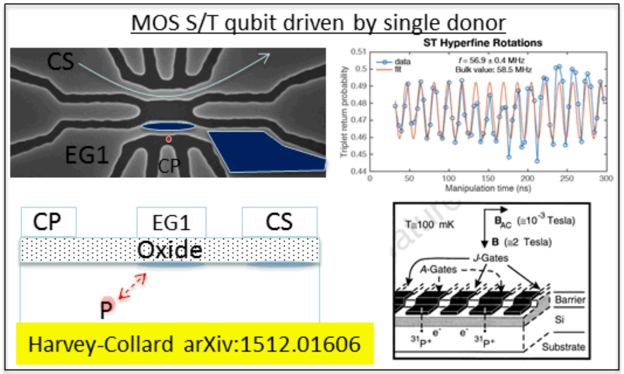
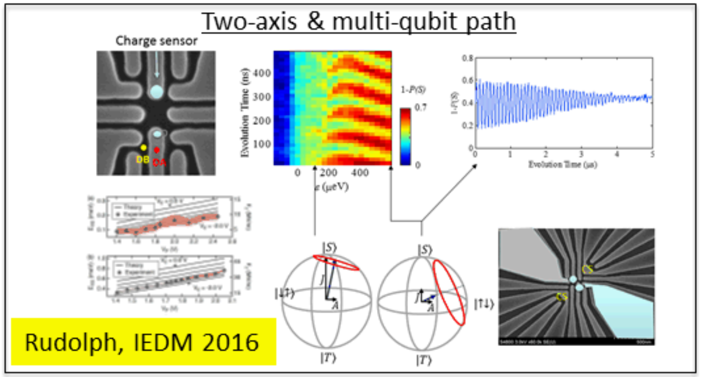
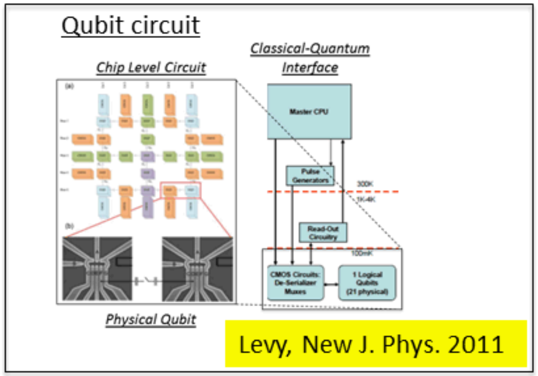
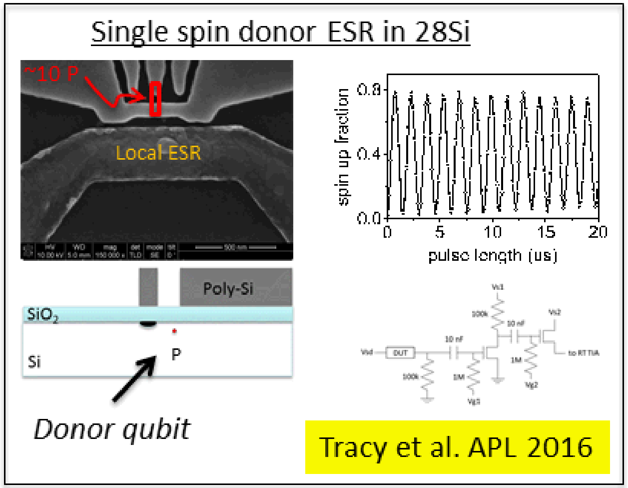
SAND2017-1586C









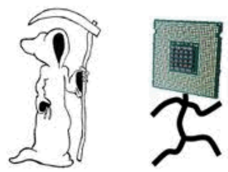
Donor quantum-dot coupled qubits

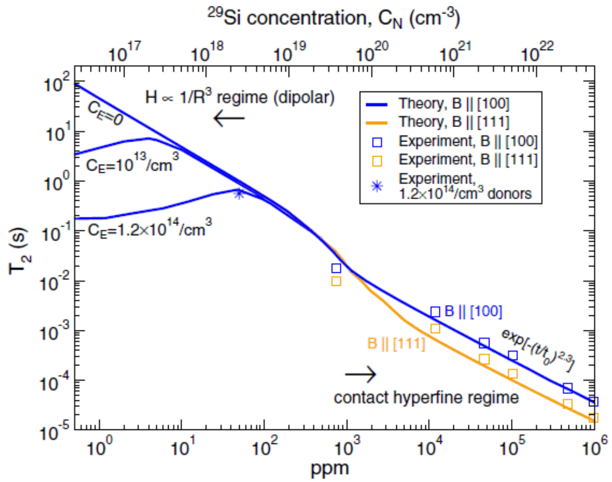
Malcolm Carroll

Sandia National Labs, Albuquerque, NM 87185

January 20, 2016

Outline

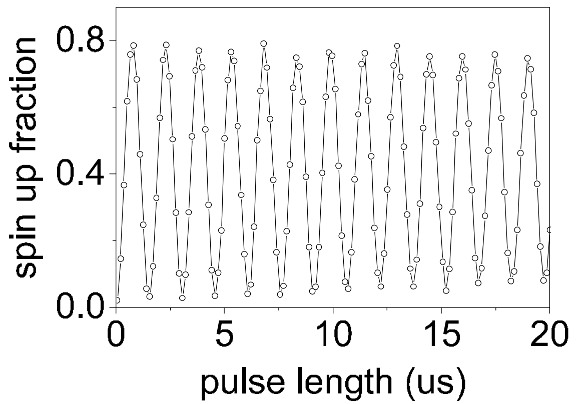


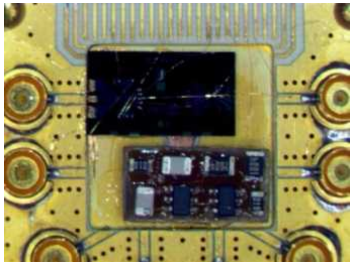


- Motivations
- Donor qubit (ESR)
- Hybridization of a QD qubit with a donor qubit
- Summary

Outline

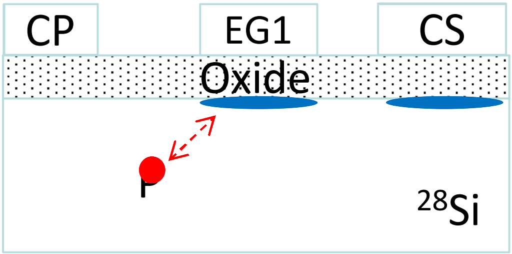
- Motivations
- Donor qubit (ESR)
- Hybridization of a QD qubit with a donor qubit
- Summary

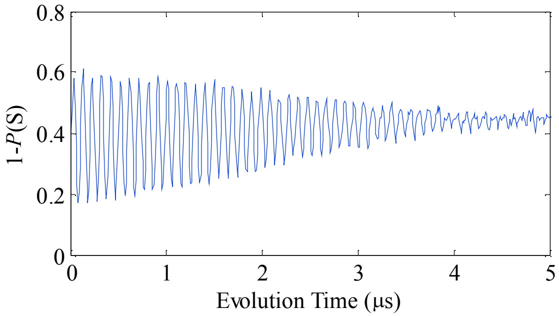




Outline

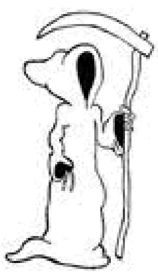
- Motivations
- Few electron QDs and donor qubit ESR
- Hybridization of a QD qubit with a donor qubit
- Summary

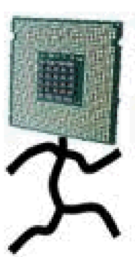


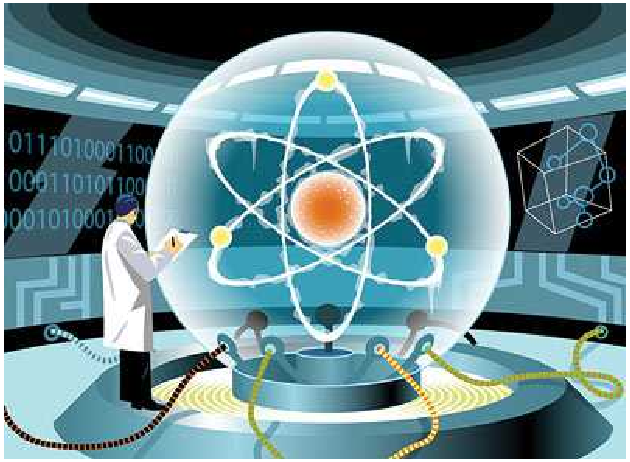


Motivations for quantum computing

- Special purpose speed-ups (e.g., quantum simulation, search)
- Opportunity as End of Moore's Law approaches





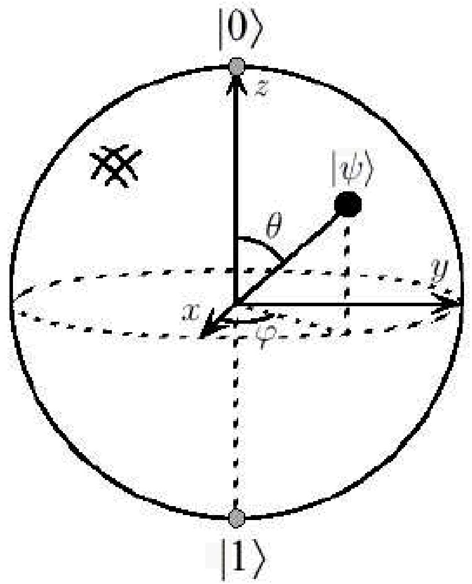


Companies investing in QC

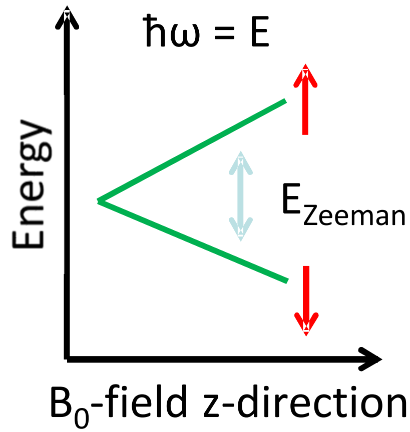
1. IBM
2. Google
3. Microsoft
4. Intel
5. Lockheed Martin
6. D-Wave
7. … and others including start-ups

Introduction to qubits and single qubit gates

Qubit



ESR/NMR qubit



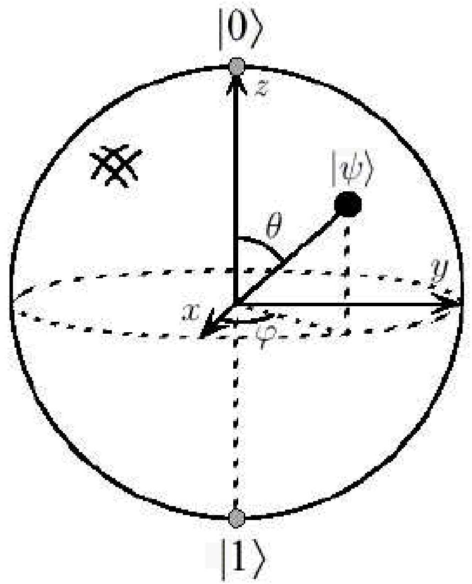
Up spin

Down spin

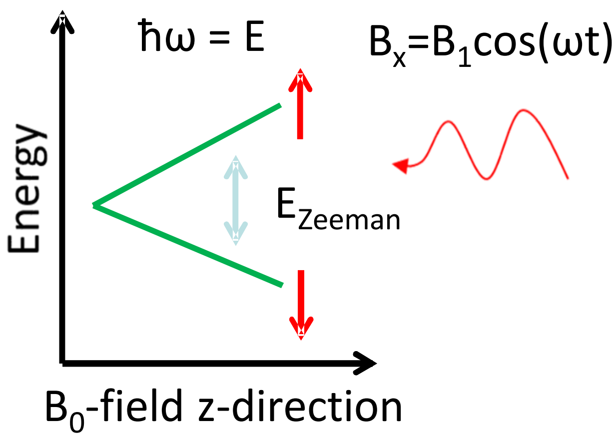
- The QC information is described with a | 0 > and | 1 > basis
- A quantum bit can be any system that has two energy levels
  - **Electron spin**, excited states of an ion or left/right position of a charge in a molecule
- DC B-field splits spin-up and spin-down energy states
  - Analogy to aligning magnets in a magnetic field

Introduction to qubits and single qubit gates

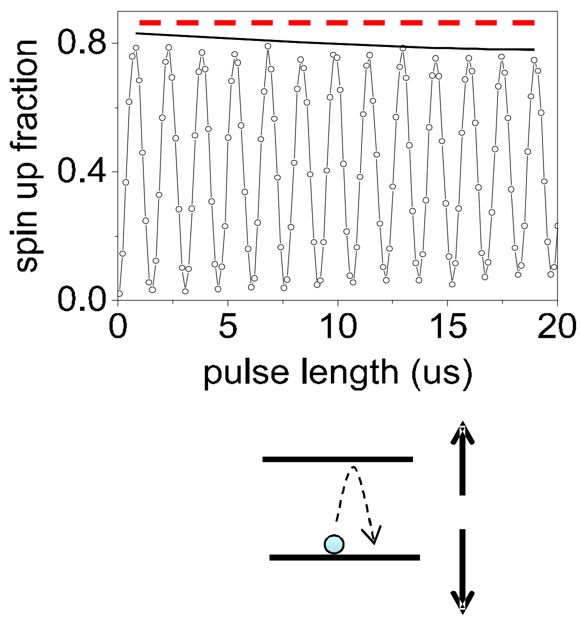
Qubit



ESR/NMR qubit

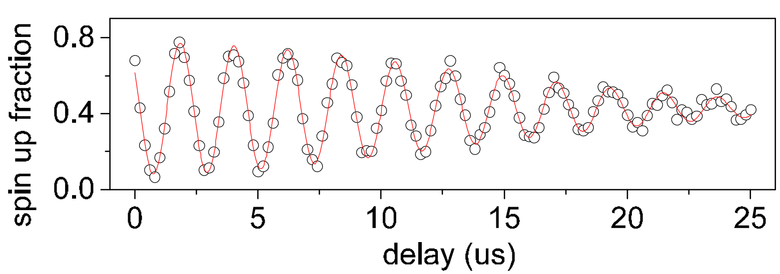


Rabi oscillations of qubit

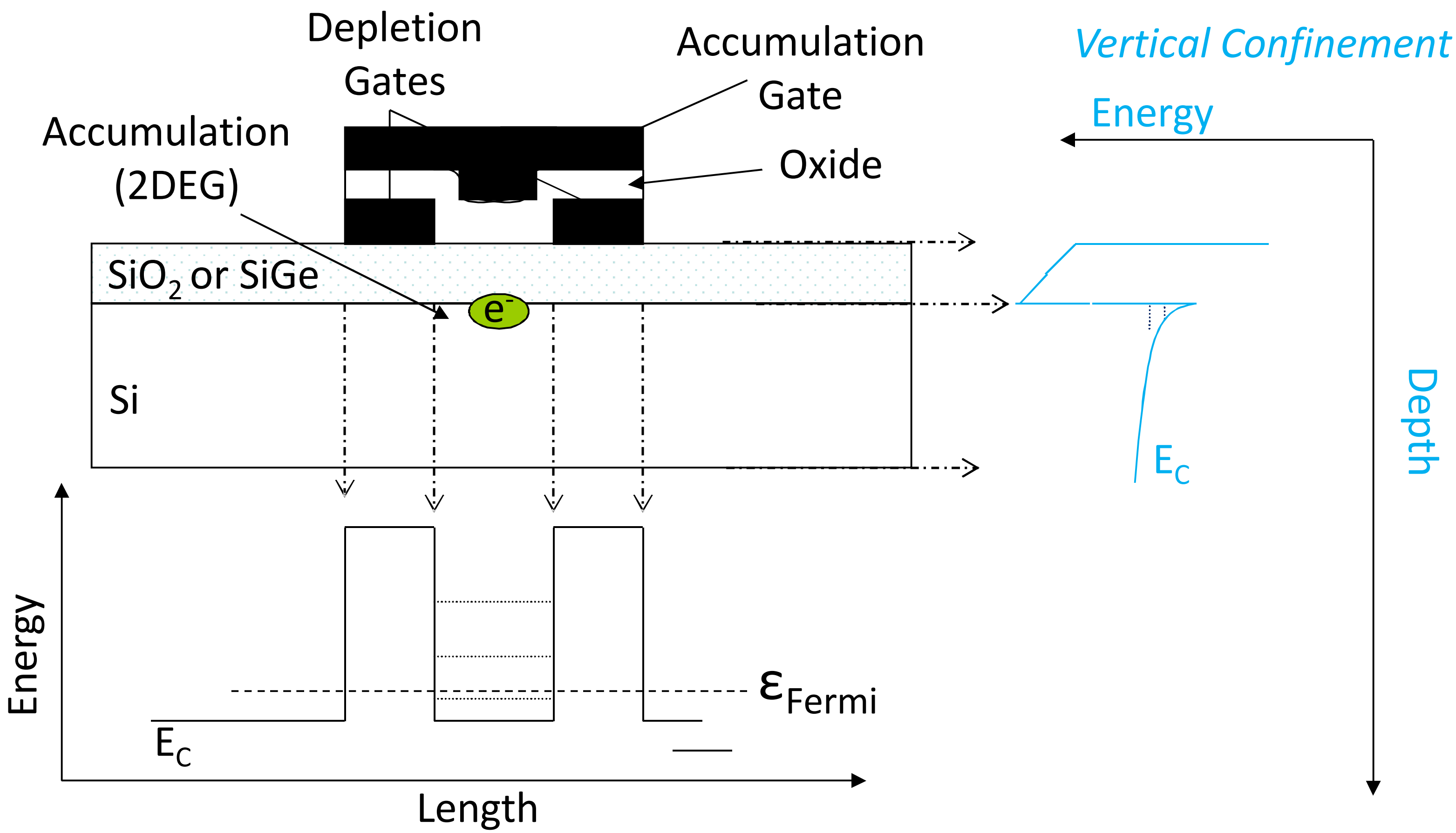


- B1 field for ESR/NMR to control qubit rotations
- Variation in local B-field cause errors (i.e., imperfect resonance & different precession)
- Skipping two-qubits and entanglement for scope of talk – but entanglement is the primary resource

