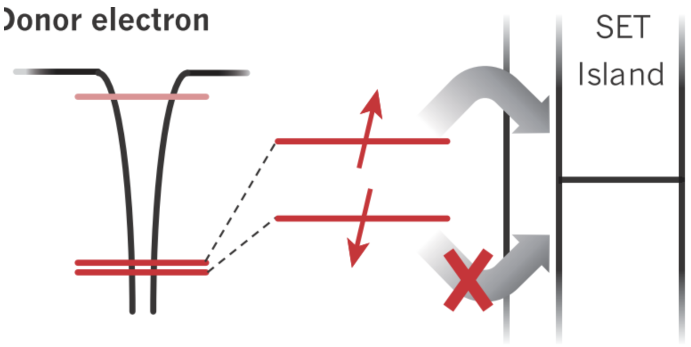
Angus, Nano Lett. **7**, 2051 (2007)

The “island”, length d, is small enough that the simple Coulomb energy to add an electron (½ e^2/C) is non-negligible. The current has spikes as a function of plunger-gate voltage, V_p.

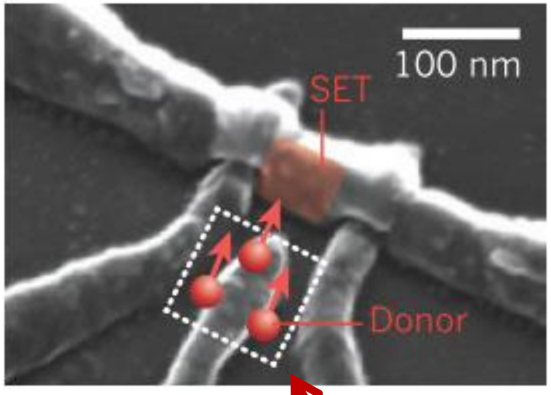




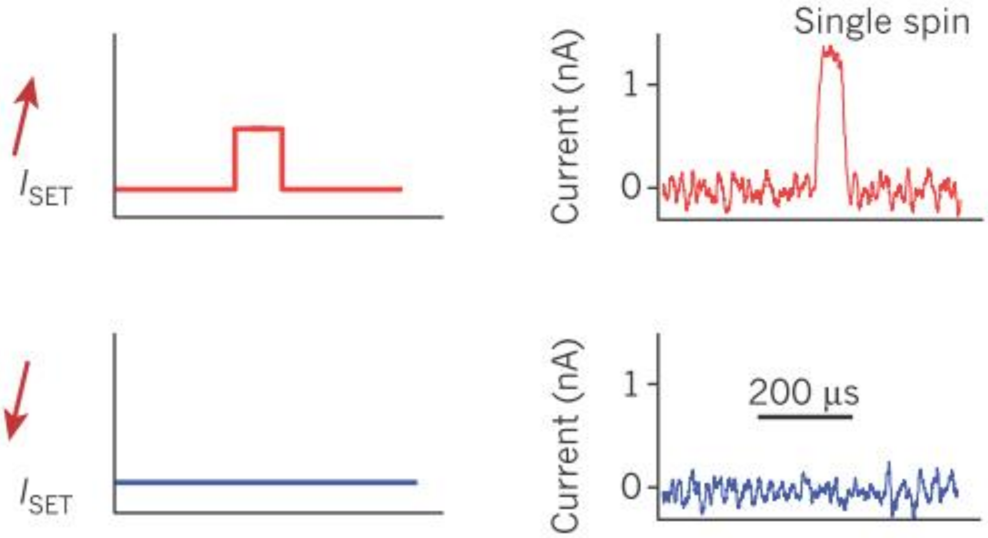
Measuring T_1 with the SET



The measurement proceeds like the quantum dot measurements of single electron, with the donor being the dot. **Obtained T_1 ~ 6 s**



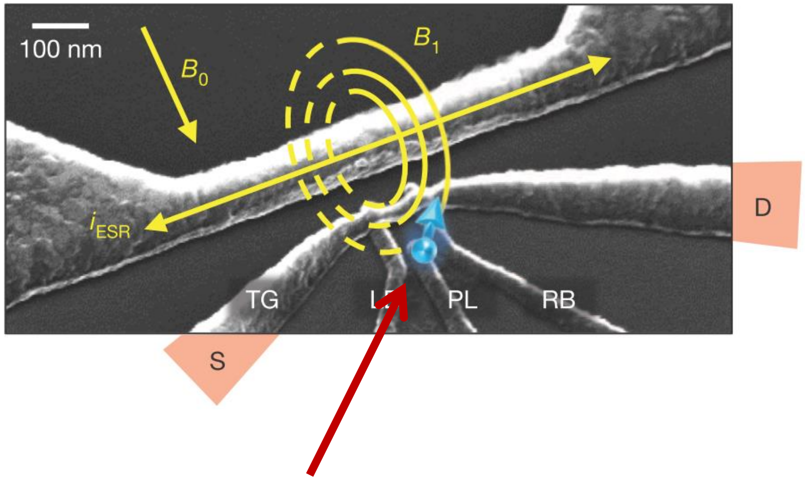
~ dozen donors



Morello, Nature, **467**, 687 (2010)

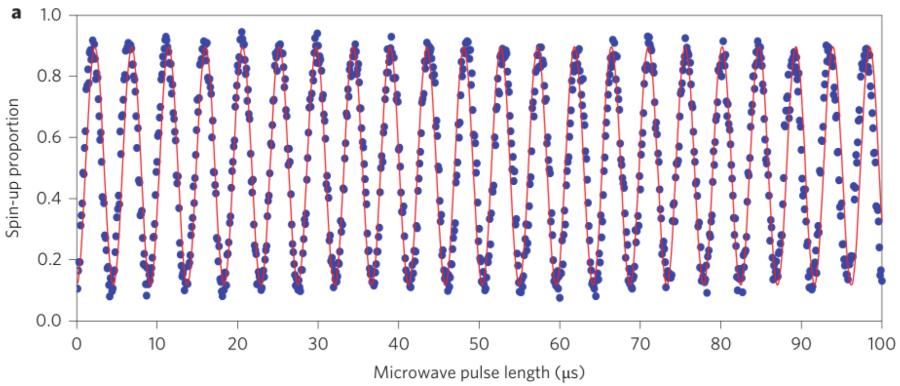
Measuring T_2 of a single donor electron

Send microwaves down shorted transmission line, as with the dots



~ dozen donors

Rabi oscillations



Muhonen, Nat. Nano, **9**, 986 (2014)

Results: T_2^* ~ 200 μs (Ramsey fringe)

T_2^{Hahn} ~ 1 ms (Ramsey echo)

$T_2^{CPMGx8000}$ ~ 0.5 s

Nuclear spin

T_2^{CPMG} ~ 35 s

Issues with Si qubits

- Stark tuning donor spin requires high fields for MHz tuning
- Donor pitch too tight
  - Donor wavefunction ~ 2nm
- Donor "exchange oscillations"
  - Exchange interaction between two donors is not monotonic in the distance between them (varies by 10x, or more, while donor moves 1 lattice constant)

Every spin is the same, right?

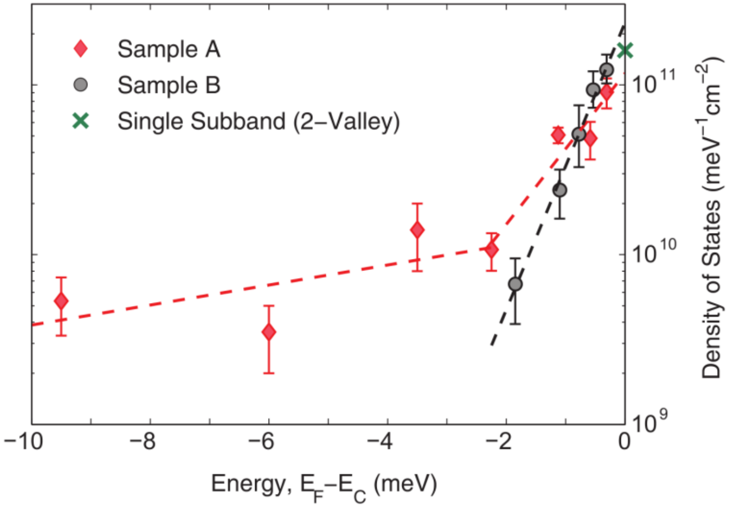
- Linewidth:
  - Assume surface code cycle = 1μs
  - Allowed phase error/cycle = 0.1% ⇒ $2\times10^{-3}\pi$
  - Maximum linewidth = 1kHz (10^{-3} cycles in 1μs)
  - Bulk ^{28}Si:P ⇒ few kHz to 10’s kHz (not really understood)
  - Epitaxial ^{28}Si:P/^{nat}Si ⇒ 100’s kHz
  - Can we individually tune 10^9 qubits?
- Large local strains from oxide & gate metals
  - Probably contributes to donor linewidth
  - Seems to be much bigger in SOI

Who Cares About Defects?

