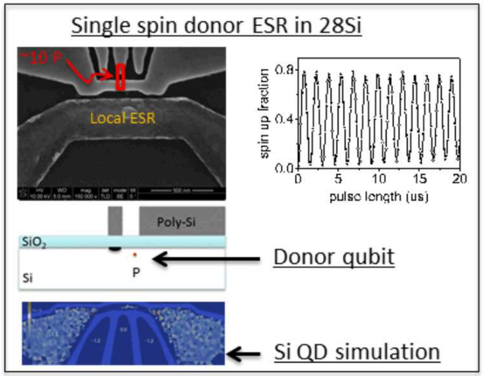
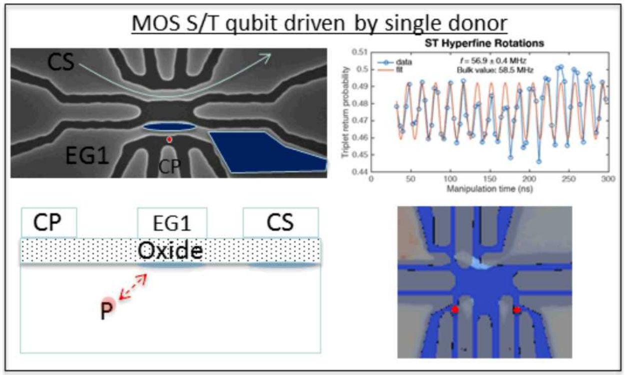
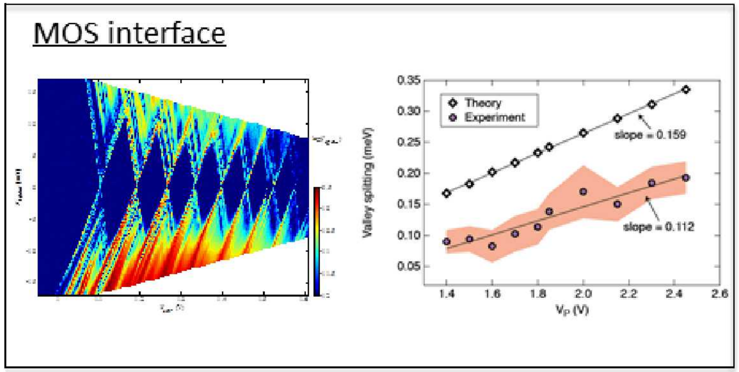
SAND2016-4842C







Silicon donor-doped MOS quantum-bits

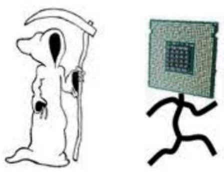
Malcolm Carroll & **QIST team**

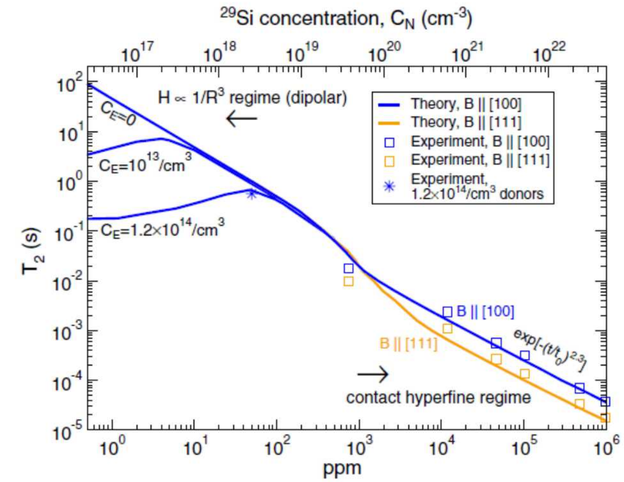
Sandia National Labs, Albuquerque, NM 87185

September 17, 2015

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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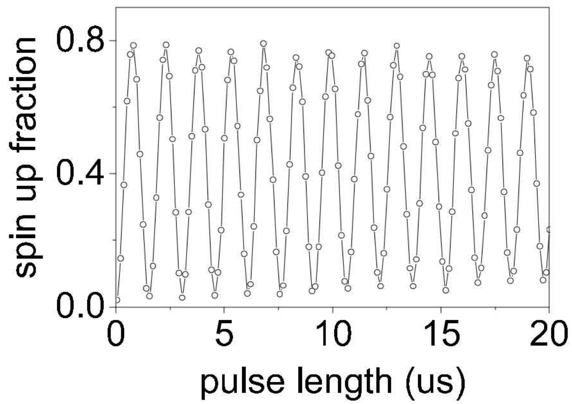

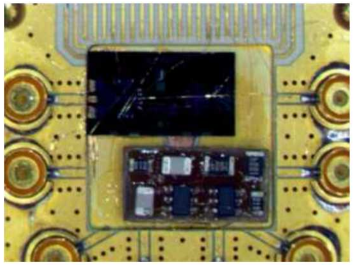

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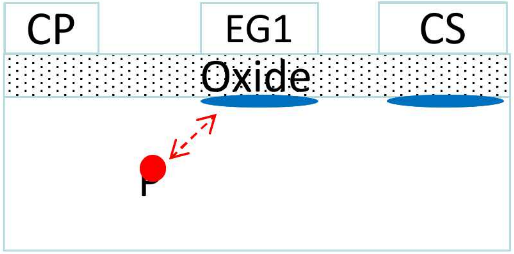

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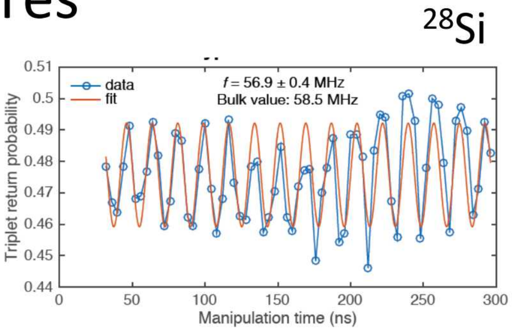

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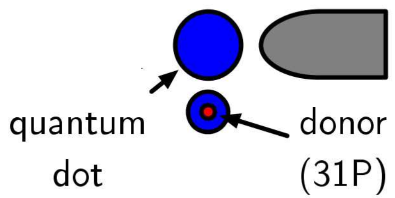
D-QD S/T qubit



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

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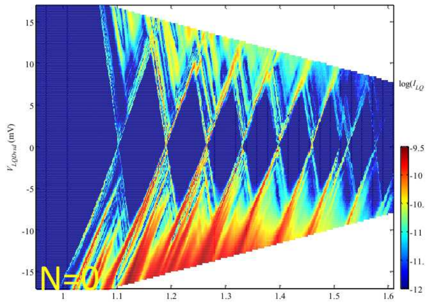

- Summary

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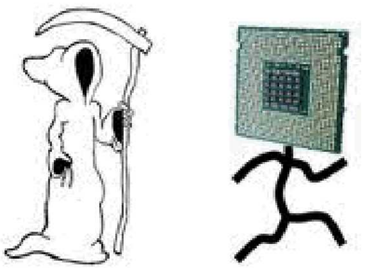
Motivations for Si quantum computing

- 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



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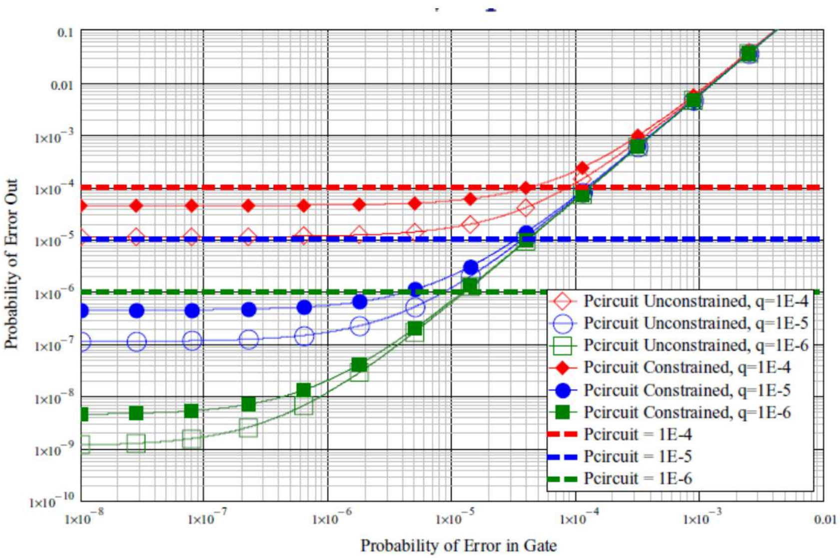
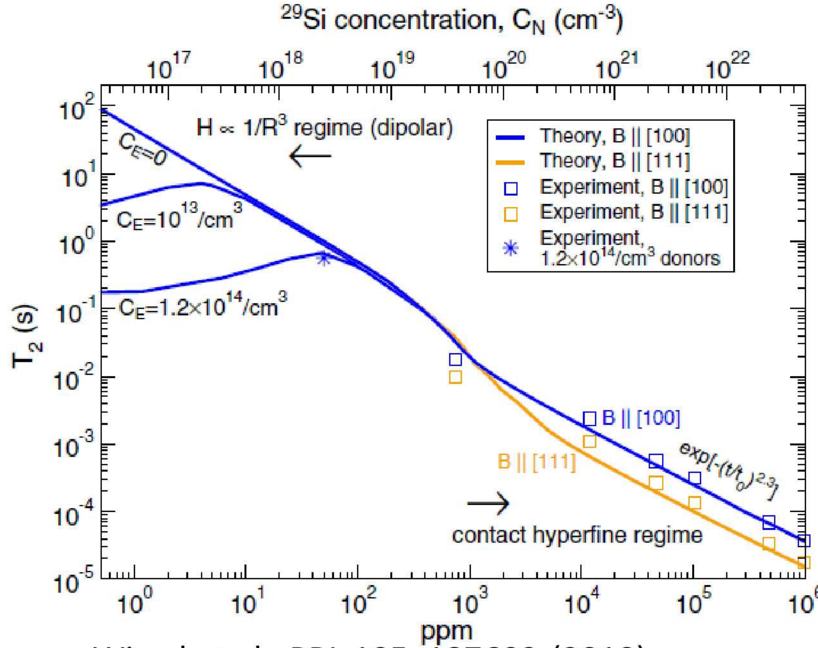
- Silicon offers promise of **realizing** higher fidelity & less QEC

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



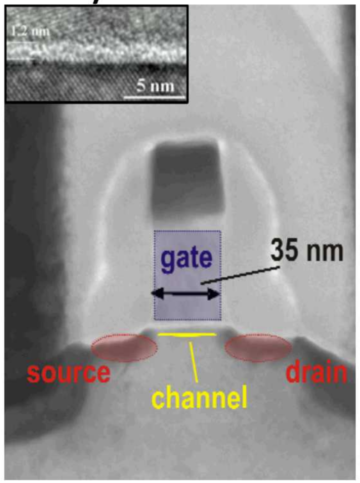
Levy et al. New Journal of Physics 13 (2011) 083021

Electron spin & 28Si enrichment

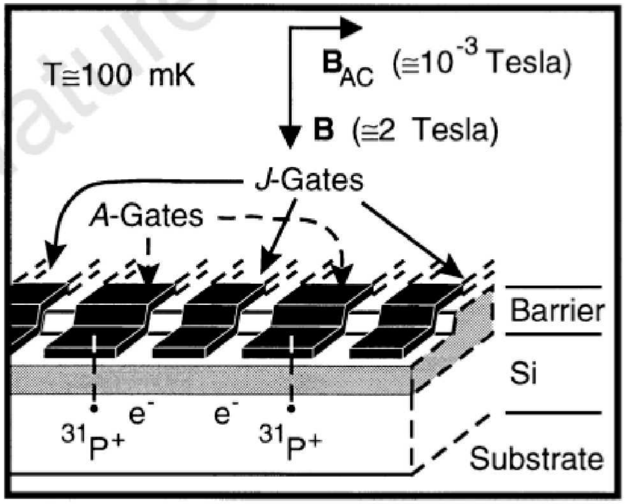


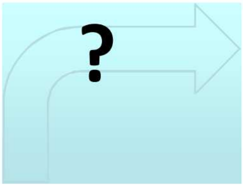
Witzel et al., PRL 105, 187602 (2010)
& PRB 86 035452 (2012)

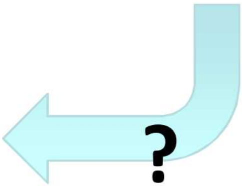
Today's Si MOSFET



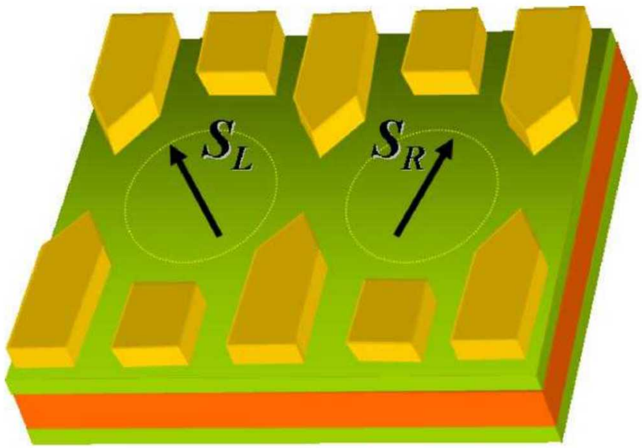
Single atom architecture (e.g., Kane)







[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)

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

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

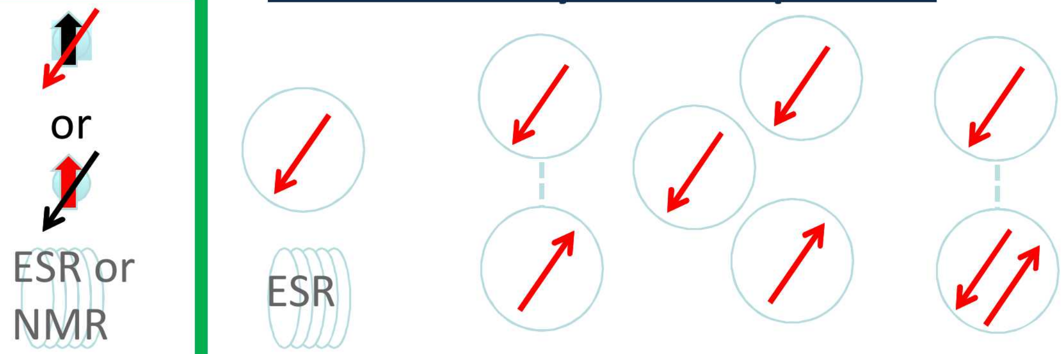
Taxonomy of Si qubits

First part of talk

Qubit

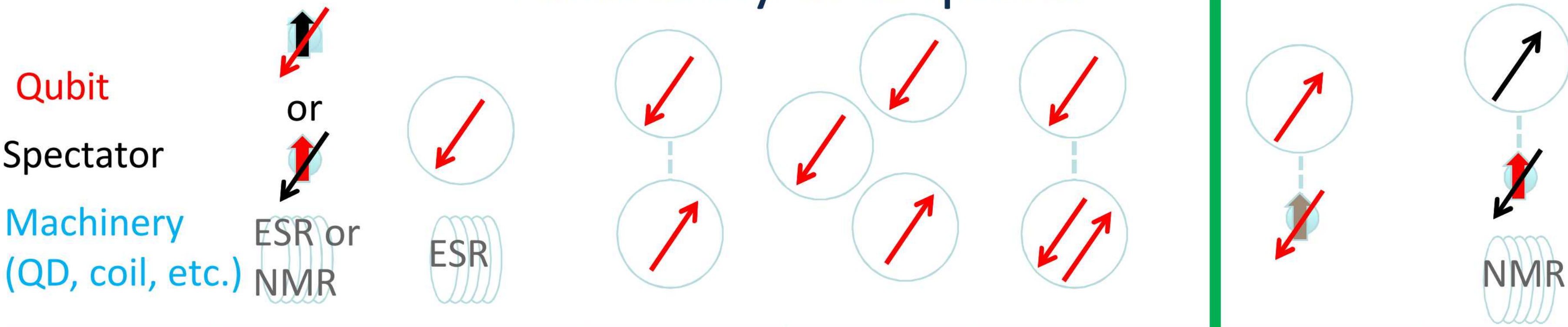
Spectator

Machinery (coil, etc.)



	Donor (D)	Quantum dot (QD)	DQD (N=2)	TQD (N=3)	DQD-hybrid (N=3)
Control	ESR (>10 GHz) or NMR	ESR or EDSR (>10 GHz)	Electrical + B-gradient or EDSR	All-electrical	All-electrical
T2* : Tgate [us] (e)	6e5 : 150 (1e-4) 200:2 (5e-3)	120 : 1 (4e-3) [nnano 2014]	0.36:0.1?(TBD) [Nat. 2012] nat. Si	2.5 : 0.1? (TBD) [Sci. Adv. 2015]	0.01 : 1e-4 (5e-2) [NPJ-Q I 2015]
Integration Advantage	Stark selection	Easier fab: 1QD & 0 barriers per qubit	Low B-field RO (<10 GHz). No MW lines.	Low B-field RO (<10 GHz). No MW lines.	Low B-field RO (<10 GHz). No MW lines.
Integration Advantage	Identical (yield)	1 barrier qubit coupling	Dipole or 1 barrier qubit coupling	Dipole or 1 barrier qubit coupling	Dipole or 1 barrier qubit coupling
Challenge	Donor to donor coupling	MW or magnet integration? Selectivity?		3 QDs & 2 barriers per qubit	

Taxonomy of Si qubits



	Donor (D)	Quantum dot (QD)	DQD (N=2)	TQD (N=3)	DQD-hybrid (N=3)	D-QD (N=2)	Nuclear D-QD (N=2)
Control	ESR (>10 GHz) or NMR	ESR or EDSR (>10 GHz)	Electrical + B-gradient or EDSR	All-electrical	All-electrical	All-electrical	NMR + electrical
T2* : Tgate [us] (e)	6e5 : 150 (1e-4) 200:2 (5e-3)	120 : 1 (4e-3) [nnano 2014]	0.36:0.1?(TBD) [Nat. 2012] nat. Si	2.5 : 0.1? (TBD) [Sci. Adv. 2015]	0.01 : 1e-4 (5e-2) [NPJ-Q I 2015]	1 : 1e-2 (TBD) [arXiv]	TBD
Integration Advantage	Stark selection	Easier fab: 1QD & 0 barriers per qubit	Low B-field RO (<10 GHz). No MW lines.	Low B-field RO (<10 GHz). No MW lines.	Low B-field RO (<10 GHz). No MW lines.	Low B-field RO (<10 GHz). No MW lines.	Solution to coupling point-like nuclei
Integration Advantage	Identical (yield)	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
Challenge	Donor to donor coupling	MW or magnet integration? Selectivity?		3 QDs & 2 barriers per qubit.	Single shot read-out?		

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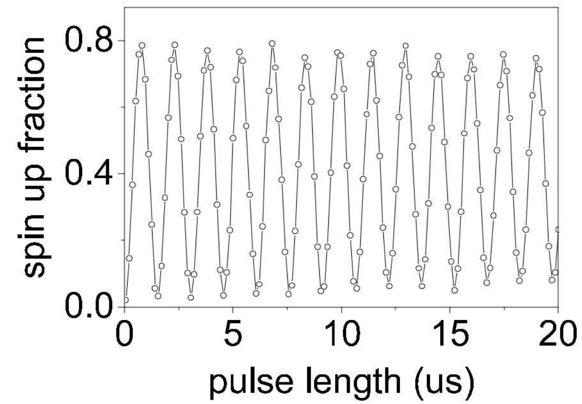
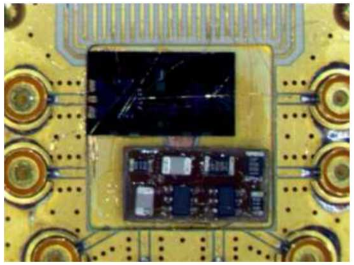
    - Cryoamplification





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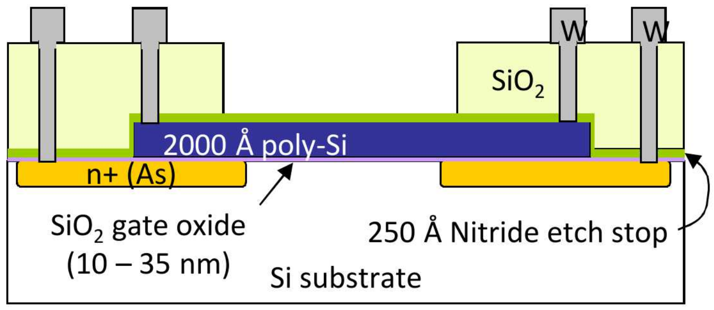
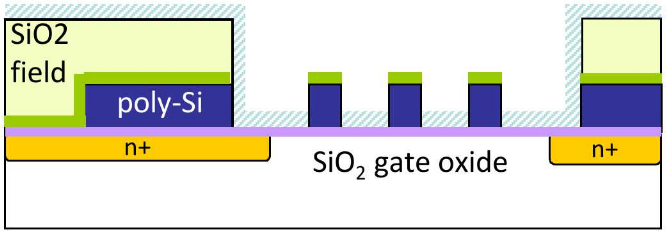
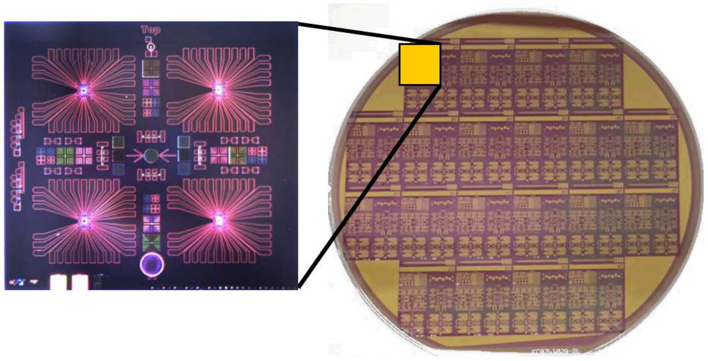
Nanostructure fabrication at Sandia National Labs

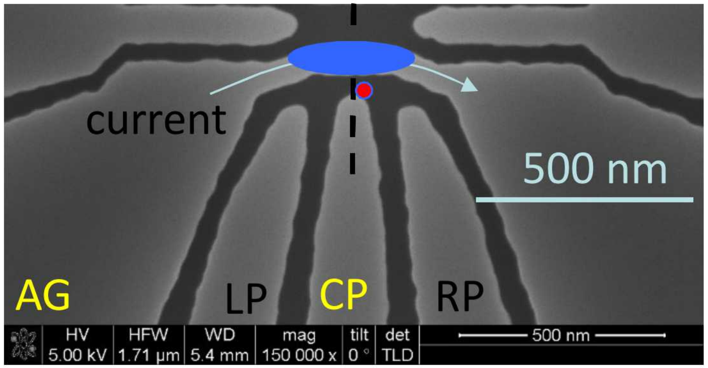
Front-end in silicon fab



Back-end nanolithography







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

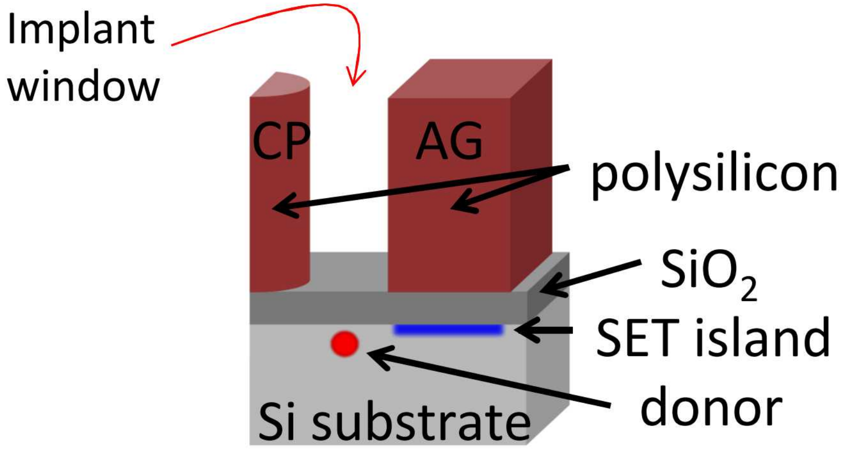
Rationale:

