SAND2012-5549C

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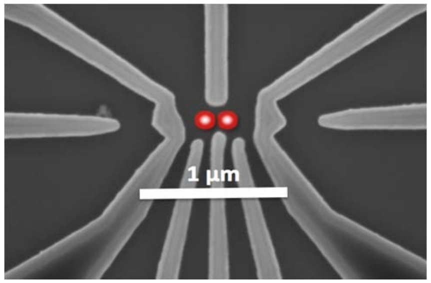
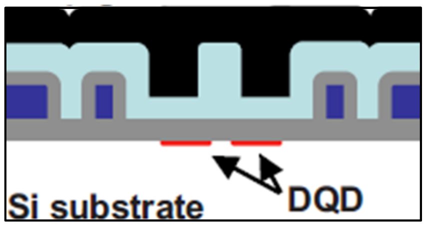
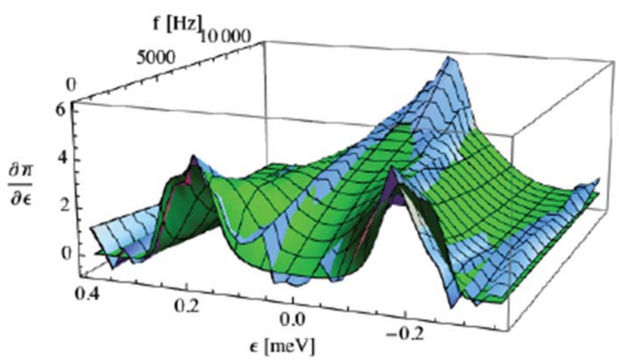
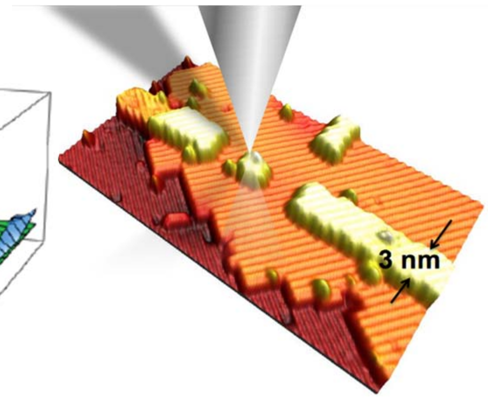
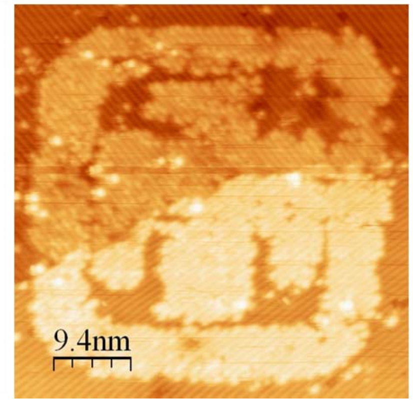










Semiconductor overview

Malcolm Carroll

Sandia National Labs, Albuquerque

June 29th, 2012

Outline

- Review (goals, qubit basics & where we were last EAB)

- Single qubit characterization & evolutions
  - Modeling of qubit relaxation & adiabaticity (Jacobson presentation)

- Development
  - Two qubit structures
  - Atomic precision fabrication (Bussmann presentation)
  - Infrastructure (lab & measurement set-up augmentations)

- Future plans & wrap-up

Overview of semiconductor approach

Goal: *2 qubit adiabatic test platform using semiconductor double quantum dots:*

- *understand AQC better w/ hardware*
- *understand viability for long term AQC*

Semiconductor

- Big gap => fast (or larger computations?)
- Relaxation => stable (self-correction?)
- Independent σ_X & σ_Z => tunable evolution
- CMOS compatible => scalable alternative to patented superconducting path?

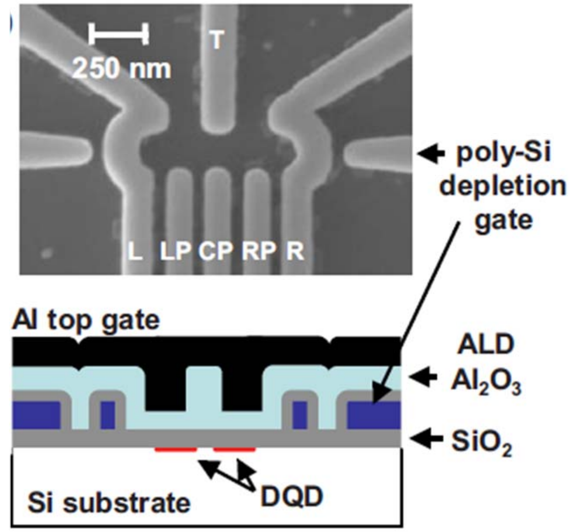
E-beam litho (double quantum dots)

- Primary 1 & 2 qubit tests
- CMOS compatible (less scaling development if it is a viable path)

STM Lithography for Si (double quantum dots)

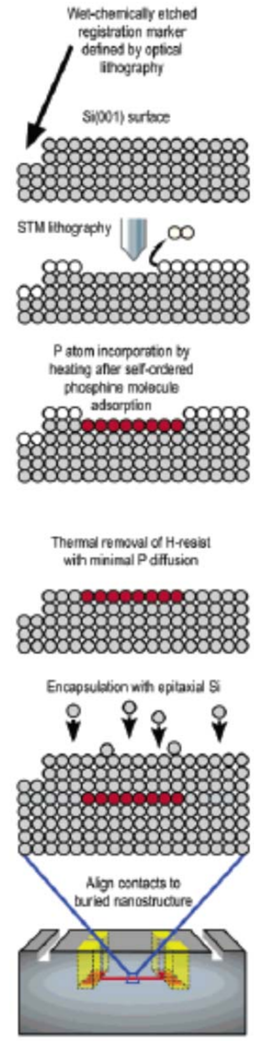
- Higher energy couplings, lower noise, higher yield?
- "Next MBE" to test limits & open new frontiers

E-beam lithography



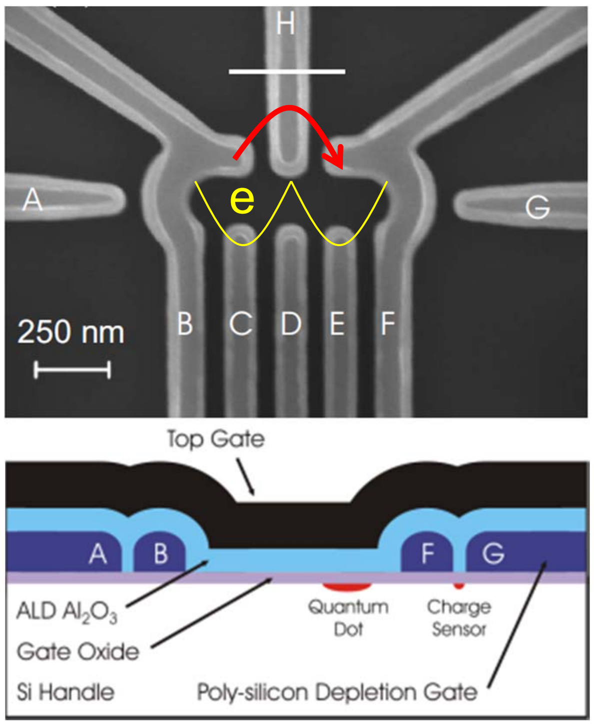
Double Quantum Dots: Sandia (2010)

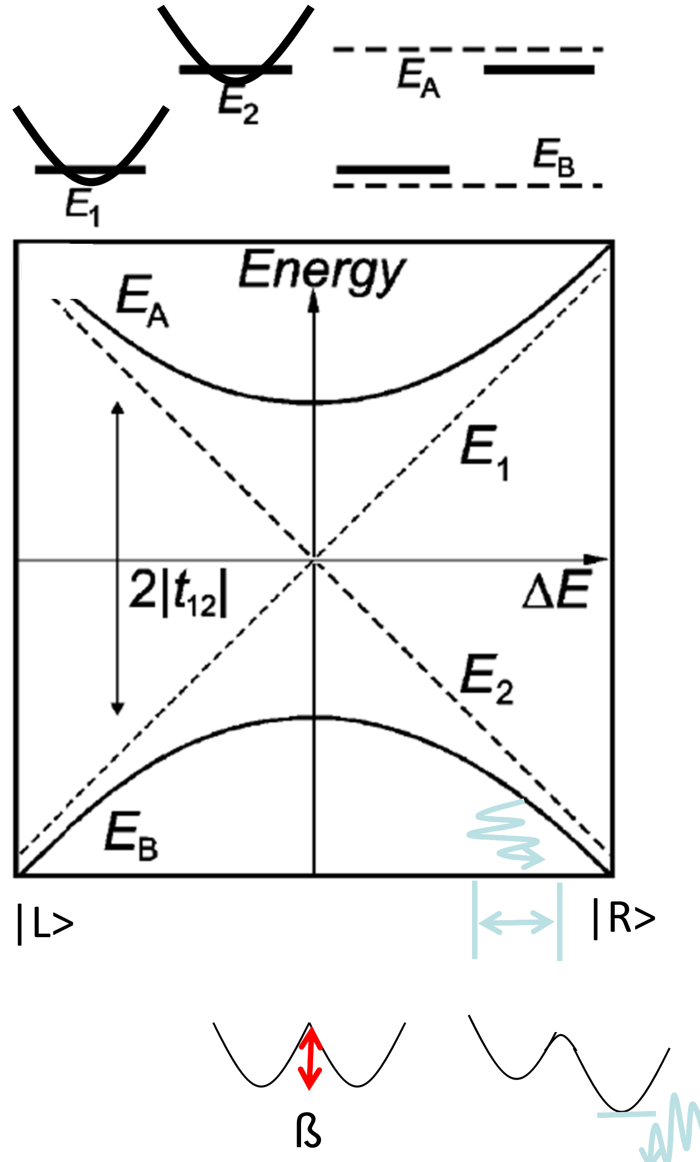
STM lithography



Fuhrer, Nanolett. (2009)

Charge qubit encoding for QUBO

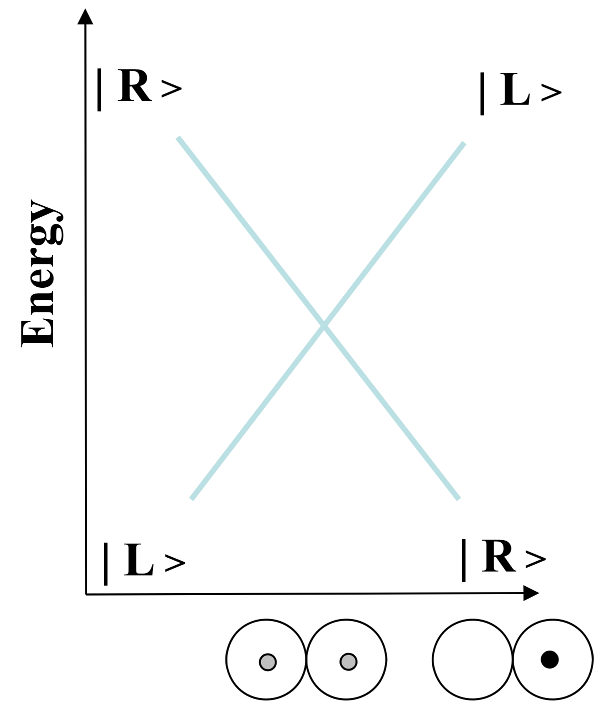




- Spin qubit encoding discussed in previous EAB
- Charge qubit encoding recognized as alternative approach
- Energy gap can be large relative to noise mechanisms
  - Dephasing produces small but manageable uncertainty in ground state energy
- Motivations:
  - Charge qubit encoding is easier to experimentally implement
  - Stable ground state (relaxation self-corrects excitation errors)

Charge qubit encoding for QUBO

$$H_{1,2} = \begin{pmatrix} \varepsilon(V) & 0 \\ 0 & -\varepsilon(V) \end{pmatrix}$$



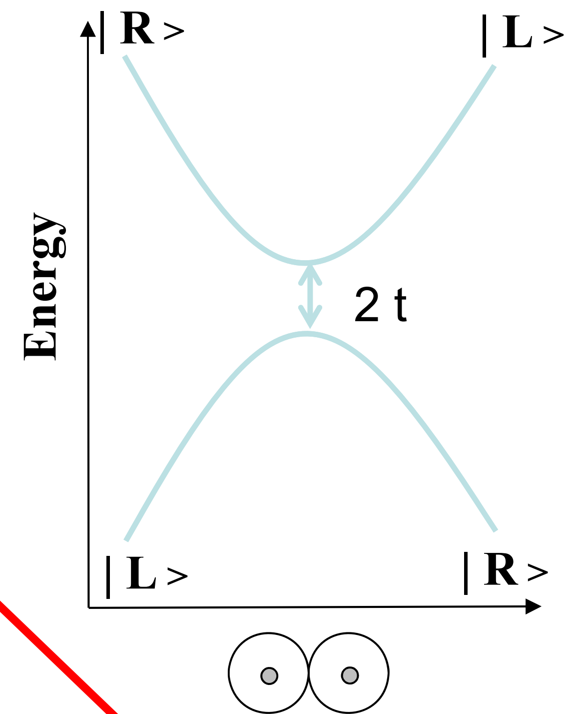
$$H = k(t)\sigma_{1z} + l(t)\sigma_{2z} + m(t)\sigma_{1z}\sigma_{2z} + H_{init}(t)$$

- Modulation of k and l can be accomplished with voltages on gates
- Negative and positive epsilon can range from -meV to +meV [~12-13 K]
- Negative J was difficult in S/T0 encoding

Initialization

$$H_{1,2} = \begin{pmatrix} 0 & -t \\ -t & 0 \end{pmatrix}$$

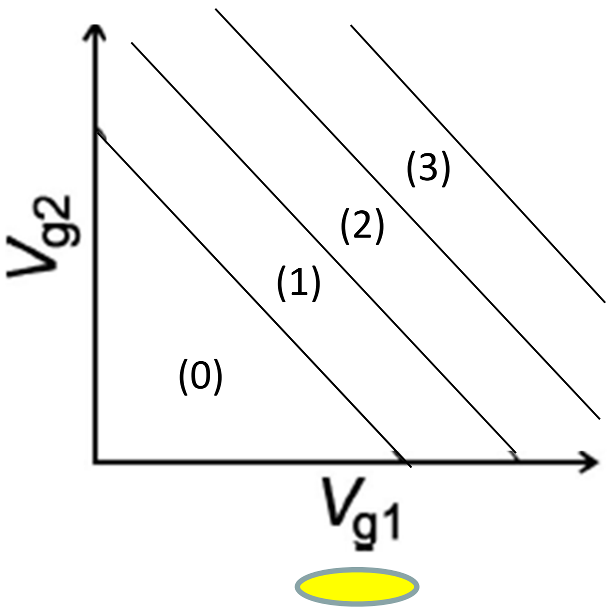
$$\psi_0 = \left| L' \right\rangle + \left| R' \right\rangle$$

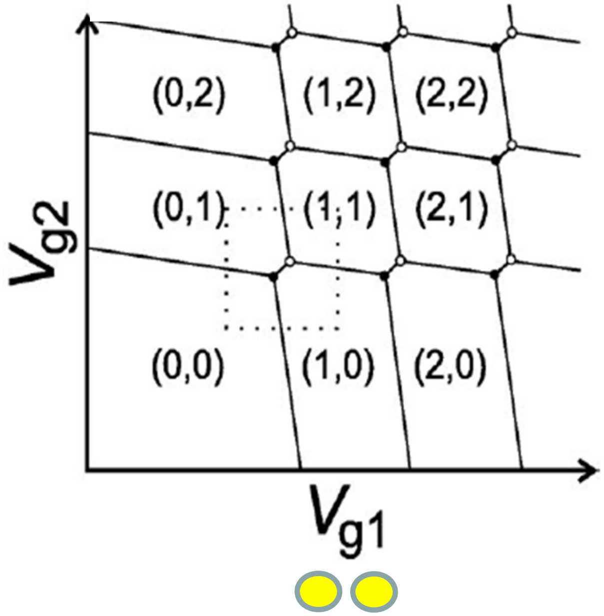


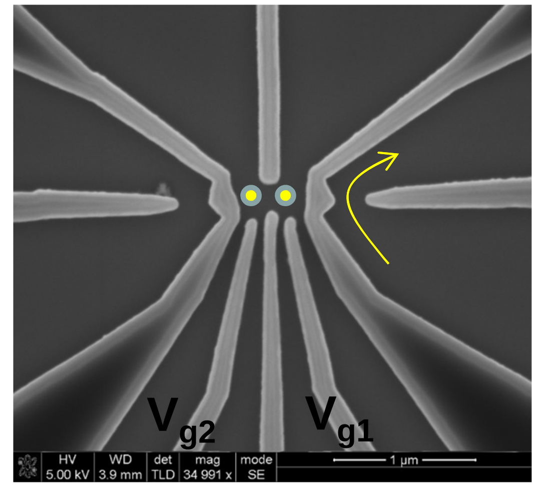
$$H = k(t)\sigma_{1z} + l(t)\sigma_{2z} + m(t)\sigma_{1z}\sigma_{2z} + H_{init}(t)$$

- Tunneling magnitude is independently tunable from neV to meV
- Only positive

Coulomb blockade and stability plots







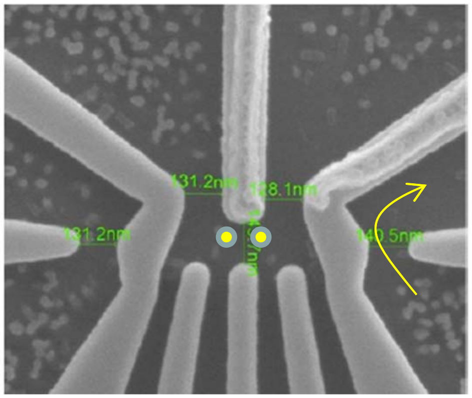
Charging energy (significant for QDs)

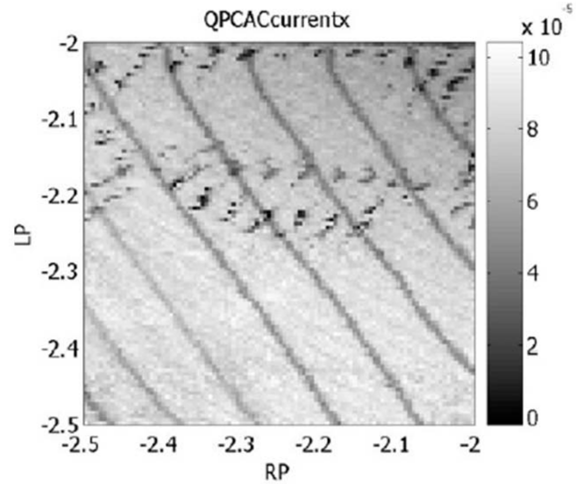
$$V \cong \frac{q}{C}$$

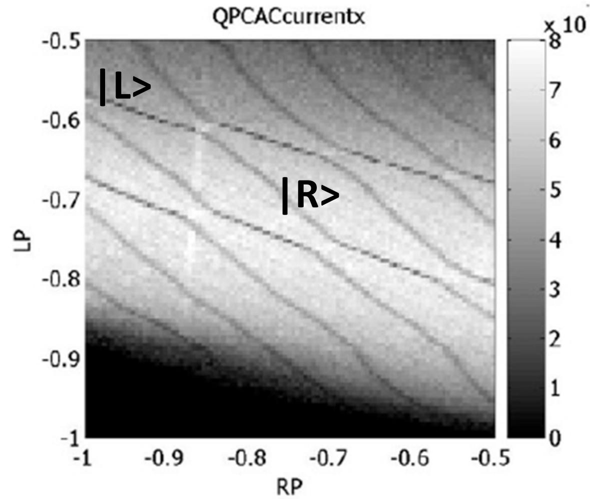
- Equally spaced energy levels related to charging energy of capacitance
- Charge sectors are formed for which charge number is fixed
- Two dots => two ladders
- Lines are not straight because of cross-capacitances & mutual capacitance
- Measurement: charge sensing or current

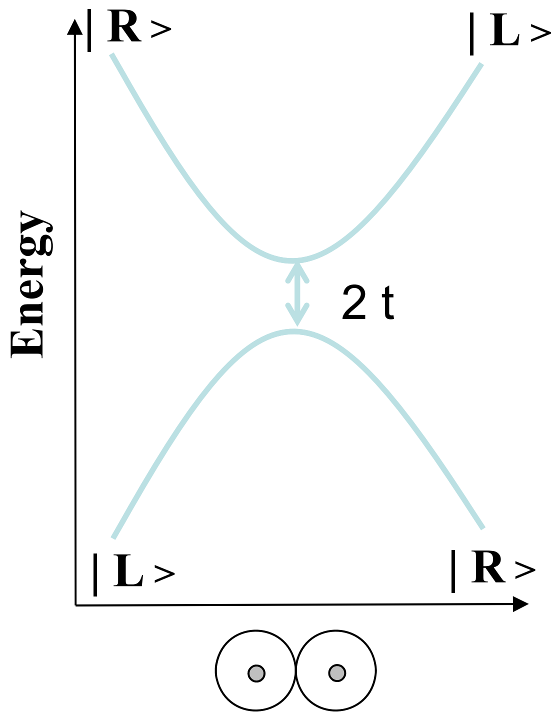
Tunability for charge qubit definition

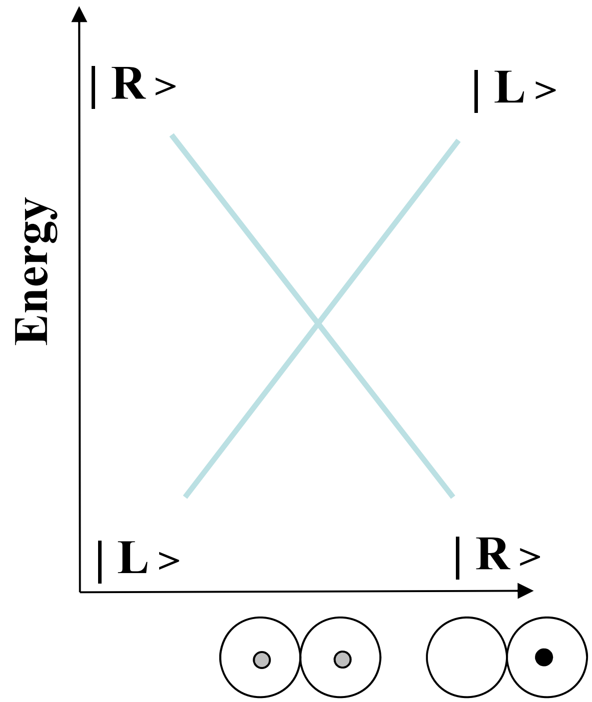
S. Carr



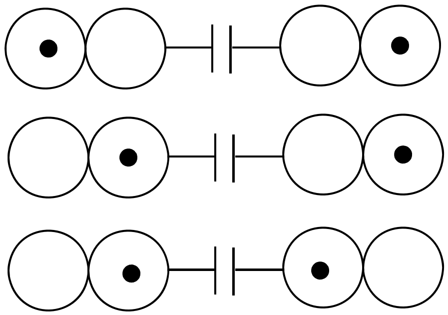


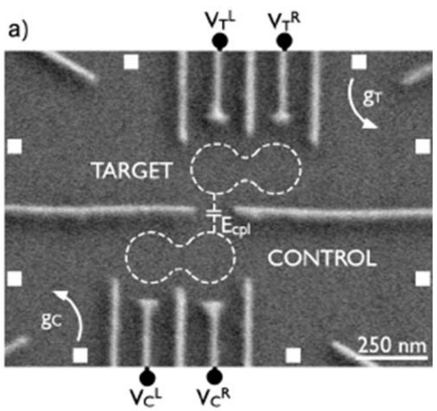






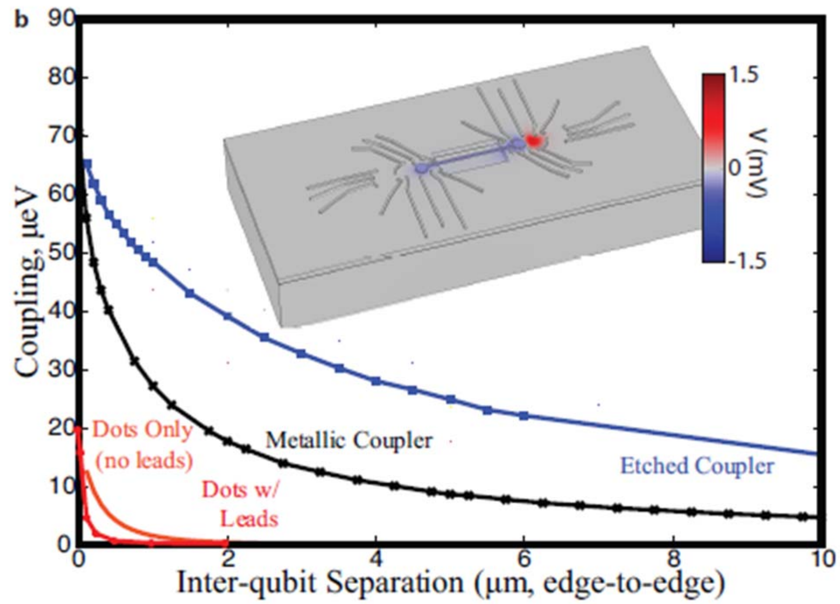
Coulomb interaction for qubit coupling





Van Weperen, PRL, 2011

L. Trifunovic et al., arXiv 1110.1342



$$H = k(t)\sigma_{1z} + l(t)\sigma_{2z} + m(t)\sigma_{1z}\sigma_{2z} + H_{init}(t)$$

- Interaction magnitude experimentally found to range from 25-85 ueV [~0.25-1K]
- In principle, strength of Z1Z2 interaction tunable & can be larger

Charge qubit milestones & status at last EAB

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- Year 1
- Set-up existing QIST cryogen free fridge
- Demonstrate few electron QD
- Demonstrate few electron DQD
- Purchase new cryogen free fridge
- Show clean hydrogen terminated surface and lithography in existing STM system (advanced DQD fabrication w/ STM)
- Design & build clean room STM (advanced DQD fab)
- Year 2
- Set-up AQUARIUS fridge
- Demonstrate qubit state read-out [charge sense DQD]
- Identify non-adiabatic limit for single qubit evolution
- Establish theoretical 2 qubit AQO scheme
- Design and fabricate 2 qubit system [DQD-DQD with coupling]
- Show silicon encapsulation in STM (advanced DQD fab)
- Incorporation of phosphorus on surface (advanced DQD fab)
- Demonstrate initial transport test devices (wires) (advanced DQD fab)
- Year 3
- Demonstrate 2 qubit system
- Identify non-adiabatic limit for two qubit evolution
- Implement 2 qubit AQO
- Fabricate DQD with advanced fab (advanced DQD fab)
- Demonstrate qubit with advanced DQD fab & evaluate approach (advanced DQD fab)

Qubit definition

Read-out

Evolution

2 qubits

Superior qubit fab demo

Charge qubit milestones

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Some of the desired measurements

