SAND2014-19313C

Exceptional service in the national interest

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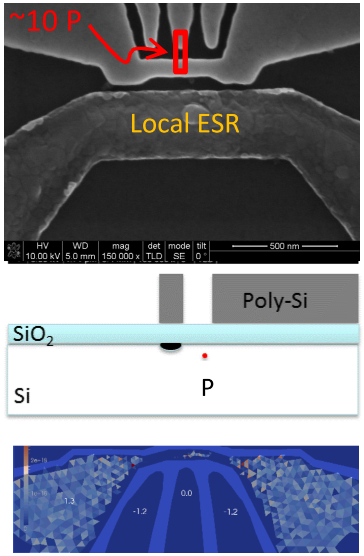
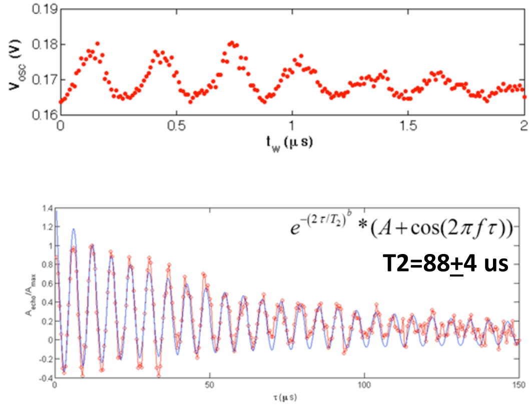
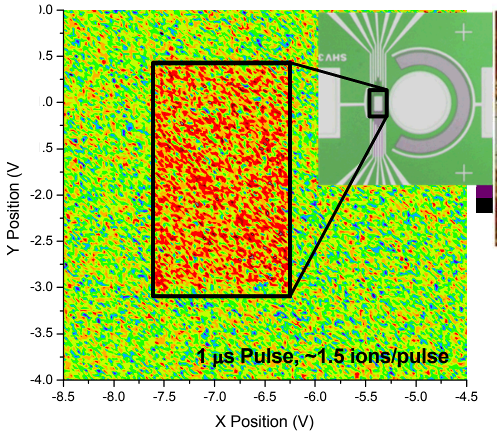
Silicon P donor qubit structure



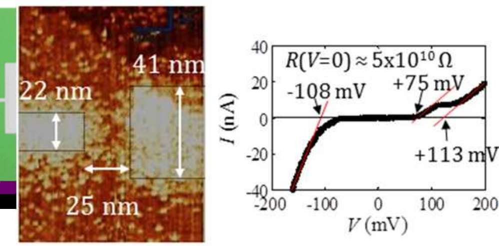
Spin read-out & Rabi oscillations



Single Sb^+ implant map (50 keV)



STM assisted nanofabrication



Tunnel barrier

Silicon qubit technologies

Malcolm Carroll

Sandia National Labs

November 13, 2014

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
LDRD

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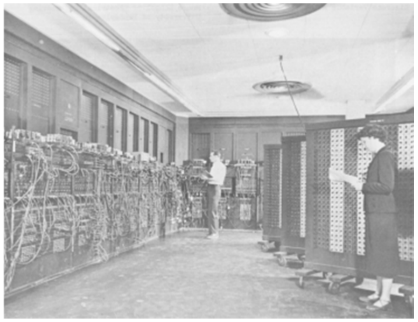
Outline

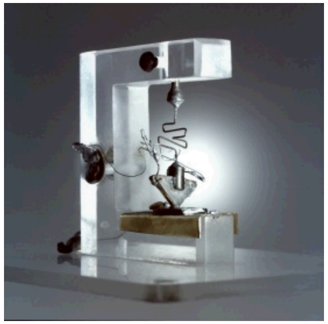
- Motivations
- MOS donor qubits
- Two qubit nanostructures
  - Single ion implant
  - STM
- Summary

Si motivation

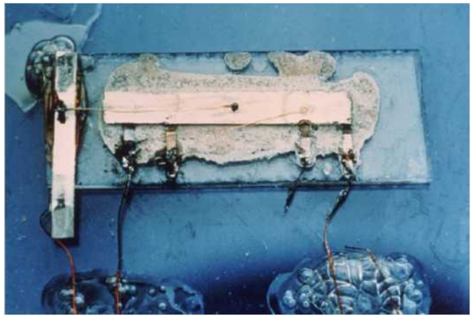
ENIAC



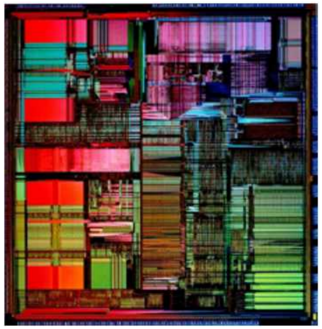
Ge BJT(1947)
Nobel Prize
***MOSFET patent (1928)**



Integration in Ge (1959)
Nobel Prize

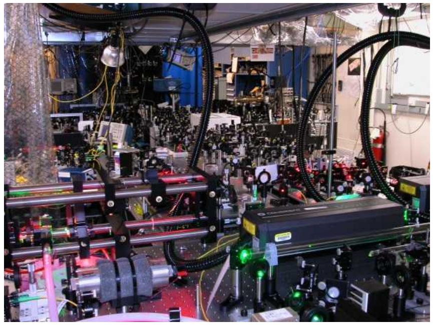


Modern CPU

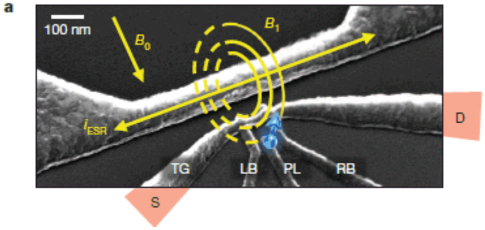


Ion traps at NIST (N < 10 qubits)

Nobel Prize (2012)

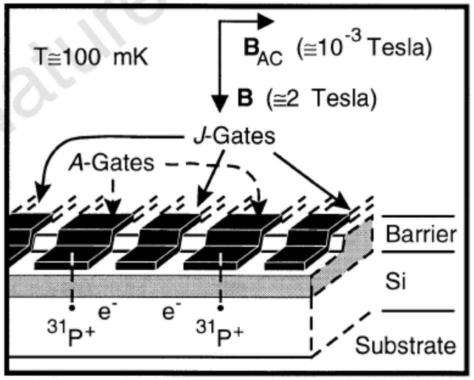


Si qubit (2012)



?

Kane (1998)

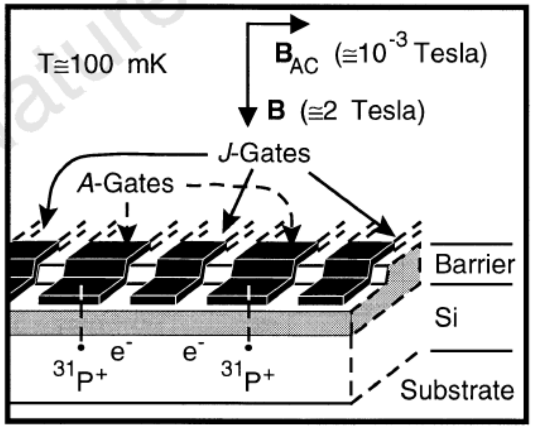


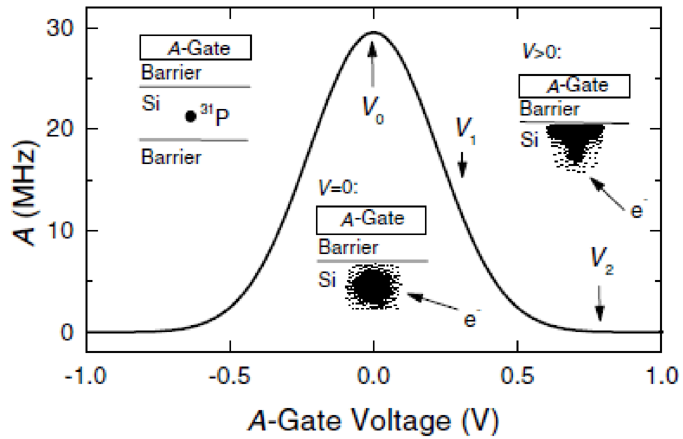
- Recent successes in silicon qubit technologies are exciting & reinforced by high fidelity gates in 28Si enriched devices
- Historical perspective: two central nobel prizes in QC, one of which was for integration at a time when End-of-Moore's Law looms
- Donor based qubits are demonstrating extraordinary good fidelity at reasonably high gate speeds in a system that is Si compatible
- Motivations for donors: nuclear spin qubit (memory & high fidelity gate), uniformity (1e12 spin ESR/NMR), atomic precision fab
- One of the big next steps: two qubit coupling
- This talk:
  - Introduce single donor qubit device fabrication & measurement
  - Discuss recent research towards exchange interaction between donor electrons at the surface

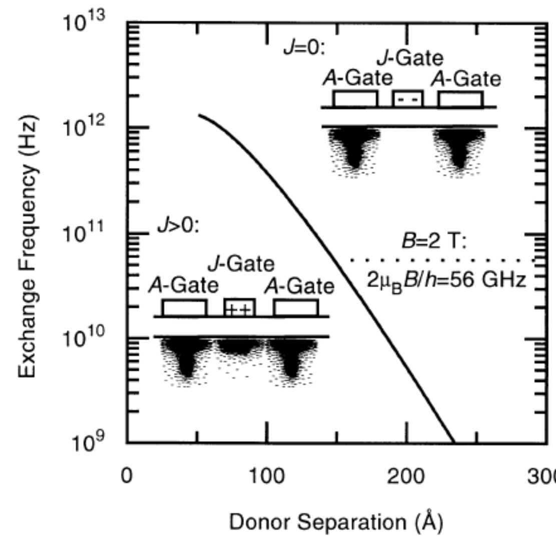
Outline

- Motivations
- MOS donor qubits
- Two qubit nanostructures
  - Single ion implant
  - STM
- Summary

Qubit approach using donors in Si





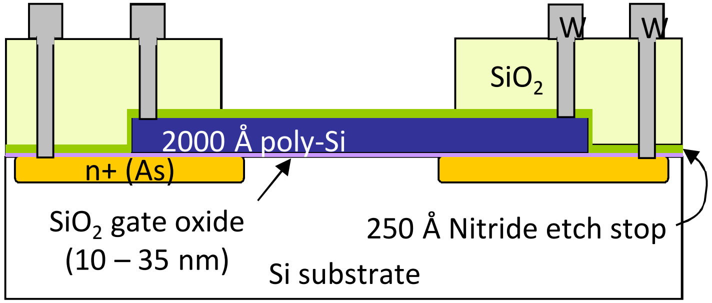


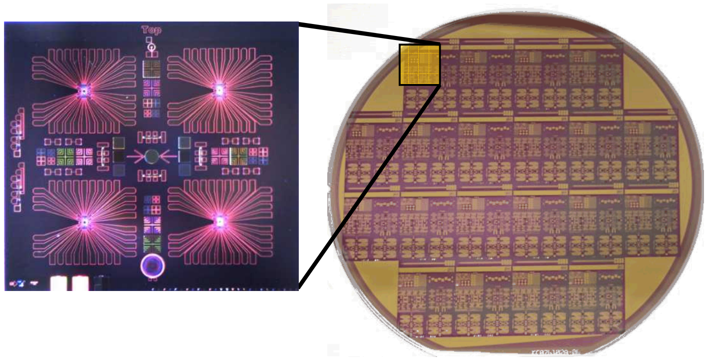
Kane, Nature, 1998

- Kane-like (electron spin only):
  - Single donor for qubit
  - One electrode on/off – frequency tuning to NMR or ESR u-waves
  - Second electrode on/off – overlap electrons for exchange (sqrt[SWAP])
- Lot's of progress in this area recently
- The big next step is donor-donor coupling. Many ideas in the literature.
- Next set of slides will discuss
  - Key elements used for connecting outside world to a single donors (making and using a QD in MOS)
  - Describe single spin ESR

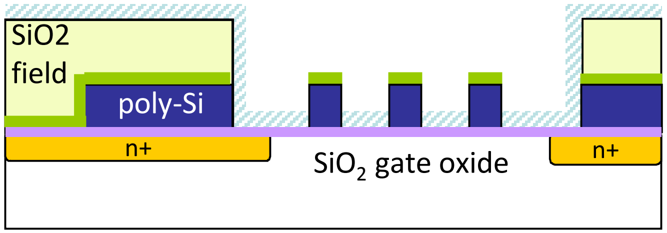
Nanostructure fabrication at Sandia National Labs

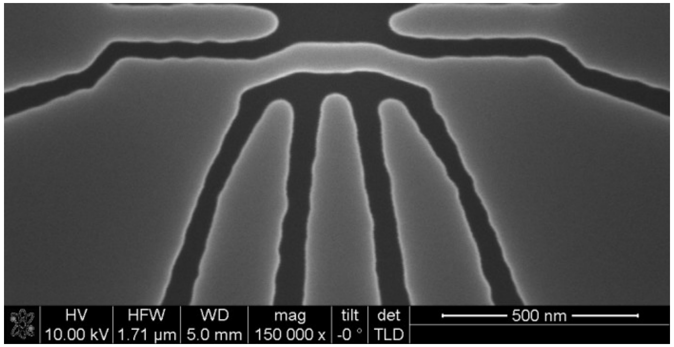
Front-end in silicon fab





Back-end nanolithography



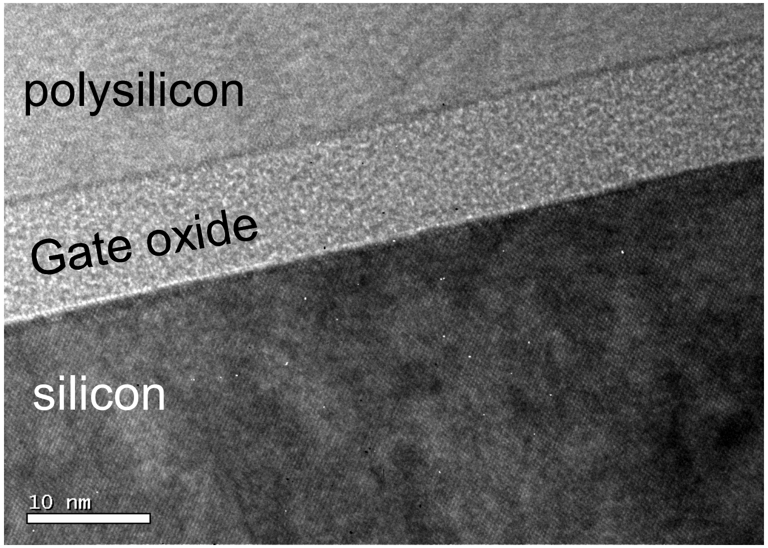


Goal: Use Poly-Si etched structures to produce donor-based qubits

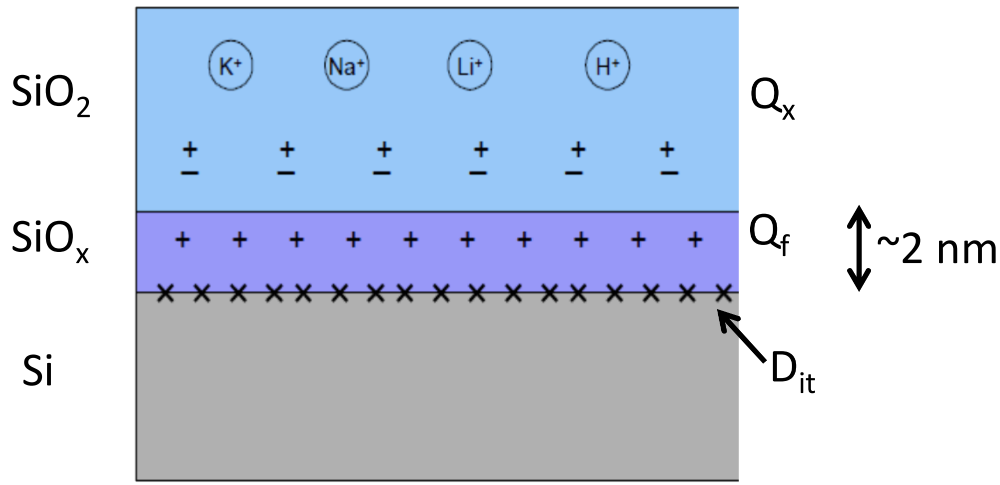
Rationale:

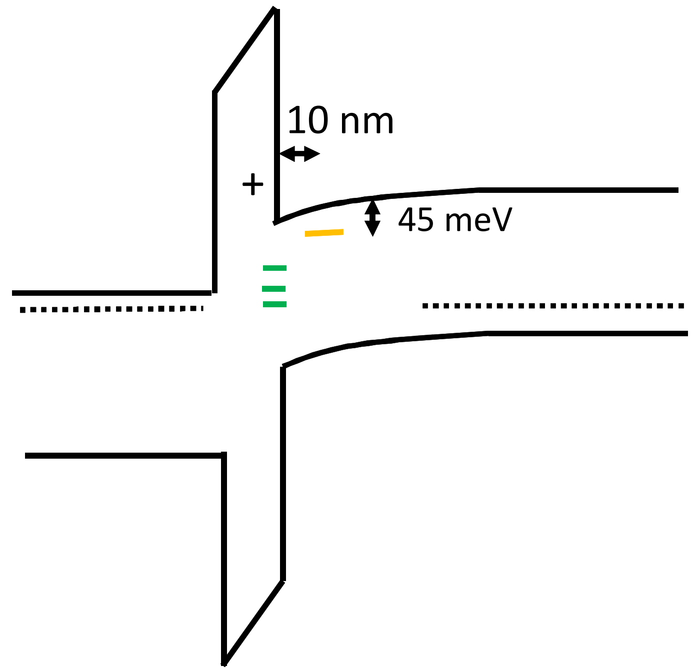
- Self aligned implant
- Foundry like processing

The MOS interface



Defects



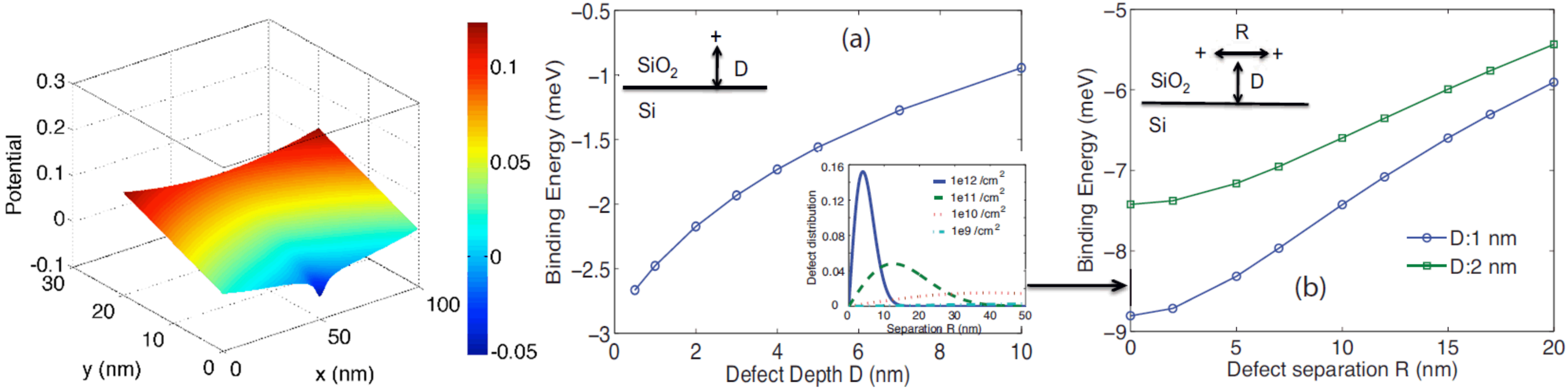


Room temperature picture

- D_{it} Interface traps and border traps within a "tunneling" distance of interface
- Q_f Fixed charge deeper in oxide

- What is relevant at low temperature?