- Defects (thermodynamics says there are some)?

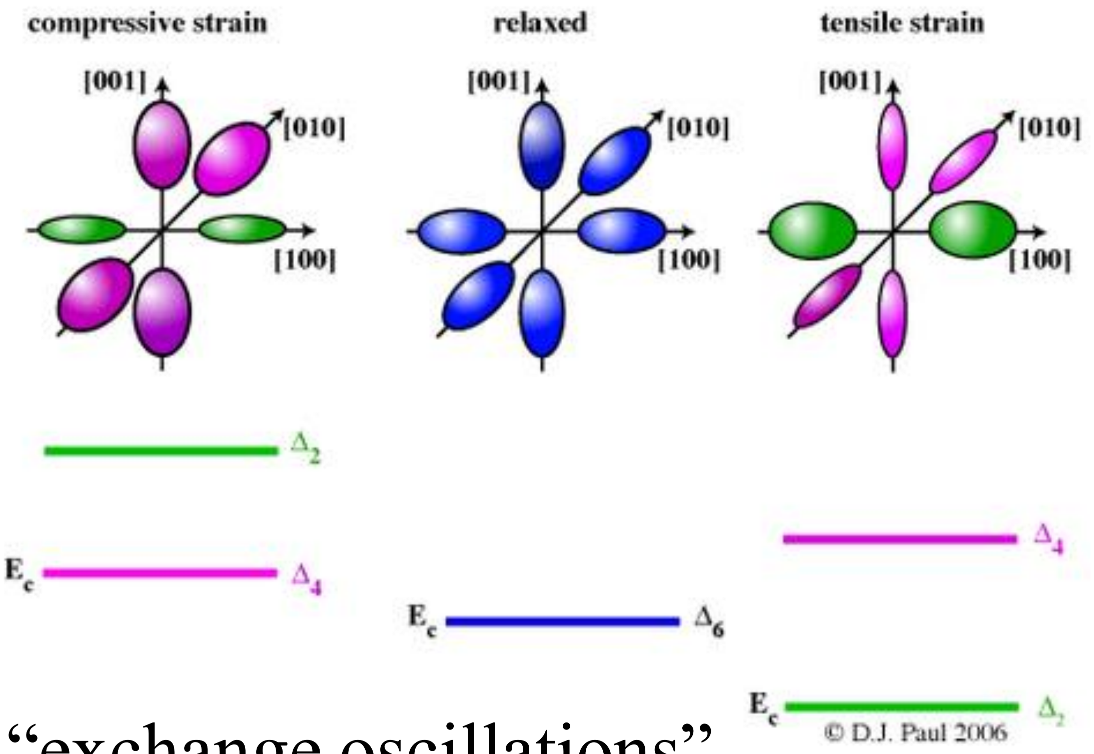
  ~$10^{10}/\text{cm}^2$ with depth ≥ 3meV at MOS interface

  ⇒ ~100nm between traps



- Are they a problem?
  - Distort donor-dot energies
    - “Just” calibration issue?
  - Extra trapped electrons
    - Exchange with dot electrons or transiting electrons?
    - Mess up microwave coupling?

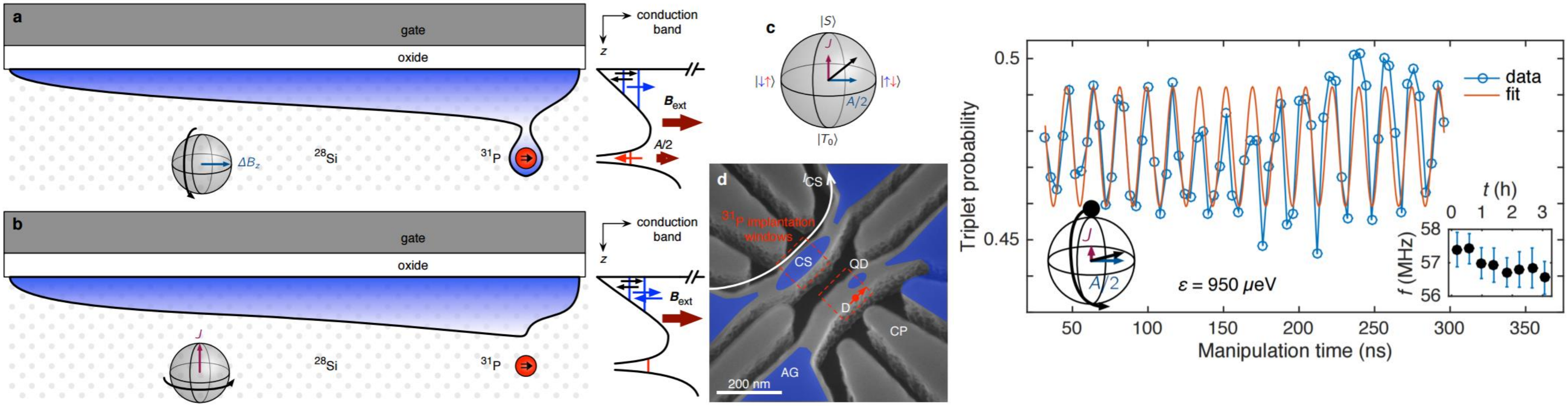
Conduction band valleys in Si



© D.J. Paul 2006

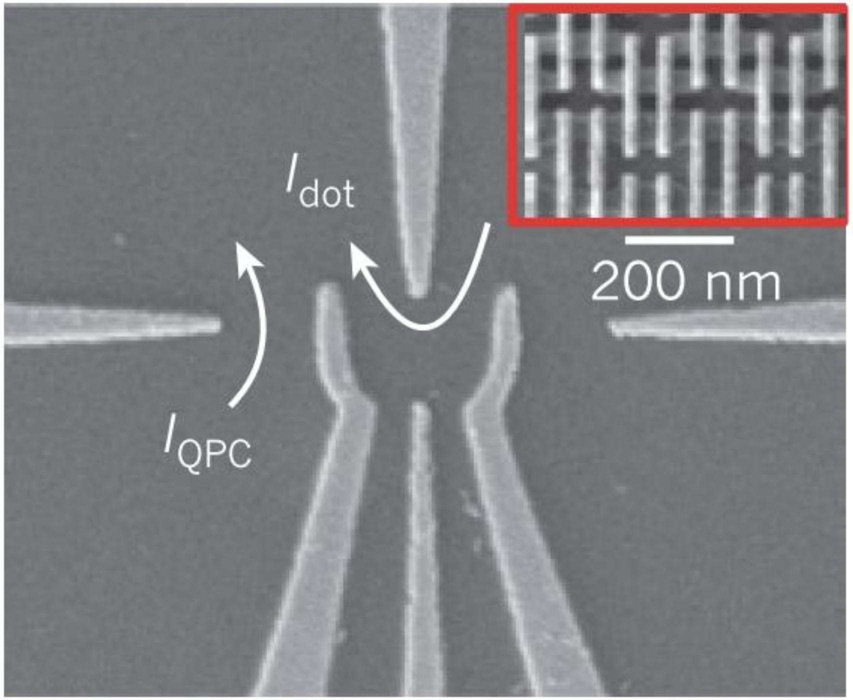
- Donor “exchange oscillations”
- Valley splitting ~ Spin splitting
  - Get valley states mixing with spin states in dots ⇒ bad!
  - Interface details (atomic steps?) ⇒ valley splitting

