SAND2016-6184C

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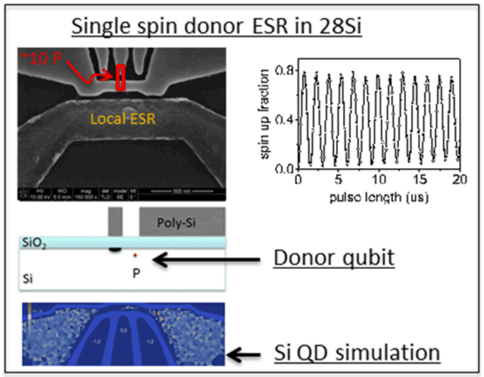
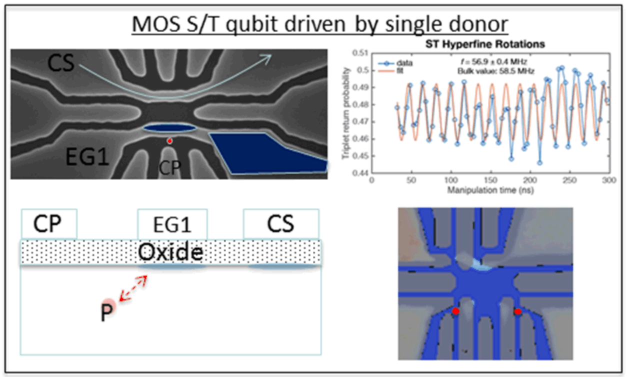
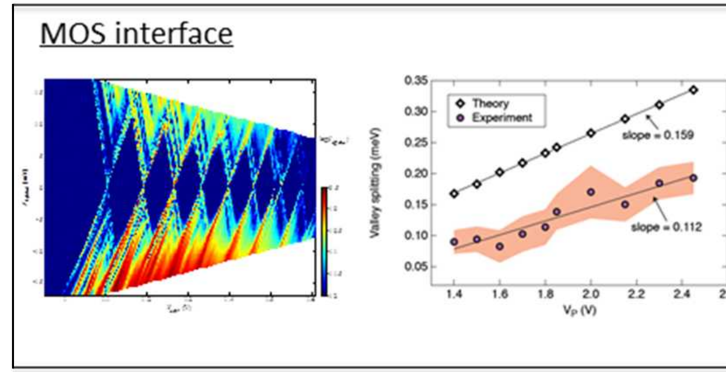






Donor quantum-dot coupled qubits

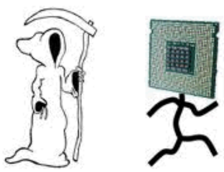
Malcolm Carroll & **QIST team**

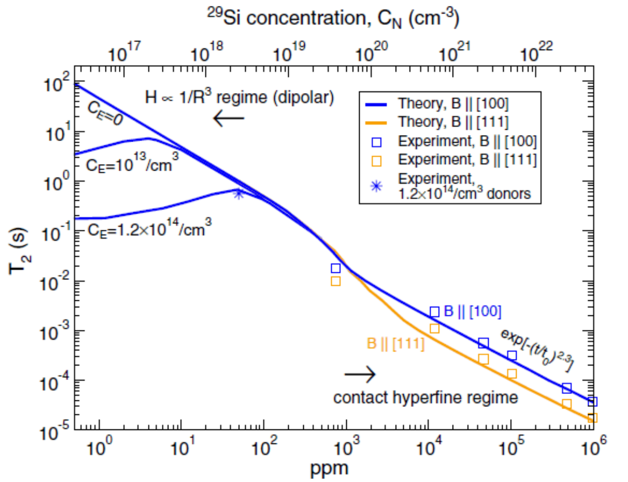
Sandia National Labs, Albuquerque, NM 87185

June 2, 2016

Outline

- Motivations





- MOS single donor ESR & NMR qubits
  - Cryoamplification

- Coherent coupling of D-QD – new qubit structures
  - Donor hyperfine driven S/T qubit
    - Coherent donor spin coupling to surface QD
  - Latch read-out for S/T qubits

- MOS QD Design for future D-QD structures

- Summary

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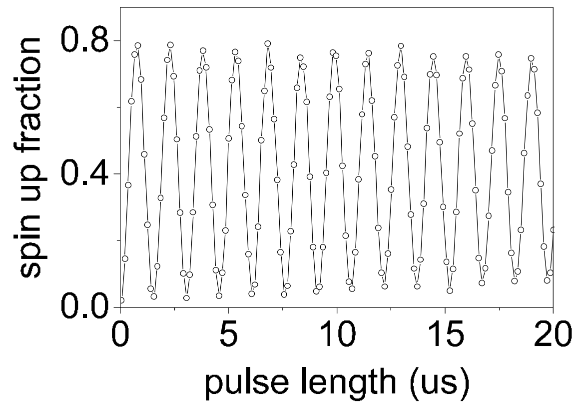
  - Cryoamplification



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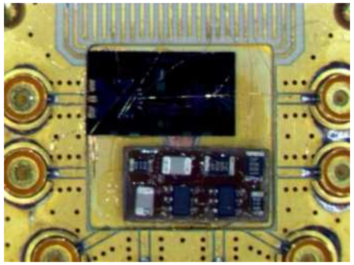

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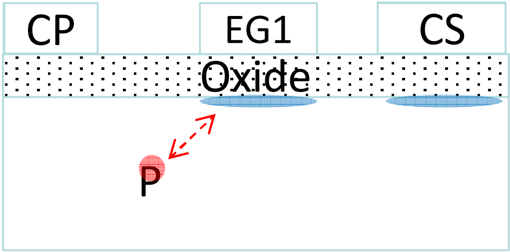

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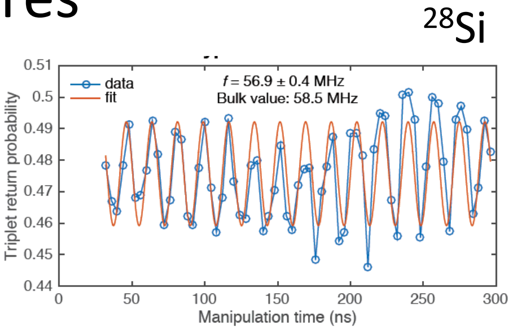

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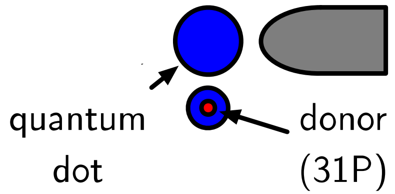
D-QD S/T qubit



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	Signal	time
Std.	0	Short (1-100 μs)
Latch	+1	Long (ms – sec.)

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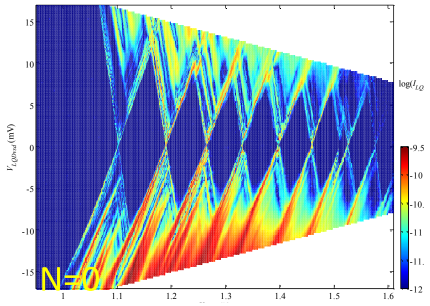

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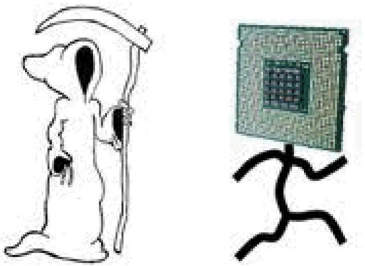
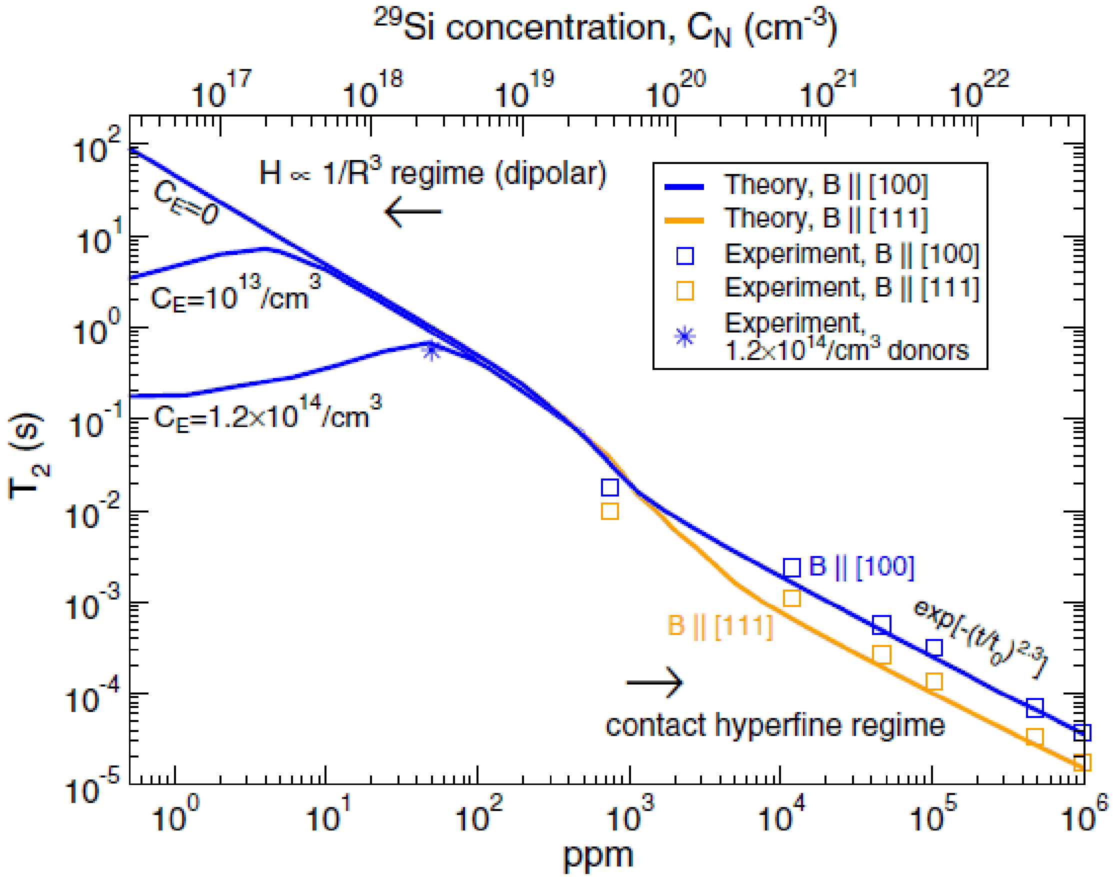
Motivations for quantum computing

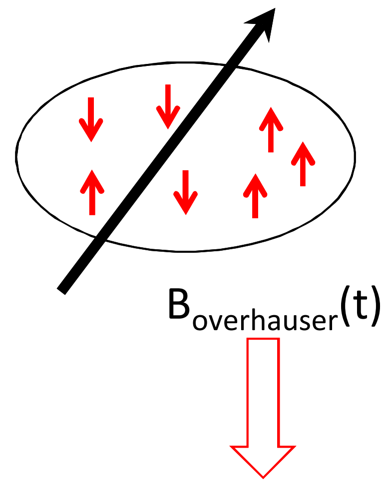
- End of Moore's law & special purpose speed-ups (e.g., quantum simulation, search)
- Qubits decohere in short times leading to errors (T2)
- Require error correction (QEC)
- Higher fidelity qubit requires less QEC
- Silicon offers promise of realizing higher fidelity & less QEC



Motivations for **silicon** quantum computing

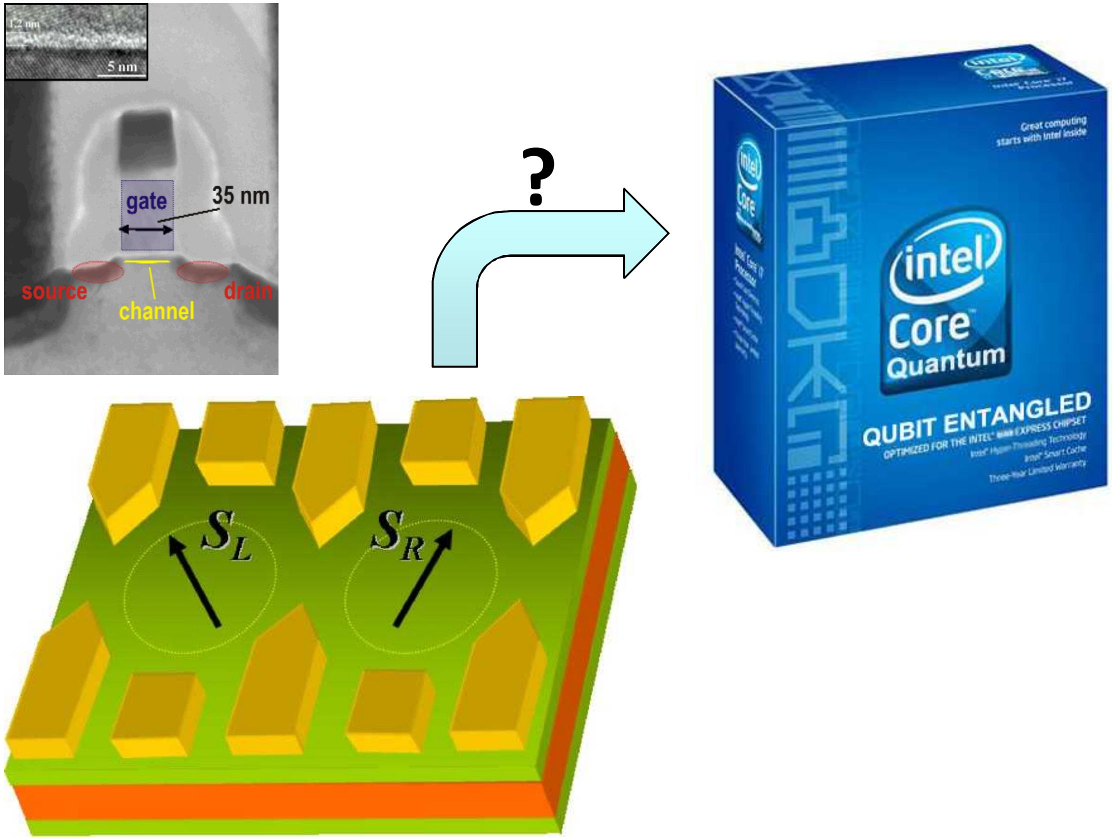


Witzel et al., PRL 105, 187602 (2010) & PRB 86 035452 (2012)



- End of Moore's law & special purpose speed-ups (e.g., quantum simulation, search)
- Qubits decohere in short times leading to errors (T2)
- Require error correction (QEC)
- Higher fidelity qubit requires less QEC
- Silicon offers promise of **realizing** higher fidelity & less QEC

- Open question as to how to proceed

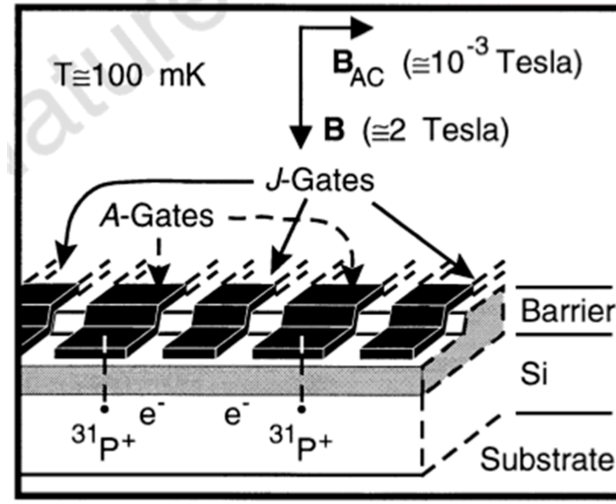


Quantum dot architecture
(e.g., Loss-DiVicenzo)

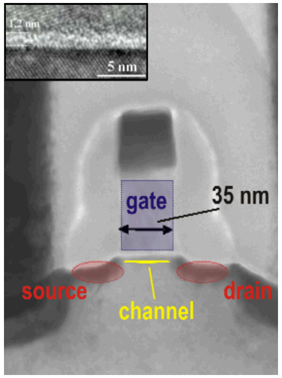
[1] D. **Loss** and D. P. **DiVincenzo**, "Quantum computation with quantum dots," Phys. Rev. A, vol. 57, no. 1, pp. 120–126, Jan. 1998.

- Open question as to how to proceed
- Question has been framed as Ds or QDs?
- One message in this talk: QD-D system, not one or the other.

Single atom architecture (e.g., Kane)

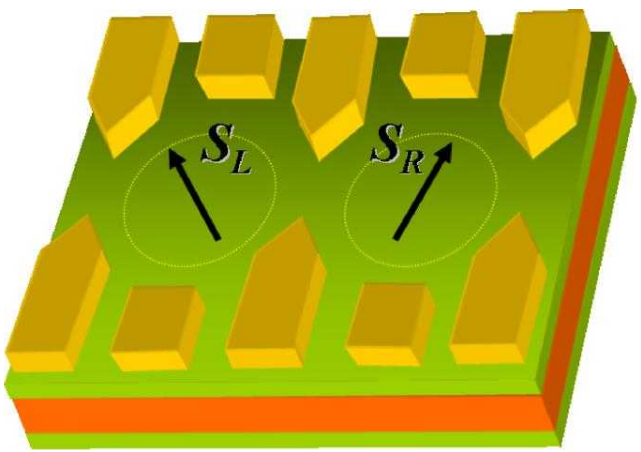


[1] B. E. **Kane**, "A silicon-based nuclear spin quantum computer," Nature, vol. 393, no. 6681, pp. 133–137, 1998.



?

?