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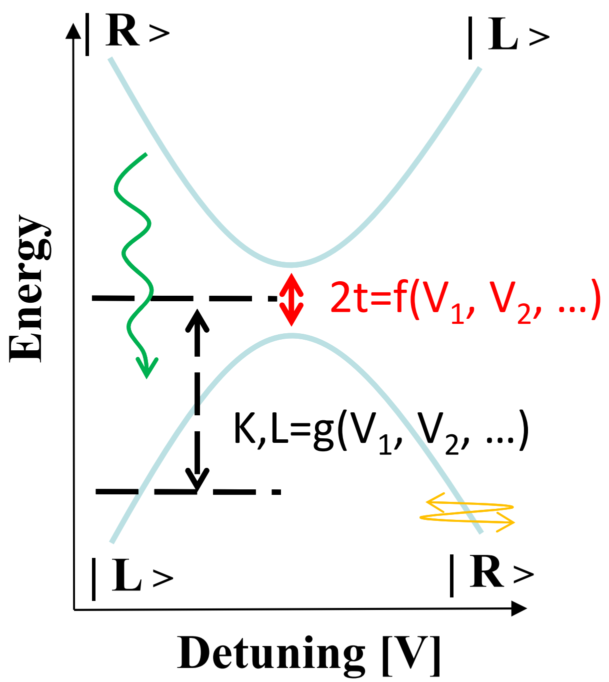
Characterization



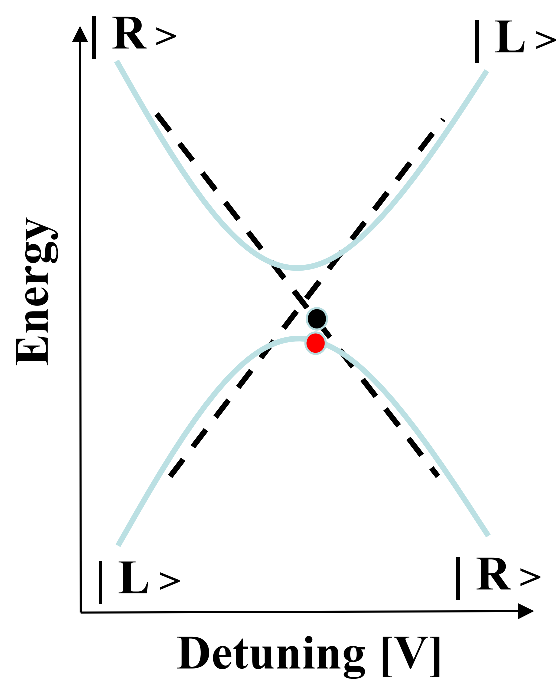
α: Voltage to energy

t: measure tunneling

tau: dissipation time

δε: dephasing noise

QUBO evolution

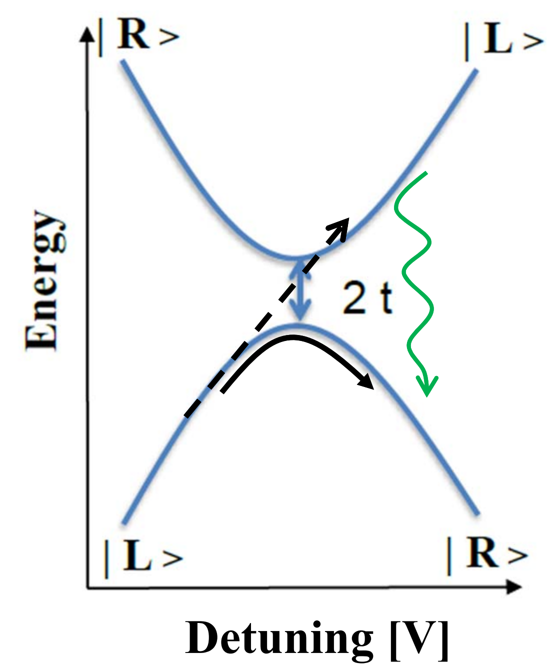


Initialize: strong σ_x

Program: detune σ_z ●

Solve: reduce σ_x ●

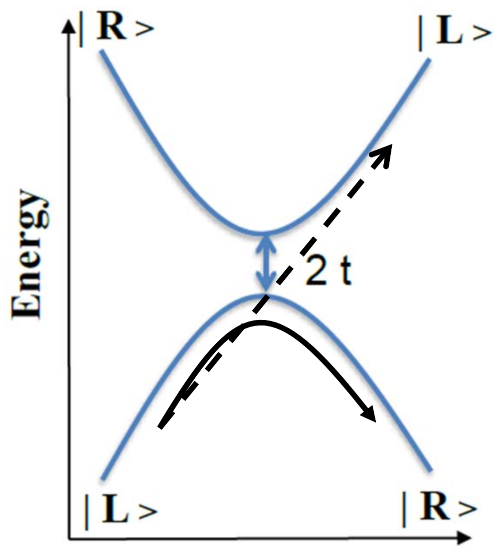
Adiabaticity test



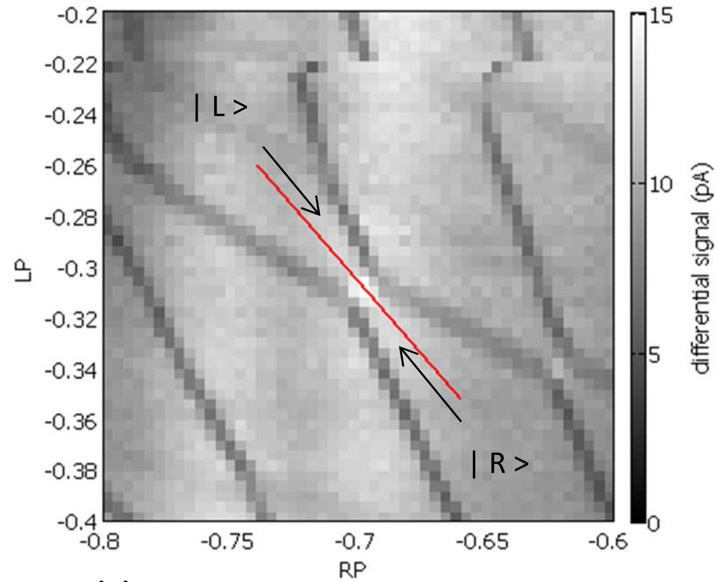
Invent test

- New regimes & material being measured
- New measurement art or technique necessary

Test limits of adiabatic evolution (last EAB)

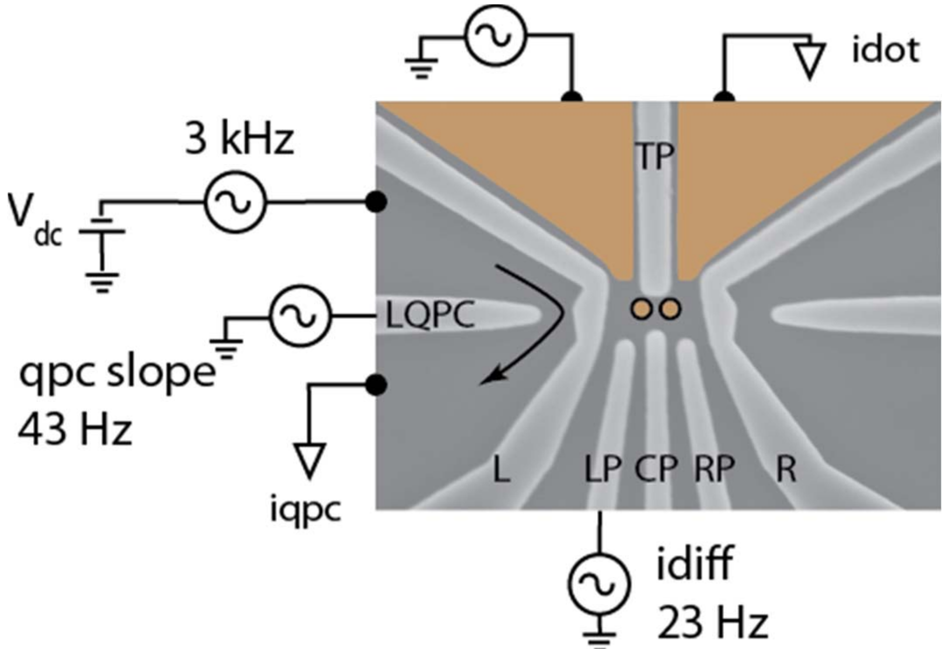


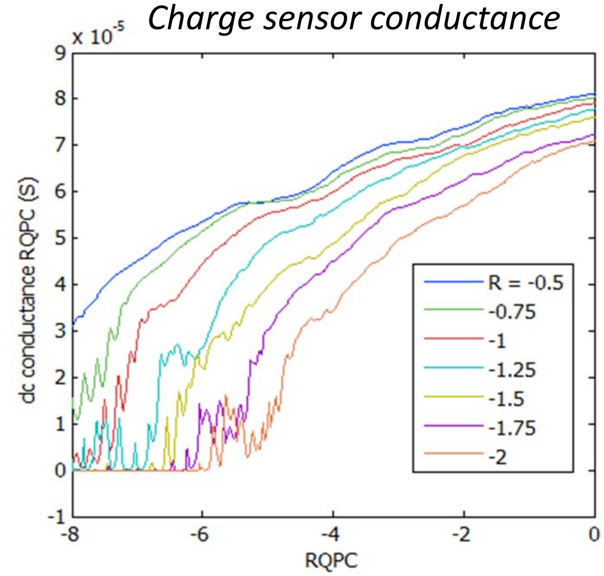
Beginning charge qubit evolutions (SNL)



- Test whether electron can keep-up with pulses through L/R transition
  - Adiabaticity test proposed but full analysis was not complete
- challenges:
  - Weak charge sensor sensitivity, poor barrier tunability, unreliable charge sensing in MOS DQDs
- Characterization:
  - Voltage to energy not well characterized (and unclear in unbalanced tunnel barrier regime)
  - No known measurement for tunnel coupling in regime < ~ 1ueV (inelastic tunnel rate possible)
  - No clearly prescribed measurement for energy dependence of relax. Times for this regime
  - No direct measurement for dephasing (in-direct noise measurement of circuit? PAT not possible)

Charge sensing technique





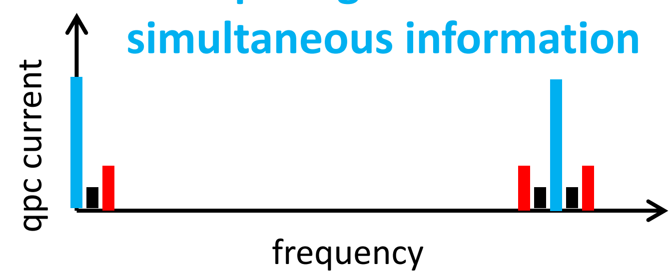
Charge sensing challenges:

1. Weak signal
2. Plunger-sensor cross capacitance
3. Drift in sensitivity (very stable dot behavior) & correlated noise?
4. Opaque tunnel barriers in dot

Charge sensing sensitivity enhancements:

1. Differential signal (AC on LP instead of directly on QPC)
2. Adaptive code with direct monitoring of the slope (AC on LQPC to monitor and lock on slope)

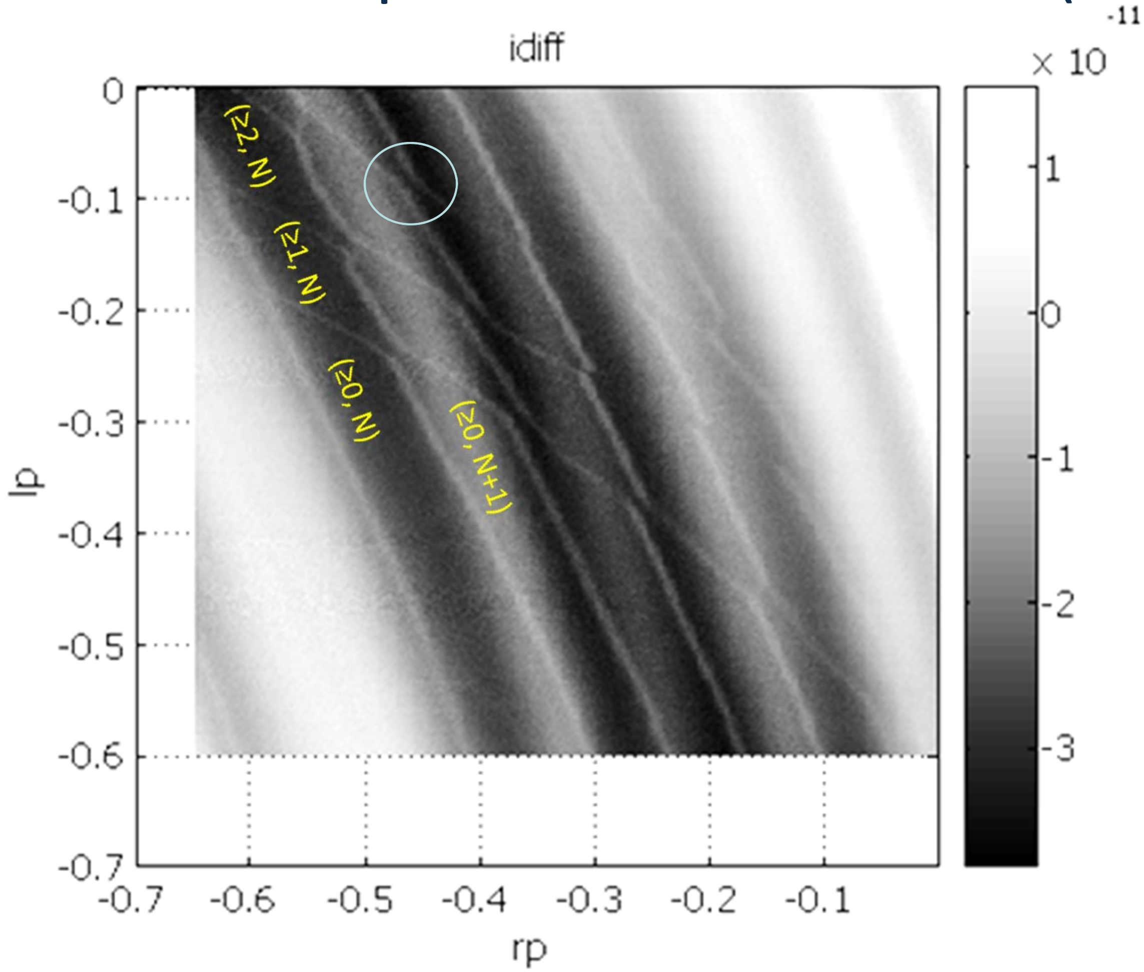
Multiple signals enables simultaneous information

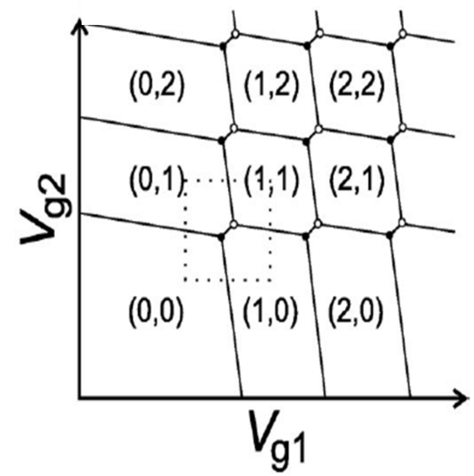


transport, direct CS, differential CS

QPC sensitivity for adaptive code

Double quantum dot behavior (charge sensed)

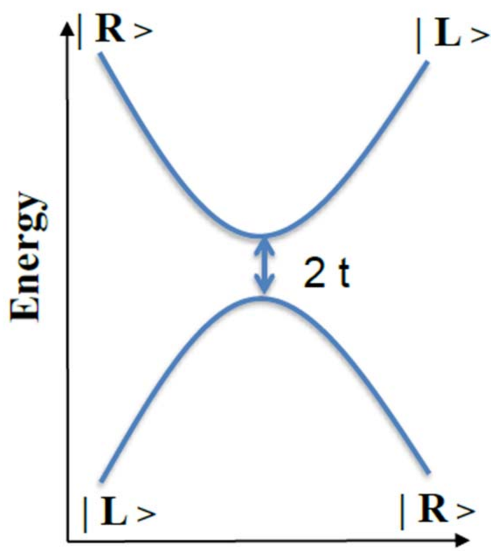


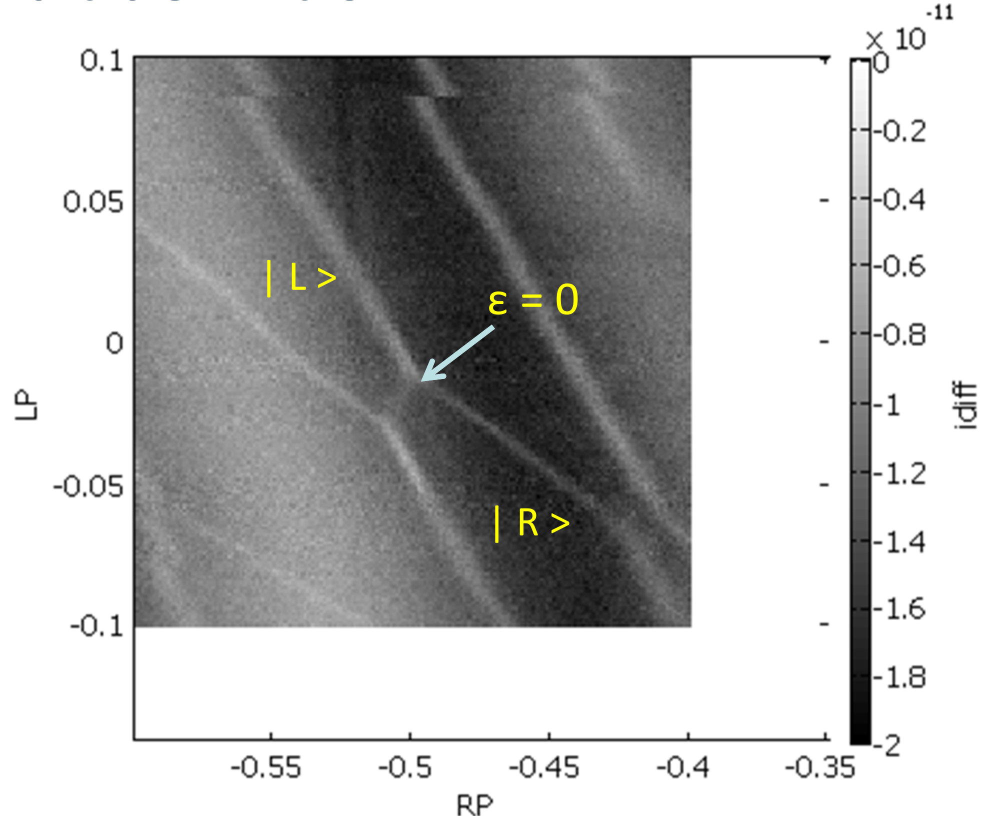


Nguyen, Lilly

- Double quantum dot behavior formed (charge sensed)
- Charge transition between |L> and |R> observable at some triple points
- Avoid Pauli-blockade cases for this measurement (bias triangles used to check)
- Lack of crossings in lower left corner: left dot appears to be N=0 in this voltage range

Charge qubit definition

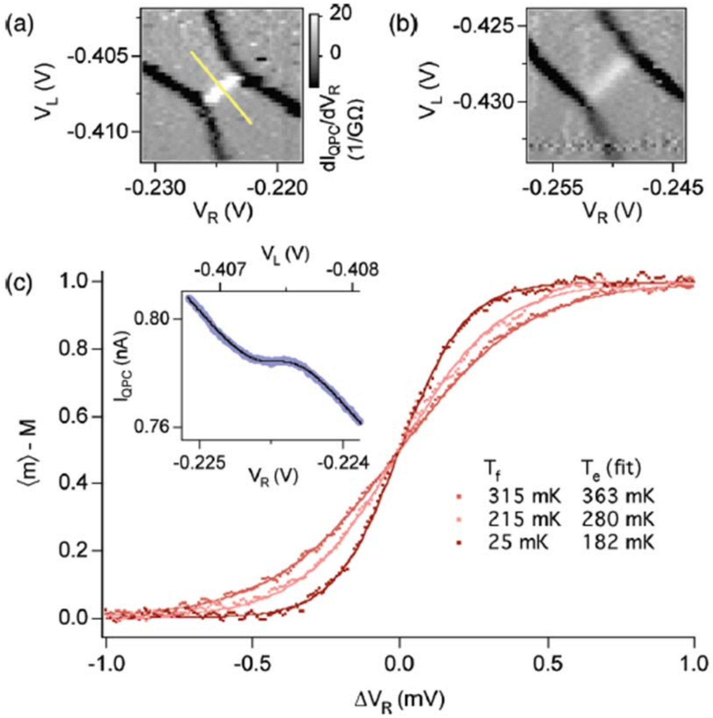


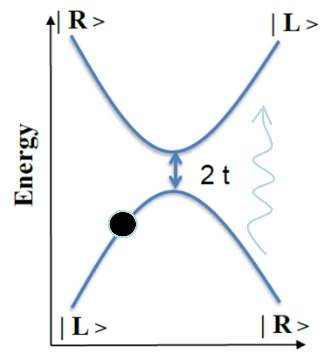


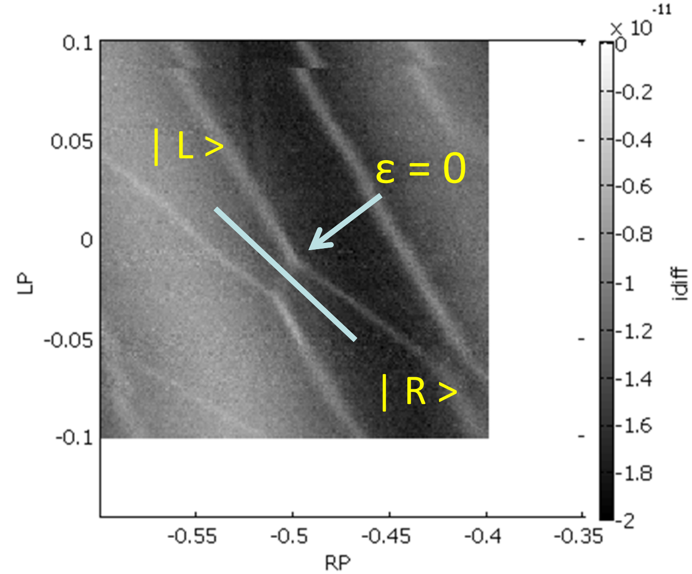
- Initialization:
  - Honeycomb is stable in time => same LP, RP recovers same charge state up to limits of long term drift in system
  - System relaxes to ground state rapidly
- Read-out:
  - Look at difference in charge signal (differential signal shows edge)
  - stare at ground state => high S/N due to averaging (single shot > error)
  - Map region if sensor drifts?

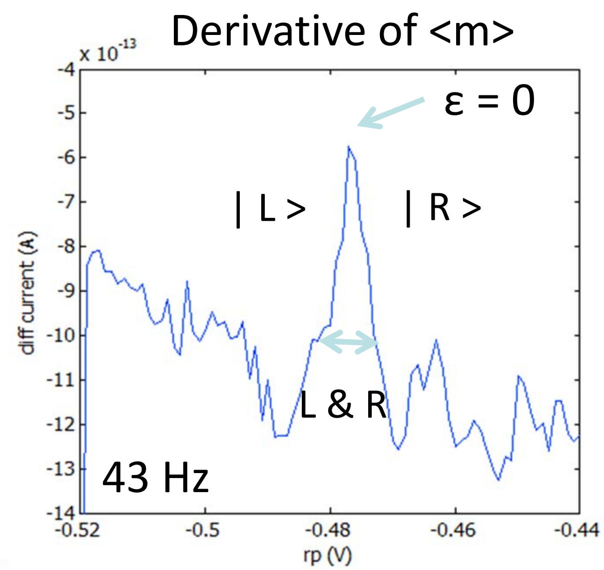
Charge transition thermal distribution: read-out error

Simmons et al., Nanoletters (2009)









- Fermi-Dirac broadening of charge transition [ueV resolution of 2t]
- Uncertainty around <m> = 0.5 defines read-out uncertainty
- For $E_{gap}/kT >> 0$ read-out approaches 100% using staring
  - ➢ Assumes zero drift in charge sensor (i.e., fast computation relative to hours or perhaps days)
  - ➢ Local map might be done to verify (requires bit flip)
- Less than kT resolution possible if (a) single shot faster than τ_{excite} ; (b) σ_x => 0 (freeze solution) then σ_z >> kT both faster than τ_{excite}; or (c) system often relaxes to ground state from thermal excited states

Some desired measurements

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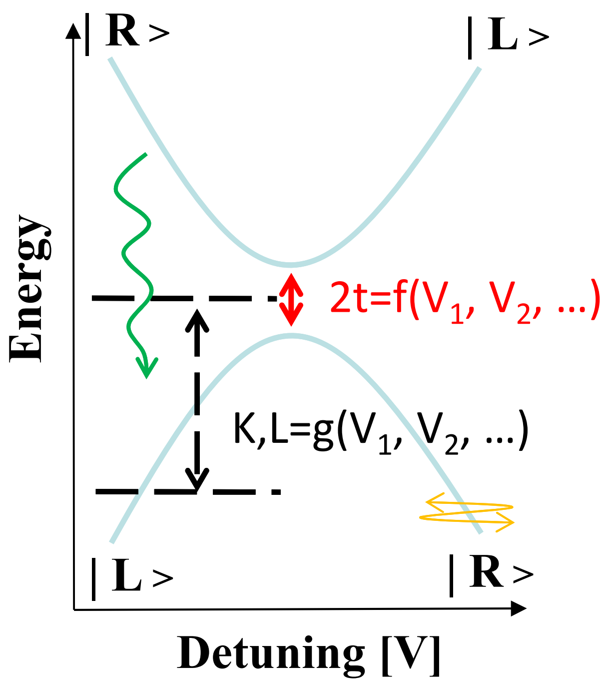
Characterization



α: Voltage to energy

t: measure tunneling

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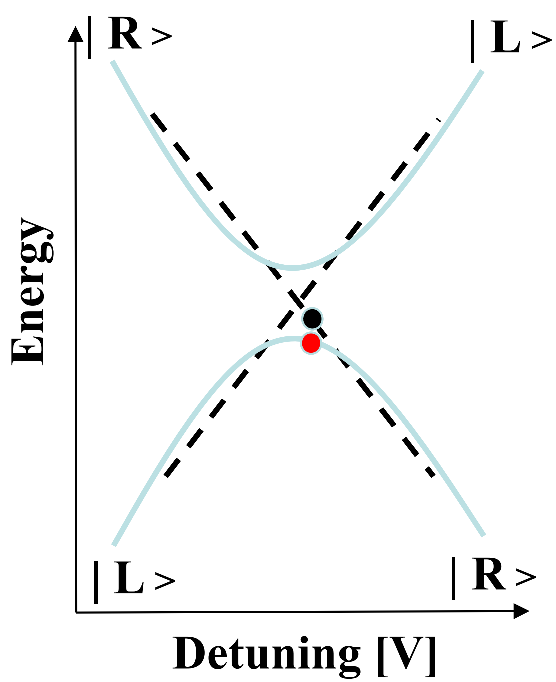
QUBO evolution