Decoherence

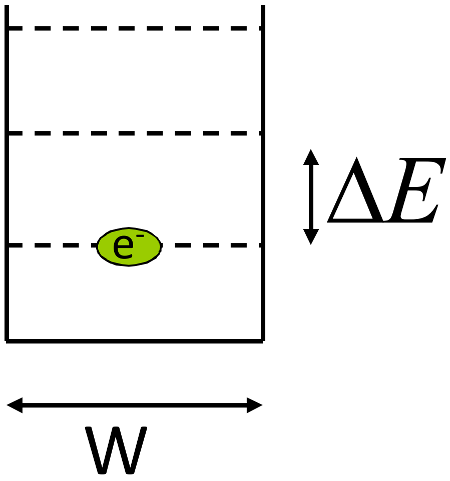


Enhancement mode quantum dots to confine spin qubits



- Modified MISFET design can be used to form quantum dots
- SiGe/sSi and MOS have both successfully been used for single QD qubits

Quantum dot potentials for single electrons



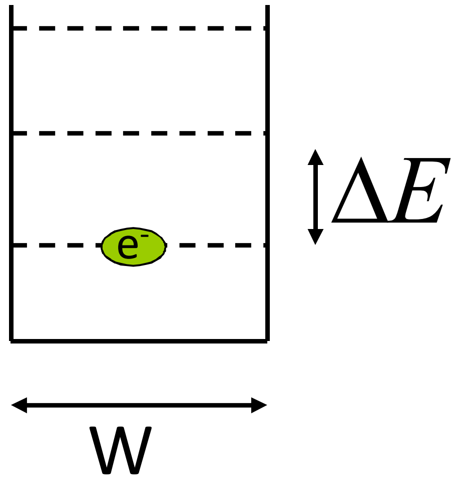
$$\Delta E = \frac{\hbar^2}{2m^*} k^2$$

$$k = \pm \frac{2\pi}{W_{Well}} n$$

- Goal: isolation of two states of the electron
- Aim for spacings ~ 5-10*kT spacing or electronic states (rule of thumb)
- Energy level separation is dependent on size of confining potential & effective mass in quantum dots
- Energy spacings for 40-50 nm Si well are order 5 meV [Si]

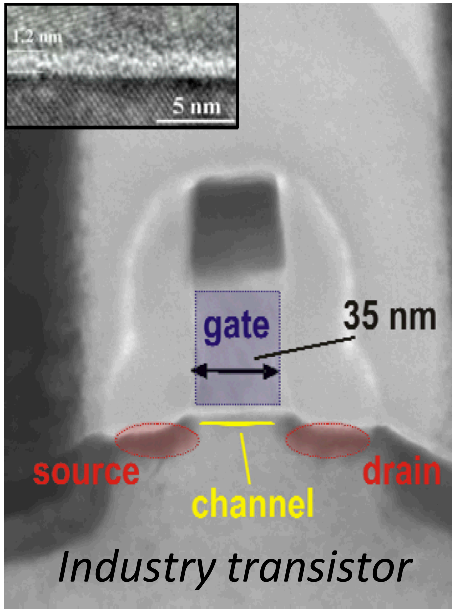
  => Cryogenic temperatures

Quantum dot potentials for single electrons



$$\Delta E = \frac{\hbar^2}{2m^*} k^2$$

$$k = \pm \frac{2\pi}{W_{Well}} n$$

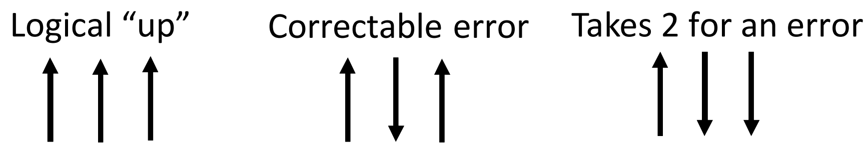


- Goal: isolation of two states of the electron
- Aim for spacings ~ 5-10*kT spacing or electronic states (rule of thumb)
- Energy level separation is dependent on size of confining potential & effective mass in quantum dots
- Energy spacings for 40-50 nm Si well are order 5 meV [Si]

  => Cryogenic temperatures

Quantum error correction and simple logical memory

Classical error correction – majority vote encoding



- Qubit errors much higher than transistors

- Big breakthrough in quantum computing was quantum error correction

- Basic idea is majority vote but phase can also be corrected

- Continuous correction is logical memory

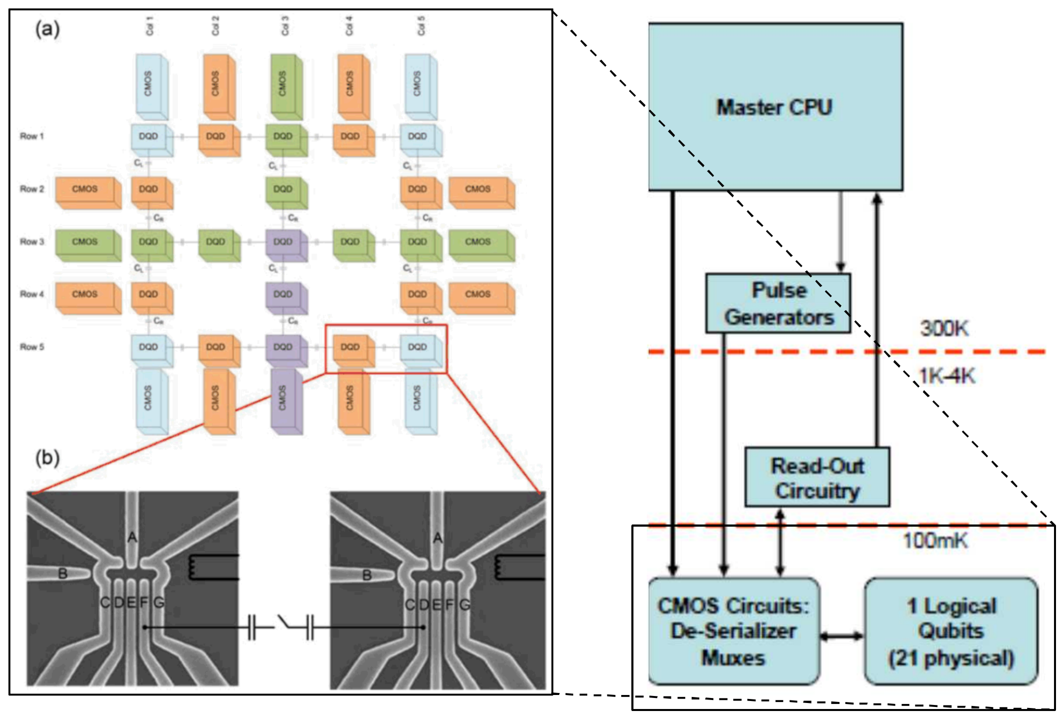
Quantum error correction and simple logical memory

- Implementation example
- Many qubits for small amount of error correction
- Break even error requires single qubit error to be ~5e-4
  - Think 1000's of visible rotations
- More error => many more qubits

Levy et al. SPAA (2009)
Levy et al. New Journal of Physics (2011)

Chip Level Circuit

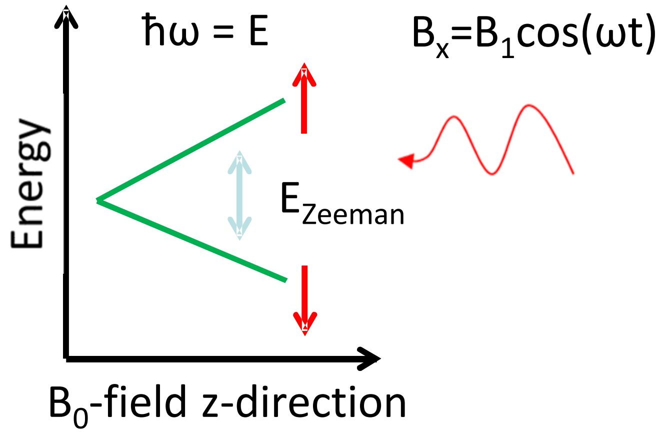
Classical-Quantum Interface



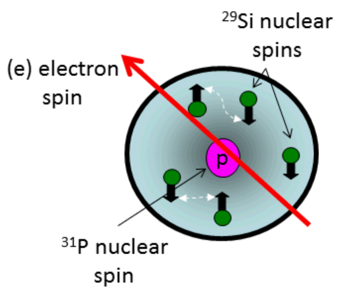
Physical Qubit

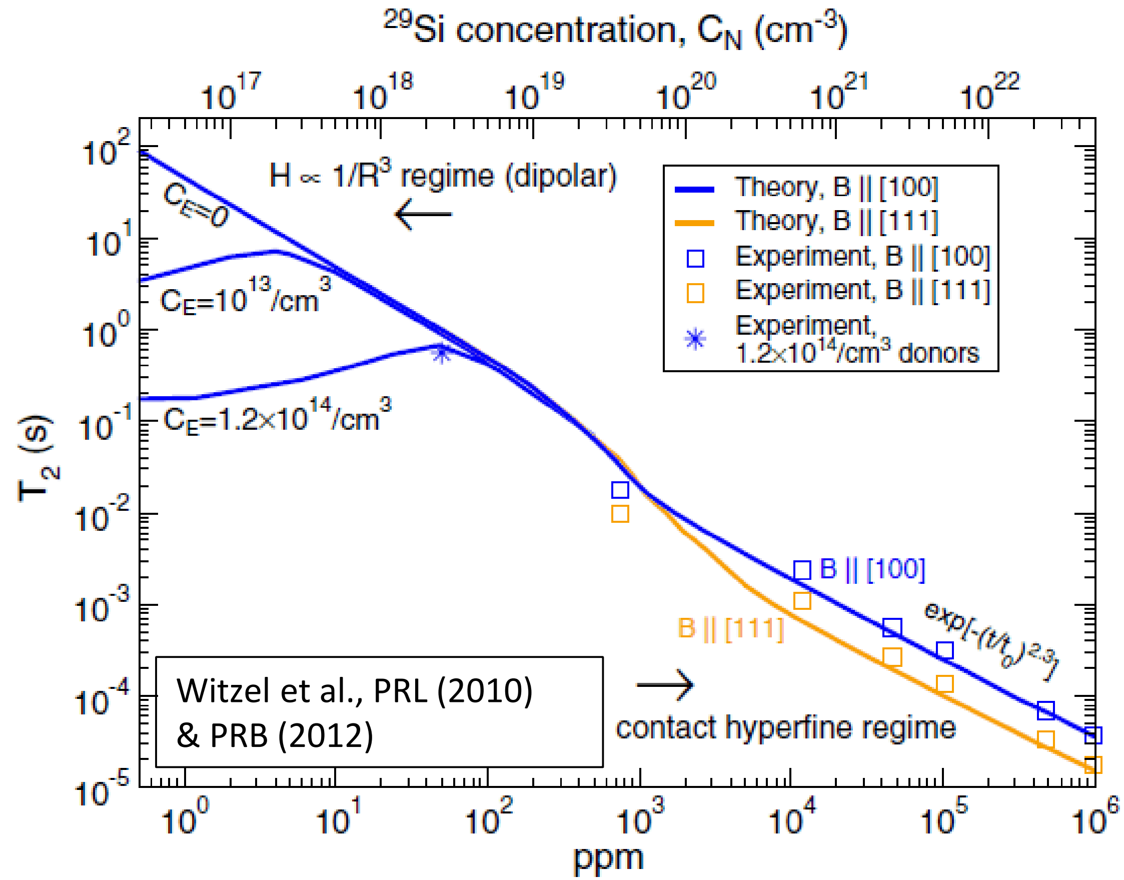
Motivations for **silicon** quantum computing

ESR/NMR qubit



29Si nuclear spins source of error



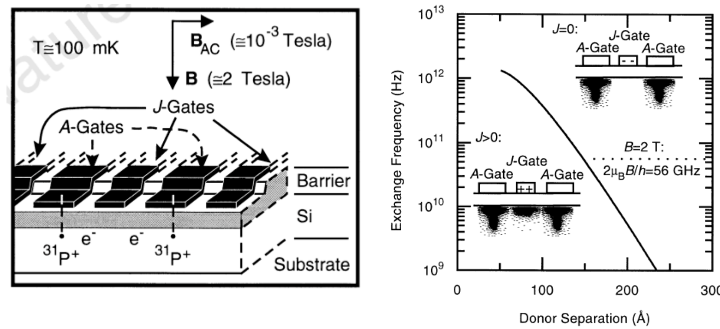


- Silicon appealing because it can be enriched to be a "magnetic vacuum" & purified of other spins
- Very long decoherence times possible
- Silicon offers promise of **realizing** very high fidelity, less error correction and Si foundry compatible

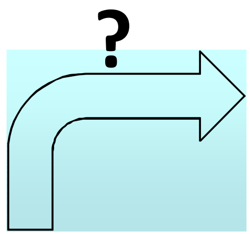
Donor qubits

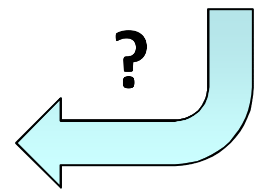
- Donor nuclear spin qubits have exceptional fidelities
- Fabricating and controlling single atoms is hard
- Many proposals access donors through surface QDs
- This talk: first coherent coupling of MOS QD with donor qubit

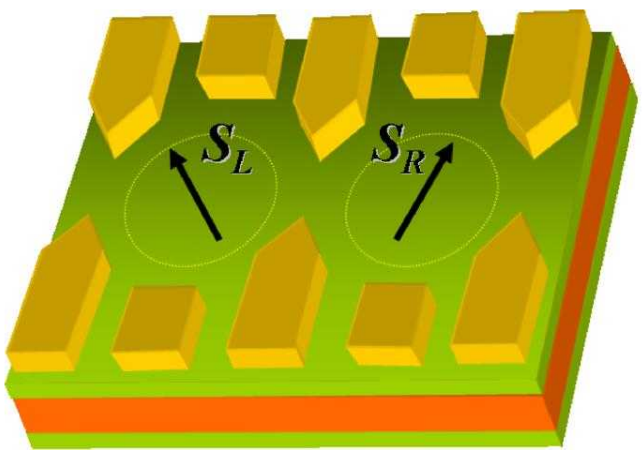
Donor qubit architecture



Kane, Nature, 1998.