Quantum dot architecture (e.g., Loss-DiVicenzo)

Nuclear spin ½ (CQC2T, Nat. Nano. 2014):

$T_2^* = 600$ ms

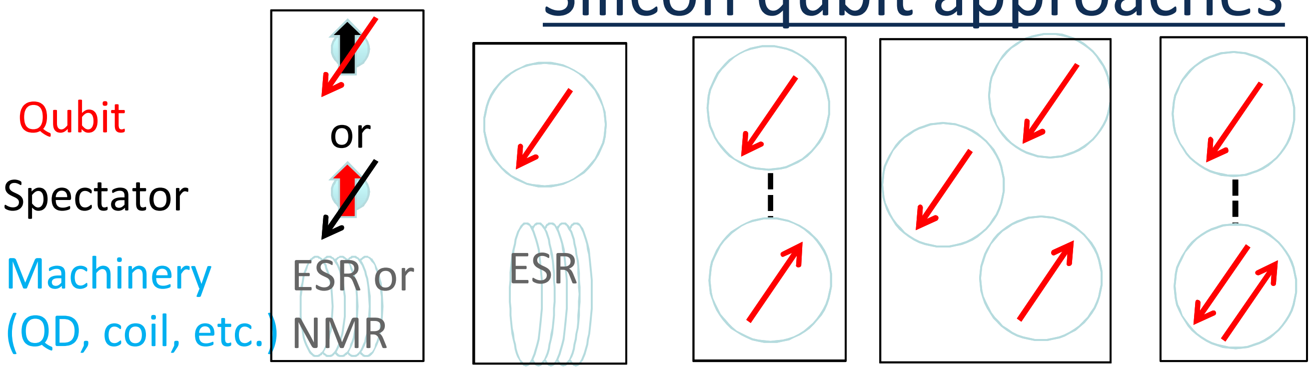
$T_{2,\,CPMG} = 36.5$ s

$F_{prep/readout} = 99.995\%$

$F_{control} = 99.99\%$

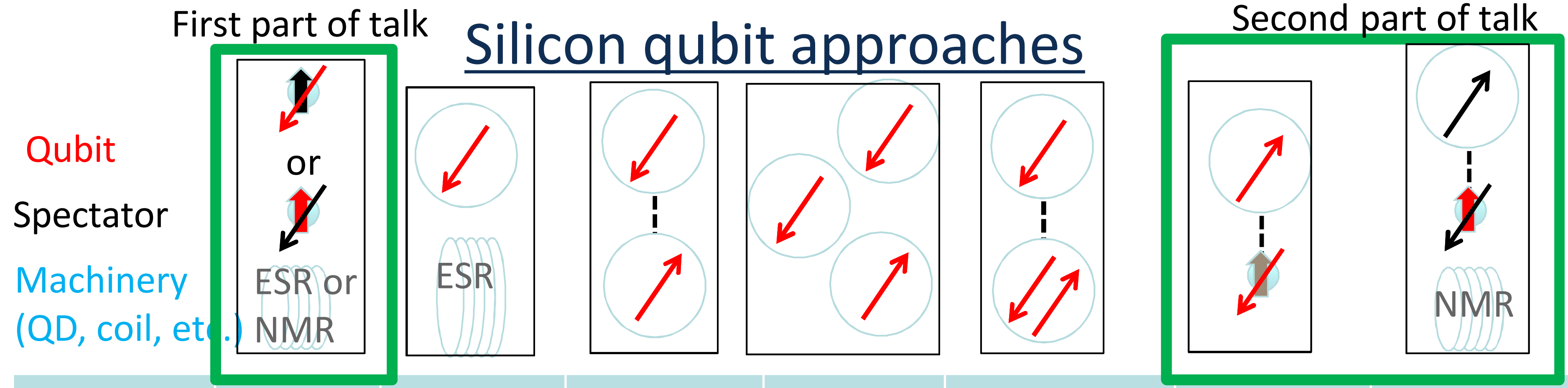
[1] D. **Loss** and D. P. **DiVincenzo**, "Quantum computation with quantum dots," Phys. Rev. A, vol. 57, no. 1, pp. 120–126, Jan. 1998.

Silicon qubit approaches



	Donor (D)	Quantum dot (QD)	DQD (N=2)	TQD (N=3)	DQD-hybrid (N=3)
Control	Slow	Slow	Moderate	Fast	Super fast
T2* : Tgate	Very Long	Long	Moderate	Moderate	Short
Integration Advantage	Hi select-ivity	1 barrier per qubit coupling	Dipole or 1 barrier per qubit coupling	Dipole or 1 barrier qubit coupling	Dipole or 1 barrier qubit coupling
Integration Advantage	Identical	Two qubit path clear	Lower B-field & freq.	All electrical	All electrical
Challenge	Coupling	B1 field, select-ivity?	Field gradient	Complex-ity?	Single shot read-out?

Silicon qubit approaches



	Donor (D)	Quantum dot (QD)	DQD (N=2)	TQD (N=3)	DQD-hybrid (N=3)	D-QD (N=1)	Nuclear D-QD (N=1)
Control	Slow	Slow	Moderate	Fast	Super fast	Moderate	Slow
T2* : Tgate	Very Long	Long	Moderate	Moderate	Short	Moderate	Long
Integration Advantage	Hi select-ivity	1 barrier per qubit coupling	Dipole or 1 barrier per qubit coupling	Dipole or 1 barrier qubit coupling	Dipole or 1 barrier qubit coupling	One QD and one barrier per qubit	One QD and one barrier per qubit
Integration Advantage	Identical	Two qubit path clear	Lower B-field & freq.	All electrical	All electrical	All electrical	No ESR w/ nuc. Spin
Challenge	Coupling	B1 field, select-ivity?	Field gradient	Complex-ity?	Single shot read-out	Repeat-ability?	Repeat-ability?

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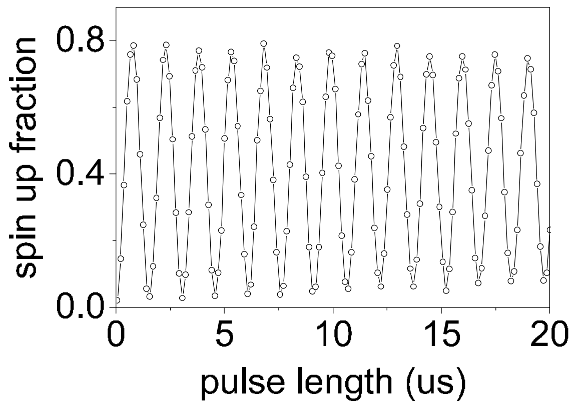
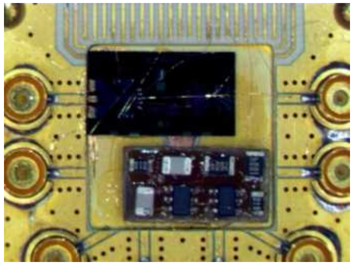
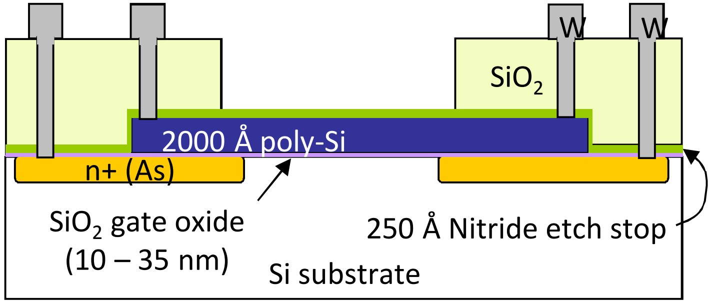
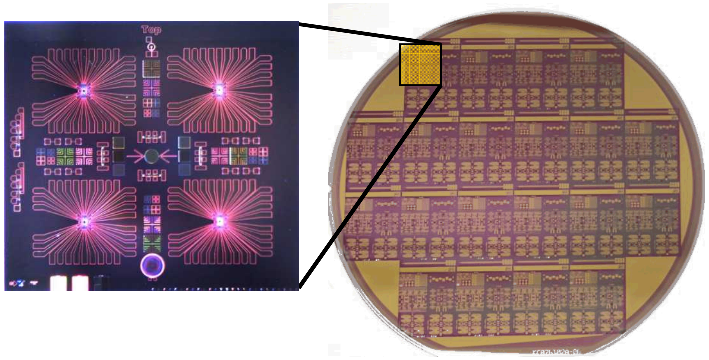




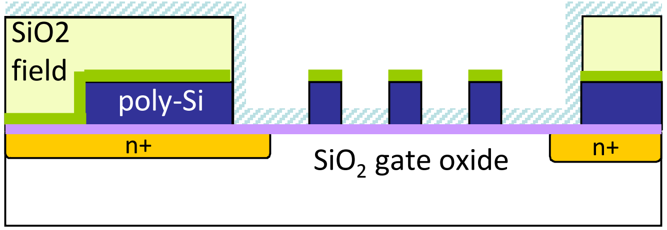
Nanostructure fabrication at Sandia National Labs

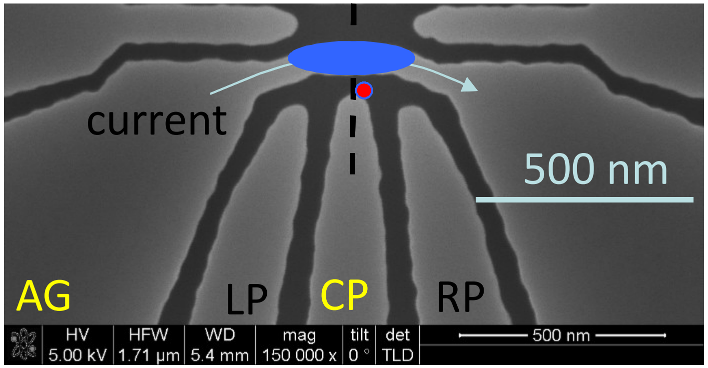
Front-end in silicon fab





Back-end nanolithography





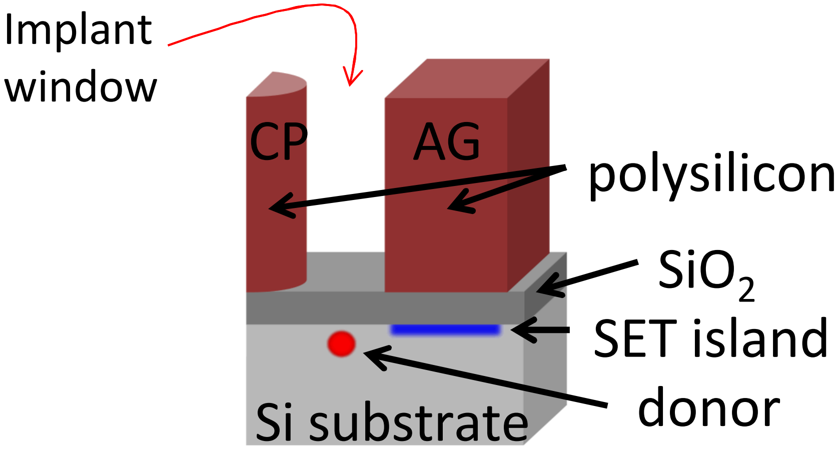
Goal: Use Poly-Si etched structures to produce donor-based qubits

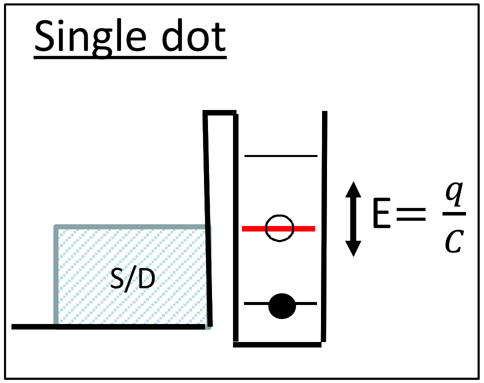
Rationale:

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

Nordberg et al., PRB 80 115331 (2009)
Tracy et al., APL 103 143115 (2013)

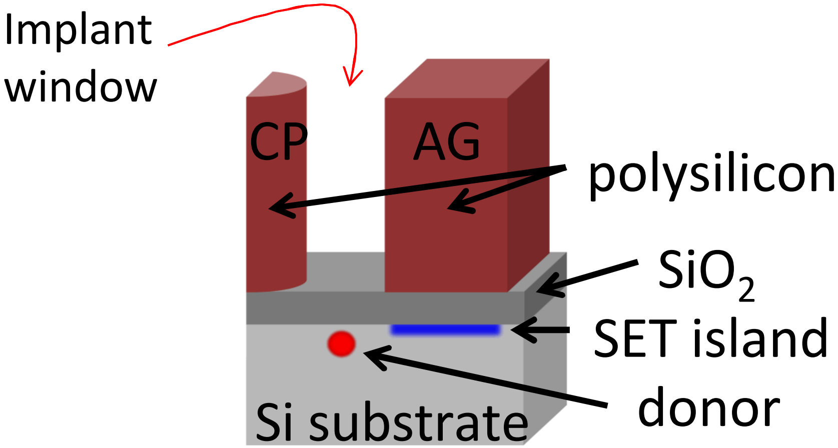
Gate wire with implant – QD coupling to donor



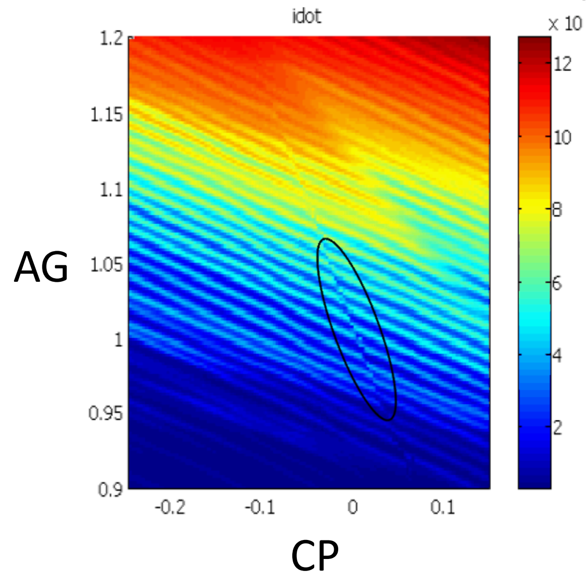


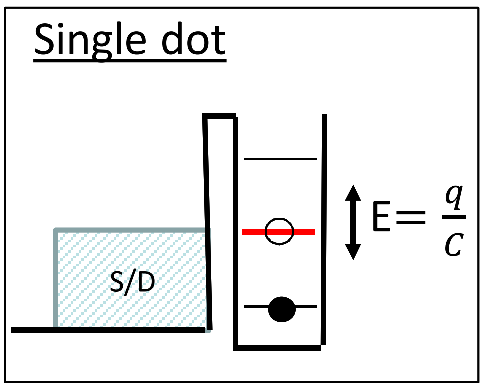
- Poly-Si gated nanostructures
- Use Poly-Si for self-alignment of donors
- Donor qubit readout through quantum dot
- Quantum dot senses the spin dependent ionization of the donor

Gate wire with implant – QD coupling to donor

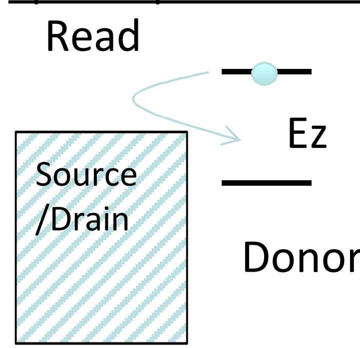


SET offsets (detection of ionization)





Spin dependent ionization



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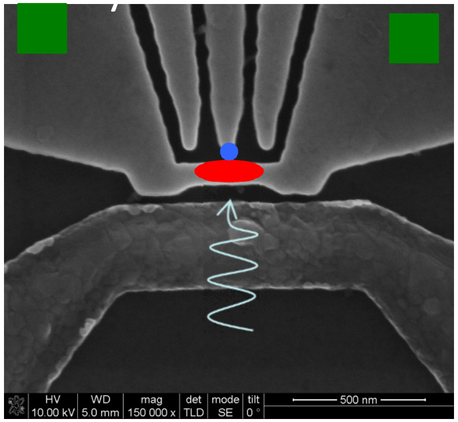
Morello et al., Nature 2010
Tracy et al., APL 2013

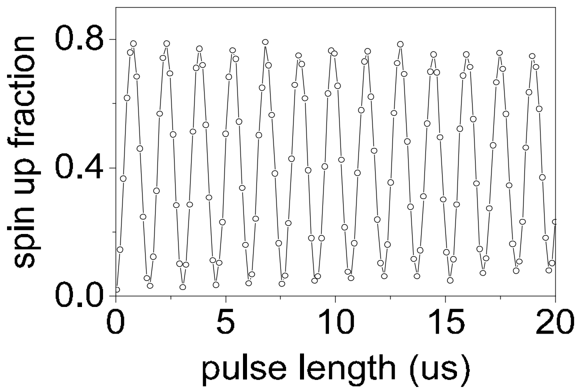
Single donor qubits & dephasing metrics

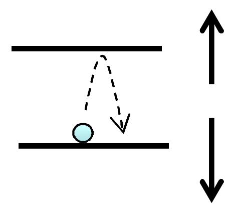


Ohmics

Donor

Quantum Dot





^{28}Si epilayer

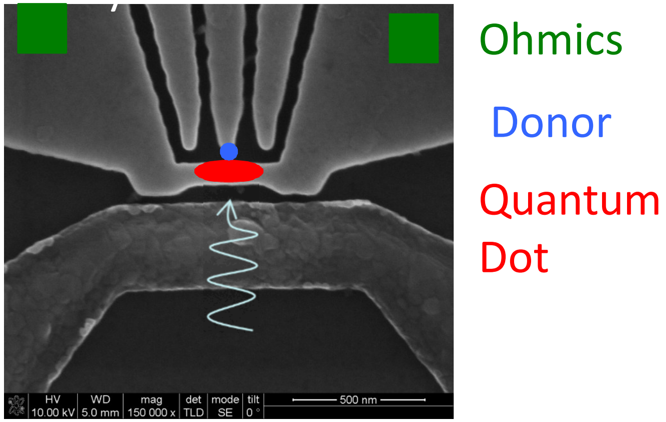
- 2.5 μm thick
- 500 ppm ^{29}Si (ToF SIMS)