Coupling Donor to Quantum Dot

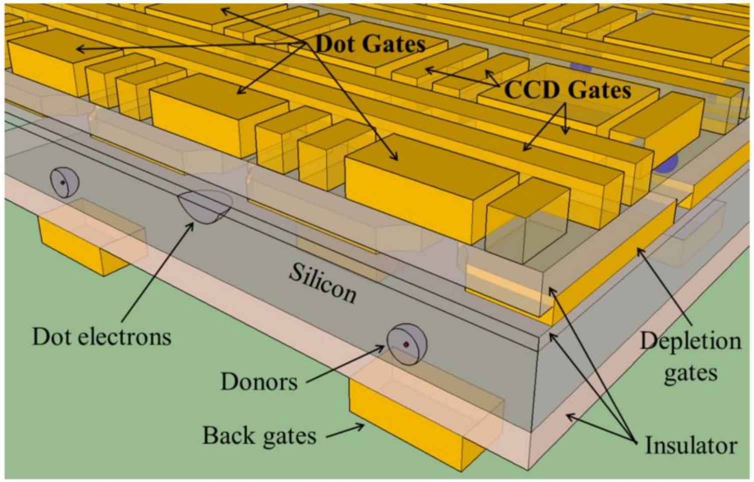


- Singlet-triplet qubit with one electron on/off phosphorus
- Electron on donor ⇒ rotate between S & T_0 (vertically)
- Electron off donor ⇒ just exchange (rotate horizontally)
- Fit oscillations, including J ≠ 0 with electron on donor
- Used 4 electrons not 2, because small valley splitting
  - Filled lower valley states, so only consider upper pair

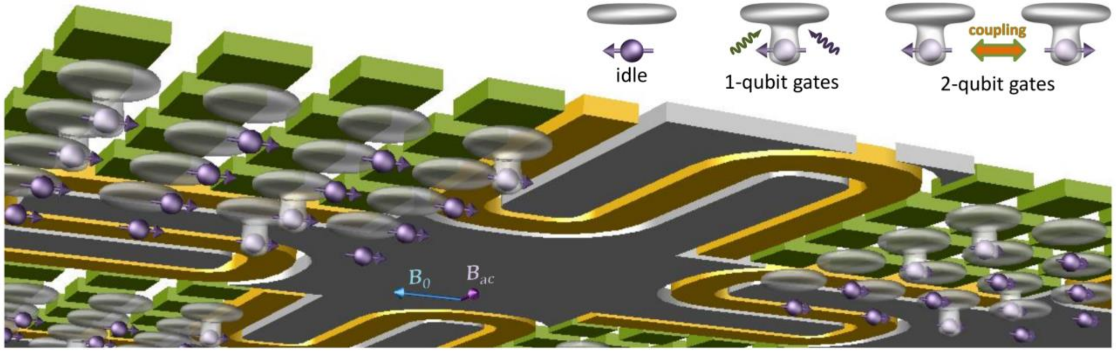
Si quantum dot vs. SRAM



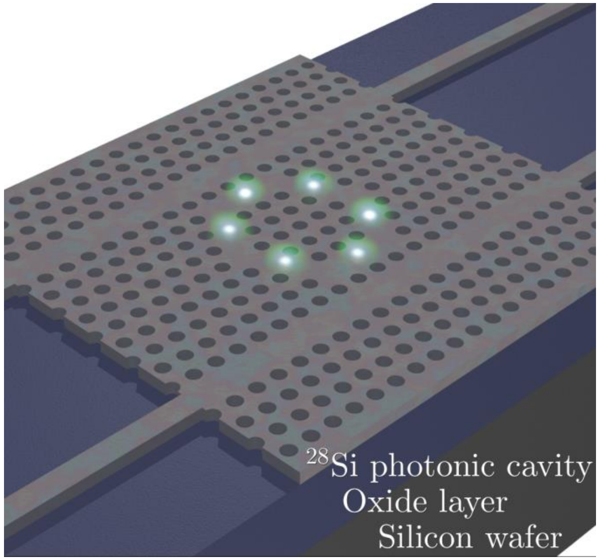
Alternate Schemes



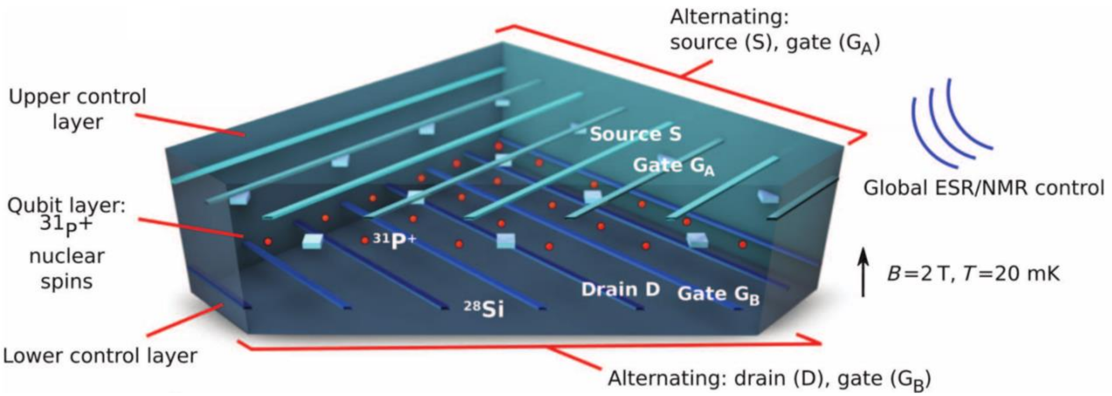
Pica, PRB **93**, 035306 (2016)



Tosi, ArXiv:1509.08538 (2105)



Morse, arXiv:1606.03488 (2016)



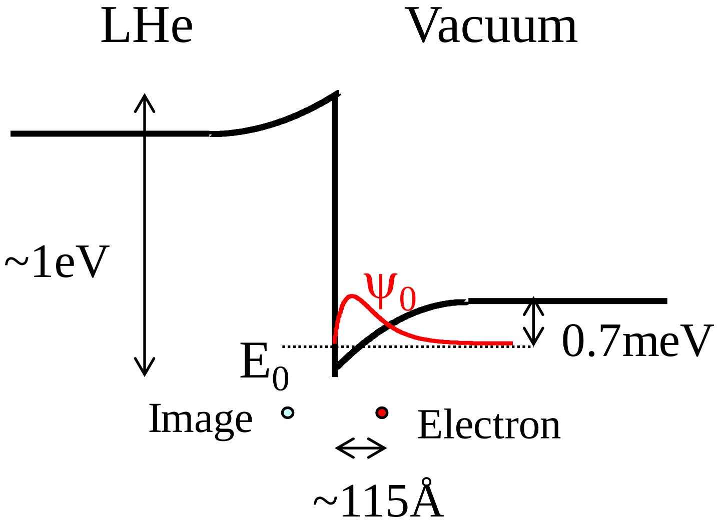
Hill, Sci Adv **1,** e1500707 (2015)