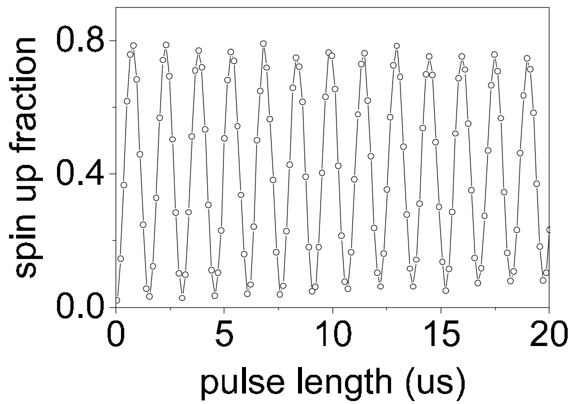
Quantum dot architecture

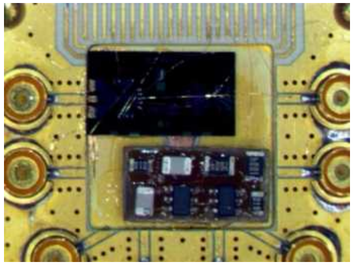
D. **Loss** and D. P. **DiVincenzo** Phys. Rev. A, 1998.

Nuclear spin ½ (CQC2T, Nat. Nano. 2014):
T_2^* = 600 ms
$T_{2,\,CPMG}$ = 36.5 s
$F_{prep/readout}$ = 99.995%
$F_{control}$ = 99.99%

Outline

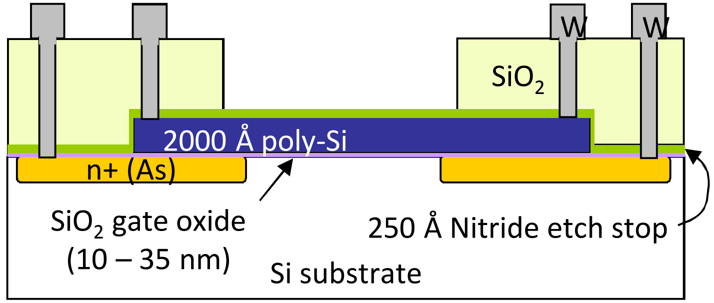
- Motivations
- Few electron QDs & donor qubit ESR
- Hybridization of a QD qubit with a donor qubit
- Summary

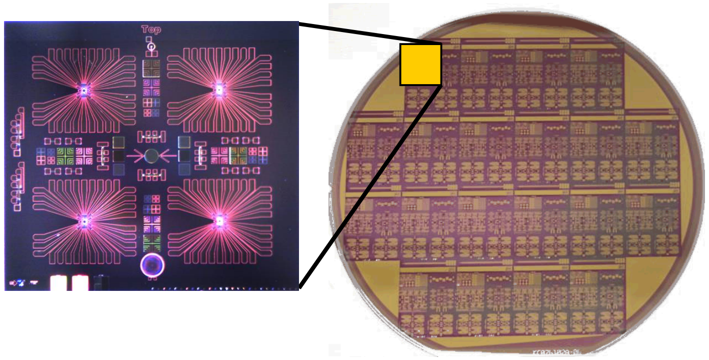




Nanostructure fabrication at Sandia National Labs (SNL)

Silicon fab



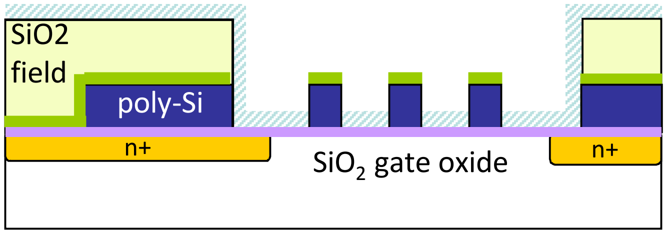


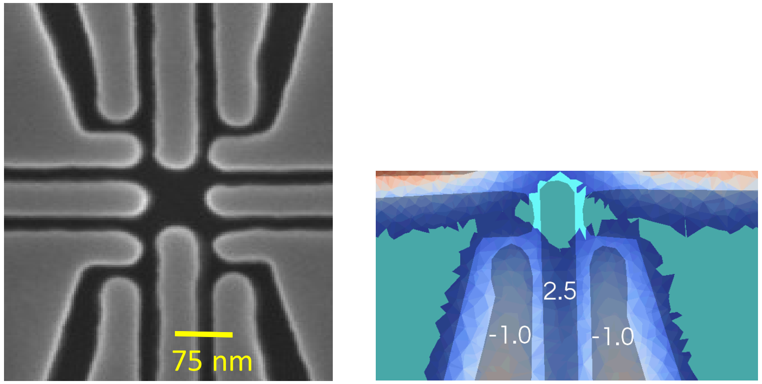
Goal: Use Poly-Si etched structures to produce donor-based qubits

Rationale:

- Self aligned implant
- Foundry like processing
- Potential long term benefits for charge stability

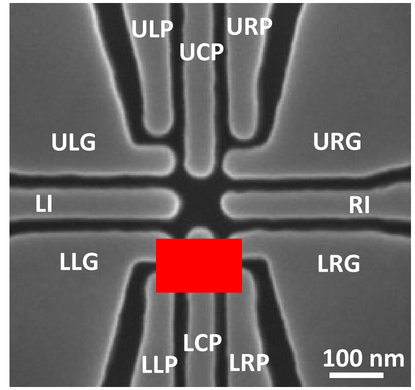
Nanofabrication in “skunk works”

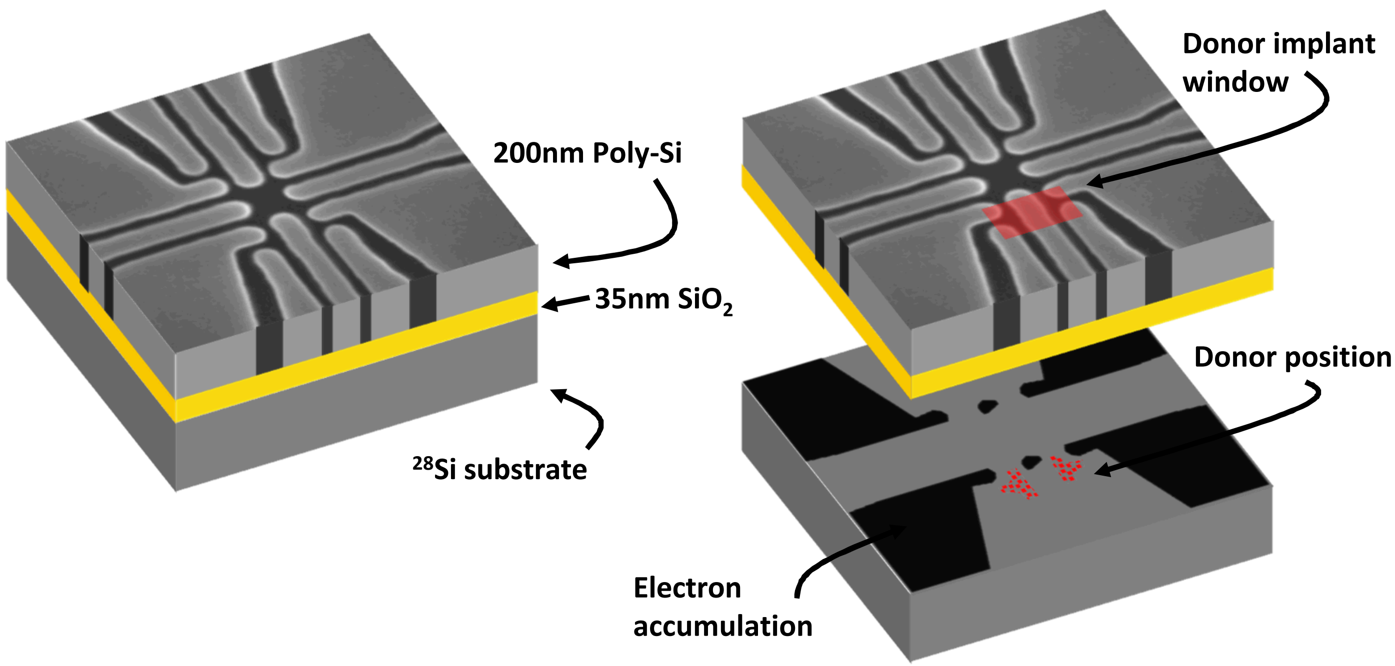




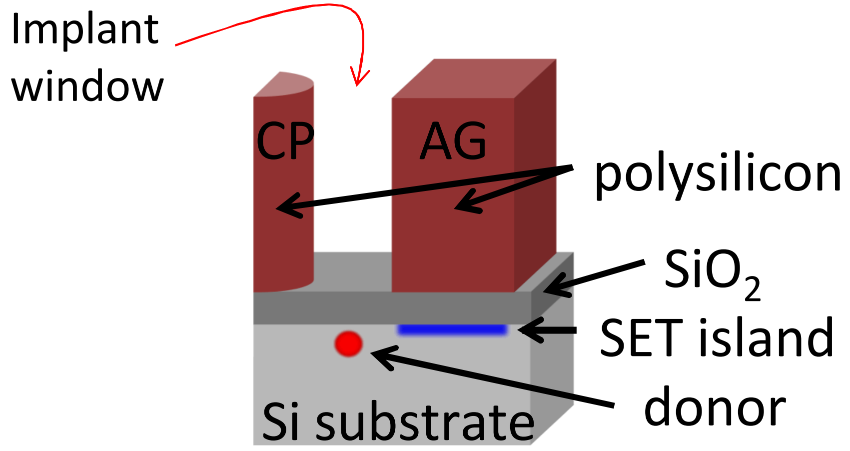
Nordberg et al., PRB 80 115331 (2009)
Tracy et al., APL 103 143115 (2013)
Rochette et al., 2016 International Si Quantum Electronics Workshop

QD-Donor Device

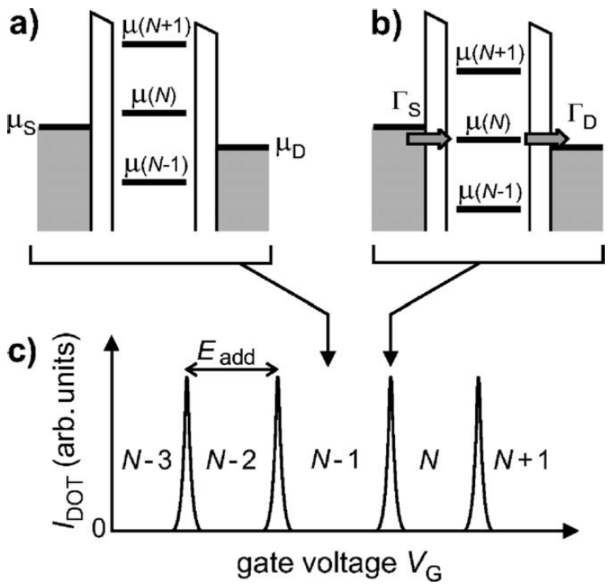




Coulomb blockade in quantum dots



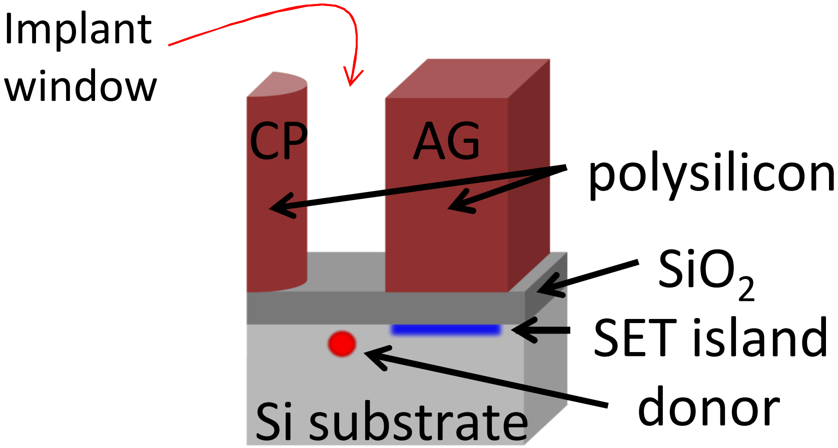
$V = \frac{q}{C}$ ↕

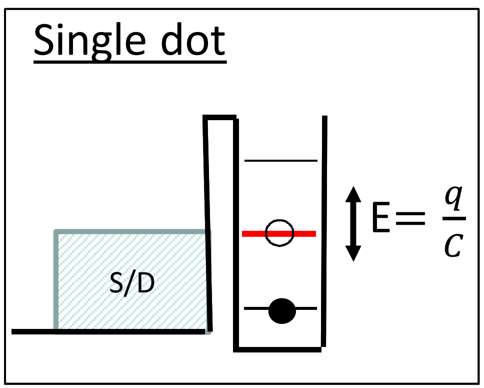


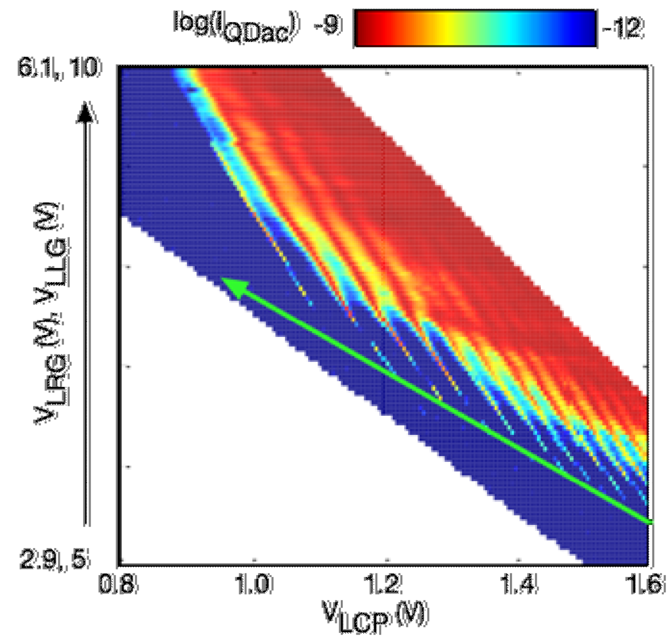
Hanson, Rev. Mod. Phys. (2007)

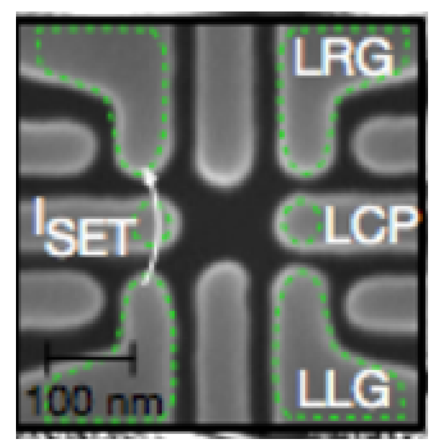
- Coulomb blockade produces "stability" regions