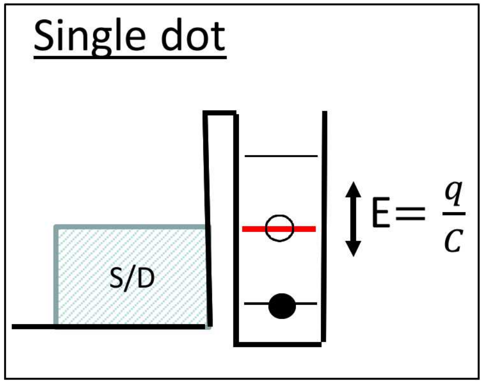
- Self aligned implant
- Foundry like processing
- Potential long term benefits for charge stability

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

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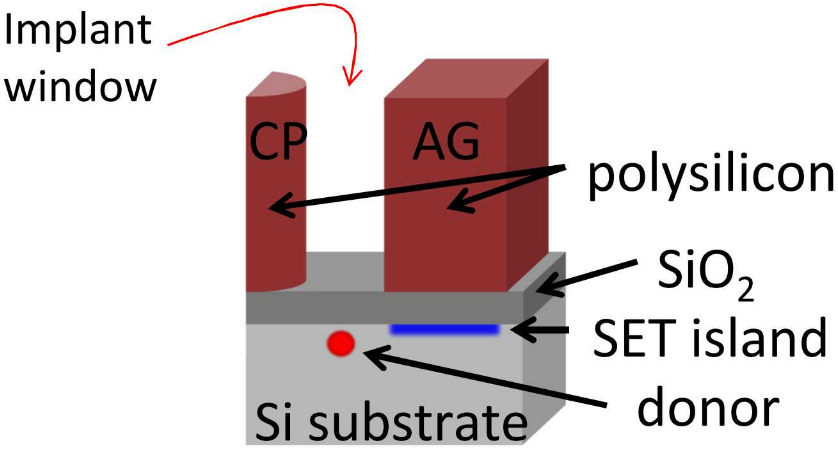
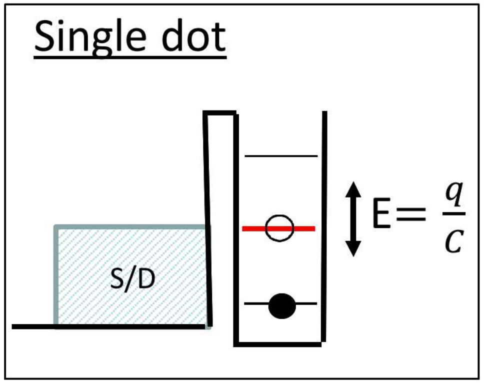
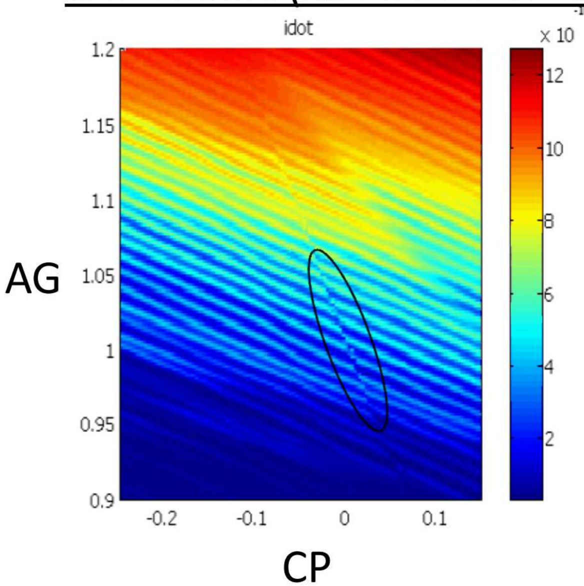
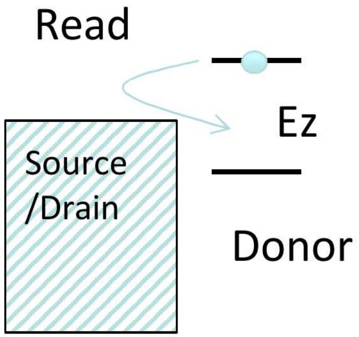




SET offsets (detection of ionization)



Spin dependent ionization



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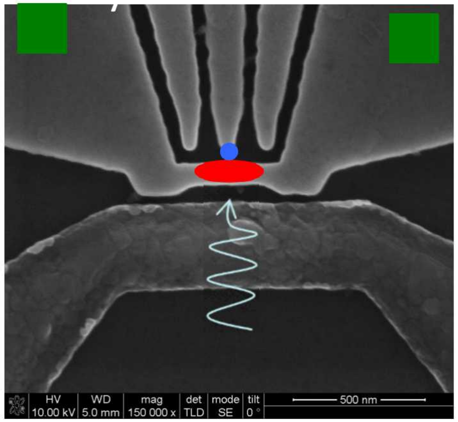
Morello et al., Nature 2010
Tracy et al., APL 2013

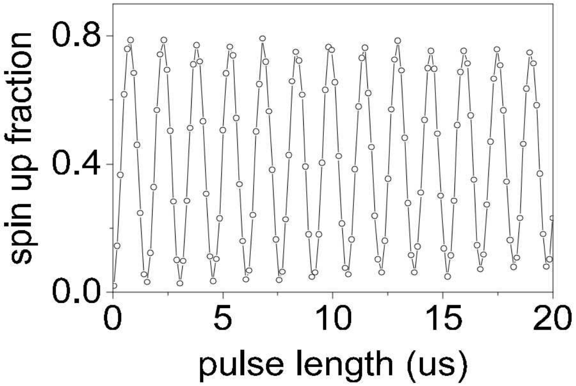
Single donor qubits & dephasing metrics

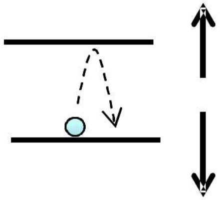


Ohmics

Donor

Quantum Dot





^{28}Si epilayer

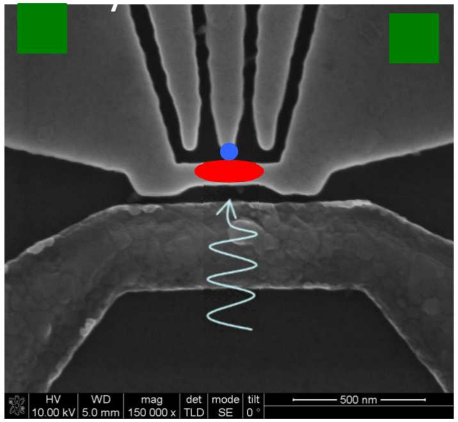
- 2.5 μm thick
- 500 ppm ^{29}Si (ToF SIMS)

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. (in preparation)

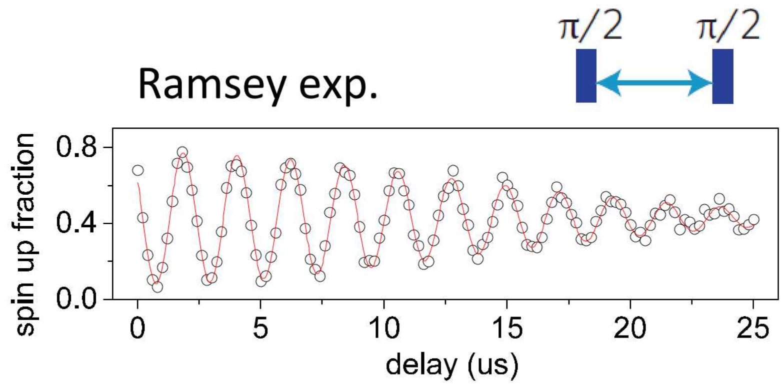
Single donor qubits & dephasing metrics

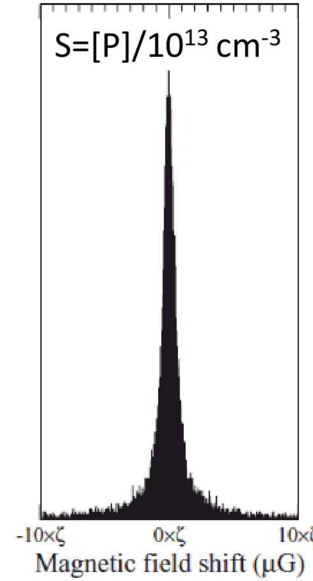


Ohmics

Donor

Quantum Dot





Witzel et al., PRB 2012

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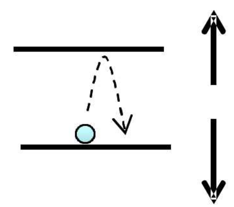
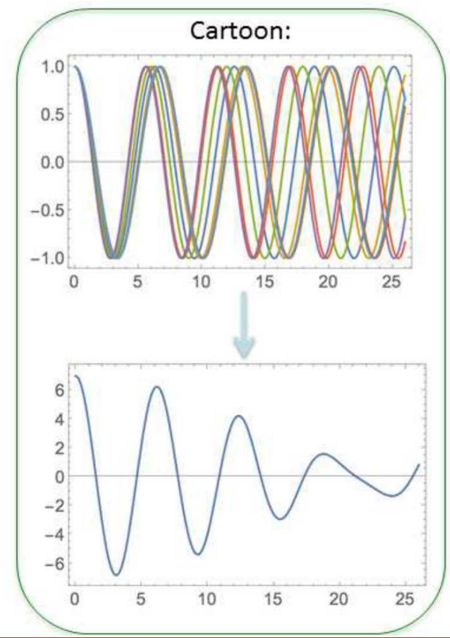




- Ramsey and Hahn-echo: T2 = 0.31 ms, T2* = 10-20 μs
- Line width is approximately 30 kHz
- B1 corresponds to

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

Sandia National Laboratories

Preliminary 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

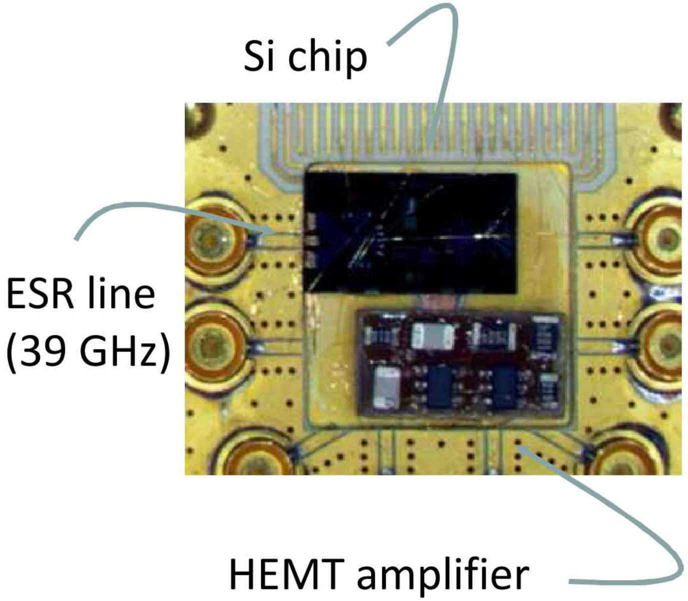
Gate	Process Infidelity
Gi	0.026748
Gx	0.047344
Gy	0.055106

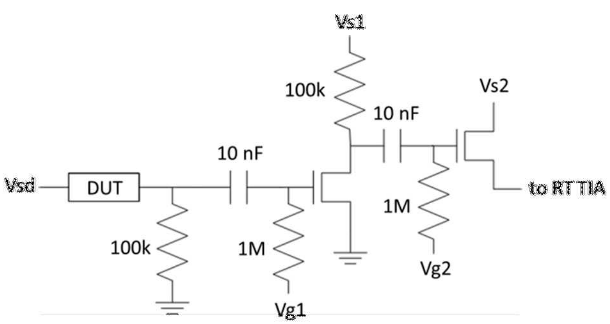
- Gate set tomography used to characterize rotations
- General idea:
  - Provide initial state of unknown "quality"
  - Provide measurement of unknown "quality"
  - Apply sequences gates and idles
  - Results characterize gates and SPAM errors

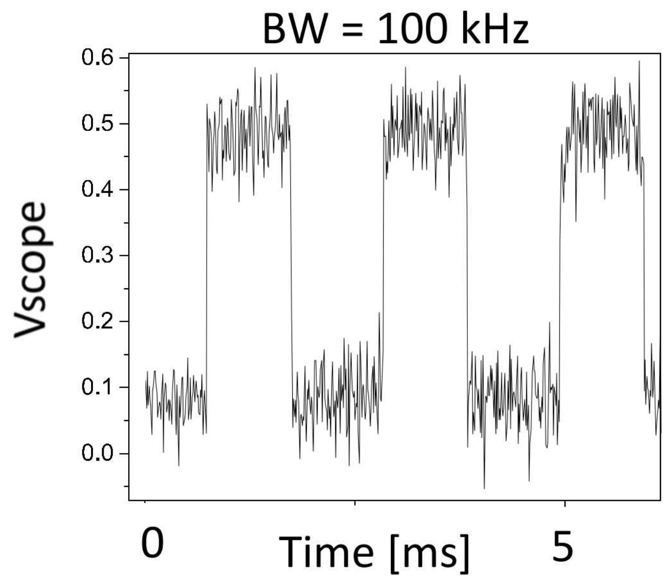
- Maximum length concatenations we used was 8.
- 400 ns pulse times, 1.8 us clock cycle, 100 kHz BW on read-out
- SPAM error of order 6% & Idle error ~3%
- X/Y rotations are of order 4-5% error. Looks like phase error between X and Y
- Order of 1 % uncertainty in infidelity estimates

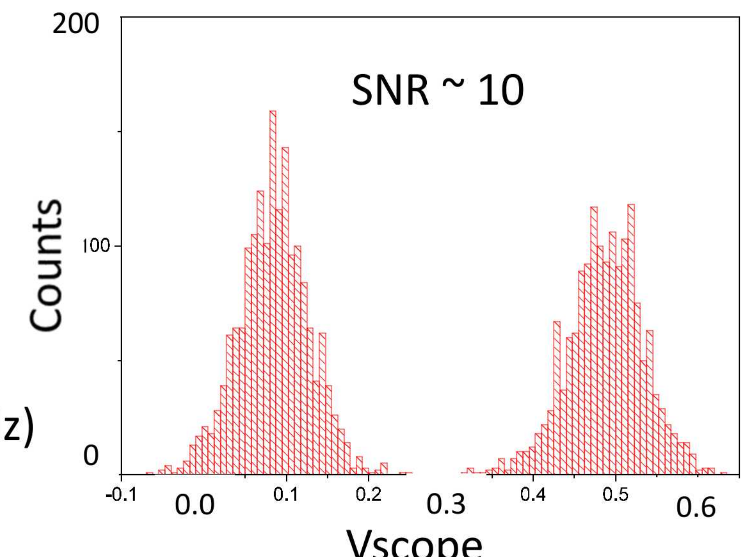
Blume-Kohout, Nielsen, Gamble

Read-out circuit (AM HEMT)







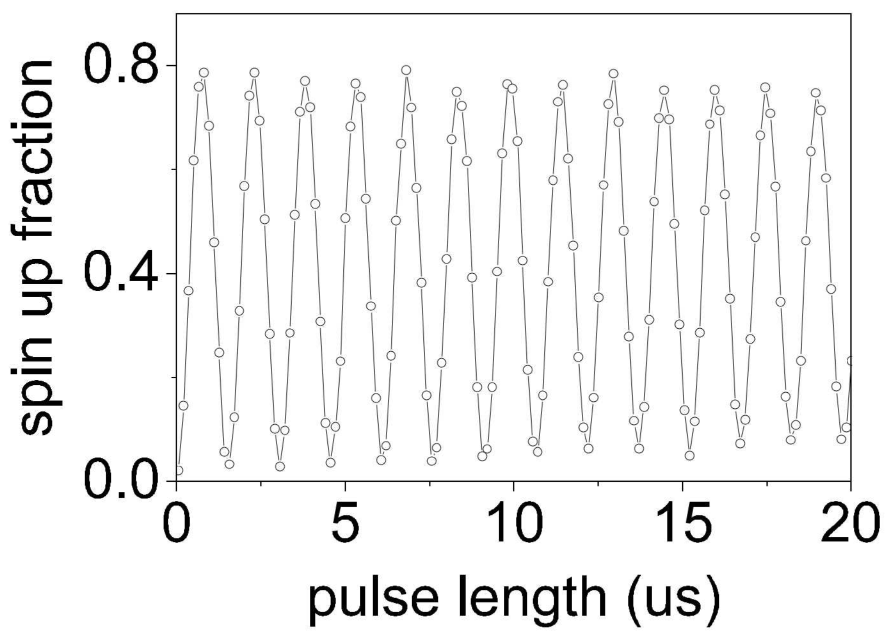


- Dry fridge noise a real nuisance
- Cryo-preamplification & AM technique (300 kHz)
- Good visibility w/ ~1% threshold overlap
- $T_{electron}$ ~ 200 mK

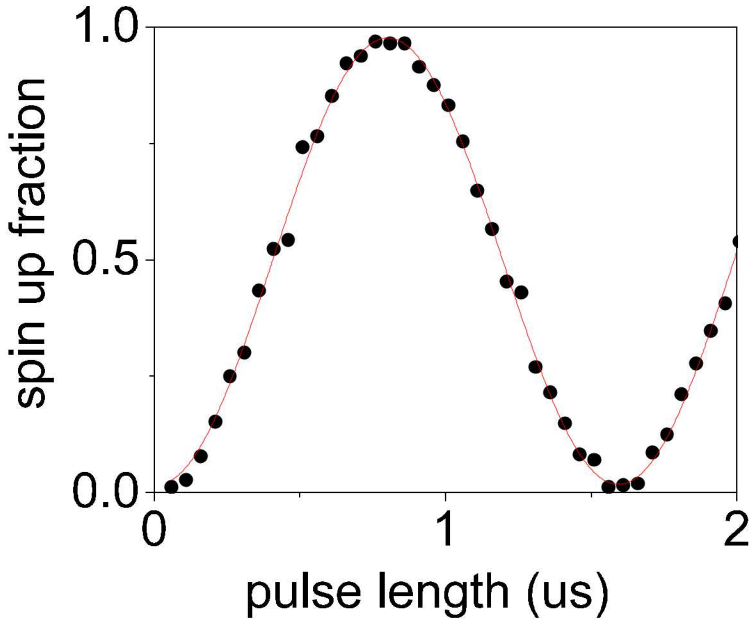
Poster: L. Tracy

Rabi oscillations

10 kHz BW



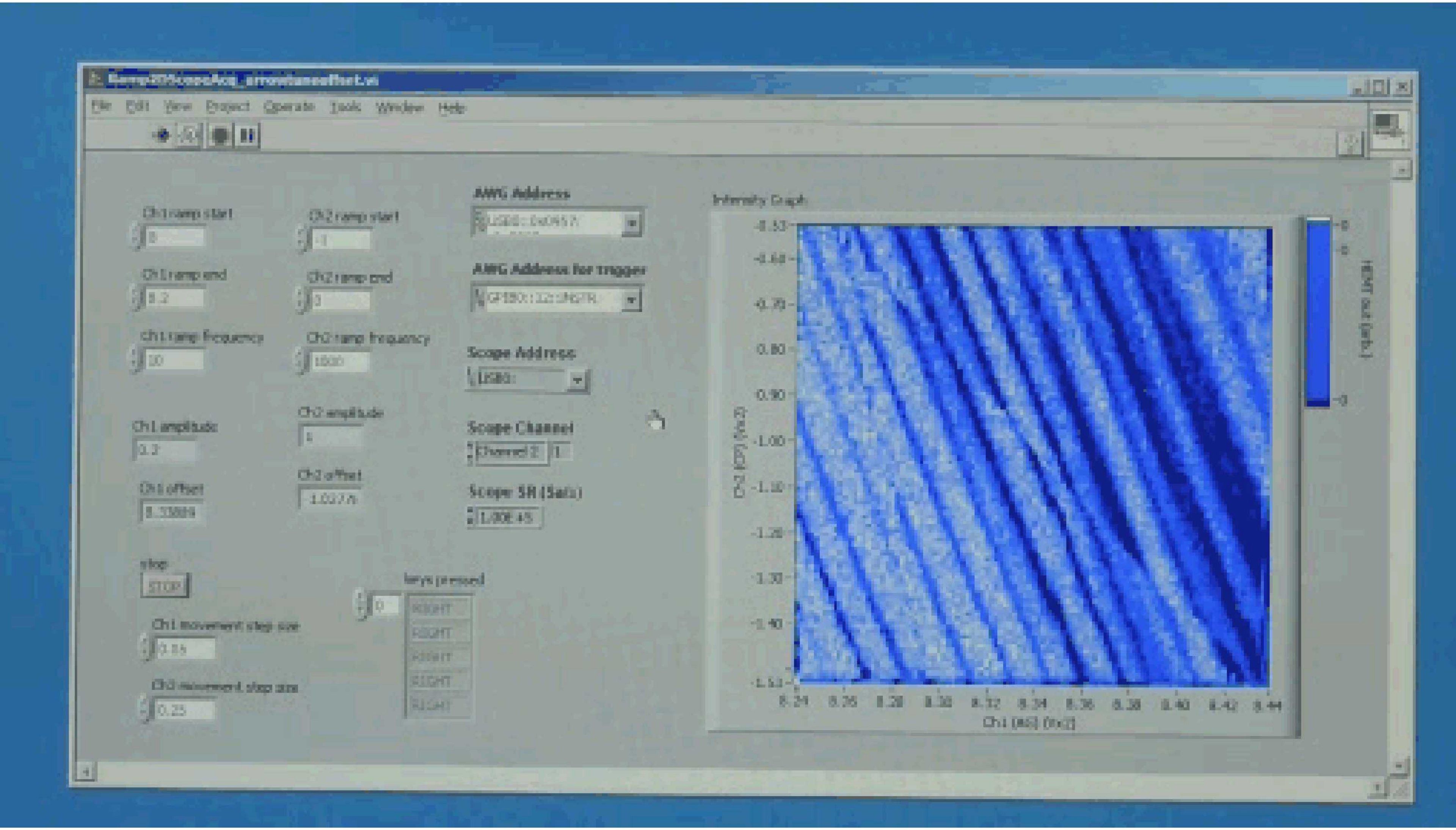
96% visibility w/100 kHz BW



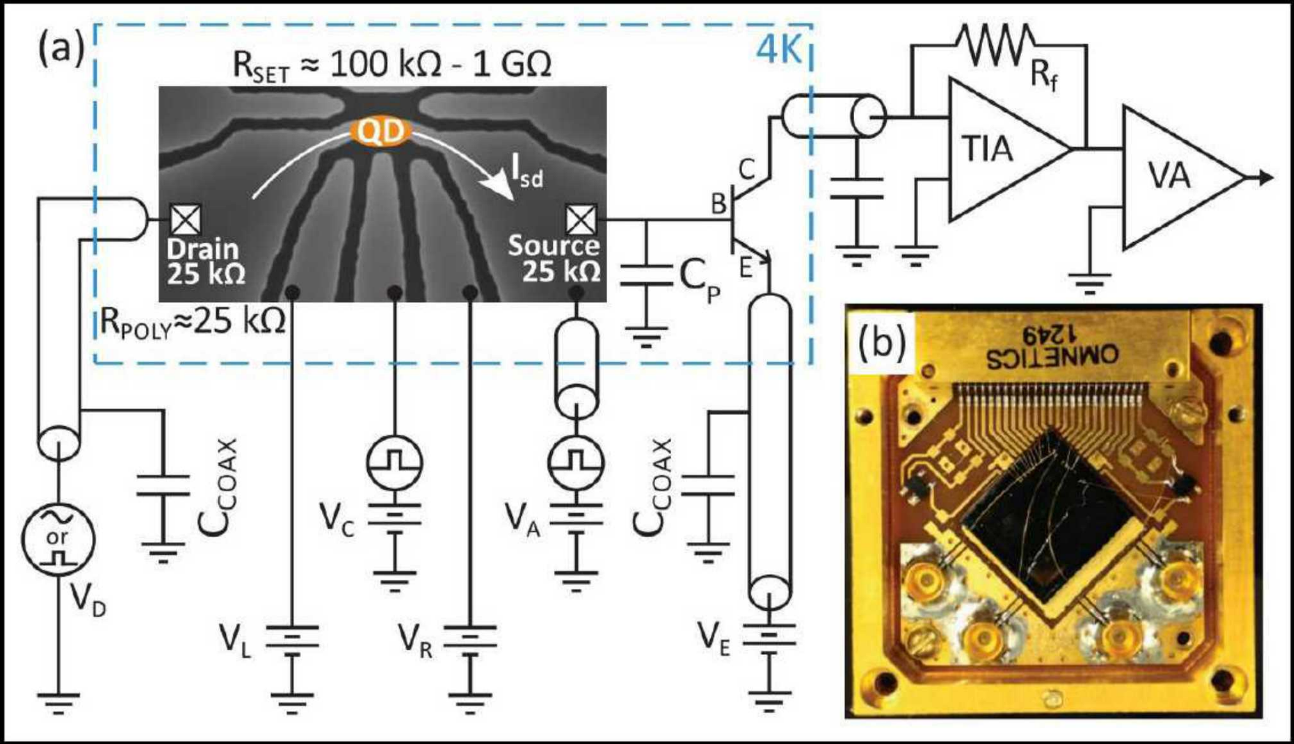
Long lived Rabi oscillations

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

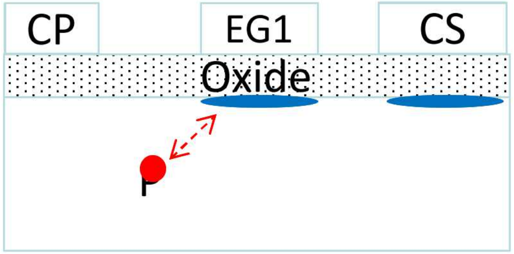
- Cryoamps motivation: low overhead & support SiPmod-SET development
- SiPmod-SET = optical isolation and modulator resonance instead of RF tank-circuit. Gain analysis promising.
- Threads of inquiry: frequency shift vs. non-linear, HEMT vs. HBT, most suitable for SiPmod-SET?