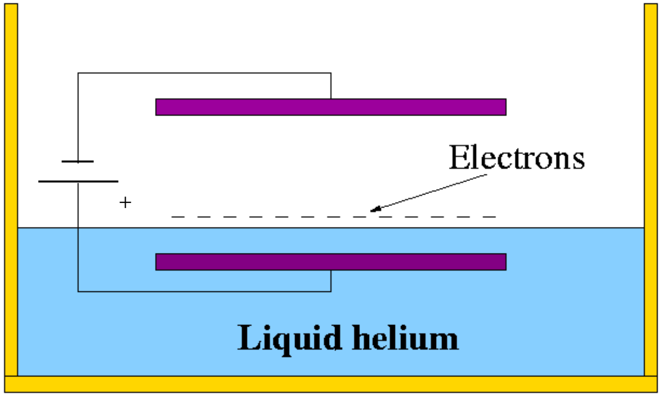
It’s the economy, stupid.*

materials

* James Carville

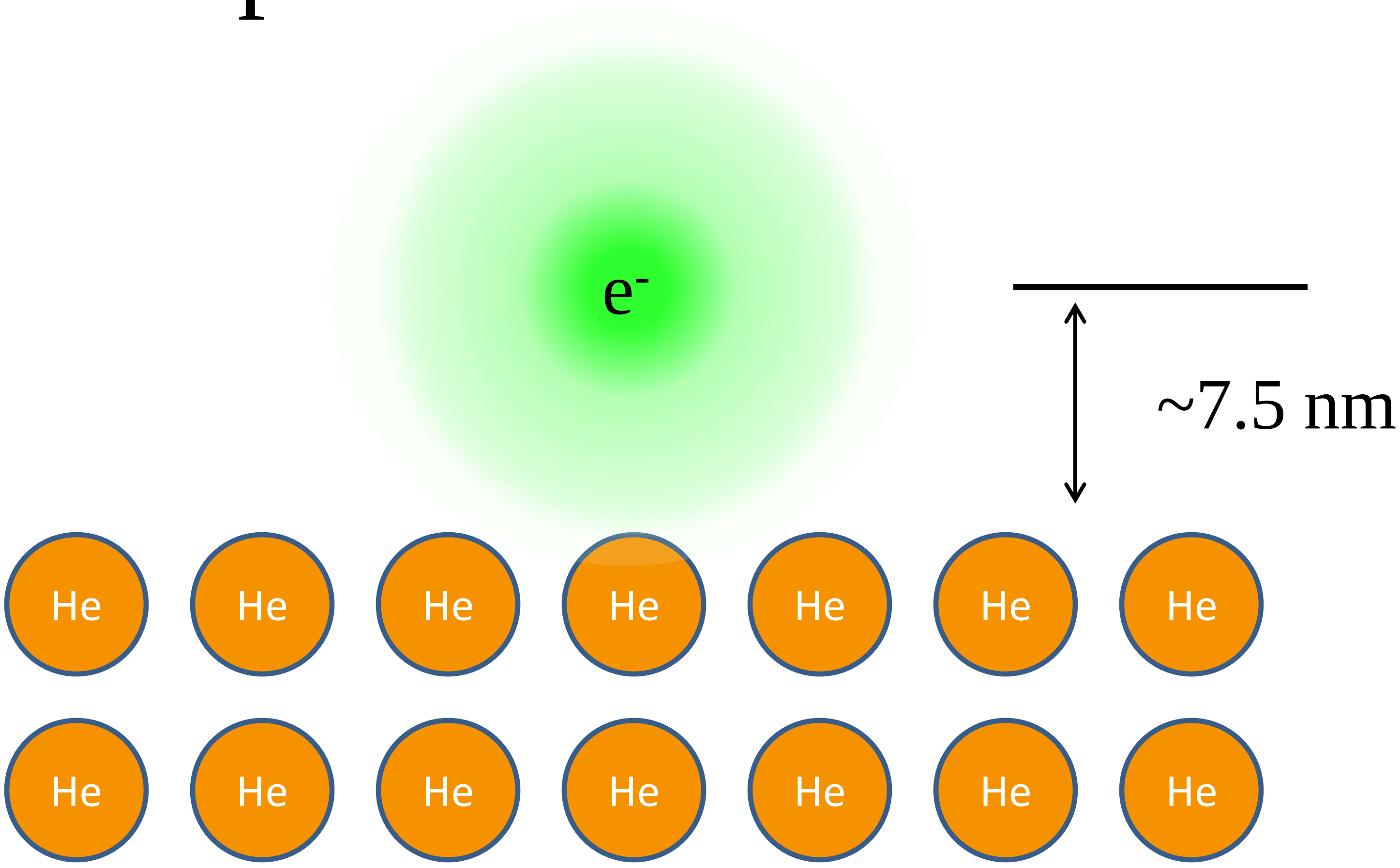
Experimental System





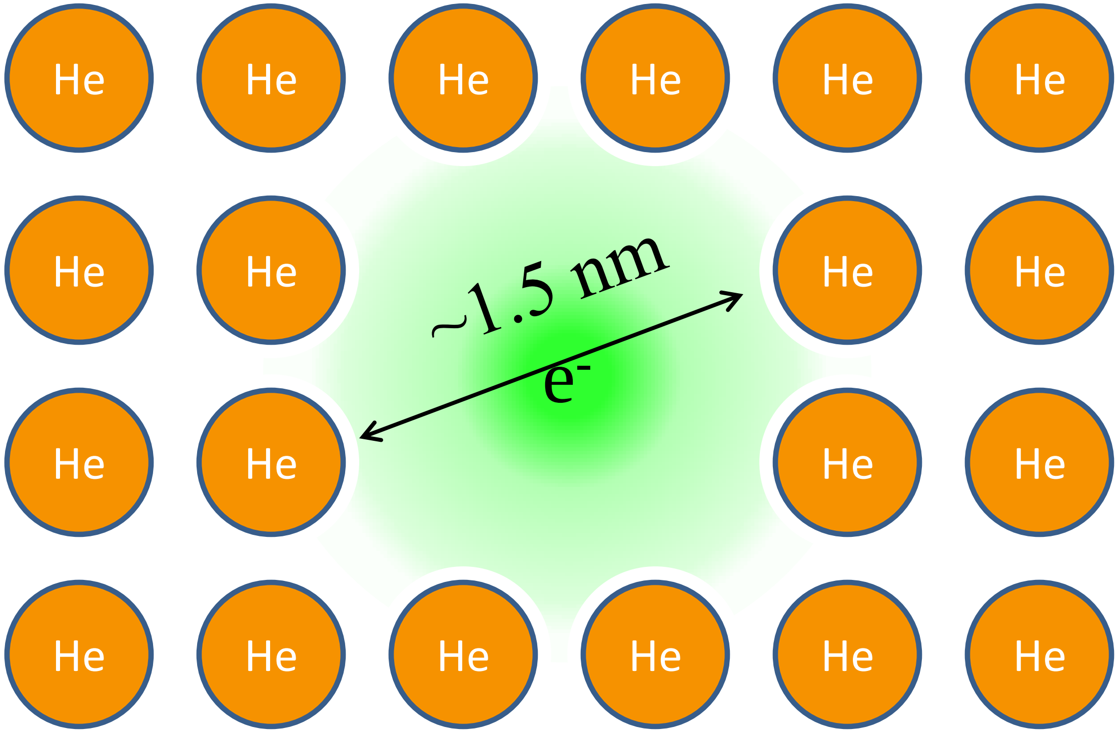
- Electron bound to image in liquid He
  - ψ_z = radial hydrogenic wave function
  - $\psi_{x,y}$ = plane waves
  - Submerged gates can modify binding
  - Extremely mobile electrons (~100 x 10^6 cm^2/V-s)
  - Low density 2D system (10^9 … $10^5/cm^2$)

Spin Orbit Interaction



Overlap of electron above surface with helium 2P-band?