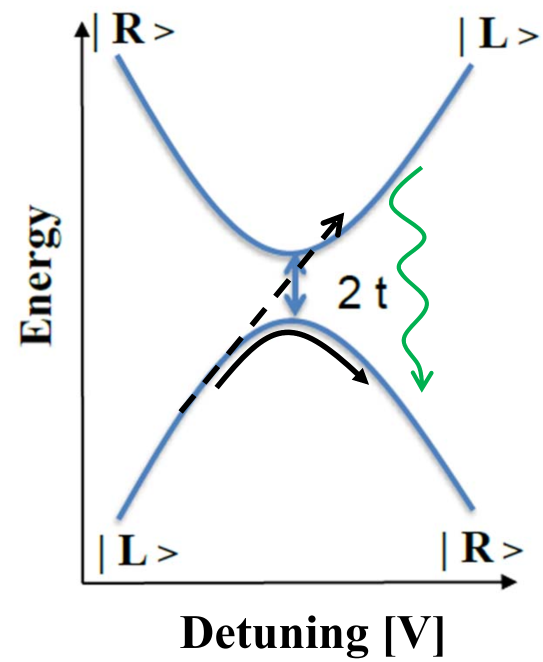


Initialize: strong σ_x

Program: detune σ_z

Solve: reduce σ_x

Adiabaticity test



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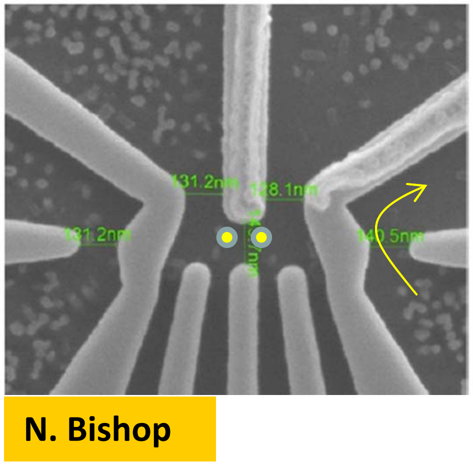
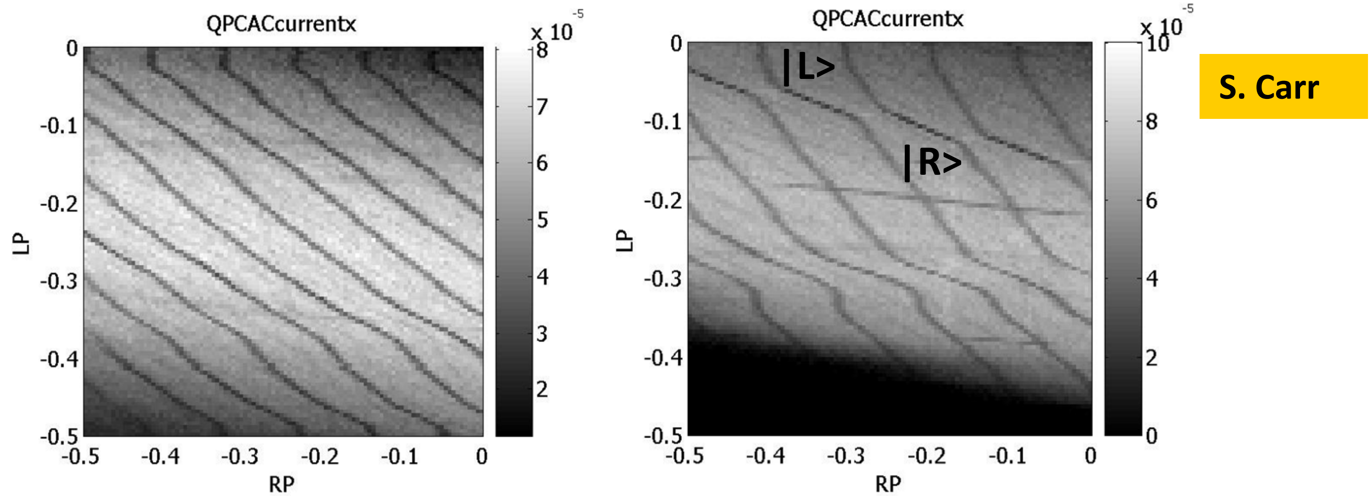
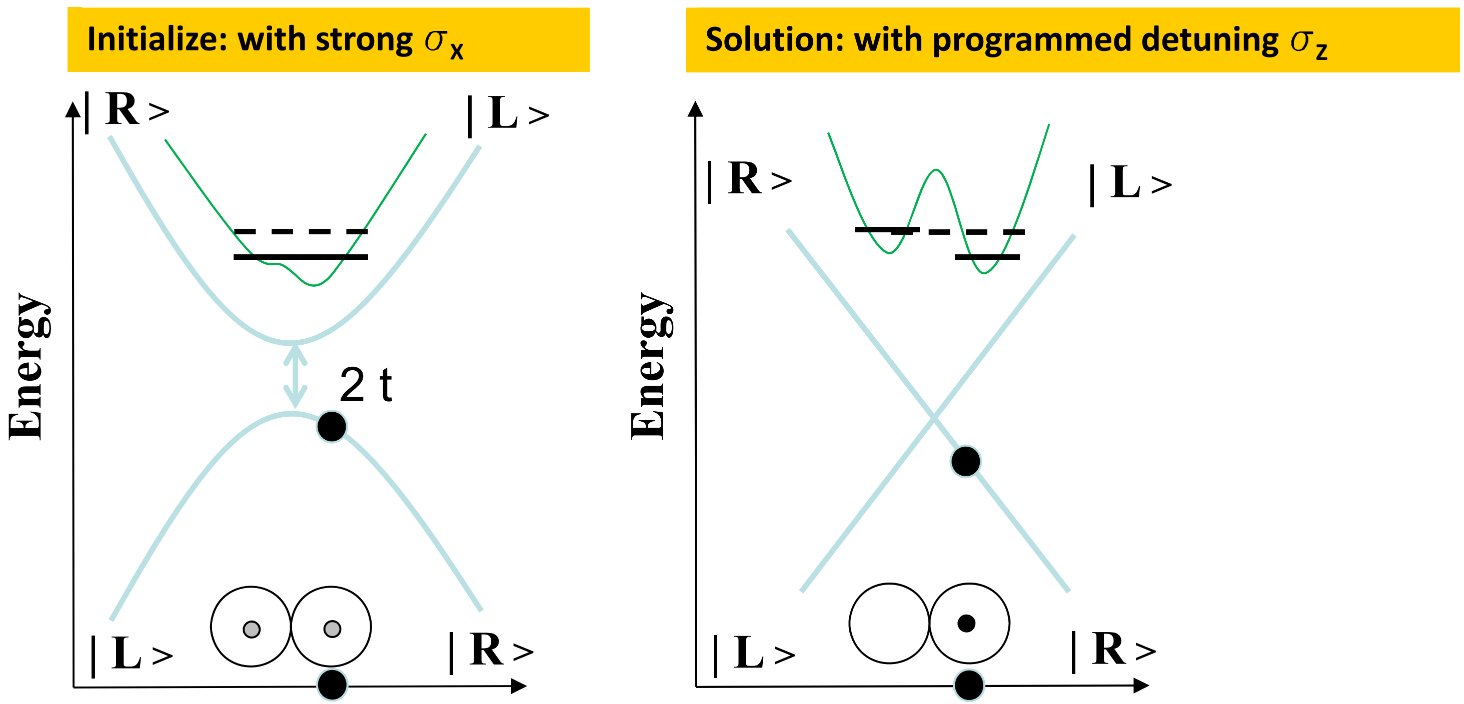
Tunability for charge qubit evolution is LUBO





- Tuning DQD from QD is the X to Z LUBO
- Must track N,M sector with knowledge of capacitance
- Evolution is likely faster than t
- **Doubt: relaxation assisted?**



Adiabatic or relaxation: experimental approach

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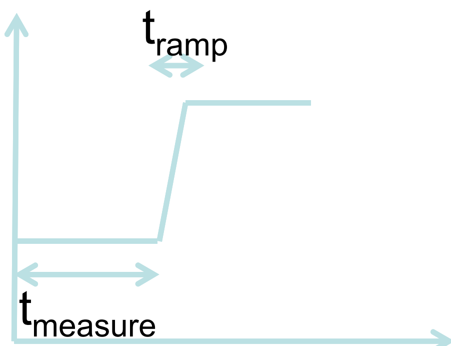
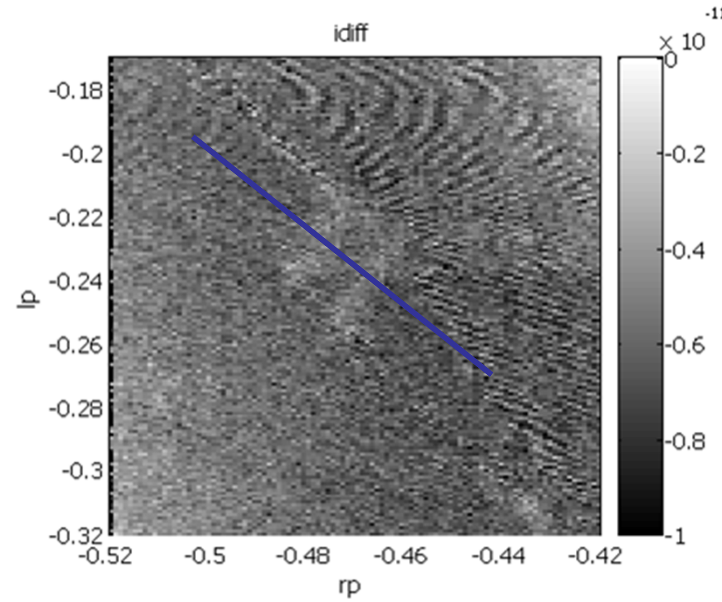
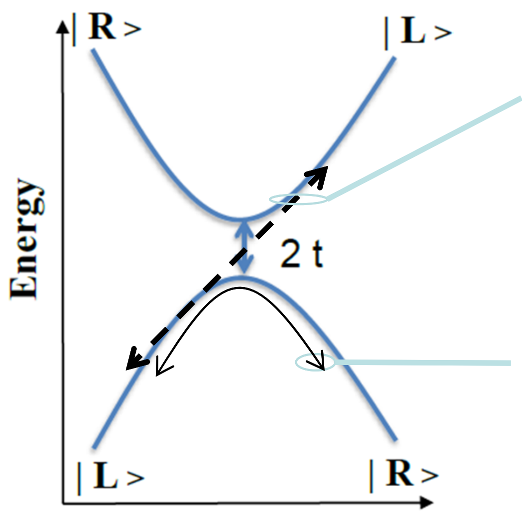
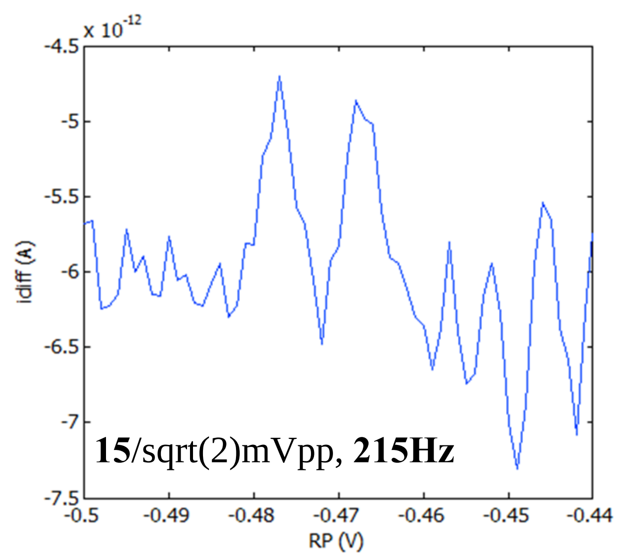
Square pulse (f & r)





- Examine frequency and ramp dependence of peaks (charge occupation) in long average limit
- If thermal distribution perturbed => non-adiabatic





Frequency dependence with fixed amplitude pulses

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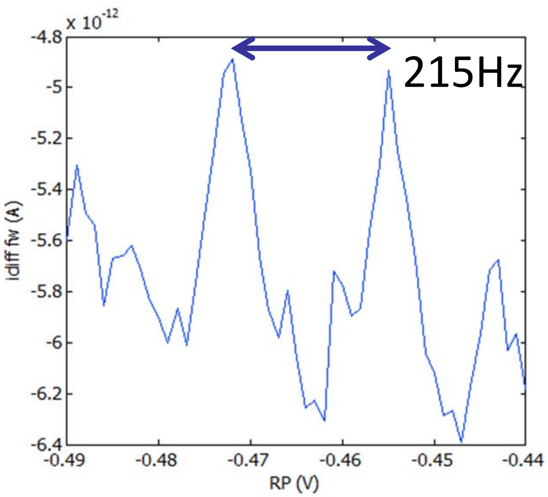
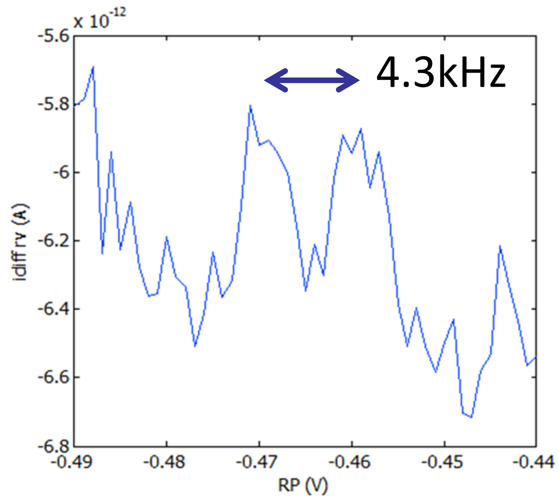
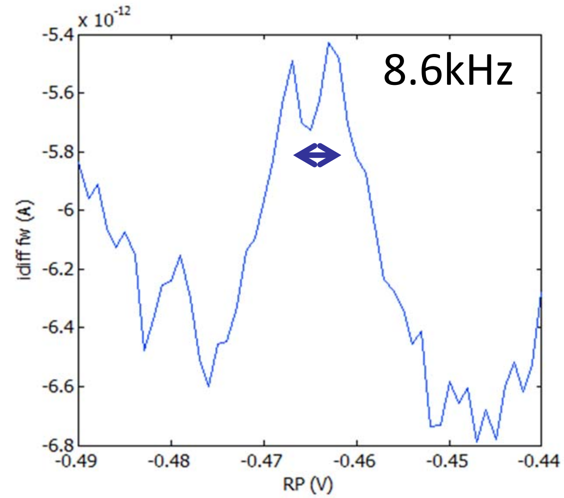
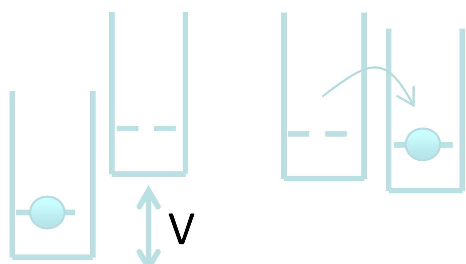


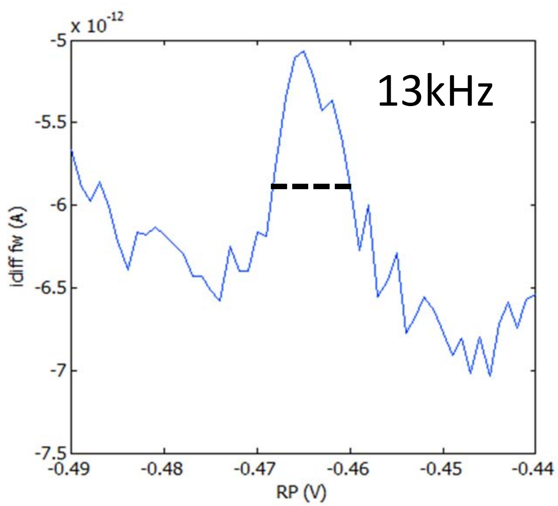


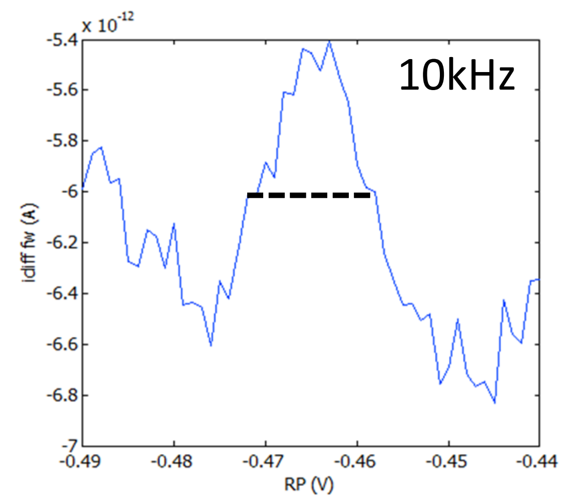


Ramp = 16 ns

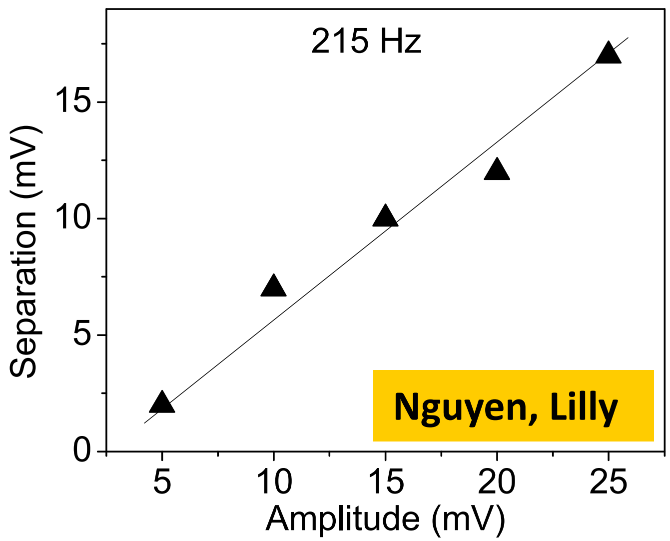


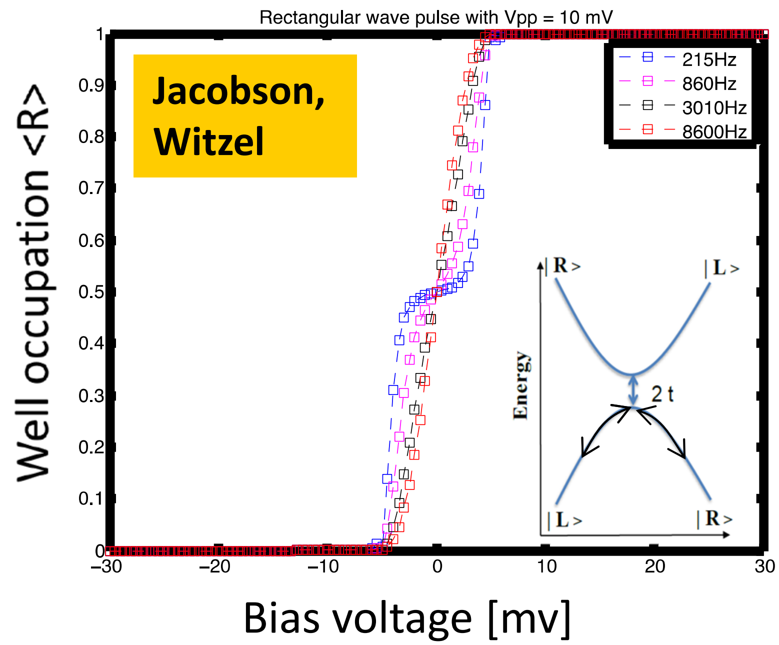
25 mVpp square wave on LP & RP

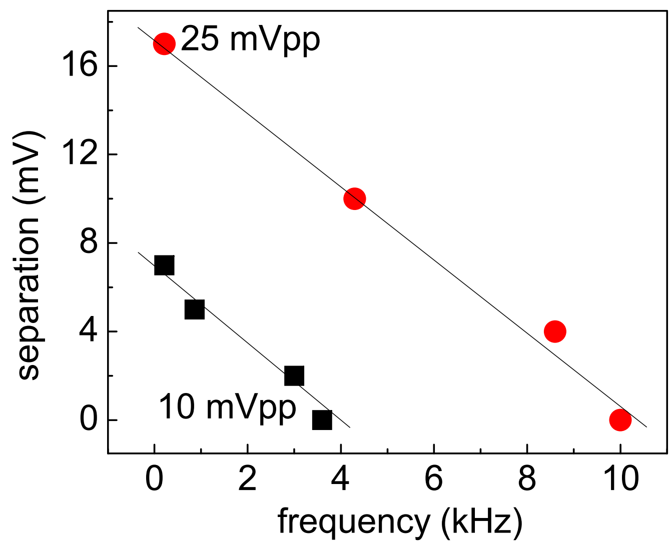


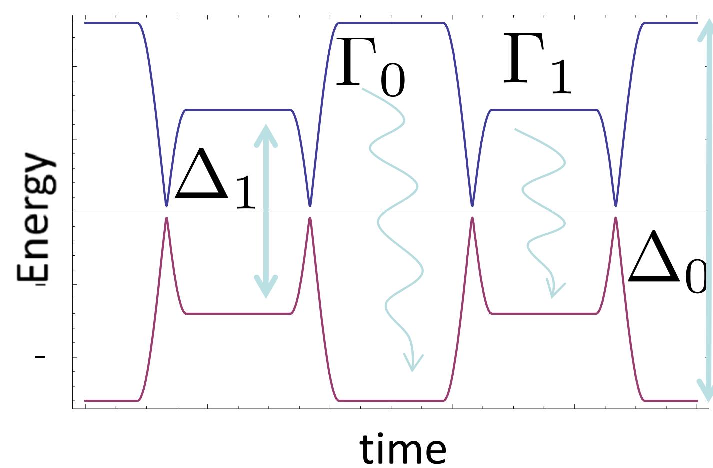


Frequency dependent average occupation







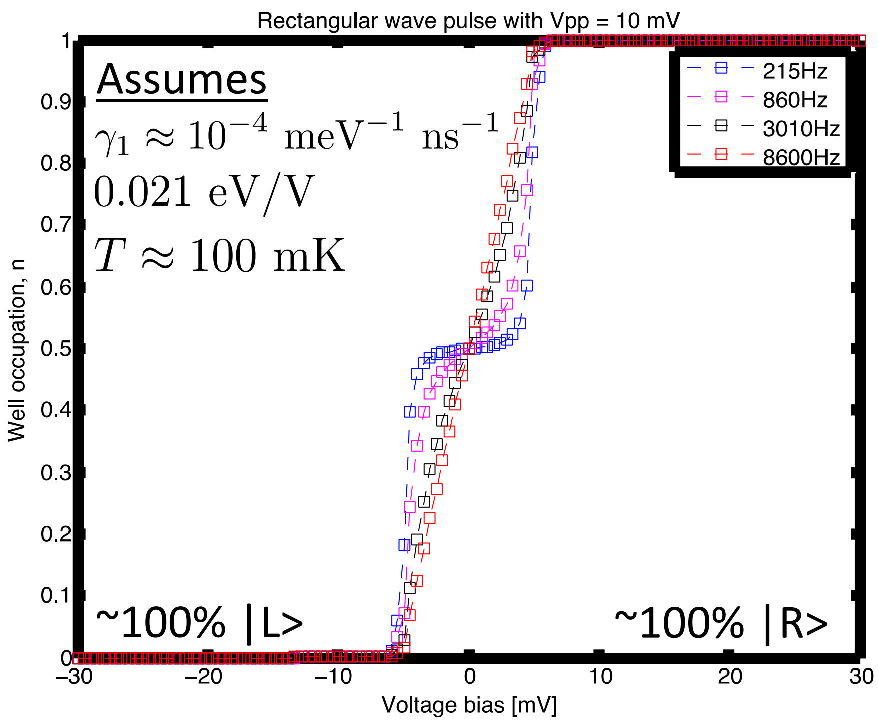


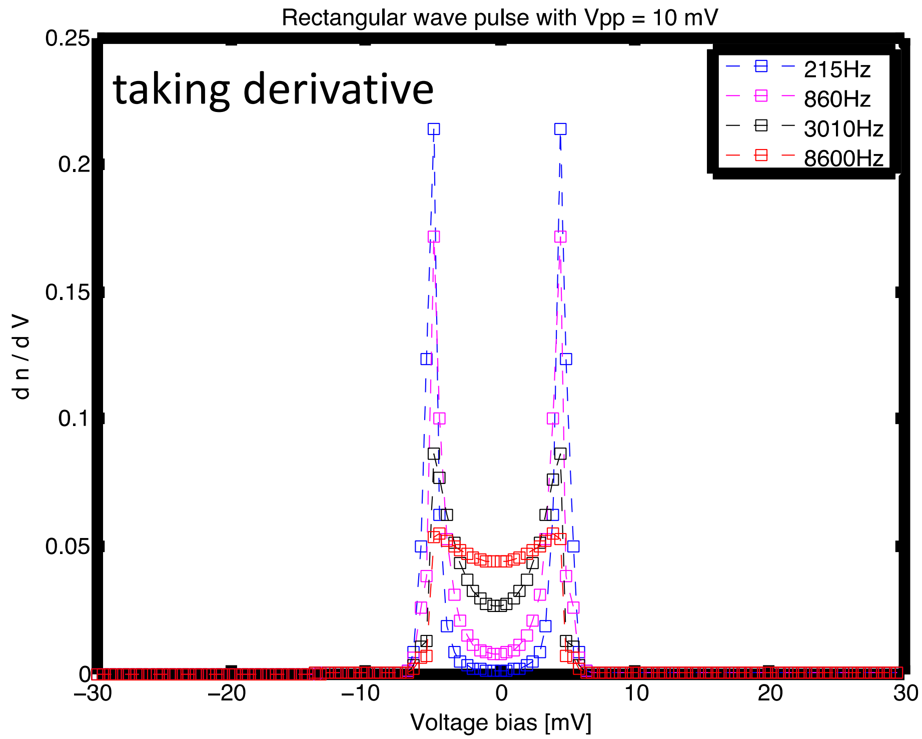
Phenomenological model

Inelastic tunneling:
$\Gamma(\omega) = \left(\frac{\Delta}{\varepsilon}\right)^2 J(\omega)$