MOS quantum dot



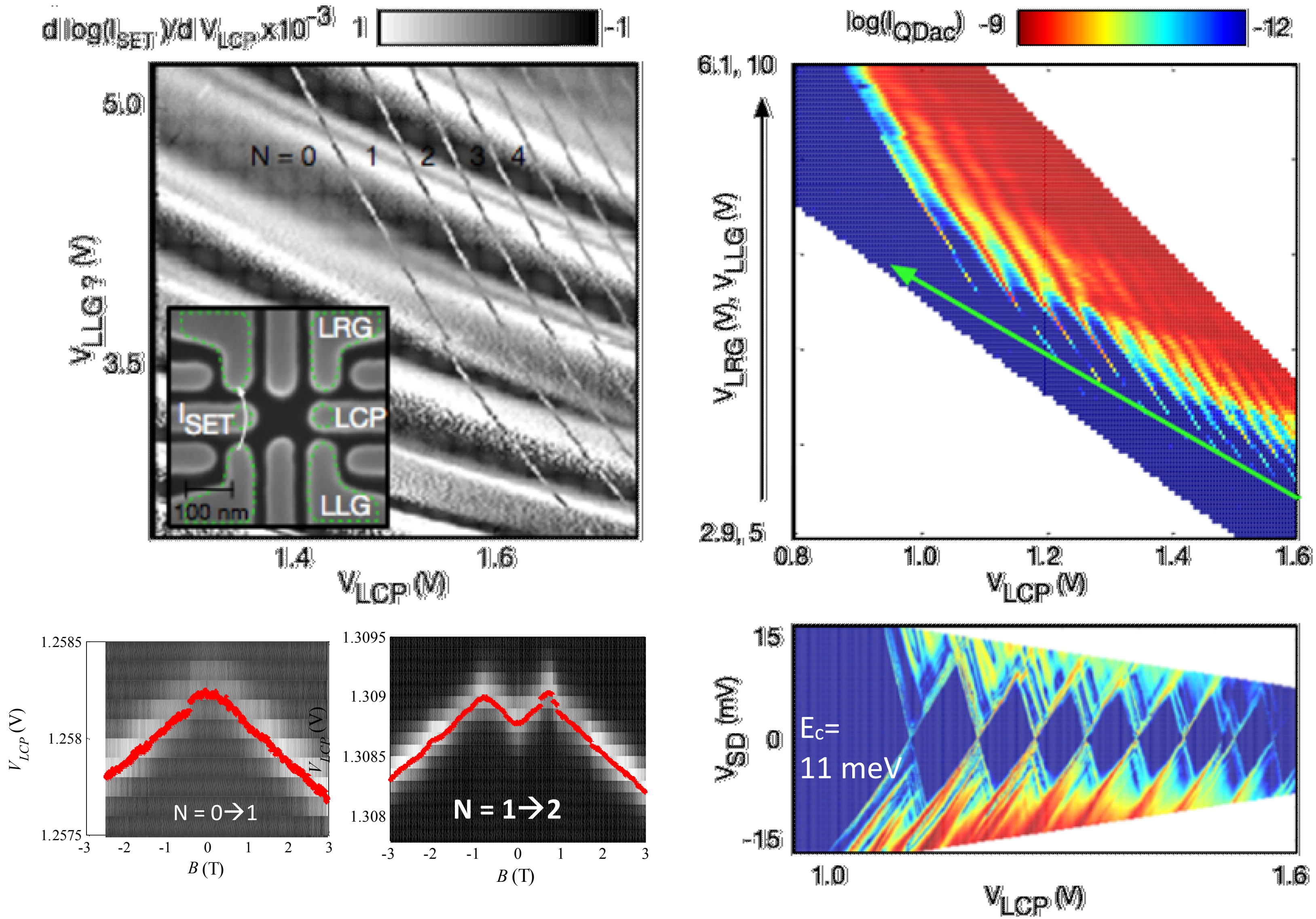






- Real example
- Quantum dot can be emptied to valence = 0
- Effective artificial atoms

Few electron occupancy

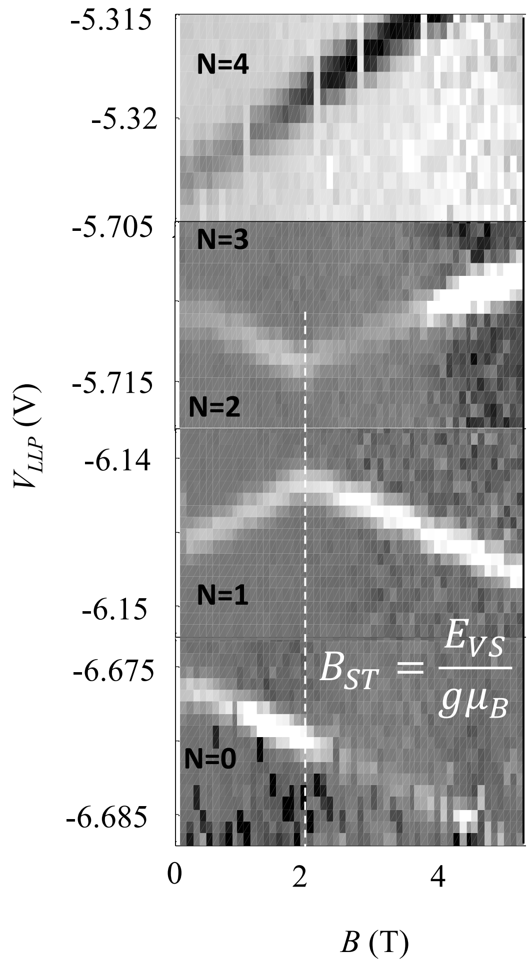


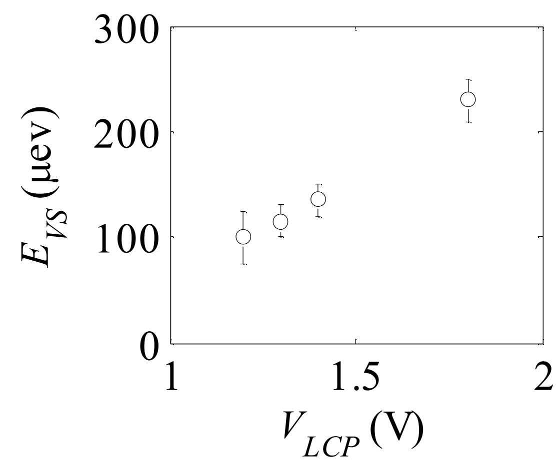
Rudolph (SNL)

QD Properties – Valley Splitting

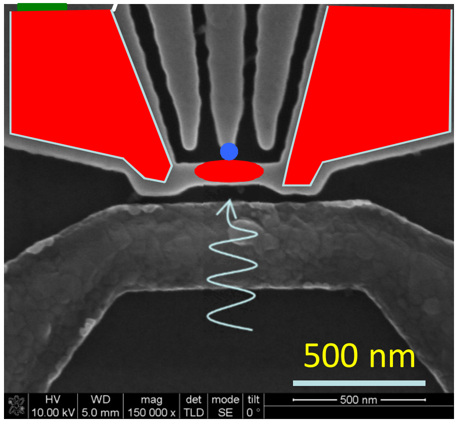
First excited state in Si is a valley state

- Valley-splitting determined by the z-confinement
- Increased vertical electric field increases valley-splitting
- Valley splitting can be increased to $E_{VS} > k_B T$
- N=4 also has a zero field singlet filling
  - Protected by an orbital splitting… $E_O \gg E_{VS}$





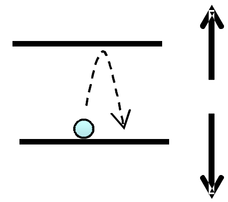
Electron spin resonance of single donor at SNL

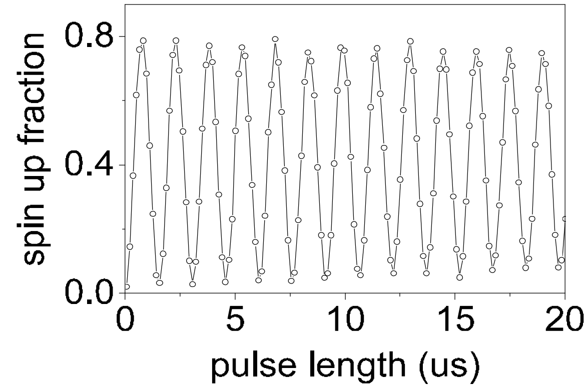


Ohmics

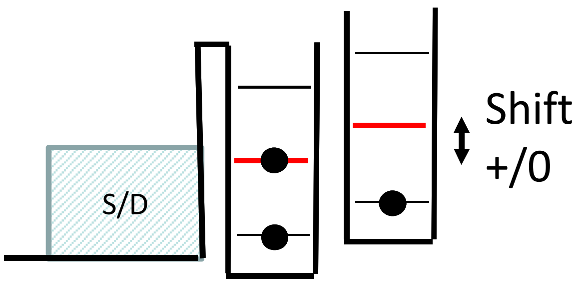
Donor

Quantum Dot



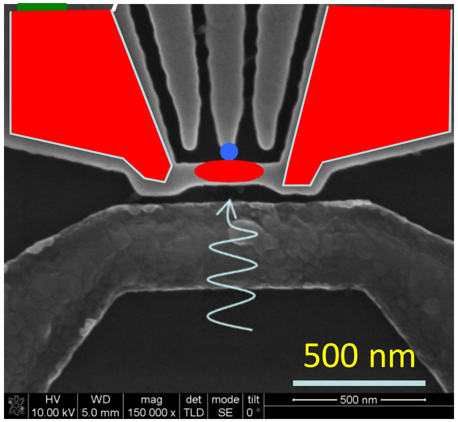


Charge sense spin dependent ionization



Tracy et al. APL 2016

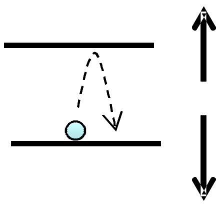
Dephasing metrics

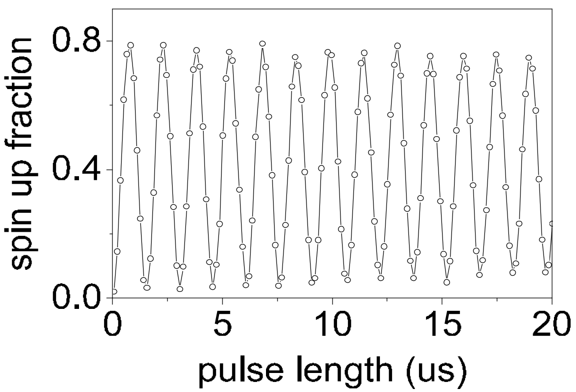


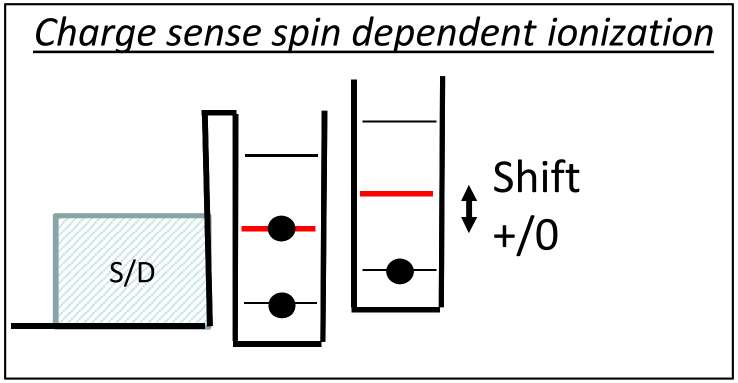
Ohmics

Donor

Quantum Dot







^{28}Si epilayer

- 2.5 μm thick
- 500 ppm ^{29}Si (ToF SIMS)

Nominally identical processing

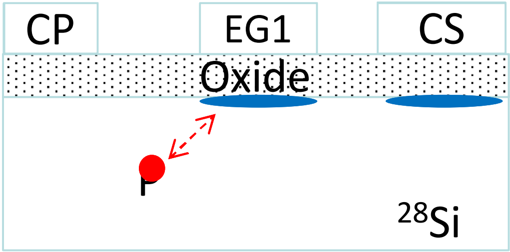
Long lived Rabi oscillations in ^{28}Si

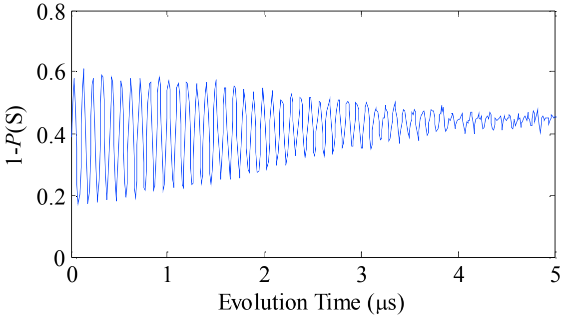
- Ramsey and Hahn-echo: T_2 = 0.31 ms, T2* = 20 μs
- Order of 20 rotations within a T_2*

Tracy et al. APL 2016

Outline

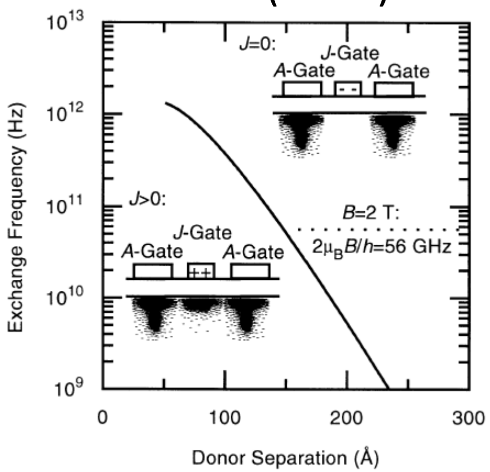
- Motivations
- Few electron QDs and donor qubit ESR
- Hybridization of a QD qubit with a donor qubit
- Summary

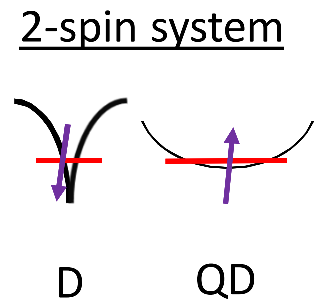


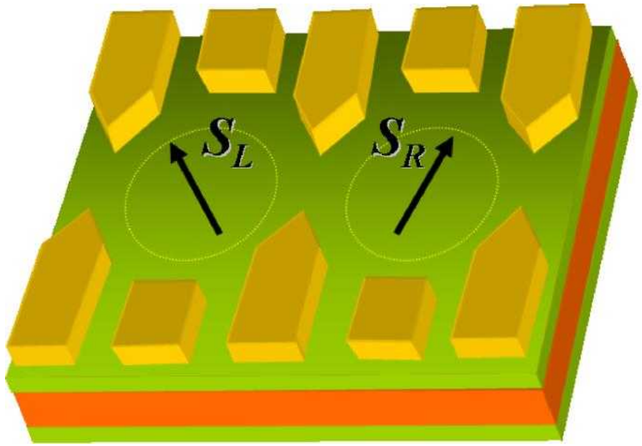


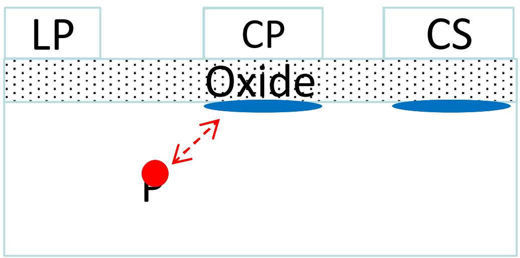
Approach: Couple a N=1QD to Donor

Kane (1998)









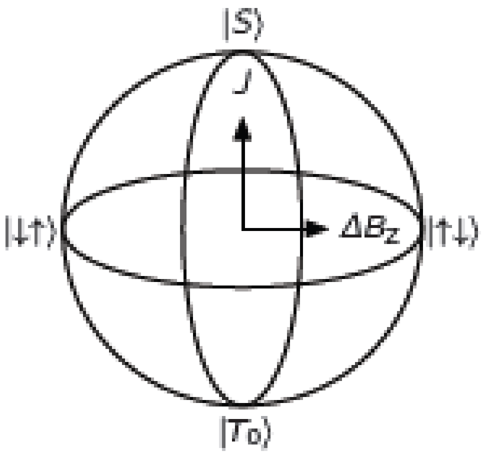
- Kane device architecture requires interaction at interface --- this is a quantum dot potential
- Couple N=1 QD with donor
- Detail: choice of two spins allows all electrical control (no microwaves)

Qubit Encoding – choose two spins (not one)

Canonical encoding of two spin logical qubit: S/T

Spin states for two electrons

$$|S\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \quad \Big\} \; m = 0$$
$$|T_0\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$
$$|T_-\rangle = |\downarrow\downarrow\rangle \qquad m = -1$$
$$|T_+\rangle = |\uparrow\uparrow\rangle \qquad m = +1$$



- For scope of this talk: encoding of two electron spins is singlet and triplet
- Electron-electron overlap introduces an “exchange” energy (J) which produces this basis
- Rotations are produced when a gradient field (dB) becomes greater than J

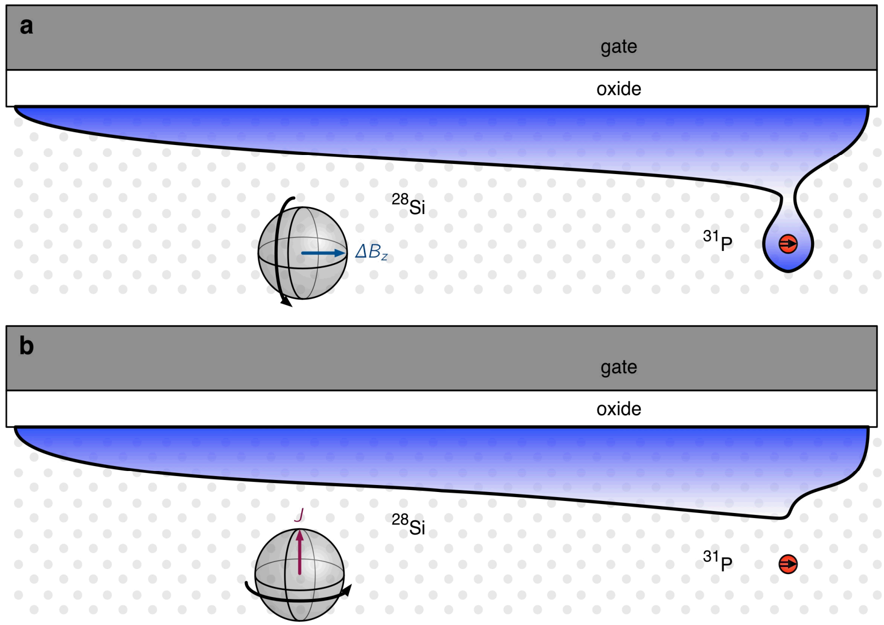
Notional coherent operation

Mathematical description

$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z(\epsilon)\hat{\sigma}_x$$