Spin Orbit in Electron Bubble

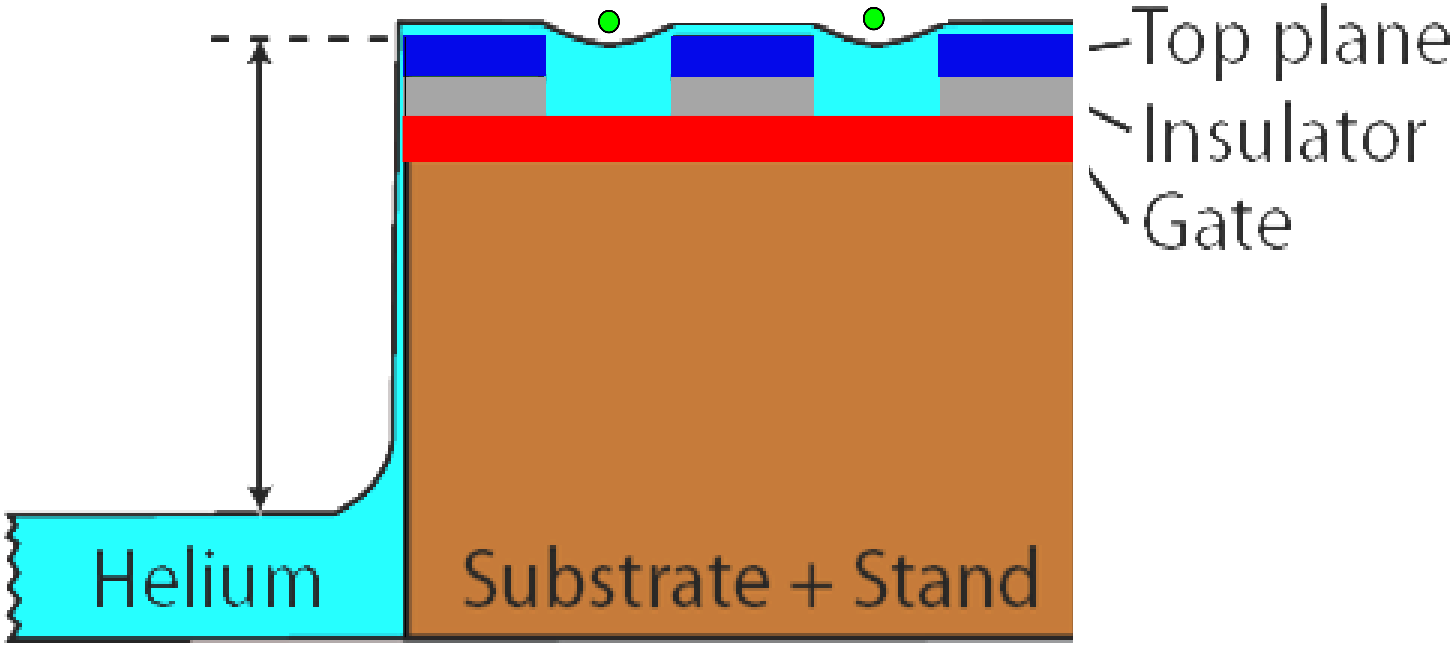


$\Delta g/g < 3\text{x}10^{-7}$ vs. Si with $\Delta g/g \sim 10^{-3}$ so 10^7 less decoherence

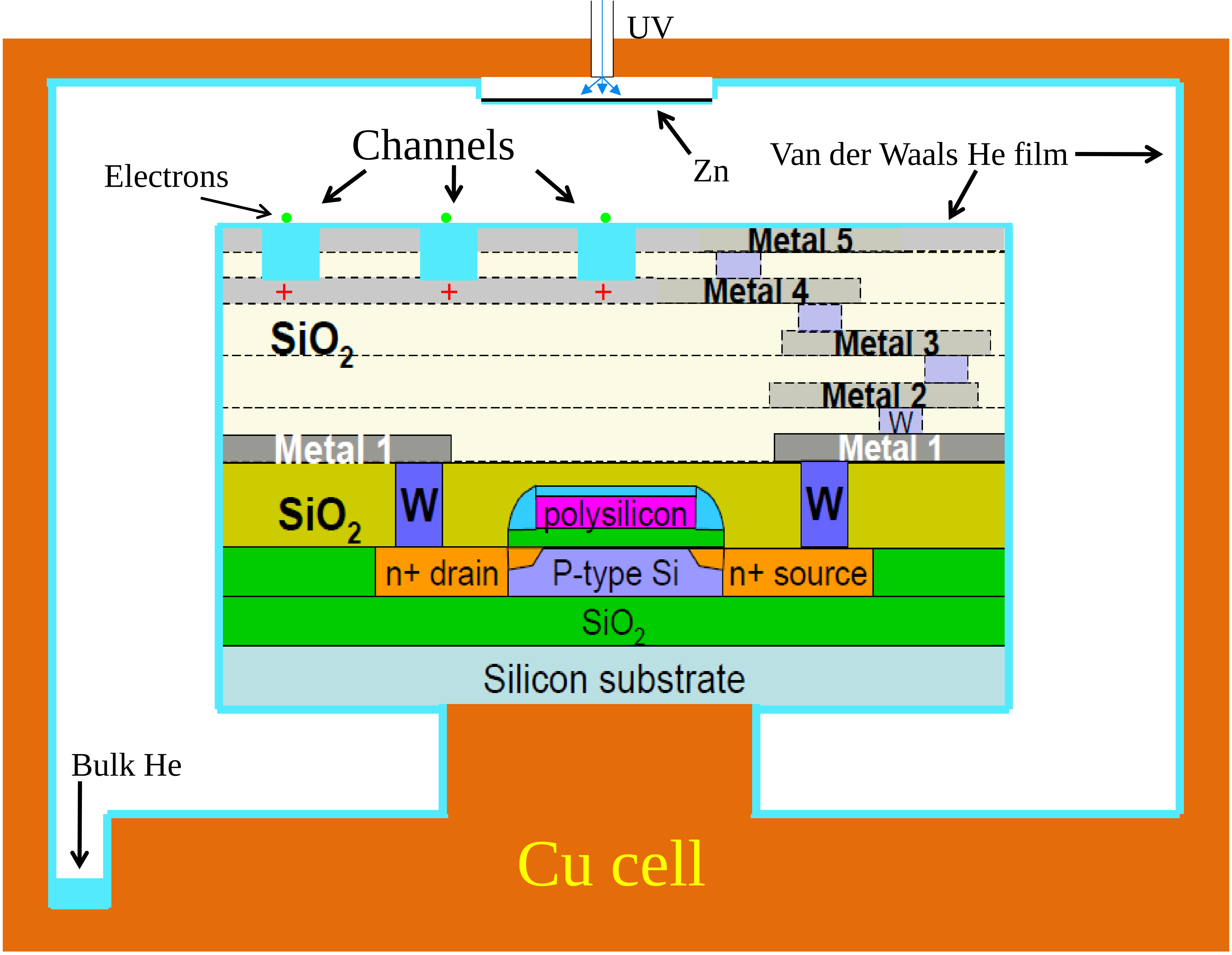
⇒ Spin coherence for *mobile* electrons > 1 second

Reichert and Jarosik, PRB **27**, 2710 (1983).

Helium-Filled Channels



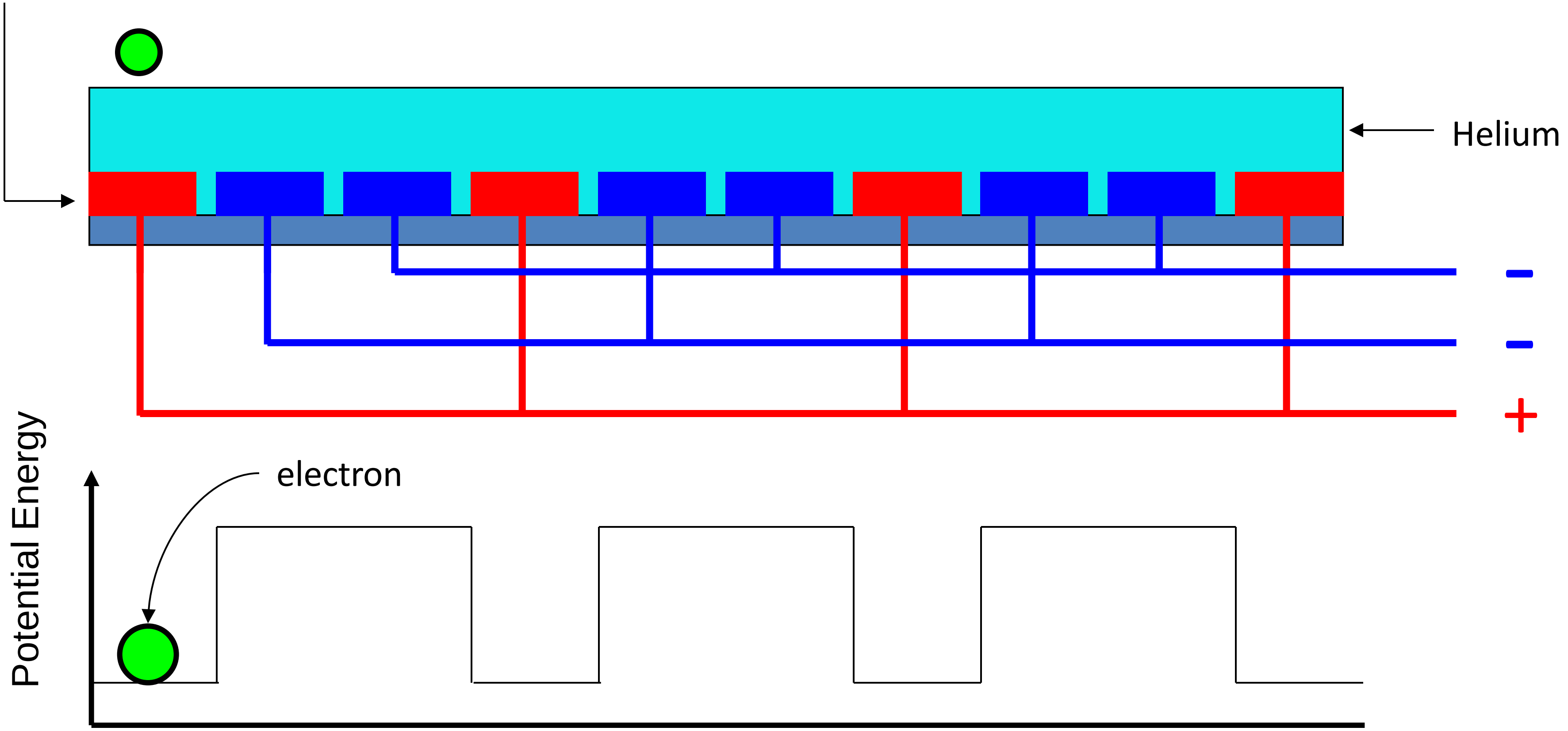
- Helium depth set by thickness of deposited layer
- Easy to make precise depths of nm to a few μm