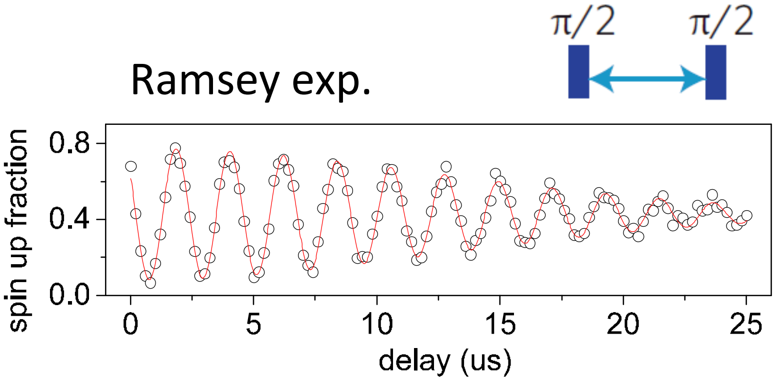
Nominally identical processing

- Coarse metrics of material quality with respect to spin "vacuum" are T2 & T2*
- Roughly, this is a measure of inhomogeneous local B-field from dipoles (T2*) & how rapidly that field is changing (T2)
- This case: ESR: T2 = 0.31 ms, T2* = 10-20 μs

Tracy et al. (APL accepted)

Single donor qubits & dephasing metrics





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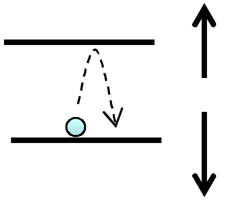


- Ramsey and Hahn-echo: T2 = 0.31 ms, T2* = 10-20 μs
- Line width is approximately 30 kHz
- Max B1 corresponds to order of MHz

- In natural silicon: line width is order of 5 MHz
- T2* ~ 50 ns

Gate set tomography (GST) results

#	Germ
1	Gx
2	Gy
3	Gi
4	Gx · Gy
5	Gx · Gy · Gi
6	Gx · Gi · Gy
7	Gx · Gi · Gi
8	Gy · Gi · Gi
9	Gx · Gx · Gi · Gy
10	Gx · Gy · Gy · Gi
11	Gx · Gx · Gy · Gx · Gy · Gy

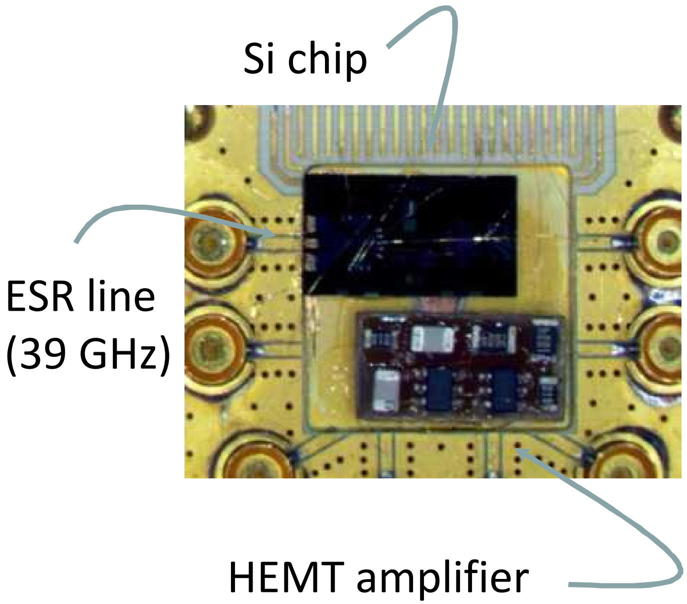
Gate	Process Infidelity
Gi	0.026748
Gx	0.047344
Gy	0.055106

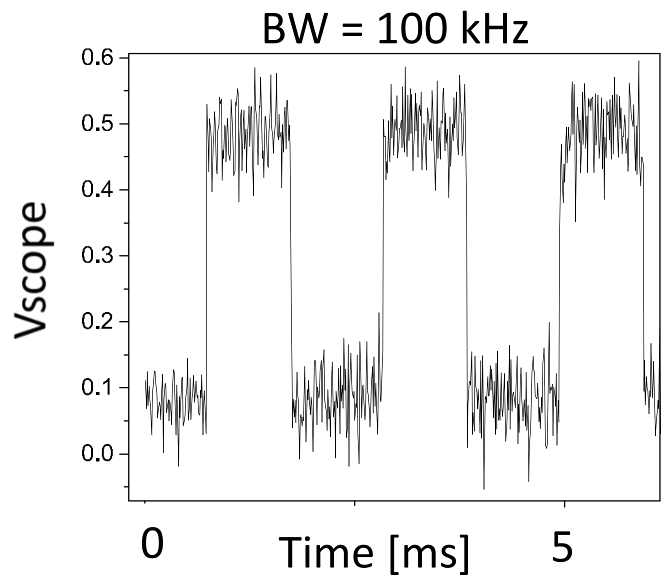
- Gate set tomography used to characterize rotations
- General idea:
    - Provide initial state of unknown "quality"
    - Provide measurement of unknown "quality"
    - Apply sequences gates and idles
    - Results characterize gates and SPAM errors

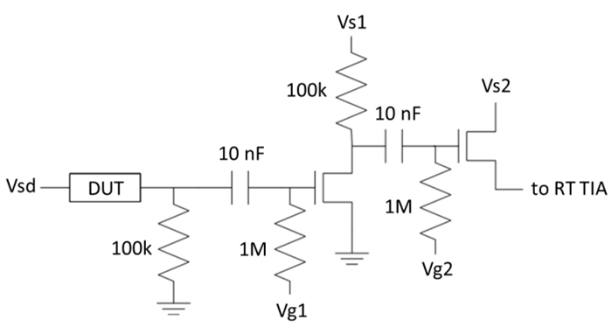
- Maximum length concatenations we used was 8. Not very long.
- 400 ns pulse times, 1.8 µs clock cycle, 100 kHz BW on read-out
- SPAM error of order 6% & Idle error ~3%
- X/Y rotations are of order 4-5% error. Looks like phase error between X and Y
- Order of 1 % uncertainty in infidelity estimates

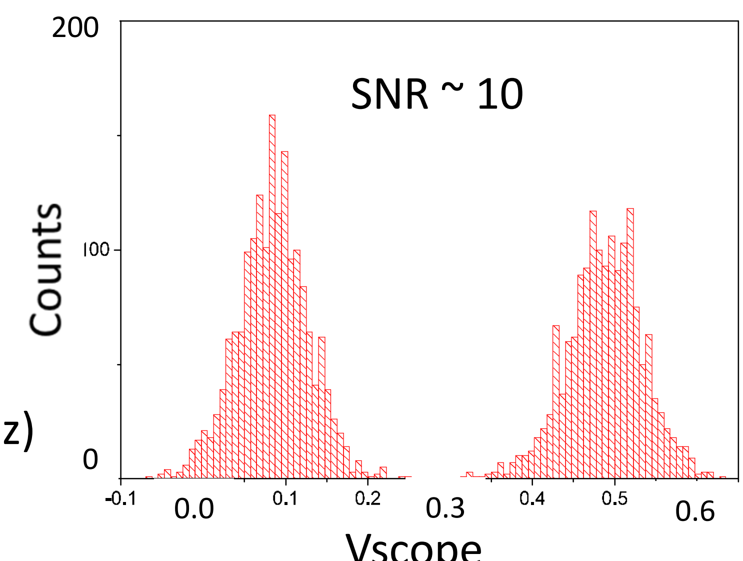
Blume-Kohout, Nielsen, Gamble

Read-out circuit (AM HEMT)





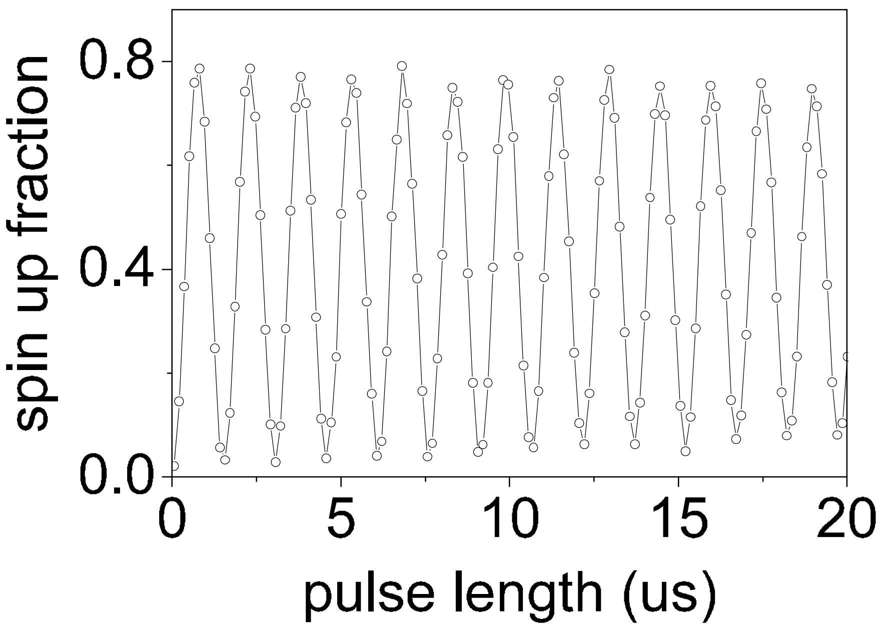




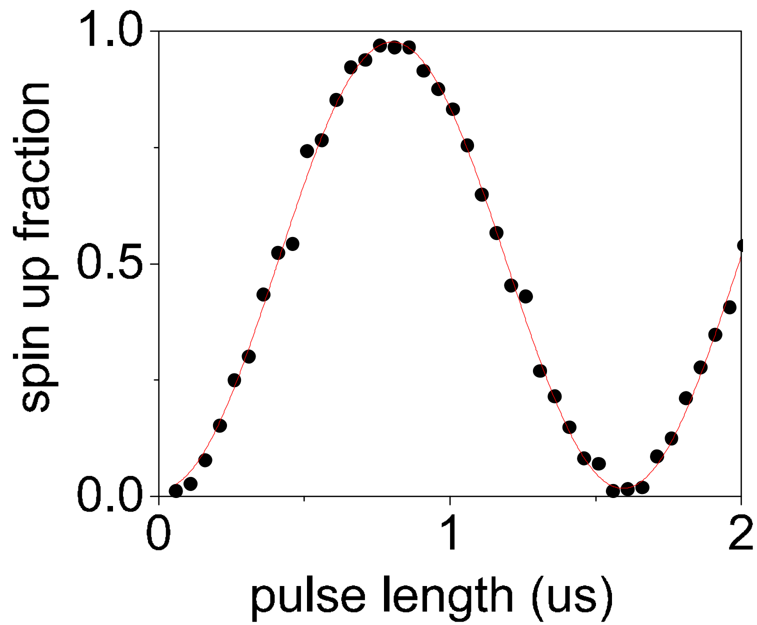
- Dry fridge noise a real nuisance (10 kHz BW)
- Cryo-preamplification & AM technique (300 kHz)
- Good visibility w/ ~1% threshold overlap
- $T_{electron}$ ~ 200 mK

Rabi oscillations

10 kHz BW



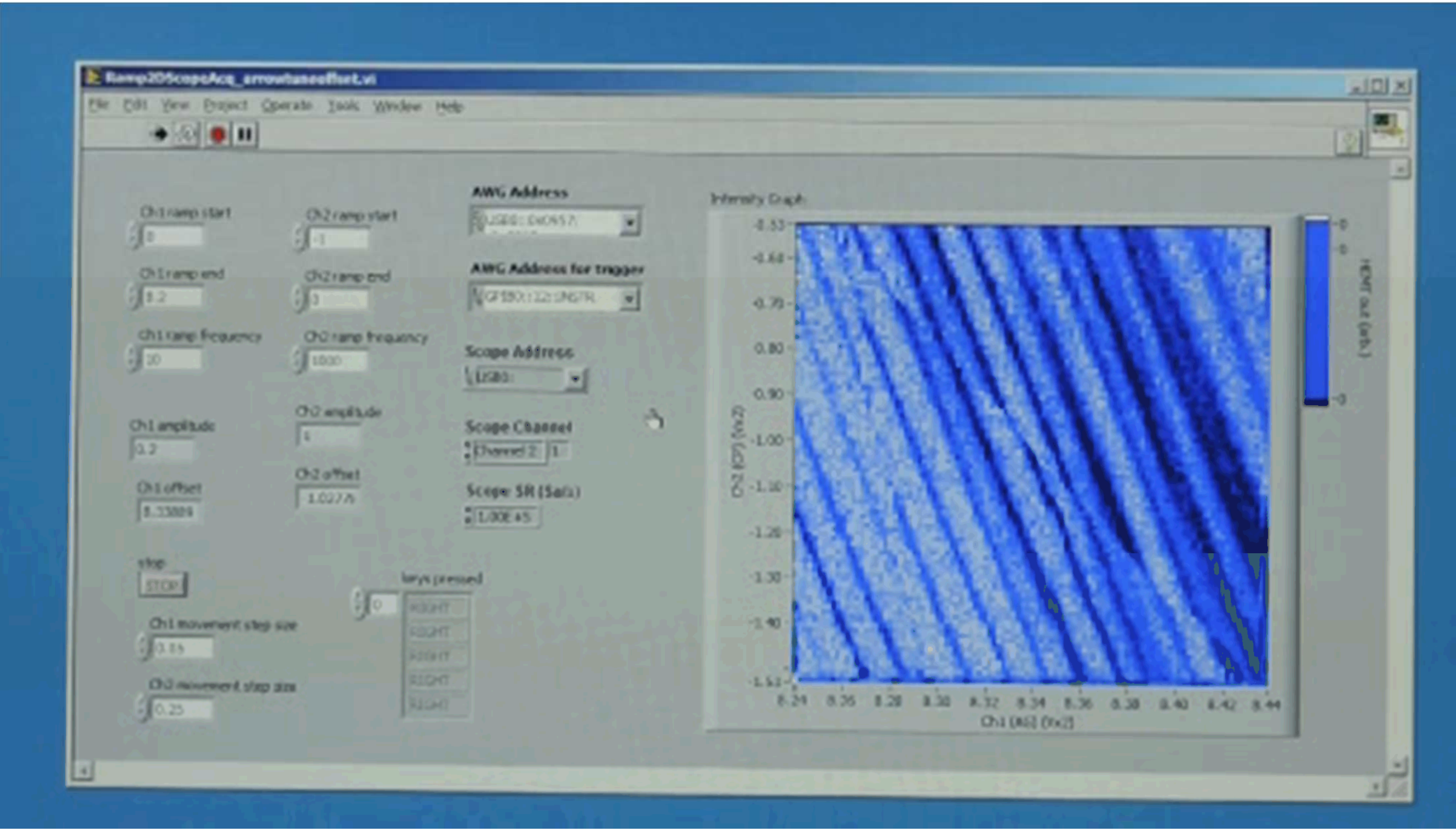
96% visibility w/100 kHz BW



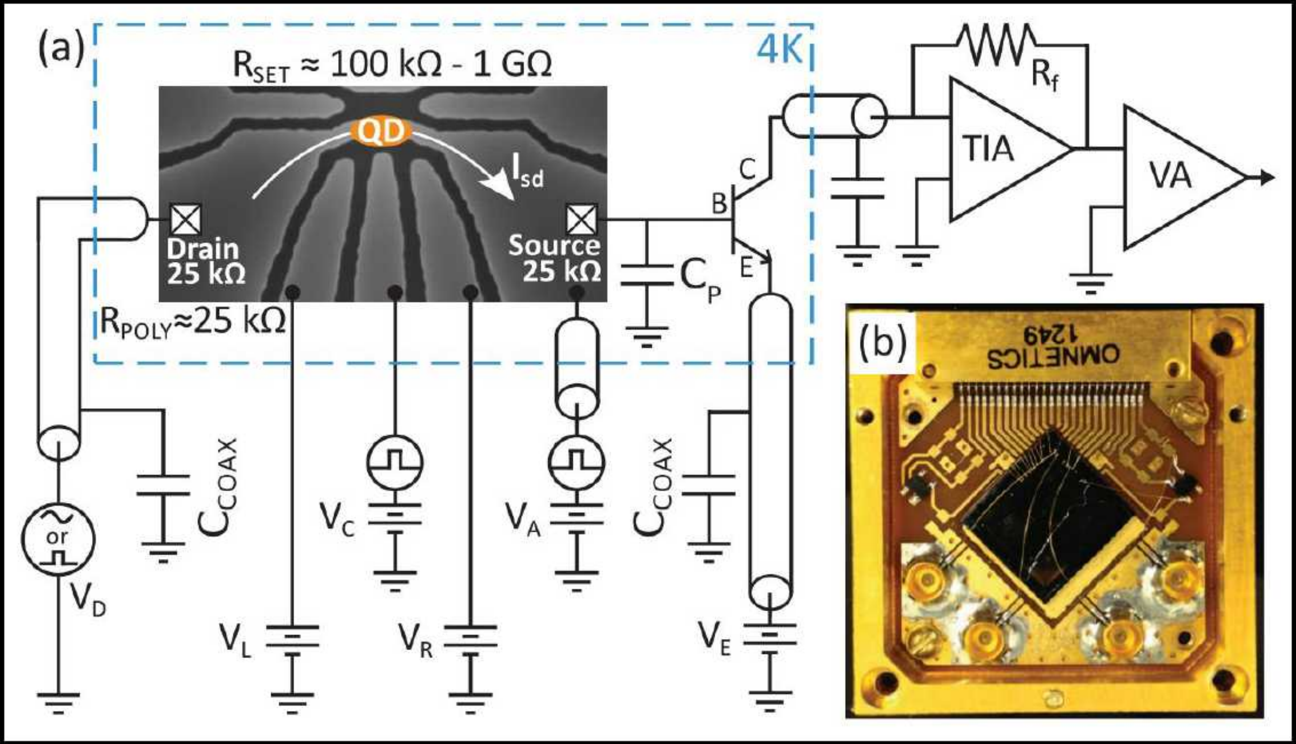
Long lived Rabi oscillations

Visibility reduced because preamplifier BW was not optimized (BW ~ 10 kHz)
For example, fast spin-up tunneling events can be missed.

Stability plot movie with charge instability



Cryogenic Preamplification Using a Heterojunction Bipolar Transistor (HBT)



M.J. Curry et al., Applied Physics Letters 106 203505 (2015)

Measurements done at T = 4 K

- SiGe HBT motivations: more uniform for design, higher G/I_{device} and possible non-linear option
- Several HBT configurations of interest.