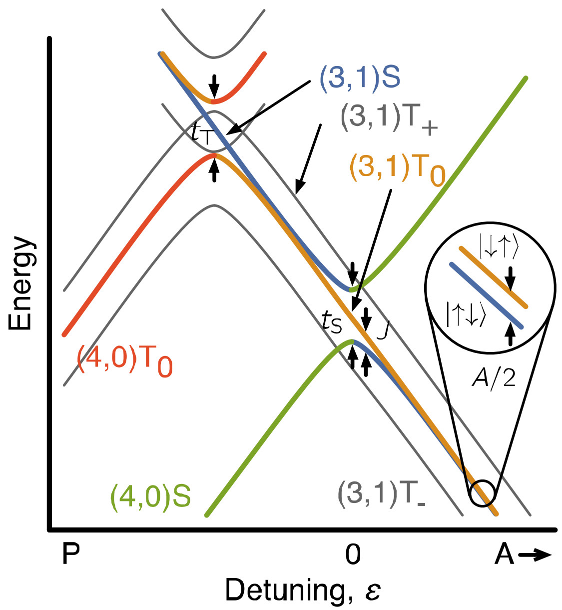
$\downarrow$

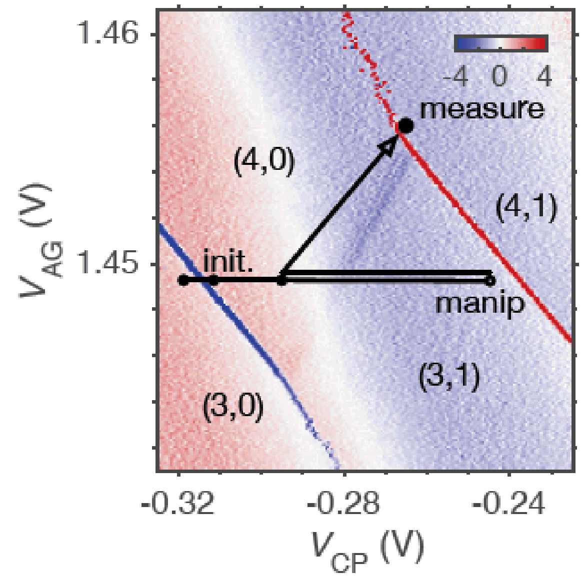
Donor-QD S/T qubit → $AI \cdot S$

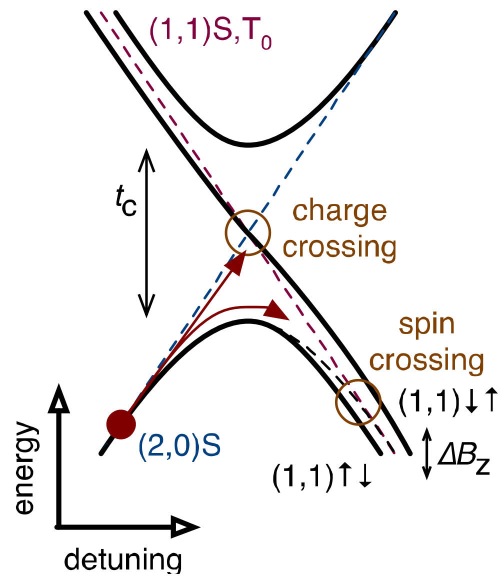


- Gradient field is supplied by nuclear spin of donor
- Electrical control of qubit rotation produced by moving electron on/off of donor
- To what does this all amount?
  - Platform to examine microscopic detail of a MOS electron qubit coupled to a buried donor qubit
  - Future path to coupling donors
  - Produces an appealing two-axis controlled S/T qubit – fast, stable, compact qubit
  - Paths to nuclear spin readout and nuclear spin entanglement

Steps towards coherent control



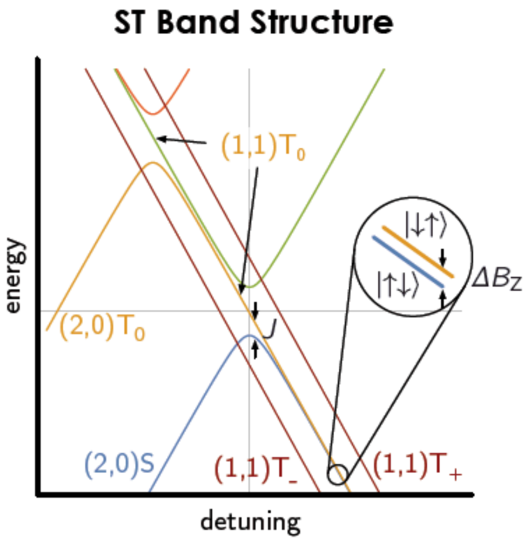


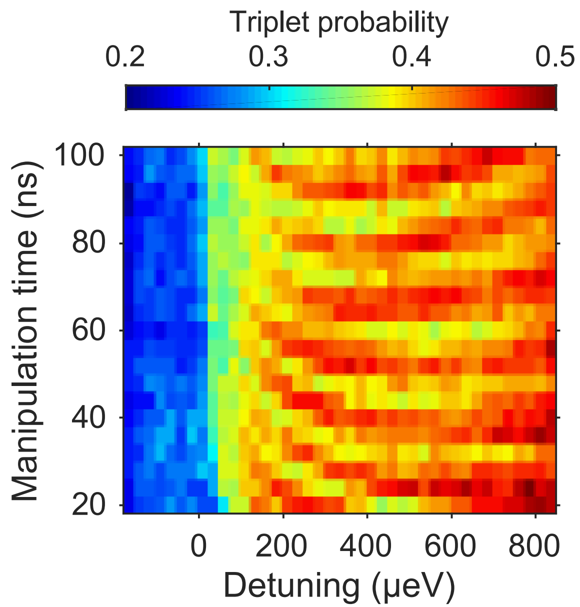


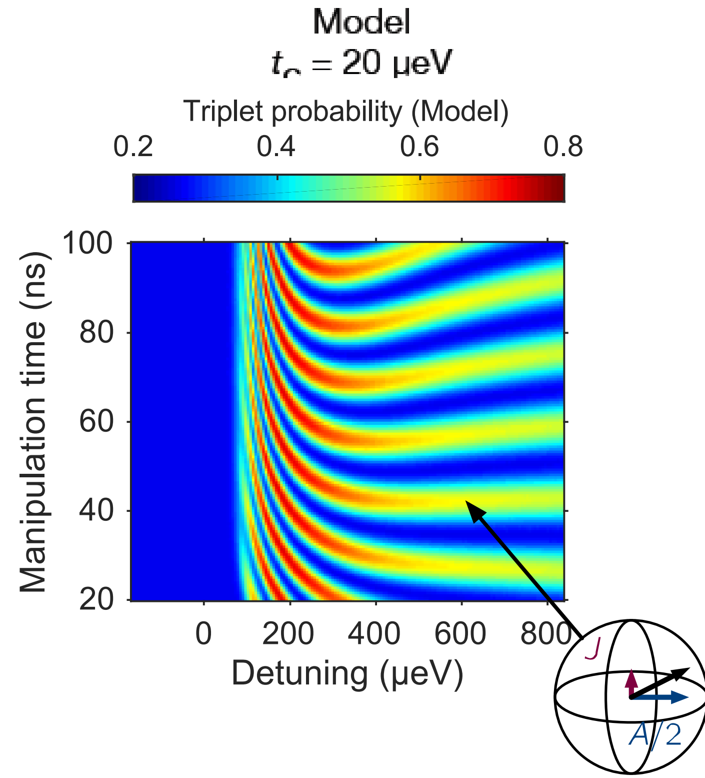
Approach

- Prepare (2,0) singlet
- Pulse into (1,1)
- Ramp rate must be balanced against charge adiabaticity but diabatic relative to the crossing where J < A
- Shift to higher tunnel coupling through higher N in QD

Comparison to numerical simulation

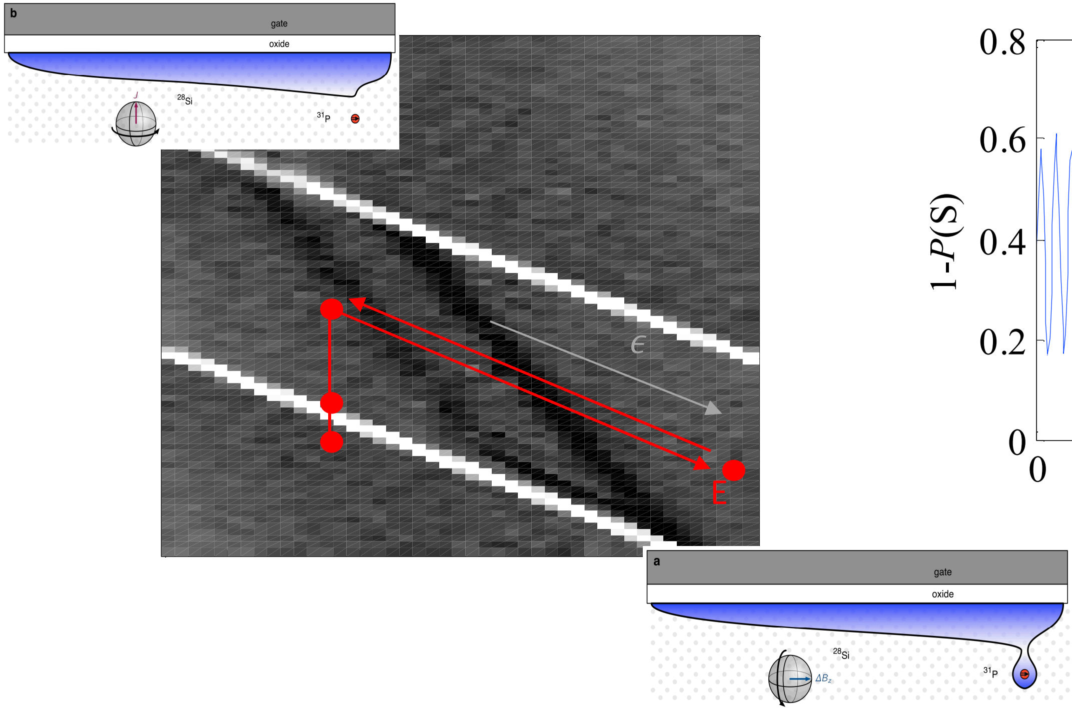


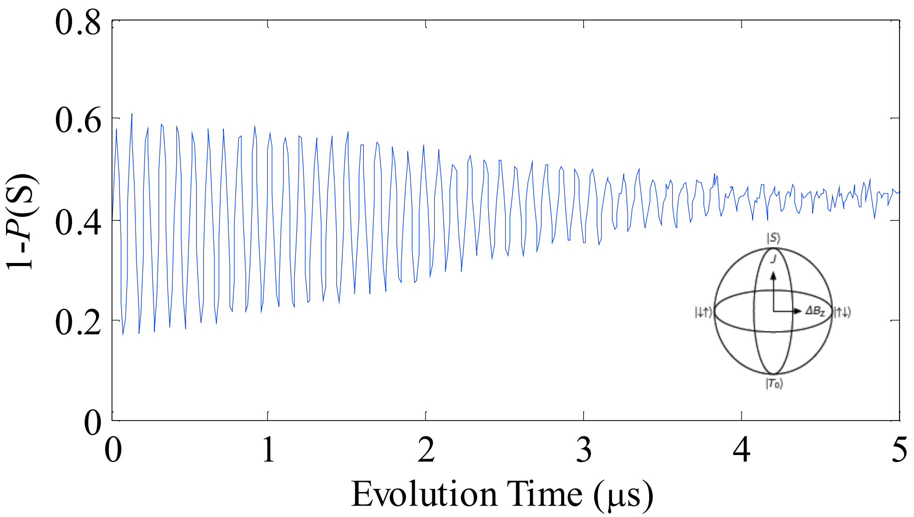


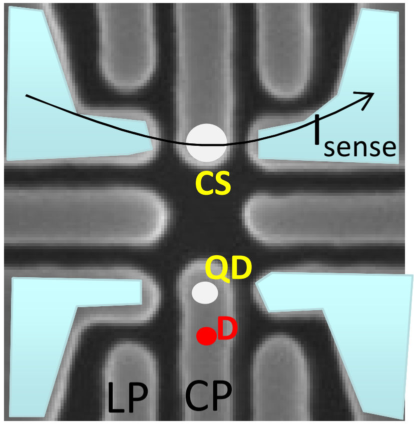


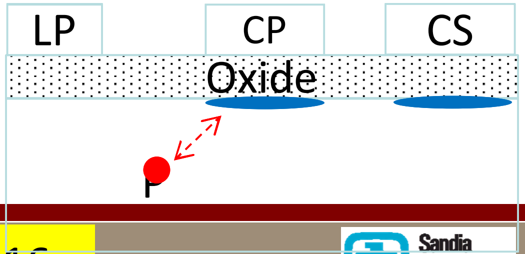
- Phenomenlogical Hamiltonian solved for relevant detuning range
- Dynamics of master equation solved using Lindblad formalism (A assumed, tunnel coupling is fit)
- A number of similar qualitative and quantitative behaviors are exhibited
  - Singlet state is preserved until it is moved to the (1,1) charge state
  - Deeper detuning target reduces J and rotation rate saturates near expected A/2 value
  - Ramp rates affect the rotations including subtle effects of changing integrated time in high J region
  - Reasonable experimental parameters (some directly measured) provide good qualitative agreement
- All consistent with a contact hyperfine driven singlet-triplet qubit
- MAJIQ: MOS, contact-hyperfine (A), exchange (J), single-nuclear-spin-driven (I), qubit