Linear dependence of relaxation rate on gap ("Ohmic"):

$$\Gamma(\omega) = \gamma_1 \omega e^{-\omega/\omega_c}$$



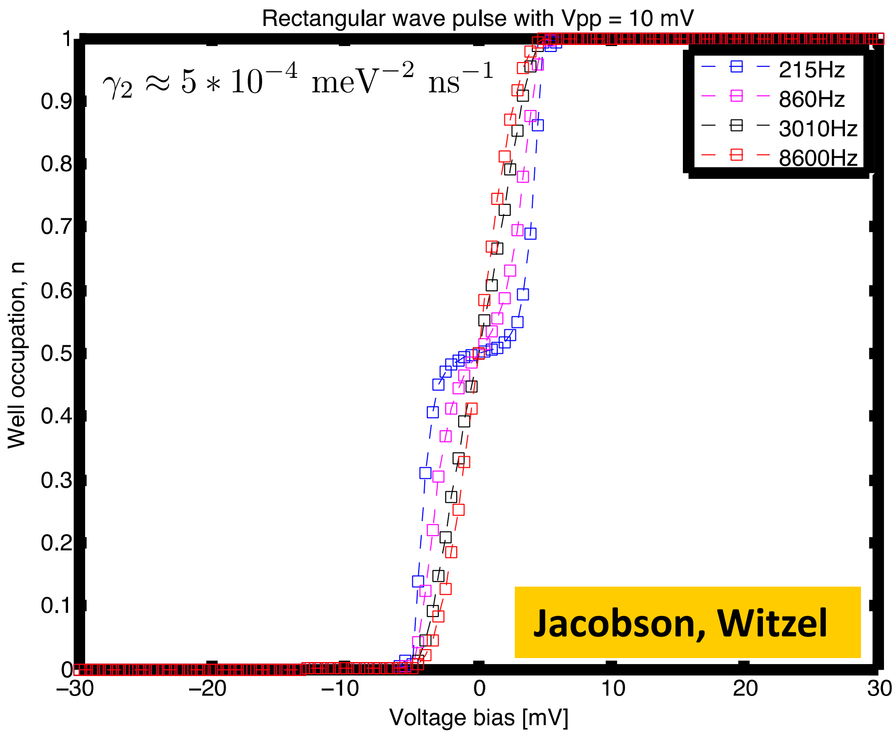


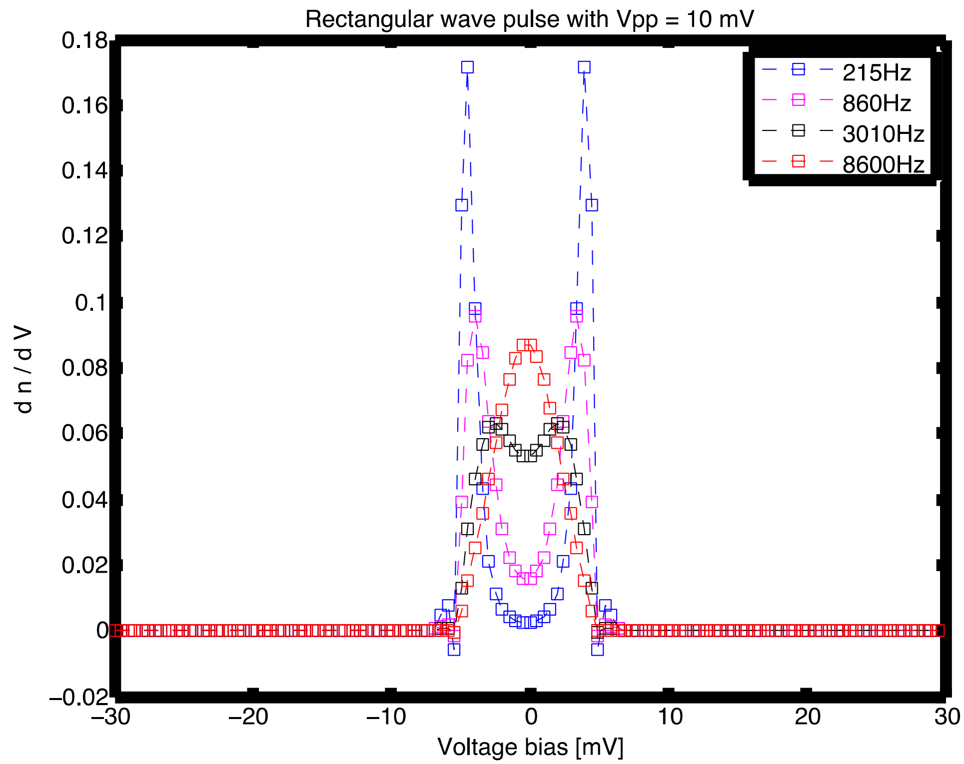
- Average charge between two peaks is 0.5 when wait time is slower than relaxation time
- Form of peak merging suggests its energy dependence
- Ohmic dependence does not qualitatively reproduce behavior

Phenomenological model

Now, choosing a quadratic dependence of relaxation rate on gap for small gap ("super-Ohmic"):

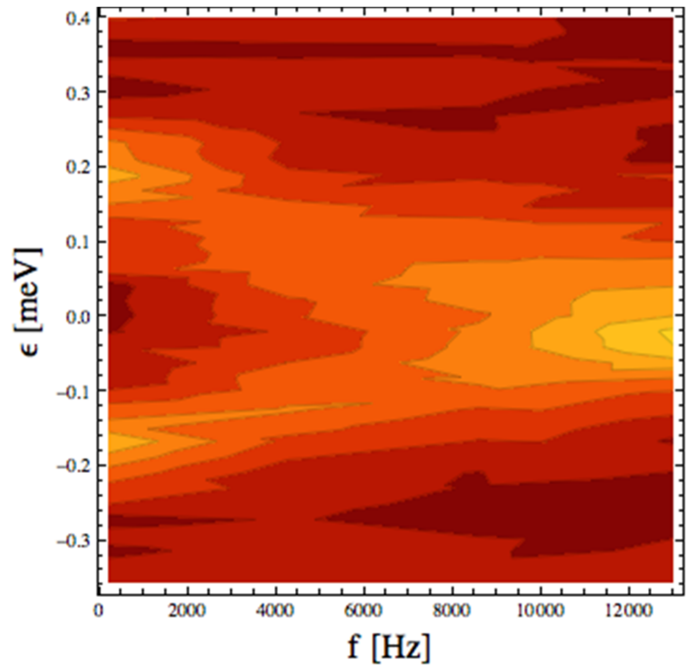
$$\Gamma(\omega) = \gamma_2 \omega^2 e^{-\omega/\omega_c}$$





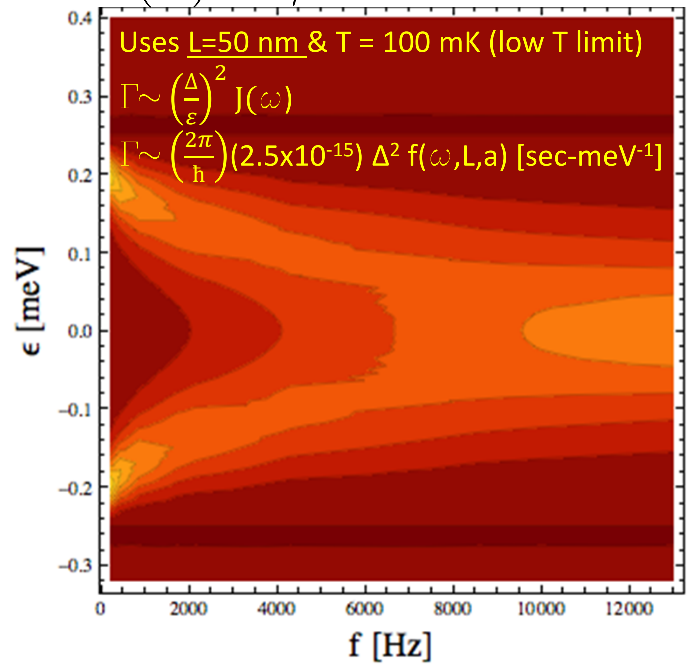
- Super-Ohmic model leads to peaks growing closer together with frequency
- Test of adiabatic evolution: two peaks emerge from one due to slower ramp or stronger tunneling

Experiment: V_{pp} = 25 mV

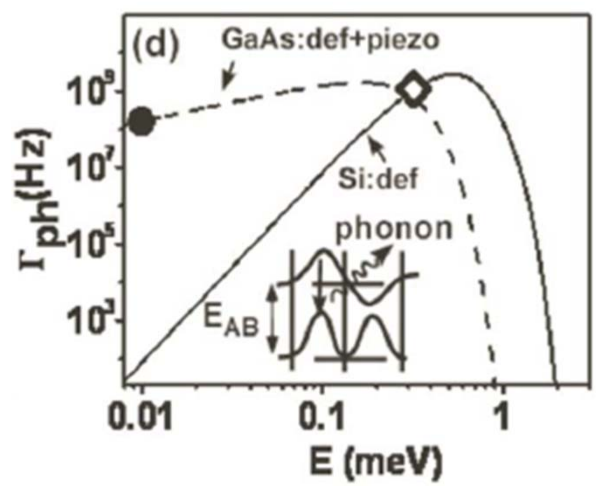


Microscopic theory :

$J(\Omega) = \gamma\Omega^5$

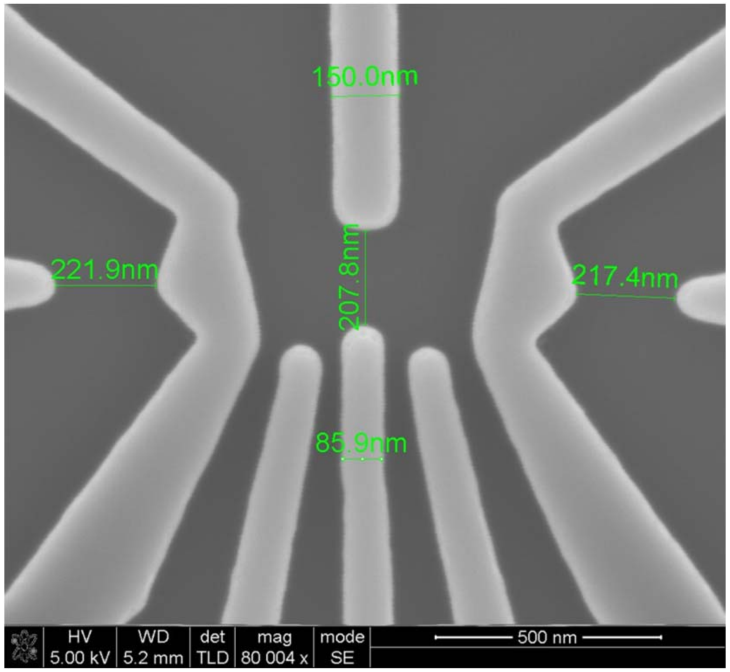


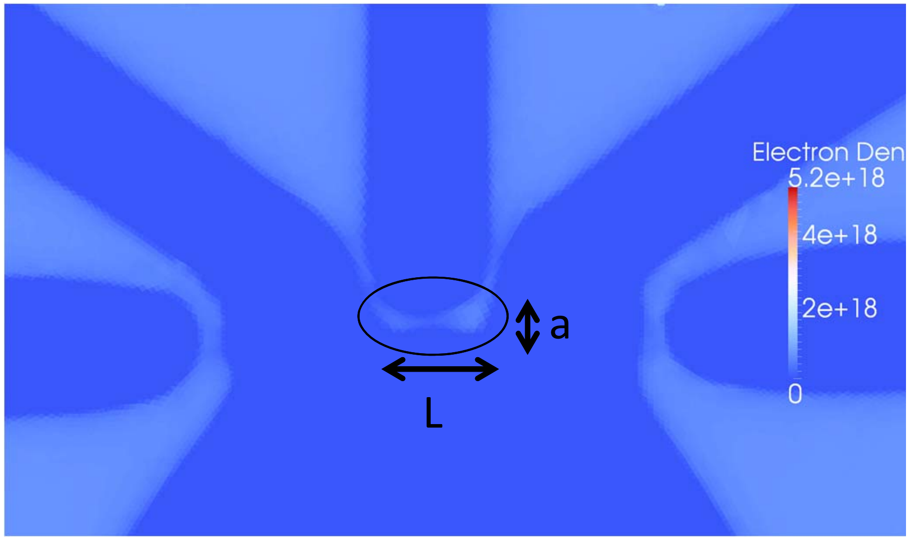
- Dependence consistent w/ acoustic phonons
- Energy dependent relaxation times extracted over wide range in new regime (low energy)
- Prefactor, γ, is an effective fitting parameter
  - ➢ Prefactor is close for several amplitudes
  - ➢ Prefactor is product of D and Δ
- Deformation potential, D, might be extracted in future (Δ is measurable w/ stronger coupling)
- Better than order of magnitude measure of Δ at splitting freq. (for low coupling regime) [different than inelastic rates!]
- Other error: model uses DQD sizes for cut-off ωs



Liu et al., PRB 2008

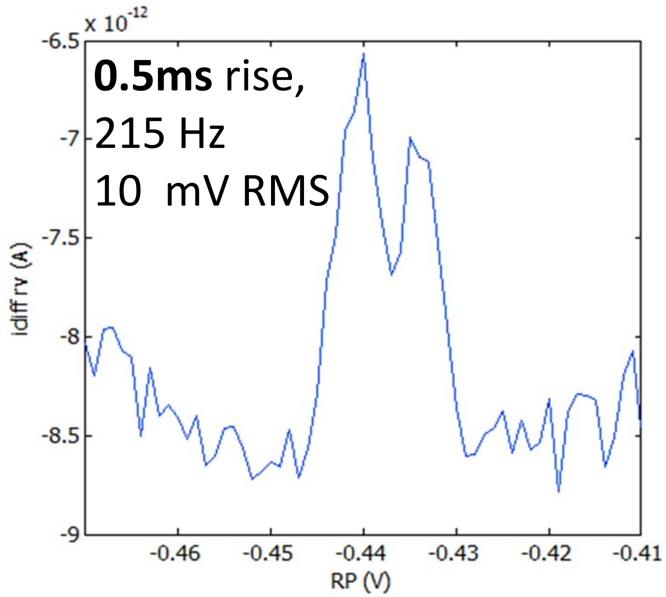
Improved estimates of dimensions w/ QCAD

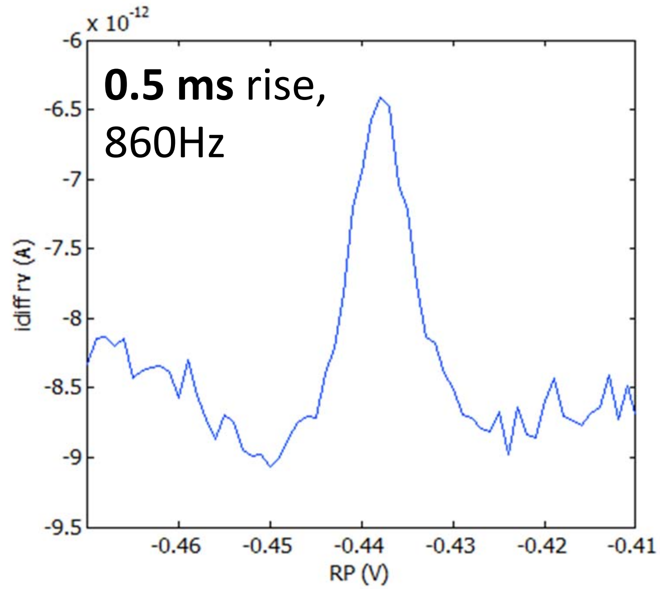


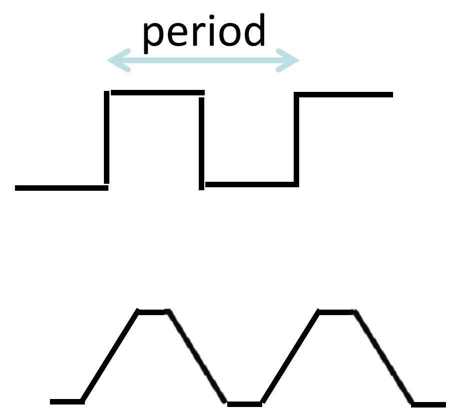


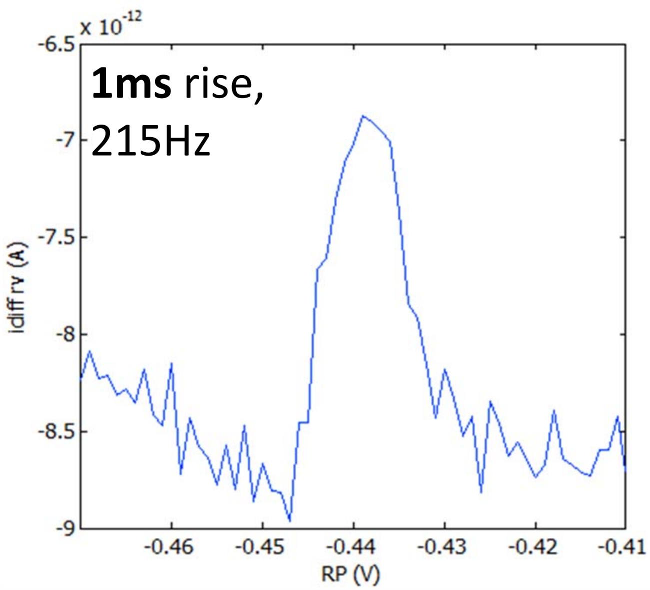
- Cut-off frequencies for phonon coupling depend on DQD dimensions
- Simulation improves confidence in choice of dimensions for fit
- Thresholds and capacitances used to calibrate defect charge

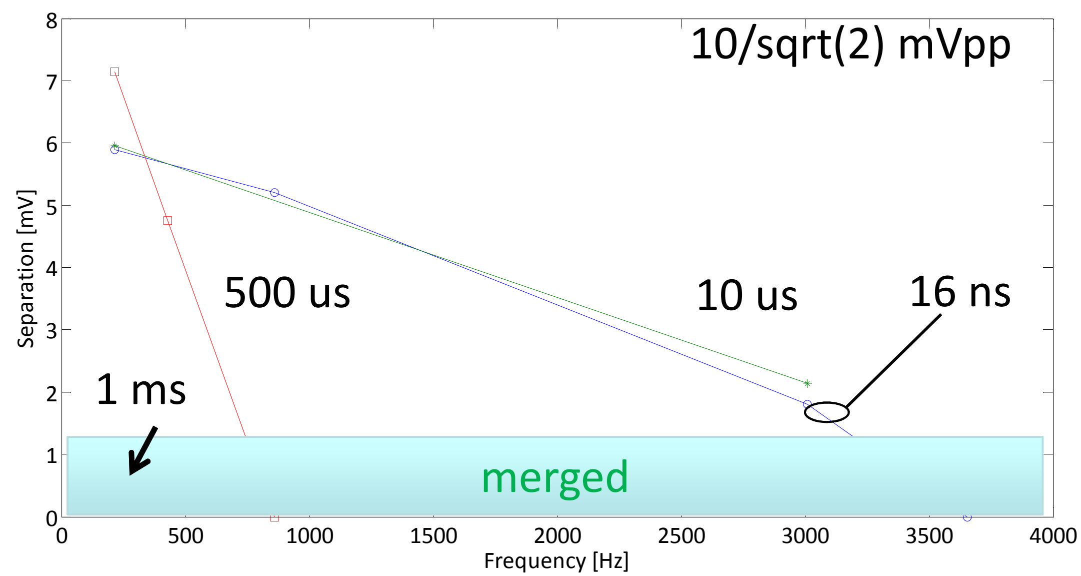
Towards adiabatic pulses (longer ramps)





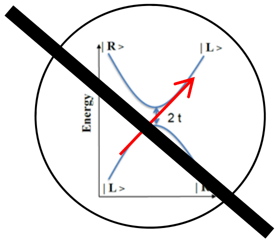






Hallmark of adiabatic L-Z transition: increase the rise time τ until the single peak splits in two, all the while respecting both conditions above.

Adiabaticity condition: $\tau_{ramp} \gg \frac{2h(\delta\varepsilon)}{\pi\Delta^2}$



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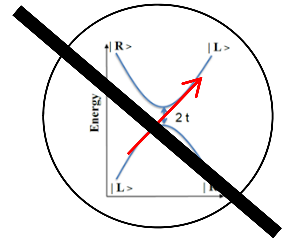
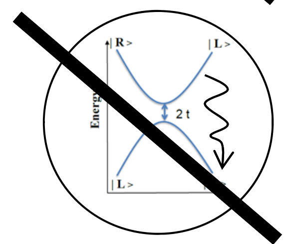
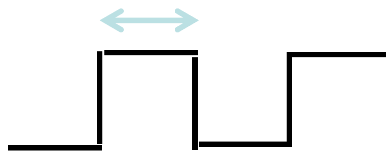
Unassisted by relaxation: $(\tau_{ramp}+\tau_{measure}) \ll \tau_{relax}$

Inelastic tunneling time: $\tau_{relax} = \frac{1}{\left(\frac{\Delta}{\varepsilon}\right)^2 J(\omega)}$





$\tau_{measure}$



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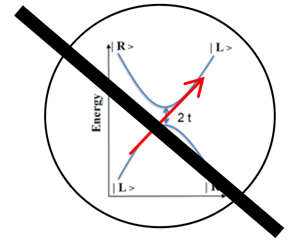
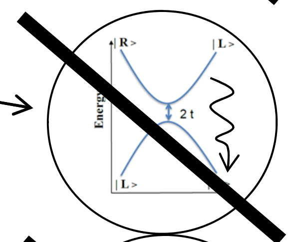
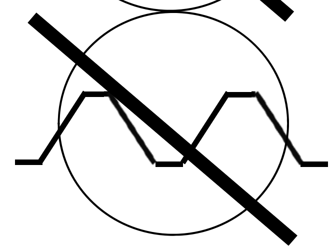
Rectangular wave ratio: $\dfrac{2h(\delta\varepsilon)}{\pi\Delta^2} \ll \tau_{ramp} \ll \dfrac{\tau_{relax}}{w}$







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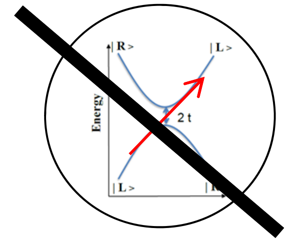

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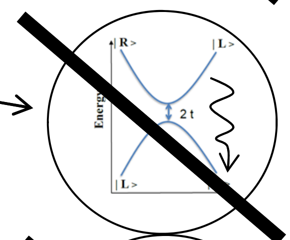
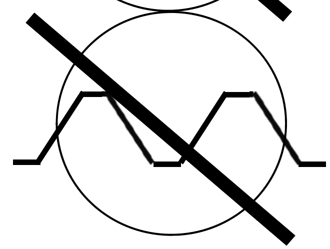


Rectangular wave ratio: $\frac{2h(\delta\varepsilon)}{\pi\Delta^2} \ll \tau_{ramp} \ll \frac{\tau_{relax}}{w}$



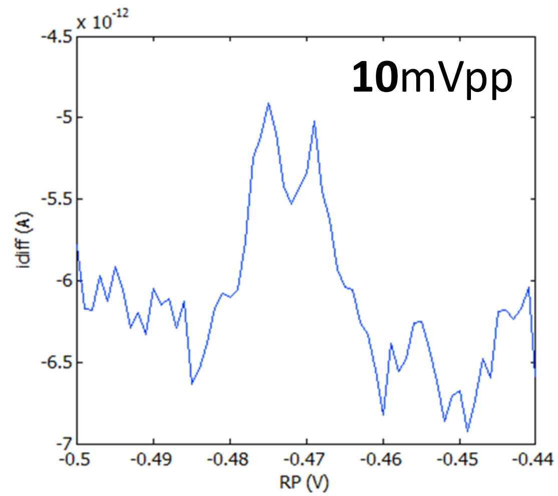
Necessary conditions $\Longrightarrow$ $w \ll \frac{\pi}{2h \times k \times (\delta\varepsilon)^{n-1}}$ & w >> 1 for resolvable peaks

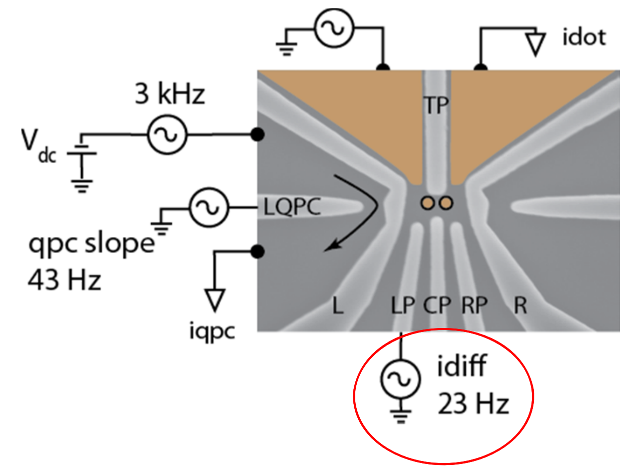
$$\tau_{ramp} \gg \frac{2h(\delta\varepsilon)}{\pi\Delta^2}$$

Future devices for adiabaticity test

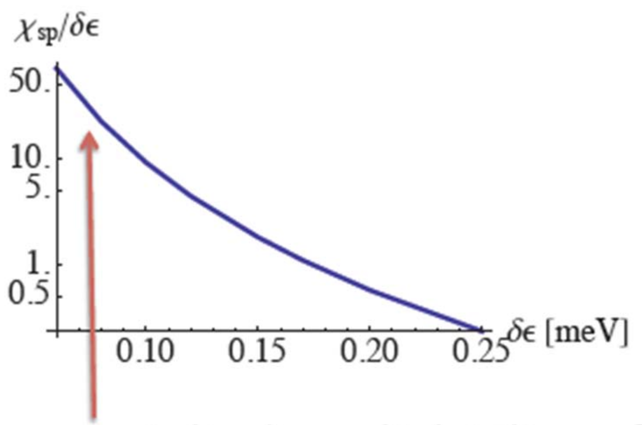
Smaller detuning!

$$w \ll \frac{\pi}{2h \times k \times (\delta\varepsilon)^{n-1}}$$





Jacobson



required toggling amplitude in this range?