Time-Domain Single-Shot Readout State of the Art

Single-Shot Readout Technique	Group	Reference	Carrier Frequency	Time-Domain Bandwidth	Time-Domain SNR	Charge Sensitivity ($\mu e/\sqrt{Hz}$)
HBT (Single-Stage)	Sandia/UNM/CQuIC	This Presentation Also: APL 106, 203505 (2015)	N/A	30 kHz 100 kHz 1 MHz 3 MHz	13 10 7 4	400 300 100 100
HEMT (Single-Stage)	Delft	APL 91, 123512 (2007)	N/A	800 kHz	3	400
HEMT (Dual-Stage)	Sandia	Manuscript In Prep. (2015)	300 kHz	100 kHz	10	300
RF-QPC	Harvard CQC2T NRC Canada	PRB 81, 161308(R) (2010) APL 91, 222104 (2007) Physica E 42, 813 (2010)	220 MHz 332 MHz 763 MHz	5 MHz 500 kHz 1 MHz	2 7 7	200 200 100
RF-SET	Harvard Wisconsin/Dartmouth	PRB 81, 161308(R) (2010) APL 101, 142103 (2012)	220 MHz 936 MHz	10 MHz 2 MHz	4 4	80 100
Gate-Dispersive RF	ARC Sydney	PRL 110, 046805 (2013)	700 MHz	30 kHz	1	6000
RF Transmission SC Cavity + JPA	Princeton	PR Applied 4, 014018 (2015)	7.88 GHz	2.6 MHz	9	80

- Cryoamps motivation: low overhead to single shot
- Threads of inquiry: frequency shift vs. non-linear, HEMT vs. HBT

Time-Domain Charge-Sensitivity Metric: Definition

$$\delta q \approx \frac{1}{(SNR)\cdot\sqrt{B}} \approx \frac{\sqrt{\tau_{int}}}{SNR} \left(\frac{e}{\sqrt{Hz}}\right)$$

$\delta q \equiv$ time-domain charge-sensitivity
$\tau_{int} \equiv$ integration time
$B \equiv$ bandwidth

M. C. Cassidy et al.
APL 91, 222104 (2007)

Commonly used SNR = 1 definition:

$$\delta q \approx \sqrt{\tau_{int}} \left(\frac{e}{\sqrt{Hz}}\right)$$

Lower δq is better!

Summary of single donor qubit (ESR/NMR)

- 28Si introduced in to local ESR donor qubit fab platform (L. Tracy)

- Line width of ~30 kHz observed two times

- T_2 comparable to previous reports

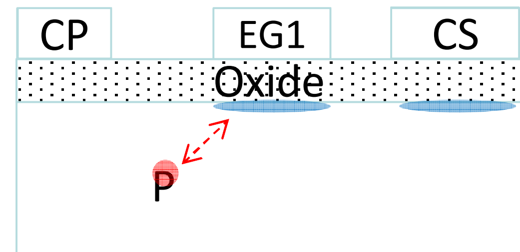
- Cryo-HEMT circuit used to overcome dry fridge noise and produce high SNR read-out
  - > 90% fidelity at 100 kHz bandwidth (high SNR)
  - Video-like stability plots (100 ksamples/sec)

- Looking in to HBT circuits (M. Curry & T. England)
  - HBT has higher gain for same current levels & details of cold noise models are also not known

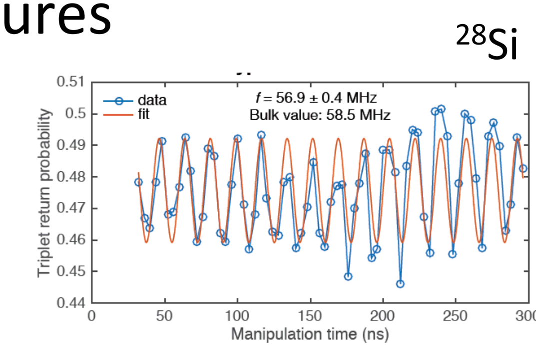
- Relatively high fidelity gates. Comparable control fidelities (Australian metric). Gate set tomography used to characterize fidelity (Nielsen, Gamble, Blume-Kohout)
  - 2-3% SPAM error
  - 4-5% X-Y rotation error
  - Analog source is possible cause of error
- NMR demonstrated and also behaving similarly

Outline

- Motivations
- MOS single donor ESR & NMR qubits
  - Cryoamplification



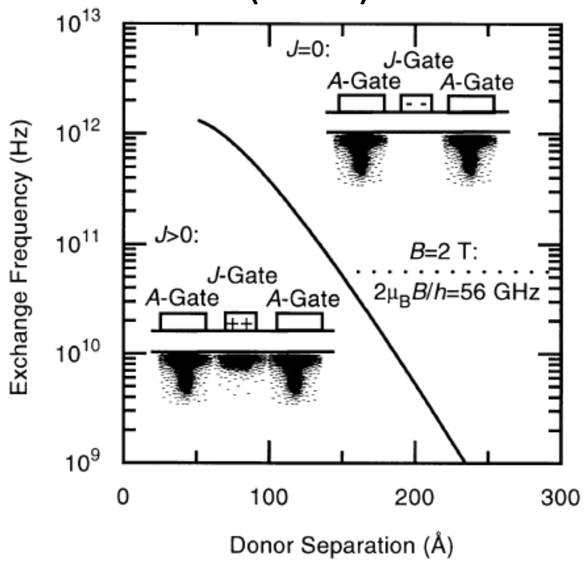
- Coherent coupling of D-QD – new qubit structures
  - Donor hyperfine driven S/T qubit
    - Coherent donor spin coupling to surface QD
  - Latch read-out for S/T qubits

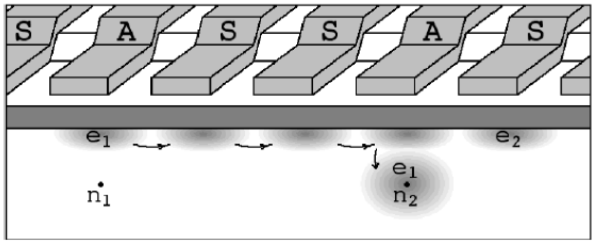


- MOS QD Design for future D-QD structures
- Summary

Donor-donor coupling concept

Kane (1998)



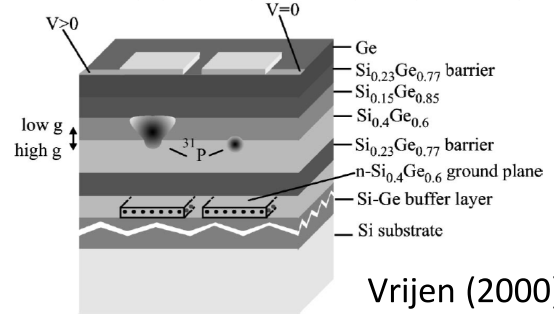


Transport: Skinner & Kane (2003)

Also transport: Hollenberg (2007), Morton (2009); Witzel (2015)

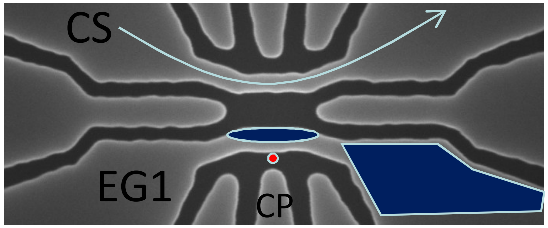
- Donors are a great qubit
- Many ideas about coupling donors that use interface
- Very general question that we are presently addressing: can a donor practically be coherently-coupled to something at an interface and can that capability be extended
- SNL: donor coherently coupled to MOS QD recently
- This is a platform to look at these questions

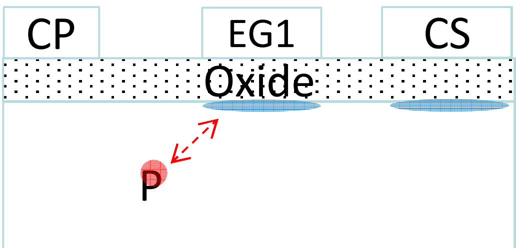
G-factor control for EDSR



Vrijen (2000)

Approach: couple buried donor to surface QD



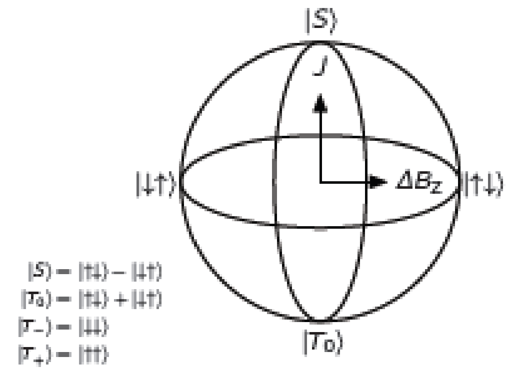


Canonical S/T qubit

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

Donor-QD S/T qubit → $AI \cdot S$

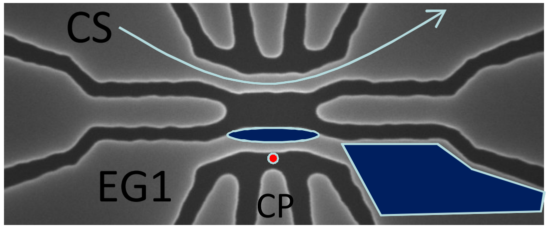
Qubit Bloch Sphere

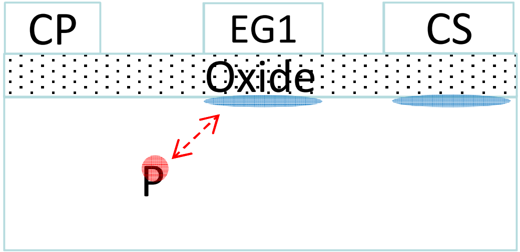


$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z\hat{\sigma}_x$$

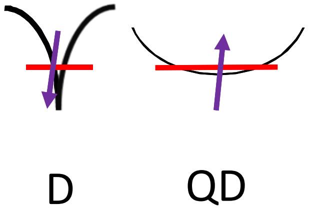
- Encode as singlet-triplet qubit
- Rationale for using this choice as test platform:
  - Platform to examine tuning of the charge & dynamics (e.g., tunnel coupling)
  - Produces an appealing two-axis controlled S/T qubit
  - Rotation frequency is chemically distinct
  - Opens up a potential electrical read-out of nuclear spin
  - Directly probes coherence times of surface-bulk-donor coupling

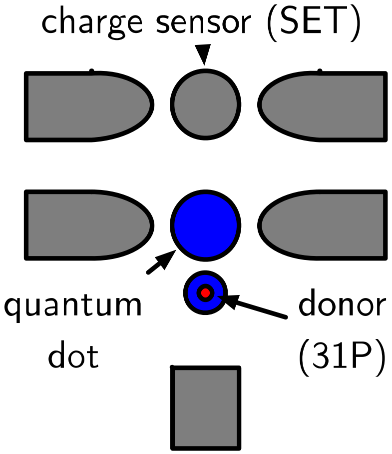
Approach: Couple a N=1 MOS-QD to a Buried Donor





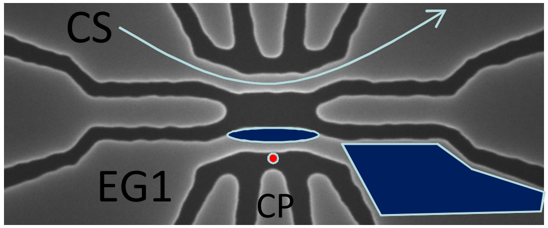
2-spin singlet-triplet qubit

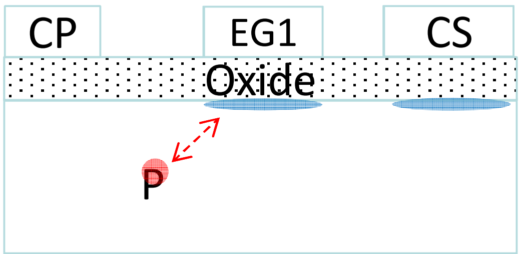




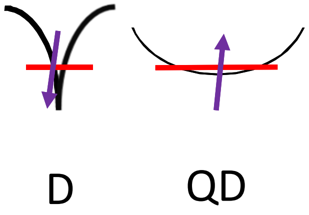
- Extend the single donor qubit lay-out to include a charge sensor
- Charge sensed donor-QD system is now an experimental double quantum dot platform to test the D to surface coupling idea

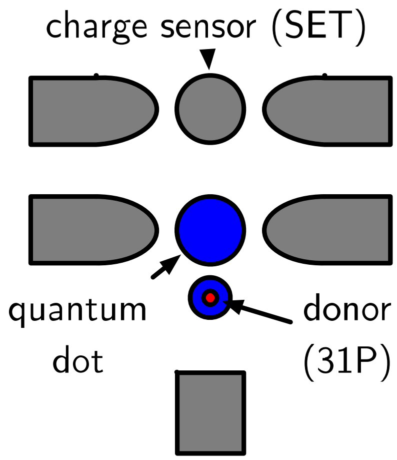
Approach: Couple a N=1 MOS-QD to a Buried Donor





2-spin singlet-triplet qubit





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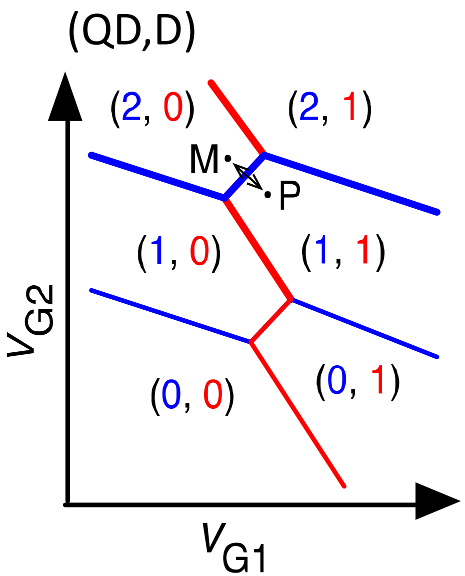
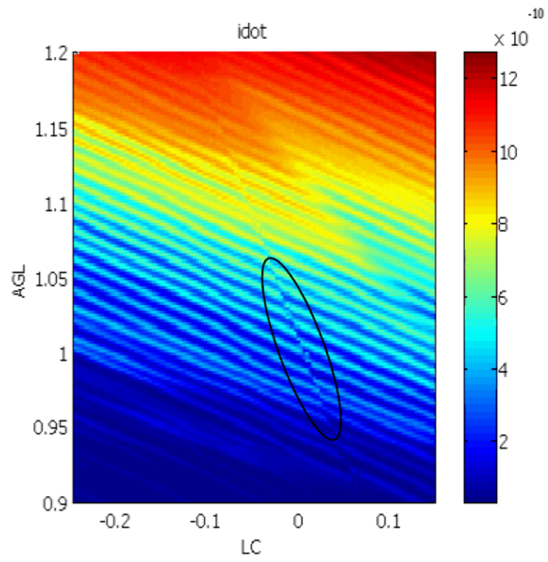
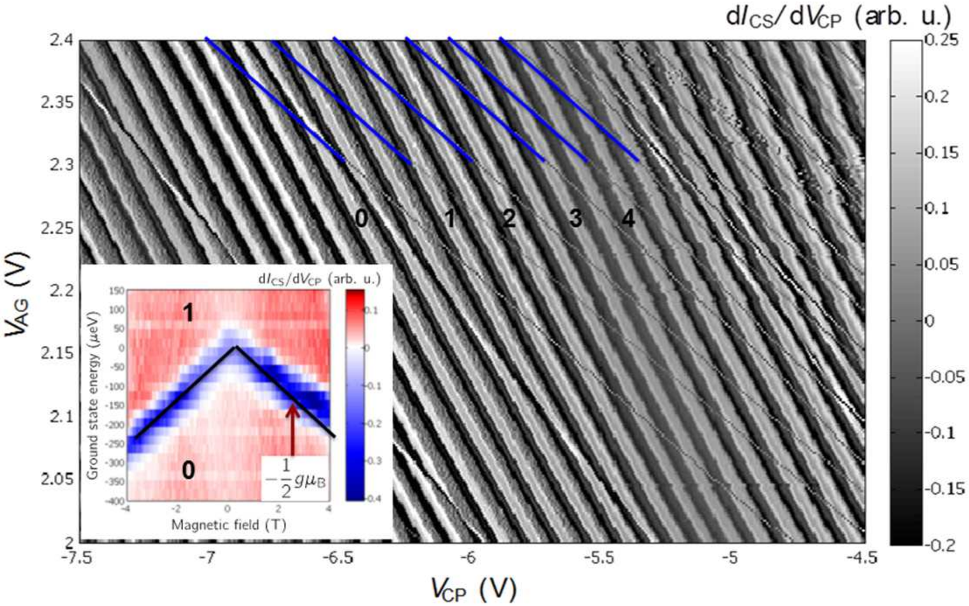
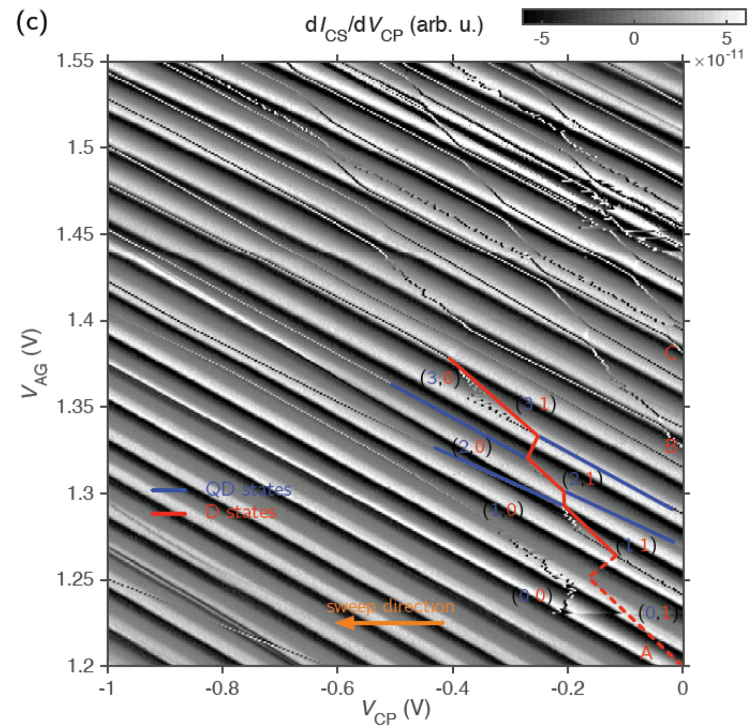