Pulse sequence & demonstration of coherent coupling





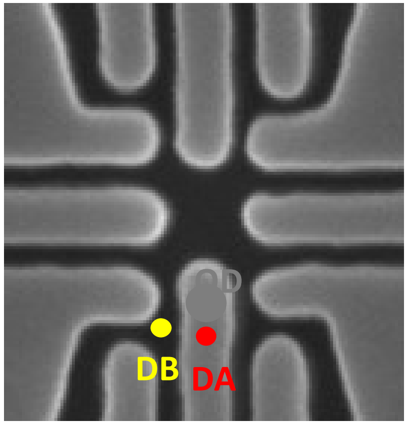


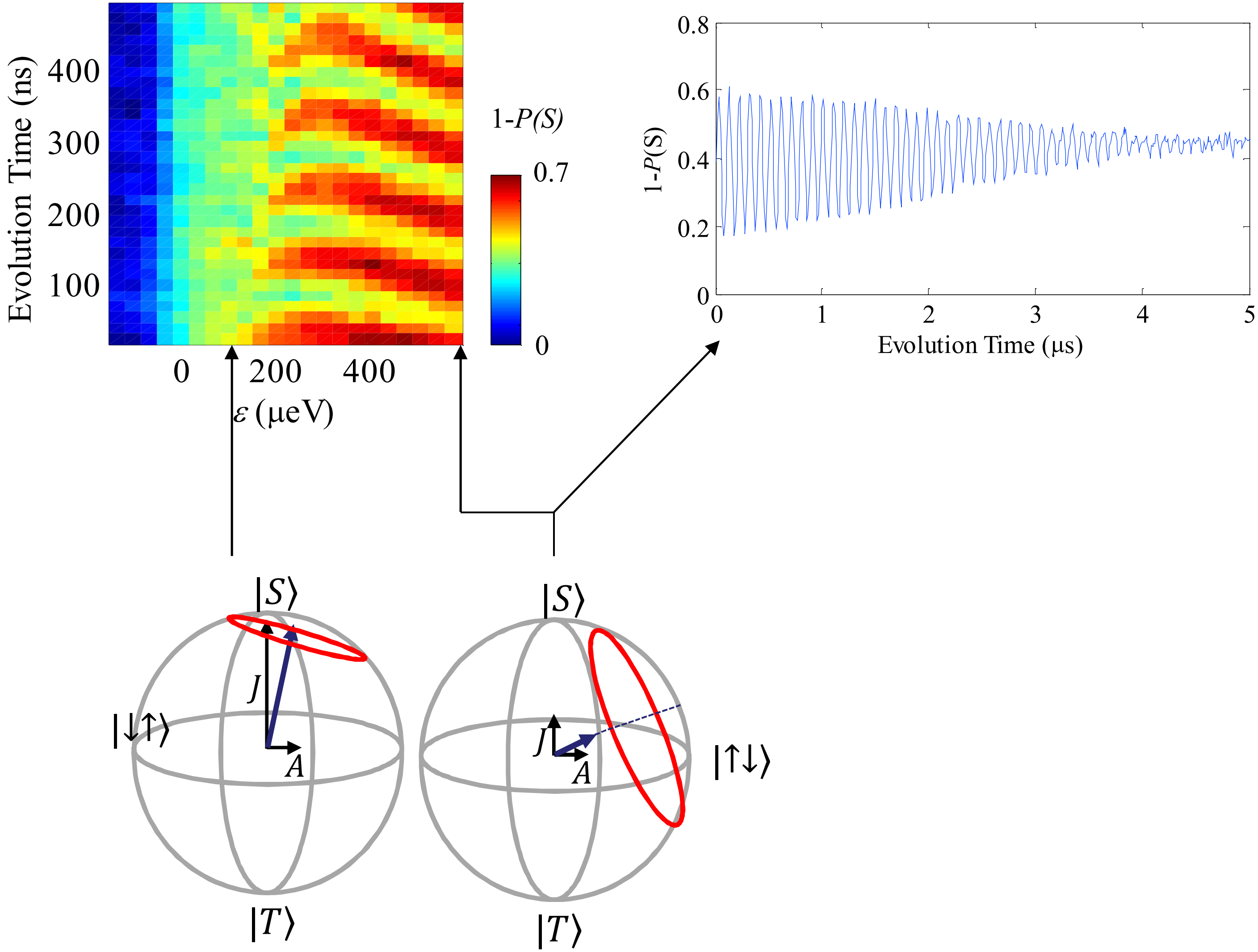


- Coherent oscillations observed for variable time & fixed detuning
- Promising start:
  - As a “hybrid” qubit: order of 50 rotations within a T2*
  - We now have a structure that can couple to other donors
- Future:
  - Couple D-QD cells
  - NMR on donor nucleus

Harvey-Collard et al. arXiv:1512.01606 & Rudolph et al. IEDM 2016

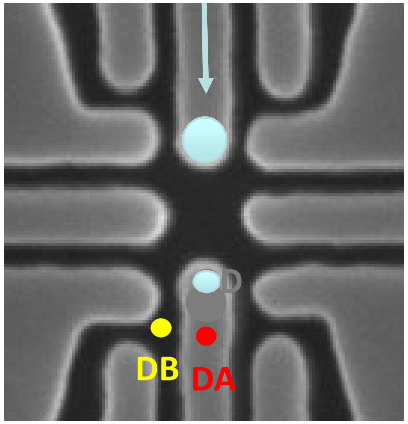
Two axis control in 2nd device

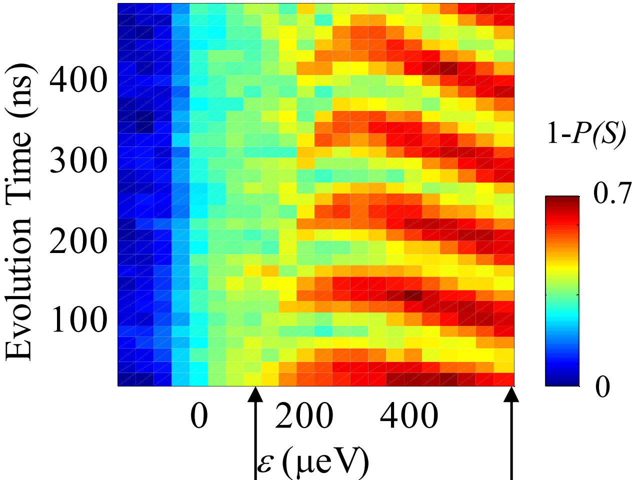


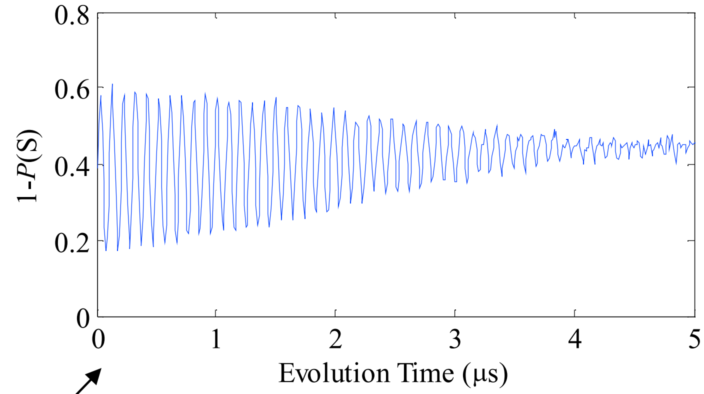


- Qualitative similar results repeated in second device
- Two axis control

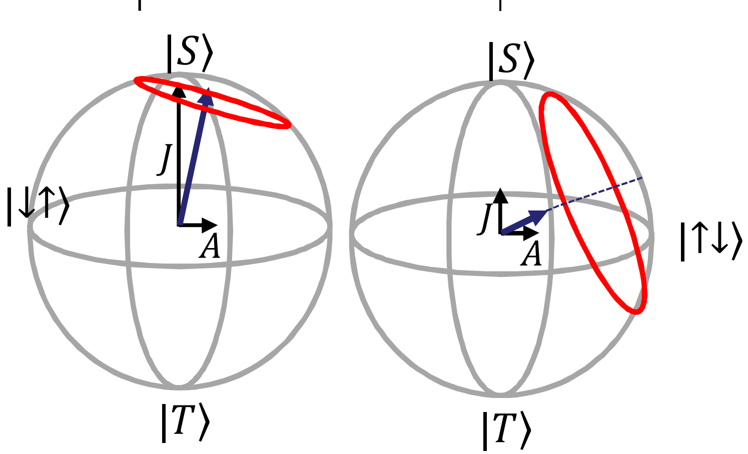
Two axis control in 2nd device

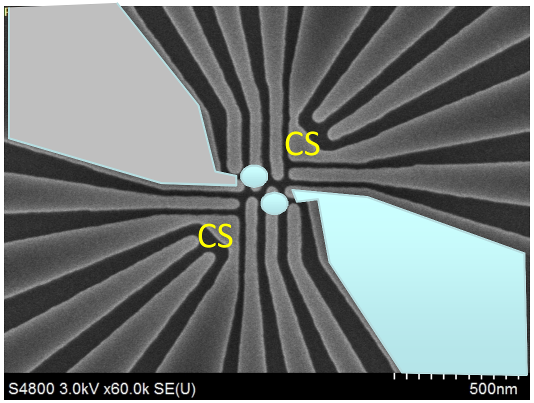






- Qualitative similar results repeated in second device
- Two axis control
- Layout is more plausibly extensible



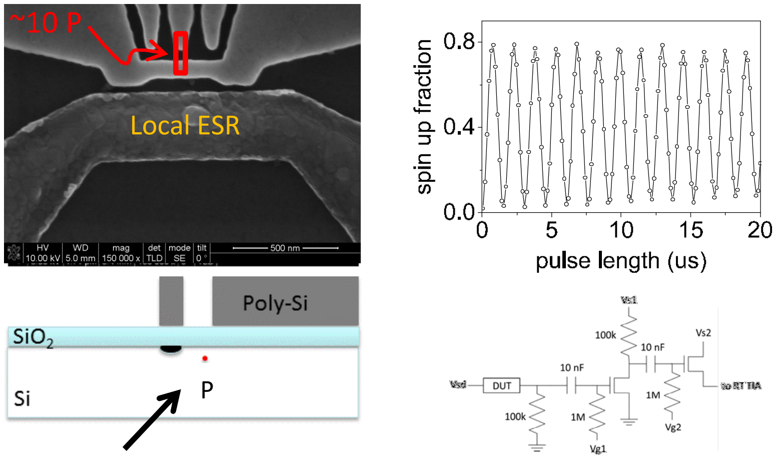


QIST team & external connections

- QIST contributors at SNL
  - **QD & Timed Implant Qubit Fab:** R. Manginell, T. Pluym, B. Silva, J. Wendt, J. Anderson
  - **Qubit control & measurement:** S. Carr, M. Curry, T. England, A. Grine, M. Lilly, T.-M. Lu, D. Luhman, J. Rivera, M. Rudolph, P. Sharma, A. Shirkhorshidian, L. Tracy, M. Wanke, A. Mounce, R. Jock
  - **Advanced fabrication (two qubit):** E. Bielejec, E. Bussmann, J. Pacheco, J. Koepke, E. Langlois, M. Marshall, B. McWatters, S. Misra, D. Perry, D. Scrymgeour, R. Simonson, G. Subramanian, D. Ward, J. Abraham
  - **Device modeling:** J. Gamble, S. Gao, M. Grace, T. Jacobson, R. Muller, E. Nielsen, I. Montano, W. Witzel, A. Baczewski
- 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, J. Petta)
  - NIST (N. Zimmerman, M. Stewart, J. Pomeroy)
  - U. Maryland (S. Das Sarma)
  - National Research Council (A. Sachrajda)
  - U. Sherbrooke (M. Pioro-Ladriere, C. Bureau-Oxton, P. Harvey-Collard)
  - Purdue University (G. Klimeck & R. Rahman)
  - U. New Mexico (I. Deutsch, P. Zarkesh-Ha)
  - U. Wisconsin (M. Eriksson, S. Coppersmith, D. Savage)
  - University College London (J. Morton)
  - Zyvex (J. Randall)
  - C.-W. Liu (U. Taiwan)
  - McGill (W. Coish, D'Anjou)