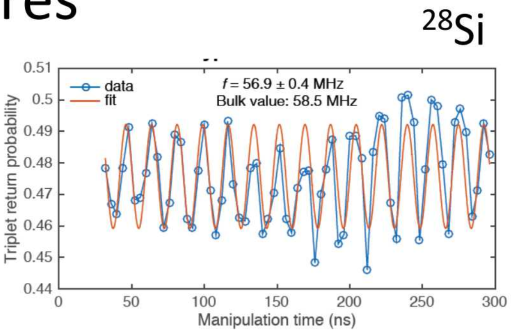
Summary of single donor qubit (ESR/NMR)

- 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

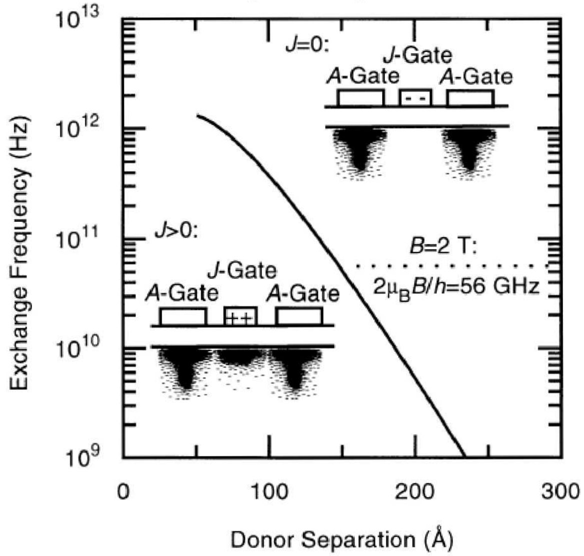
- Motivations
- MOS single donor ESR & NMR qubits
  - Cryoamplification
- Coherent coupling of D-QD – new qubit structures
  - Donor hyperfine driven S/T qubit
    - Coherent donor spin coupling to surface QD
  - Latch read-out for S/T qubits
- MOS QD Design for future D-QD structures
- Summary

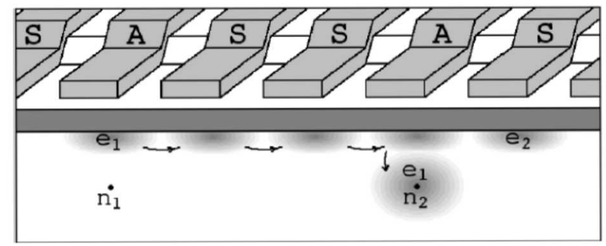




Donor-donor coupling concept

Kane (1998)



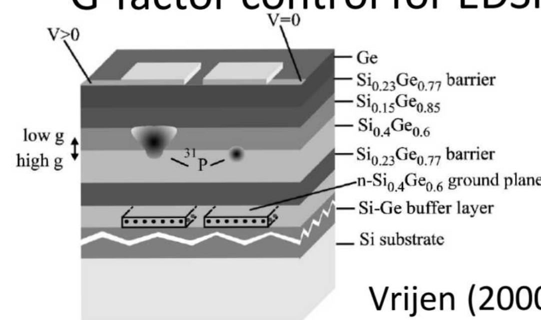


Transport: Skinner & Kane (2003)

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)

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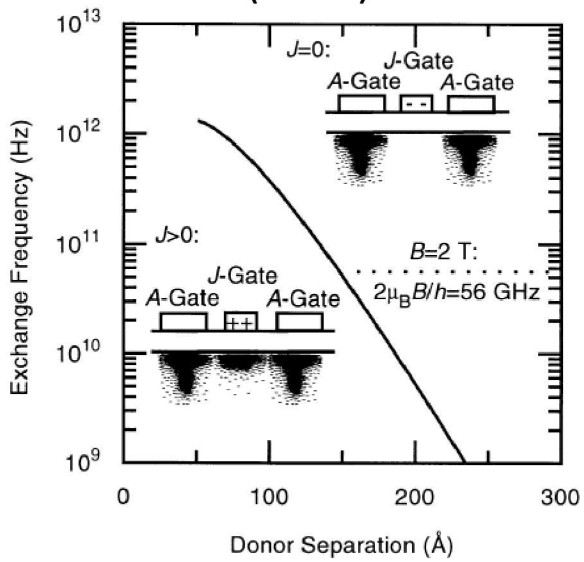

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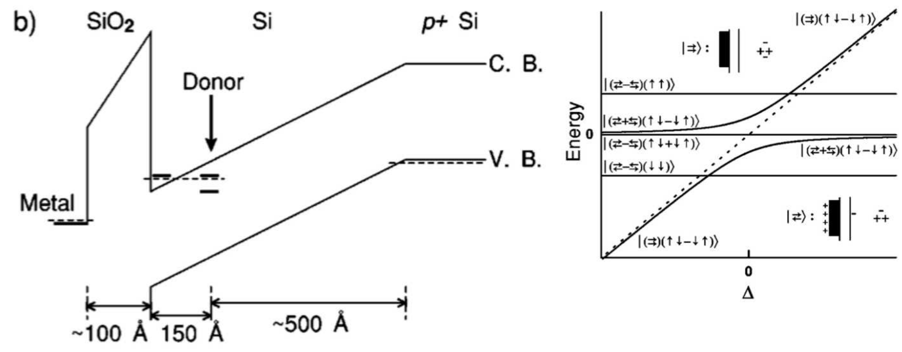

[1] B. E. Kane, N. S. McAlpine, A. S. Dzurak, R. G. Clark, G. J. Milburn, H. B. Sun, and H. Wiseman, Phys. Rev. B 61, 2961 (2000).

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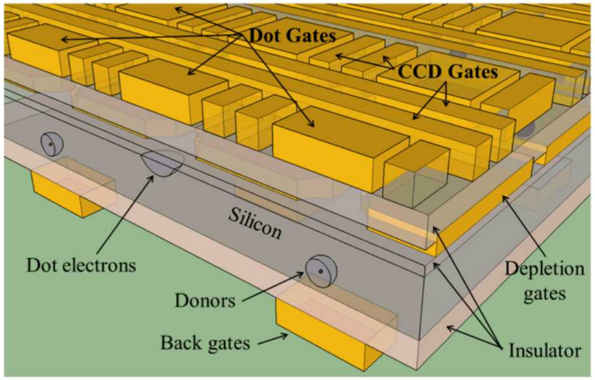
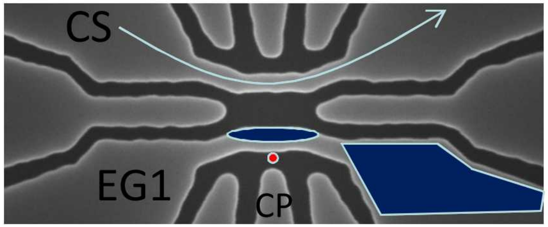
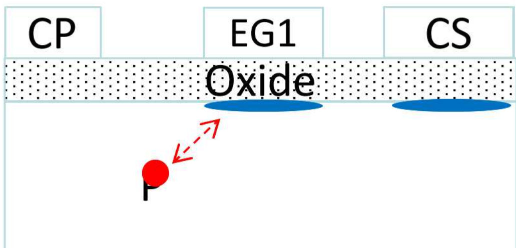


Pica & Lyon (2015)

And others: Vrijen (2000) for EDSR through g-factor modulation

Approach: couple buried donor to surface QD



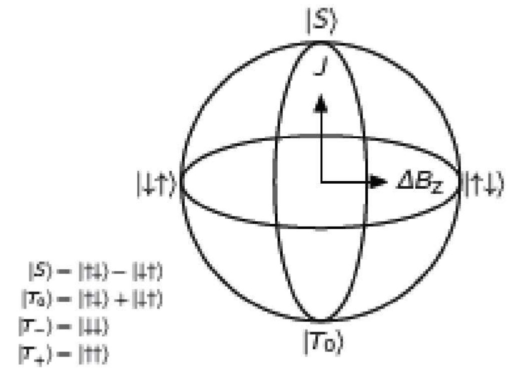


Canonical S/T qubit

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

Donor-QD S/T qubit → $AI \cdot S$

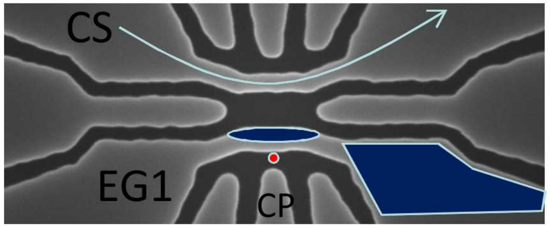
Qubit Bloch Sphere

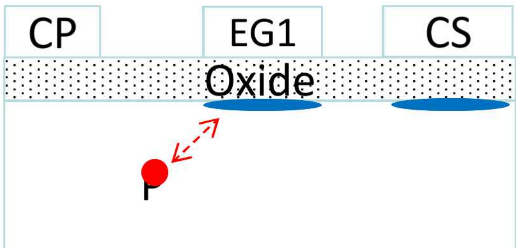


$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z\hat{\sigma}_x$$

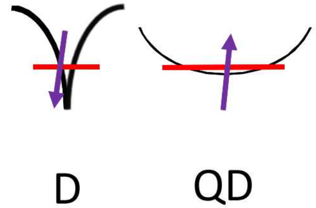
- Encode as singlet-triplet qubit
- Rationale for using this choice as test platform:
  - Platform to examine tuning of the charge & dynamics (e.g., tunnel coupling)
  - Produces an appealing two-axis controlled S/T qubit
  - Rotation frequency is chemically distinct
  - Opens up a potential electrical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

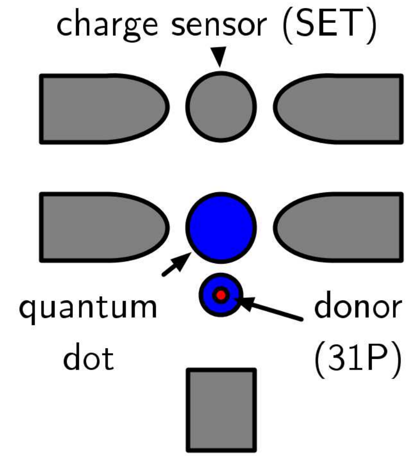
Approach: Couple a N=1 MOS-QD to a Buried Donor





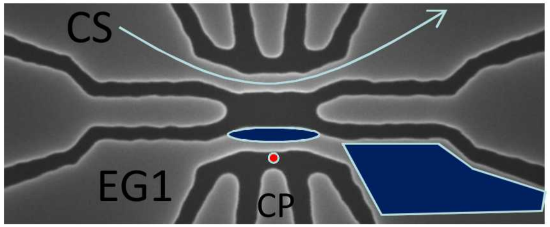
2-spin singlet-triplet qubit

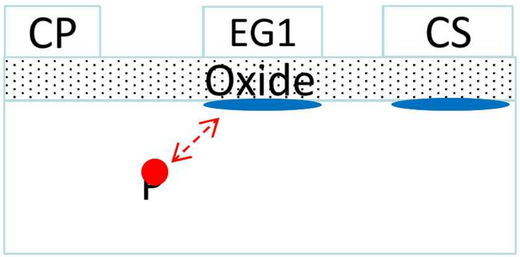




- Extend the single donor qubit lay-out to include a charge sensor
- Charge sensed donor-QD system is now an experimental double quantum dot platform to test the D to surface coupling idea

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





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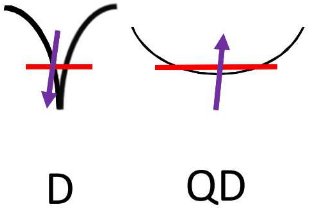

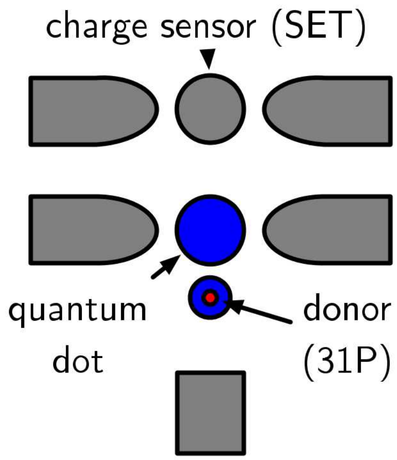

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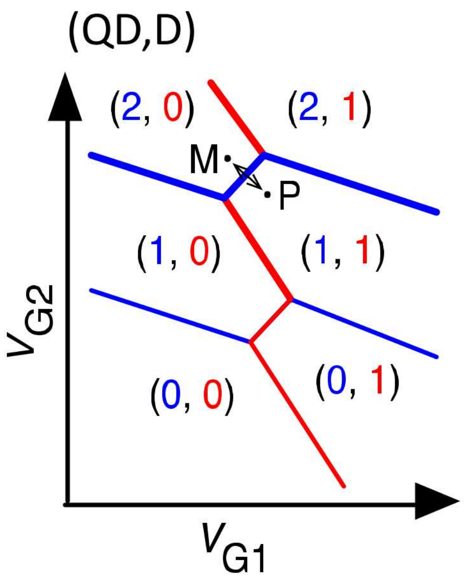
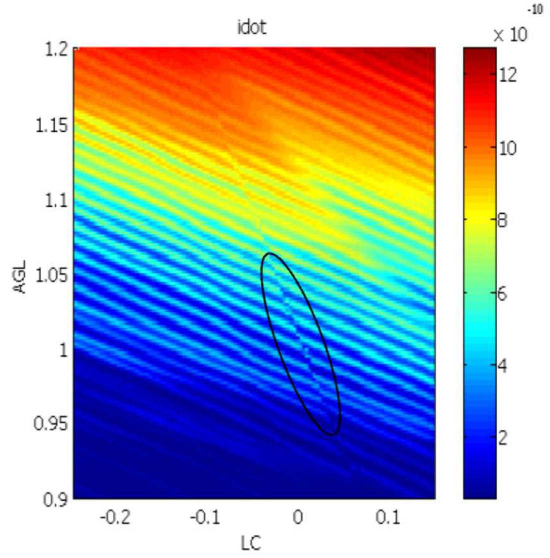
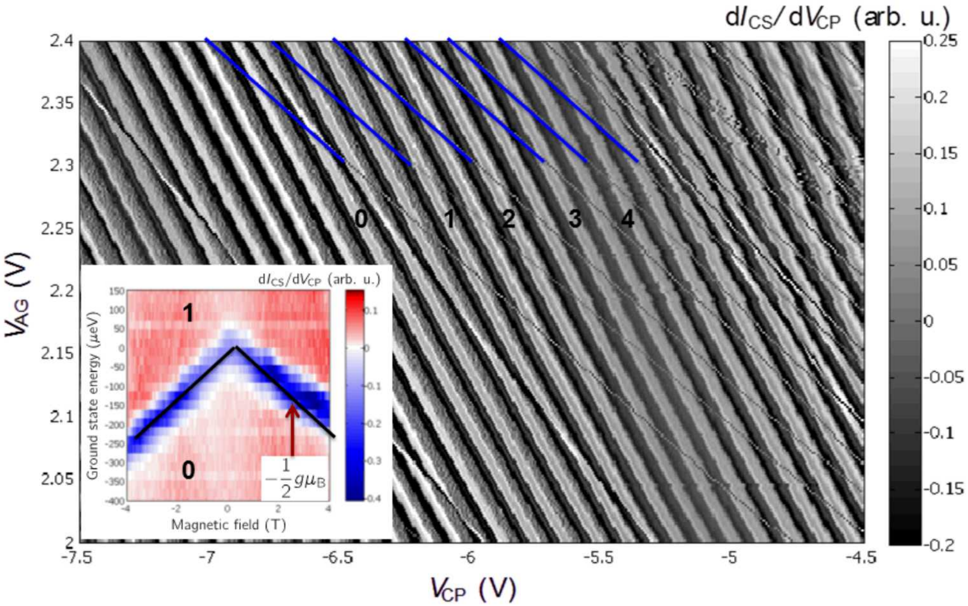
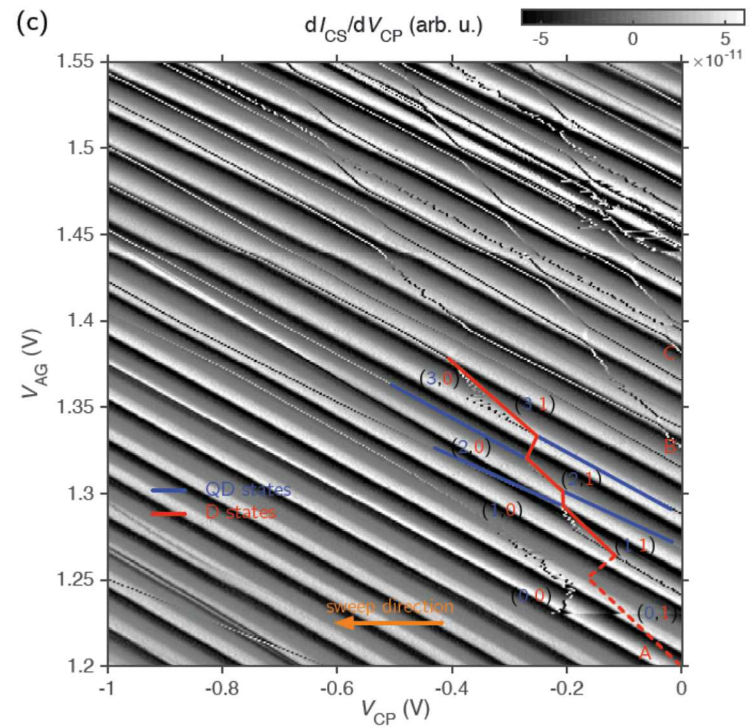


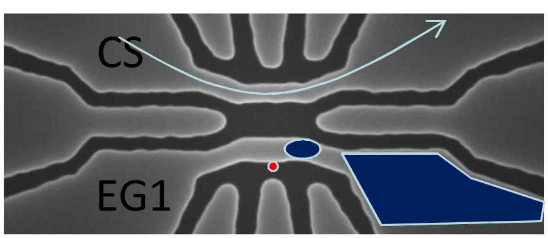


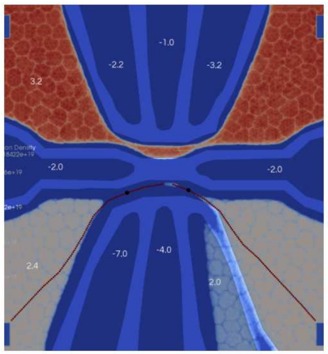
Device tuning to donor crossing at N=1





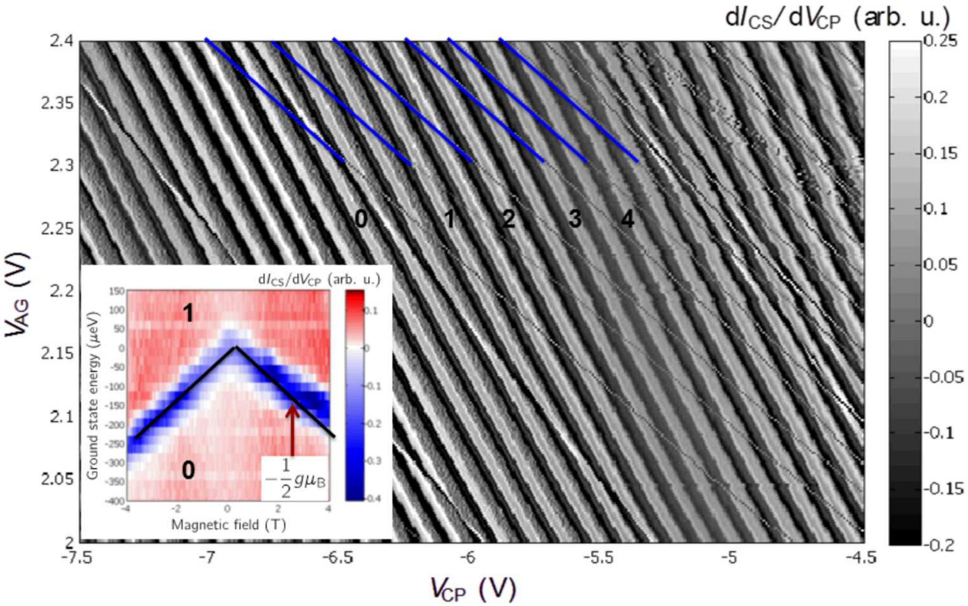
- Device can be tuned over wide range
- This allows donor crossings to be identified at N=1
- Magnetospectroscopy used to check for singlet to triplet like transition