UV
Channels
Electrons
Zn
Van der Waals He film
Metal 5
Metal 4
Metal 3
Metal 2
W
Metal 1
Metal 1
SiO$_2$
SiO$_2$
W
W
polysilicon
n+ drain
P-type Si
n+ source
SiO$_2$
Silicon substrate
Bulk He
Cu cell

3-phase CCD

Potential

Underlying gates



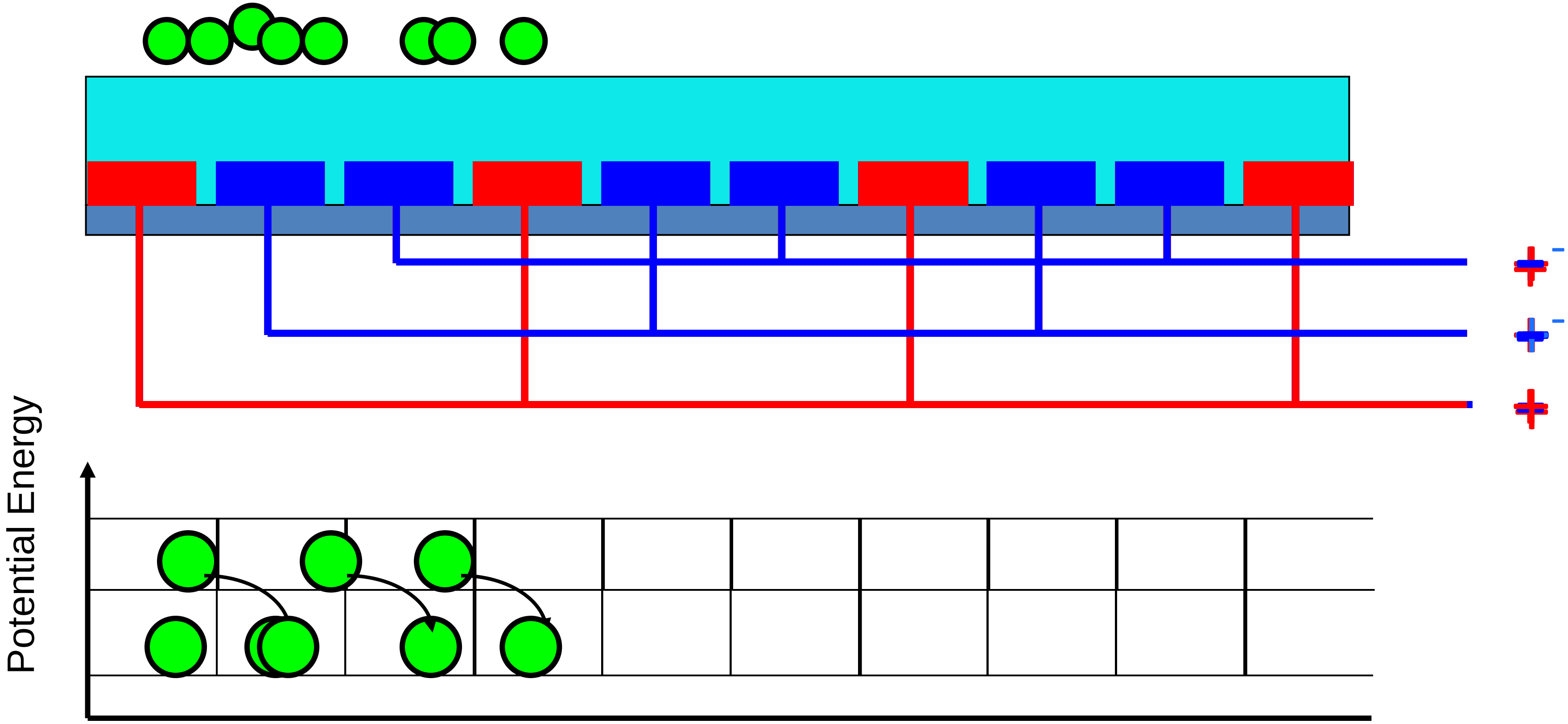
Helium

electron

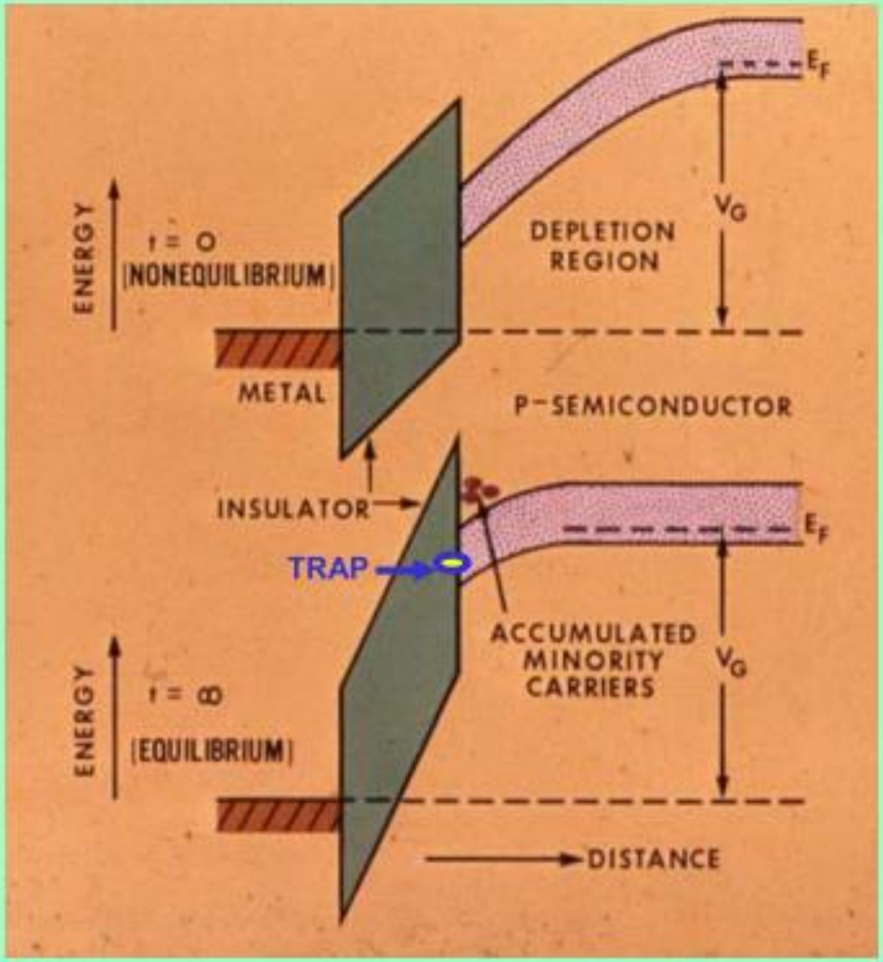
3-phase CCD

Clocking 8