The influence of fixed charge

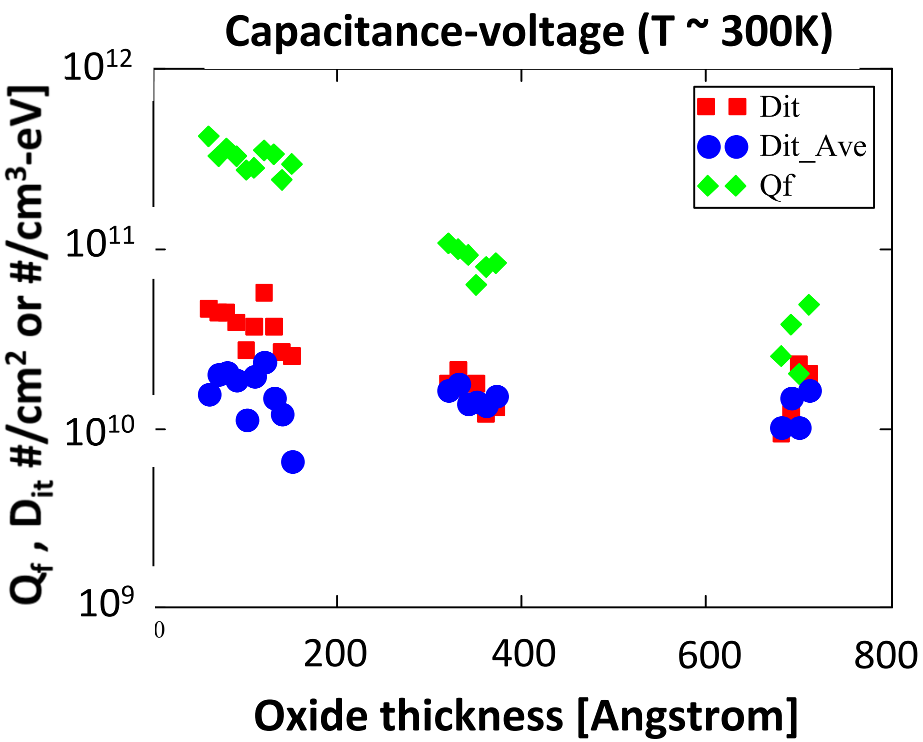


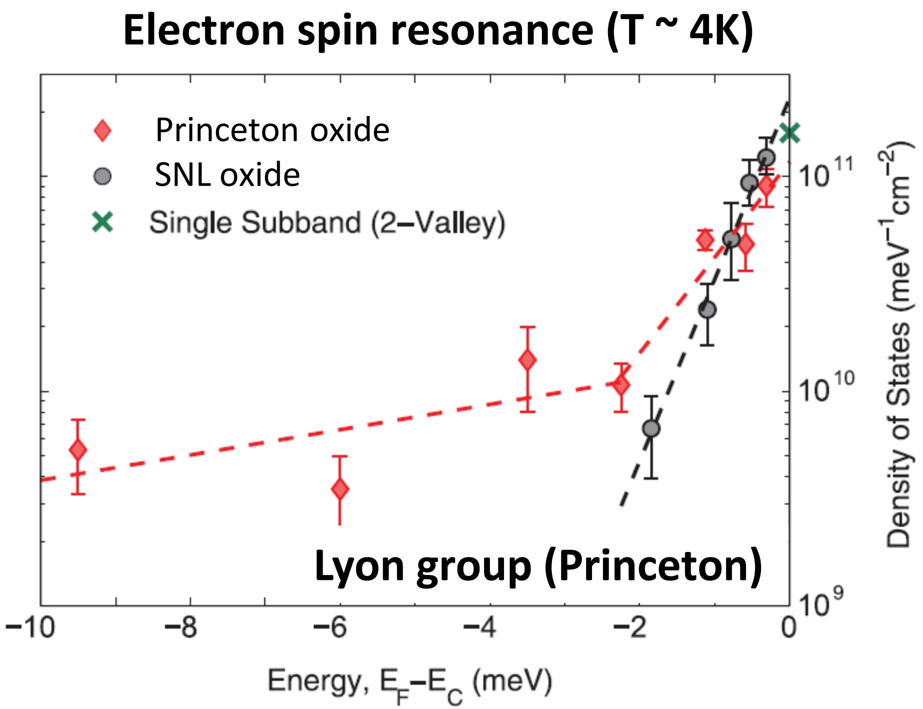
PHYSICAL REVIEW B 85, 125423 (2012)

Voltage controlled exchange energies of a two-electron silicon double quantum dot with and without charge defects in the dielectric

Rajib Rahman,* Erik Nielsen, Richard P. Muller, and Malcolm S. Carroll

Oxide defect densities





5,000 cm² / V-s < peak mobility < 15,000 cm² / V-s
***peak mobility probably not the best metric**

Jock et al., APL 2012

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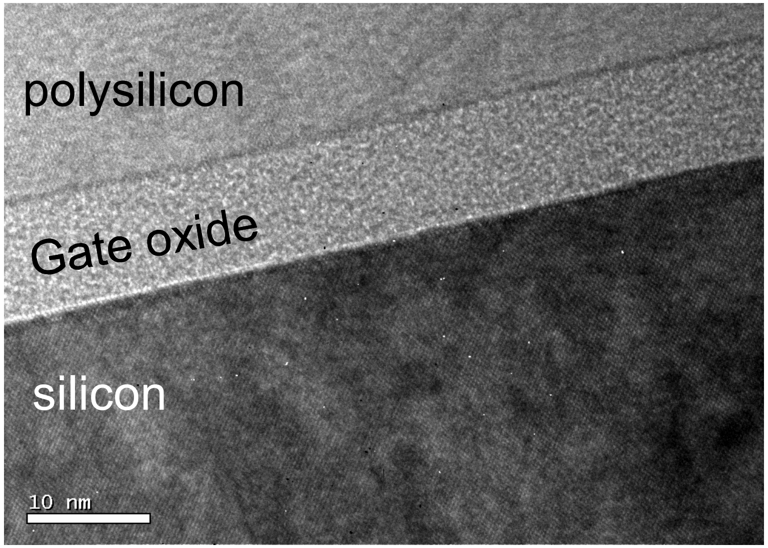
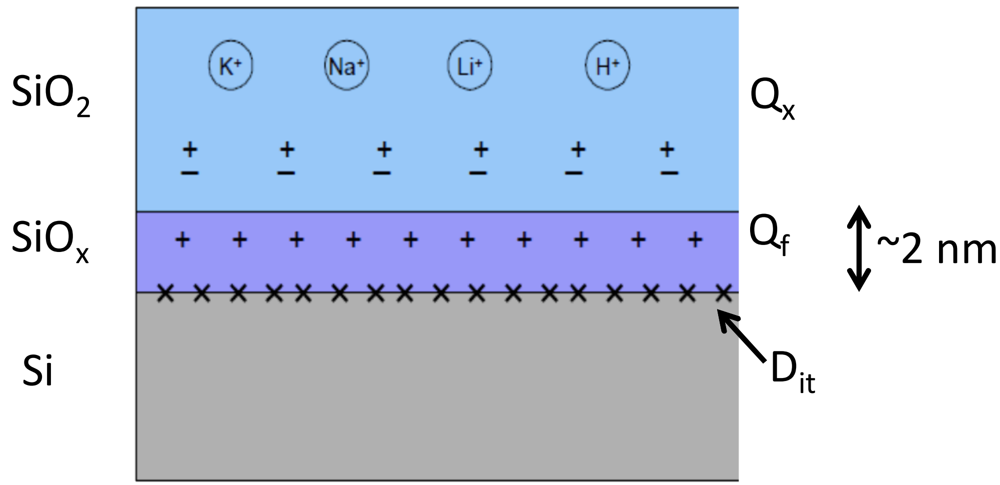
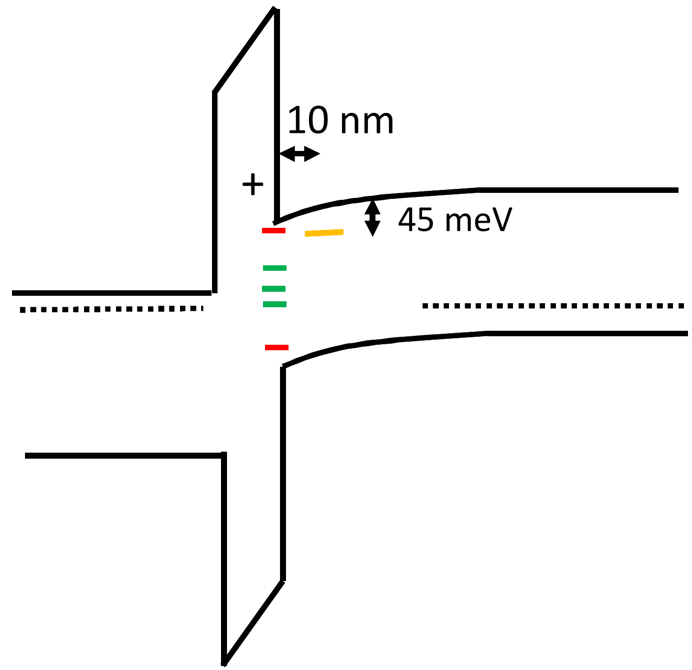
The MOS interface



Defects





Room temperature picture

- D_{it} Interface traps and border traps within a "tunneling" distance of interface
- Q_f Fixed charge deeper in oxide

Low temperature picture

- Shallow traps are most relevant
- Not much known about interface traps close to band edge
- Fixed charge could be producing a dynamic state at the interface

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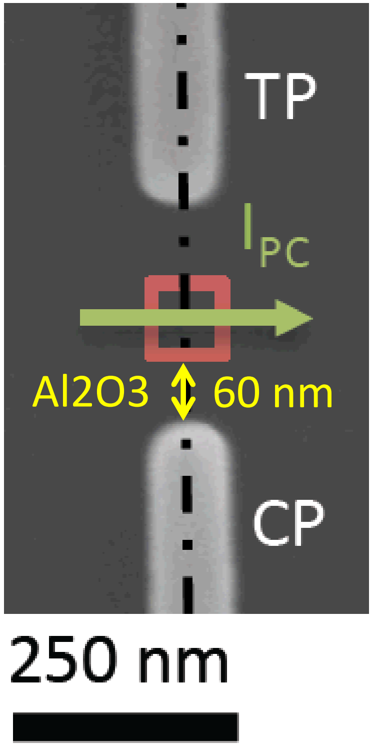
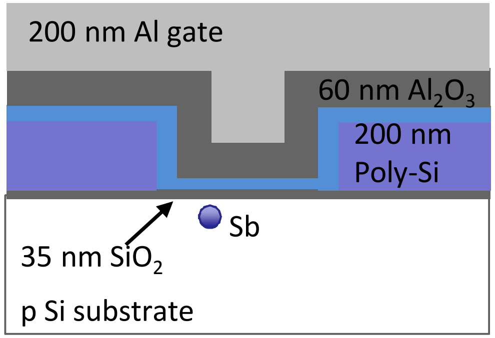
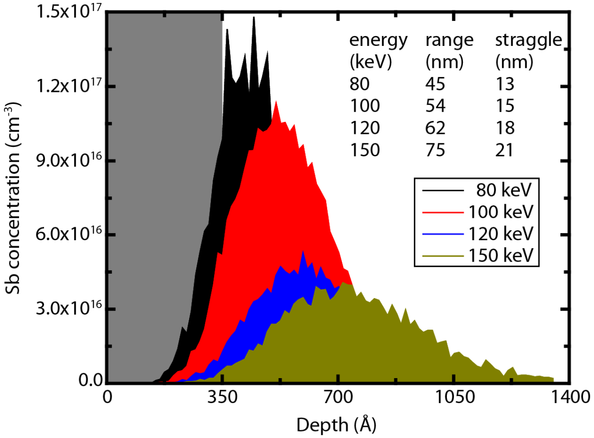
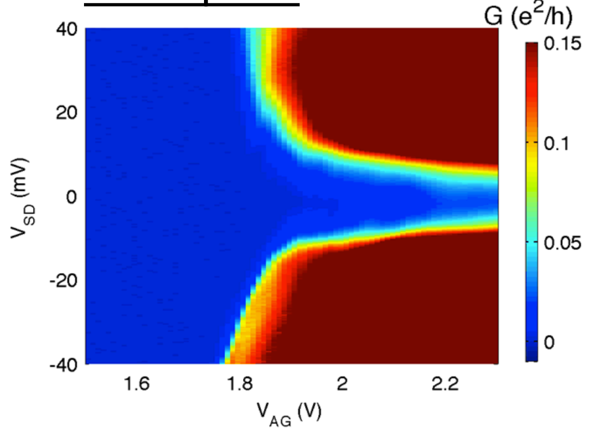
Barriers without resonances and after implant





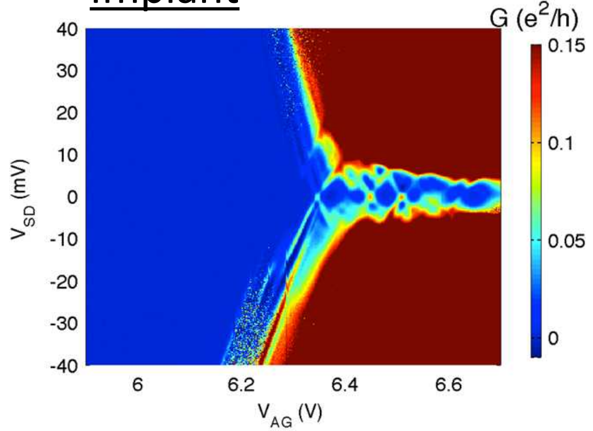


No implant



T ~ 4K

Implant



T ~ 4K

- Simple point contact (no implant) shows no resonant behavior
- Existence proof that MOS interface can produce 'clean' tunnel barrier in large area
- Sb implanted point contact shows many resonances & threshold shift

Shirkhorshidian

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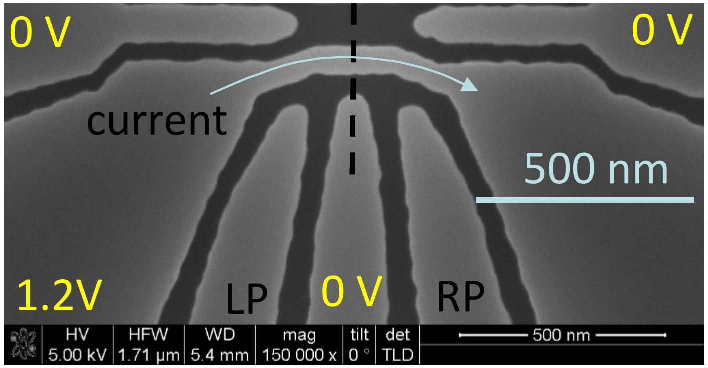
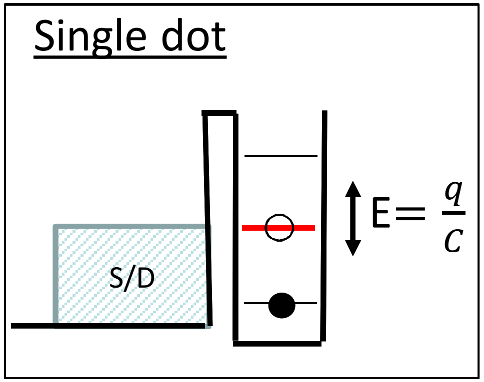
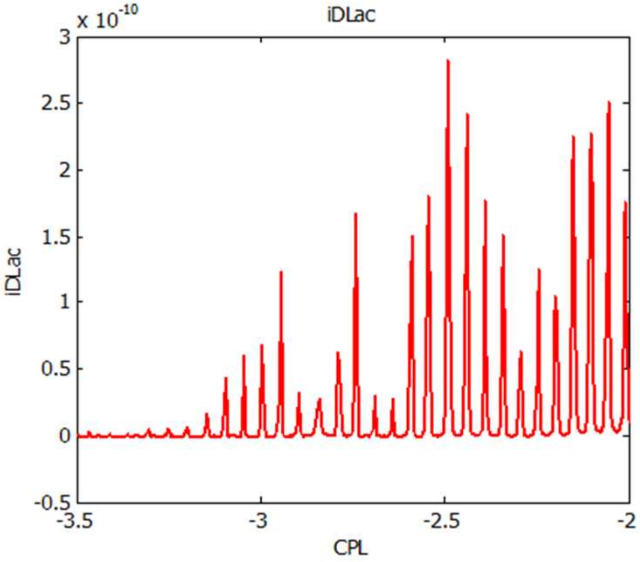
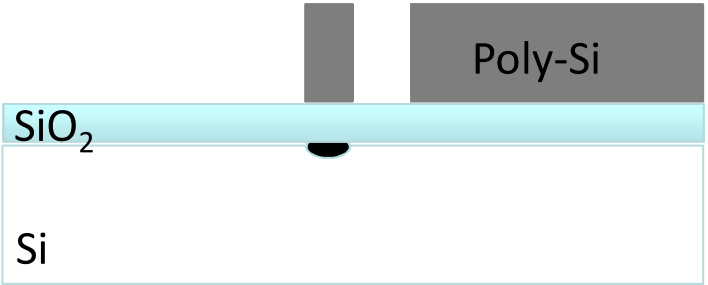
Poly silicon quantum dot