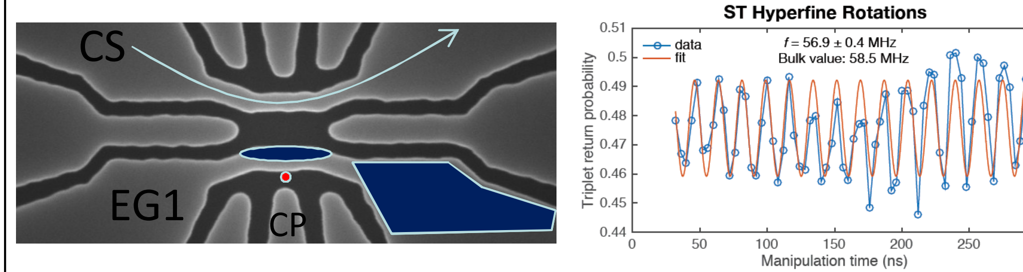
Summary

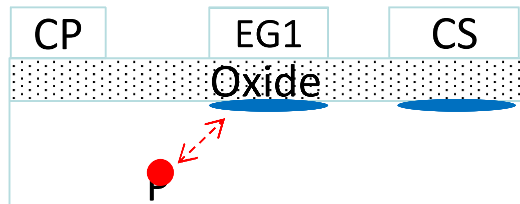
Single spin donor ESR in 28Si

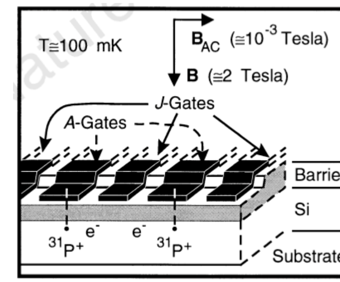


Tracy et al. APL 2016

MOS S/T qubit driven by single donor

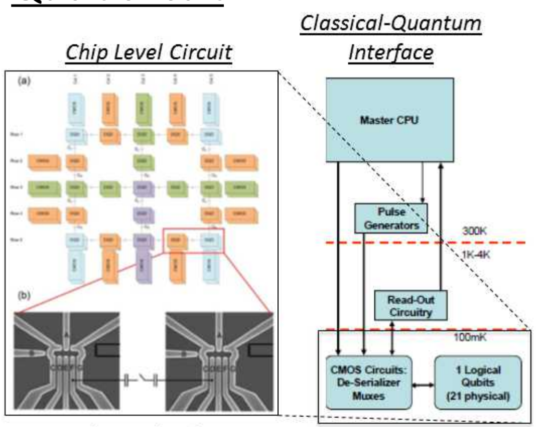






Harvey-Collard arXiv:1512.01606

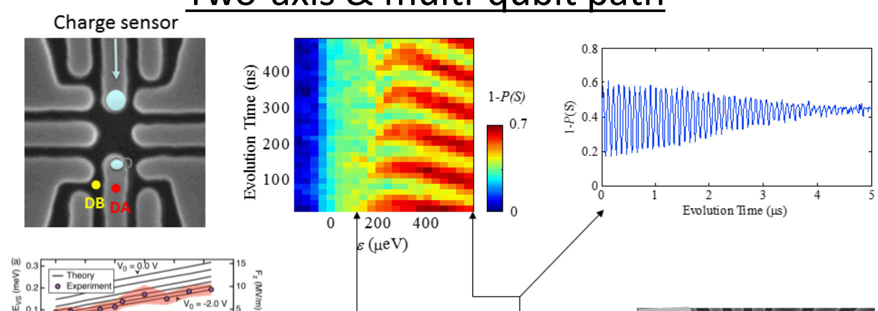
Qubit circuit

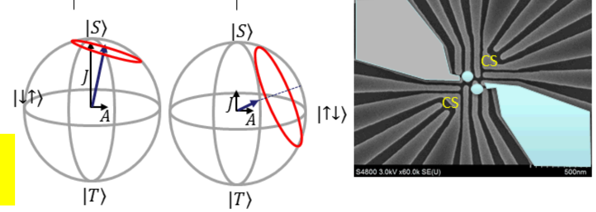


Physical Qubit

Levy, New J. Phys. 2011

Two-axis & multi-qubit path

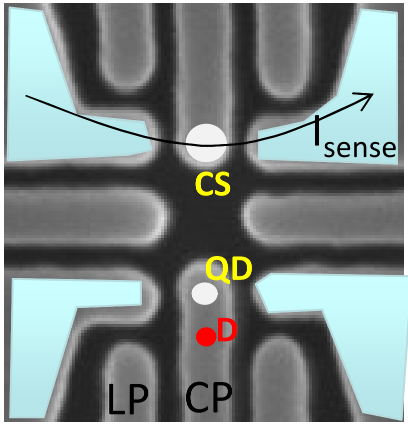


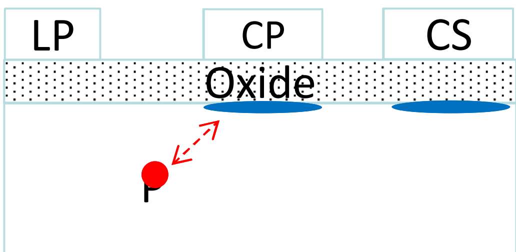


Rudolph, IEDM 2016

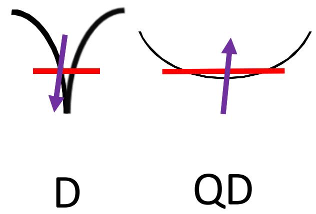
STOP

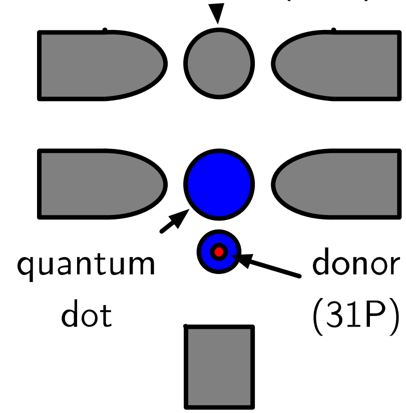
Approach: Couple a N=1QD to Donor



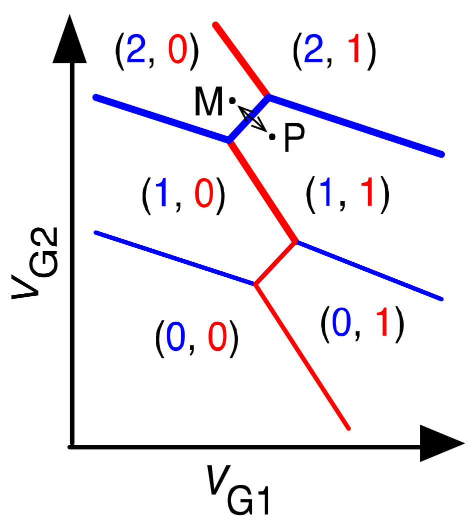


2-spin singlet-triplet qubit

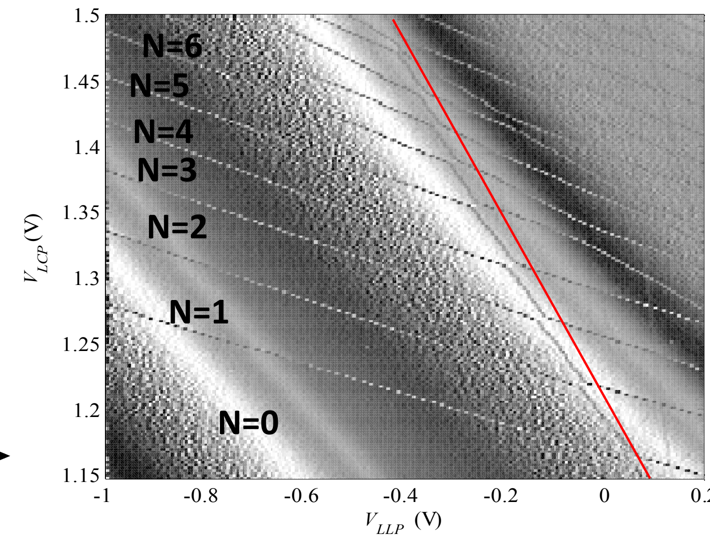




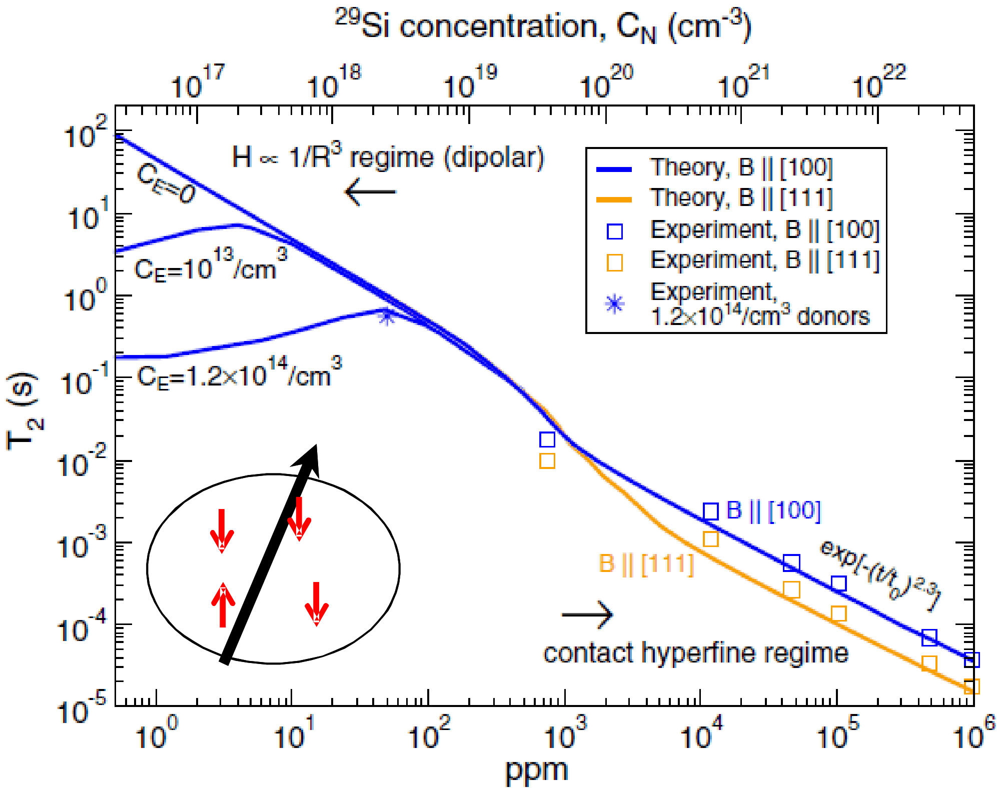
- Extend the single donor qubit lay-out to include a charge sensor
- Charge sensed donor-QD system is now an experimental double quantum dot platform to test the D to surface coupling idea



Actual measurement

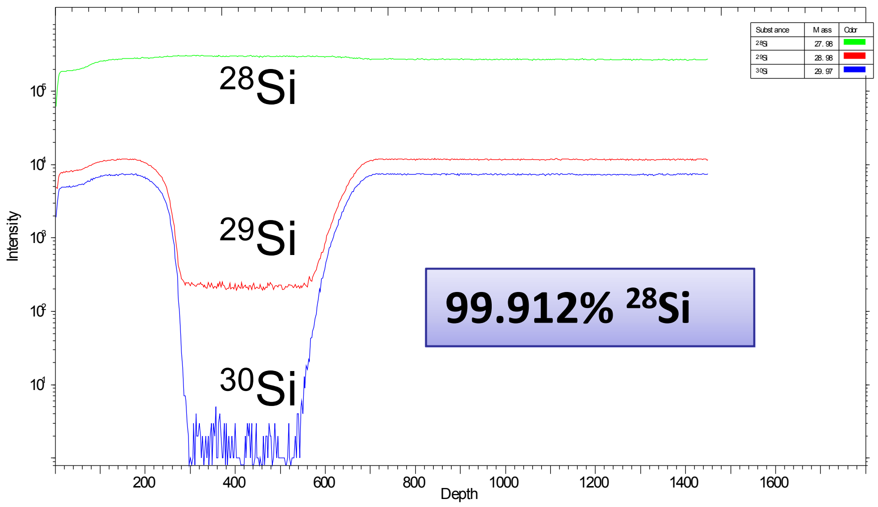


Motivations for **silicon** quantum computing



Witzel et al., PRL 105, 187602 (2010)
& PRB 86 035452 (2012)

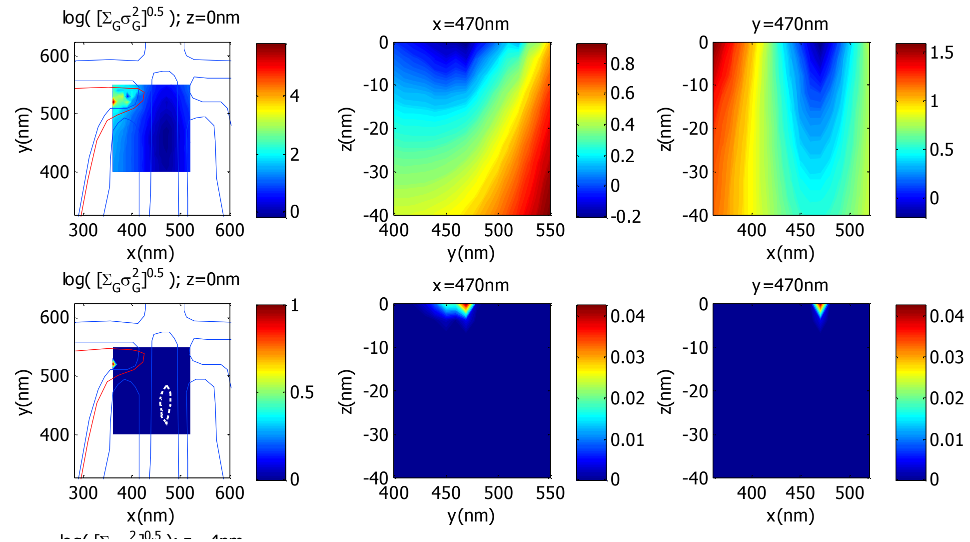
SIMS of ^{28}Si epitaxy layer



Sandia National Laboratories

QD Donor Locations

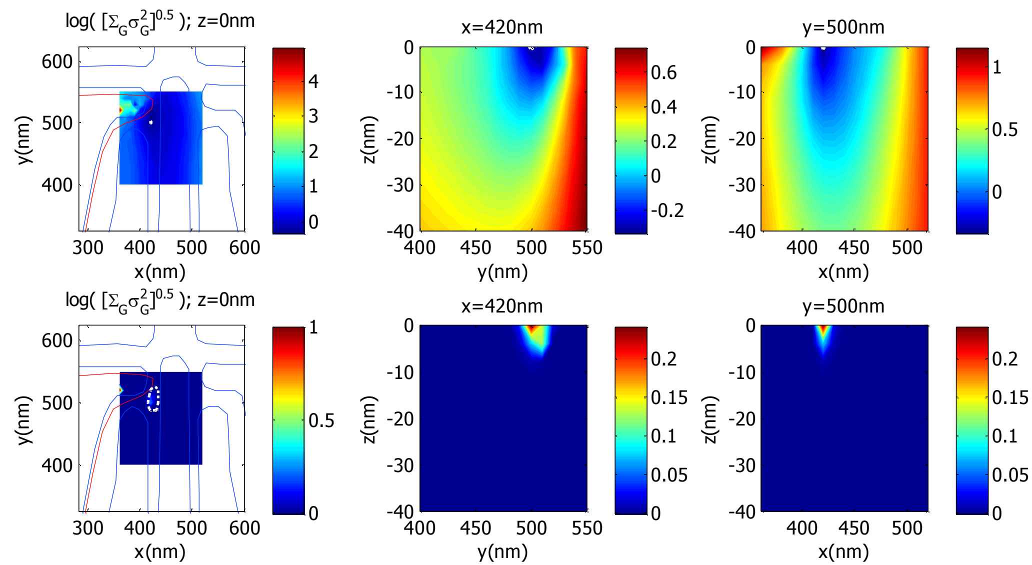
Donor A



Optimum: (470,470,0) nm
$\sigma_F/G^{0.5}$ = 0.25604
GOF = 0.043333

	C`_exp	C`_sim	alpha_exp	alpha_sim
LLP	0.2100	0.1920	0.0700	0.0516
LRP	0.2600	0.2852	0.0870	0.0766
LLG	0.0340	0.0499	0.0110	0.0134
LRG	0.1100	0.1424	0.0370	0.0382
LI	0.0510	0.0385	0.0170	0.0103
RI	0.0570	0.0512	0.0190	0.0137
LCP	1	1	0.3330	0.2685

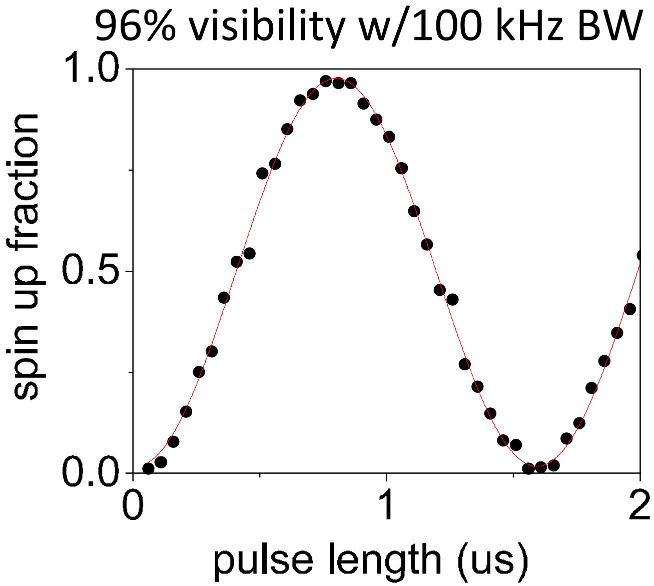
Donor B

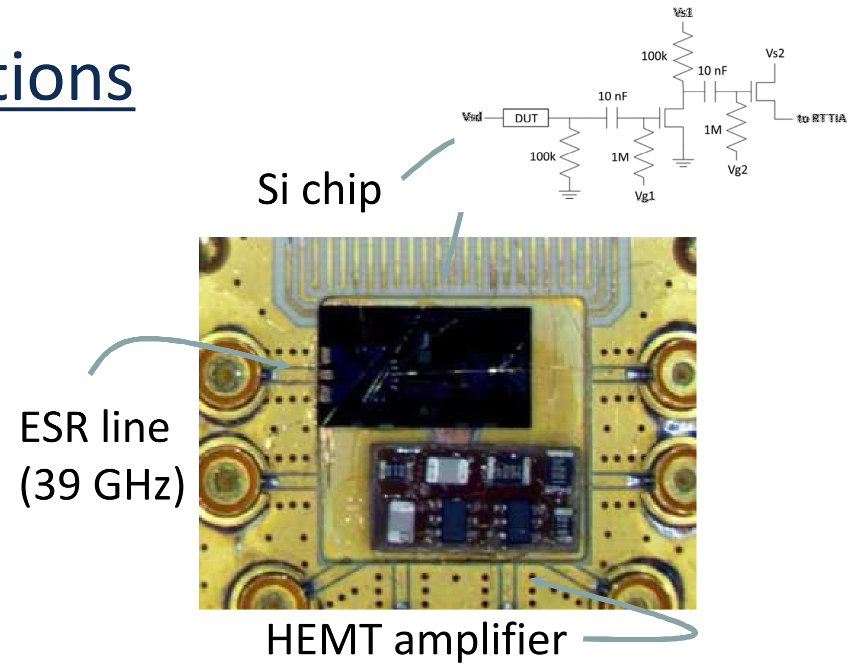


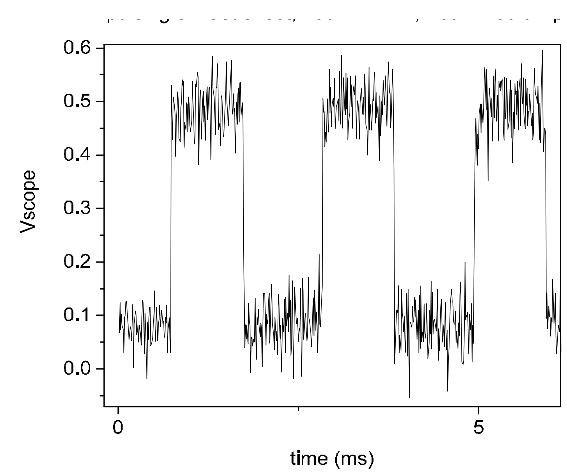
Optimum: (420,500,0) nm
$\sigma_F/G^{0.5}$ = 0.19061
GOF = 0.24415

	C`_exp	C`_sim	alpha_exp	alpha_sim
LLP	0.5200	0.5258	0.0630	0.0660
LRP	0.1600	0.1819	0.0190	0.0228
LLG	0.2800	0.2734	0.0340	0.0343
LRG	0.1000	0.1314	0.0120	0.0165
LI	0.1200	0.0921	0.0150	0.0116
RI	0.0870	0.0683	0.0110	0.0086
LCP	1	1	0.1210	0.1255

Rabi oscillations





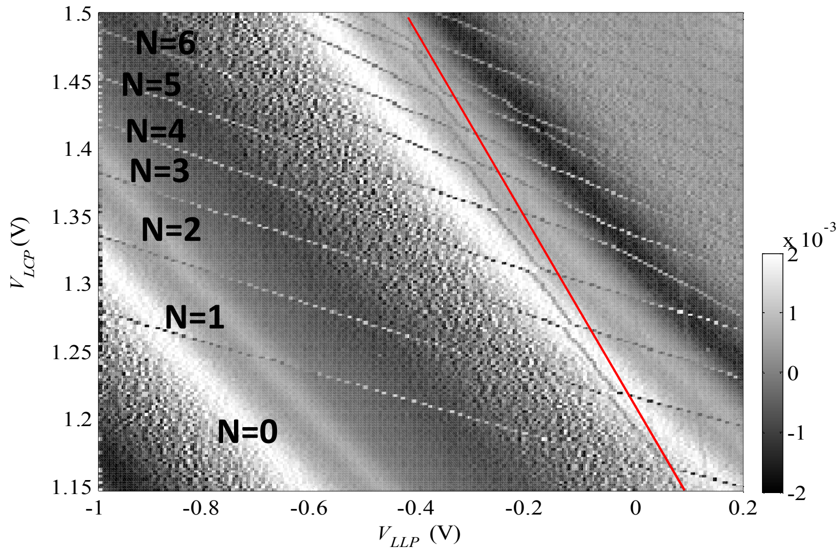


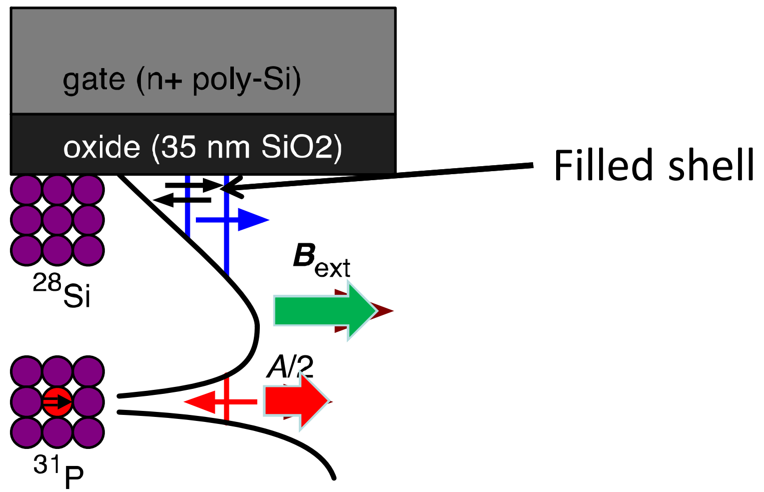
Long lived Rabi oscillations in ^{28}Si

- Ramsey and Hahn-echo: T2 = 0.31 ms, T2* = 10-20 µs
- Approximately 200 times better T2* than natural Si
- Max B1 corresponds to order of MHz
- Order of 10-20 rotations within a T2*