Better charge sensor, more tunability => stronger coupling for D extraction and for photon assisted tunneling

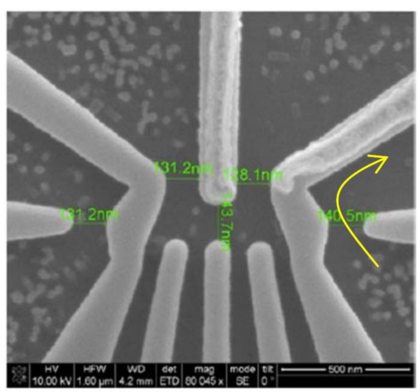
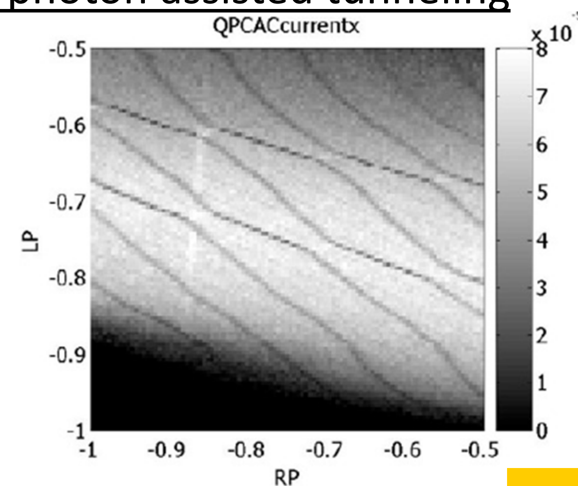


Image of fabricated device: SEM after Poly-Silicon Etch



S. Carr

Summary of adiabiticity experiments & theory

Sandia National Laboratories

- Charge qubit & elements of LUBO evolution demonstrated (MOS DQD)

- Double pulse reveals deviation from thermal distribution
  - non-adiabatic pumping of excited state
  - Probe of energy dependent relaxation when combined with frequency and detuning magnitude

- Modeling indicates super-Ohmic energy dependence of relaxation consistent w/ acoustic phonons
  - Bounds on tunnel coupling and deformation potential, D, in difficult to probe regime
  - Separate measurement of tunnel coupling is possible for measurement of D

- Adiabaticity test: signature identified for evolution that is unassisted by relaxation
  - Additional consequence: improved estimate of tunnel coupling in difficult to probe regime possible

- Unassisted regime requires small detuning to minimize relaxation times

- Next step: better charge sensing to probe smaller detuning and test whether unassisted regime is observable

Some of the desired measurements

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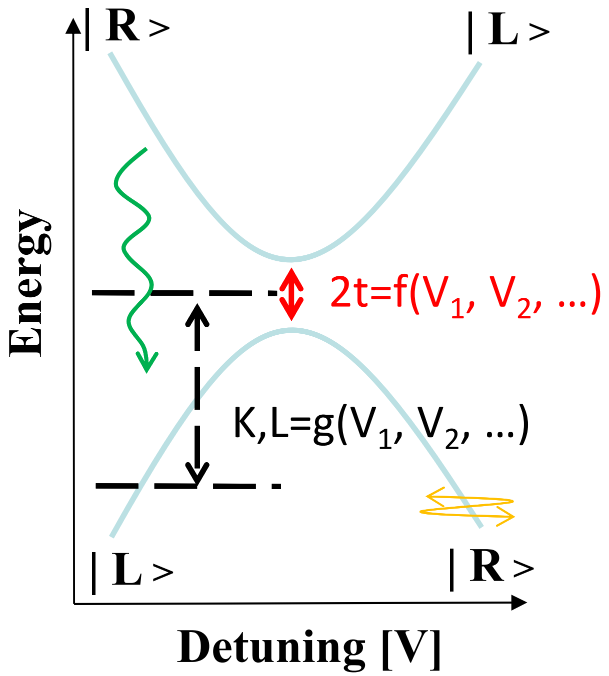
Characterization



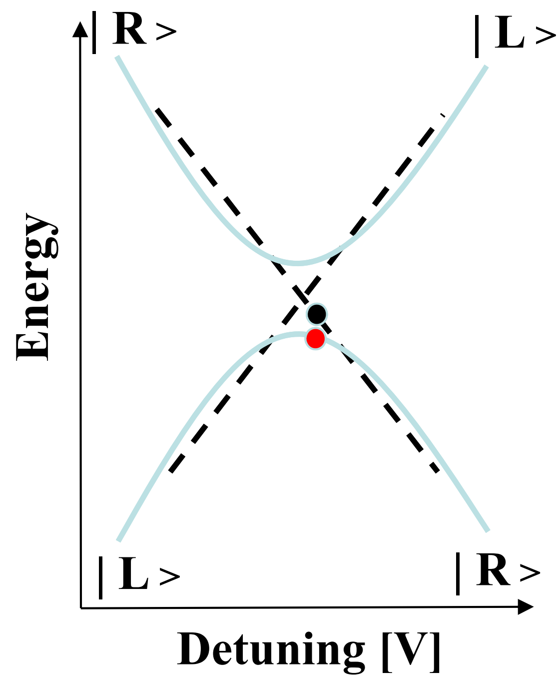
α: Voltage to energy

t: measure tunneling

tau: dissipation time

δε: dephasing noise

QUBO evolution

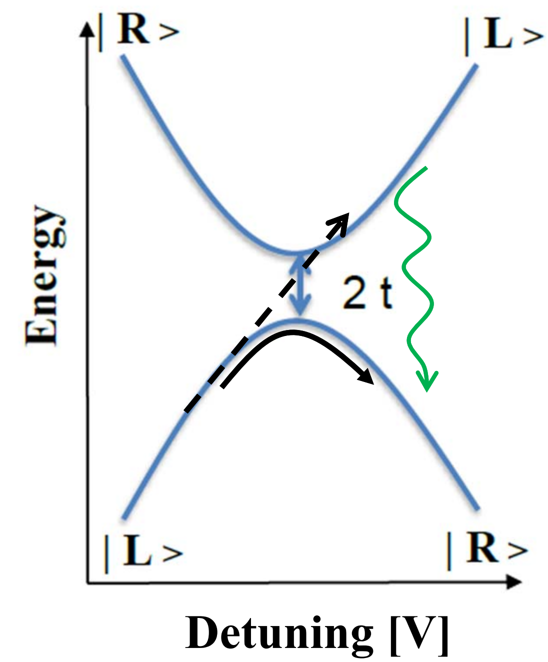


Initialize: strong σ_x

Program: detune σ_z

Solve: reduce σ_x

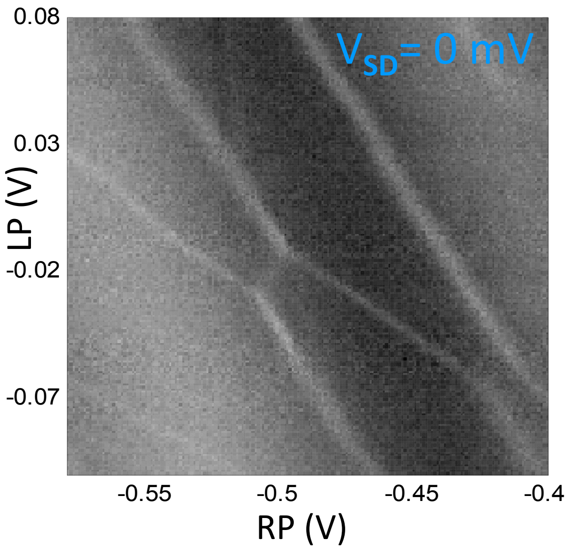
Adiabaticity test

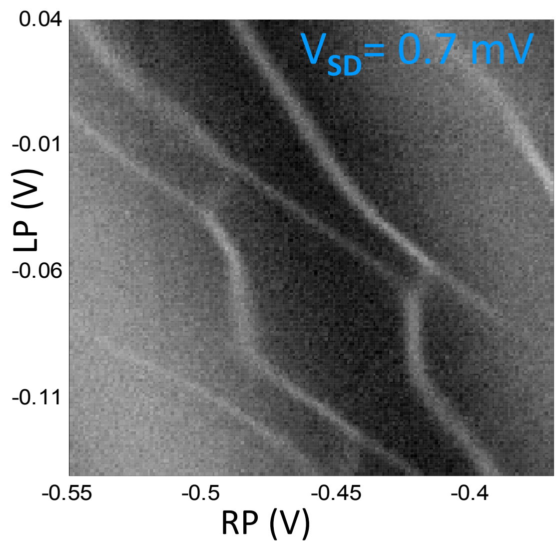


Invent test

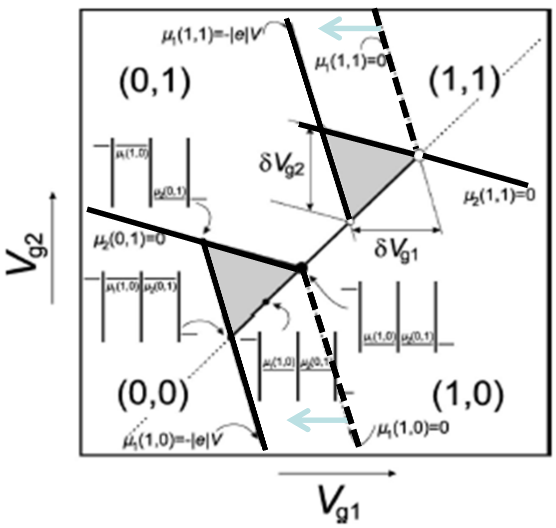
- New regimes & material being measured
- New measurement art or technique necessary

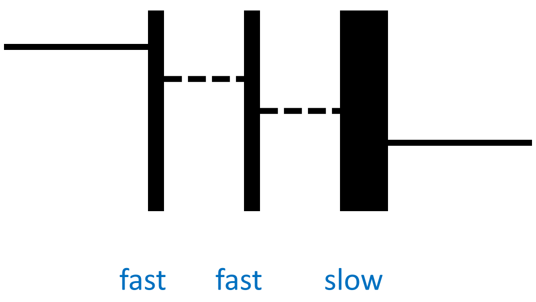
Missing lines in charge sensing



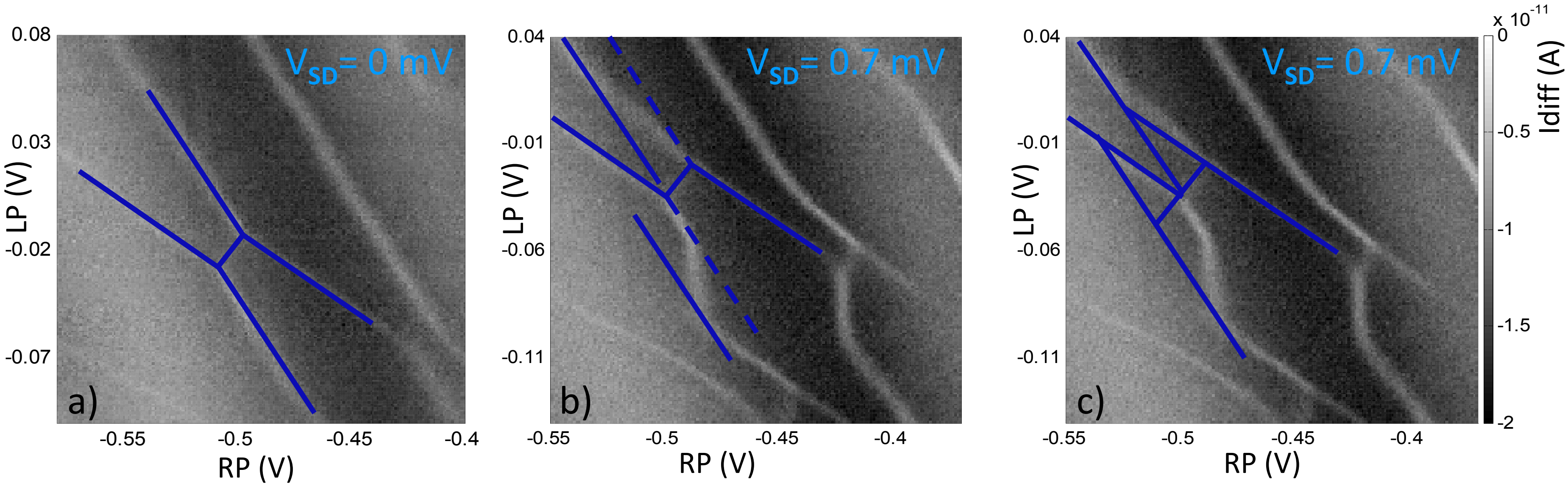


W.G. Van der Weil, RMP (2003)





Missing lines in charge sensing



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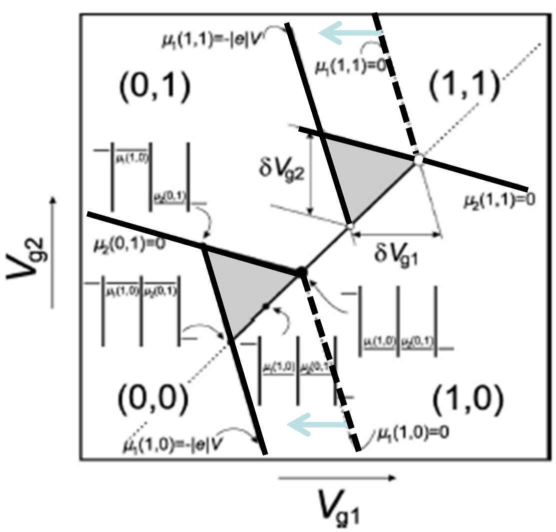
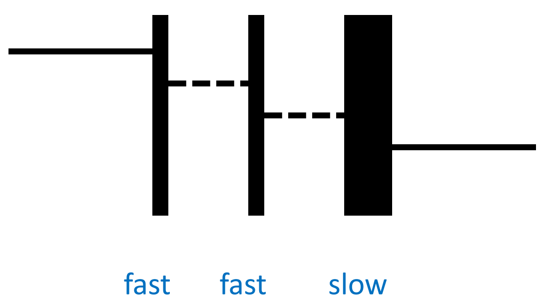
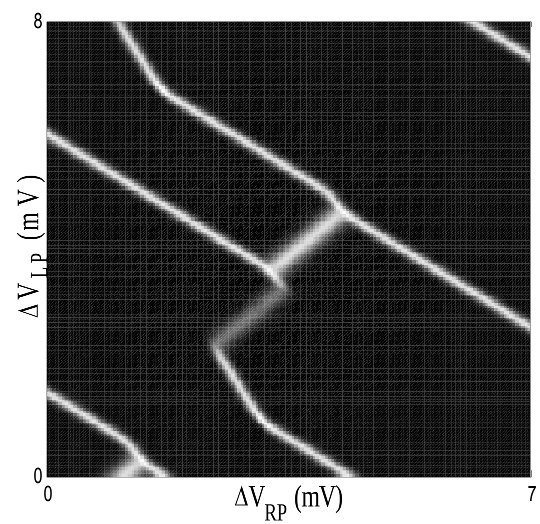






Summary of additional technique development

Sandia National Laboratories

- Tunnel barriers unbalanced in charge qubit
  - Standard approach, balance as much as possible (difficulty reported elsewhere in MOS as well as SNL)
- Developed characterization for voltage to energy for unbalanced tunnel barriers
  - New simulation tool developed to improve accuracy of estimates and understanding
- Observed Pauli blockade (in order to avoid it for charge qubit context)

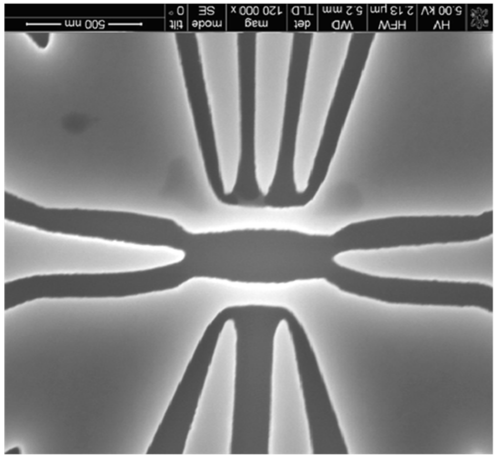
Outline

Sandia National Laboratories

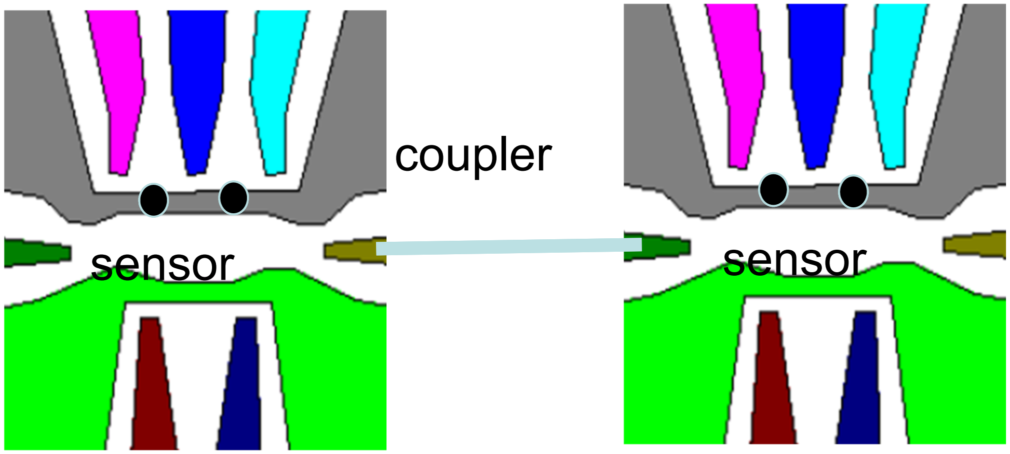
- Review (goals, qubit basics & where we were last EAB)
- Single qubit characterization & evolutions
  - Modeling of qubit relaxation & adiabaticity (Jacobson presentation)
- Development
  - Two qubit structures
  - Atomic precision fabrication (Bussmann presentation)
  - Infrastructure (lab & measurement set-up augmentations)
- Future plans & wrap-up

Qubit fabrication & development topics

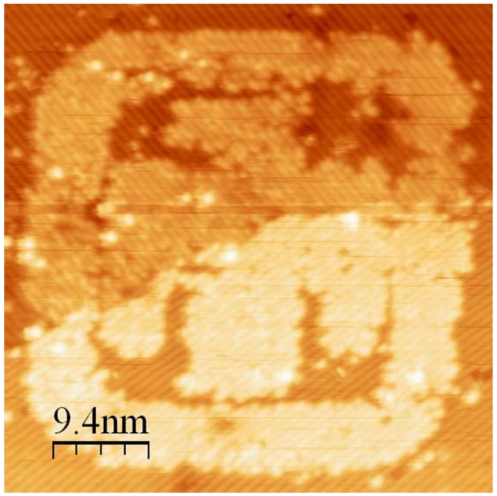
Charge sensing



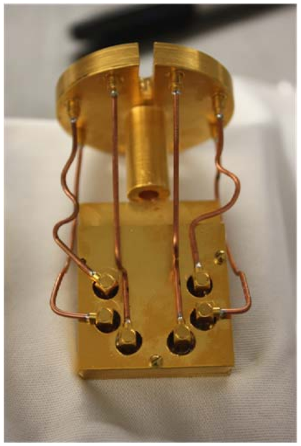
Two qubit structures



STM

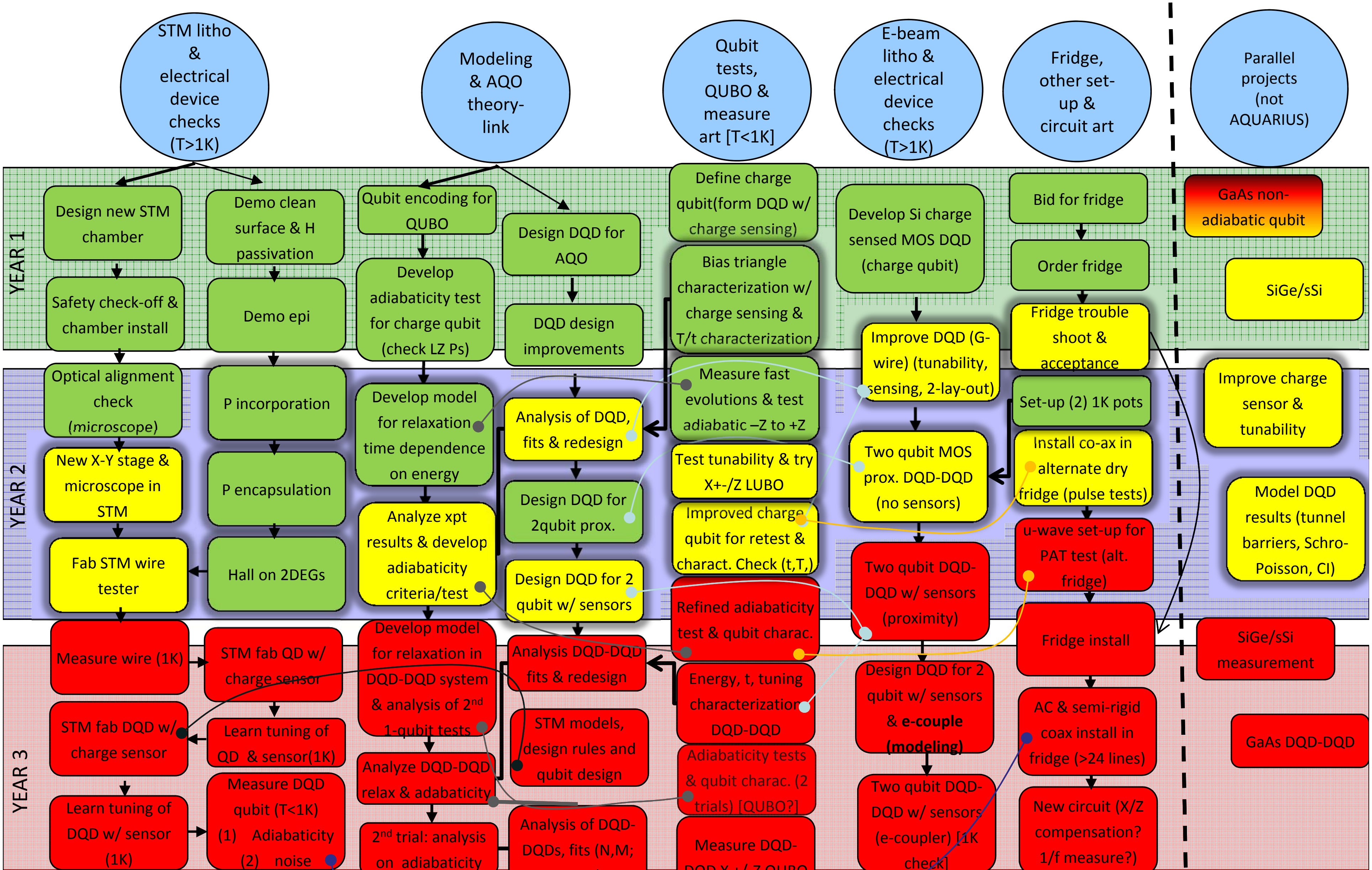


Measurement set-up



Flow chart with milestones

Sandia National Laboratories



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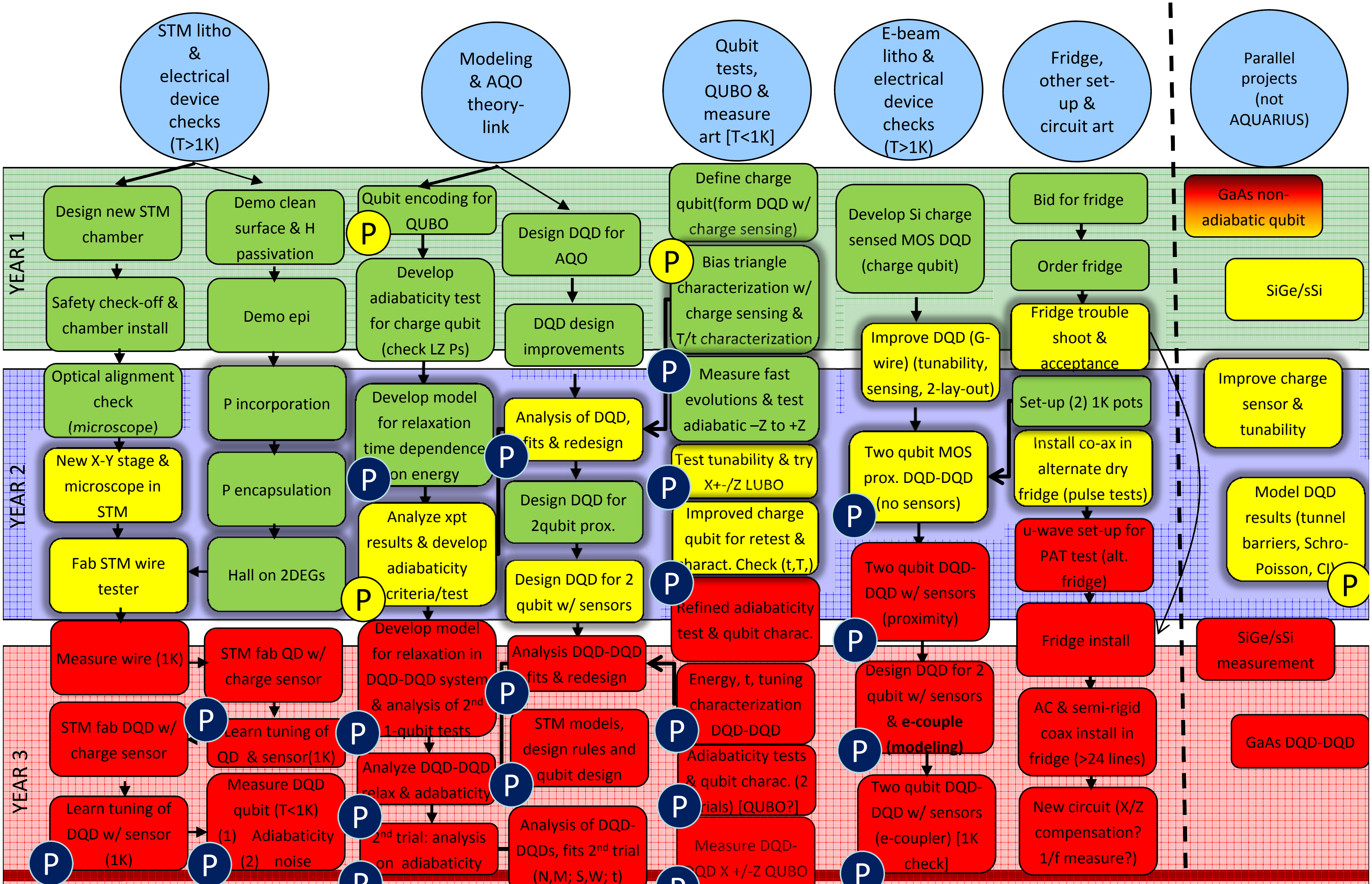
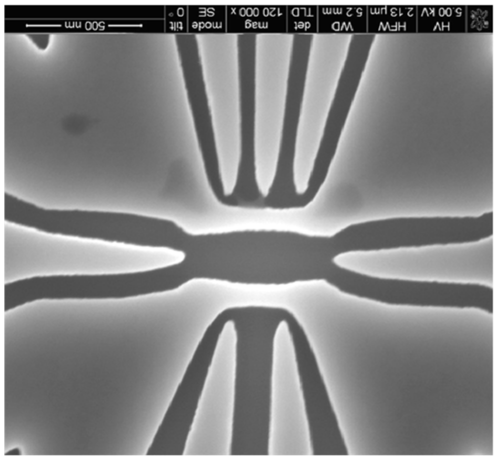
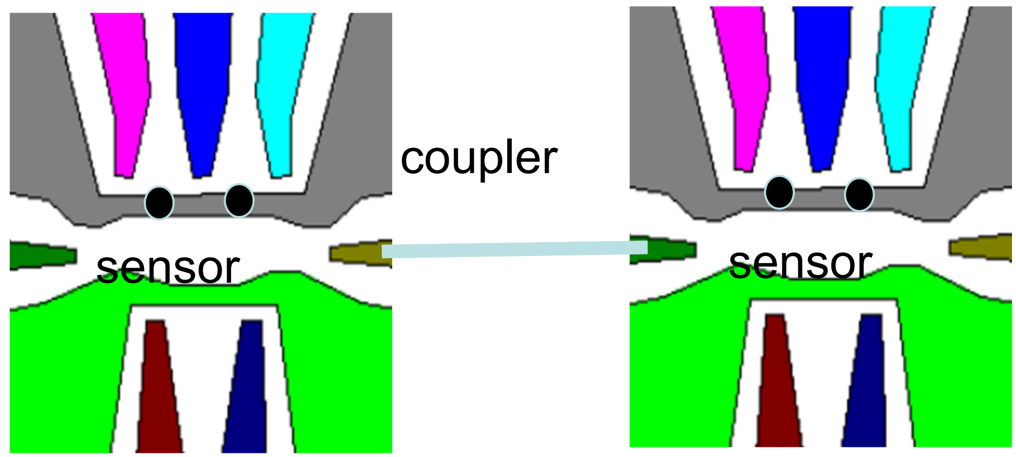