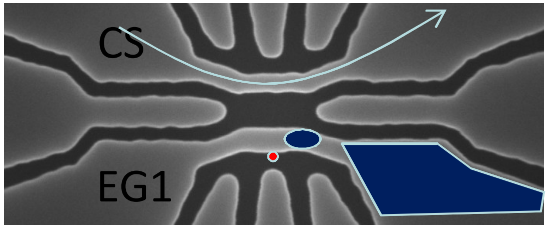


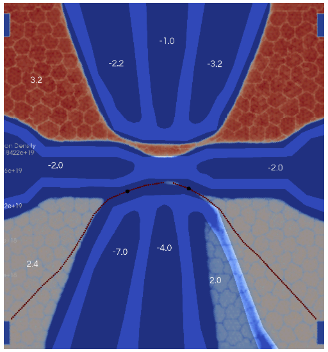
Device tuning to donor crossing at N=1





- Device can be tuned over wide range
- This allows donor crossings to be identified at N=1
- Magnetospectroscopy used to check for singlet to triplet like transition





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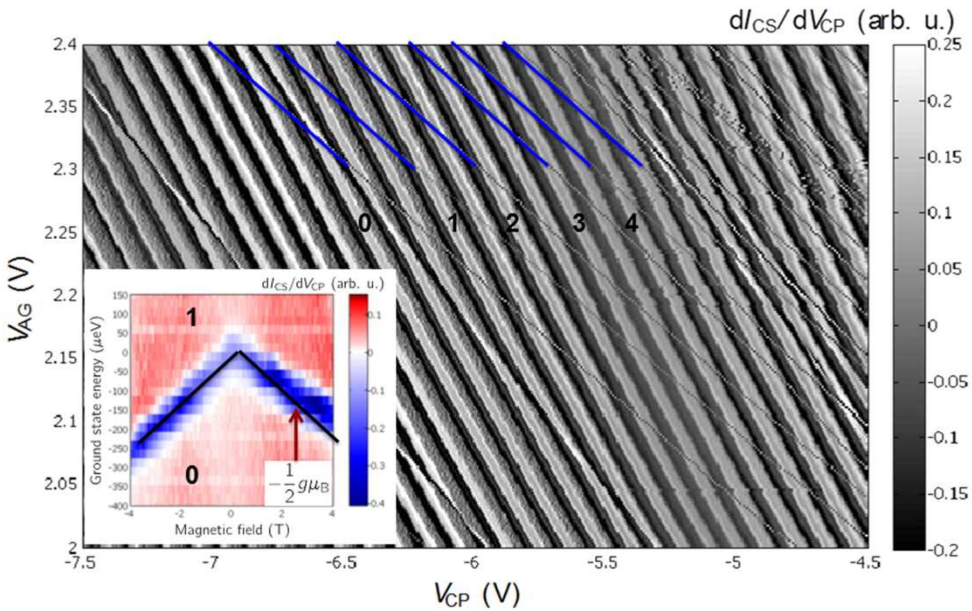
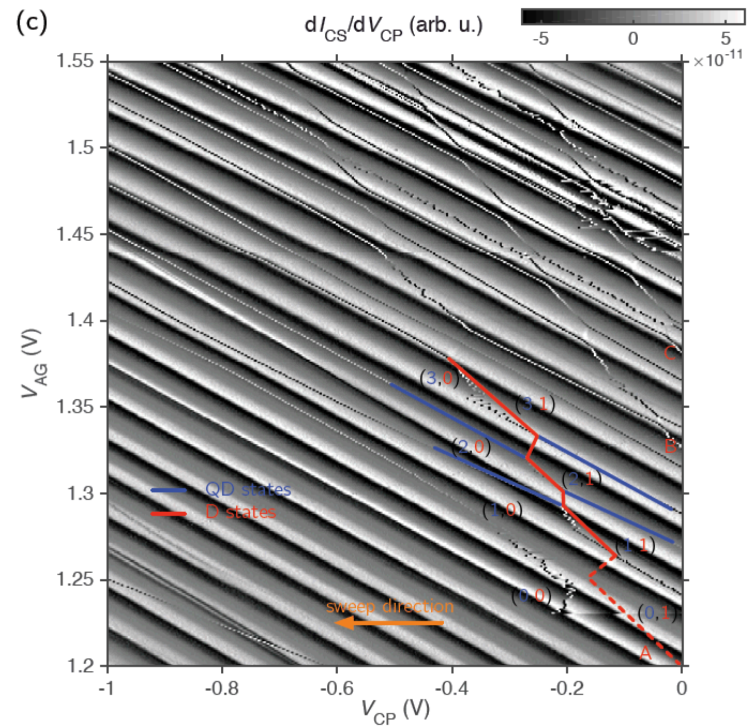
Device tuning to donor crossing at N=1





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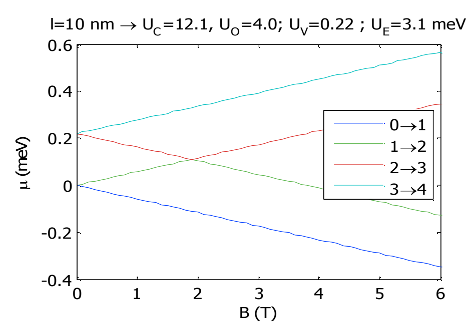
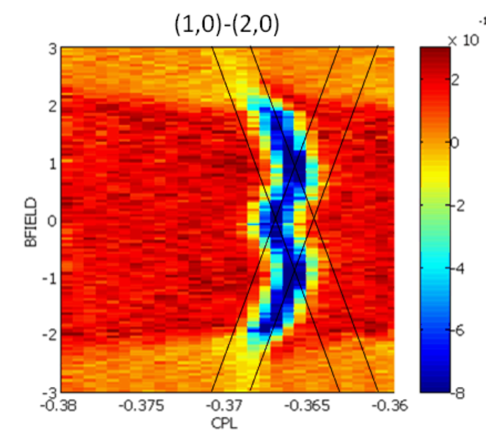
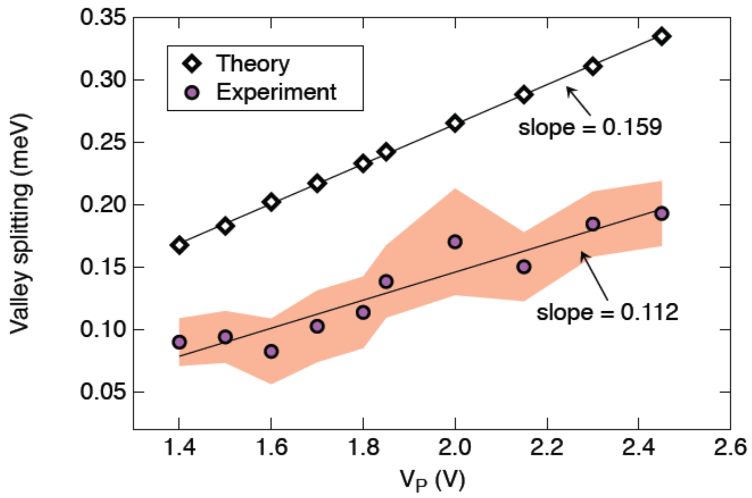
Illustrative example

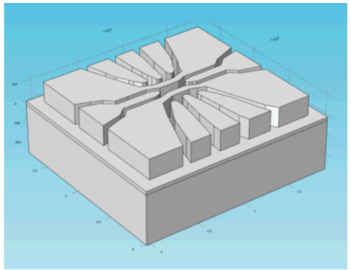


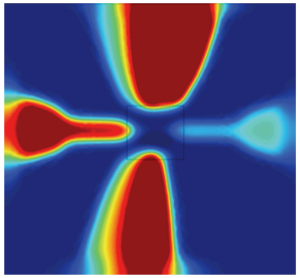


Valley splitting in MOS QD

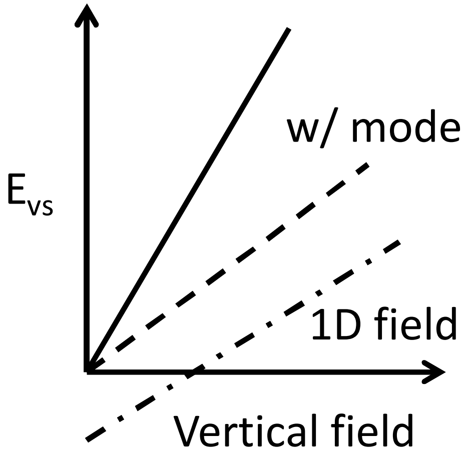


Vertical field





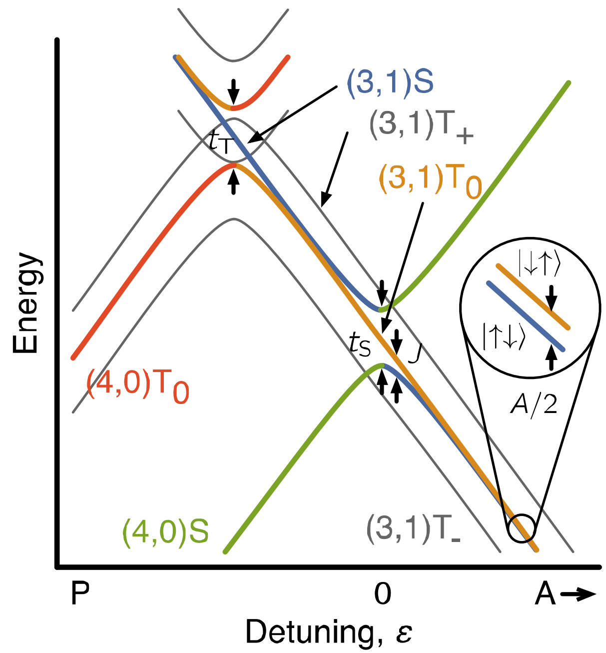
Full 3D calculations to extract vertical field and predicted valley splitting

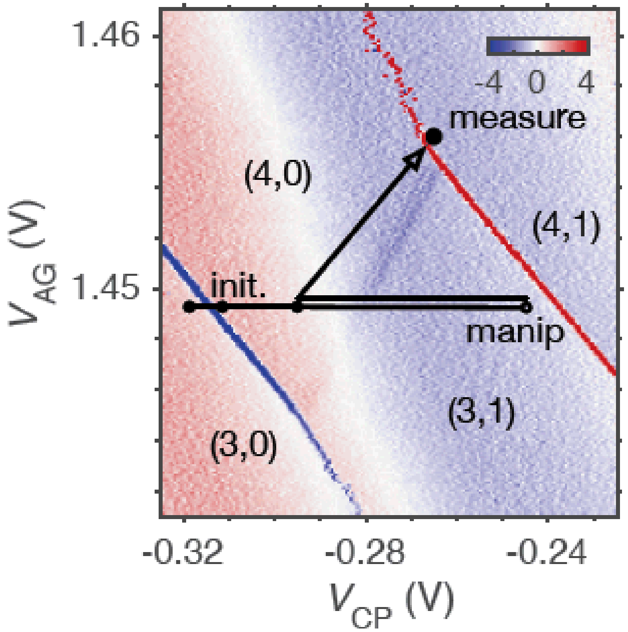


- The valley splitting is measured using pulsed spectroscopy
  - Measured in multiple MOS QDs with comparable results
- Valley splitting was measured over large range of voltages (i.e., -8 < CP <0)
- Barrier tuned at each location to enable pulsed spectroscopy
- E_{vs} theoretically predicted to go to zero at zero vertical field
- Modelling of actual field in QD appears to be important

Gamble et al. in preparation

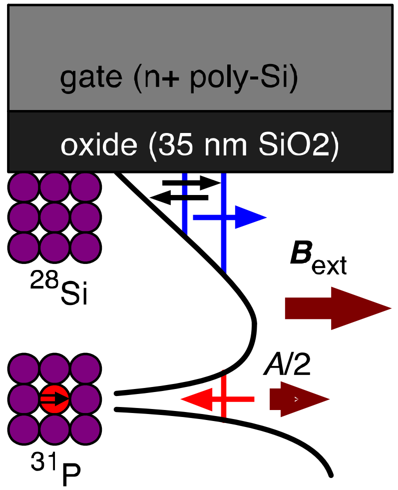
Steps towards coherent control





Approach

- Prepare (2,0) singlet – note we are working in (4,0) for ST splitting
- Pulse into (1,1)
- Ramp rate must be balanced against charge adiabaticity but diabatic relative to J-A anti-crossing
- Shift to higher tunnel coupling through higher N in QD



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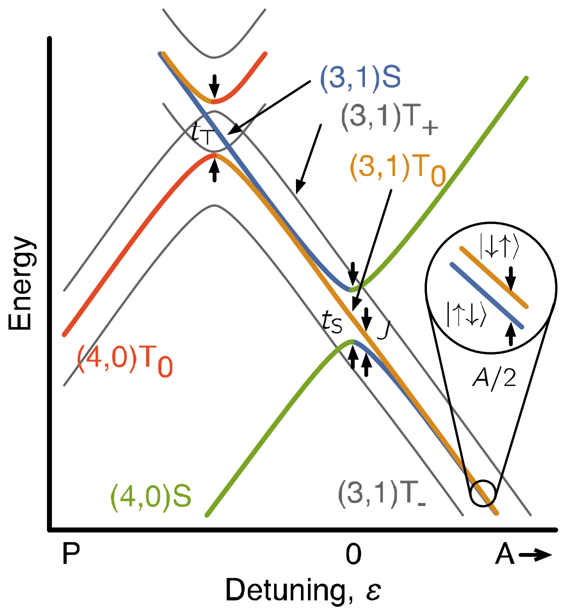
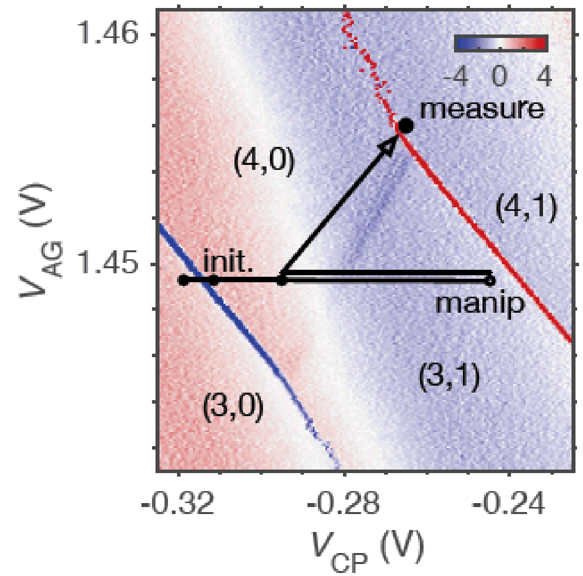
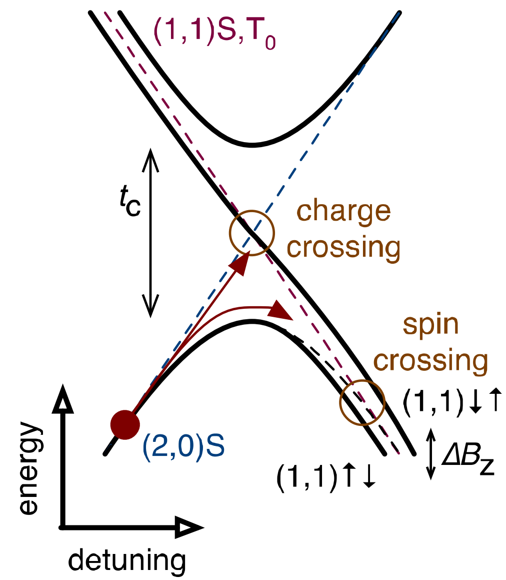


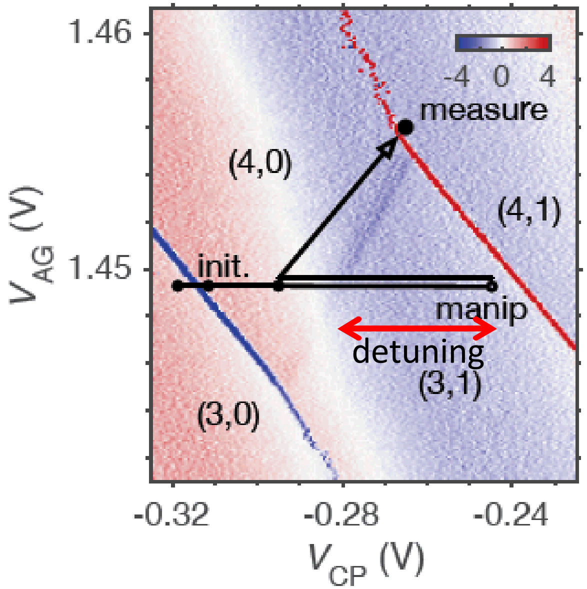


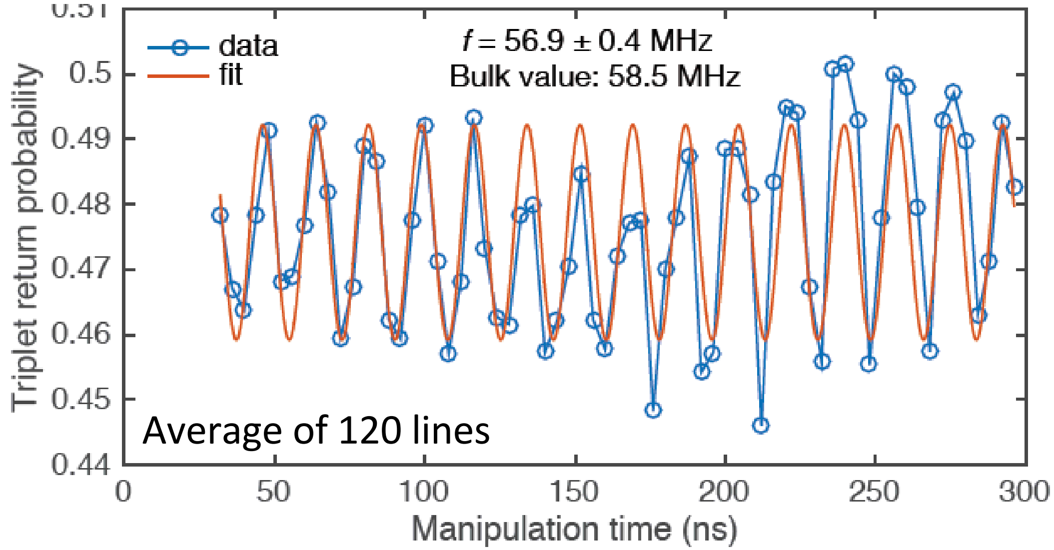
Approach

- 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



Pulse sequence & singlet-triplet rotations



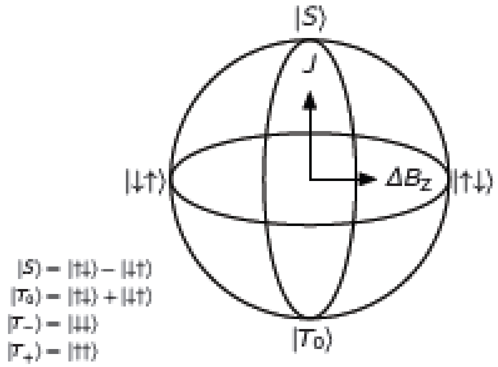


- Coherent oscillations observed for variable time & fixed detuning
  - Note: only the measurement point differs