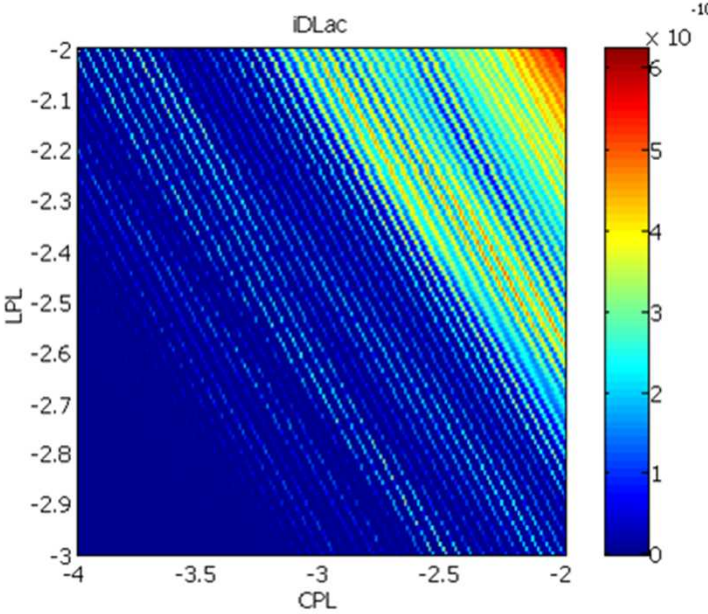








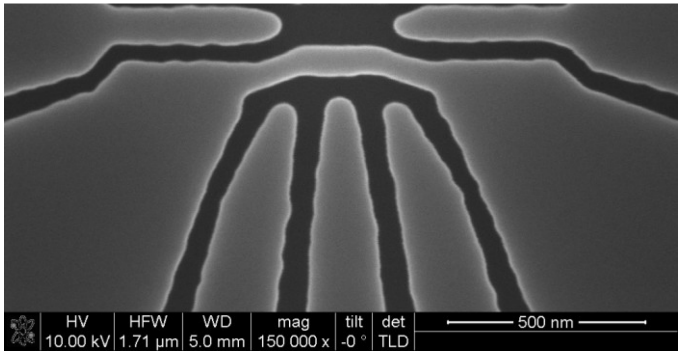
- Relatively regular period Coulomb blockade achieved in poly silicon SET
- Wire width ~50-70 nm with gaps between wire and plunger of ~40-50 nm at tips
- Disorder in potential is still observed in effects on non-linear modulation of tunnel barriers
  - Modulation of conductance not monotonic

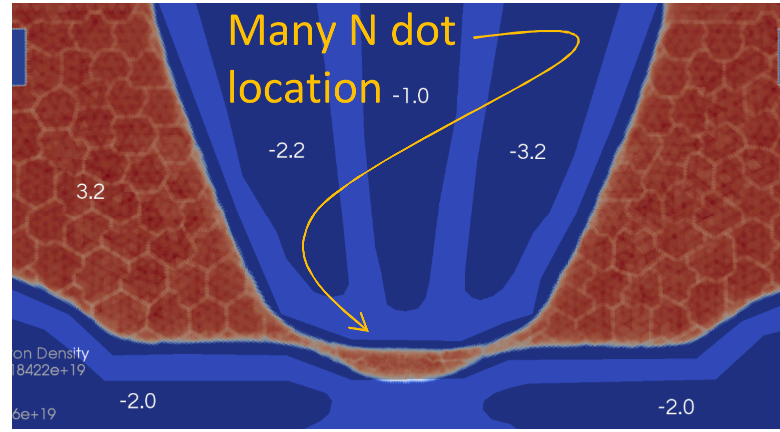


Harvey-Collard

Sandia National Laboratories

Semiclassical modeling of lithographic dot





- QCAD is semi-classical simulation capability developed at SNL
- Gate to quantum dot capacitances are similar to QCAD predictions in multiple devices
  - Order of 20-30% disagreement in many cases

Metric	Measured	Simulated
C_{lp}	2.2 +/- 0.3	2.3
C_{rp}	2.1 +/- 0.4	2.1
C_{lc}	3.7 +/- 0.3	4.1
C_{l}	2.1 +/- 0.2	2.4
C_{r}	2.0 +/- 0.2	2.0
C_{ag}	17 +/- 1.3	26.2

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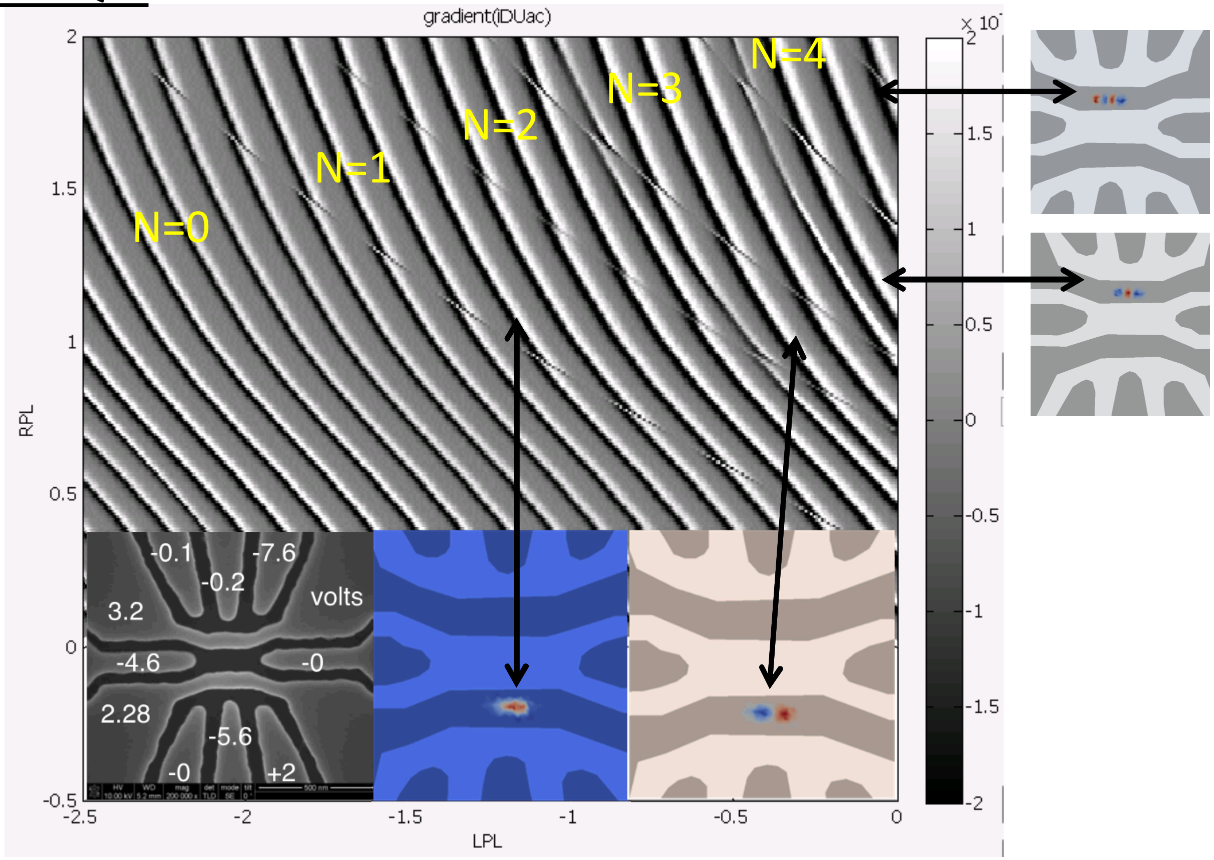
Few electron QD



- Last electron signatures: high tunnel rate, spin filling, charging energy
- Top gate capacitance is 3.2 aF
- Corresponding size N=1 57 x 57 nm^2 and N=2 67 x 67 nm^2
- Single particle simulations from QCAD
- Areas of simulated few electron QD approximately the same but elongated (energy levels defined by long axis)
  - W ~ 25 nm and L ~60-75 nm
- Curved slope is due to accumulation under plunger and shift in C

SET – Few electron regime

Tunnel rates

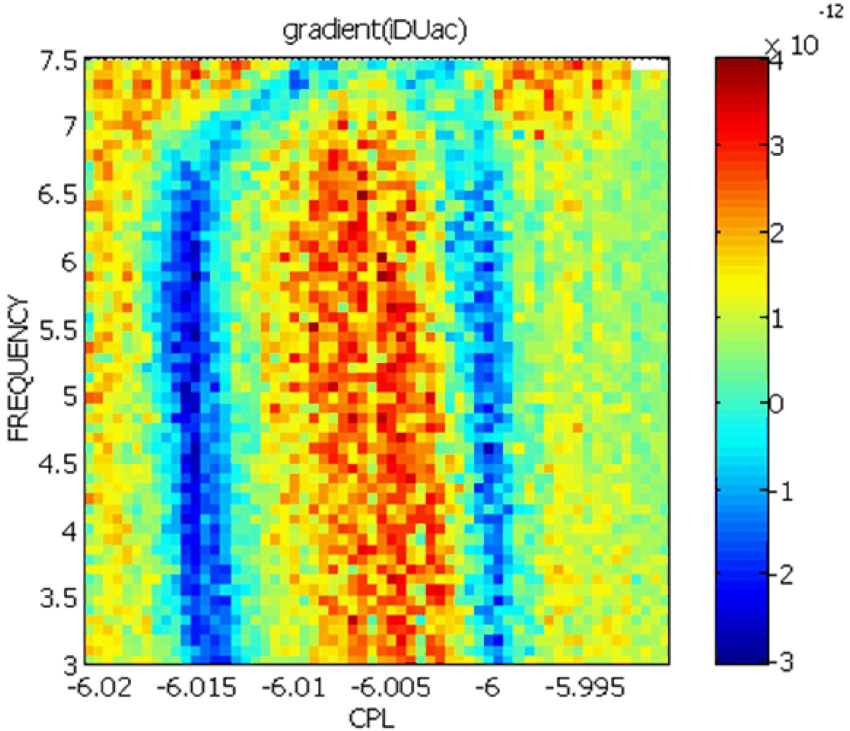
N	1	2	3	4	5
Rate (MHz)	5.6	5.6	5.6	5.6	5.6

All lines have the same (fast) tunnel rate.

Last lines are all instrumentally bandwidth limited

Last transition is wide open and change in tunnel rate between transitions not producing sufficient drop-off to expect trapped electrons below last transition

Example



20140926T112757

N = 3

SET – Few electron regime - Summary

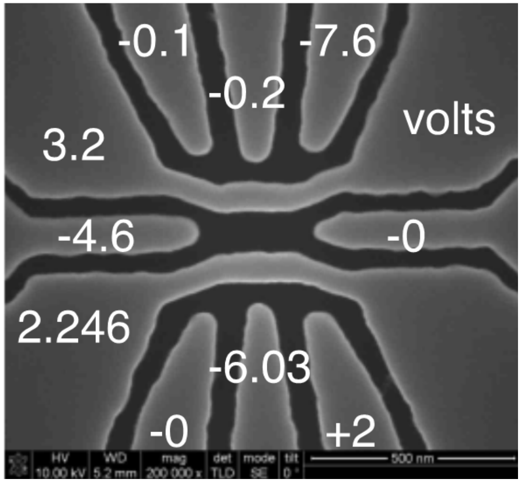
Periods

Gate	N = 1 (mV)	N = 2 (mV)	N = 3 (mV)	N = 4 (mV)
AGL	50	36	46	36
CPL	276	192	256	192
LPL	630	530	570	480
RPL	590	440	580	470
Gate	**N = 1 (aF)**	**N = 2 (aF)**	**N = 3 (aF)**	**N = 4 (aF)**
AGL	3.20	4.45	3.48	4.45
CPL	0.58	0.83	0.63	0.83
LPL	0.25	0.30	0.28	0.33
RPL	0.27	0.36	0.28	0.34

Charging energy (using CPL lever arm 46 ueV/mV)

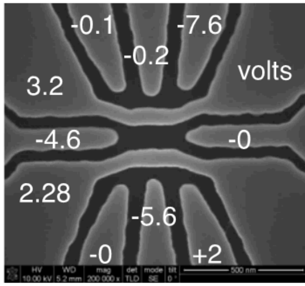
	N = 1	N = 2	N = 3	N = 4
E_C (meV)	12.7	8.82	11.8	8.83

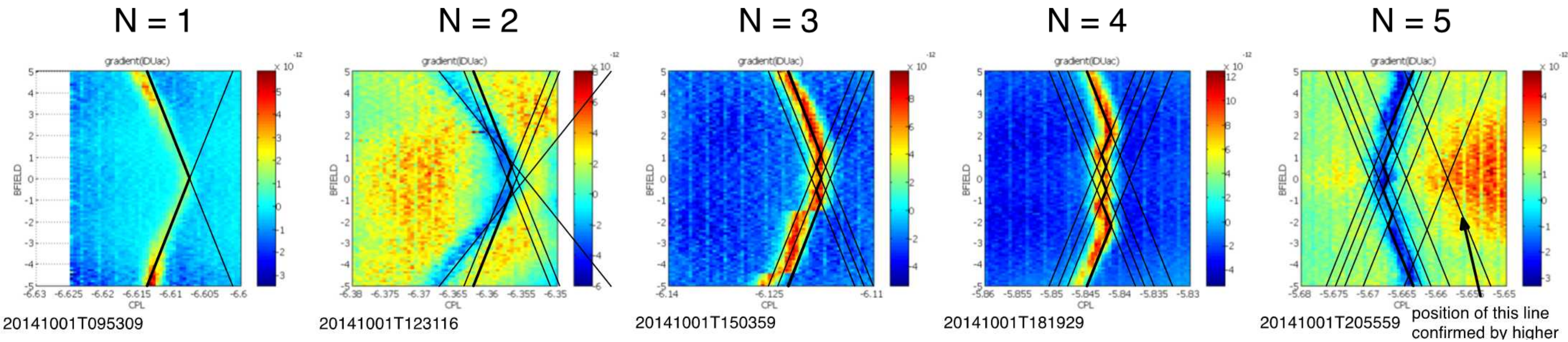
Configuration for N = 1.



Dot for N = 1 is 57 nm x 57 nm (AGL parallel plate capa model) and 67 x 67 for N = 2.

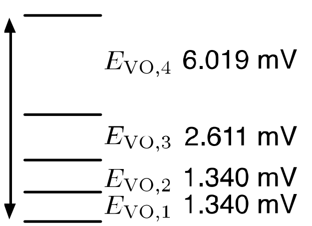
SET – Few electron regime – Spin filling





- N=1 transition behaves as spin down
- No kinks w/ N=1 consistent with last electron
- Single particle model can be fit to this data and produces 60-300 ueV spacing
- Vertical field is large and would predict ~500 ueV valley splitting from previous work
- Valley-orbital spacings similar to simple elliptical QD with ~75 nm long axis up to at least N=4

Lever arm 46 ueV/mV	mV	μeV
$E_{VO,1}$	1.340	61.6
$E_{VO,2}$	1.340	61.6
$E_{VO,3}$	2.611	120
$E_{VO,4}$	6.019	277



Spin filling – Energy spacing estimation

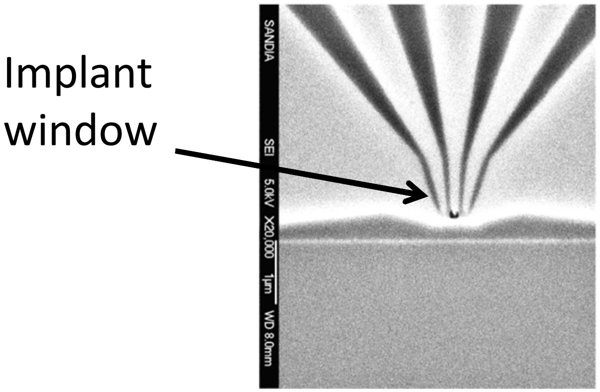
Valley splitting

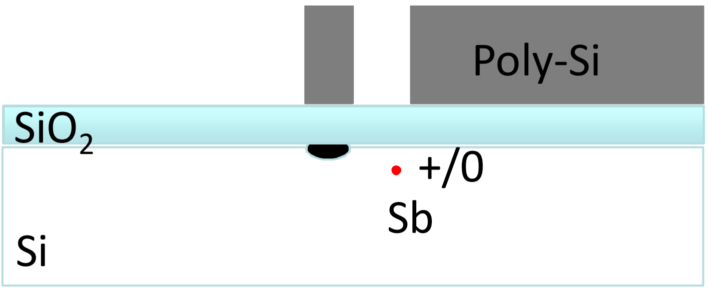
- Two lowest valleys (-kz, +kz).
- V_{th} = 1.3 V. V_{AGL} = 2.28 V. Hence field E = 28 V/m.
- This is 0.5 meV of valley splitting according to [1].
- [1] C. H. Yang, A. Rossi, R. Ruskov, N. S. Lai, F. A. Mohiyaddin, S. Lee, C. Tahan, G. Klimeck, A. Morello, and A. S. Dzurak, "Spin-valley lifetimes in a silicon quantum dot with tunable valley splitting," Nat Commun, vol. 4, 2013.