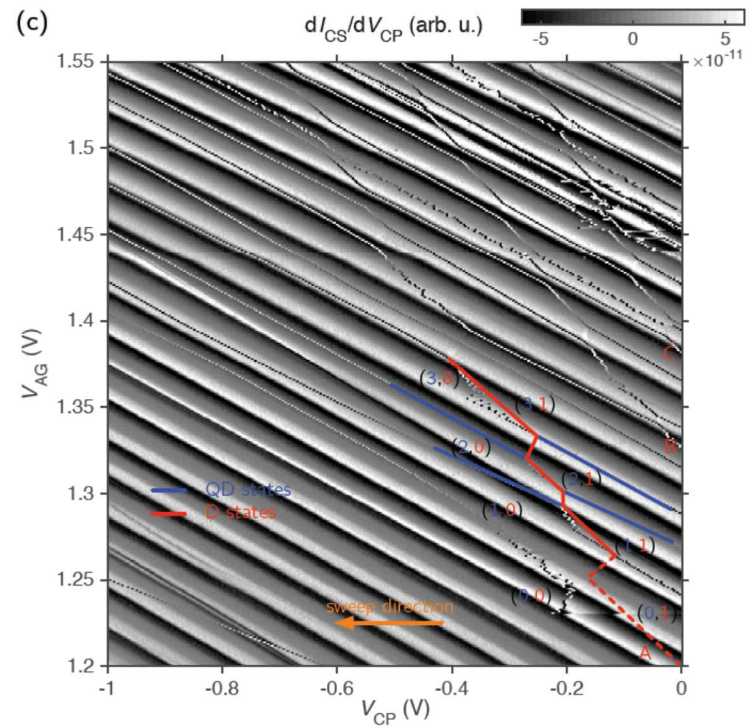




Harvey-Collard

Device tuning to donor crossing at N=1





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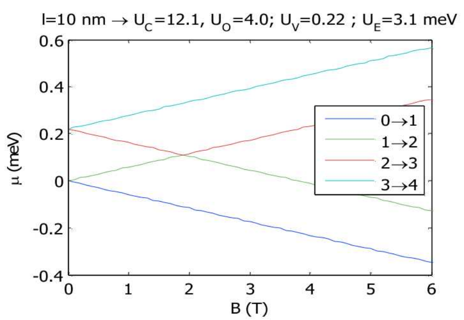
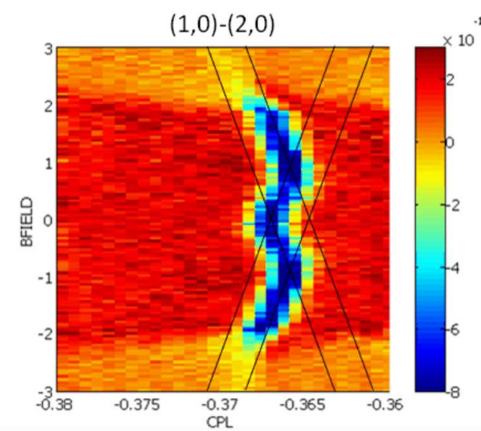
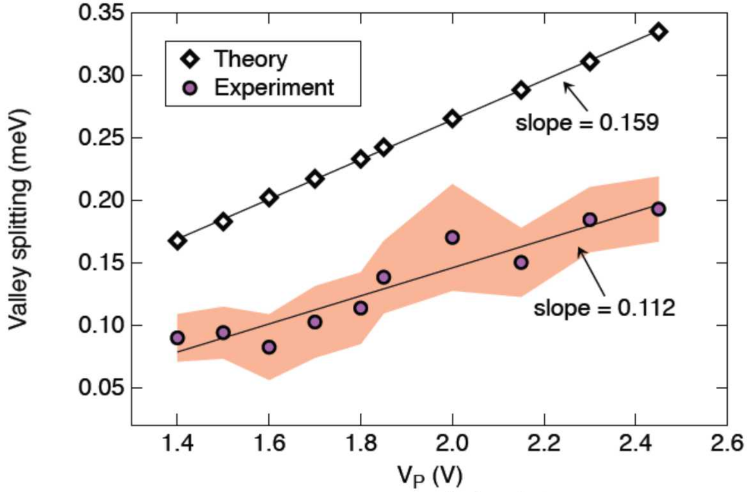
Illustrative example

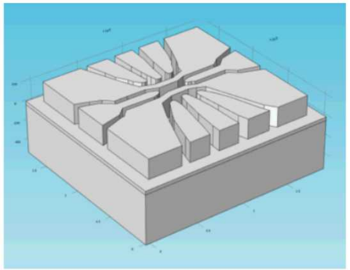


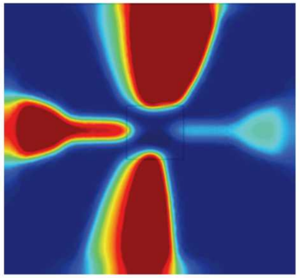


Valley splitting in MOS QD



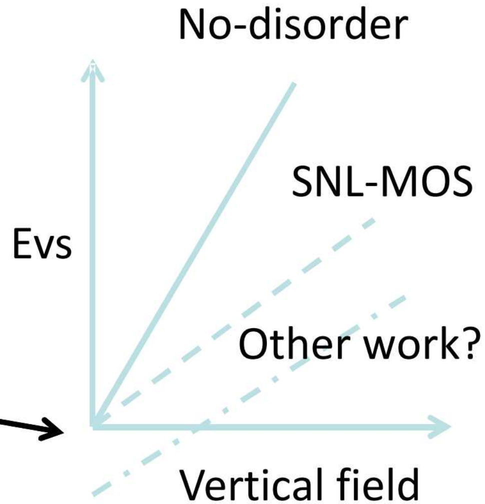
Vertical field





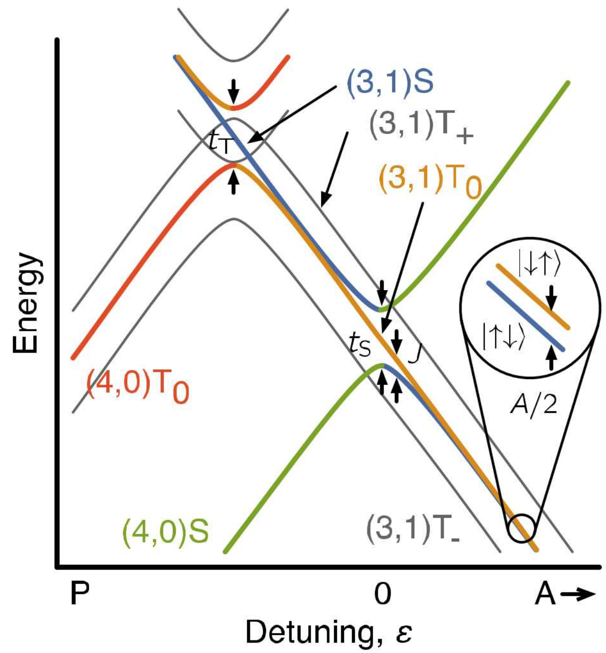
Full 3D calculations to extract vertical field and predicted valley splitting

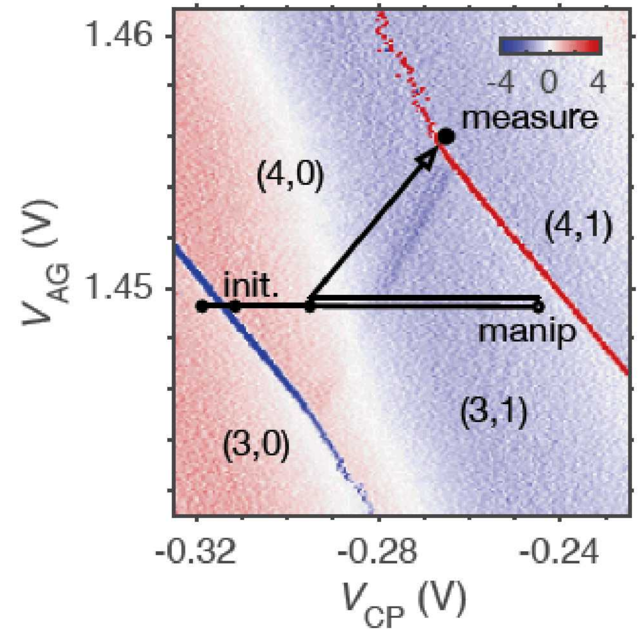
- The valley splitting is measured using pulsed spectroscopy
    - Measured in multiple MOS QDs with comparable results
- Valley splitting was measured over large range of voltages (i.e., -8 < CP <0)
- Barrier tuned at each location to enable pulsed spectroscopy
- Evs theoretically predicted to go to zero at zero vertical field
- Disagreement between ideal interface model & experiment is being investigated (e.g., disorder, accuracy of threshold, …)



Gamble et al. in preparation

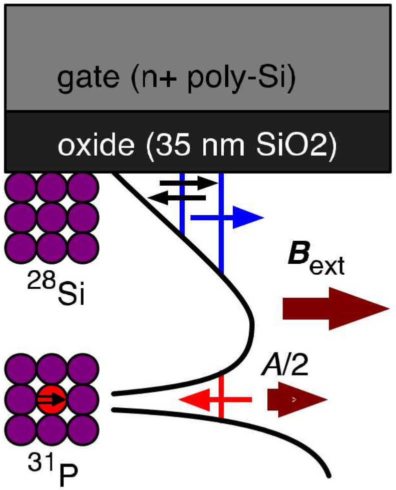
Steps towards coherent control



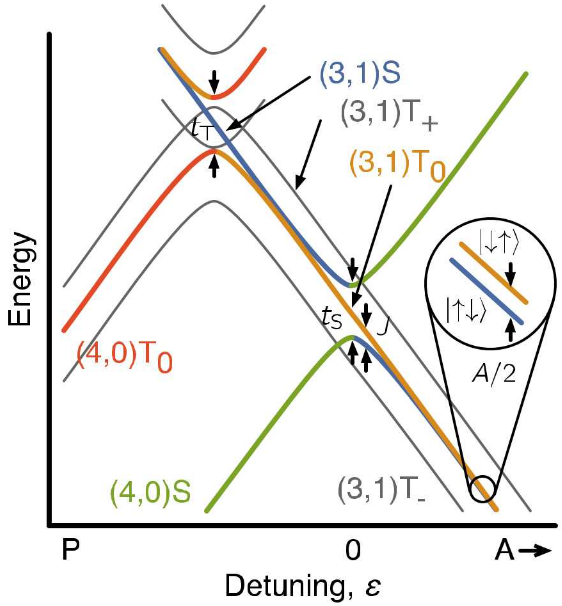


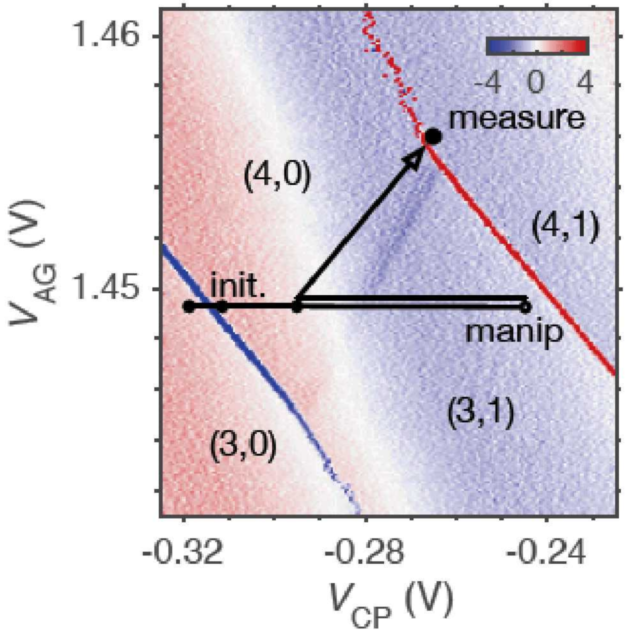
Approach

- 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



Steps towards coherent control





Approach

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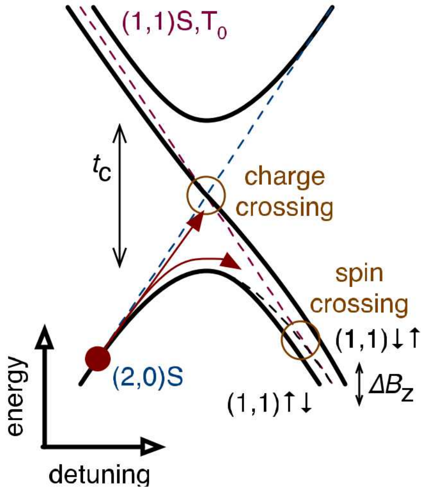
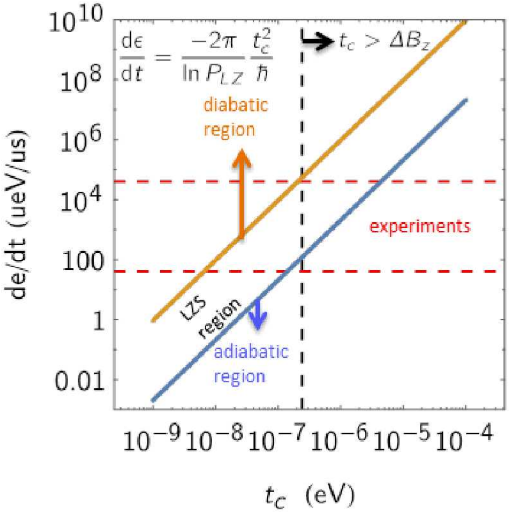
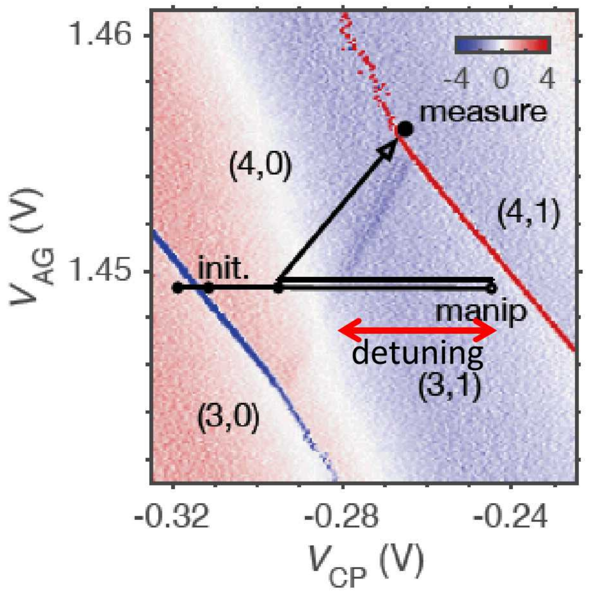
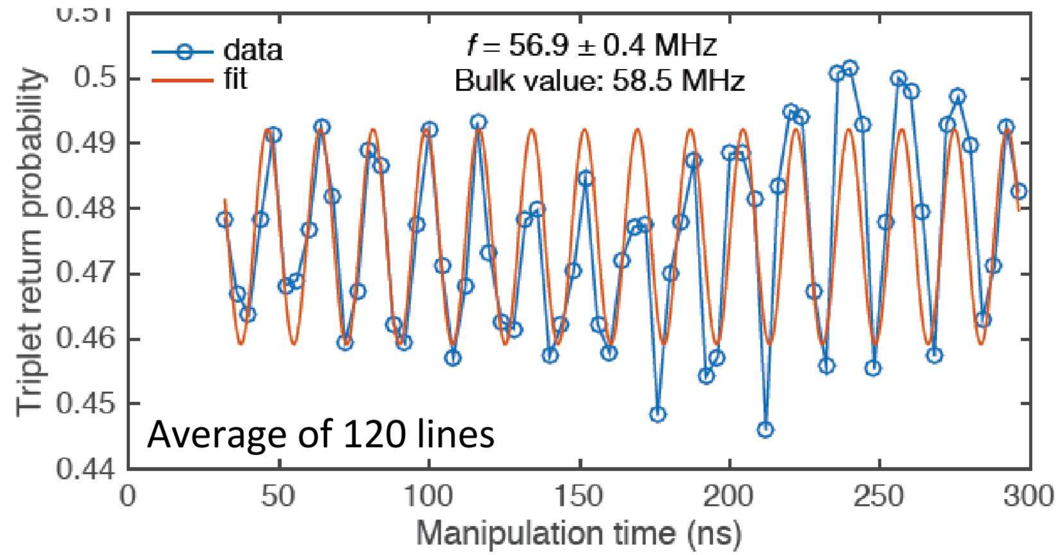


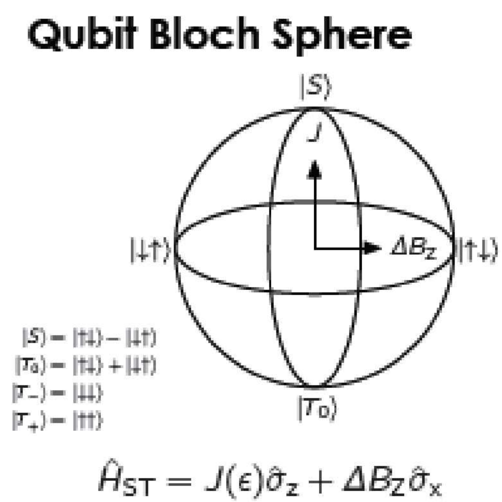


Pulse sequence & singlet-triplet rotations





- 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
  - Closer to measured single donors in ESR case
- Frequency is detuning dependent – J changes
- T2* order of 1 us from coarse measures at longer times and different detunings



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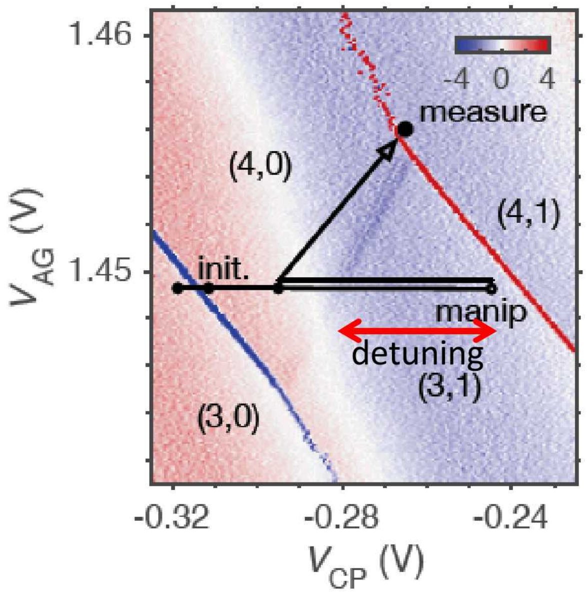

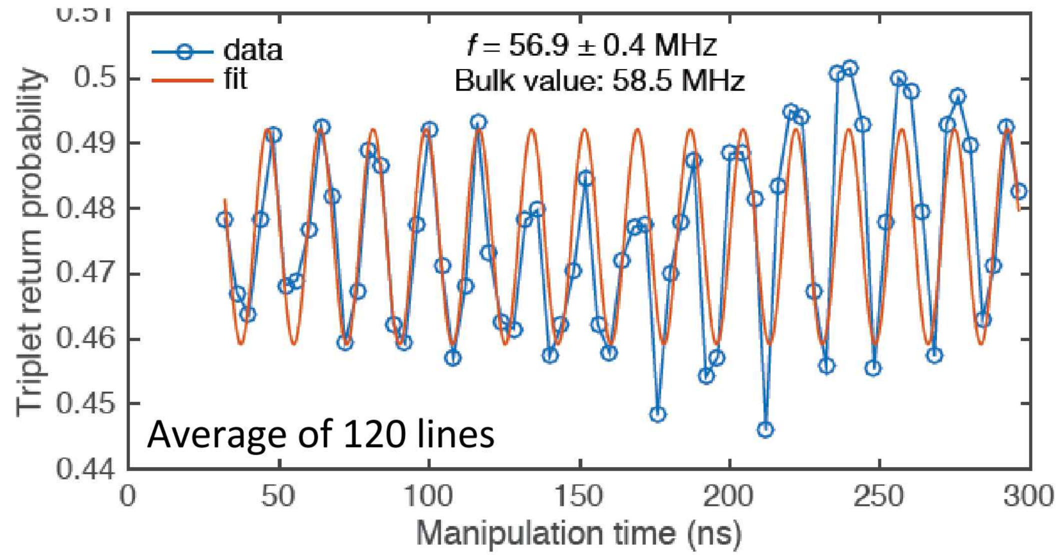

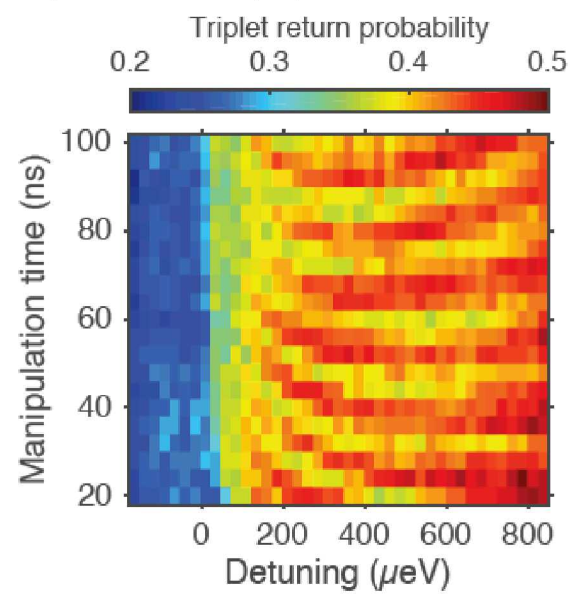

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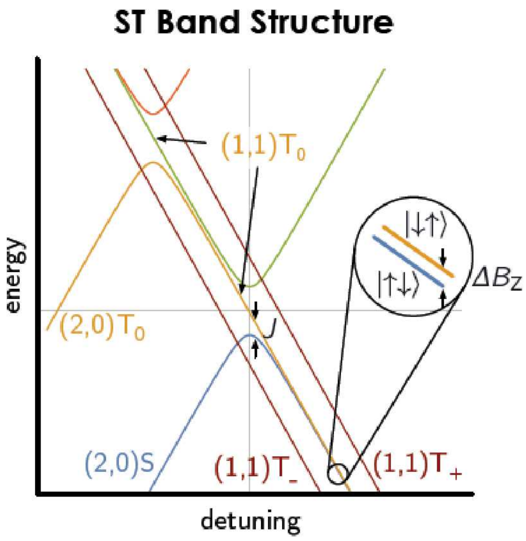
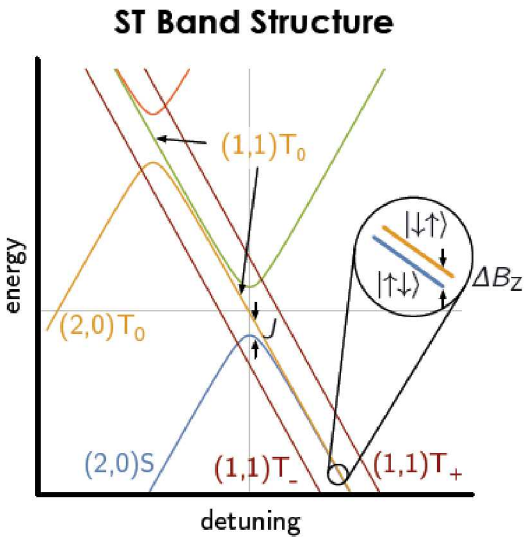
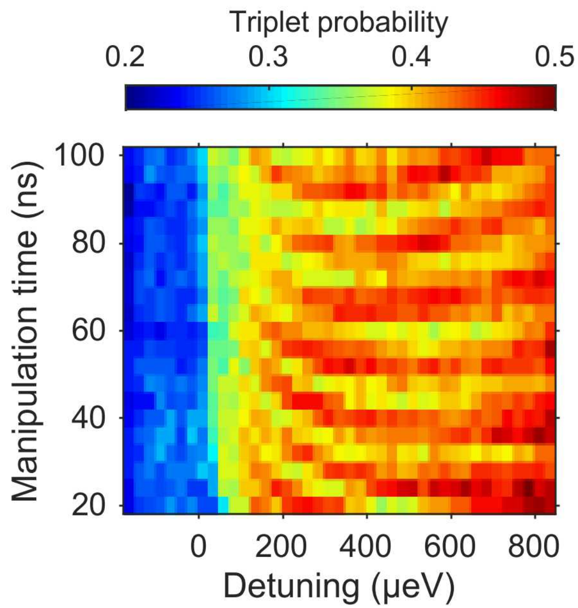
Comparison to numerical simulation