Electron has moved one pixel (3 gates) to the right

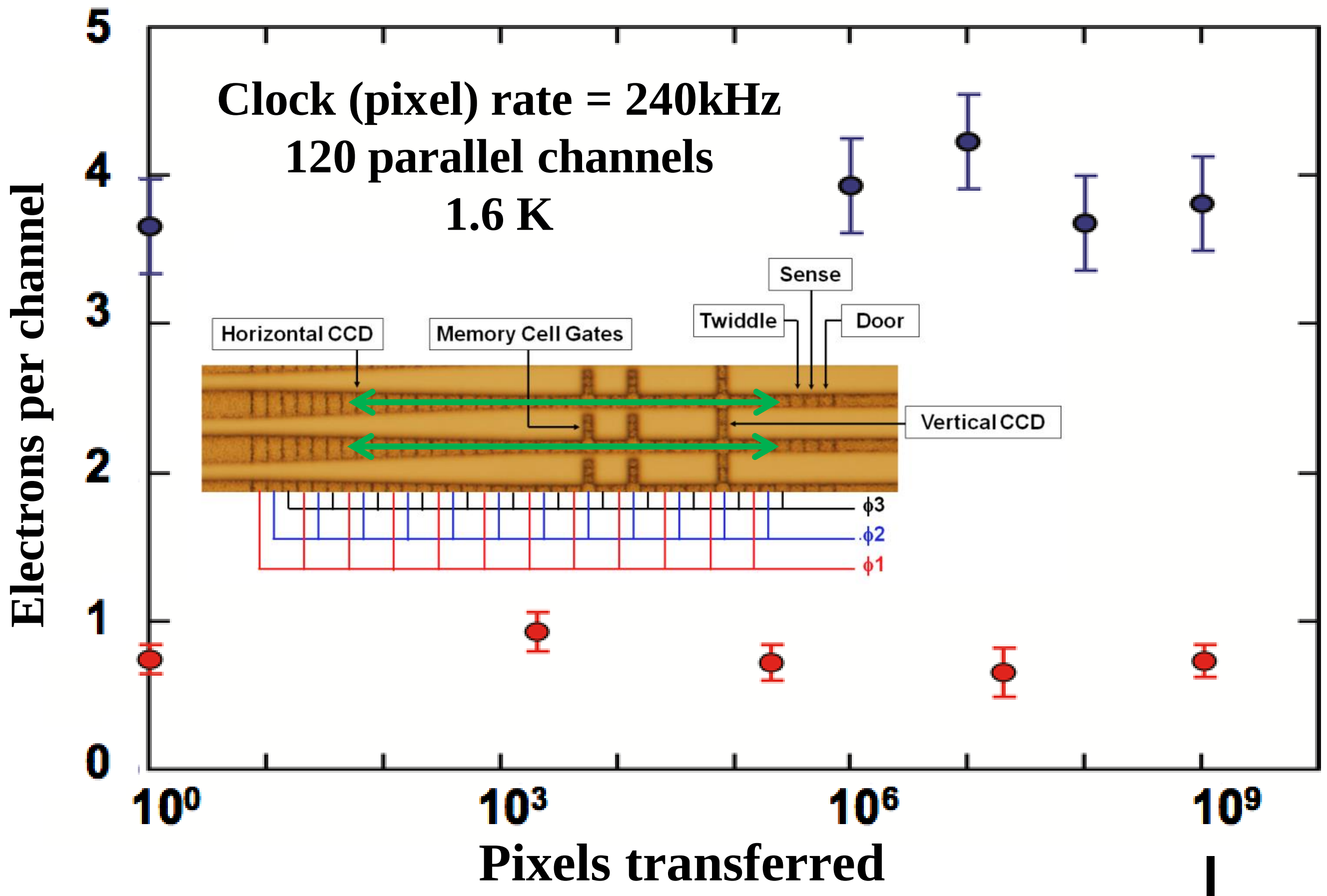


MOS Energy Diagram



George Smith, Nobel Prize Lecture on CCDs, 2009

Horizontal Clocking Efficiency



Clock (pixel) rate = 240kHz
120 parallel channels
1.6 K

No measurable errors

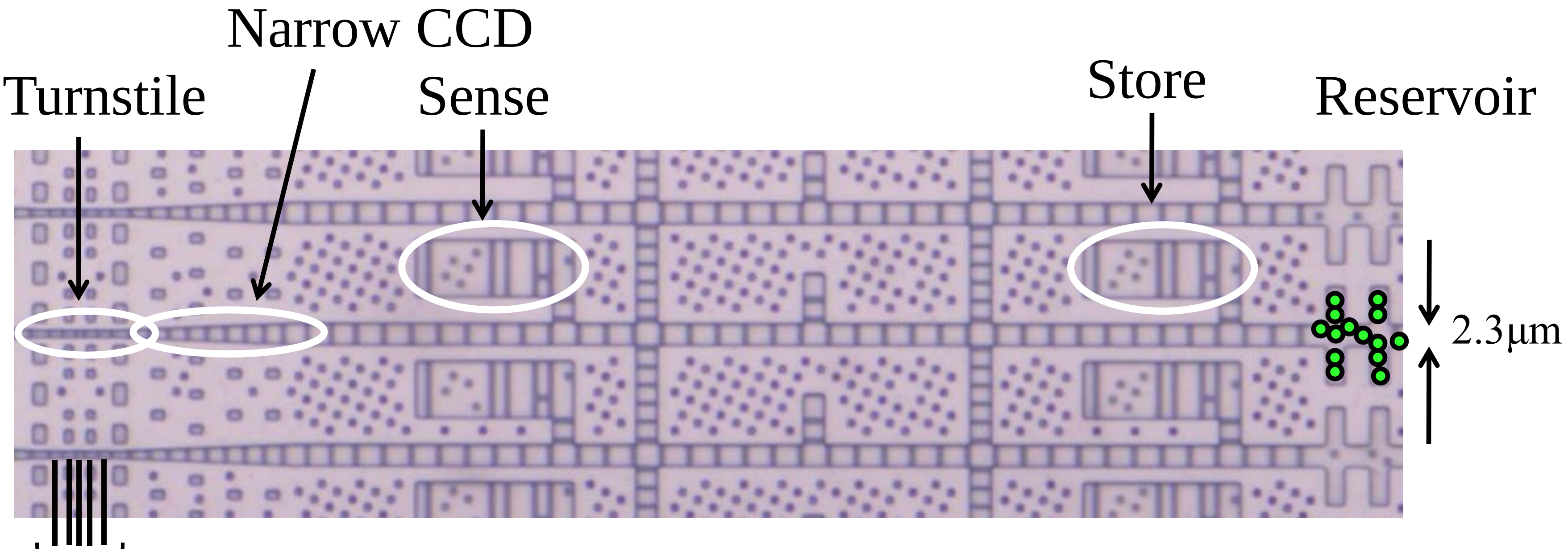
~ 70 min.

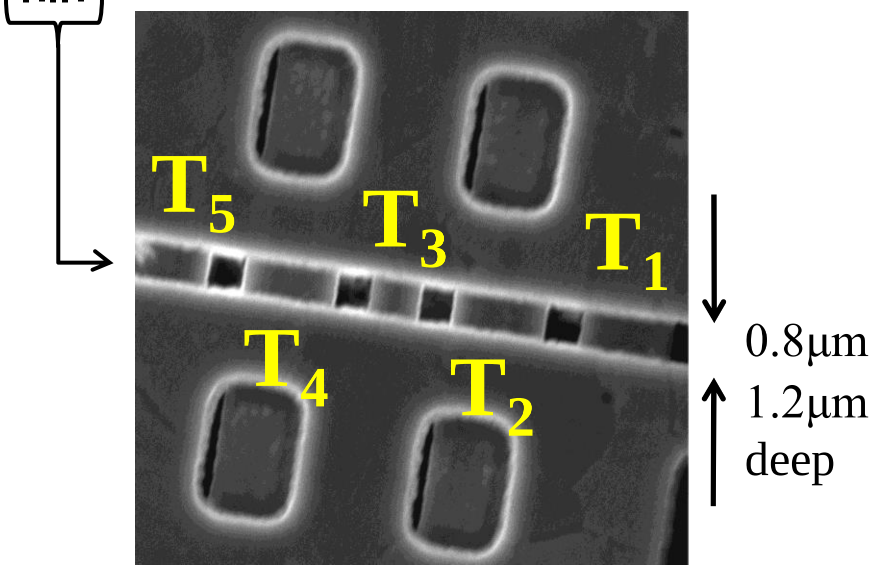
~ 9 km.