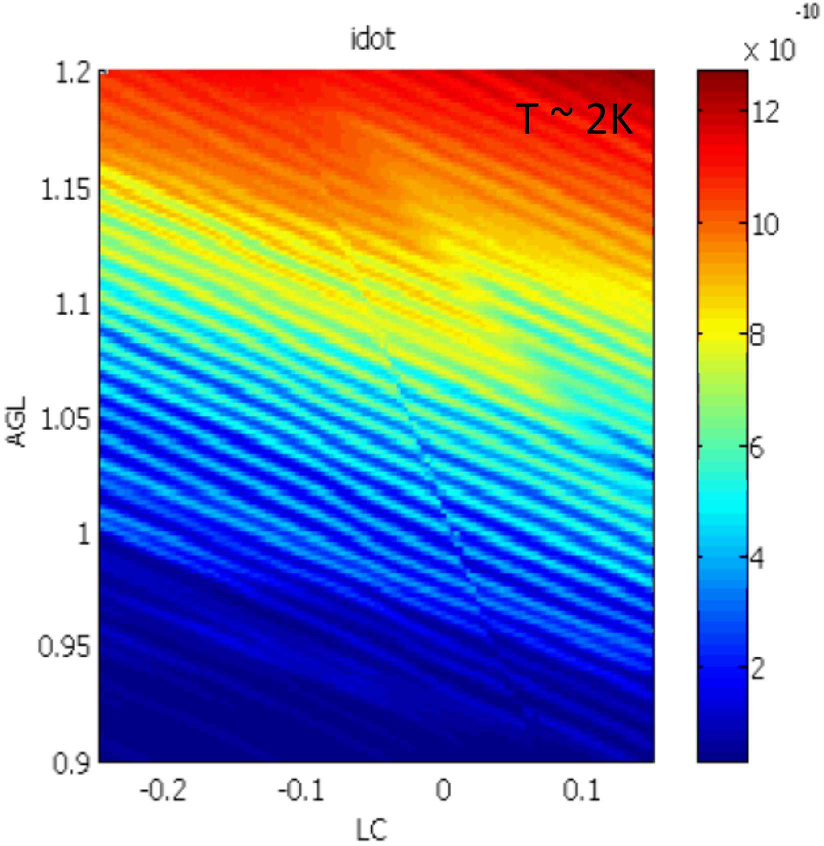
Orbitals

- Take simple square well potential model.
- E(n) = $hbar^2 k^2/2m$. k = n*pi/L. m = 0.98 m_e.
- Taking L = 67 nm (valid for N = 2) E =86 µeV for n=1. Delta between levels is order of 100 ueV

Gate wire with implant – QD coupling to donor

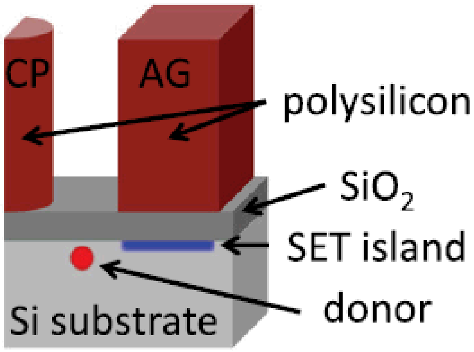


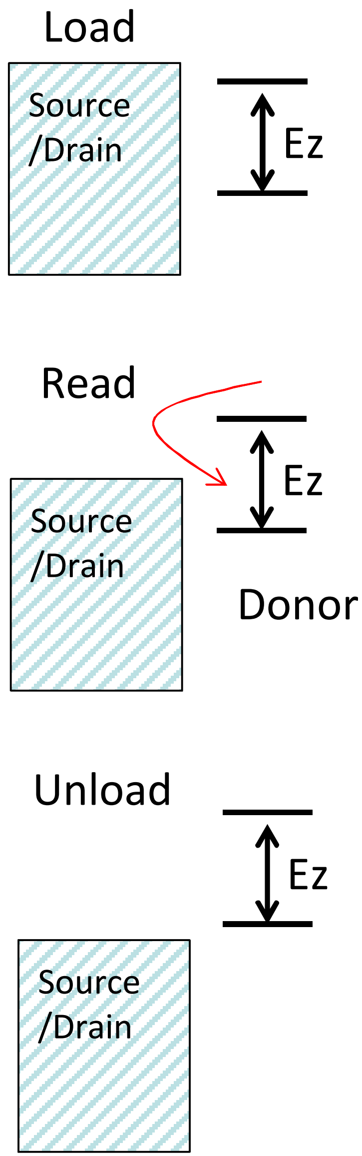




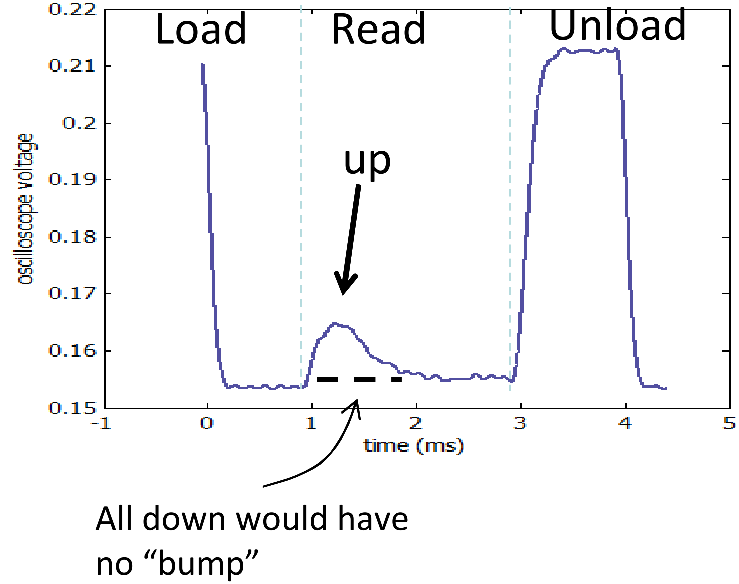
- Typical implant conditions:
- 120 keV implant, range ~28 nm below SiO_2/Si interface, 18 nm vertical straggle
- 4e11/cm^{-2} dose → ~ 14 Sb donors in 60 x 60 nm^2 window
- Charge offsets are seen in these implanted poly-MOS devices

Tuning spin readout

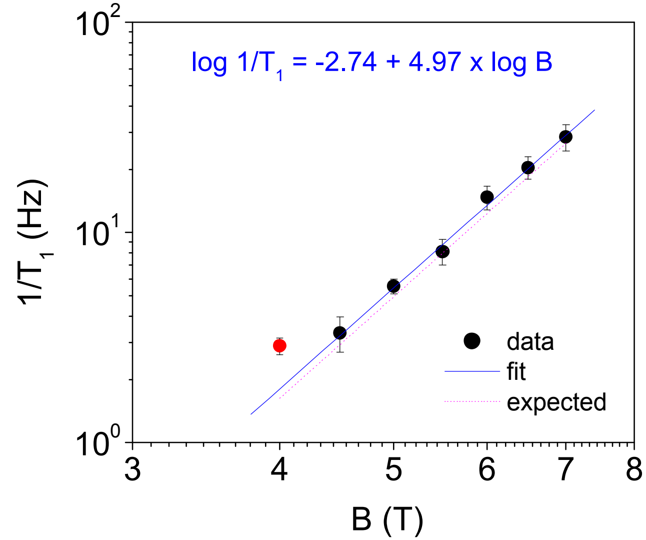




Spin bump with 256 averages

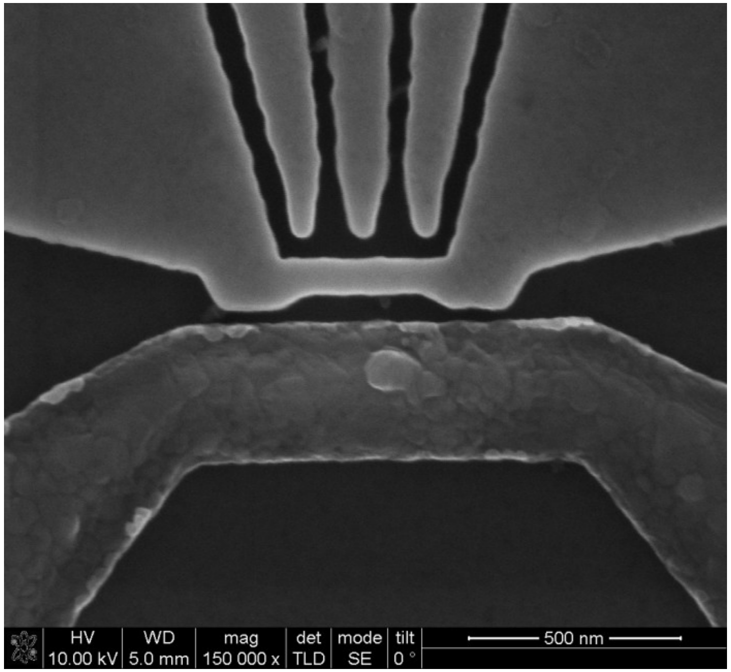


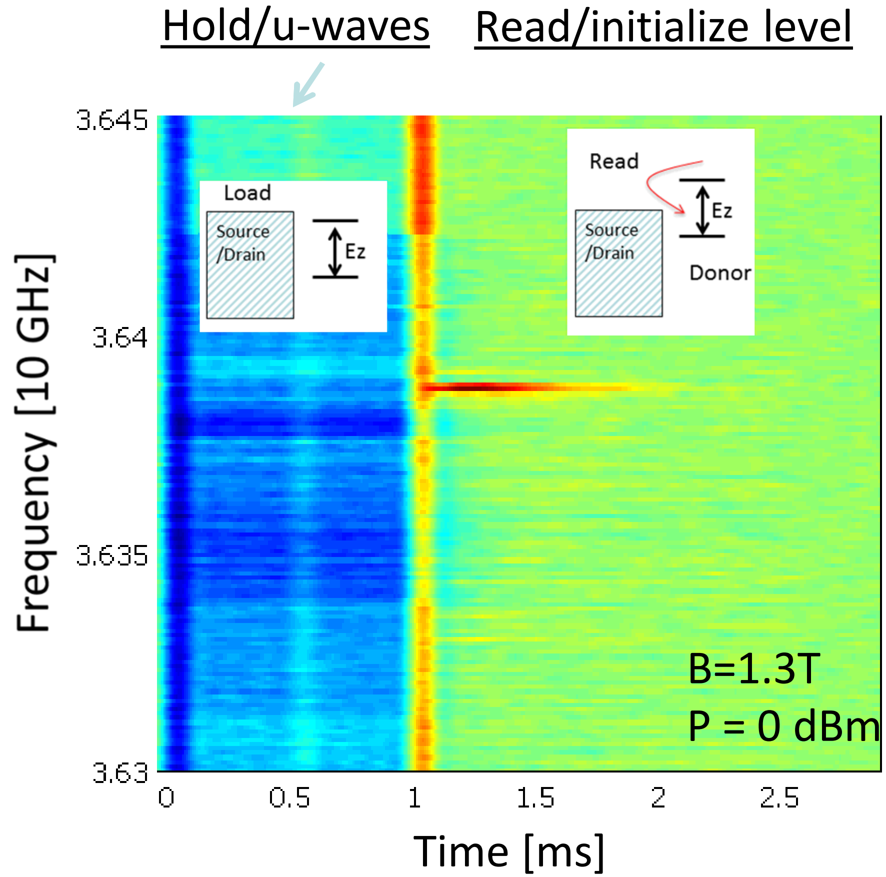
- T1 observed to have B^5 dependence
- Wilson & Feher ensemble Sb: T_1 = 1111 s at 1.25 K, B = 0.8 T for B along (100) direction
- Fairly close when kT scaled (T_e~400 mK)



Tracy et al. APL 2013 (Sb donor)

Electron spin resonance of single spin



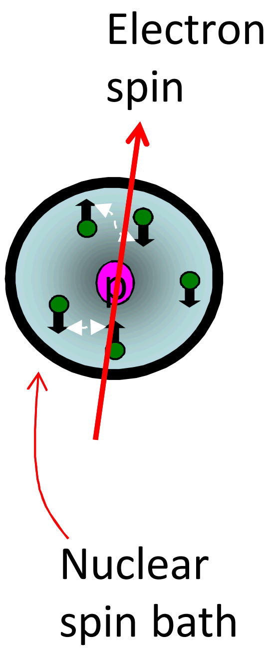


- Two level test with ESR detects spin resonance
- Phosphorus implanted sample (~ 400 nm from center)
- Similar approach to Al-Si SET devices [Pla et al. (2012)]
- Line width ~ 5 MHz

Nguyen

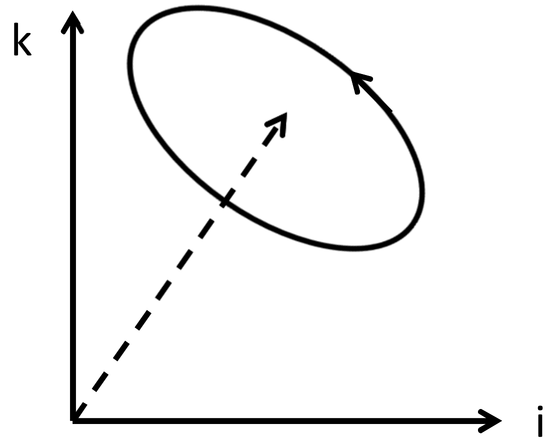
Tilting angle picture of ESR

Rotating frame



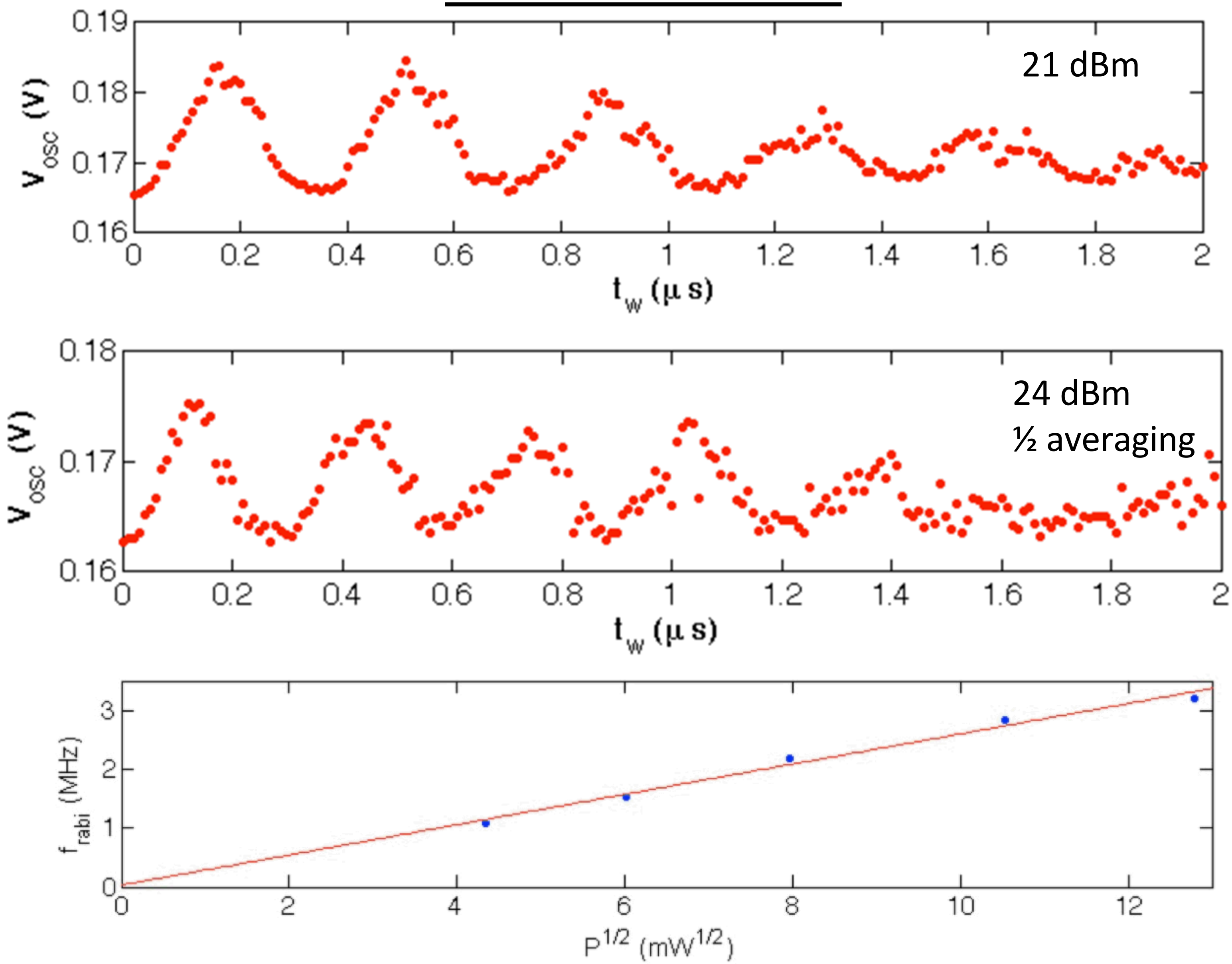
$$\tilde{H}_Q = \hbar\Delta\omega\sigma_e^z + \mu_B B_{ac}\sigma_e^x$$

$$\mathbf{n} = \hbar\Delta\omega\hat{k} + \mu_B B_{ac}\hat{i}$$



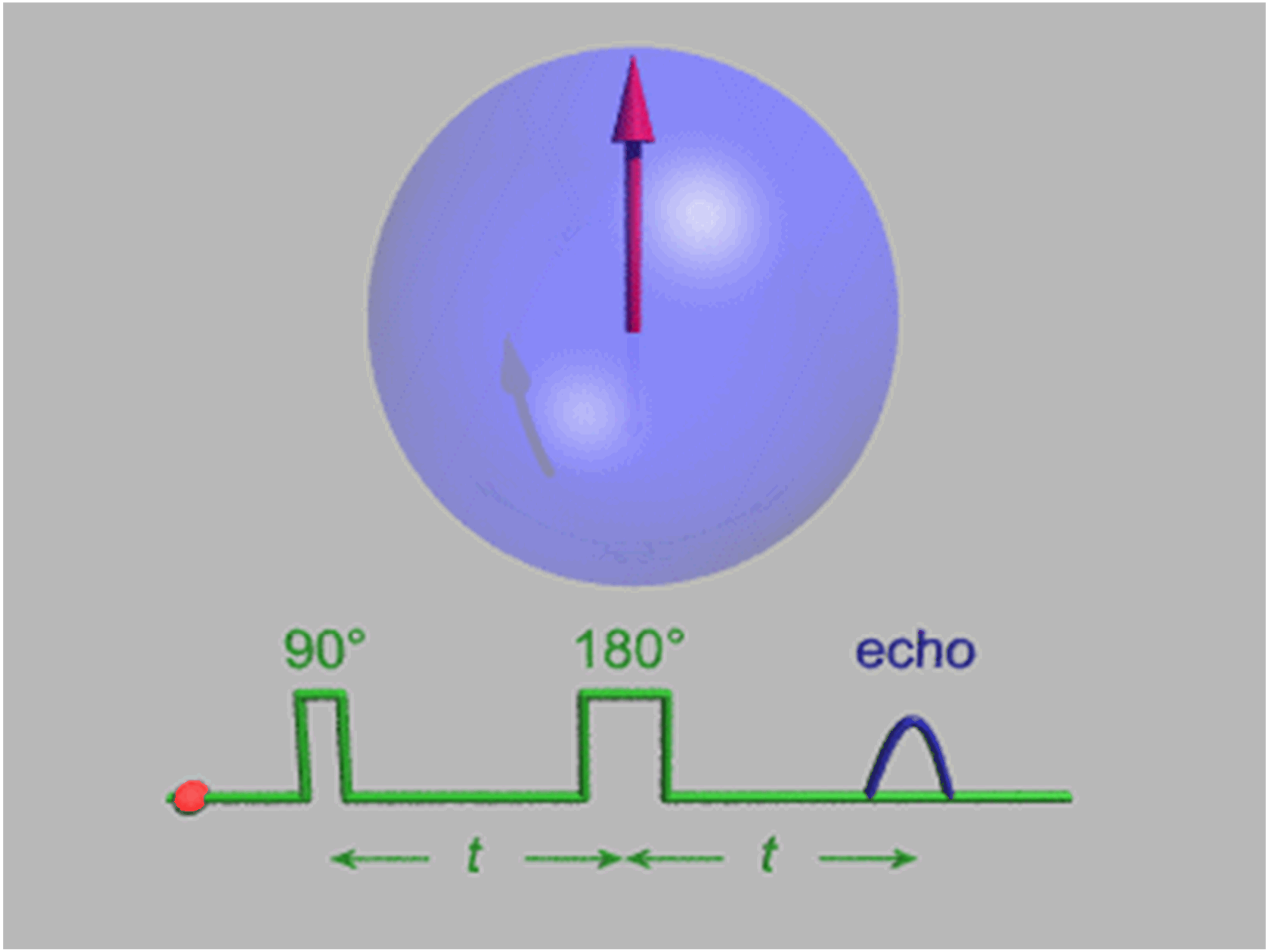
- Order of 5 MHz line width in natural silicon
- B1 is comparable magnitude => relatively large errors in rotation on some pulses