- Oscillation frequency is close to bulk donor contact hyperfine value of 58.5 MHz
  - Close to measured ESR case – but a little misleading
- Frequency is detuning dependent – J changes

- T2* order of 1 us from coarse measures at longer times and different detunings

Qubit Bloch Sphere



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Harvey-Collard

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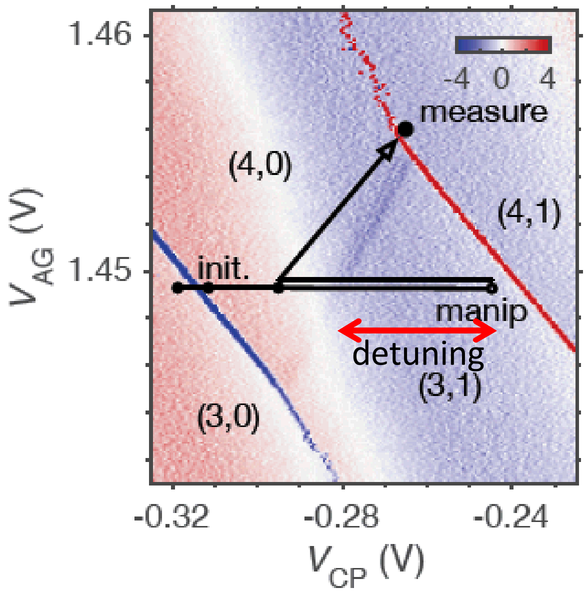

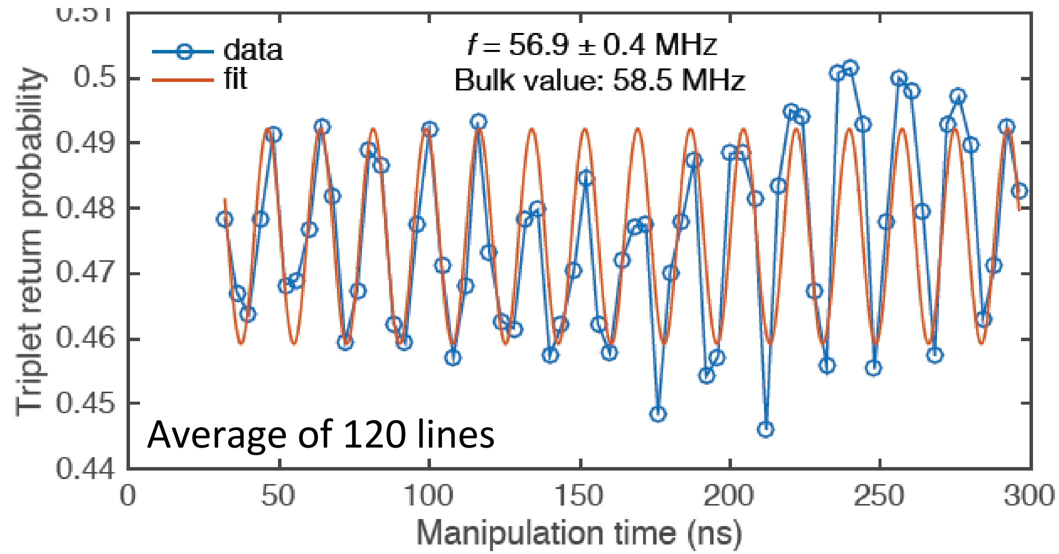

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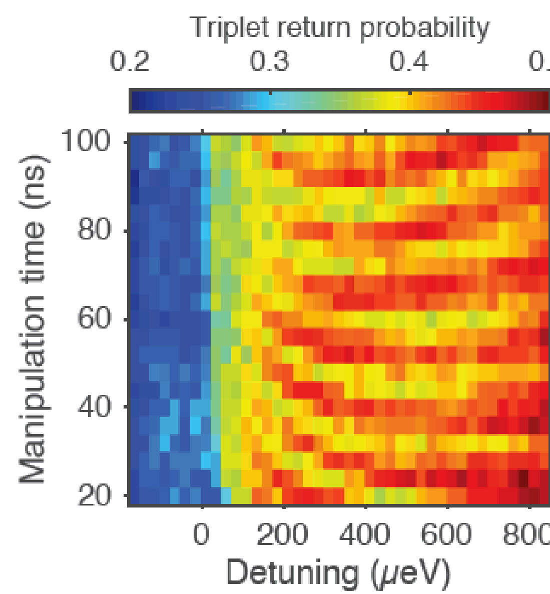
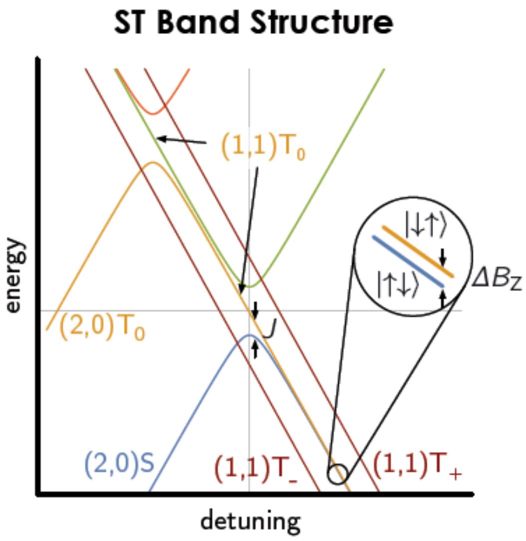


Comparison to numerical simulation



- 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

Jacobson
Sandia National Laboratories

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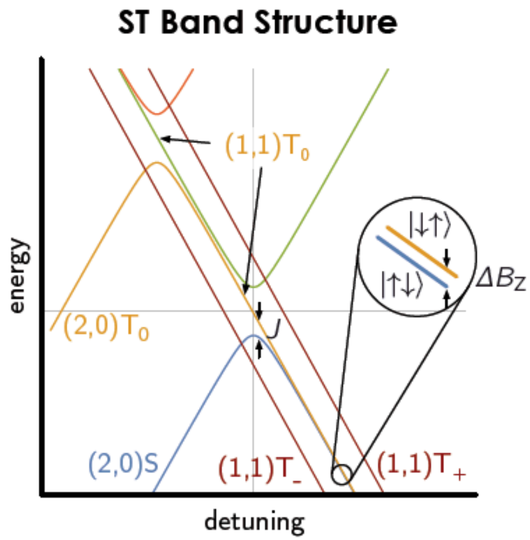

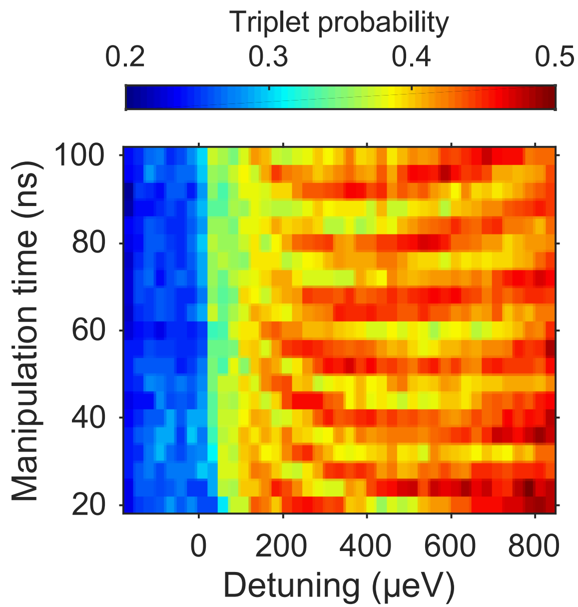

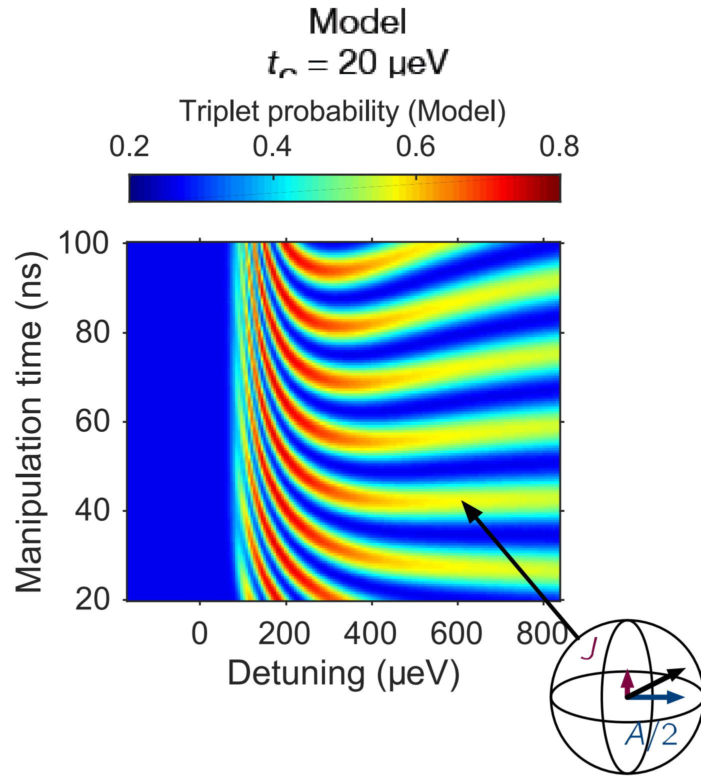

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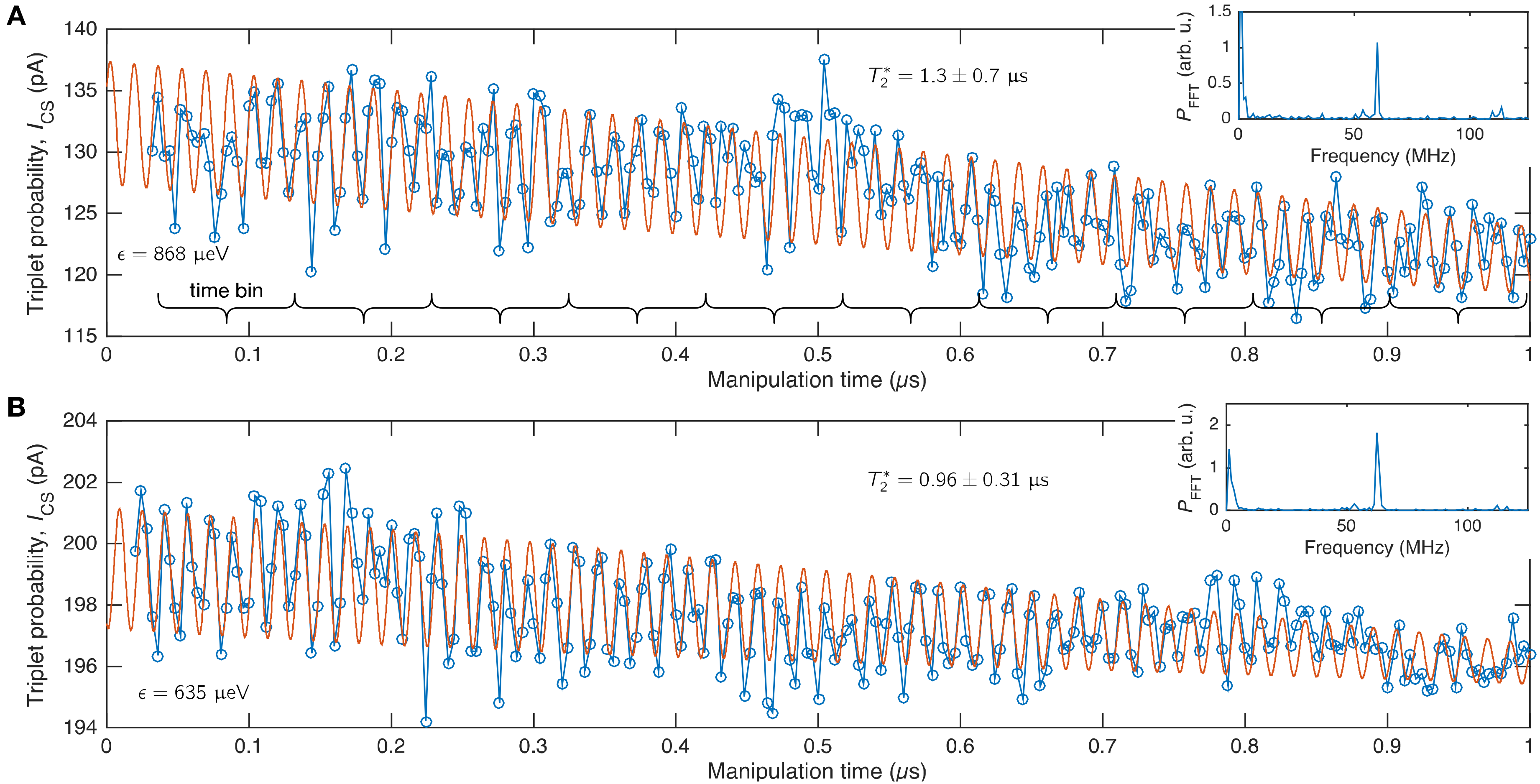
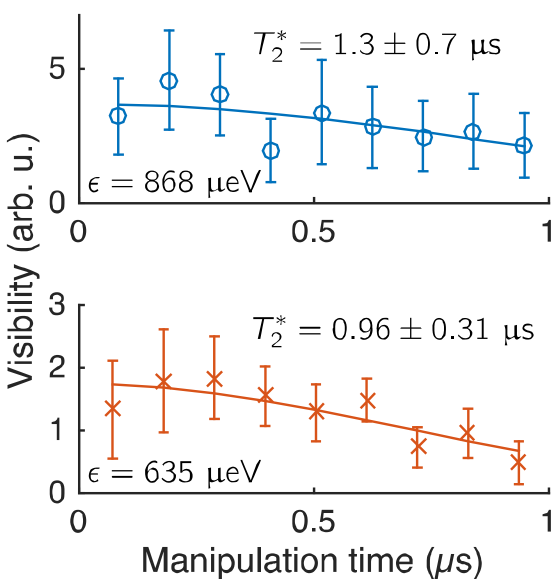
Extended time trace & coarse T2* estimate



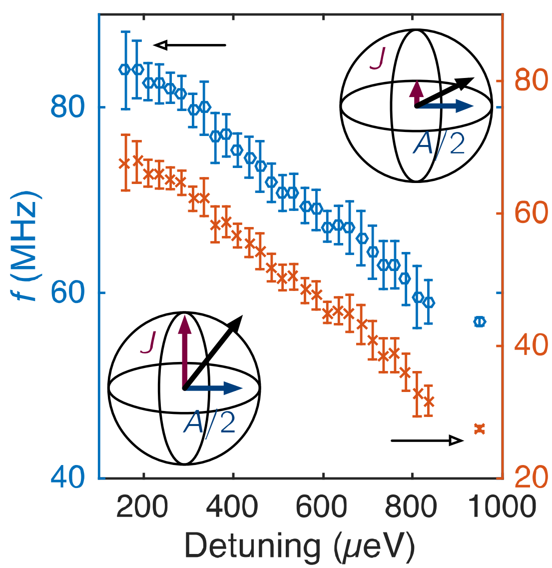
- Long time trace. Average of 10 lines
- T2* order of 1-2 us
- Detuning dependent
- Width of frequency is less than 1 MHz (enriched Si)