Qubit fabrication & development topics

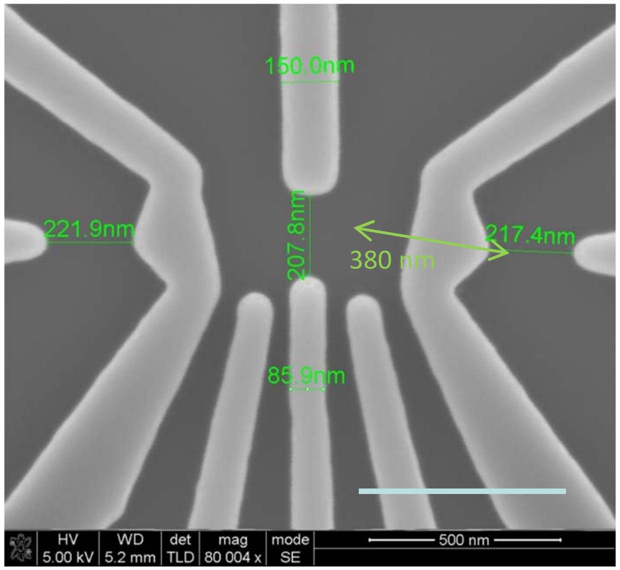
Charge sensing

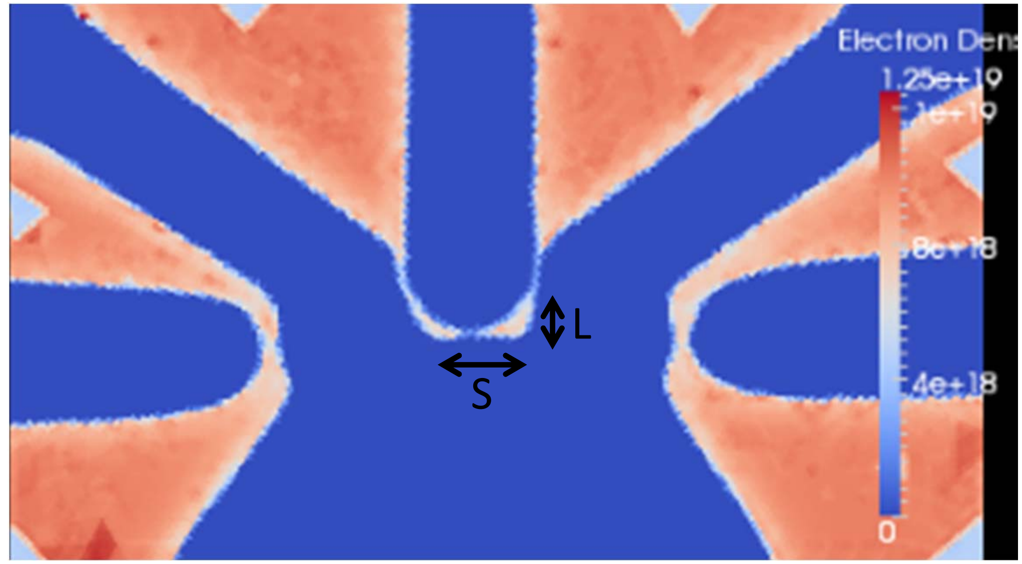


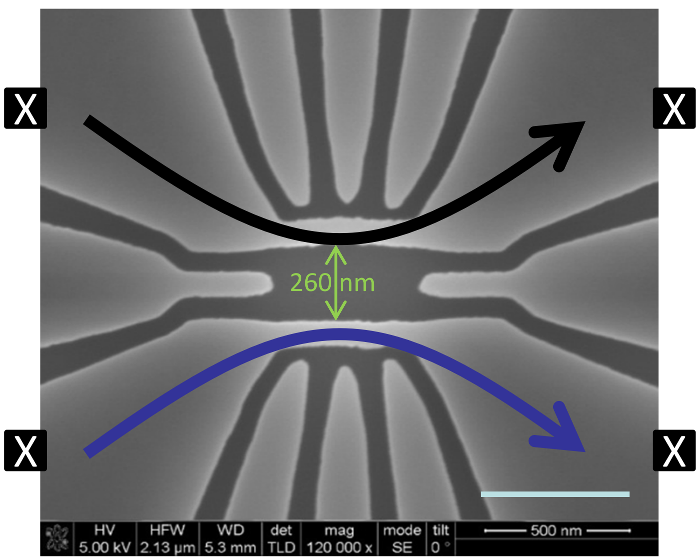
Two qubit structures

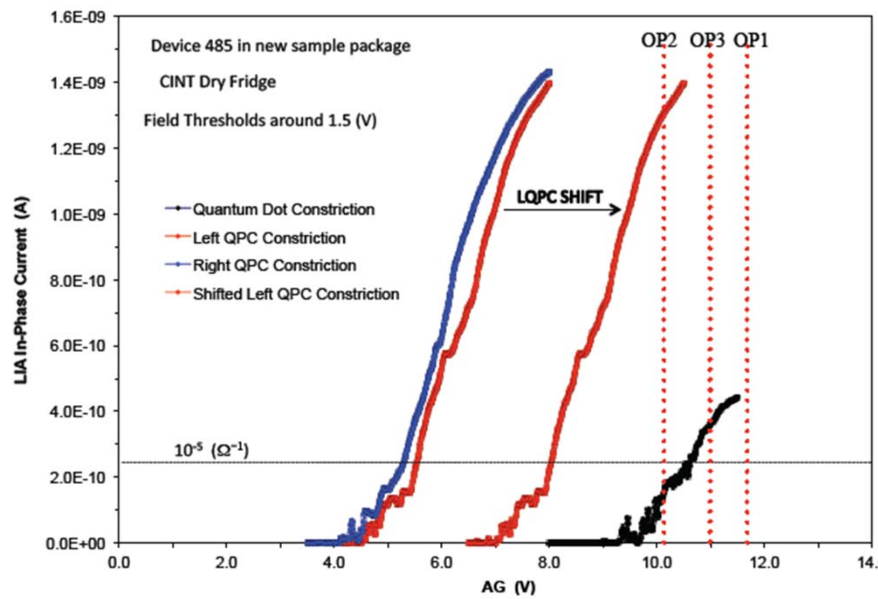


Charge sensing, variable thresholds & improved design

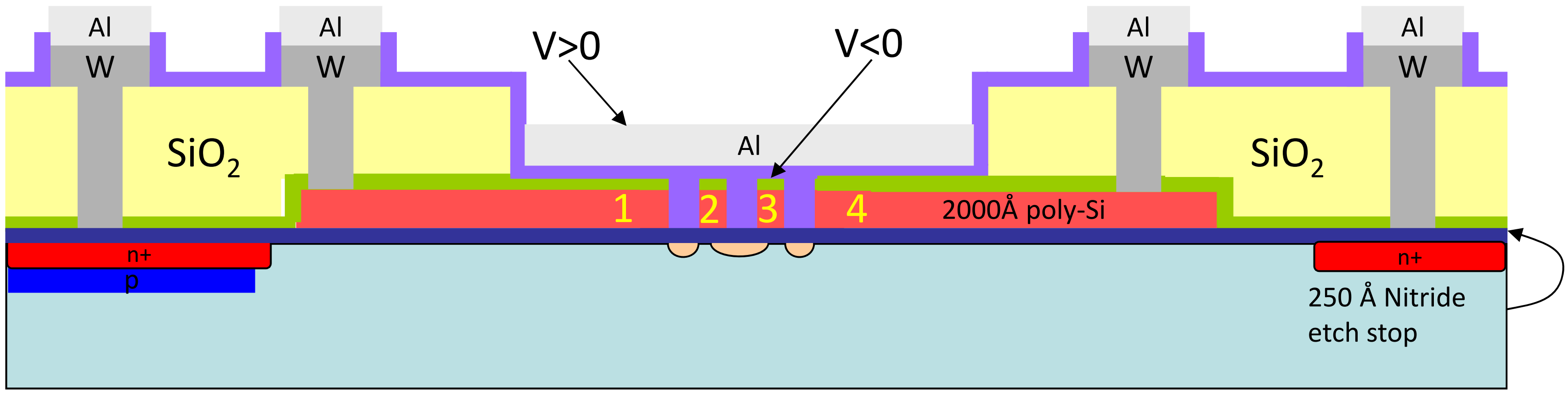


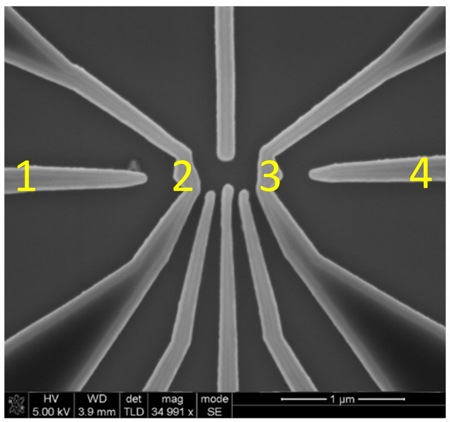


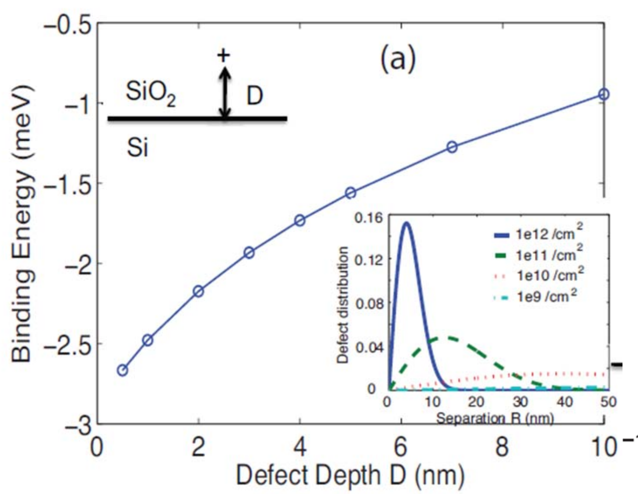




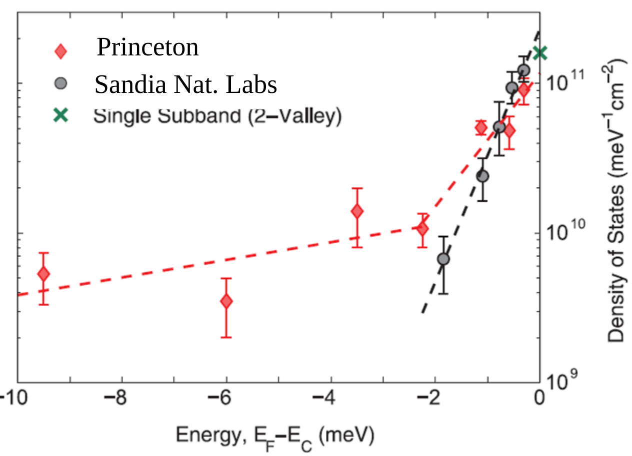
Silicon foundry, back-end & question of other materials (SiGe/sSi) or better processing (STM)?







5,000 cm² / V-s < μ < 15,000 cm² / V-s

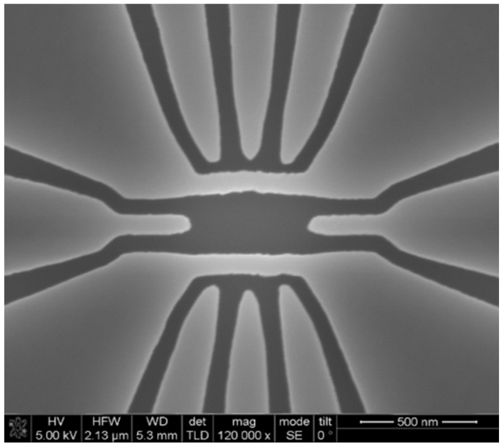


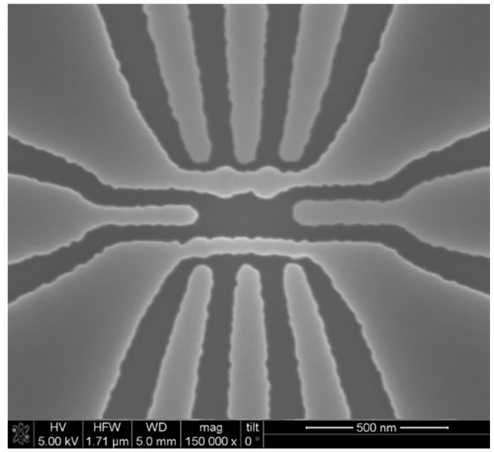
N. Bishop, J. Dominguez, T. Pluym, G. Ten Eyck

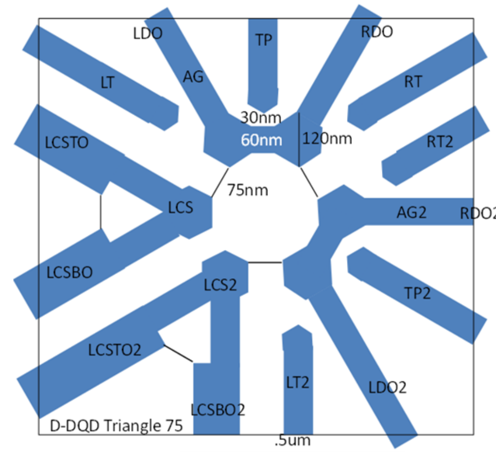
Rahman, arXiv 2012

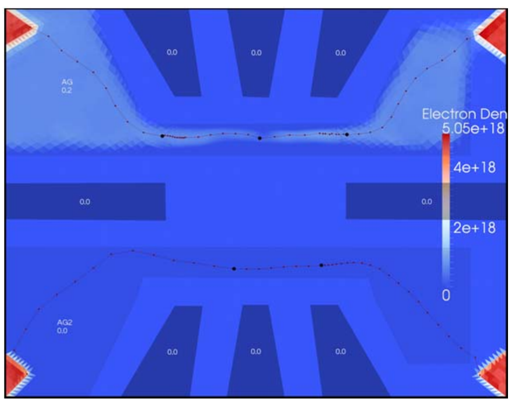
Jock et al., APL 2012

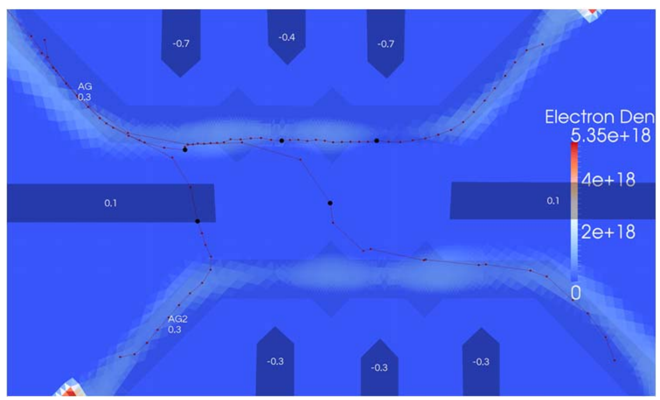
2-qubit designs using proximity coupling

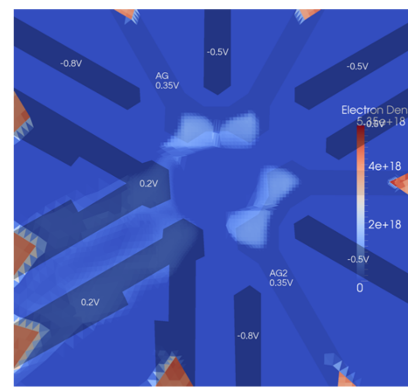






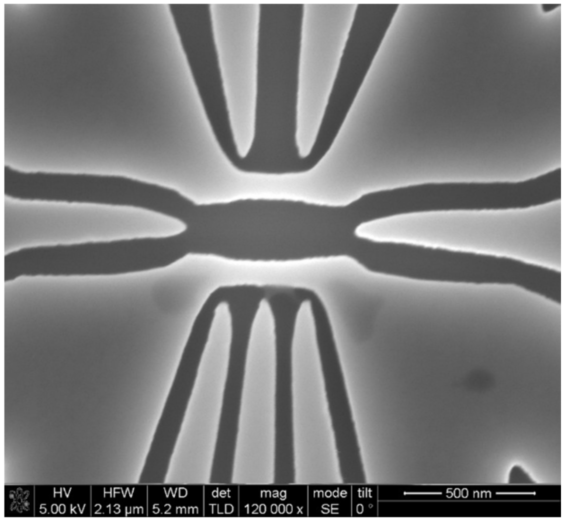


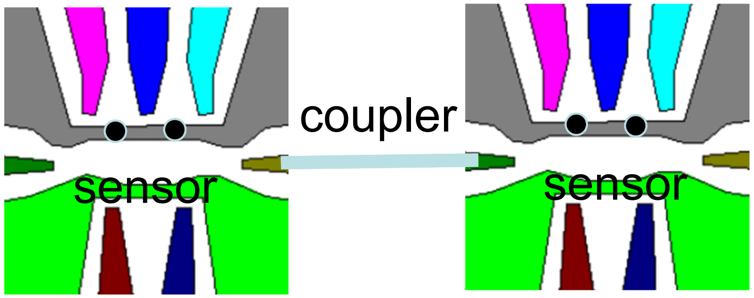


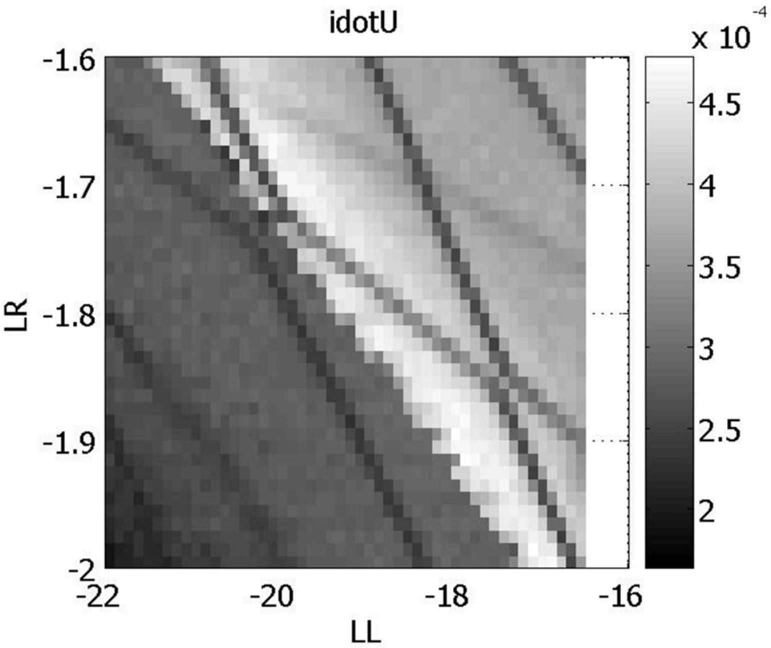


Two qubit test structure & e-coupler

First steps towards two qubit system



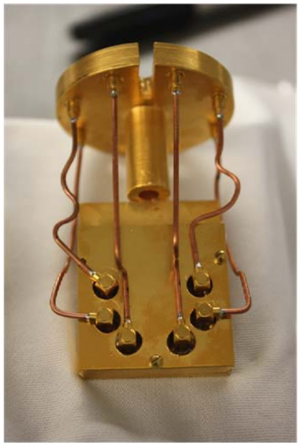




- DQD to DQD coupling in progress
- Charge sensed DQD established
  - Indicates QDs are close enough to produce appreciable charge offset
  - Observable offset is promising for adiabatic QC coupling between DQDs

Qubit fabrication & development topics

Measurement set-up



New lab space and equipment (last EAB)

Sandia National Laboratories

October 2010

September 2011

August 2011

October 2011

Bishop

New lab space and equipment (update)

June 2012

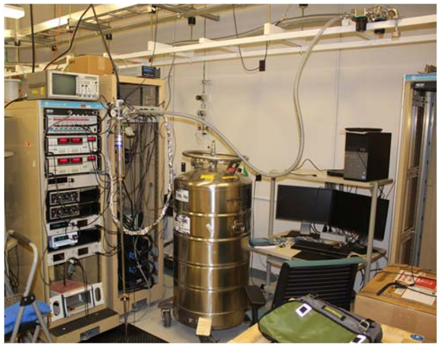
(2) 1K pots set-up

Cryomag. Fridge sent back & scheduled return ?

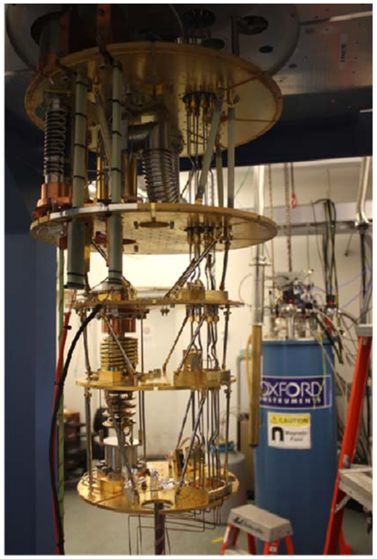
Coax install for fast pulse measurements

New board design for fast pulse/RF

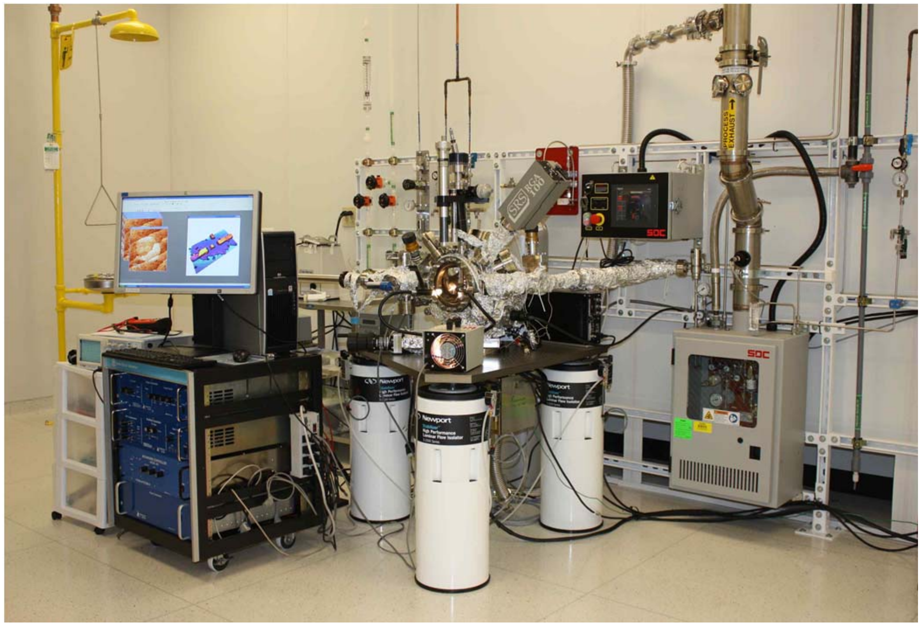
1K pot (Lilly, Dominguez)



RF co-ax (Carr, Dom.)