Rabi Oscillations



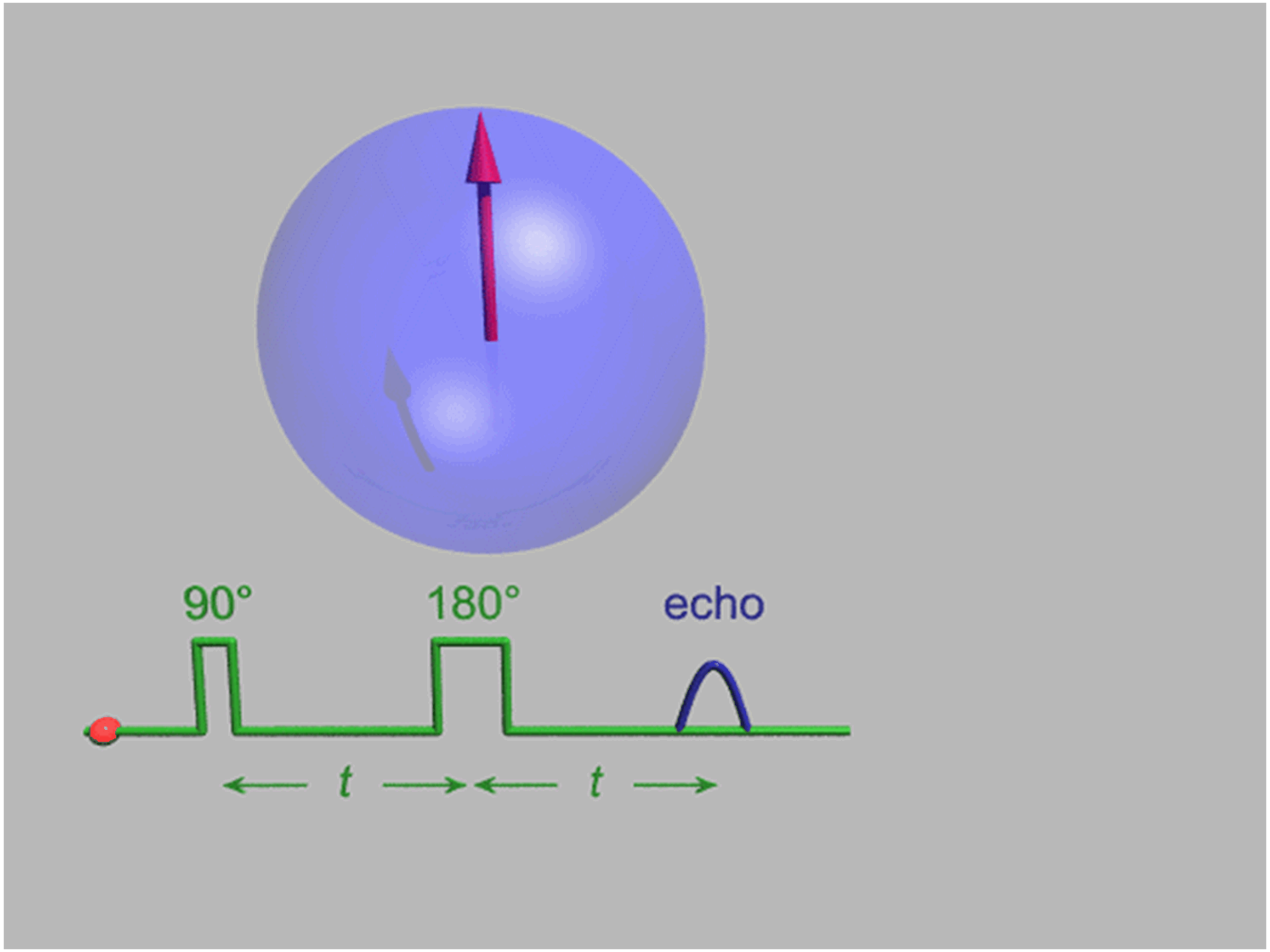
Luhman

Hahn-echo



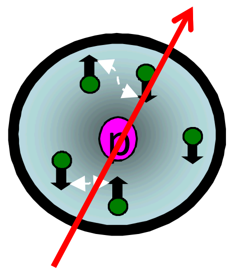
http://en.wikipedia.org/wiki/Spin_echo

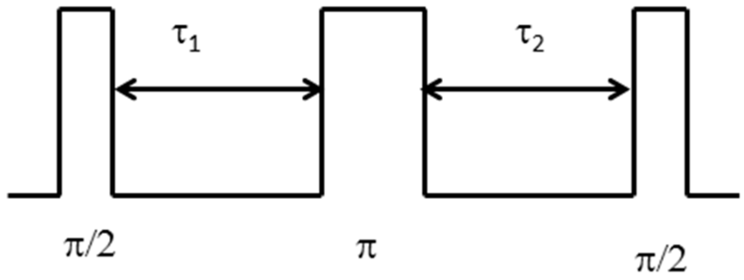
Hahn-echo

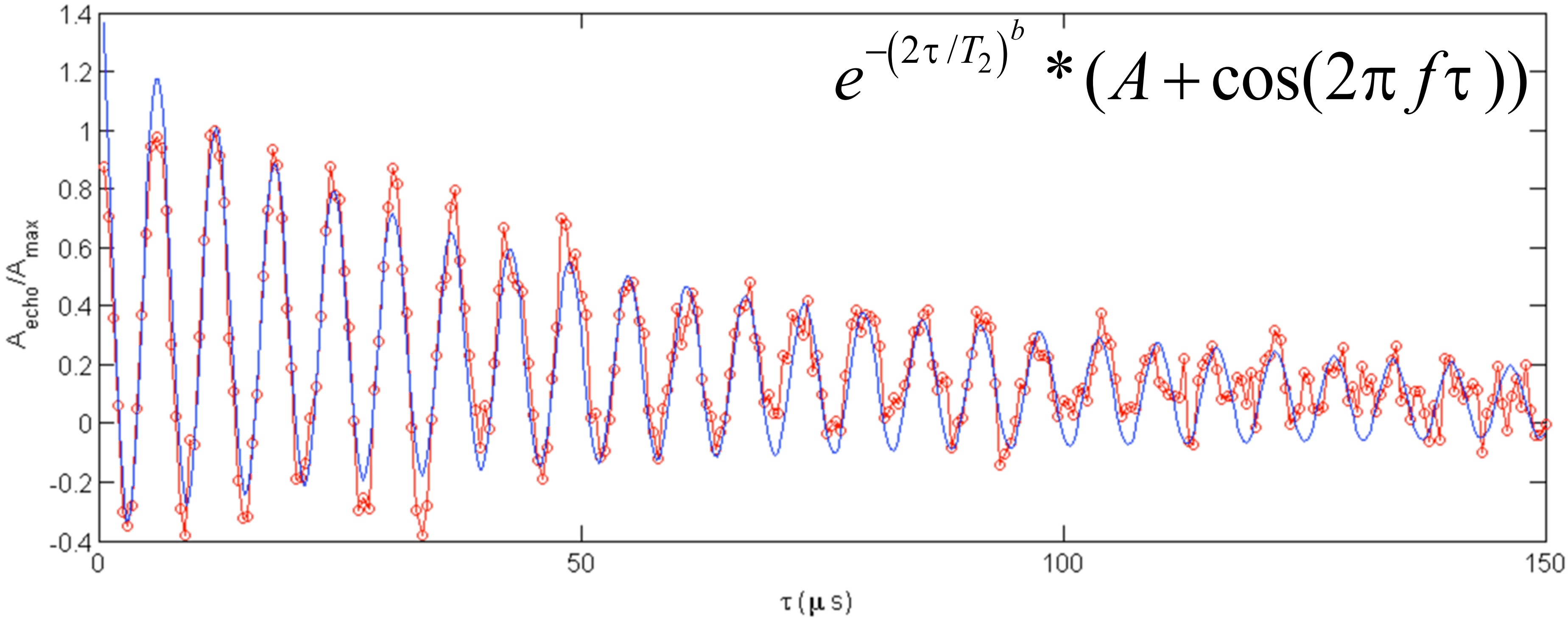


http://en.wikipedia.org/wiki/Spin_echo

Hahn echo







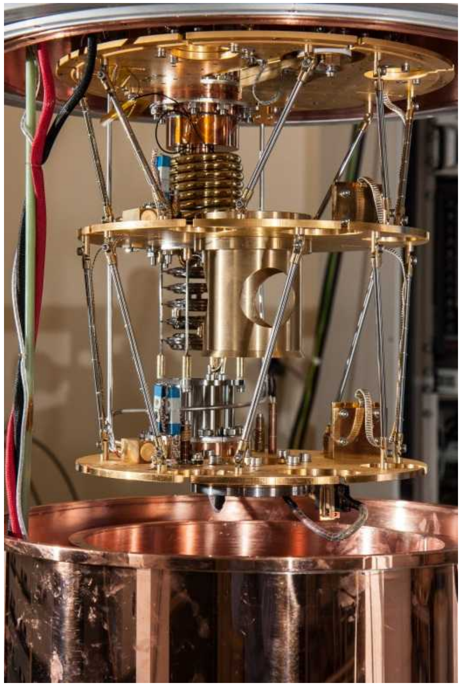
T2=88±4 us; (0.5 us step size)
b=0.61±0.03;
f=0.164±0.001 MHz

18 dBm

B=1.3 T

6400 averages

Multiple bandwidths in a dilution refrigerator



DC lines

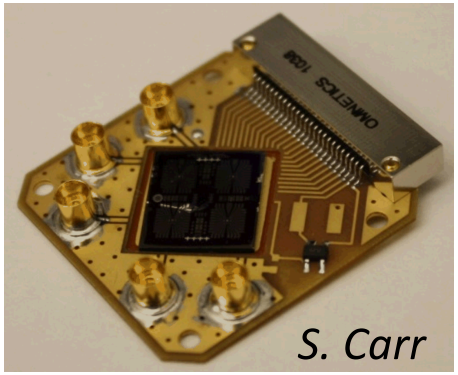
- static bias, or slowly changing bias

Pulsing lines and fast current measurement

- SS/SS flexible coax (10 MHz BW)a
- 400 kHz current preamp
- x10 voltage preamp with filters

High frequency ESR lines

- AG-SS/SS at high T
- NbSn at low T
- extremely delicate
- good microwave techniques required



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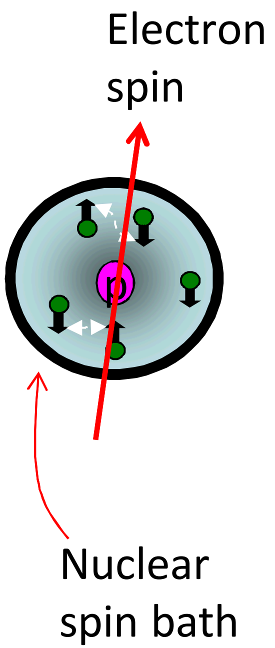
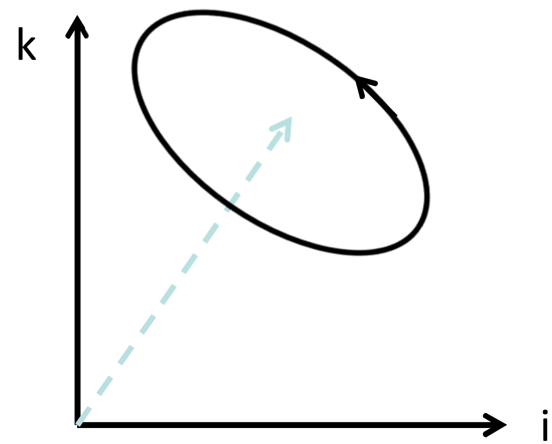
Adiabatic operations



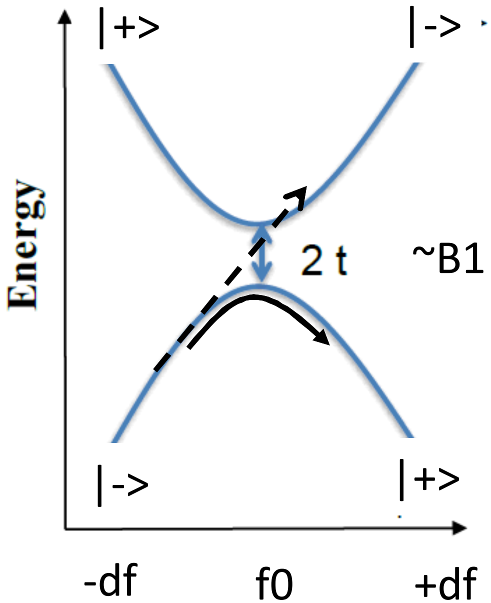
Rotating frame

$$\tilde{H}_Q = \hbar\Delta\omega\sigma_e^z + \mu_B B_{ac}\sigma_e^x$$

$$\mathbf{n} = \hbar\Delta\omega\hat{k} + \mu_B B_{ac}\hat{i}$$



Adiabatic inversion



- Order of 5 MHz line width in natural silicon
- B1 is comparable magnitude => relatively large errors in rotation on some pulses
- Adiabatic inversion is approach to reduce sensitivity to changing resonant frequency
- Sweep frequency slowly
- Two level system picture describes the evolution

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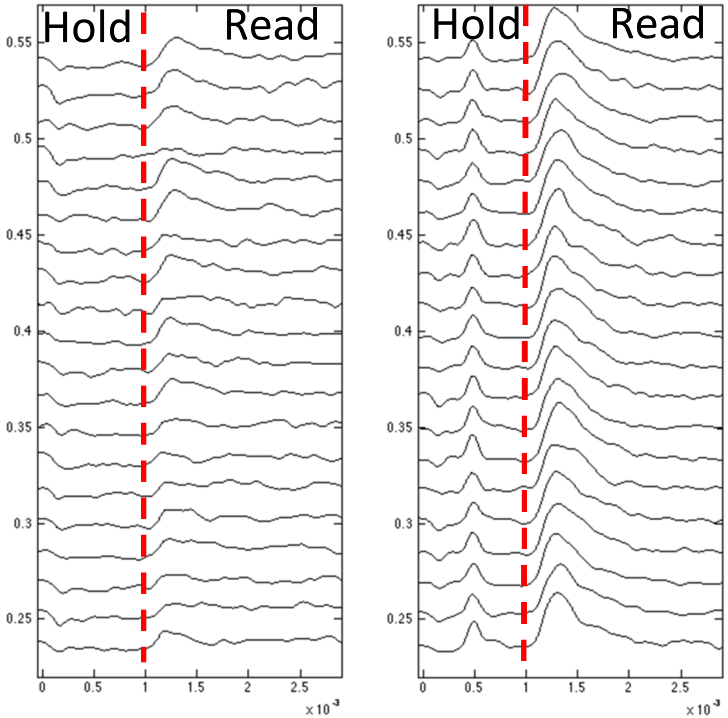
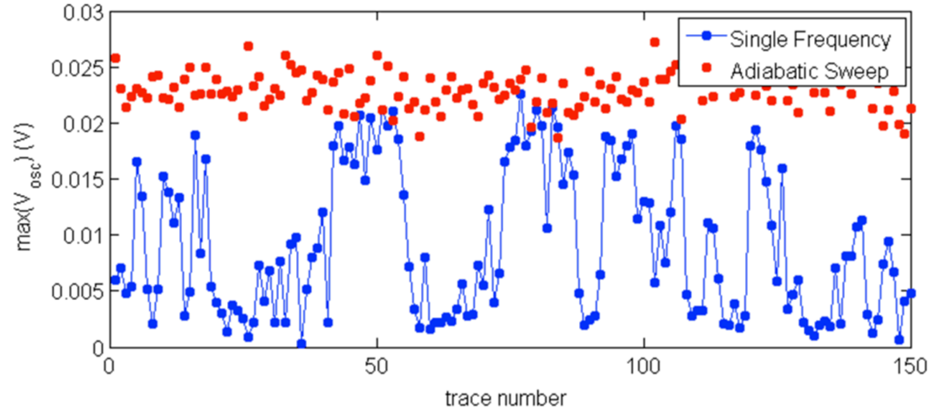
Adiabatic sweep compared to on-resonant pulse