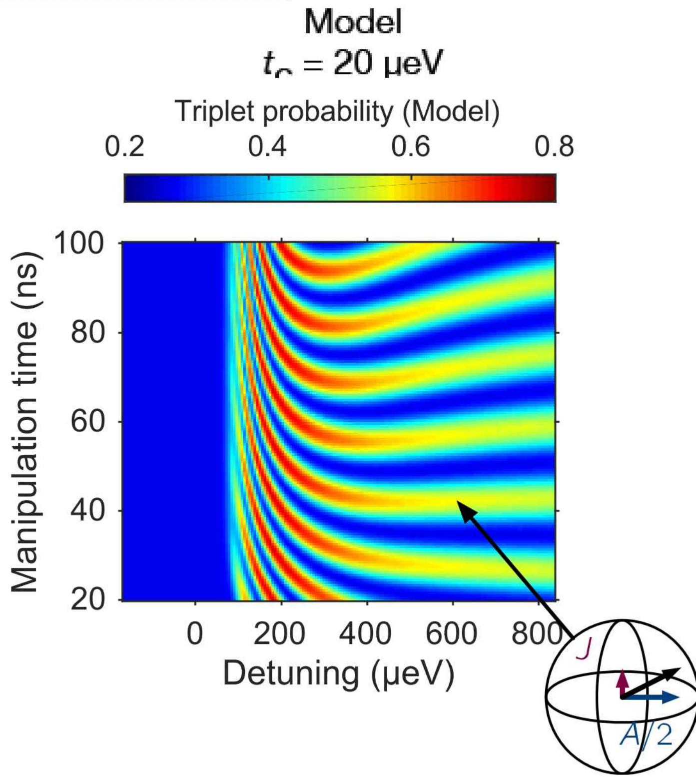


- Phenomenlogical Hamiltonian solved for relevant detuning range
- Dynamics of master equation solved using Lindblad formalism (A assumed, tunnel coupling is fit)
- A number of similar qualitative and quantitative behaviors are exhibited
  - Singlet state is preserved until it is moved to the (1,1) charge 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

Comparison to numerical simulation







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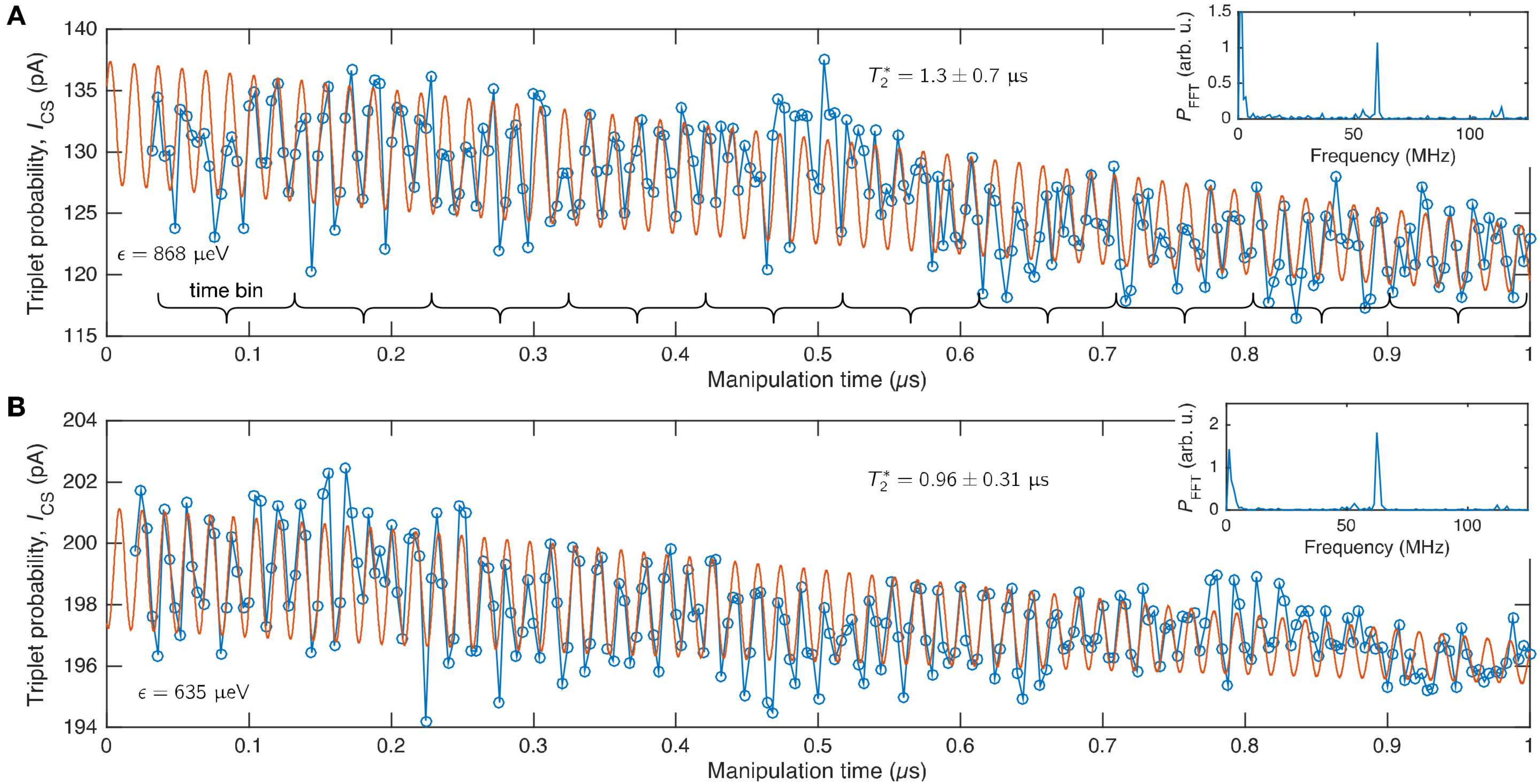
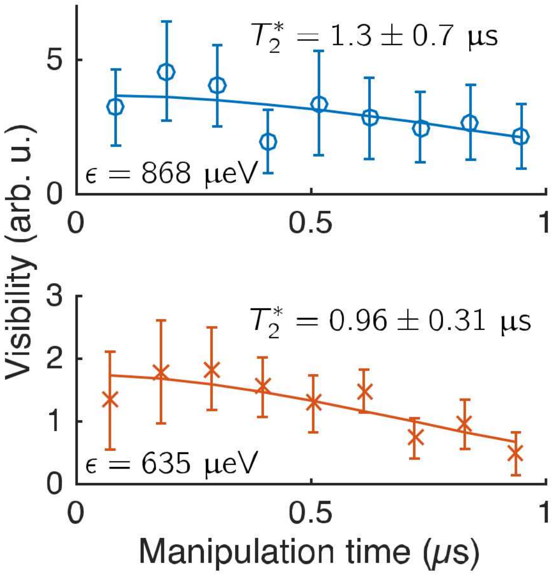
Extended time trace & coarse T2* estimate



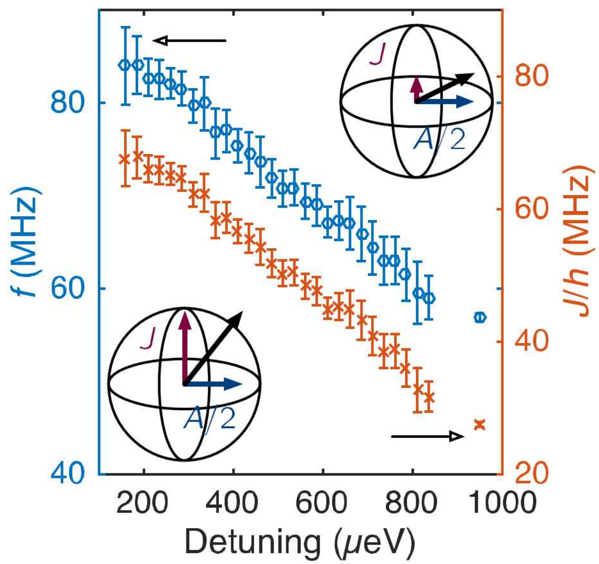
- Long time trace. Average of 10 lines
- T2* order of 1-2 us
- Detuning dependent
- Width of frequency is less than 1 MHz (enriched Si)

Exchange extraction & charge noise model

Visibility decay

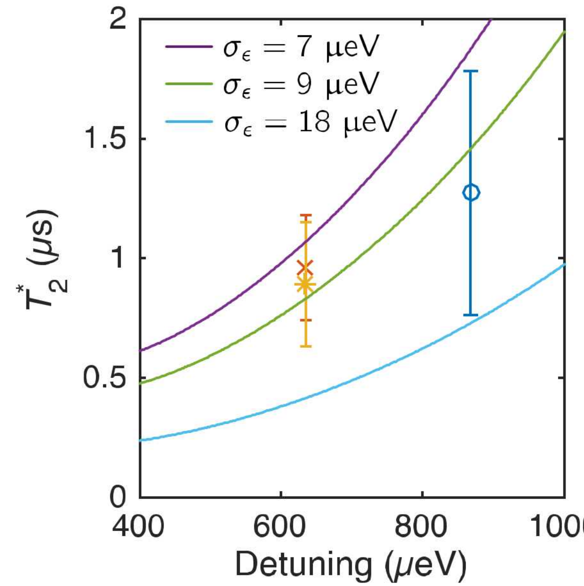


J extraction



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

Charge noise model



Charge-noise limited.
Possibly extended to > 10 µs

Summary of few electron D-QD & MAJIQ

- Few electron QD regime identified and QD brought in to resonance with donors
- Singlet-triplet spin filling behavior identified using magnetospectroscopy

- We see Pauli-blockade signatures at (2,0)-(1,1) and (4,0)-(3,1) however (4,0) is bigger splitting
- Possible full shell argument. Caution: this isn't yet bullet proof.

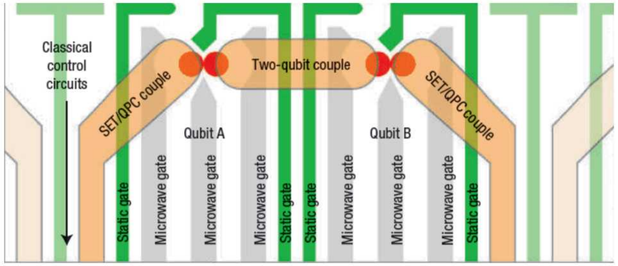
- We can prep singlets preferentially N=2 on QD
- We show coherent rotations between S/T
- The rotations and dependence on detuning are consistent with a phosphorus nuclear spin producing the gradient (f ~ 50 MHz possible)
- The decoherence is consistent with enriched silicon that is limited by charge noise (T2* ~ 1 us)

Future directions:

- Repeat & test tunability of D-QD tunnel coupling
- Full control of qubit space
- Single shot read-out

- NMR
- Capacitive coupling between qubits

S/T qubit (dB for 2nd-axis)

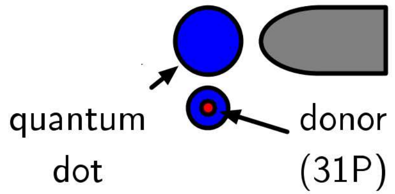


Taylor (2005); Levy (2009); Trifunovic (2013)

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 ⟷

D-QD S/T qubit

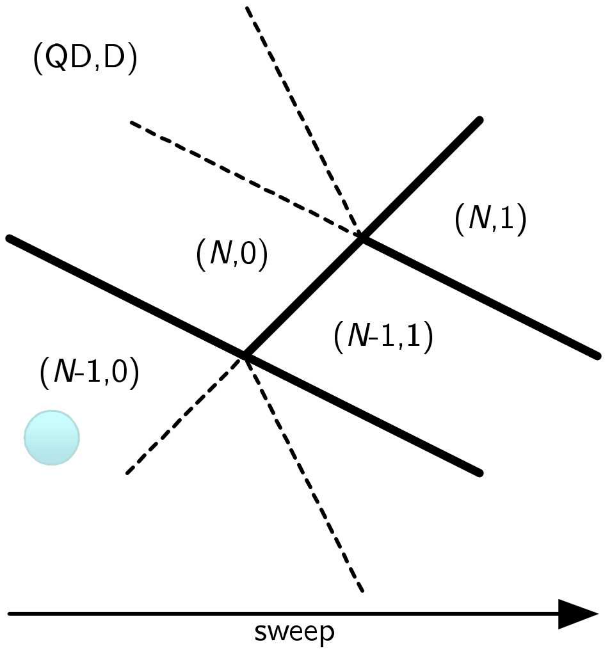


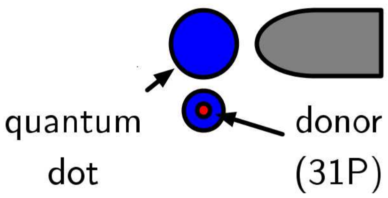
- MOS QD Design for future D-QD structures
- Summary

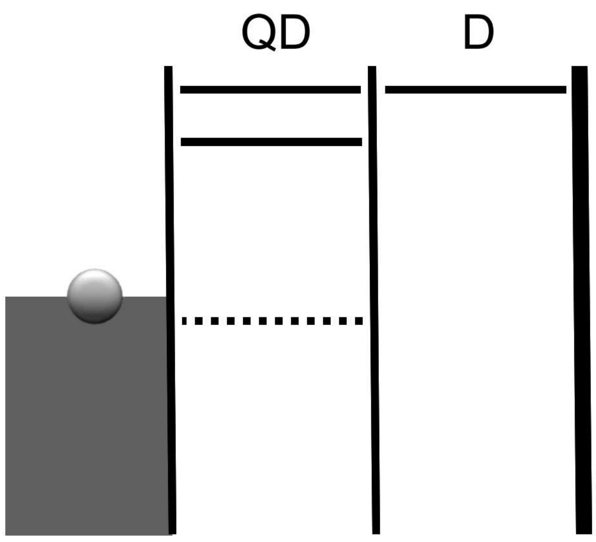
	Signal	time
Std.	0	Short (1-100 μs)
Latch	+1	Long (ms – sec.)

QD-D system has hysteretic charge transitions due to single-sided reservoir

Charge stability diagram

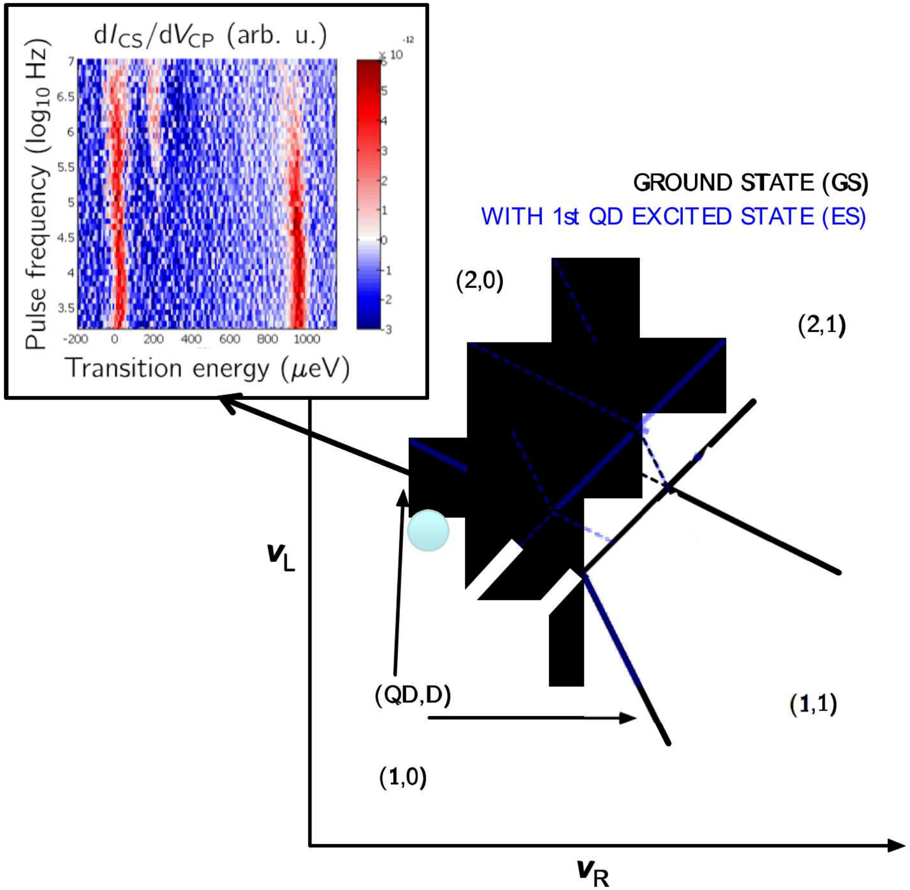


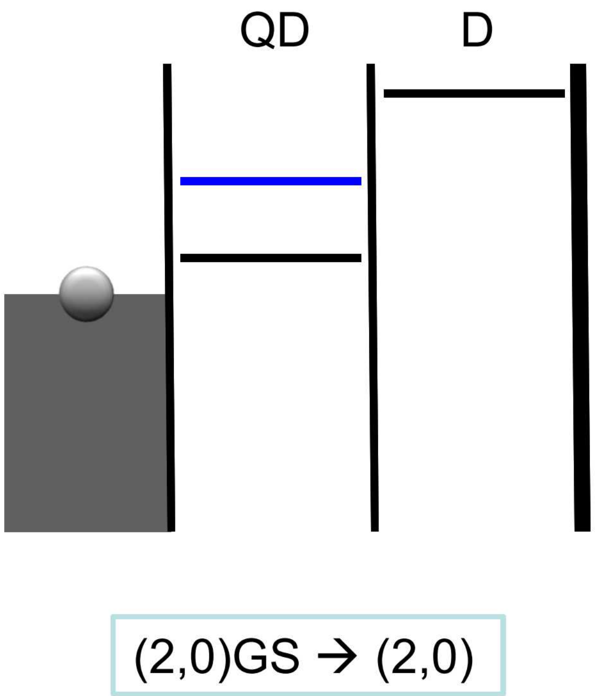




For DQD version: C. H. Yang, A. Rossi, N. S. Lai, R. Leon, W. H. Lim, and A. S. Dzurak, “Charge state hysteresis in semiconductor quantum dots,” Appl. Phys. Lett., vol. 105, p. 183505, 2014.

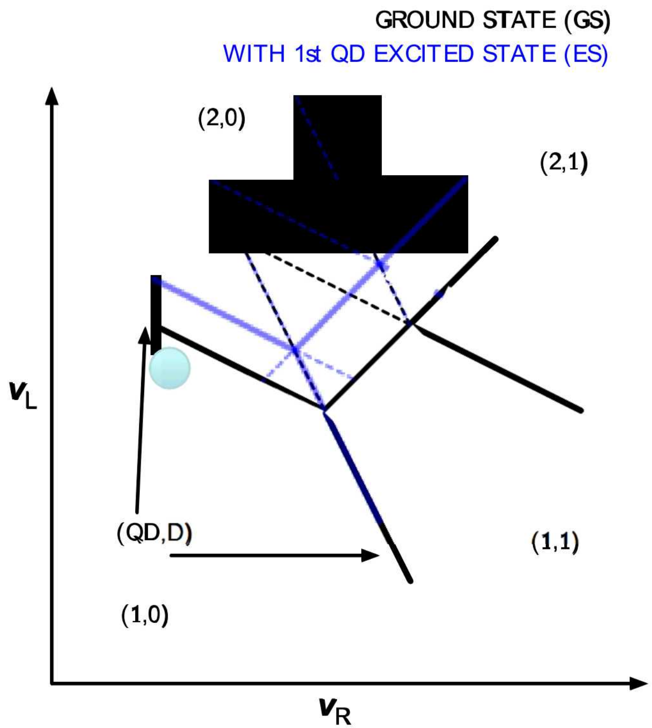
New read-out concept using latching behavior (illustrated)

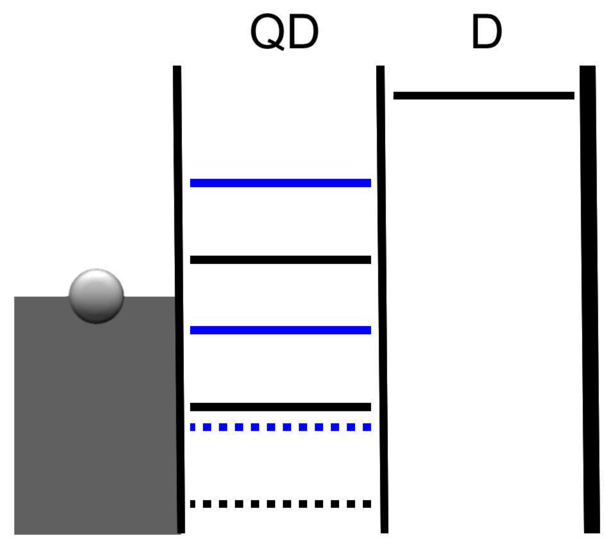




Inspired from: S. A. Studenikin, J. Thorgrimson, G. C. Aers, A. Kam, P. Zawadzki, Z. R. Wasilewski, A. Bogan, and A. S. Sachrajda, “Enhanced charge detection of spin qubit readout via an intermediate state,” Applied Physics Letters 101, 233101 (2012).

Readout concept (illustrated)





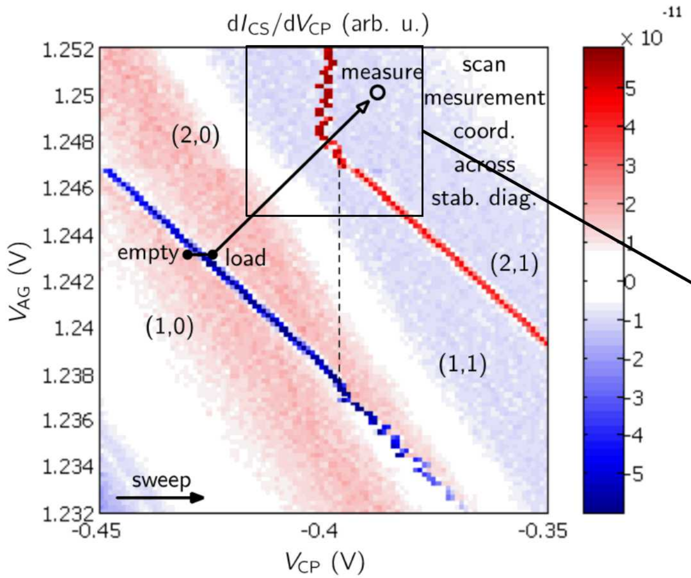
(2,0)ES → (2,1)
(2,0)GS → (2,0)

Excited state is associated with a triplet manifold and consistent with magnetospectroscopy (0.3T)

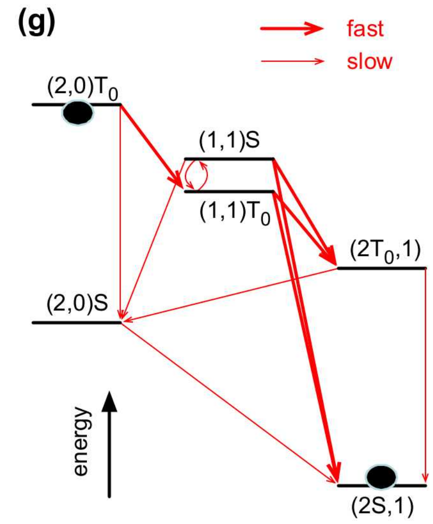
Inspired from: S. A. Studenikin, J. Thorgrimson, G. C. Aers, A. Kam, P. Zawadzki, Z. R. Wasilewski, A. Bogan, and A. S. Sachrajda, “Enhanced charge detection of spin qubit readout via an intermediate state,” Applied Physics Letters 101, 233101 (2012).