Exchange extraction & charge noise model

Visibility decay

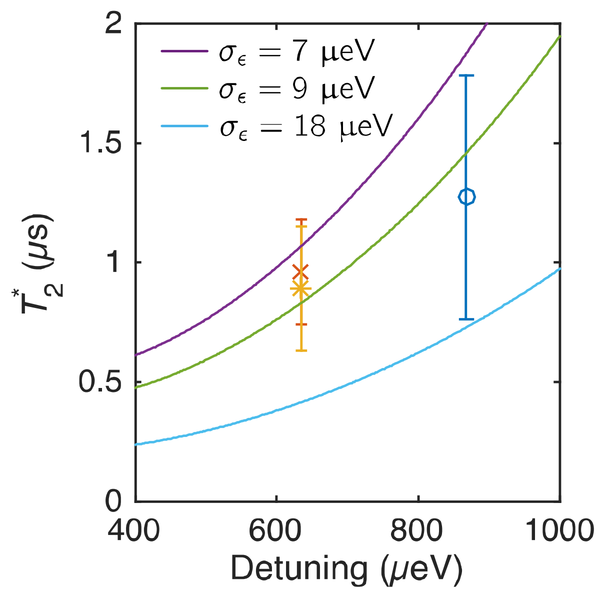


J extraction



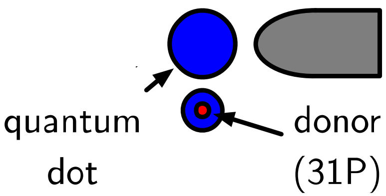
$A/2h = 49.8 \pm 2.3$ MHz

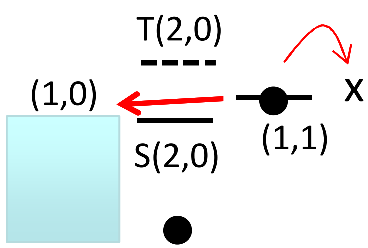
Charge noise model



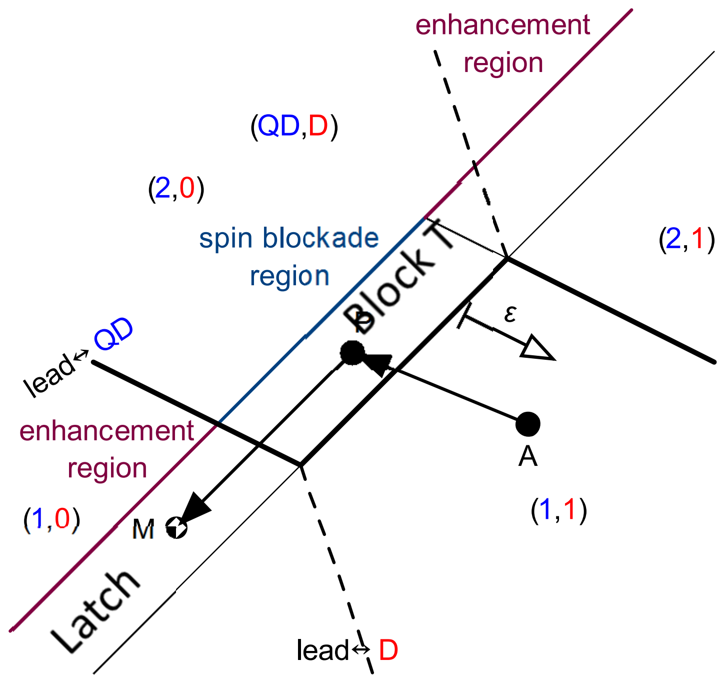
Charge-noise limited.
Possibly extended to > 10 µs

Single shot read-out

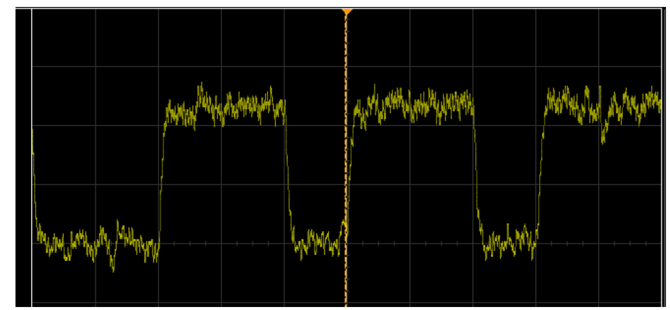




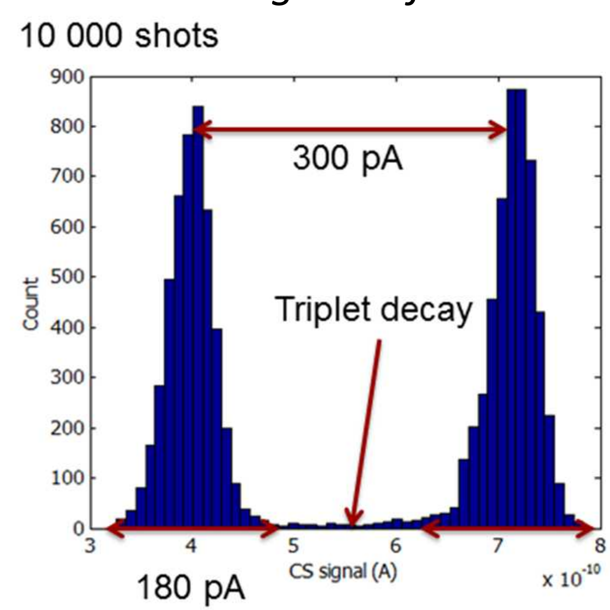
Anti-crossing



Scope Trace



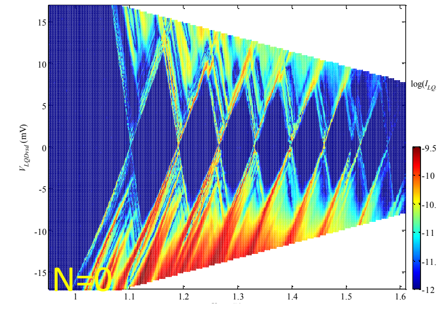
Histogram of shots



- Either see (1,1) for triplet or (1,0) for singlet
- +1 charge differential compared to standard ST read-out
- Latch lasts approximately 15 ms
- Without amplification, single shot RO demonstrated
- Initial estimate: fidelity > 99%. Present limit is BW relative to triplet relaxation time

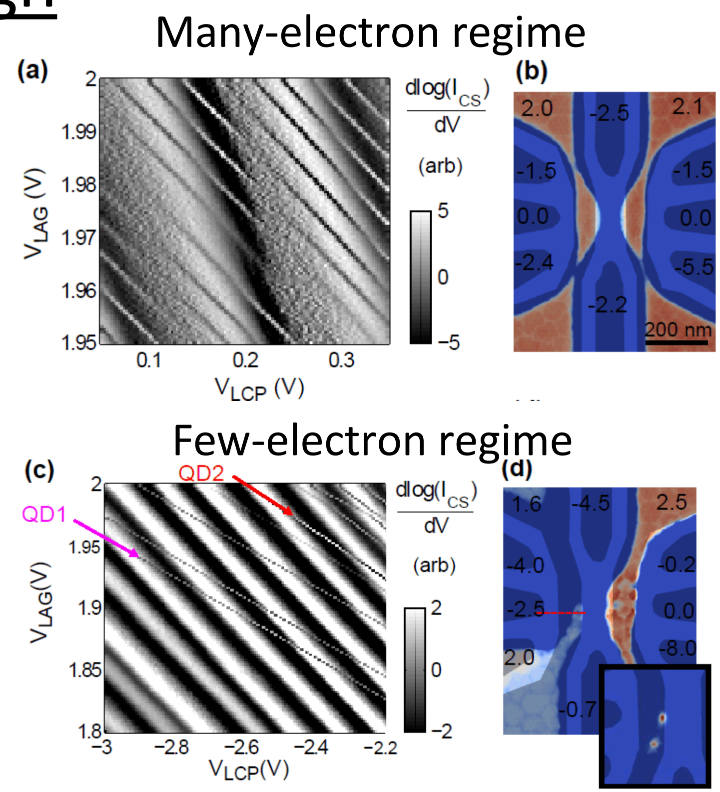
Outline

- Motivations
- MOS single donor ESR & NMR qubits
  - Cryoamplification
- Coherent coupling of D-QD – new qubit structures
  - Donor hyperfine driven S/T qubit
    - Coherent donor spin coupling to surface QD
  - Latch read-out for S/T qubits
- MOS QD Design for future D-QD structures ⟷
- Summary



New QD design

- Limitations of gated wire design
  - Wire is long (250nm), so transport is difficult through small QD
  - Very asymmetric biasing conditions are necessary for few-electron QD
    - Creates oblong well and preferentially supports a DQD
  - *QD is difficult to physically move*
  - LAG gate has large C to ground, limited BW
  - Extended tunnel barriers susceptible to disorder QD formation



- Community has been moving towards separate reservoir gates
- New design that shrinks dimensions & separates reservoir gates from QD gate
- Separate wire accumulation gates (SWAG)

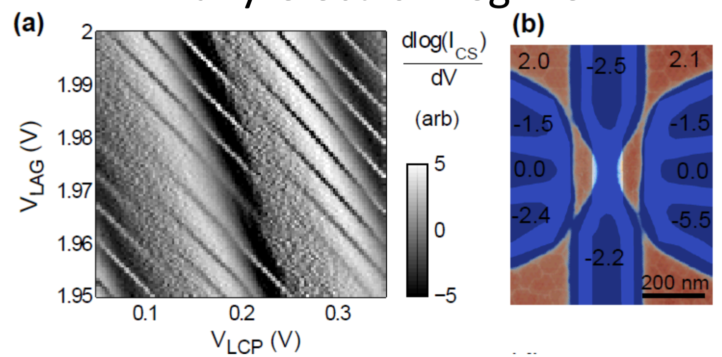
Gamble, Carroll, Curry, Rudolph

New QD design

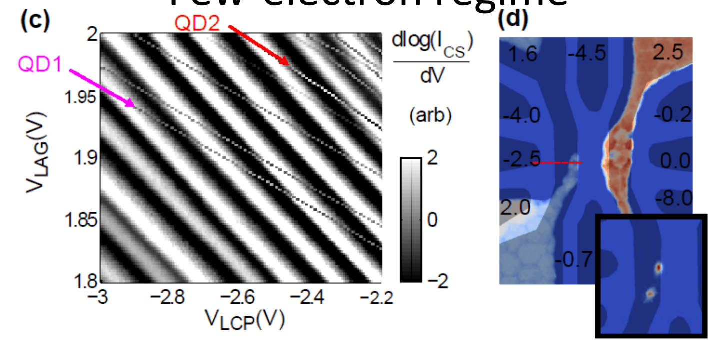
- Limitations of gated wire design
  - Wire is long (250nm), so transport is difficult through small QD
  - Very asymmetric biasing conditions are necessary for few-electron QD
    - Creates oblong well and preferentially supports a DQD
  - *QD is difficult to physically move*
  - LAG gate has large C to ground, limited BW

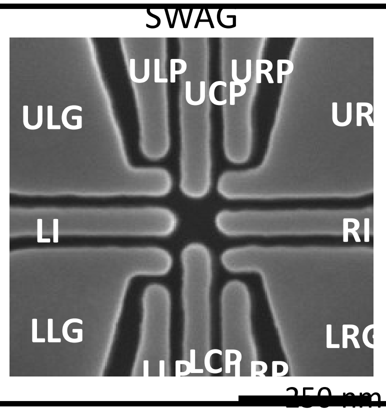
- Community has been moving towards separate reservoir gates
- New design that shrinks dimensions & separates reservoir gates from QD gate
- Separate wire accumulation gates (SWAG)

Many-electron regime

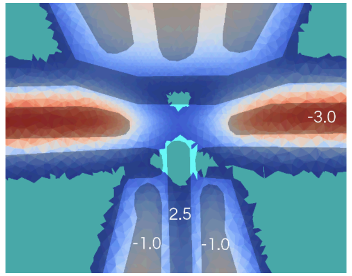


Few-electron regime





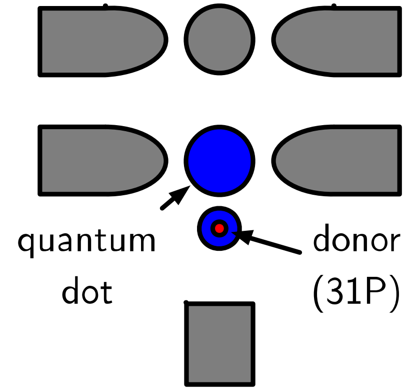
Check for donor transitions

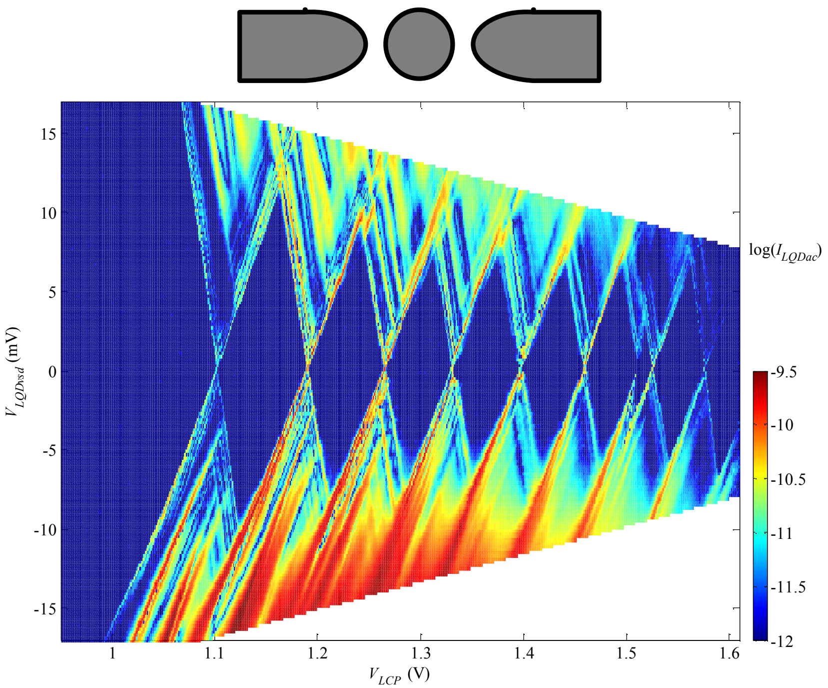


Gamble, Carroll, Curry, Rudolph

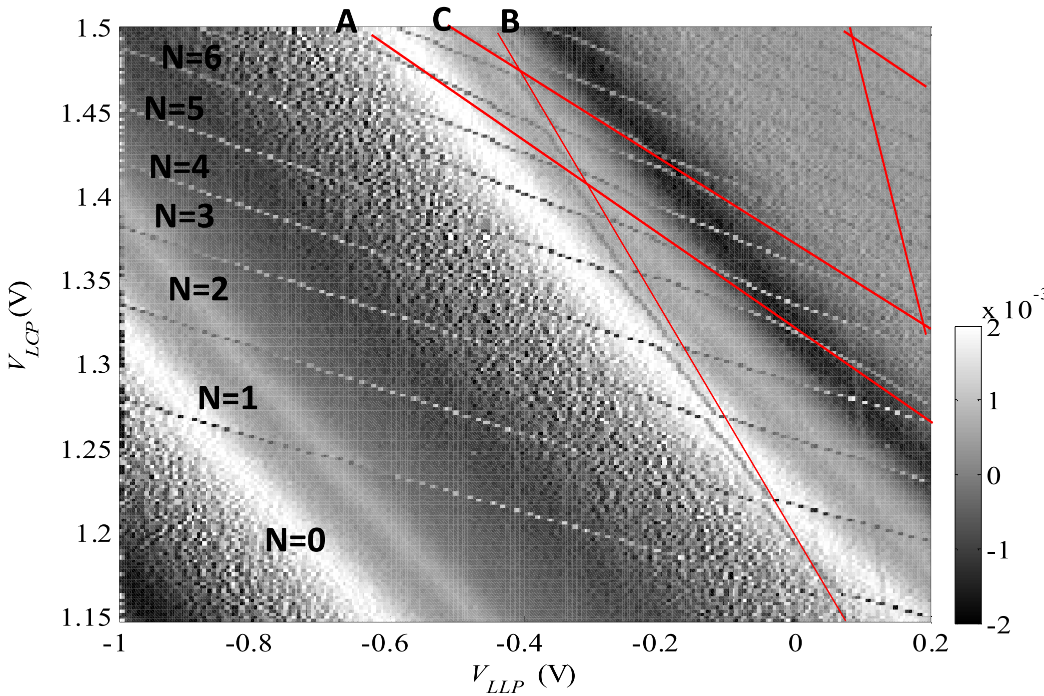
Very good and tunable quantum dots in MOS

- Can tune MOS QD to N=1 while keeping both barriers open
- Good charge sense signal from neighboring QD
- Stable or can be tuned to stable regions
- Hypothesis: design is central to controlling the potential at the interface with small enough spatial resolution
- Still a good topic – can we do better?