Pulsed pi rotation   Adiabatic Sweep

Spin bump signal



Comparison w/ adiabatic inversion



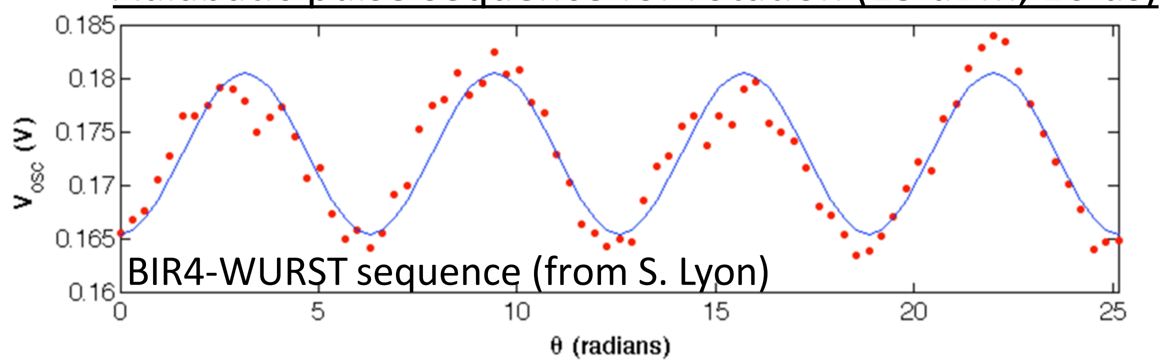
Adiabatic approach

$$P_{up} \propto 1 - e^{-\frac{\pi^2 f_r^2}{\Delta\nu / t_{pulse}}}$$

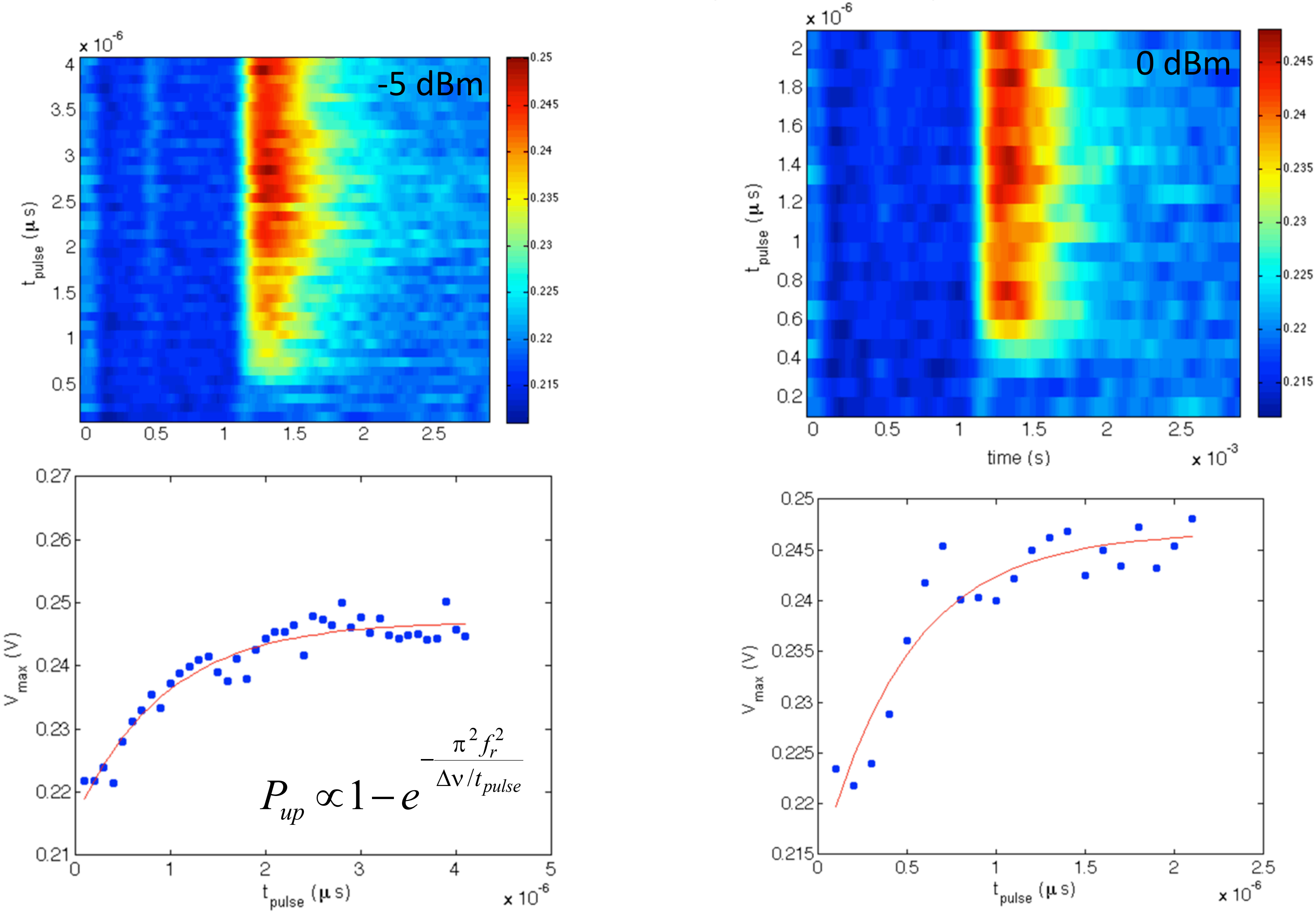
$\Delta f/t << f_{rabi}^2$

Δf=25 MHz; t=10 us

Adiabatic pulse sequence for rotation (15 dBm, 10 us)



Characterization of adiabaticity of sweep



Luhman

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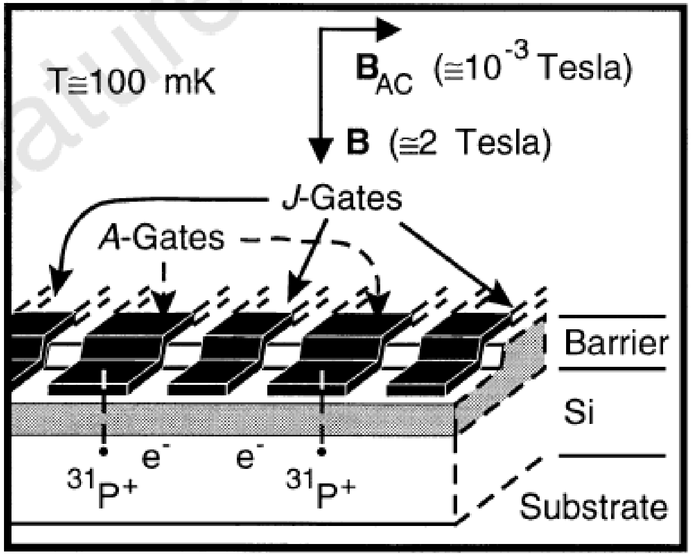
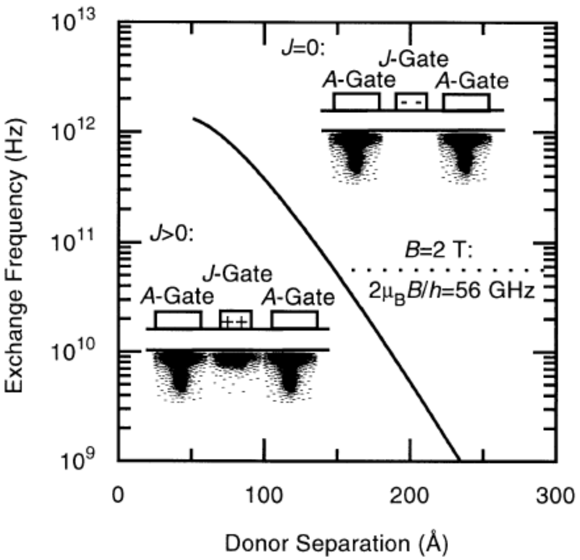
Outline

- Motivations
- MOS donor qubits
- Two qubit nanostructures
  - Single ion implant
  - SiGe/sSi STM
- Summary

Donor-donor coupling concept



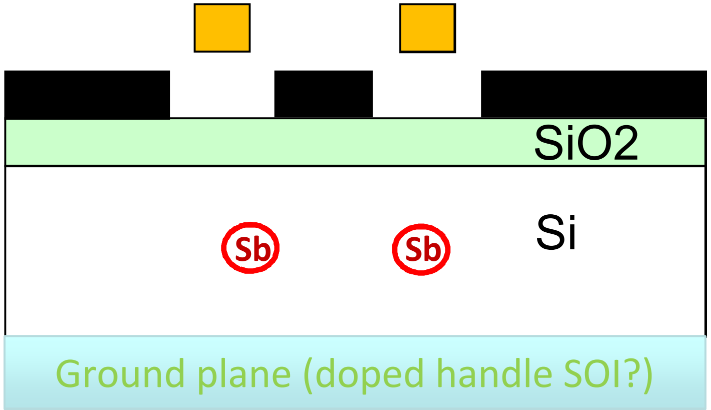
Kane (1998)



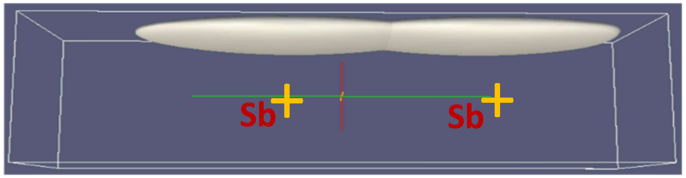
- Vision: Kane-like architecture with exchange gate
- Can this really be done?
- Can it be done with this configuration?

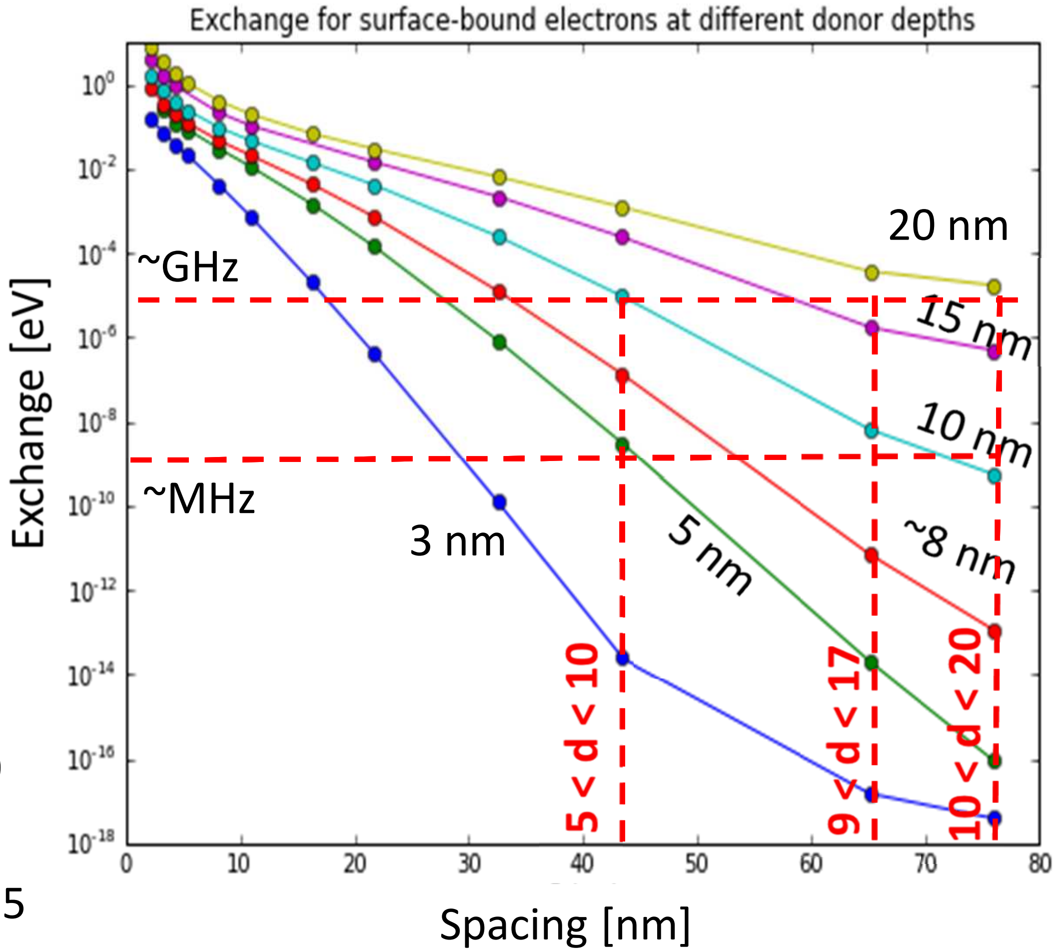
J dependence on depth & spacing (no J-gate)

Low vertical E-field



High vertical E-field

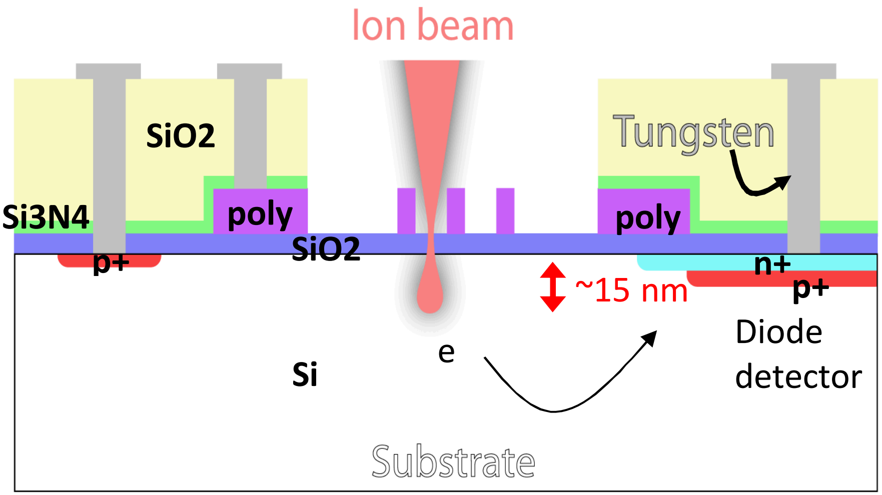




- EMT calculations from Calderon et al. addressing J after ionization (JAP 2009)
- Target gate speeds order GHz to MHz
- If you choose target spacing 70 nm +/- 5 (for each donor)
  - Target depth: 13.5 nm +/- ~3.5

NEMO calculations: Muller et al.

Getting to single donors w/ the CMOS approach



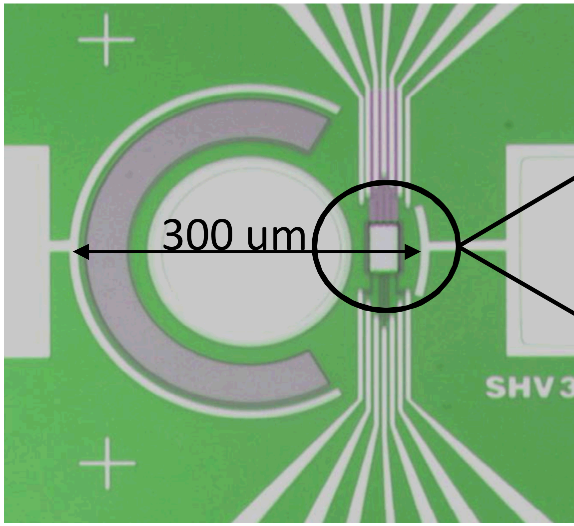
Ion	Energy (keV)	Range (nm)	# e-h pair
P	24	36 ± 16 ± 13	~2500
Sb	55	36 ± 10 ± 8	~4600
Sb	10	12 ± 3 ± 3	~600

Range — Depth Straggle — XY Projection Straggle

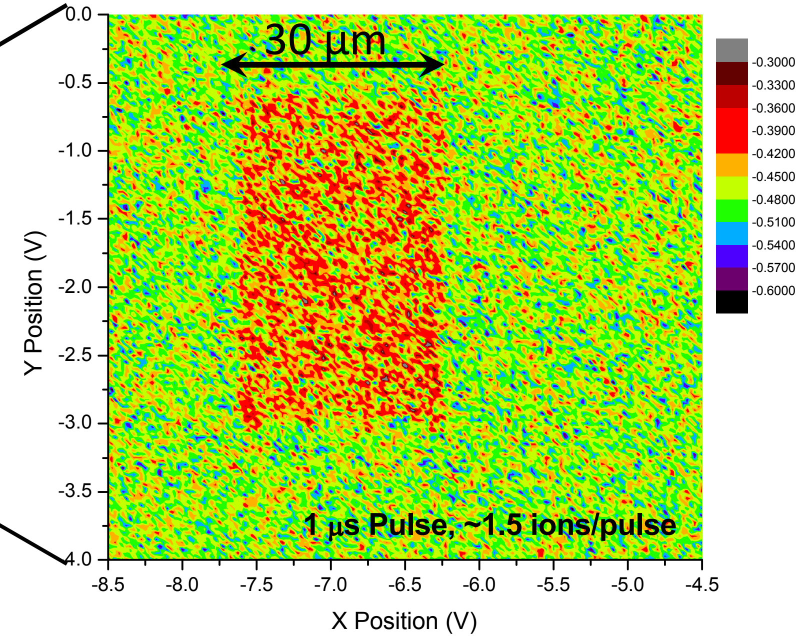
- Approach
  - Integrated diode detector senses arrival of single ion
  - E-beam lithography or advanced litho (EUV) defines lateral position
  - Energy of ion determines vertical position

Devices fabricated w/ single ion detection

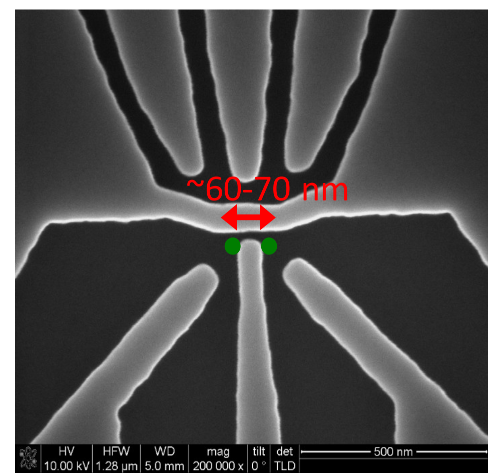
Bielejec



Ion Beam Induced Charge (IBIC) map

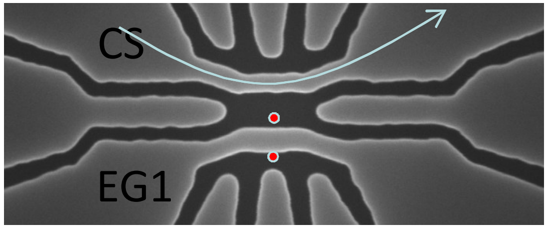


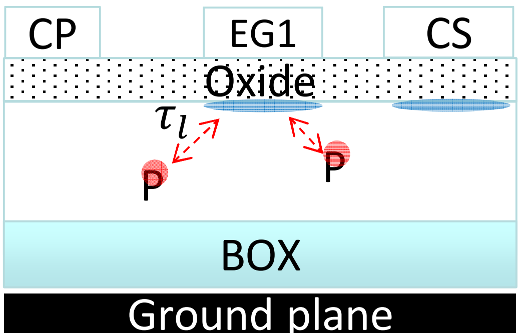
- Single ion 50 keV Sb detected in construction zone
- 7 nm gate oxide counted ion quantum dots fabricated
- Low activation in 7 nm gate oxide?