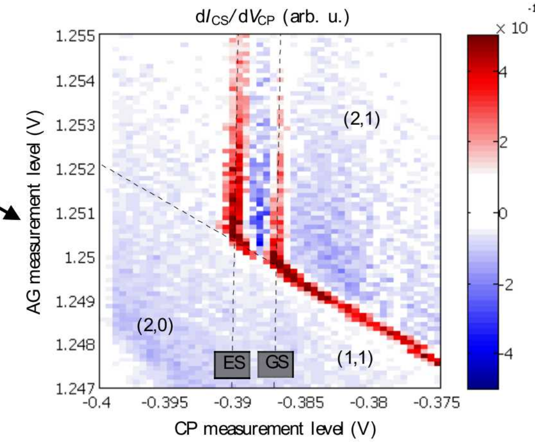
Enhanced hysteretic energy selective readout

Pulse sequence



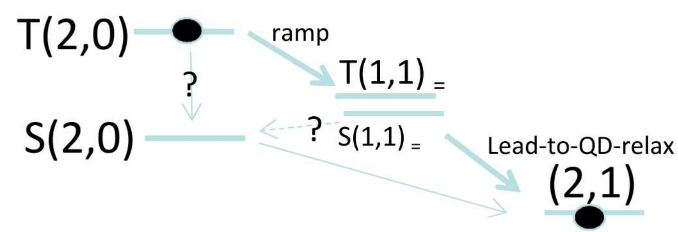
load ES



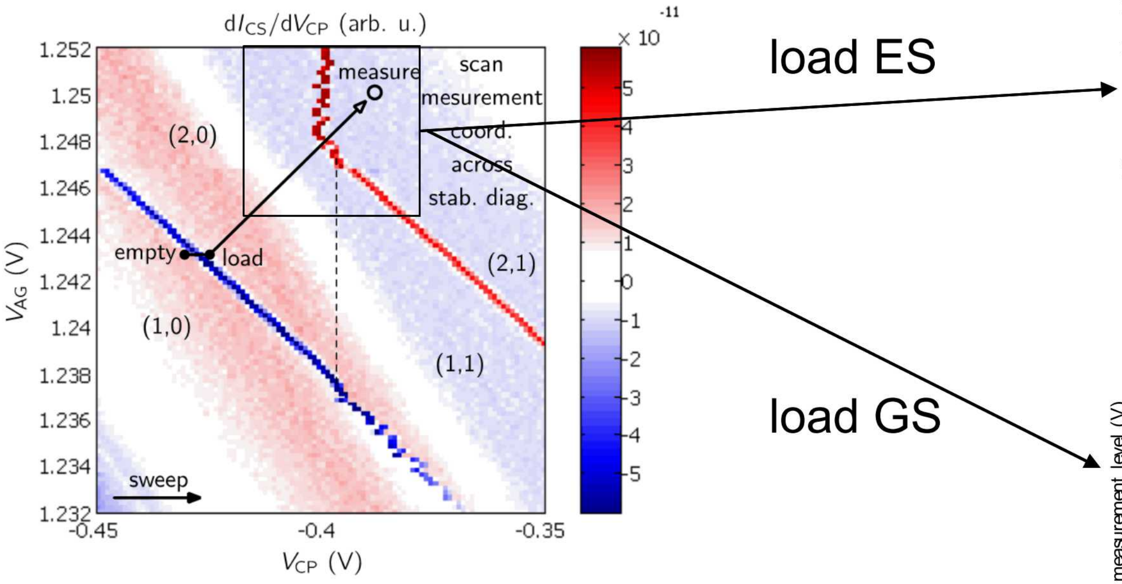


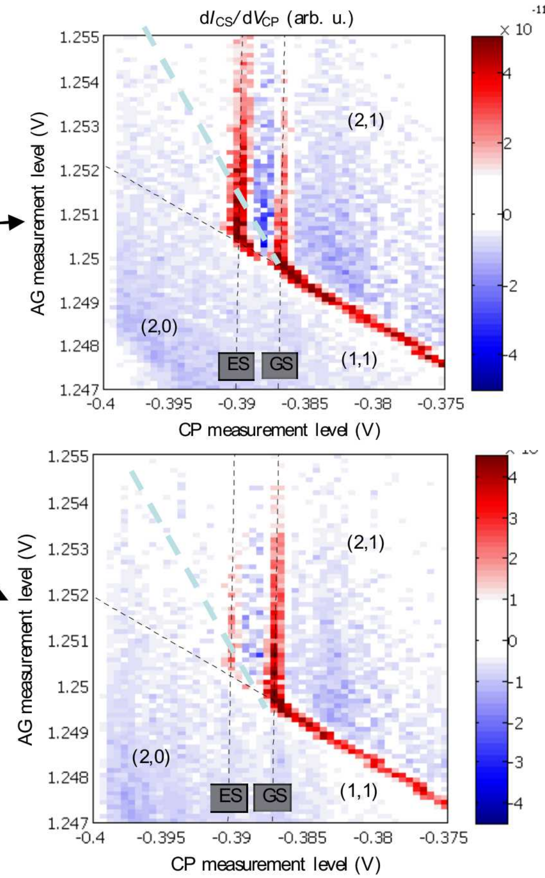
- Readout is based on GS-ES energy splitting (**energy selective**).
- Readout signal is **enhanced** by mapping states with same N_{TOT} to different N_{TOT}.
- Lifetime of readout signal can be extended through the **latching** transition
- Note: empty and load points always the same – signal is for a moving measurement point (new pulse sequence each time)

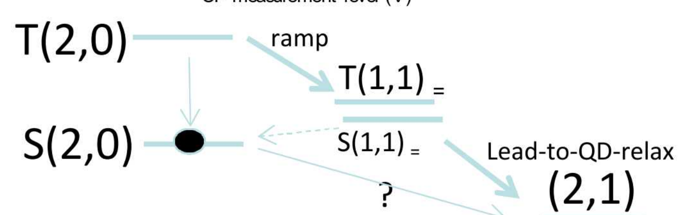
Enhanced hysteretic energy selective readout



Pulse sequence







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Summary of latching read-out

- D-QD system in this lay-out produces hysteretic single lead coupling

- Selective loading of either singlet or triplet can be produced by tuning tunnel coupling to lead and pulsed loading
- The hysteretic behavior can be used to convert an excited triplet in to a latched (2,1) condition
- This approach producing a full charge difference for detection. It also can produce a long lived (2,1) state to detect
    - Long integration time can produce a high SNR for S/T read-out
- This approach might be engineered in other DQDs provided there is sufficient tuning in the coupling to the leads

- Acknowledgement: B. D'Anjou & B. Coish for supporting calculations

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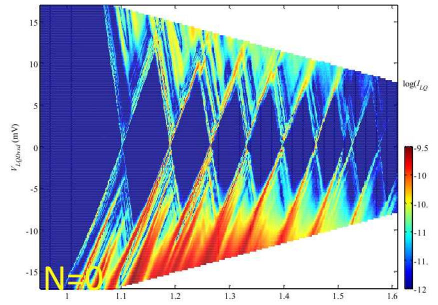
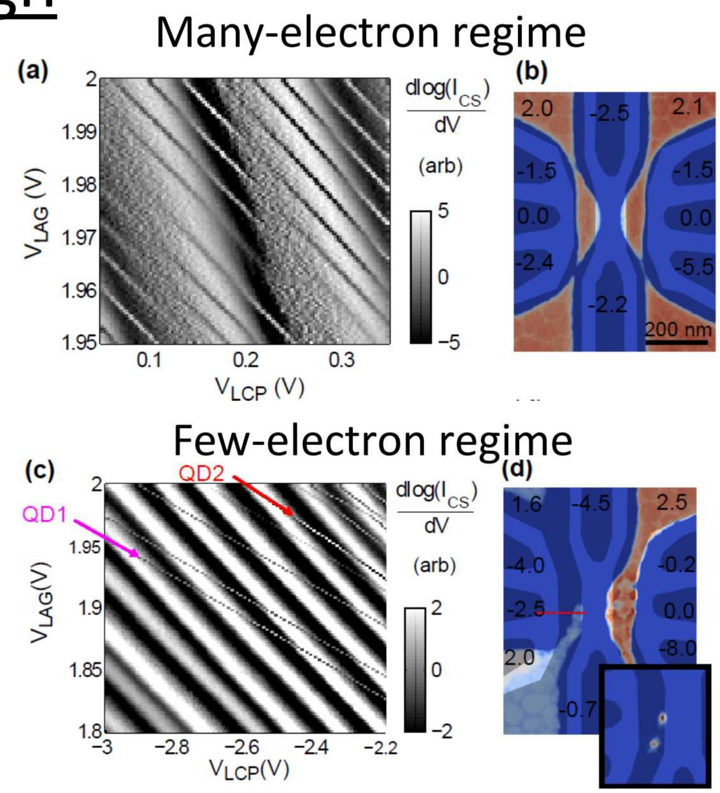
  - Latch read-out for S/T qubits
- **MOS QD Design for future D-QD structures** ⟷



- 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

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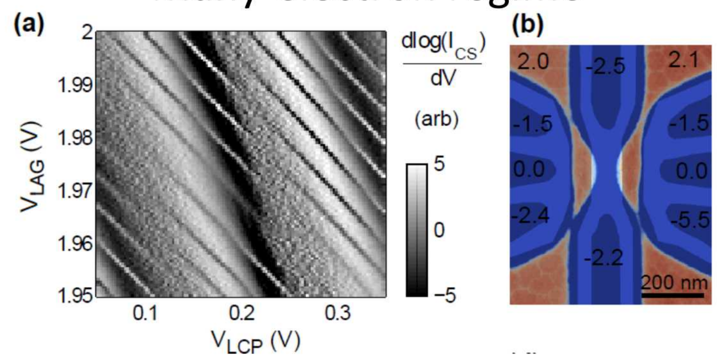
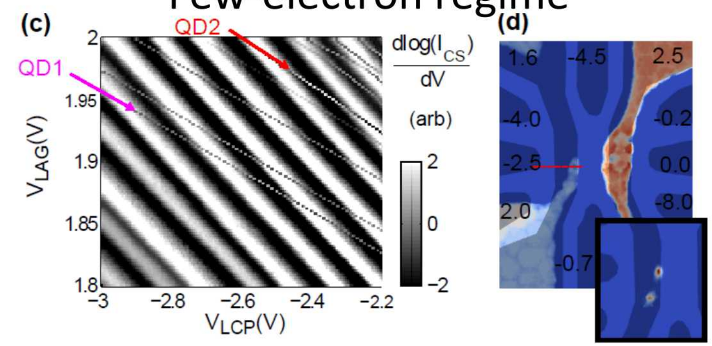
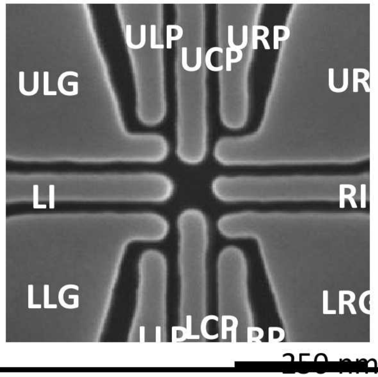
Many-electron regime



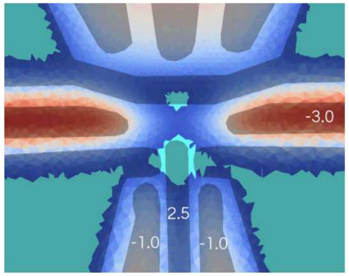
Few-electron regime



SWAG



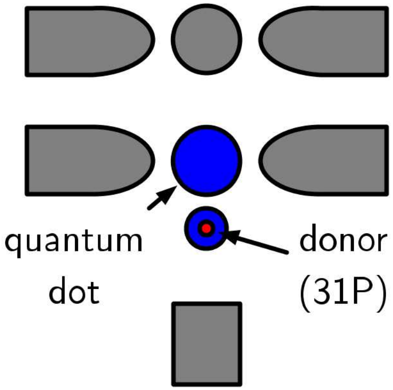
Check for donor transitions

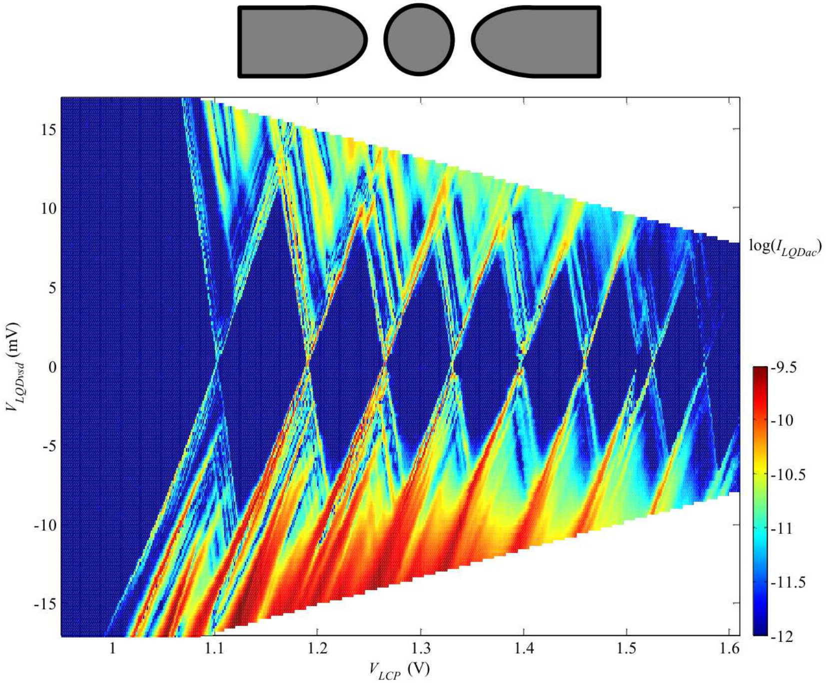


Gamble, Carroll, Curry, Rudolph

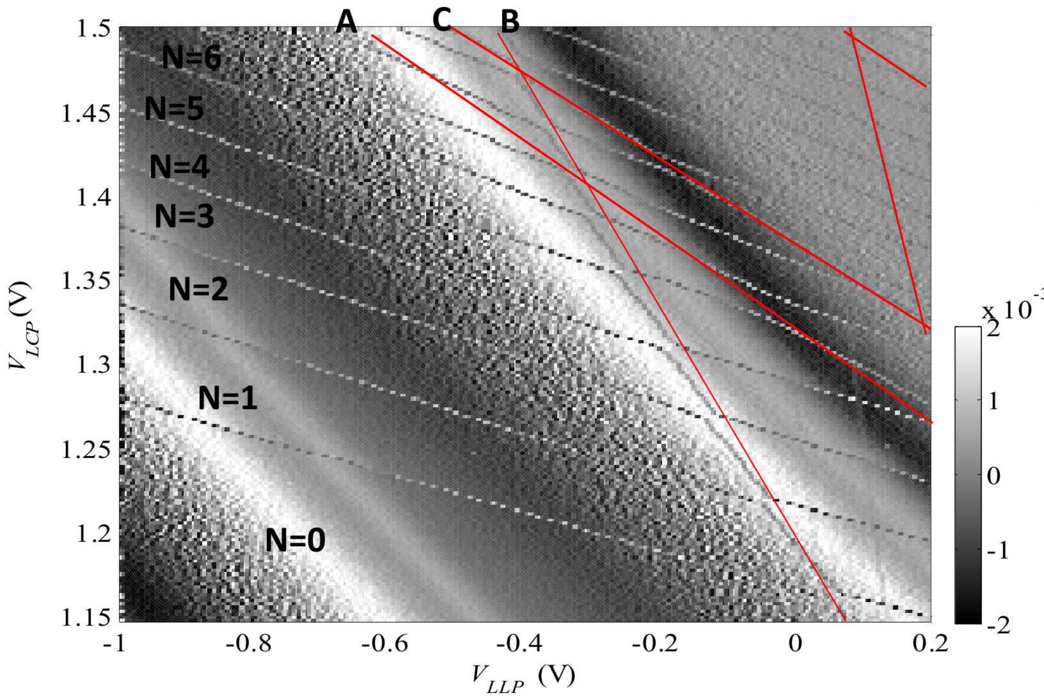
Very good and tunable quantum dots in MOS

- 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?



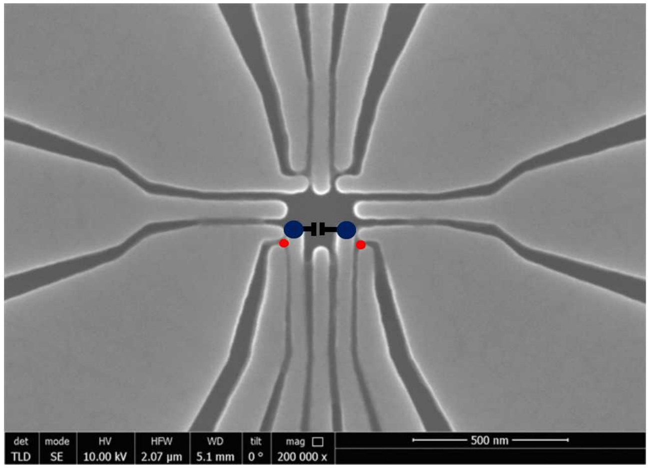


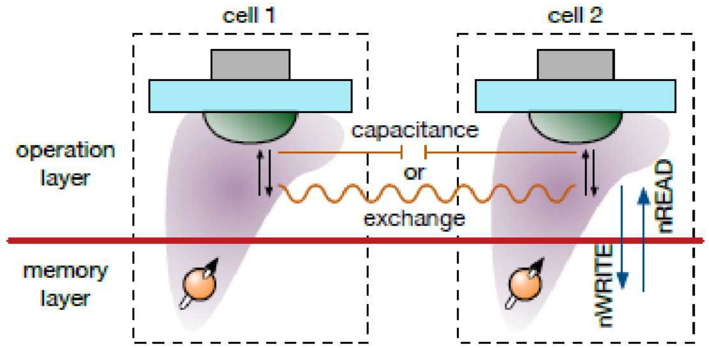
Transport



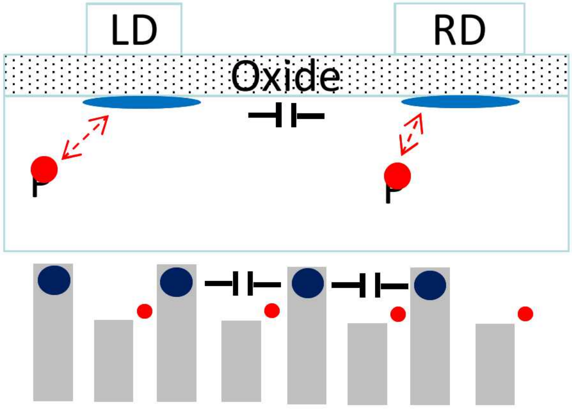
Rudolph

Possible future lay-outs for MAJIQ

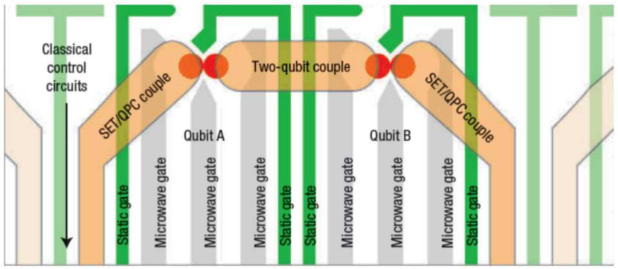




Capacitance coupling of MAJIQ-SWAG



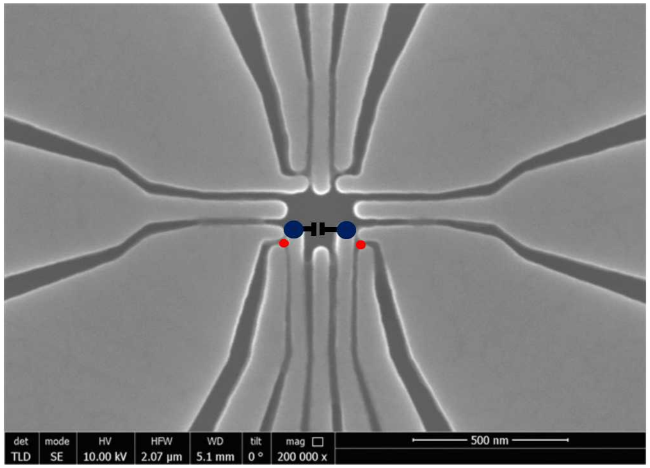
Simplified lay-out from old Taylor proposal



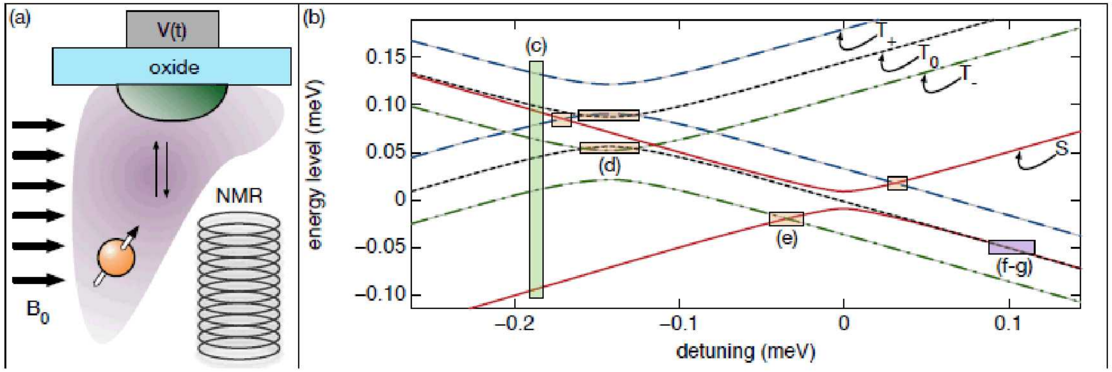
Taylor (2005); Levy (2009); Trifunovic (2013)

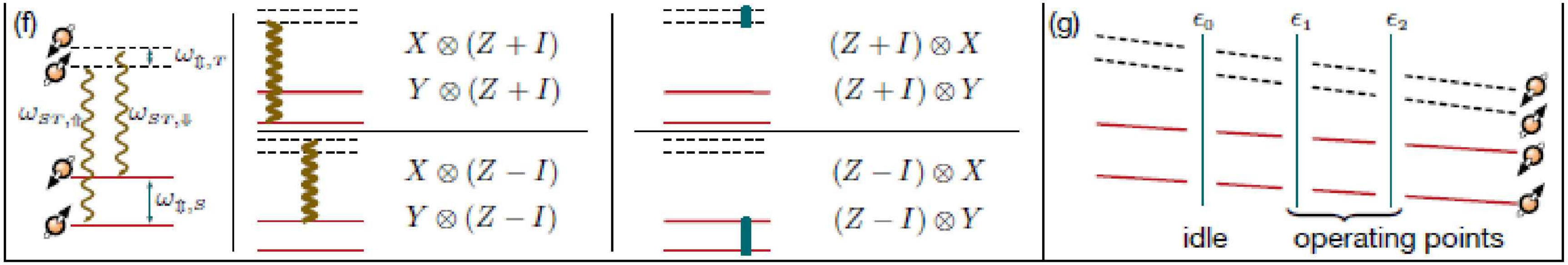
- Capacitance coupling by proximity for two qubit gate
- Approach would use resonant voltage drive and energy selection for each qubit location
- Might use nuclear spin as memory – might use other species for faster ST rotation