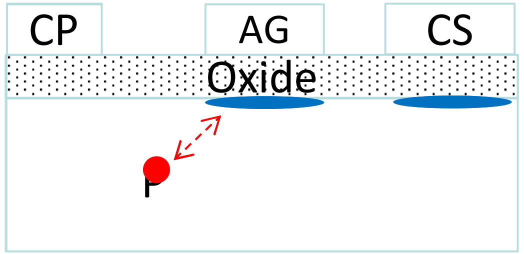
Note: readout visibility increased with addition of preamp allowing higher BW

Charge Sensed QD coupled to donor

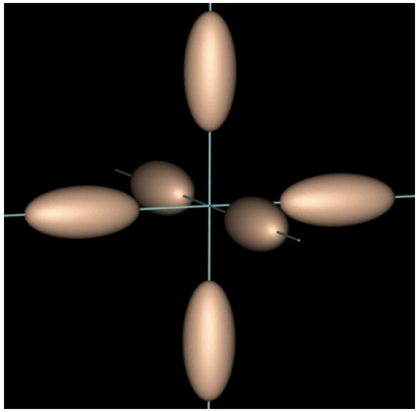


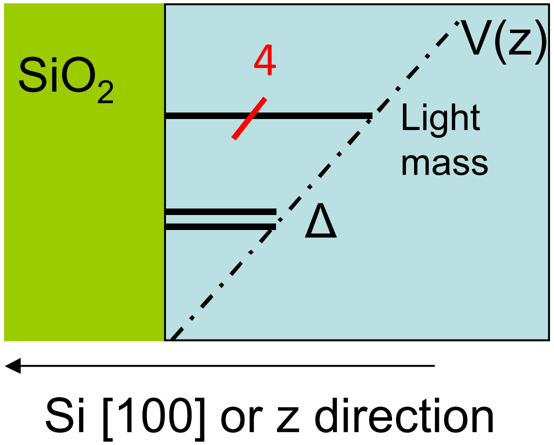


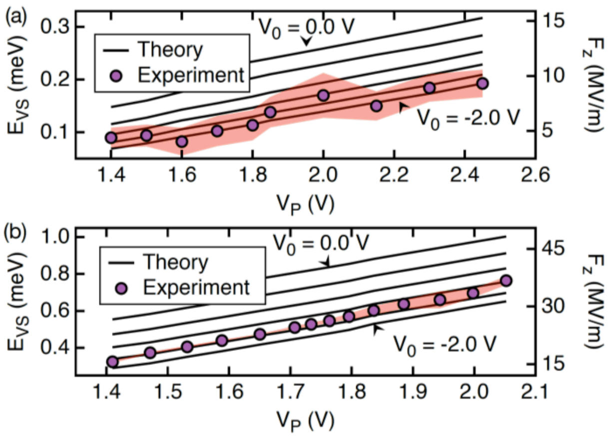
Approach
- Quantum dot is tuned to region of filled shell +1 electron
- Donor is tunnel coupled to quantum dot



Conduction band valleys and valley splitting



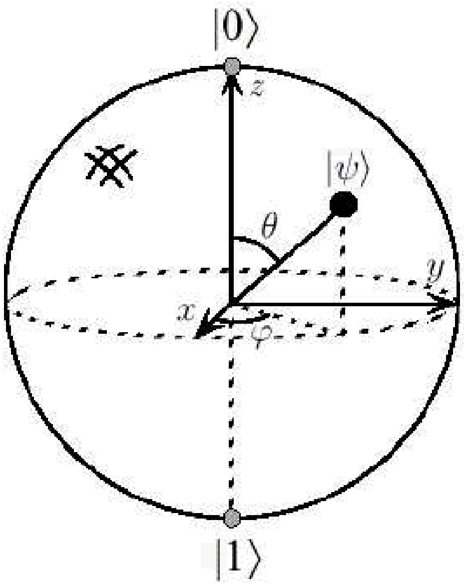




Gamble et al., arXiv 1610.03388

- Conduction band degeneracy is split 2/4 because of vertical confinement
  - This splitting is big relative to confinement energies
- Two level degeneracy is split, 0-0.5 meV, but details of the magnitude are still being investigated
  - Small splittings are produce errors (qubit states are not well isolated)
- Recent theory indicates interface roughness and vertical field are important [Friesen et al., PRB 81 115324 (2010), Culcer et al., PRB 82, 205315 (2010)]
- MOS QDs valley splitting can be tuned to usable regime

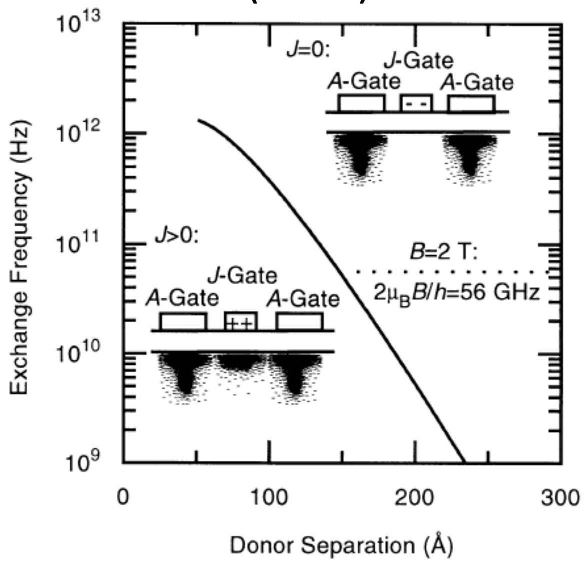
Introduction to qubits and single qubit gates

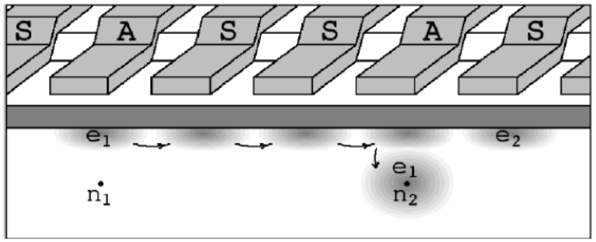


- The QC information is described with a | 0 > and | 1 > basis
- A quantum bit can be any system that has two energy levels
  - Electron spin, excited states of an ion or left/right position of a charge in a molecule
- A non-classical feature of two-level systems is superposition states
- QC compute advantage is more related to the utility of non-classical correlations due to entanglement of these qubits (beyond scope of this talk)

Donor-donor coupling concept

Kane (1998)

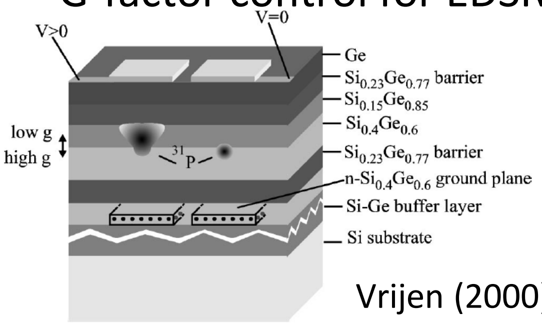




Transport: Skinner & Kane (2003)
Also transport: Hollenberg (2007), Morton (2009); Witzel (2015)

- Donors are a great qubit
- Many ideas about coupling donors that use interface
- Very general question: can a donor practically be coherently-coupled to something at an interface
- Answer is yes

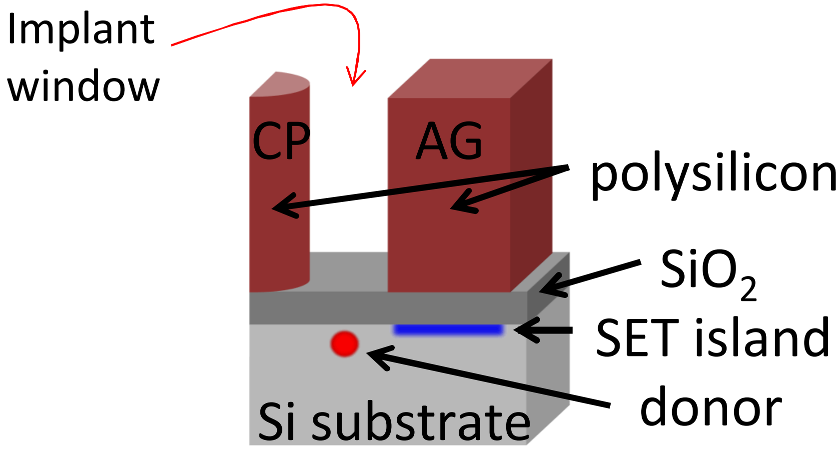
G-factor control for EDSR

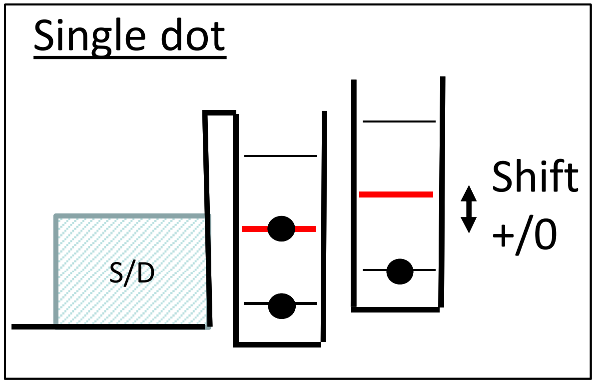


Vrijen (2000)

Quantum dot as a charge sensor

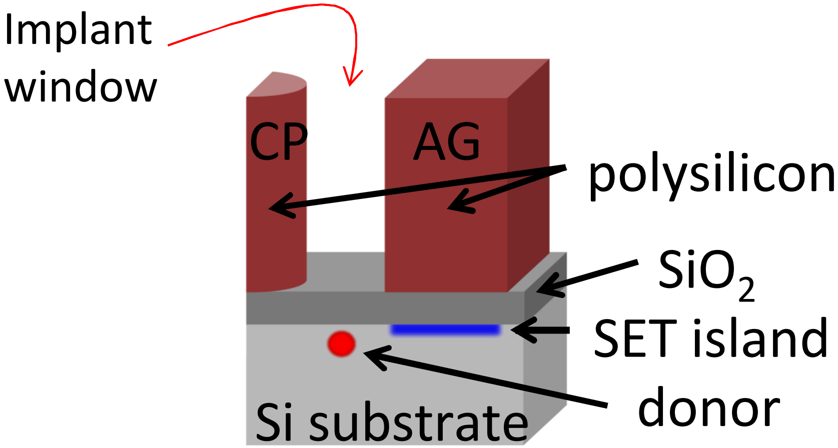
QD offsets (detection of donor ionization)

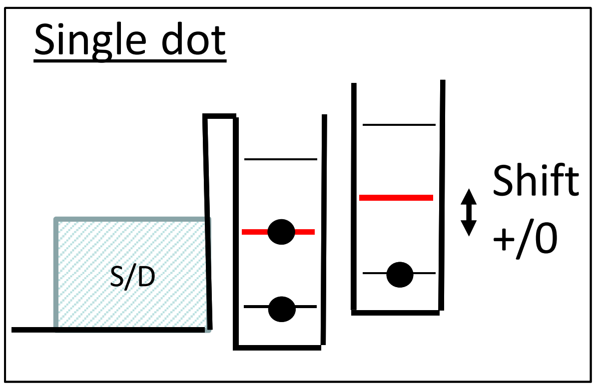




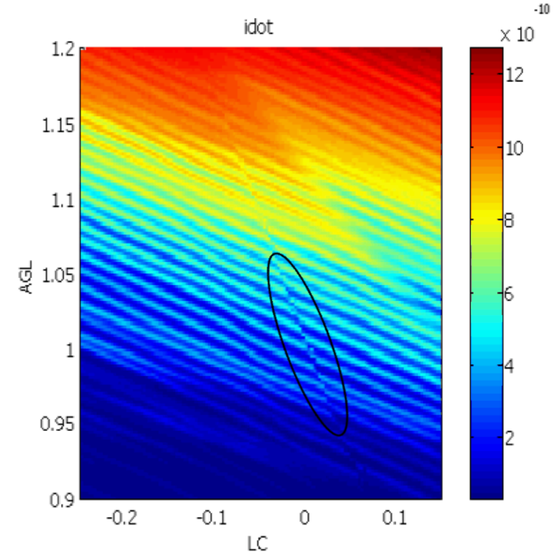
- Quantum dot can be used as sensitive electrometer
- Senses changes in electrostatic environment like ionization of a local donor

Quantum dot as a charge sensor

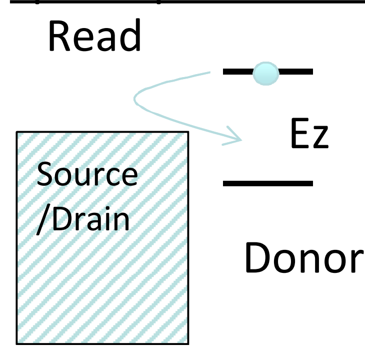




QD offsets (detection of donor ionization)



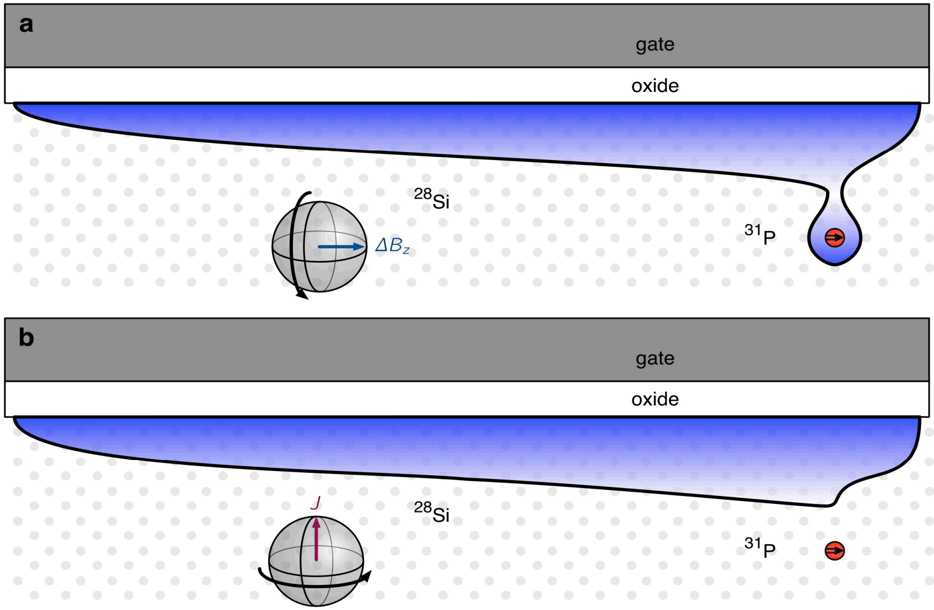
Spin dependent ionization



- Use Poly-Si for self-alignment of donors
- Donor qubit readout through quantum dot
- Quantum dot senses the spin dependent ionization of the donor

Tracy et al., APL 2013

More specifically what will this look like?



Harvey-Collard et al. arXiv:1512.01606
Rudolph et al., IEDM 2016

- A MOS nanostructure will isolate a single electron
- A voltage will control the electron occupation on the donor
- The decoherence time will be long enough to allow visible coherent rotations of the qubit state