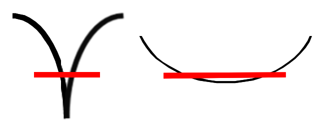
Luhman/Singh

Donor-QD two spin system

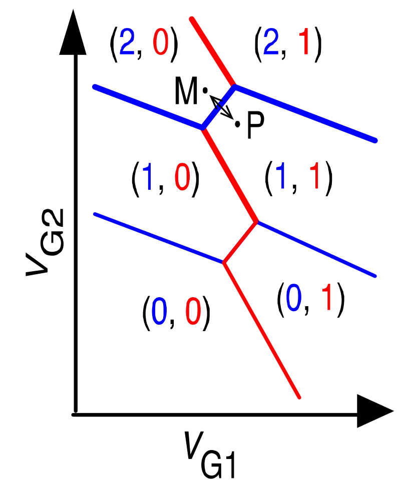




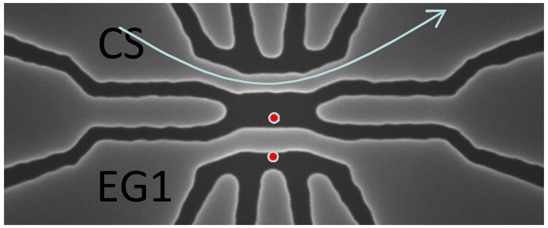
- Charge sensed donor-QD system is experimental platform:
  - Look at transfer to surface
  - Look at two spin exchange (w/ QD spin)
  - Donors on both sides for D-D exchange mediated by dot

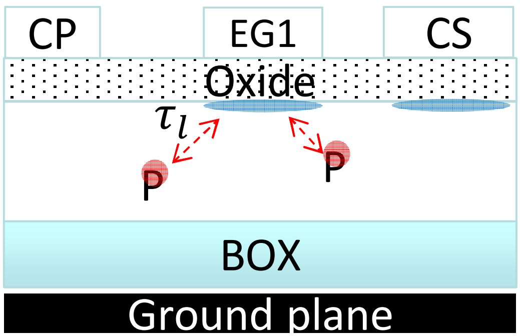


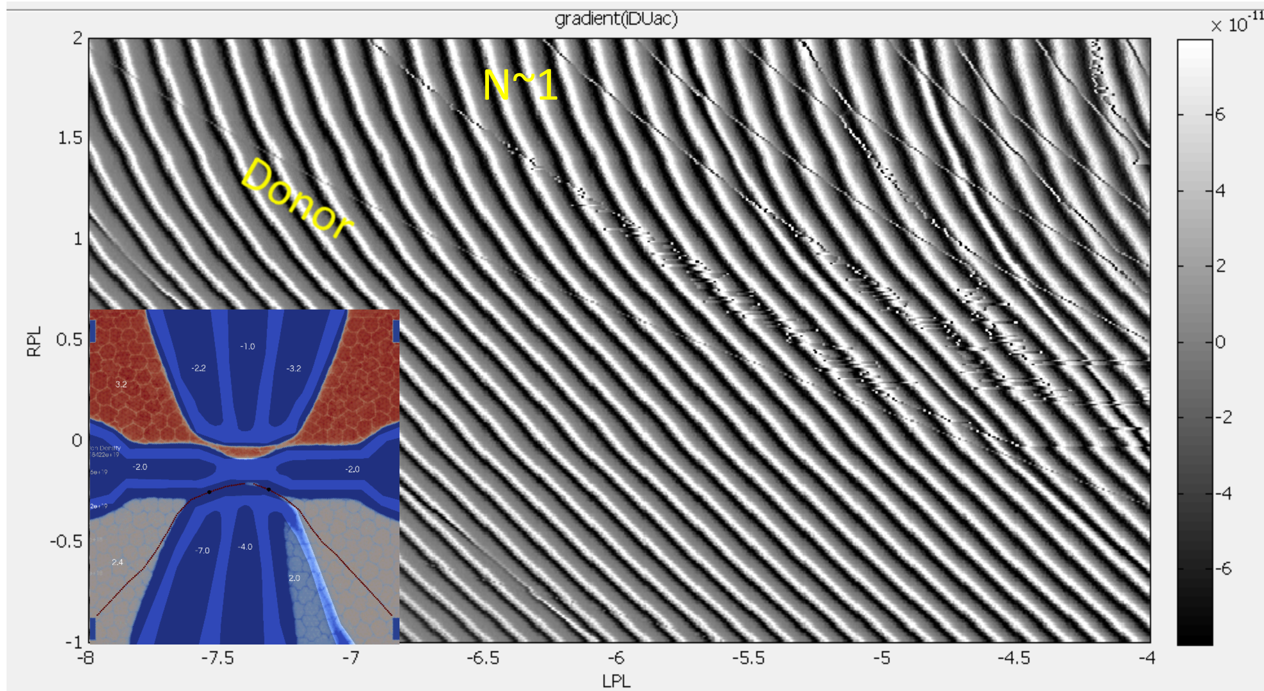
$$H = \begin{pmatrix} J(\varepsilon) & A(V) \\ A(V) & 0 \end{pmatrix}$$



Donor-QD two spin system







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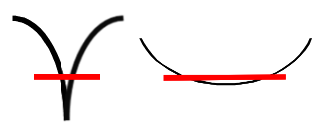

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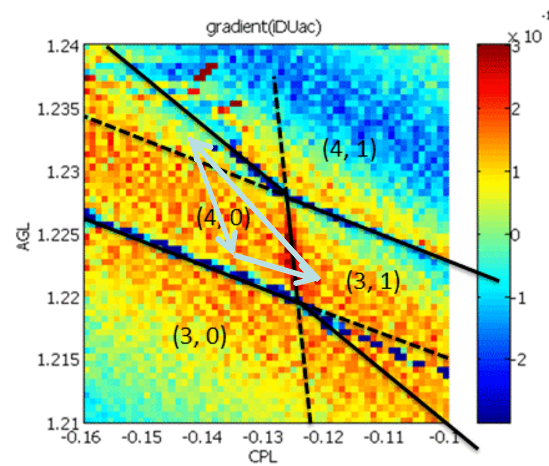


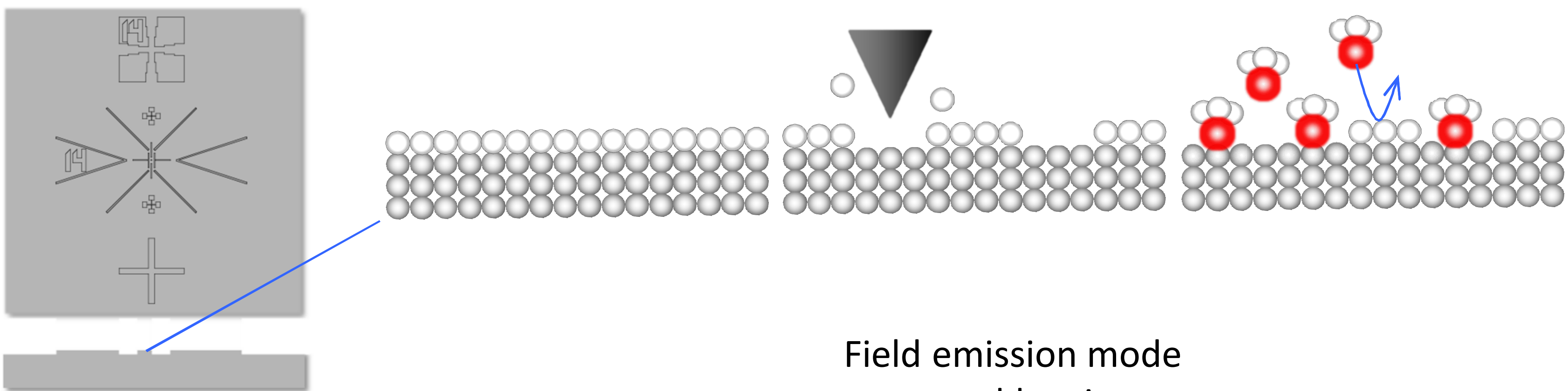
Ultimate lateral and vertical control of donors

1. Start w clean Si(001)

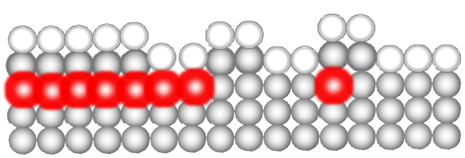
2. Adsorb H resist
Self-limiting 1 monolayer

3. Pattern w STM
Atomic-precision

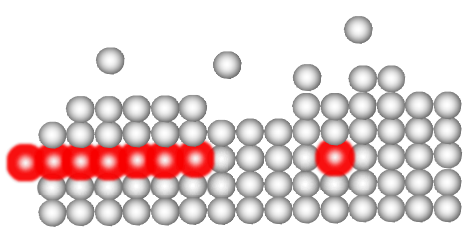
4. Adsorb PH_3



Etched alignment marks

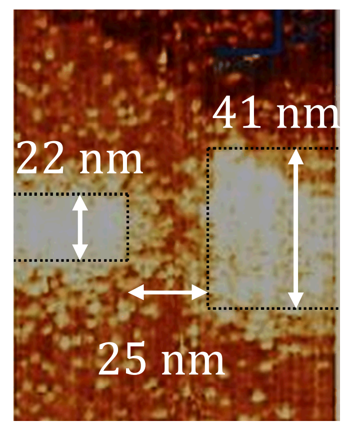


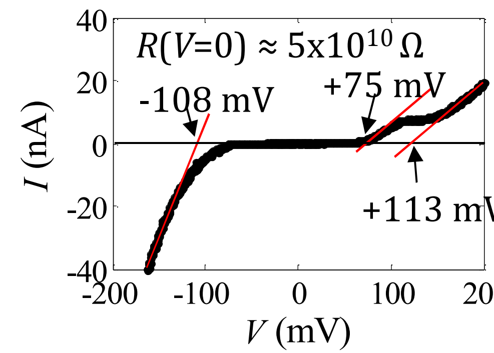
5. Incorporate P
-Anneal→ Si-P swap
-H resist constrains P



6. Desorb H & bury P in Si

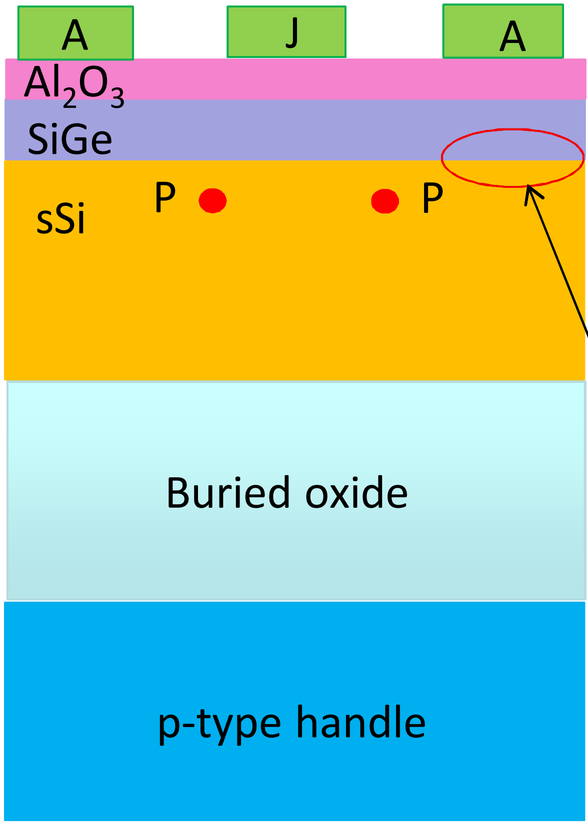
Field emission mode tunnel barrier





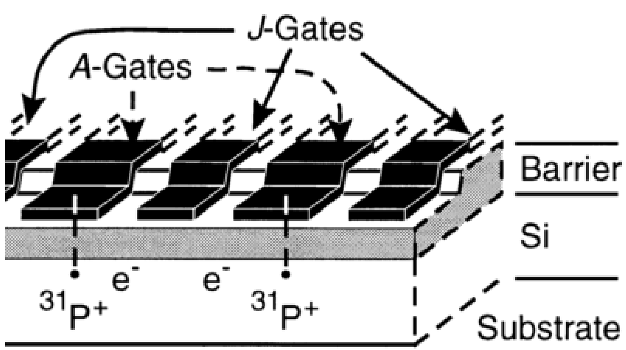
Bussmann & Rudolph

Strained silicon-on-insulator (sSOI)



- sSOI to allow for high temperature clean step [Lee et al., Appl. Surf. Sci. 2012]
- We have ~1% tensile strain in films
- Sharpness of interface is important
- Relaxed SiGe can be used as low temperature capping layer instead of a dielectric

Can we make a good interface?



Kane, B., Nature 393, 133 (1998)

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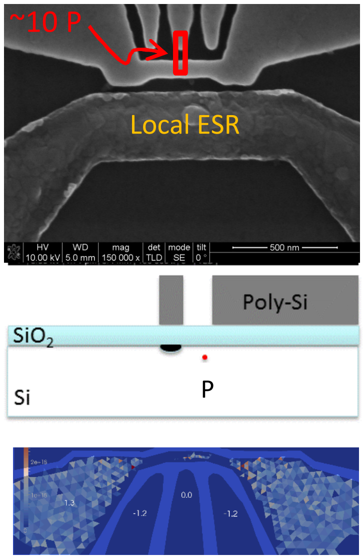
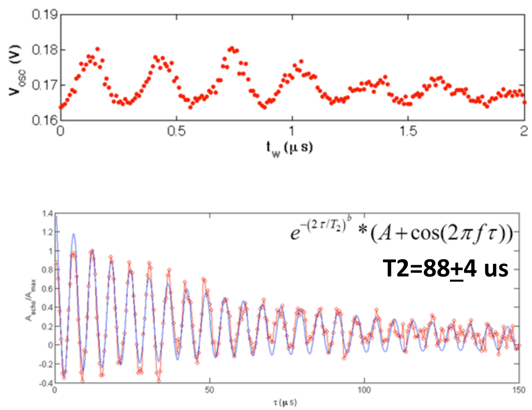
Summary

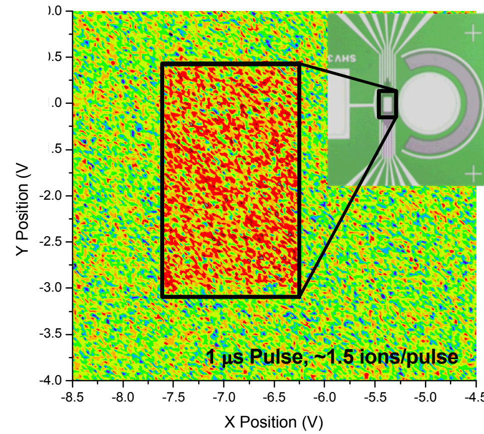
Silicon P donor qubit structure



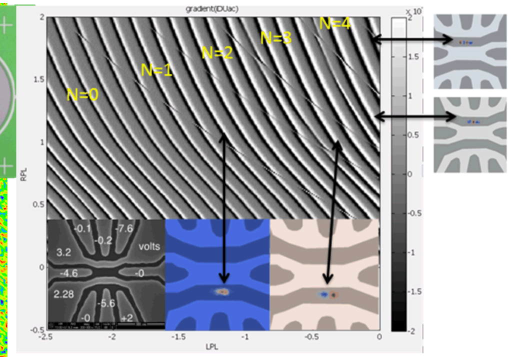
Spin read-out & Rabi oscillations



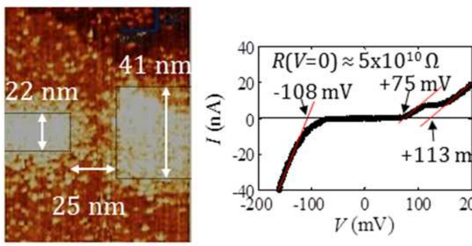
Single Sb^+ implant map (50 keV)



Few electron QD & D-QD coupling



STM assisted tunnel barrier fab



- Local ESR demonstrated in poly-Si process flow
  - T2 ~88 us consistent with natural silicon
- Adiabatic manipulation of spin leads to higher fideilty spin inversion
- Dot behavior is more regular in newer designs
  - Device modeling agrees reasonably well with measured QDs
  - MOS interface defects not an immediate show stopper through QD design – unclear importance in future
- Few electron QD behavior observed and coupled to donor-like transitions (D-QD qubit)
- Single ion implant capability integrated w. similar process flow
  - Activation of single donors near interface is a future challenge for this path
- STM assisted tunnel barrier fabricated (examining limits of field emission writing mode)

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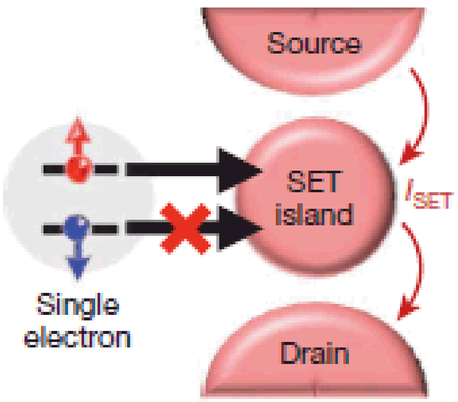
QIST team & external connections

- QIST contributors at SNL
  Qubit fab: M. Busse, J. Dominguez, T. Pluym, B. Silva, G. Ten Eyck, J. Wendt, S. Wolfley
  Qubit control & measurement: N. Bishop, S. Carr, M. Curry, S. Eley, T. England, M. Lilly, T.-M. Lu, D. Luhman, K. Nguyen, M. Rudolph, P. Sharma, A. Shirkhorshidian, M. Singh, L. Tracy, M. Wanke
  Advanced fabrication (two qubit): E. Bielejec, E. Bussmann, E. Garratt, A. MacDonald, E. Langlois, B. McWatters, S. Miller, S. Misra, D. Perry, D. Scrymgeour, D. Serkland, G. Subramanian, E. Yitamben
  Device modeling: J. Gamble, T. Jacobson, R. Muller, E. Nielsen, I. Montano, W. Witzel, R. Young