Nuclear MAJIQ (nMAJIQ)



Nuclear MAJIQ (nMAJIQ)





Baczewski et al. [SNL in preparation] (2016)

- Motivation: use the high fidelity nuclear spin (i.e., use high fidelity NMR gates as well as memory)
- Use the S/T qubit as short time coupling qubit
- Only tunnel coupling is between D-QD – circumvents disorder between MOS QD tunnel barriers
- NMR coil can be added around sample enclosure – no need for microwave striplines

Summary of SWAG & MAJIQ-SWAG

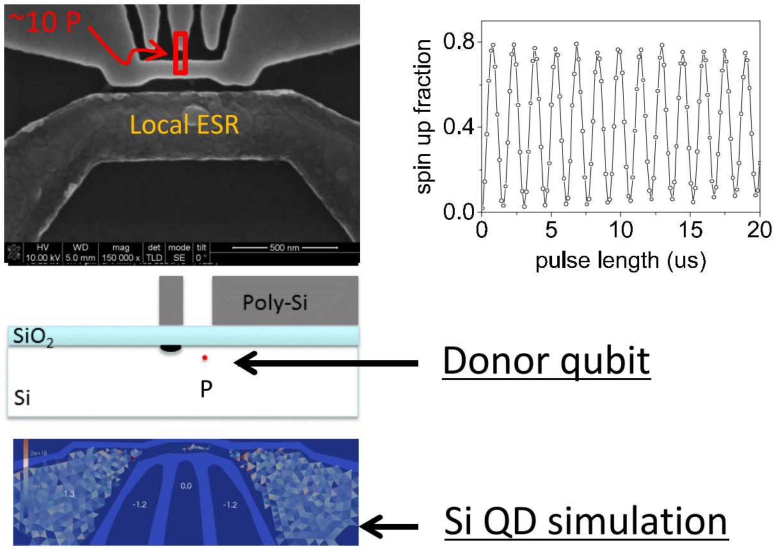
- The gated wire design has important limitations so a new design was developed (separate wire accumulation gate – SWAG)
- Central idea was to move to approach similar to many in the community, separate the reservoir gates. This produces a much more compact device with more tunability down to N=1
- Very 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

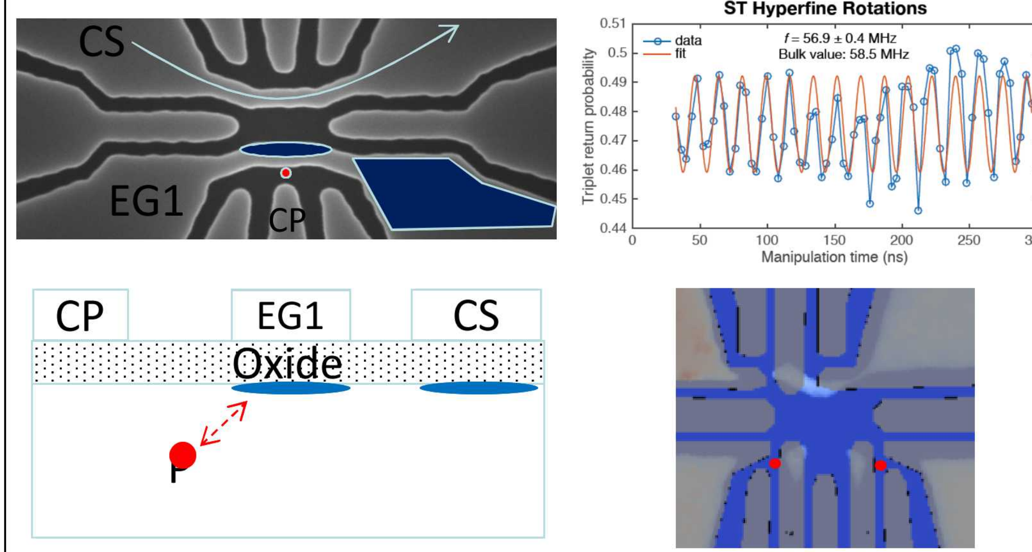
- QIST contributors at SNL
  QD & Timed Implant Qubit Fab: J. Dominguez, R. Manginell, T. Pluym, B. Silva, J. Wendt, S. Wolfley
  Qubit control & measurement: S. Carr, M. Curry, T. England, A. Grine, K. Fortier, R. Lewis, M. Lilly, T.-M. Lu, D. Luhman, J. Rivera, M. Rudolph, P. Sharma, A. Shirkhorshidian, 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

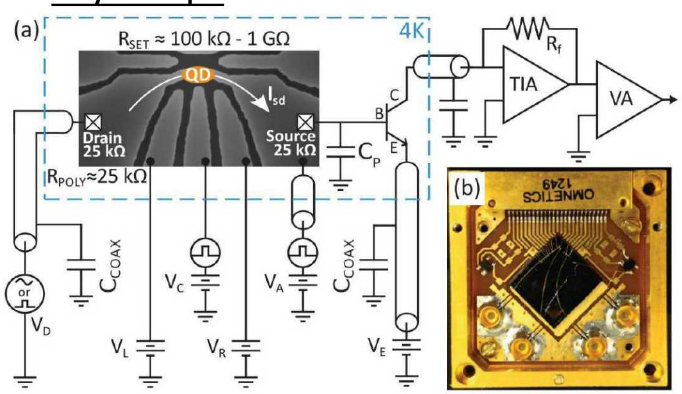
Single spin donor ESR in 28Si



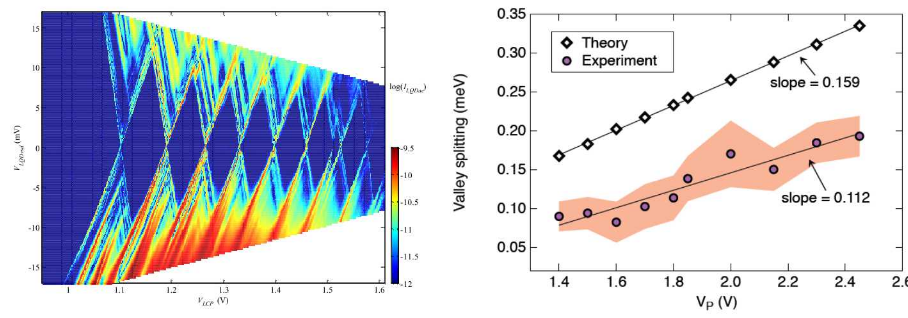
MOS S/T qubit driven by single donor



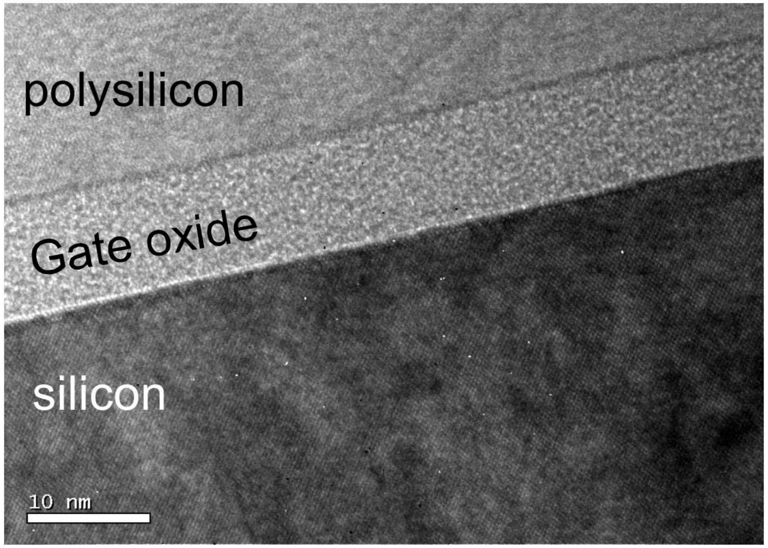
Cryoamps



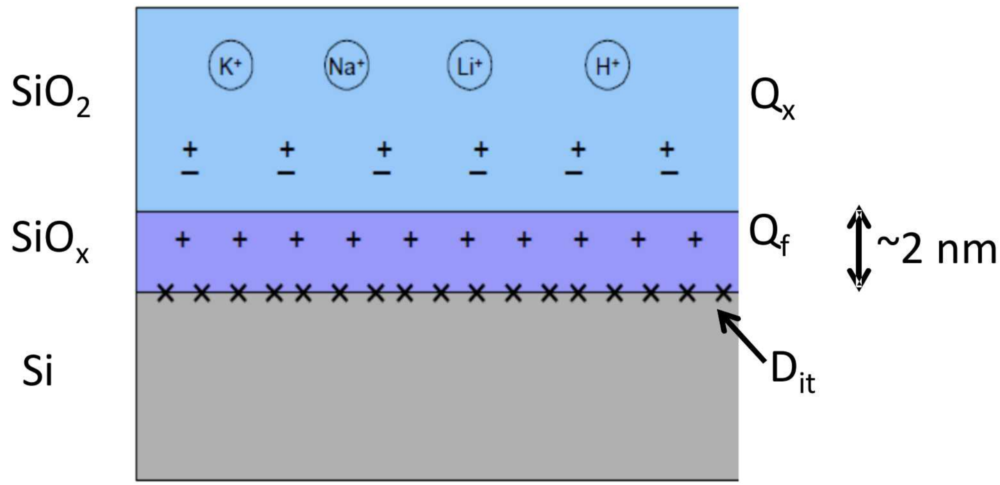
MOS QDs & SWAG



The MOS interface



Defects

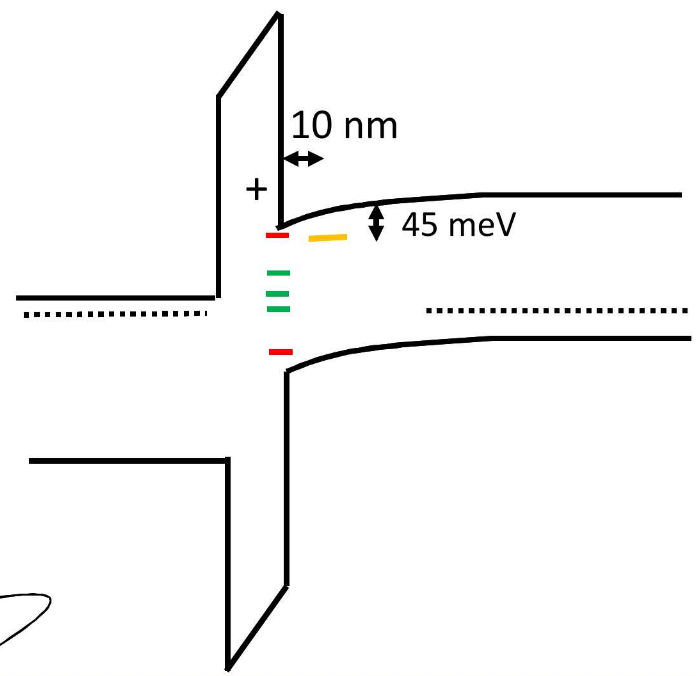


Room temperature picture

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

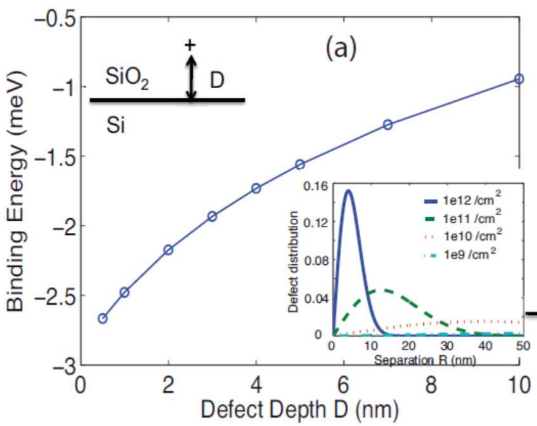
Low temperature picture

- 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
- Paramaganetic effect on decoherence

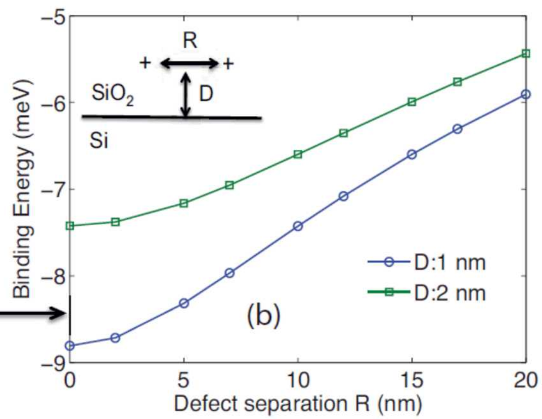


Oxide defects and trapping potentials

Binding E of single charge

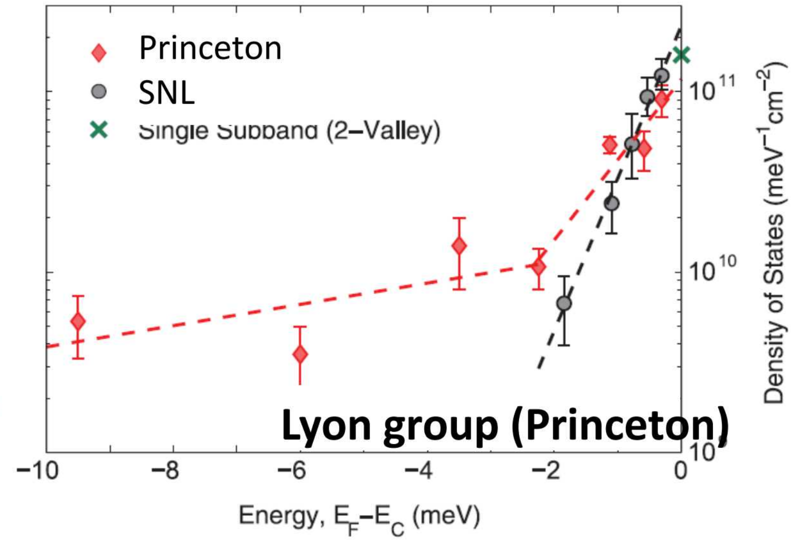


Binding E of two charges



Rahman et al., PRB 85 125423 (2012)

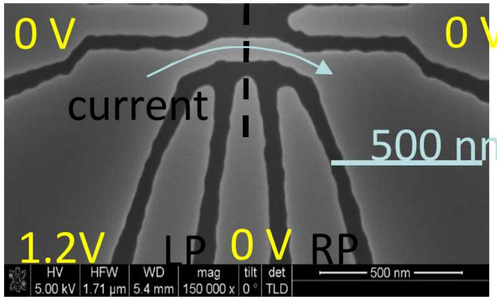
Electron spin resonance (T ~ 4K)

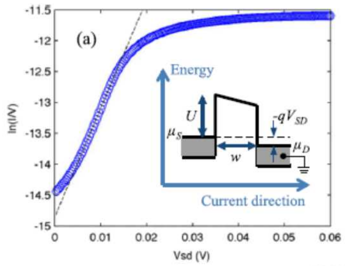


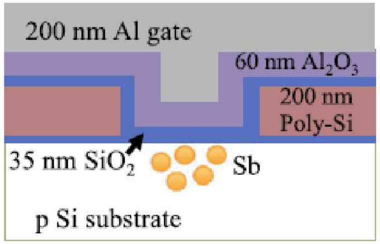
Jock et al., APL 100 023503 (2012)
Rahman et al. PRB 85 125423 (2012) [trap energies]
Pinsook et al., APL (2013) [bandedge DOS]

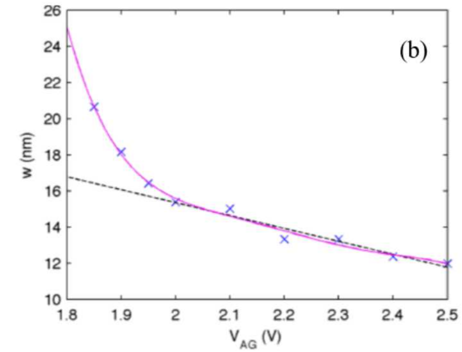
- Fixed charge produces distribution of trapping centers with DOS in energy
- Calculations predict energies similar to what is observed in ESR

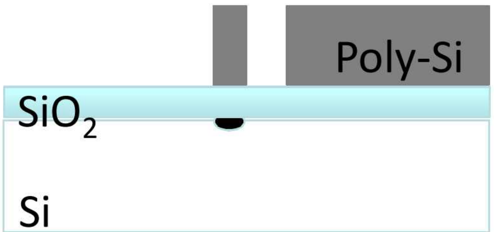
Characterization of tunnel barriers

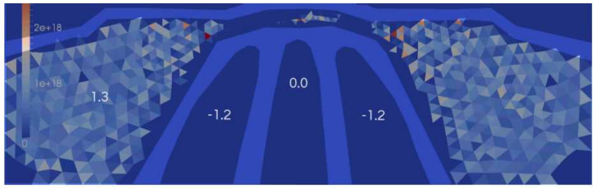


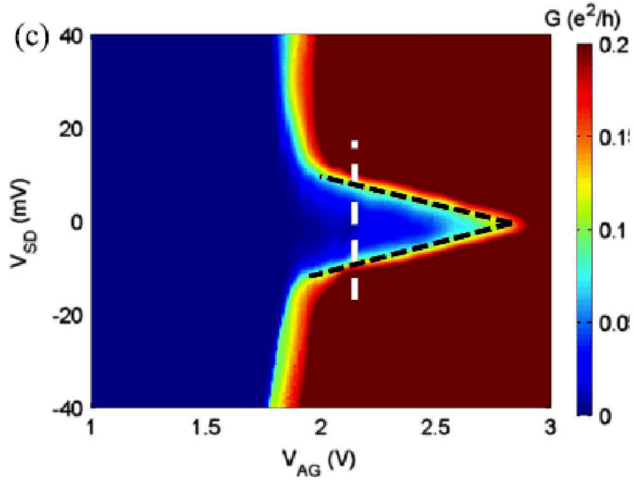


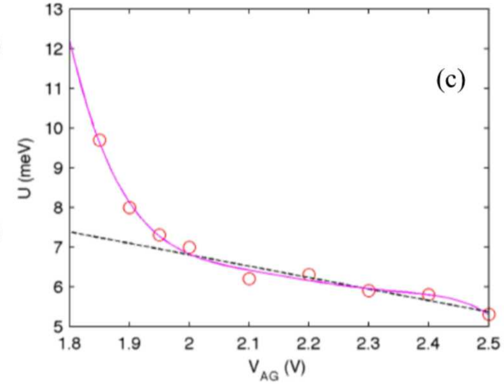








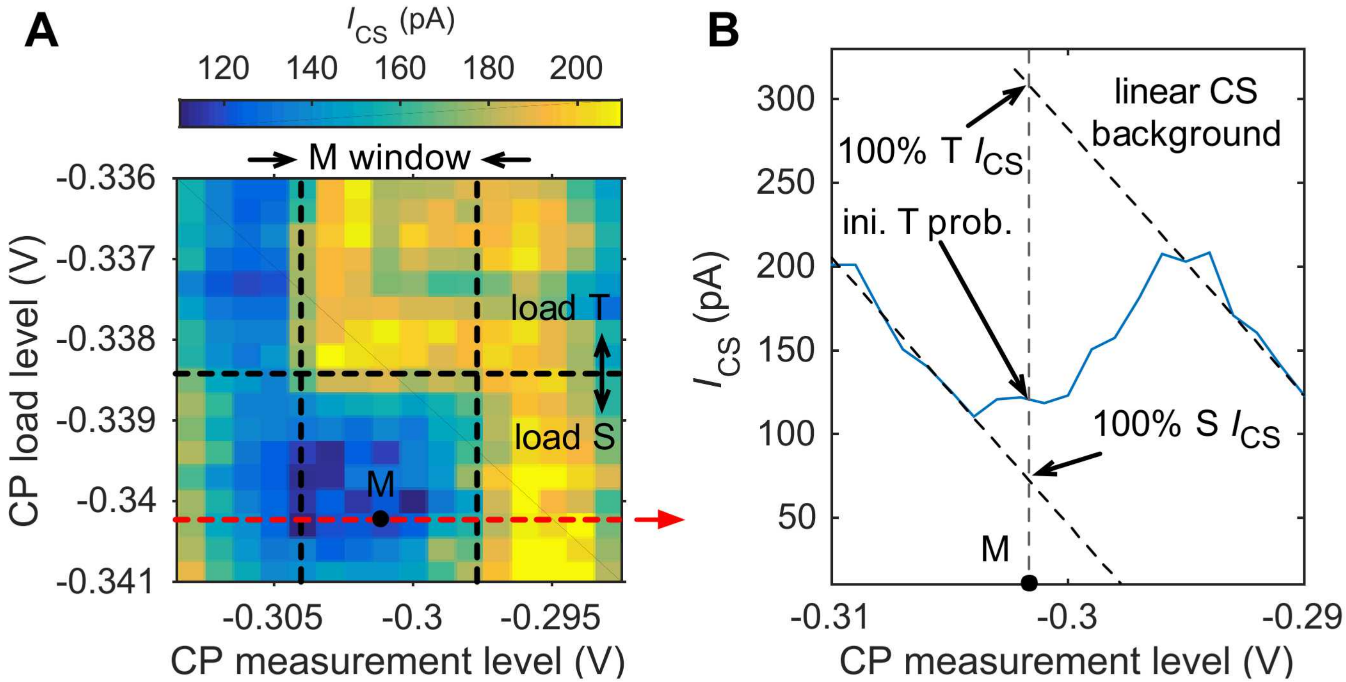




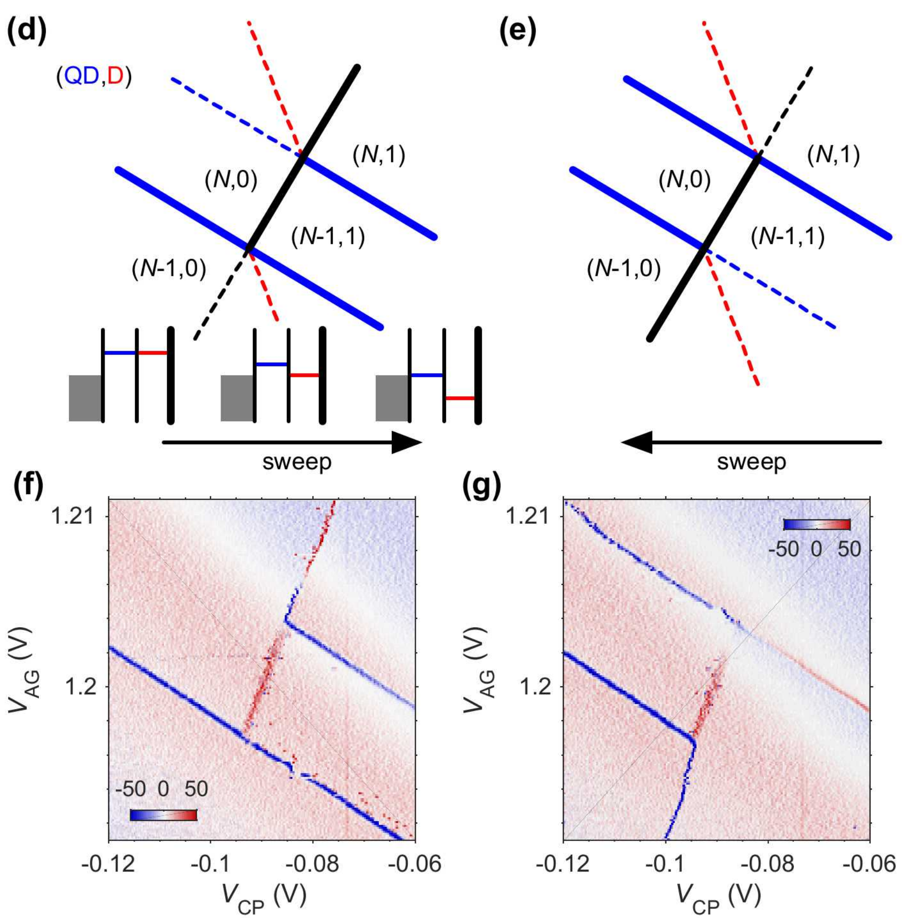
- Central component of quantum dots is the tunnel barrier
- Challenge: complex dependences on geometry and voltages [Friesen et al., …] – hard to model
- Crude first approach:
  - Use simplified parameteric model that captures barrier height, width, V dependence
  - Find measurement method that can produce rapid characterization
  - Begin to calibrate models