One Sheep per Clock

Device Structure

78 parallel channels

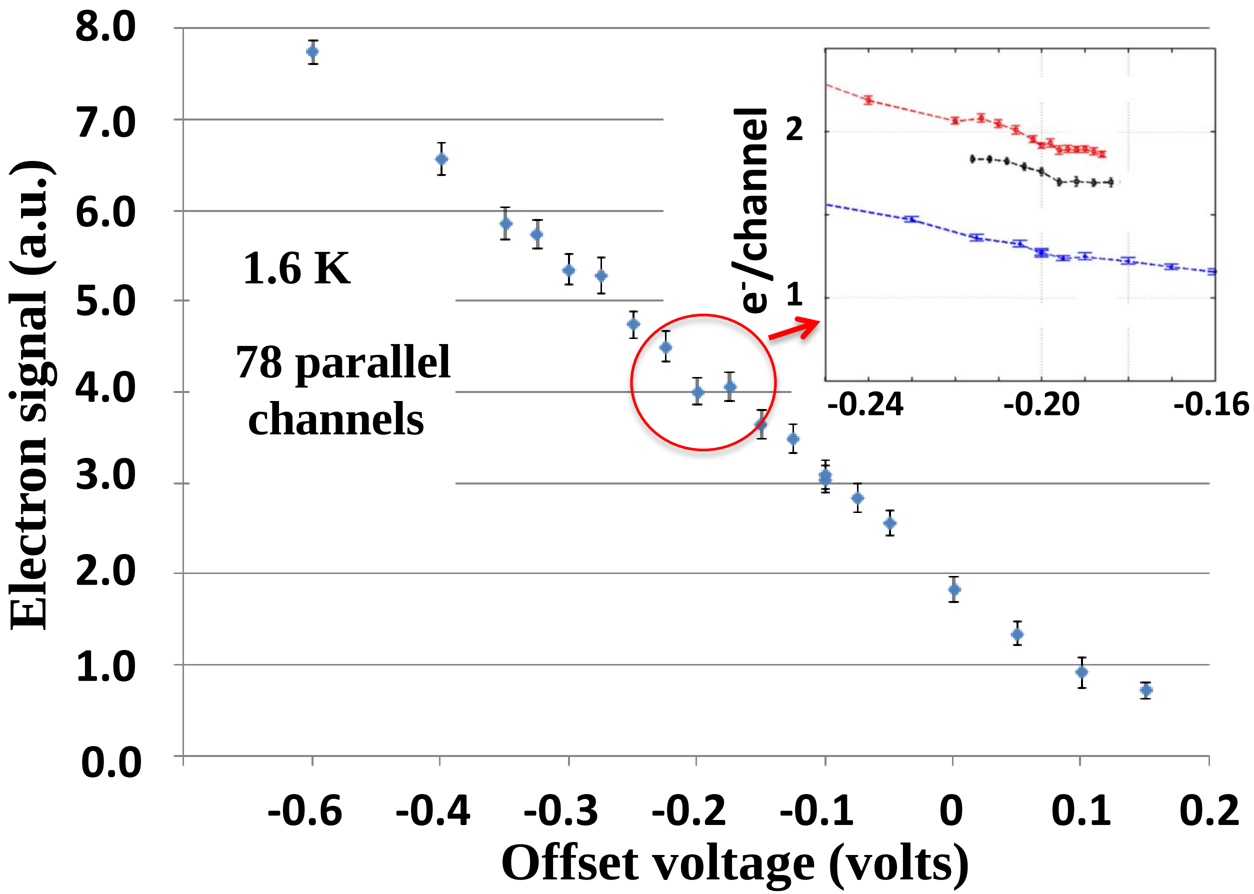




- Electrons deposited in reservoir
- Clock into channel and measure
- Go through narrow CCD
  - Extras back to reservoir
- Clock into turnstile region
  - ~20 electrons/channel

Plateau

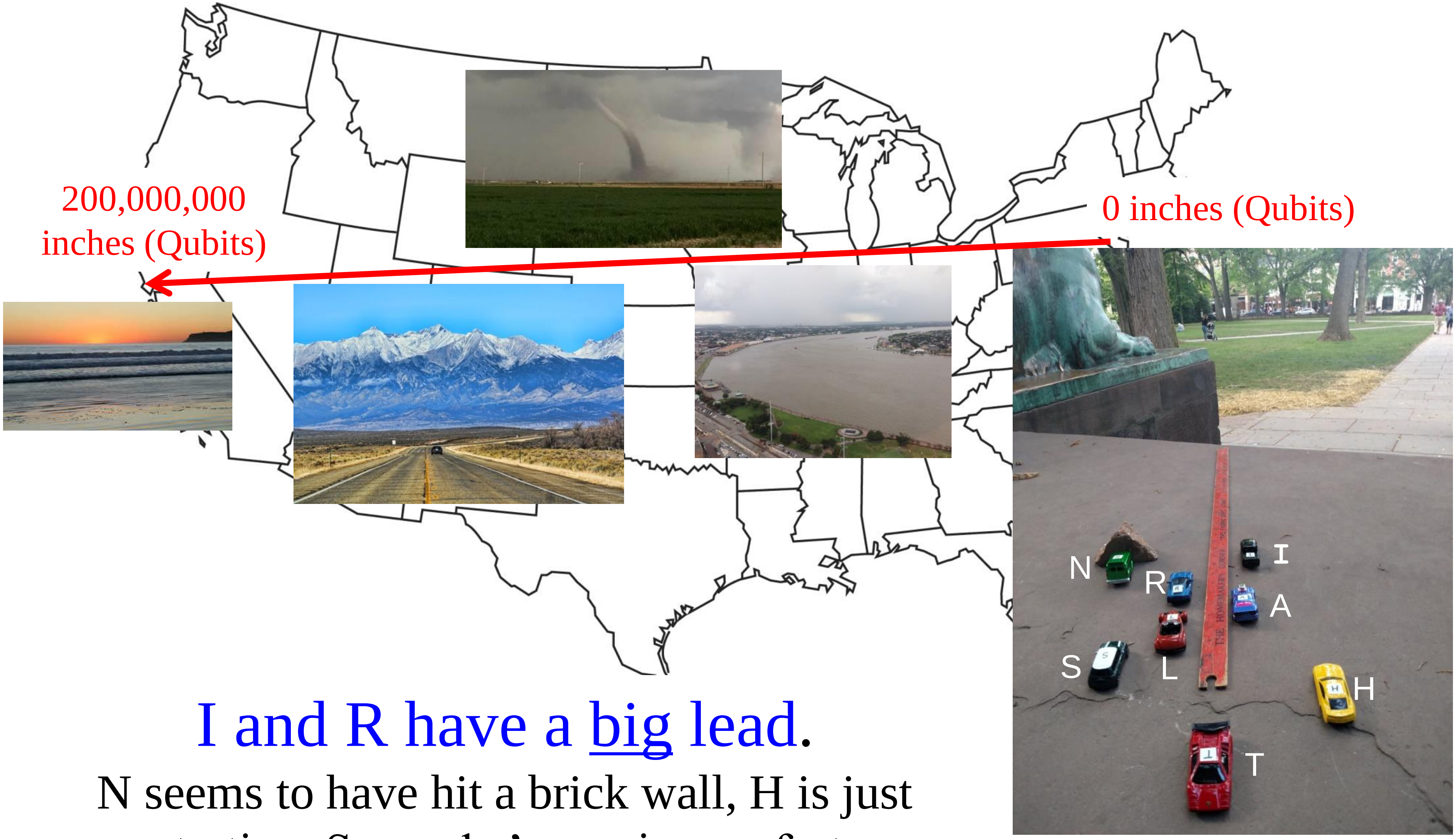
(measuring 78 channels in parallel)



Conclusions

- Electron spin qubits in Si have long enough coherence for quantum computing
- 1 and 2 qubit gates have been demonstrated using electrons in quantum dots and electrons bound to donors
- Devices can be very small and fast
- Individual devices can have high fidelity
- Scaling to a large quantum computer will require solving some difficult materials issues
- People working on various approaches to dealing with these issues

Race to a Quantum Computer



I and R have a big lead.

N seems to have hit a brick wall, H is just starting, S says he’s coming on fast, and T says he knows a shortcut