- Joint research efforts with external community:
  - Australian Centre for Quantum Computing and Communication Technology (D. Jamieson, A. Dzurak, A. Morello, M. Simmons, L. Hollenberg)
  - Princeton University (S. Lyon)
  - NIST (N. Zimmerman)
  - U. Maryland (S. Das Sarma)
  - National Research Council (A. Sachrajda)
  - U. Sherbrooke (M. Pioro-Ladriere)
  - Purdue University (G. Klimeck & R. Rahman)
  - U. New Mexico (I. Deutsch, P. Zarkesh-Ha)
  - U. Wisconsin (M. Eriksson)
  - University College London (J. Morton, S. Simmons)

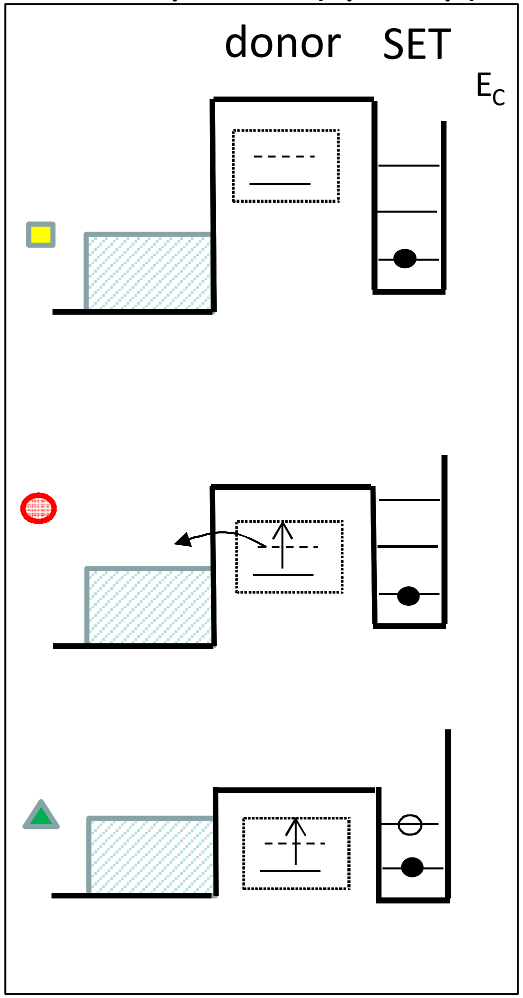
Single donor spin read-out concept

Concept
- SET or QD detects nearby charge center ionization
- Spin dependent ionization



Morello et al., Nature 2010

Read sequence (spin up)



3. Unload

2. Read

1. Load

- ● Charge state is static
- ○ Charge state is changing in time due to tunneling

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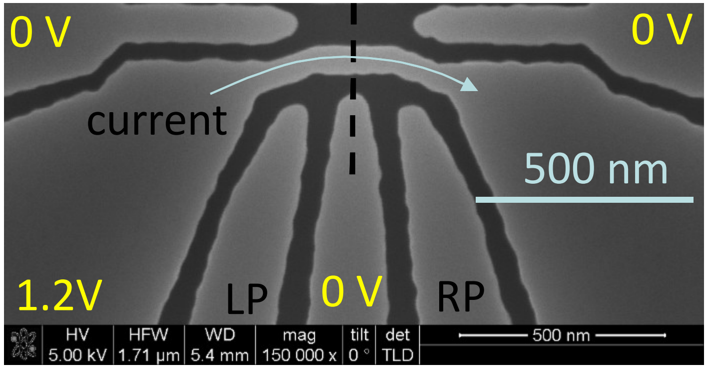
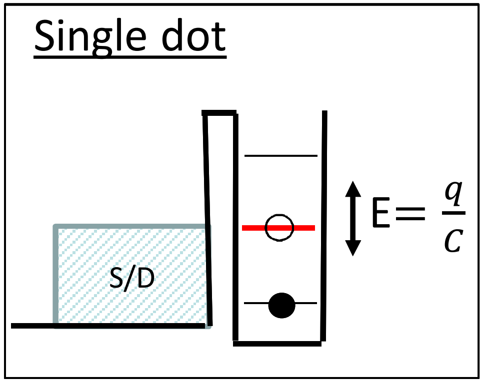
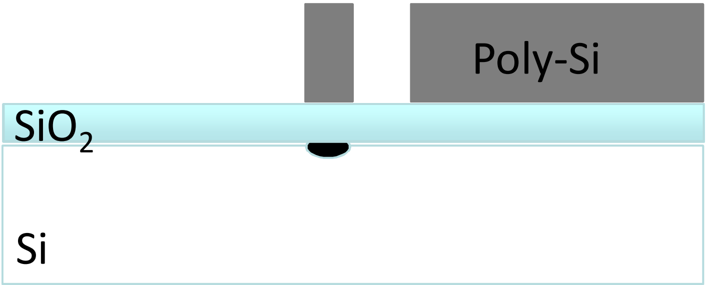
Poly silicon quantum dot





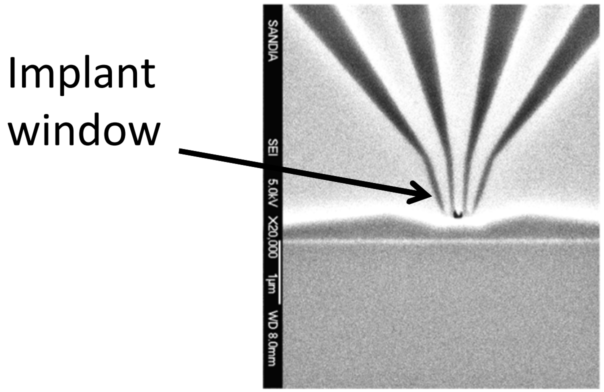


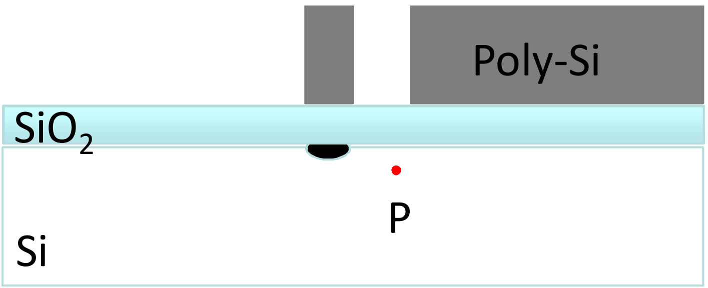
- Simplify SET for donor read-out
  - Implant will be self-aligned

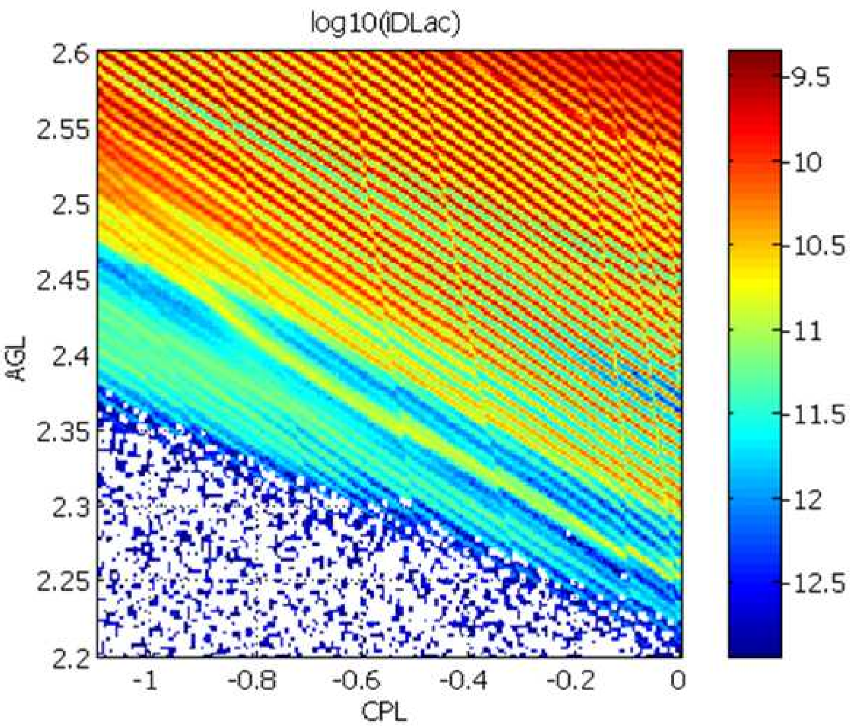
Harvey-Collard

Sandia National Laboratories

Gate wire with implant – QD coupling to donor







- Typical implant conditions:
- 45 keV implant, 8e11/cm^{-2} dose → ~ 80 P donors in window between plunger and QD
- Order of 5-10 offsets are seen in these implanted poly-MOS devices

Motivations for studying adiabatic quantum computing

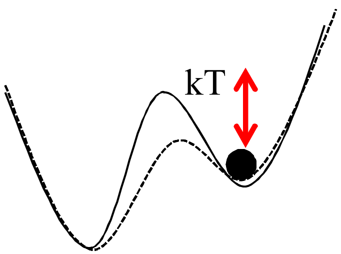
1. **High fidelity adiabatic qubit operations**

2. **Quantum annealing**

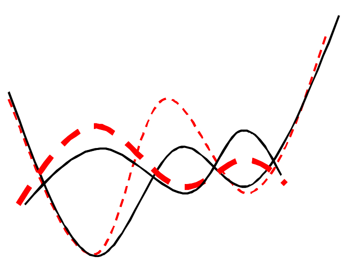
Ising spin glass maps to useful optimizations

$$H_{problem} = -\sum_{i} h_i \sigma_{iz} + \sum_{i,j>1} K_{ij} \sigma_{iz} \sigma_{jz}$$

Quantum annealing speed-up?

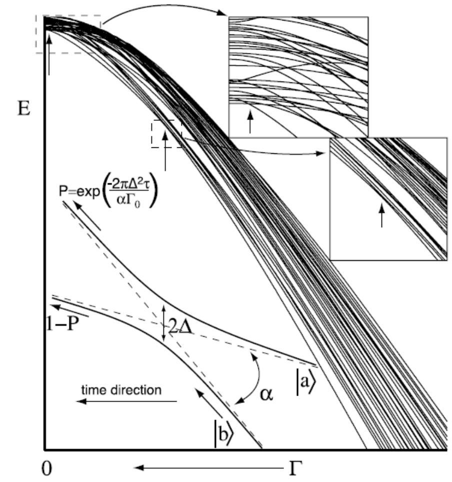


Thermal hopping



Quantum tunneling

$$H_{problem} + H_{init} = -\sum_{i} h_i \sigma_{iz} + \sum_{i,j>1} K_{ij} \sigma_{iz} \sigma_{jz} - \Gamma(t) \sum_{i} \sigma_{ix}$$



Santoro et al. Science 2002

Concept: Ground state computation

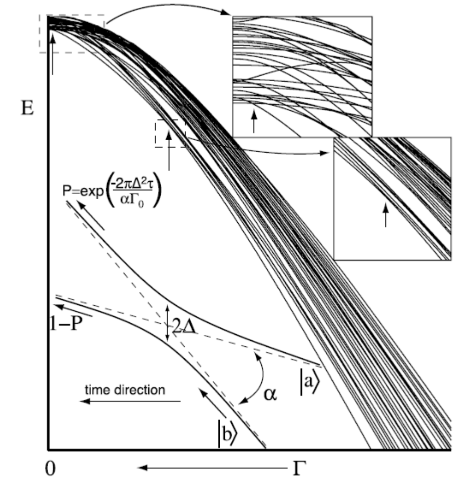
More tolerance to decoherence in qubits (T2 processes)?

Easier to fabricate and implement

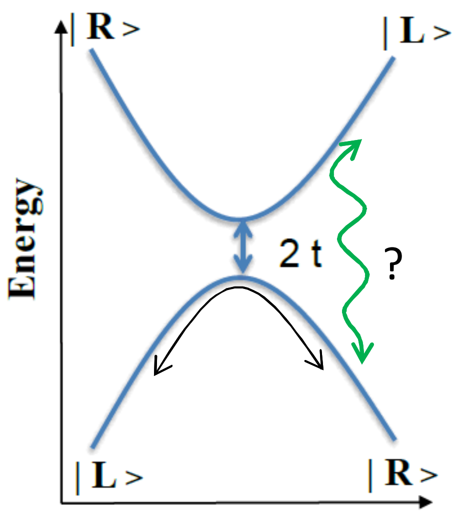
Sandia National Laboratories

Motivations and research direction

- What are the limits and extensions of adiabatic control of one or several qubits? (e.g., adiabatic inversion)



- Questions about quantum annealing
  - Are there tests with one and a few qubits that inform the "black box" testing approach
  - What are the microscopic dynamics and how does it break?
    - Is fast relaxation helpful? (what dependence?)
    - $kT >> E_{gap}$?
    - What role does T2 play?
  - What makes a good qubit for quantum annealing?
    - Is there benefit to using a semiconductor qubit for QA?



- Our approach:
  - Examine silicon (or semiconductor) qubits in context of adiabatic quantum computation (or annealing)

Silicon motivation: decoherence figure of merit

- Common back of the envelope targets
  - Error < 10^{-4} for many qubit schemes by this metric
  - Error ~ $O(T_{gate} / T_2)$
- Also important to consider is $T_{measure}$
  - Measurement is often the longest idle time in QEC circuit
  - Error ~ $O(T_{meas} / T_2)$

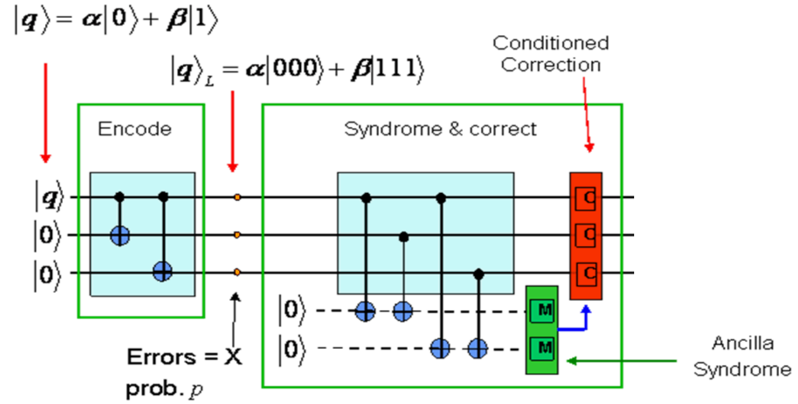
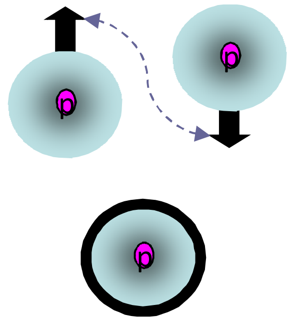
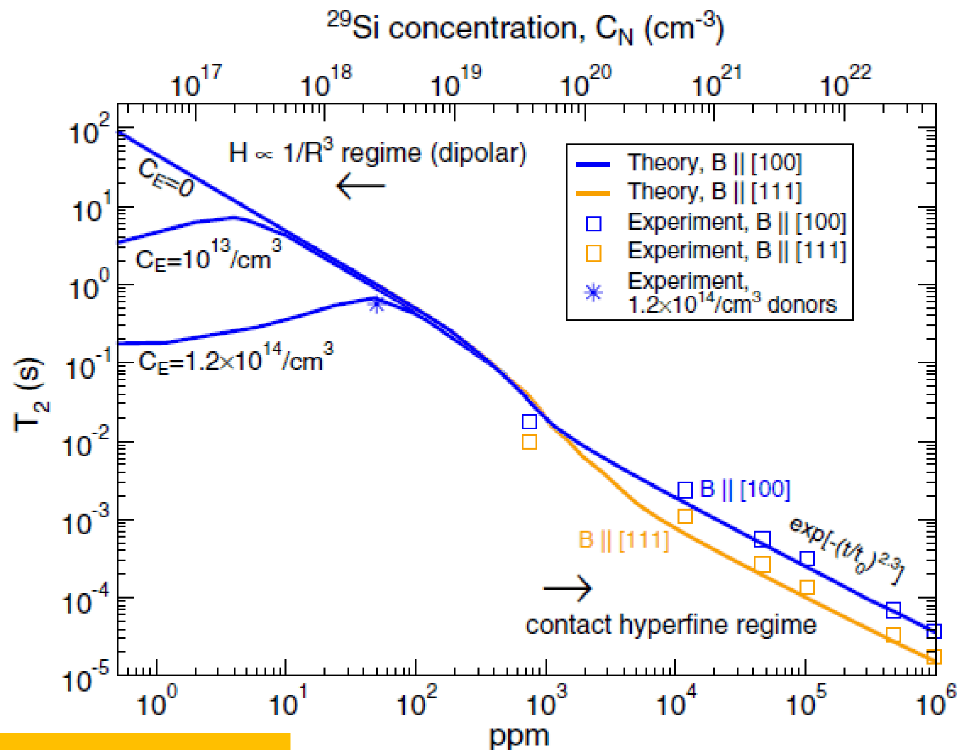


Image of circuit from L. Hollenberg

Why silicon? Long spin decoherence times



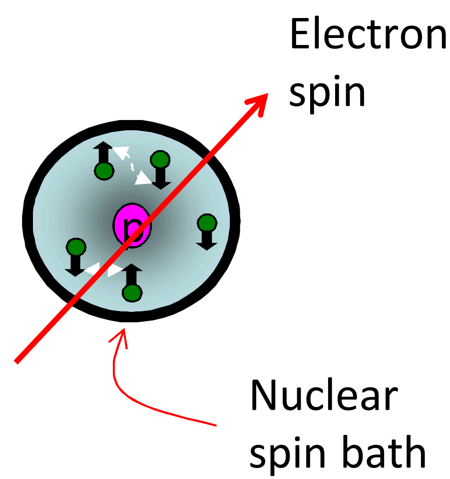


T_{meas} ~ O(10^{-6} sec)

T_2 (10^{-4}) ~ 10^{-2} seconds

>10 ms possible with Si enrichment

Which other qubits satisfy this?



Witzel et al, PRL 105, 187602 (2010) [SNL]