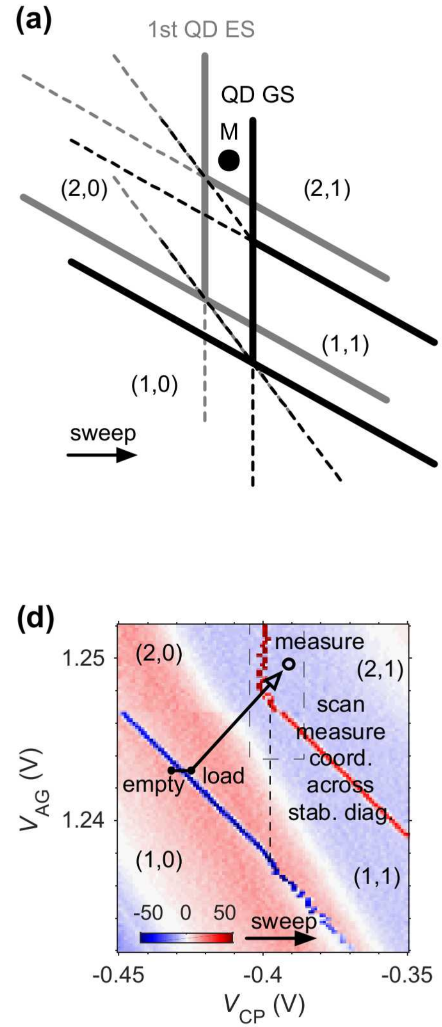
Shirkhorshidian et al. Nanotechnology 26 (2015) & Gao et al. JAP (2013)

Measurement calibration details

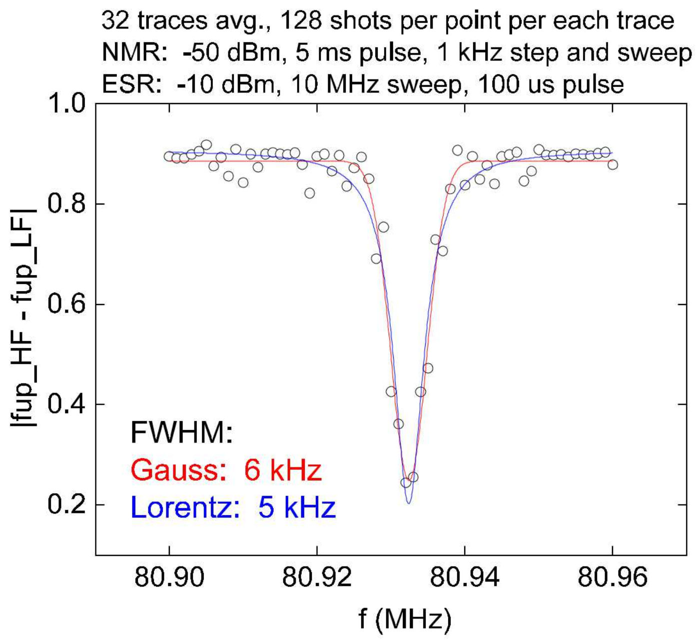


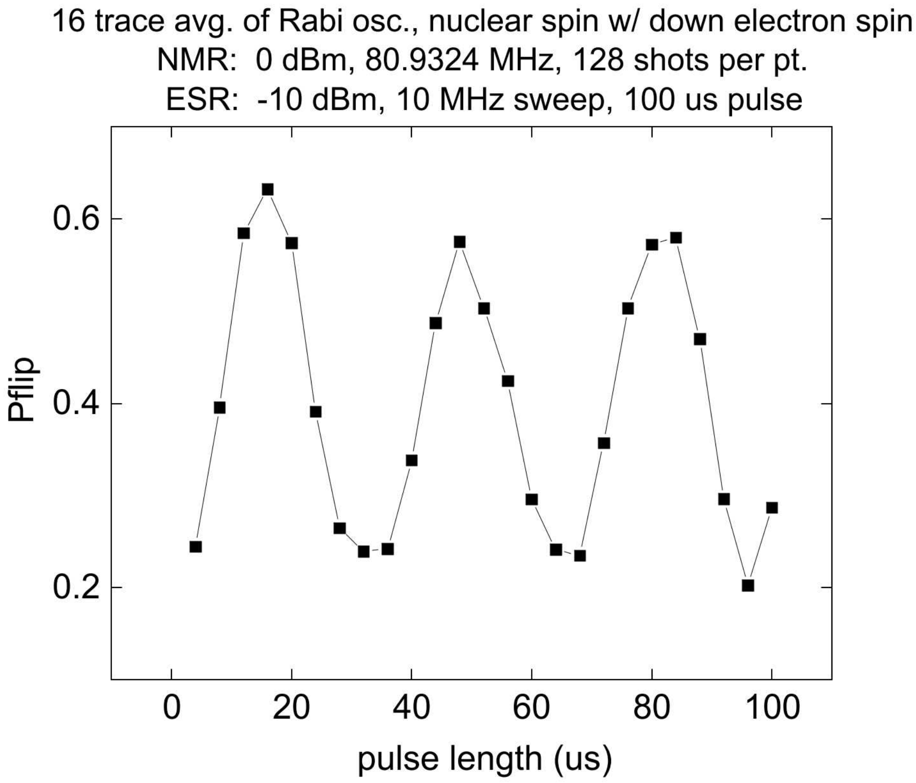
Back-up latch read-out figures



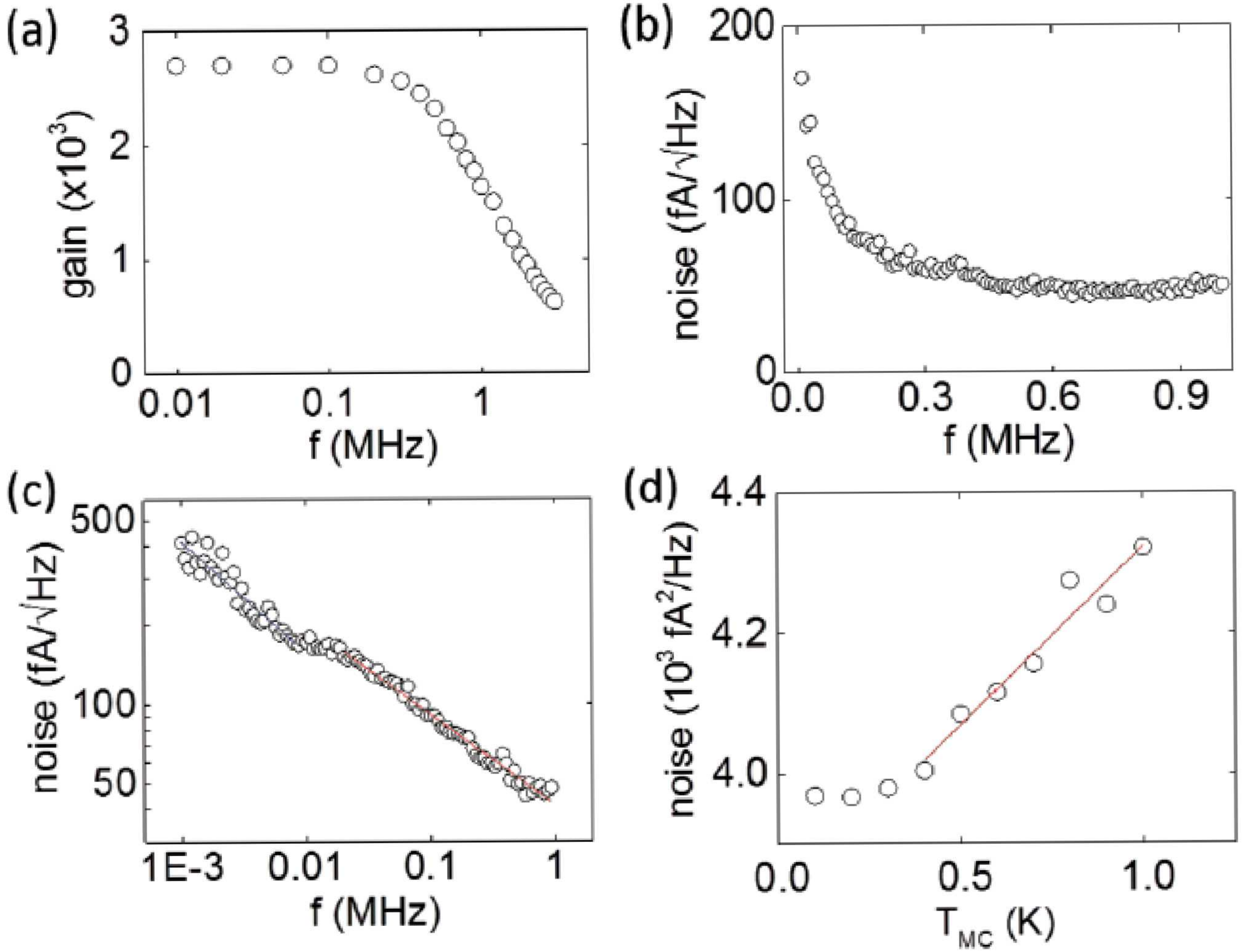


Nuclear Rabi Osc. (electron down spin loaded on donor)

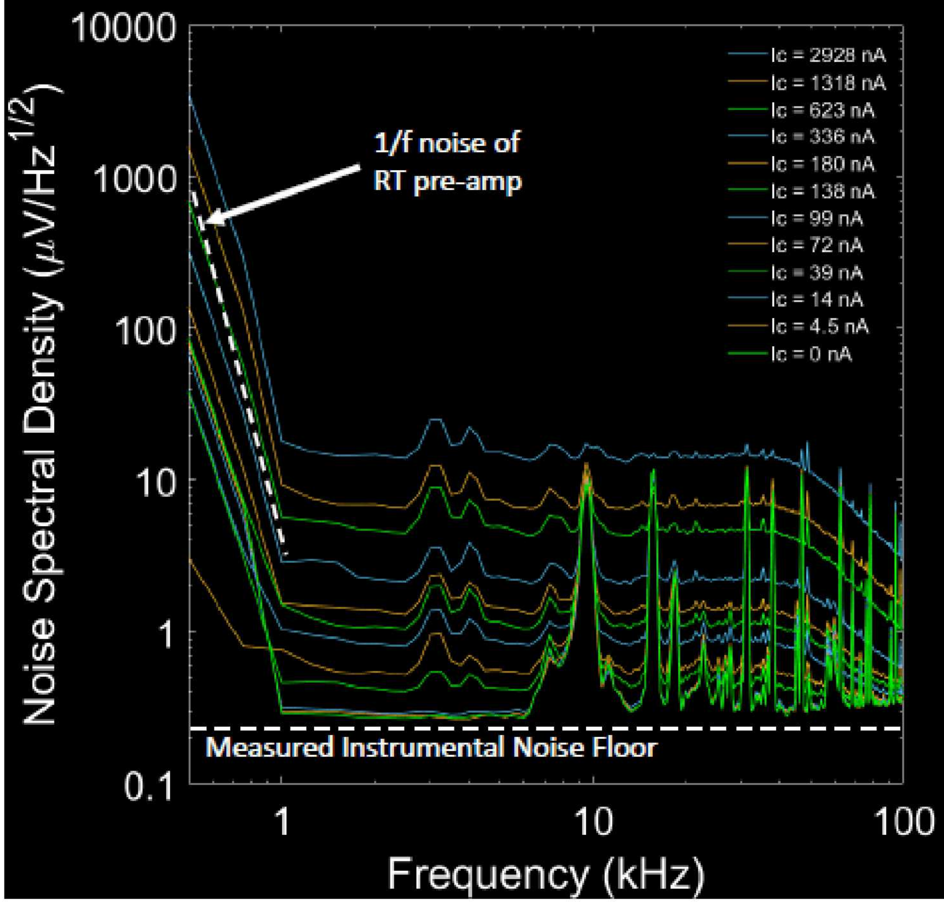


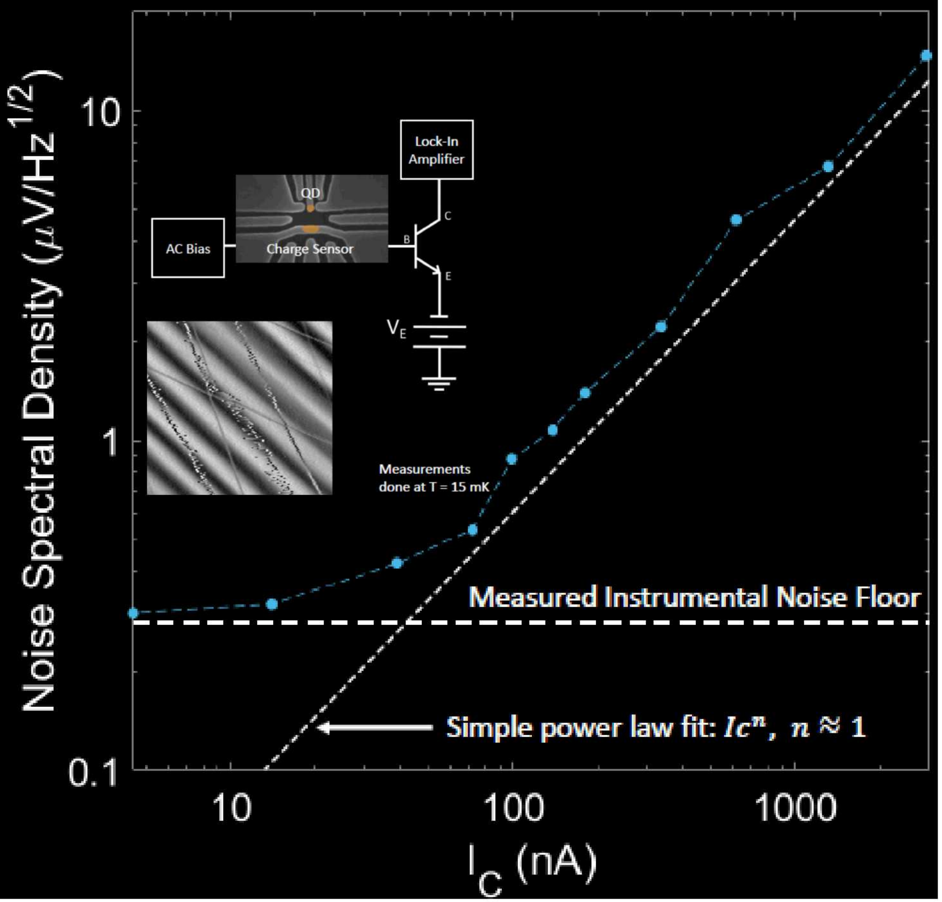


HEMT circuit noise performance



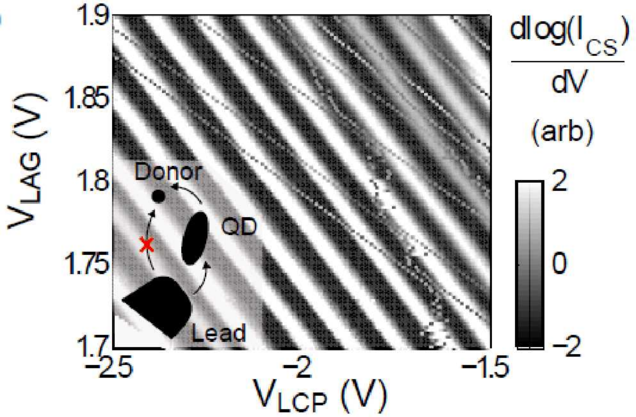
Readout Circuit Output-Referred Noise Spectral Density

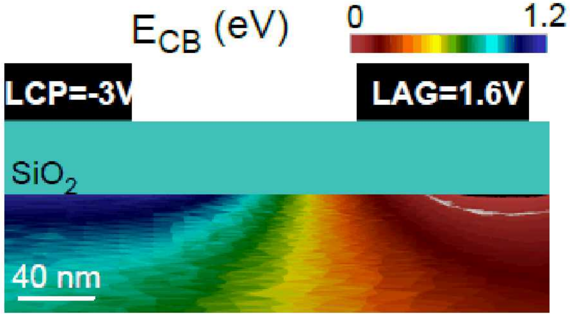


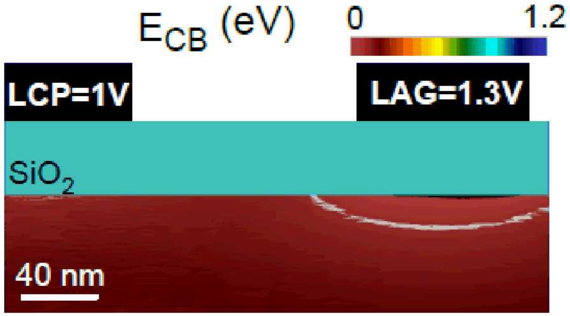


- Amplification is improving SNR. Pulse tube noise “after” amp.
- Shot noise limited regime achieved if sufficient power allowed

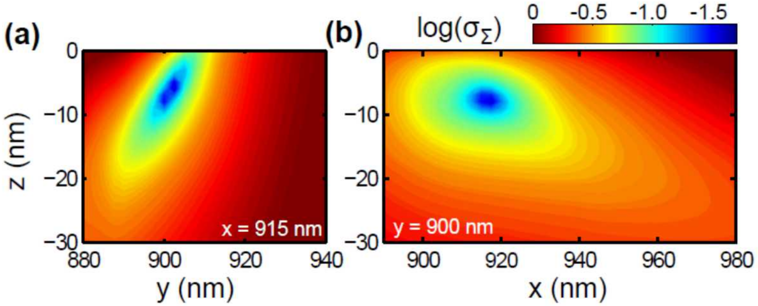
Triangulation of donor position





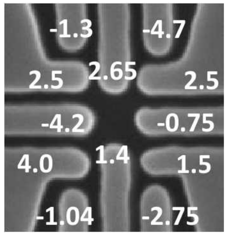


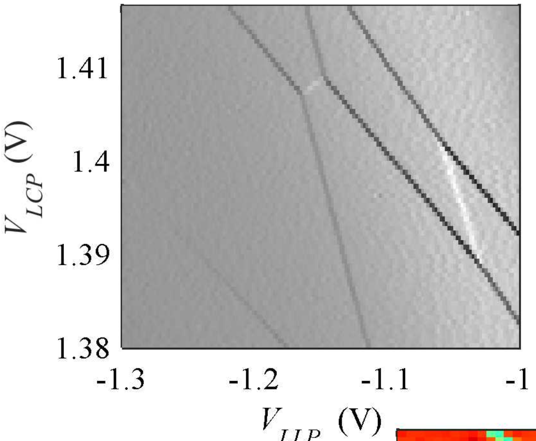
- Modeling of slopes in stability diagrams (against all gates) to help identify position of object
- Capacitances of multi-gate system are sufficient to locate position
- Visible donors are underneath LAG
- Depth/lateral extent of donors:
  - $7 < z < 15$ nm
  - $15 < x,y < 35$ nm
- This observation is also consistent with semi-classical QCAD calculations of 45 meV "ionization contours"

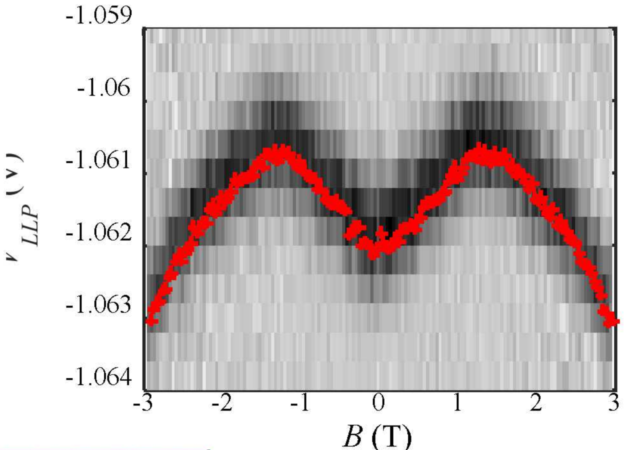


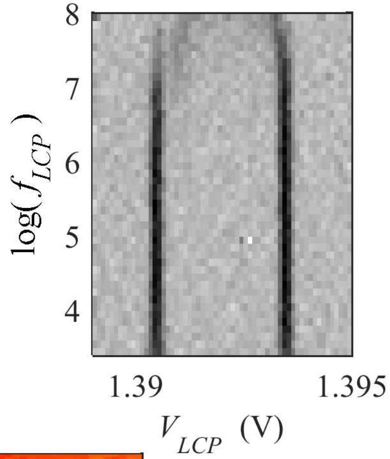
Rudolph et al. (in preparation)

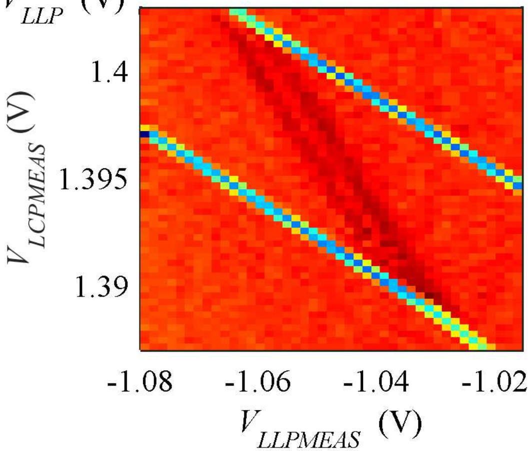
Pauli-blockade in D-SWAG system

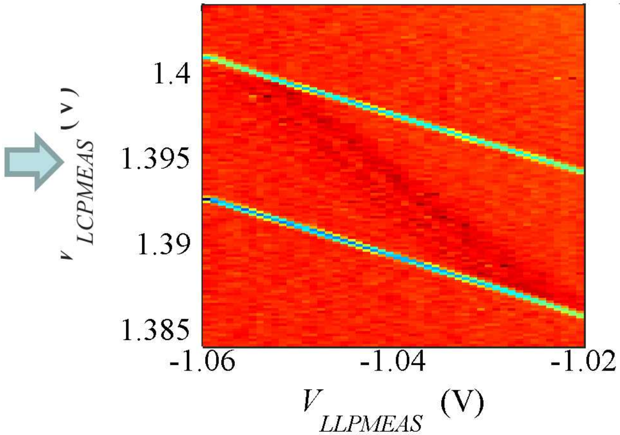


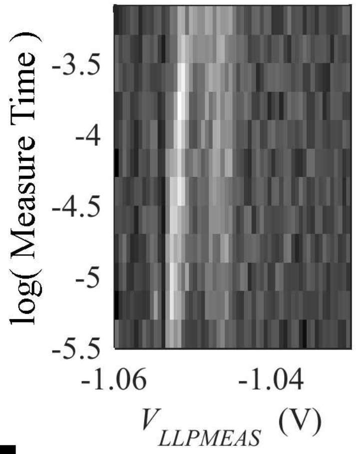












α_{QD4}	α_{DA}	α_{QD4-DA}	t_c (uev)	S/T (ueV)	ES/GS (ueV)	E_m QD4	E_m DA	T1 (us)
47	68	28	30	150	140	2.3 meV	2.3 meV	>200us