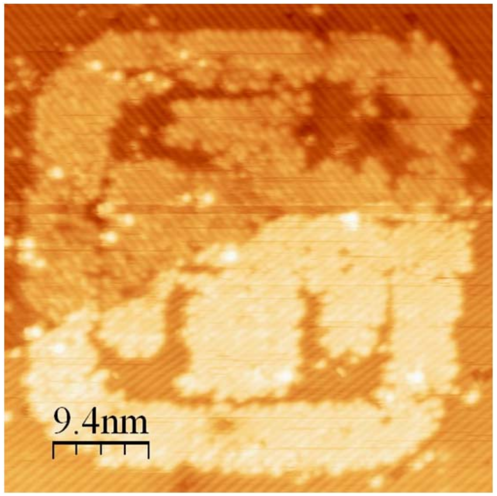
Phosphine installed & turned-on (Bussmann)



Cryomagnetics fridge at company

Qubit fabrication & development topics

STM



Last EAB

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Testing PH_3 system

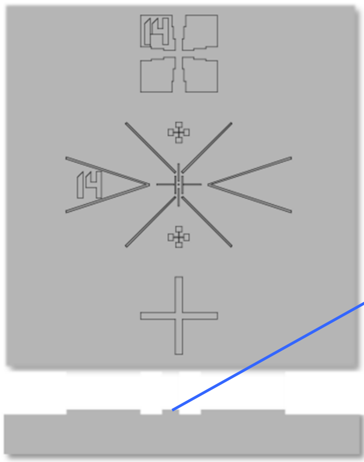
satisfactory

1. Start w clean Si(001)

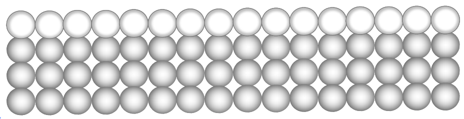
2. Adsorb H resist
Self-limiting 1 monolayer

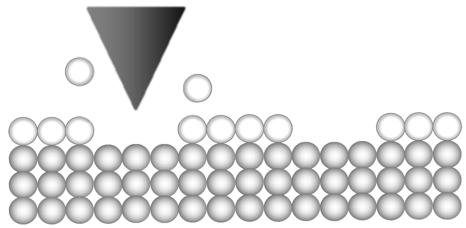
3. Pattern w STM
Atomic-precision

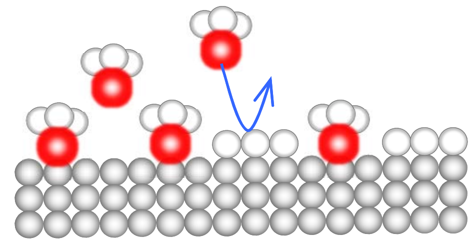
4. Adsorb PH_3



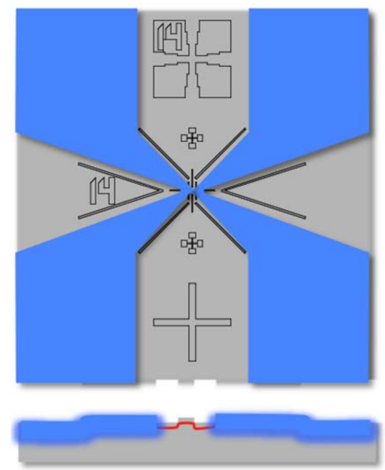
Etched alignment marks
J. Dominguez

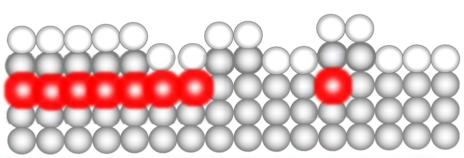


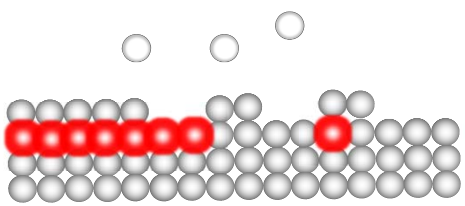


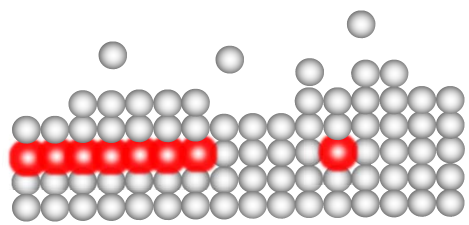


Al depo+liftoff
J. Dominguez









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

6. Desorb H
anneal

7. Bury P in Si

8. Add contacts

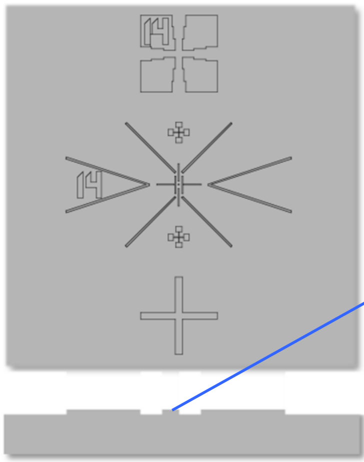
Progress on fabrication steps

1. Start w clean Si(001)

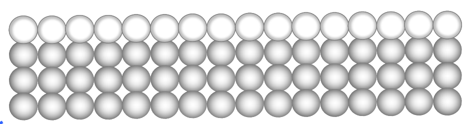
2. Adsorb H resist
Self-limiting 1 monolayer

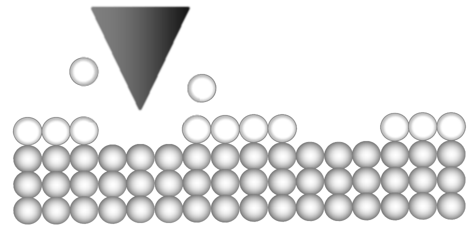
3. Pattern w STM
Atomic-precision

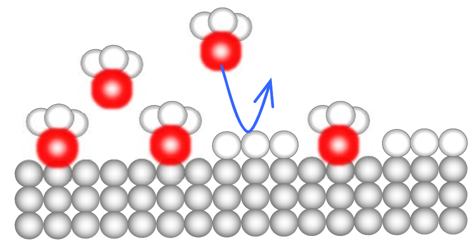
4. Adsorb PH_3



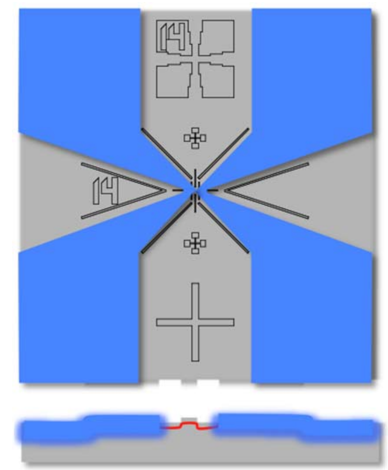
Etched alignment marks
J. Dominguez

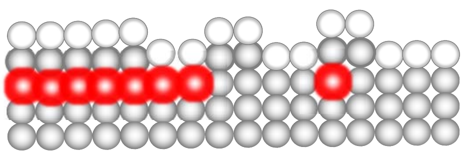


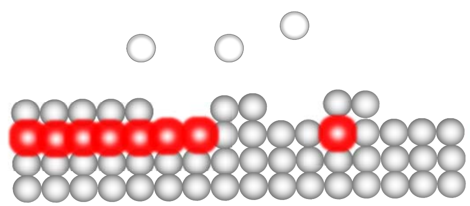


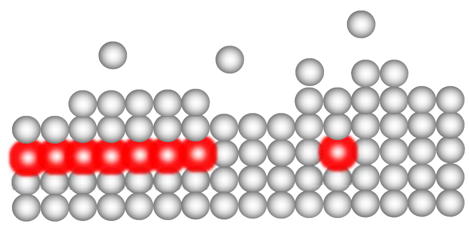


Al depo+liftoff
J. Dominguez









5. Incorporate P
-Anneal→ Si-P swap

6. Desorb H
anneal

7. Bury P in Si

8. Add contacts

Initial transport test devices

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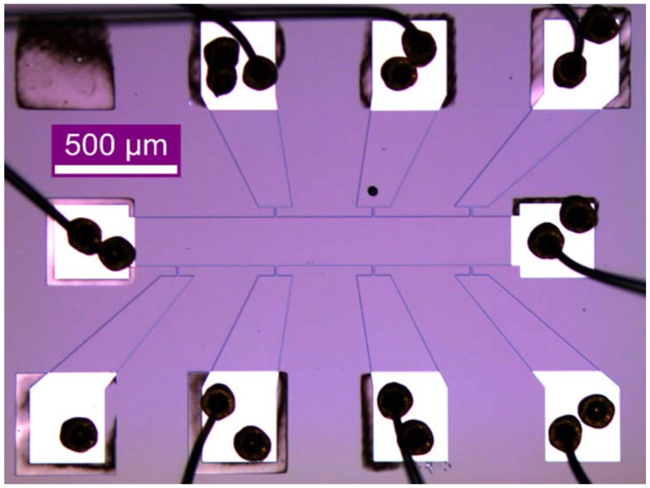
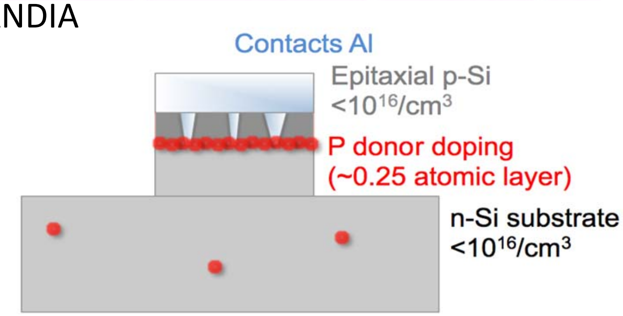
Trench isolated Hall device



SANDIA



- Extract e- density & mobility from longitudinal R_{xx} and transverse R_{xy} Hall resistance

Electron density and mobility at T=4K

Device	e^- density n_e 10^{14} /cm²	e^- mobility cm²/Vs
1	0.7	127
2	0.7	143
3	1.2	122

- Similar Hall effect devices from Simmons yielded n = 1.2-1.7x10^{14}/cm² mobility<100 cm²/Vs

- **Donor and electron density sufficient for atomic precision devices**
- **Next step: implement complete atomic-precision fab technique**

STM two donor qubit lay-out (crowding)

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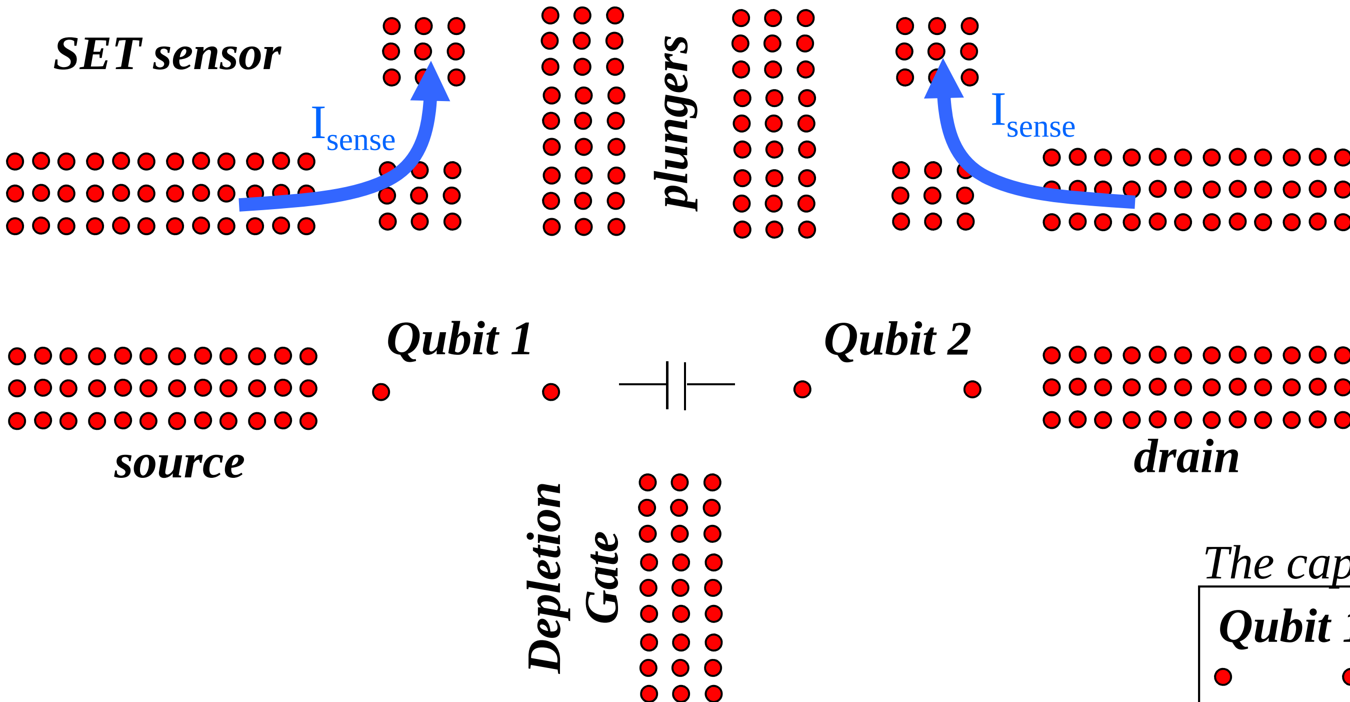
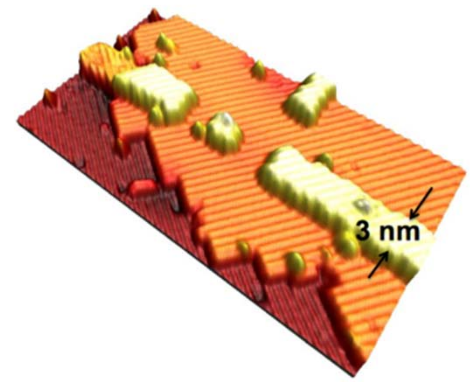
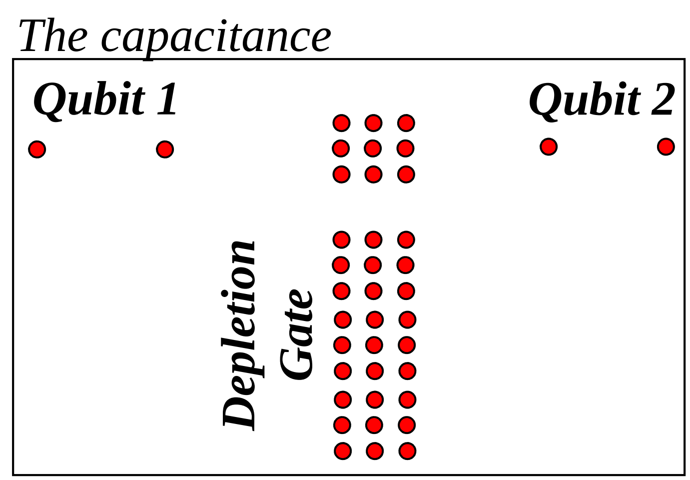




Bussmann (Sandia)



- DQDs are two donors or clusters
- Each DQD needs a charge sensor and plungers
- Coupling between DQDs also necessary
- Crowded lay-out
- Improvements
  - Source/drain are not necessary (no supply of electrons necessary)
  - Dogbone with multi-layer would help
  - Still need to connect electrodes to outside world?

Outline

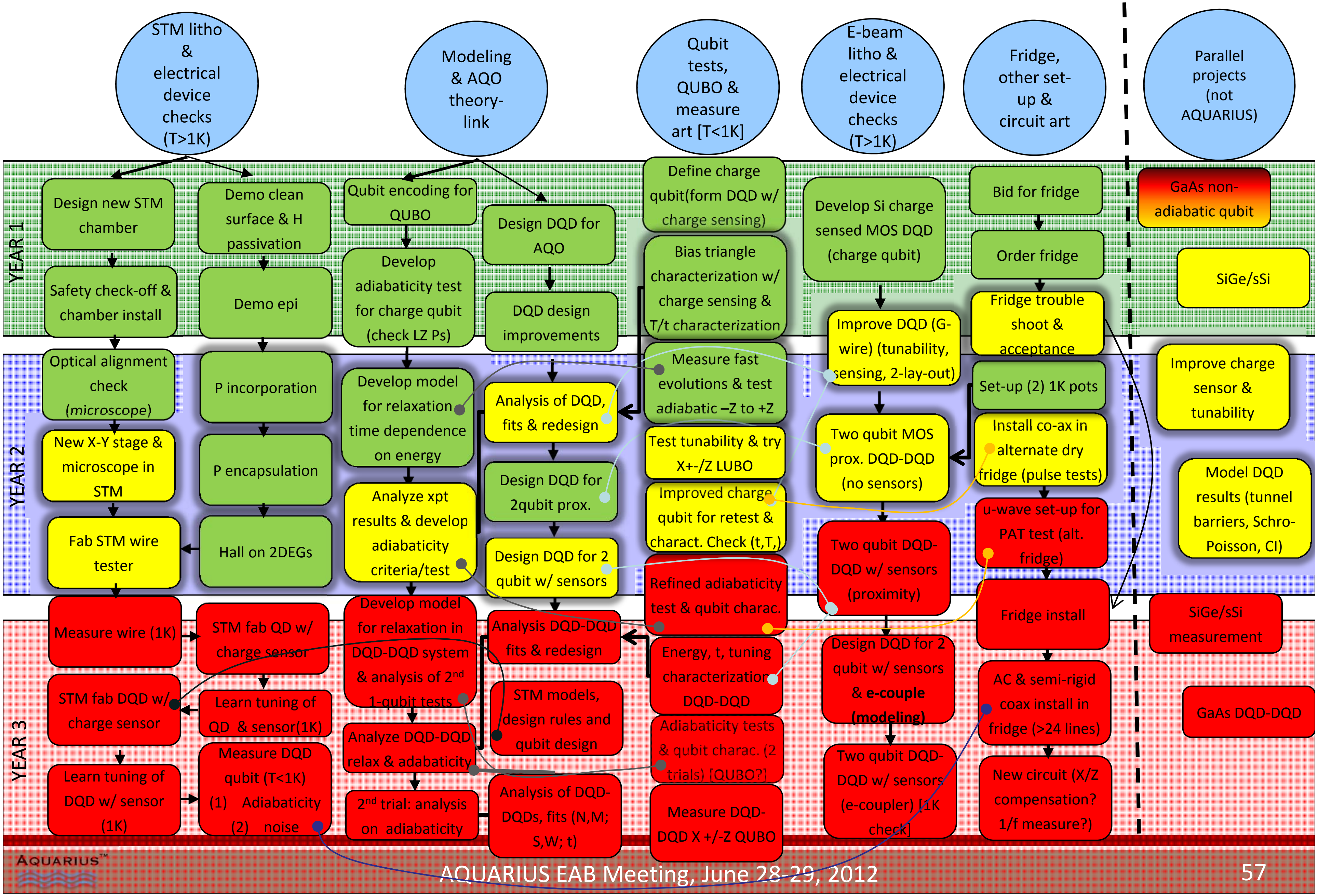
- Review (goals, qubit basics & where we were last EAB)

- Single qubit characterization & evolutions
  - Modeling of qubit relaxation & adiabaticity (Jacobson presentation)

- Development
  - Two qubit structures
  - Atomic precision fabrication (Bussmann presentation)
  - Infrastructure (lab & measurement set-up augmentations)

- Future plans & wrap-up

Flow chart with milestones



Next steps (before next EAB)

Single qubit: Improve DQD & test adiabatic limits

- Rerun energy dependent relaxation measurement w/ more tunable device
  - ❑ Extract tunnel coupling separately for measurement of D
- Rerun benchmark test on DQD with better charge sense signal (& tunable)
  - ❑ Test whether unassisted regime is observable
  - ❑ Test whether tunnel coupling can be characterized at low t-coupling
  - ❑ Test X to Z LUBO in unassisted regime if observable
- Attempt dephasing measurement to characterize noise (photon assisted transport)

Continue developing 2 qubit system (DQD-DQD)

- Characterize magnitude of coupling between wires [QD-DQD]
- Measure existing DQD-DQD devices & tune 2 qubit interaction (transport measurement)
- Fabricate and tune-up charge sensed 2 qubit structures (1st trial)
- Develop adiabatic and relaxation test for two qubits

Develop electrical devices using atomic precision fab processing

- Demonstrate first lithographic devices (put all pieces together)
- Demonstrate charge sensed SET
- Fabricate charge sensed DQD

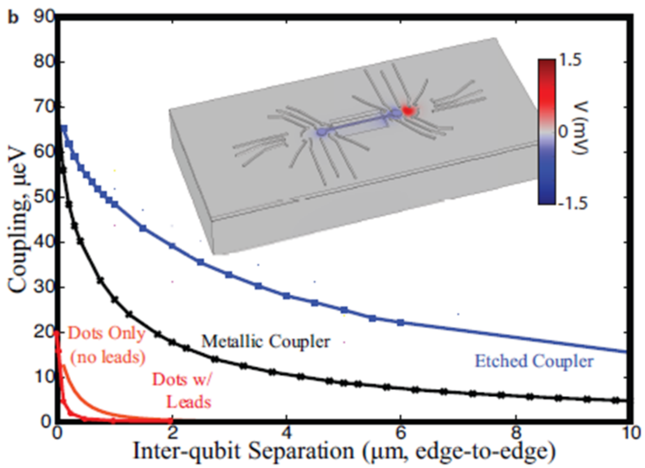
Get fridge running

Fine grain for next 2 months on measurements

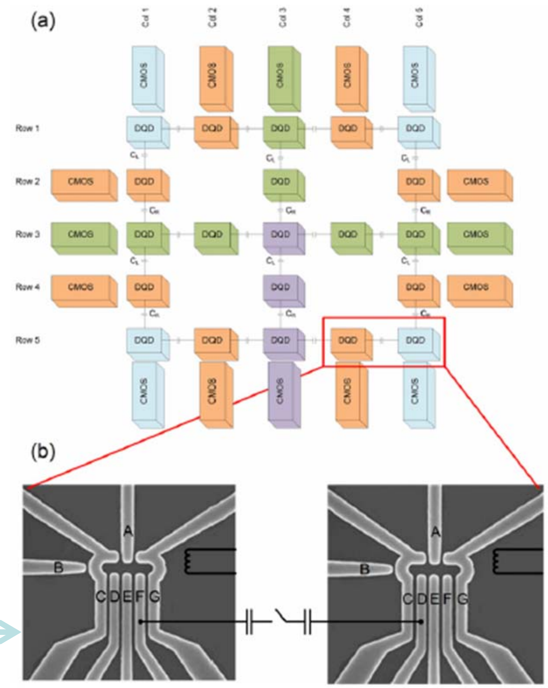
Dates	STM devices & other 1K pot items	tau(E), t, D characterization => adiabatic evolutions => PAT	charge sensed DQD => DQD-DQD coupling => 2-qubit checks
18-Jun		Problem with fridge. Fridge T not sustainable	#740 characterize leakage between wires (H gate dependence & AGL); look for last electron; charge sensor sensitivity vs. H gate [Mike, 3He]
EAB (June 28-29)	talk [Ezra]		poster [Khoi]
2-Jul	Test SiGe gated wire; check for CB, charge sensing, tunability to DQD [Nathan, 1K518]	troubleshoot low thermal cooling power [Steve, Mike]	tune tunneling with AGL & retune to DQD (charge sensed) [Khoi, 3He]
16-Jul	Start STM wire, conductance vs. width check; start STM SET if available? [Lisa, 1K-CINT]	lever arm & estimated t (DiCarlo) of #485 OR continued troubleshooting [Steve, DD1]	Test emptying the DQD with new bias point; OR new sample DQD-DQD (proximity) [Khoi, 3He]
to July 30	STM SET: identify Coulomb blockade vs. plunger; measure diamonds [Lisa, 1K-CINT]	pulsed evolutions (adiabatic test) [Steve, DD1]	New sample: tune charge sensing; test tunability to DQD [Khoi, 3He]
13-Aug	STM SET: identify leakage limits; start SET+DQD if available? [Lisa, 1K-CINT]	attempt photon assisted tunneling [Mike, Steve DD1]	New sample: test DQD1 as DQD charge sensor for DQD2 (opposite side); test tunability of DQD2 => first trial to form DQD-DQD [Khoi, 3He]

Future perspective for semiconductors

Physical lay-out, CMOS compatible and easier I/O w/ AQO



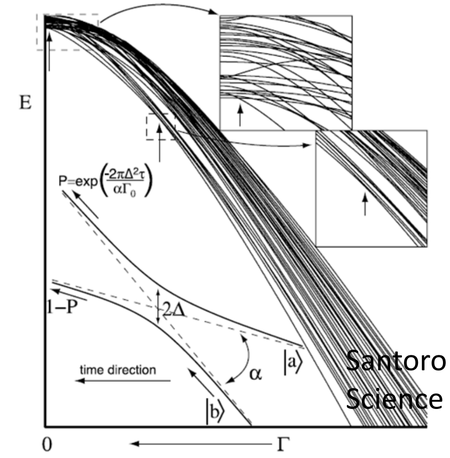
L. Trifunovic et al., arXiv 1110.1342



J. Levy et al., J. New Physics (2011)

Can it stay in the ground state?

How common are errors?



Santoro et al. Science 2002

How bad is an error?

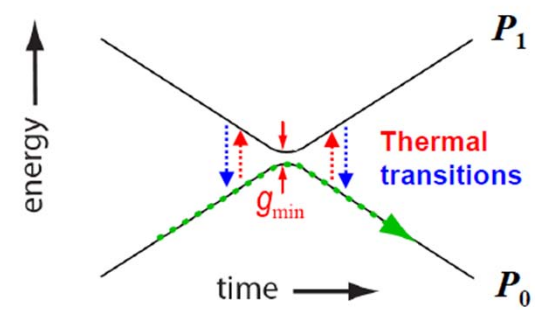
Does relaxation help?

Can errors be suppressed?

How much quantum is needed?

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

- Many fewer qubits needed to produce interesting optimizations?
  - In small qubit number regime: no show-stoppers observed yet for semiconductor approach
  - Is there a sweet spot for size of useful problem that still has sufficient gap/noise?
- Ideas about error suppression and gap enhancement being developed that semiconductor qubits could adopt => extend the sweet spot
- Need experiments and probably bigger experimental systems to test ideas



Amin et al., NASA workshop 2011

Summary

Motivation and approach

- A new semiconductor encoding for QUBO is proposed (independent X-Z, large gap, stable, CMOS)
- DQD platform for 3 year demonstration of 2 qubit QUBO
  - Test encoding concept, develop measurement technique for AQO and examine 1 or 2 qubits
  - Characterize qubit parameters specific to AQO (e.g., relaxation times, noise for AQO)
  - Develop tests for adiabaticity in semiconductor approach (i.e., charge qubit)
    - Possibly of general applicability in systems with relaxation?
- Atomic precision fabrication approach proposed for:
  - Low defects and noise, stronger couplings, larger overall energies
  - End of scaling fab capability (legacy benefit) – "next MBE"

Experimental progress

- STM: all individual steps shown and unpatterned donor devices with equivalent performance as published elsewhere
- Charge sensed double quantum dot progress
  - Measurement of |L> and |R> qubit states demonstrated & elements for X to Z LUBO demonstrated
  - Adiabatic test developed: test for relaxation assisted evolution
  - New technique to characterize energy dependent relaxation
    - Extraction of deformation potential and tunneling in new regimes maybe also possible
  - DQD-DQDs designed and preliminary measurements in progress
- No show stopper yet identified for charge qubit
- Generally – learning more about charge qubits in silicon, adiabaticity and application to AQO

Resources

- STM modifications for lithography, alignment and phosphorus incorporation
- (2) 1K pots set-up to assist w/ device tuning, charge sensing and characterization of charge coupling
- Dry fridge install in progress (returned to factory)

Backup slides

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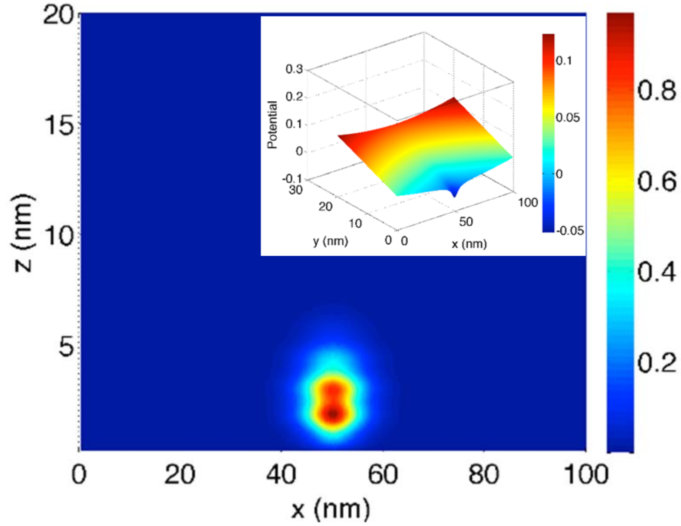
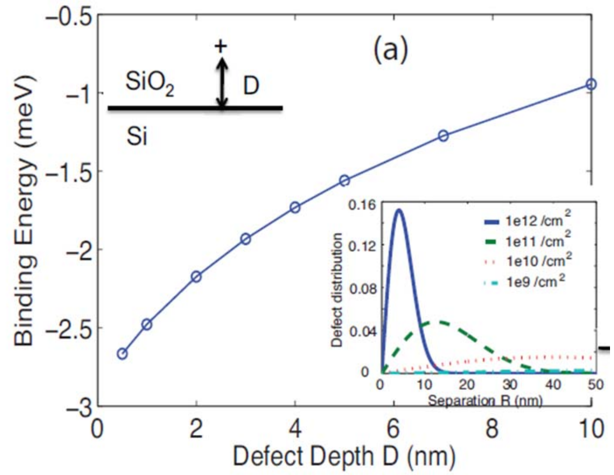
Oxide defects and many electron DQD regime