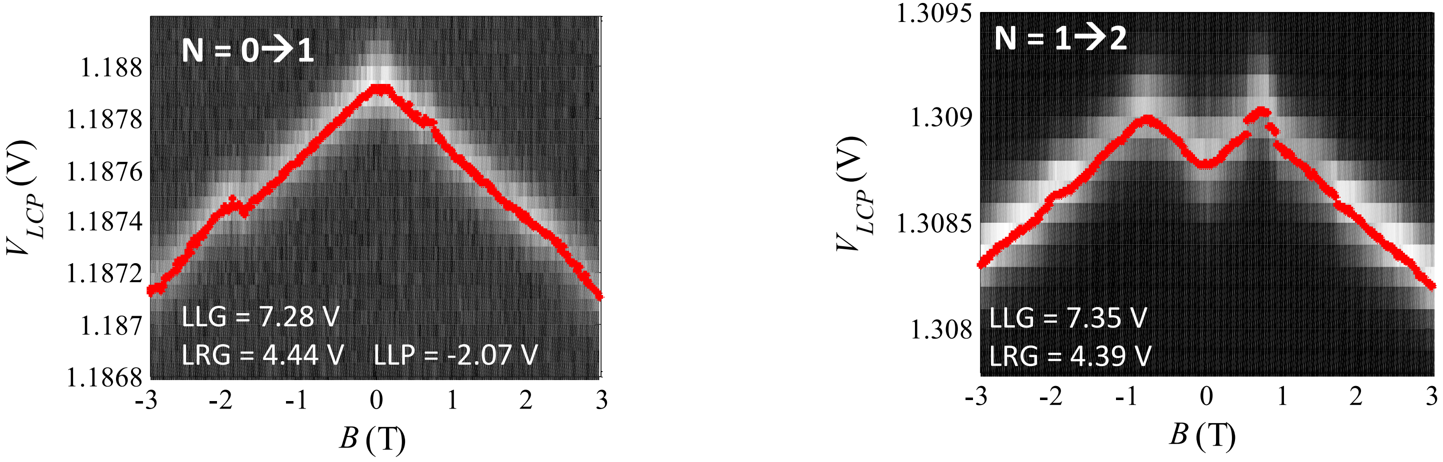
Transport



Rudolph

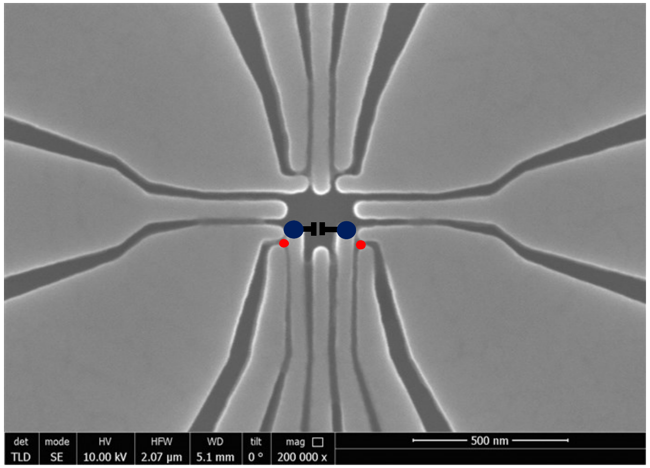
Sandia National Laboratories

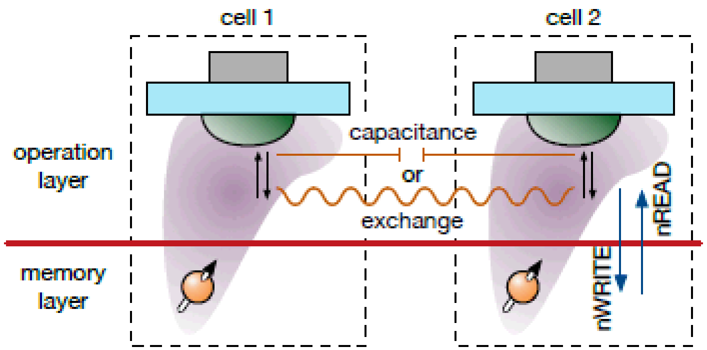
Magnetospectroscopy



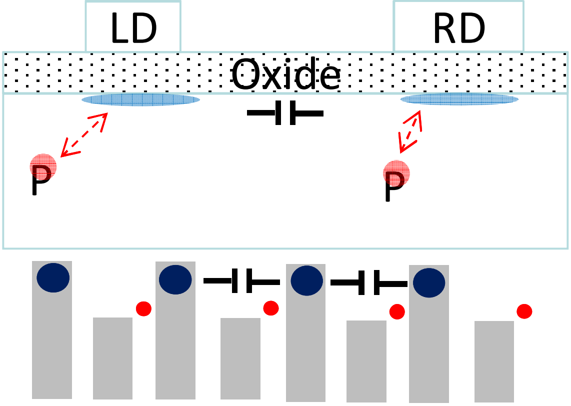
- Stable – allows reasonably sharp magnetospectroscopy
- Single spin filling for N=1
- Singlet triplet splitting of 1T for N=2
    - Assume lowest lying ES is a valley state → valley splitting is 110 ueV
- Valley splitting appears tunable through vertical field (in other measurements)

Possible future lay-outs for MAJIQ

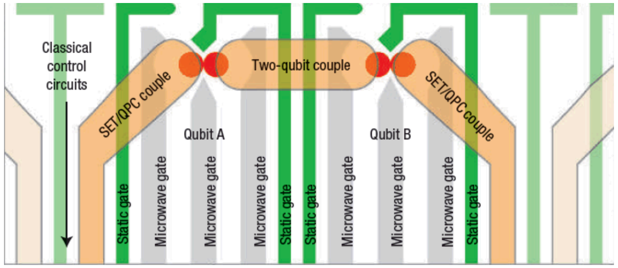




Capacitance coupling of MAJIQ-SWAG



Simplified lay-out from old Taylor proposal



Taylor (2005); Levy (2009); Trifunovic (2013)

- Capacitance coupling by proximity for two qubit gate
- Approach would use resonant voltage drive and energy selection for each qubit location
- Might use nuclear spin as memory – might use other species for faster ST rotation

Summary of SWAG & MAJIQ-SWAG

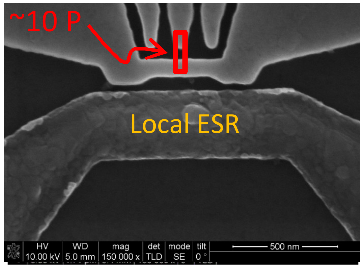
- The gated wire design has important limitations so a new design was developed (separate wire accumulation gate – SWAG)
- Central idea was to move to approach similar to many in the community, separate the reservoir gates. This produces a much more compact device with more tunability down to N=1
- Very good single QD behavior is observed
- Tuning with implanted donors is also observed
  - D-QD transitions can be identified at few electron regime
  - Evidence that tunnel coupling between D and QD can be tuned
  - Implication:
    - Hunt-and-peck for "goldilocks" D-QD tunnel coupling might be relaxed
    - Timed implant D-QD structures might be coupled with reasonable yield
- A double quantum dot (SWAG) has been designed to investigate coupling D-QD qubit structures
  - Two neighboring MAJIQ-SWAG coupled by capacitance proximity (Shulman, Science 2012)
  - Nuclear MAJIQ is being considered as an approach to using and coupling nuclei

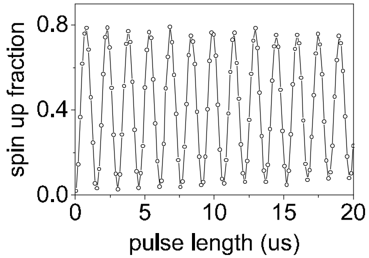
QIST team & external connections

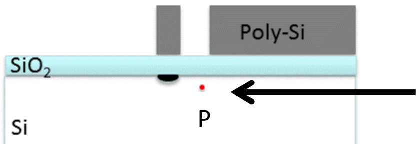
- QIST contributors at SNL
  - **QD & Timed Implant Qubit Fab:** J. Dominguez, R. Manginell, T. Pluym, B. Silva, J. Wendt, S. Wolfley
  - **Qubit control & measurement:** S. Carr, M. Curry, T. England, A. Grine, K. Fortier, R. Lewis, M. Lilly, T.-M. Lu, D. Luhman, J. Rivera, M. Rudolph, P. Sharma, A. Shirkhorshidian, M. Singh, L. Tracy, M. Wanke
  - **Advanced fabrication (two qubit):** E. Bielejec, E. Bussmann, E. Garratt, J. Koepke, A. MacDonald, E. Langlois, M. Marshal, B. McWatters, S. Miller, S. Misra, D. Perry, S. Samora, D. Scrymgeour, R. Simonson, G. Subramanian, D. Ward, E. Yitamben
  - **Device modeling:** J. Gamble, S. Gao, M. Grace, T. Jacobson, R. Muller, E. Nielsen, I. Montano, W. Witzel, K. 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, 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)
  - Chee Wee (U. Taiwan)
  - McGill (W. Coish, D’Anjou)

Summary

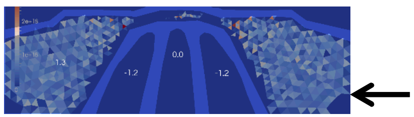
Single spin donor ESR in 28Si





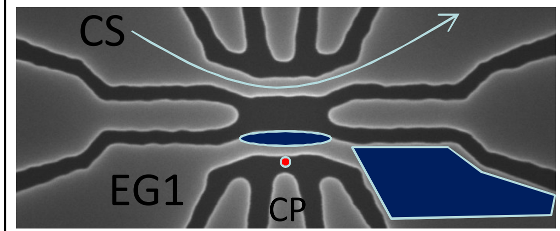


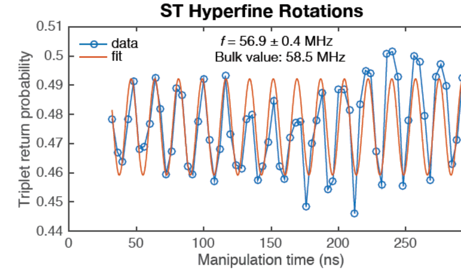
Donor qubit

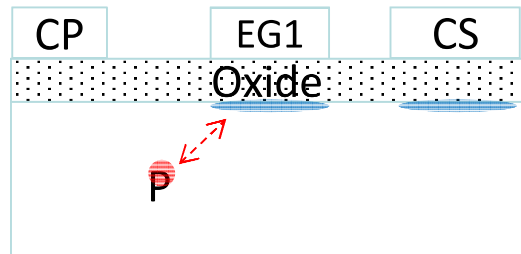


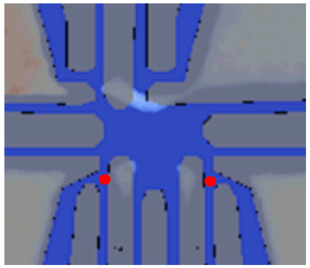
Si QD simulation

MOS S/T qubit driven by single donor

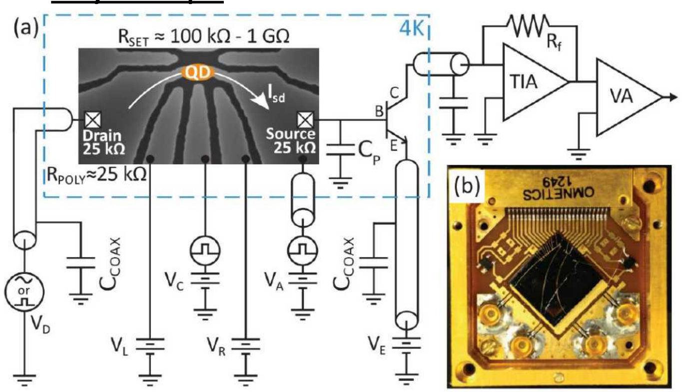




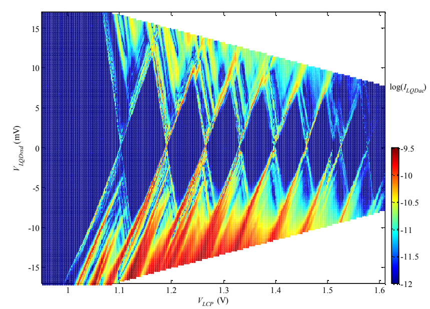


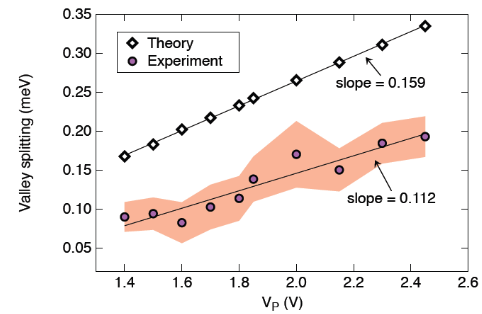


Cryoamps



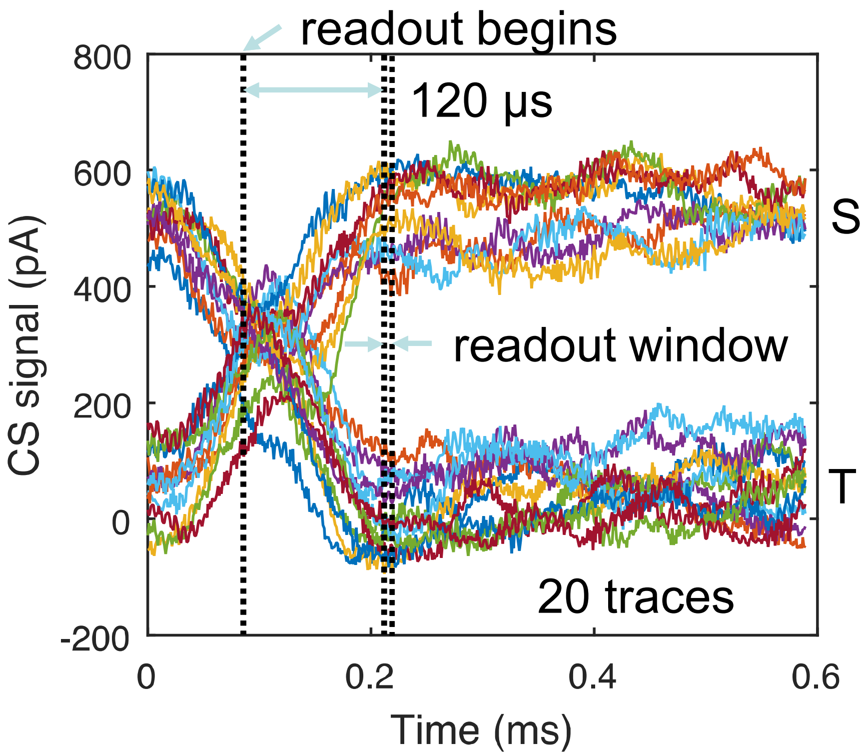
MOS QDs & SWAG





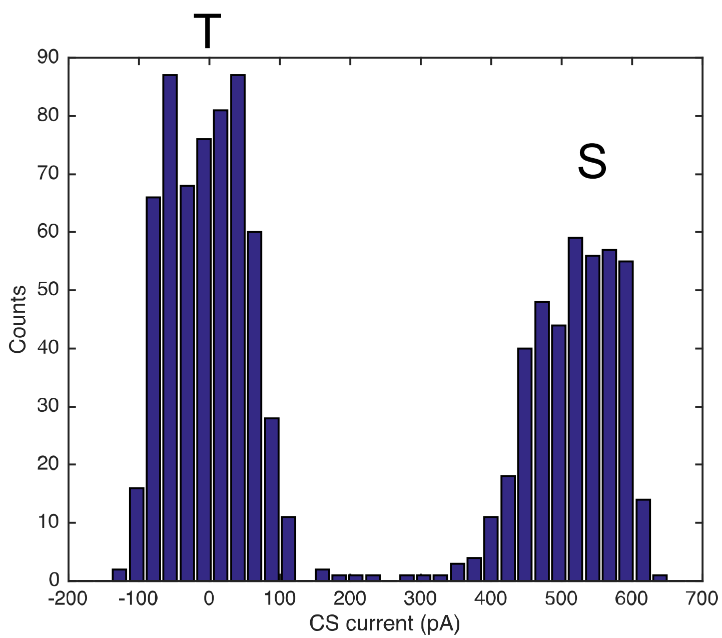
High fidelity enhanced latching readout

Single shot traces



Signal relaxation time: 38 ms

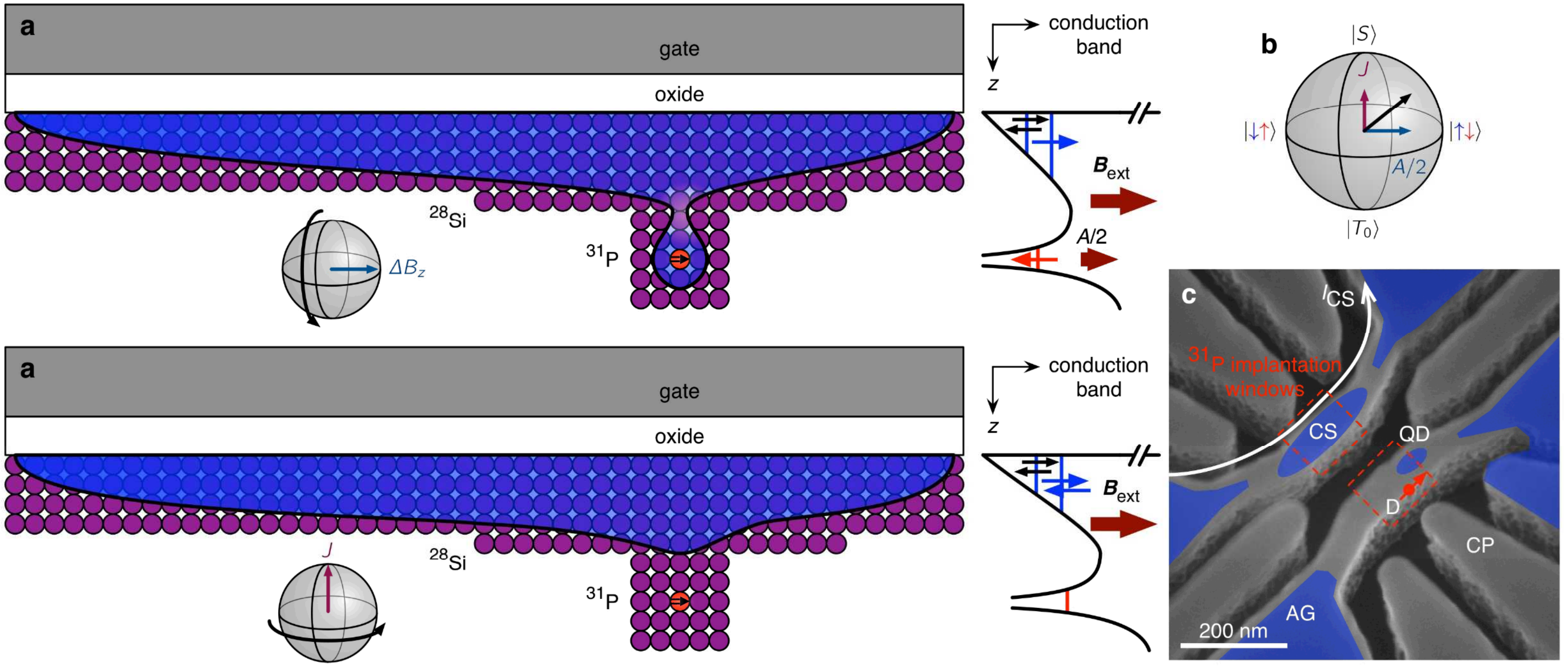
Readout window histogram



Singlet fidelity: >99.95 %
Triplet fidelity: 99.7±0.1 %
Avg. fidelity: 99.8±0.1 %

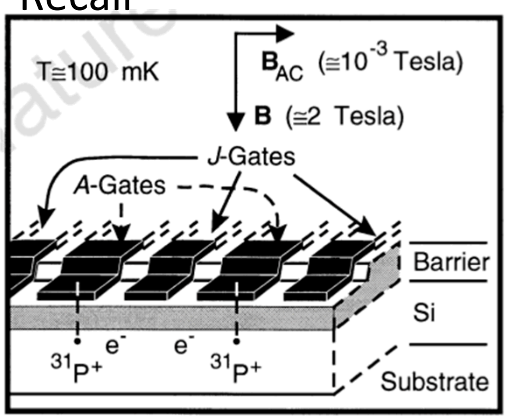
- Low bandwidth (DC filters)
- No cryo pre-amplification
- **Can get better!**

Where we are going



Harvey-Collard et al. arXiv:1512.01606

Recall



- Donor qubits
- Couple qubits to electron qubits at interface
- Interface is where the qubit coupling occurs