Localization due to defects



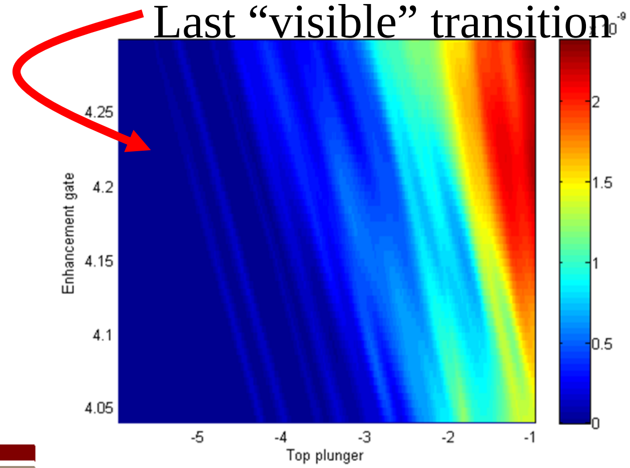
Defect binding energies



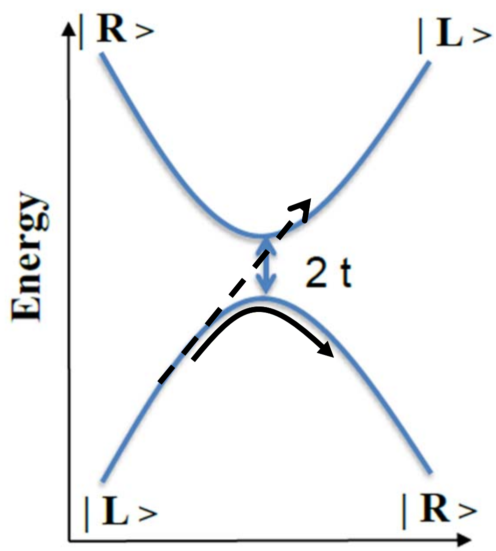
Rahman, arXiv 2012

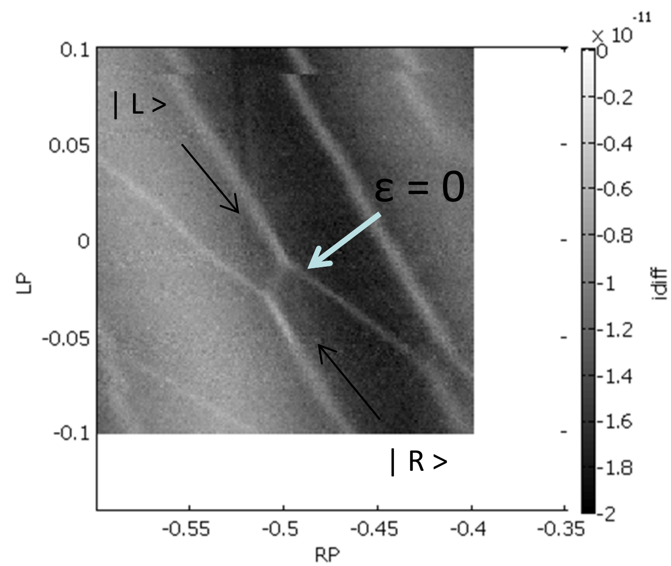
- Measurements suggest isolated defect regime for our devices
- Two defect regime leads to ~6-10 meV binding energy
- This talk: several electron regime – these defects are probably negligible effect (screened defects)
- Other work: single electron regime also observed (challenging)

Last "visible" transition

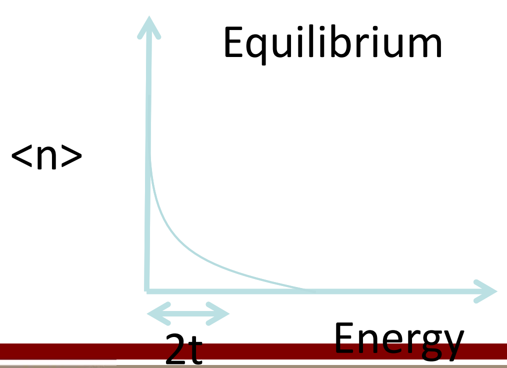


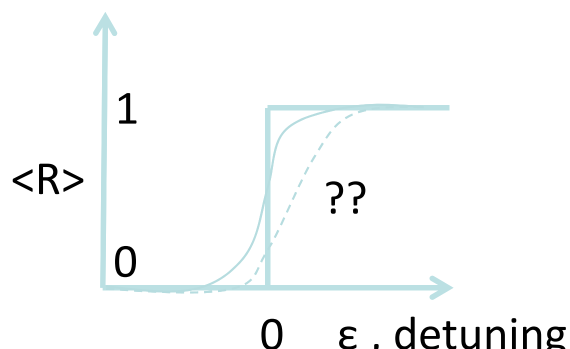
Tests for quantum annealing (charge qubit)

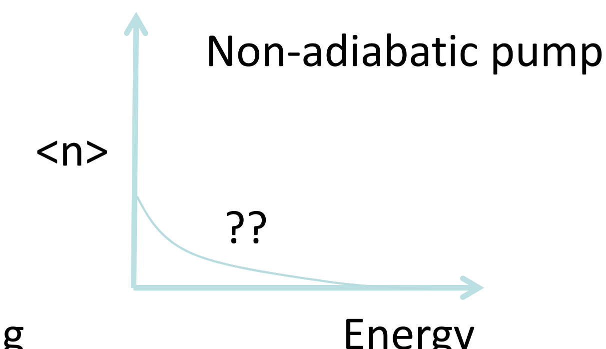




- Test whether electron can keep-up with pulses through L/R transition
- If evolution time is slow, then no perturbation to thermal equilibrium







Theory expectation from evolution w/out relaxation

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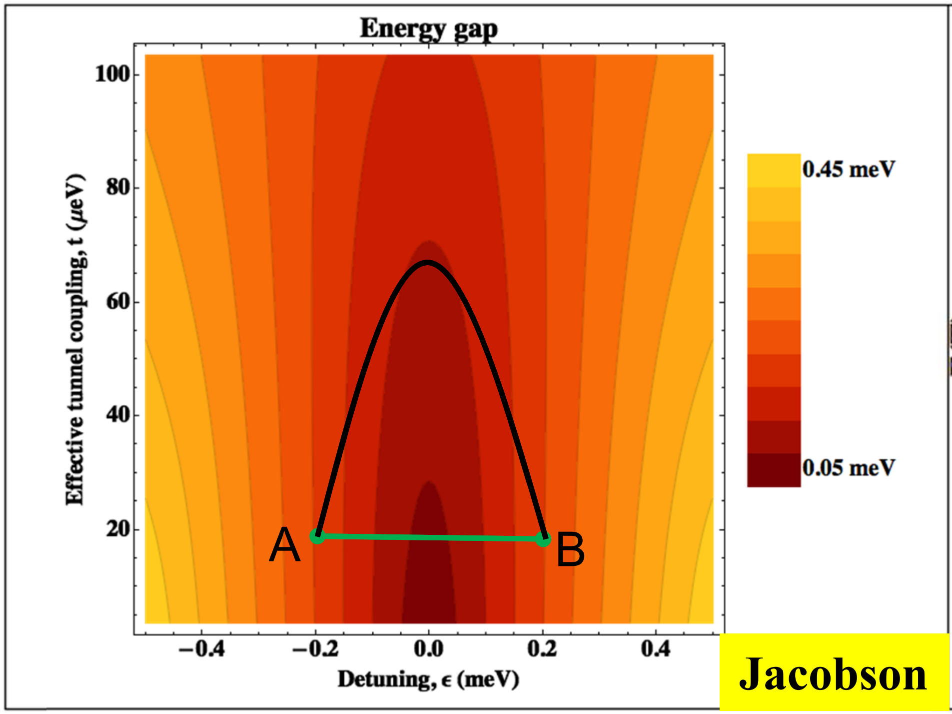
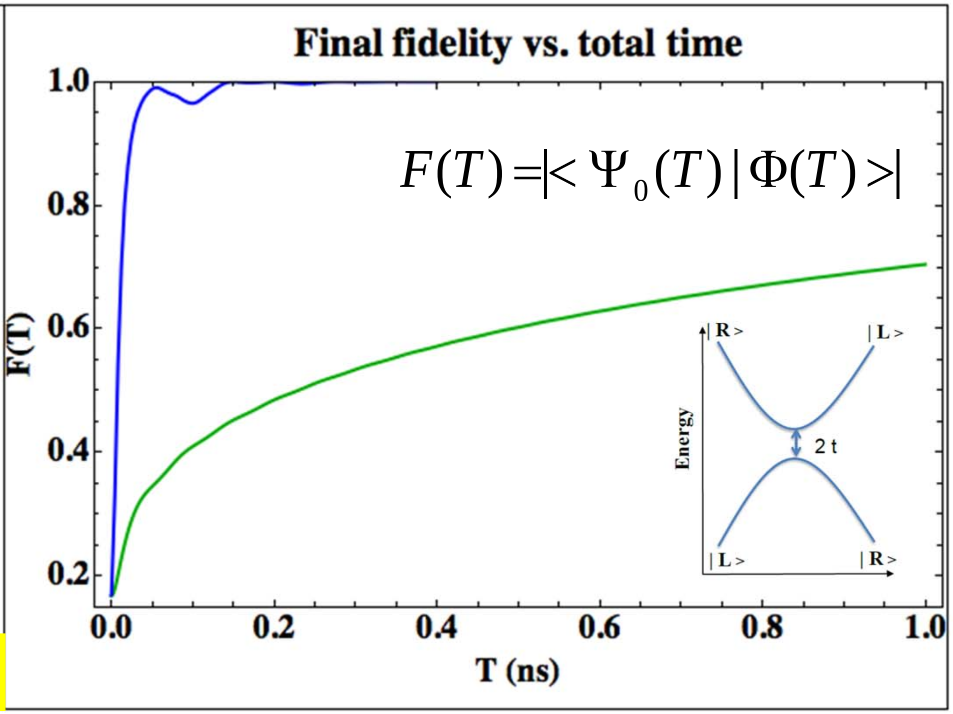


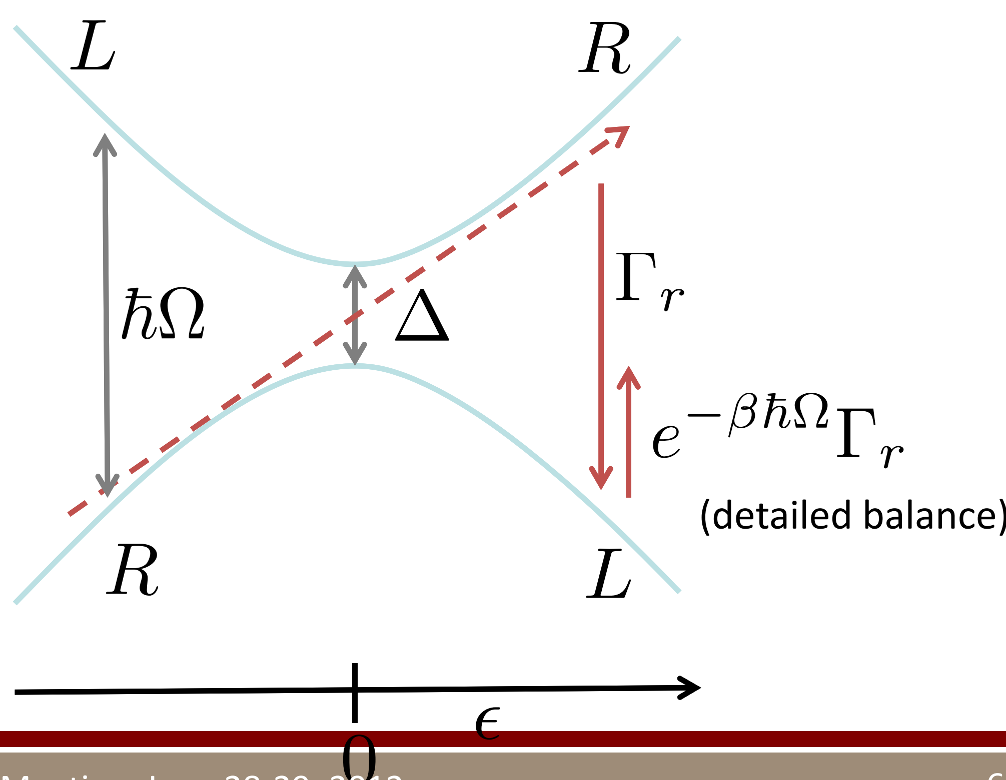


- Linear path leads to different probabilities of success (depends on t and rate)
- Paths that trade-off reduction of tunneling gap with increased detuning are better than straight path
- Relaxation complicates this picture
- Adiabatic does not require temporal phase coherence (wiggles in probabililty?)

Relaxation rate: $$\Gamma_r(\Omega) = \frac{2\pi}{\hbar^2}\left(\frac{\Delta}{\hbar\Omega}\right)^2 \coth\left[\frac{\hbar\Omega}{2k_BT}\right] J(\Omega)$$

(energy gap = $\hbar\Omega = \sqrt{\epsilon^2 + \Delta^2}$)

Note: In the following fits, the coupling factor γ and the elastic tunnel coupling Δ act in the same way (overall prefactor for relaxation rate), so for now I can't fit for these two parameters independently.

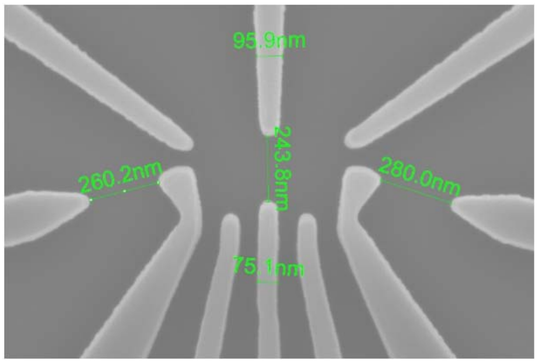


Many assumptions, including:

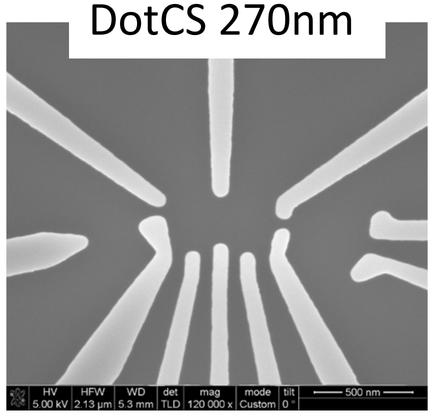
- Two-level description for system
- Weak coupling to bath
- Born-Markov approximations
- Secular approximation
- Transitions assumed diabatic
- Quasi-static description for relaxation
- Power-law for phonon spectral density at low frequencies

Pattern comparison

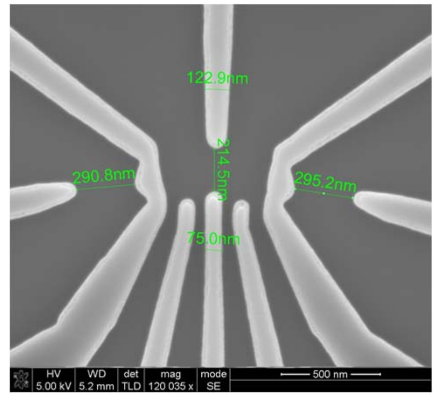
Ottawa Thin B 270nm



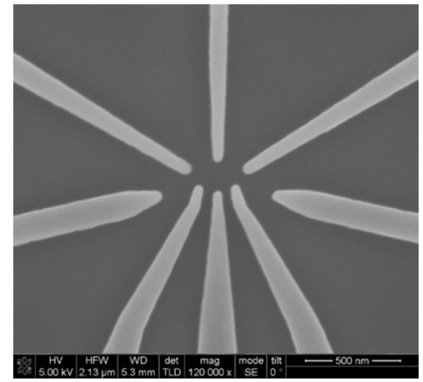
Ottawa Thin B DotCS 270nm

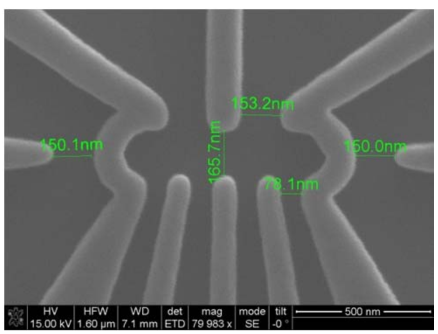


Ottawa Thin 270nm

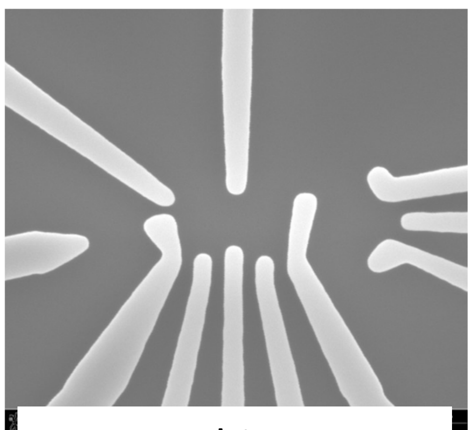


Radial 2CS

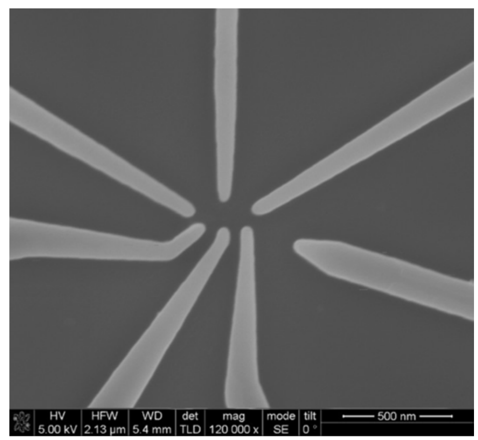




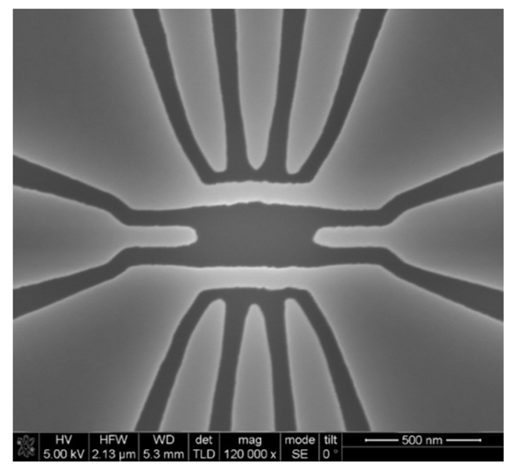
Ottawa Fanned Mod



Ottawa Thin B Open DotCS 270nm

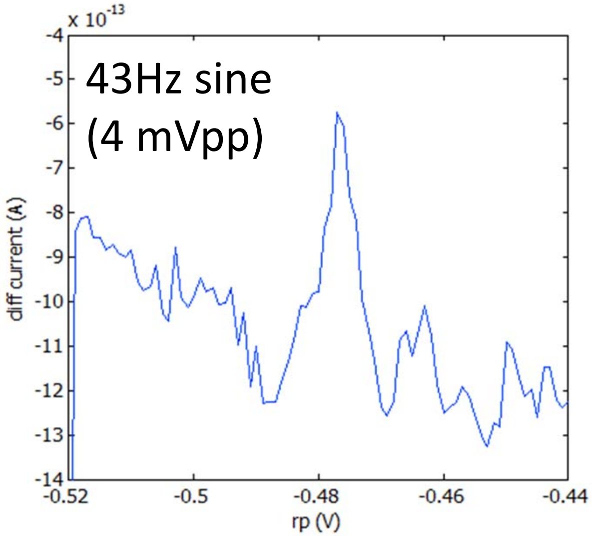


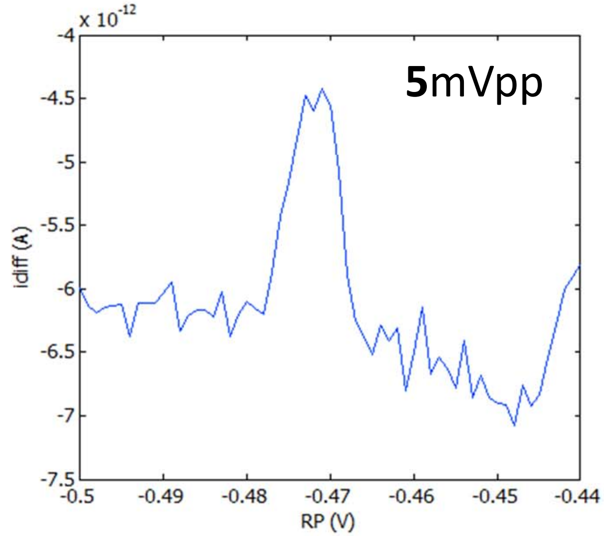
Radial 1CS

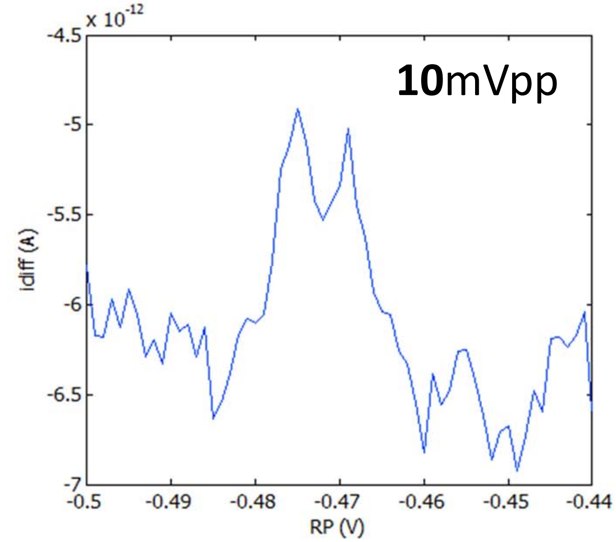


Gated Wire 60nm

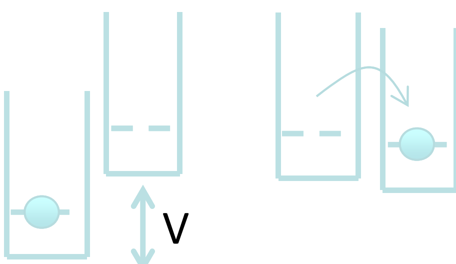
Pulse amplitude dependence at 215 Hz

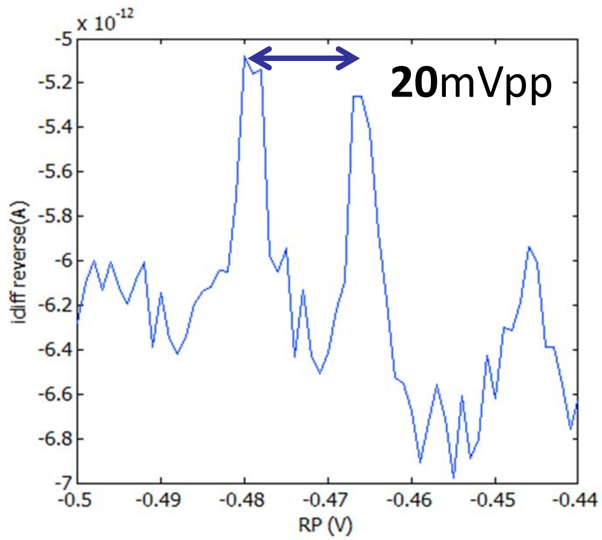


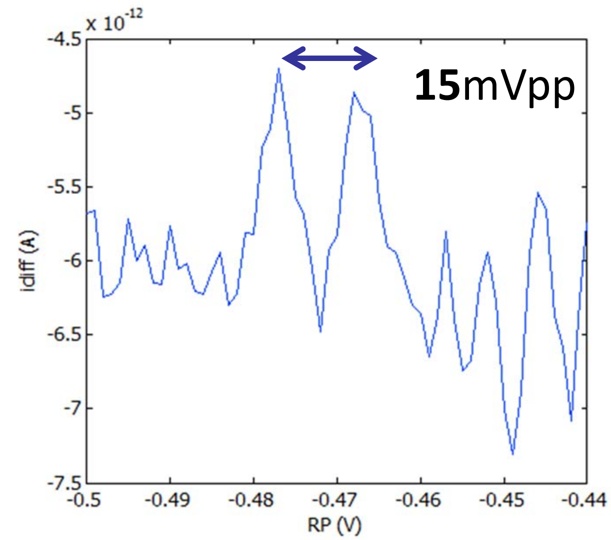




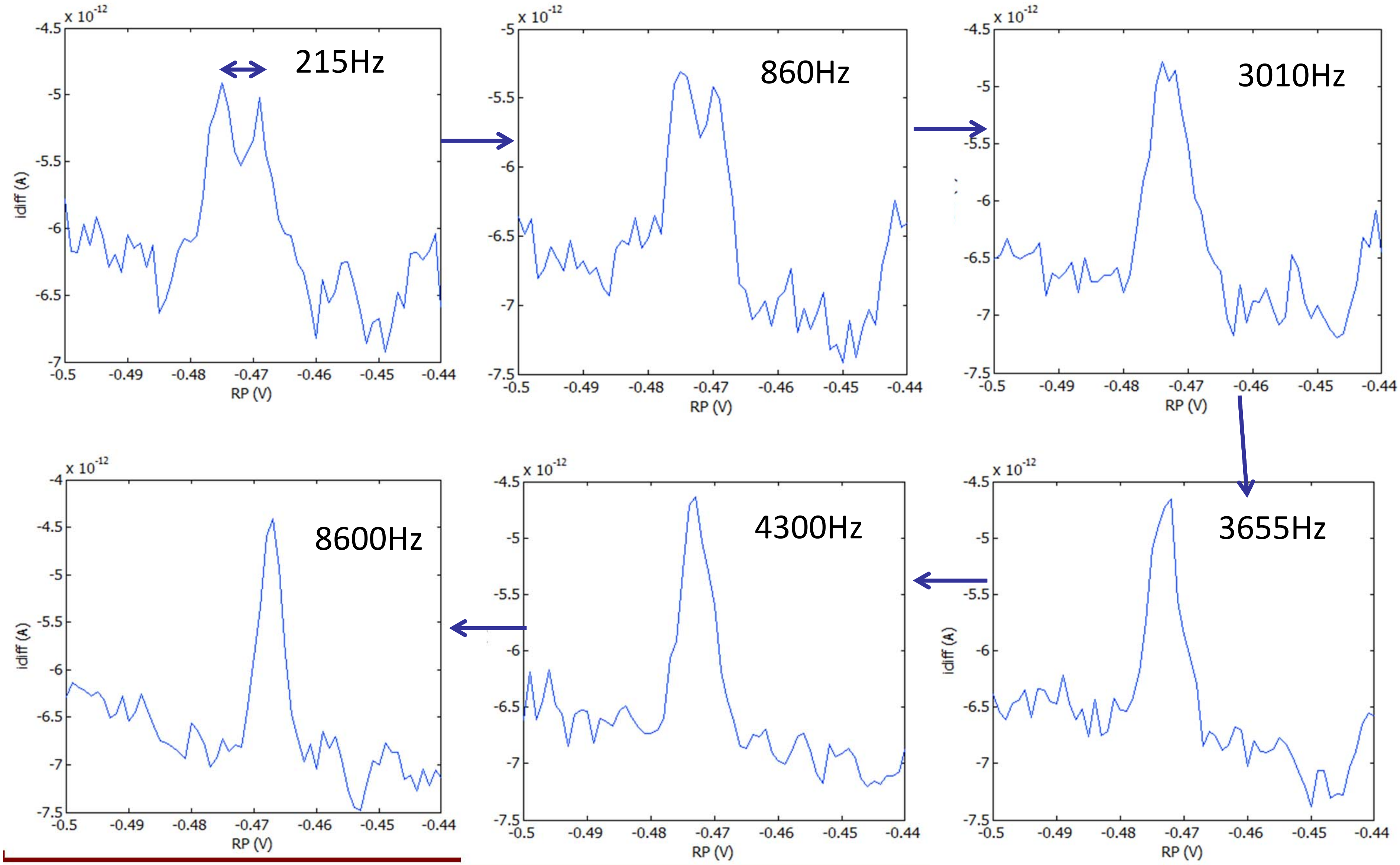
Ramp = 16 ns







Pulse frequency dependence at 10mVpp amplitude



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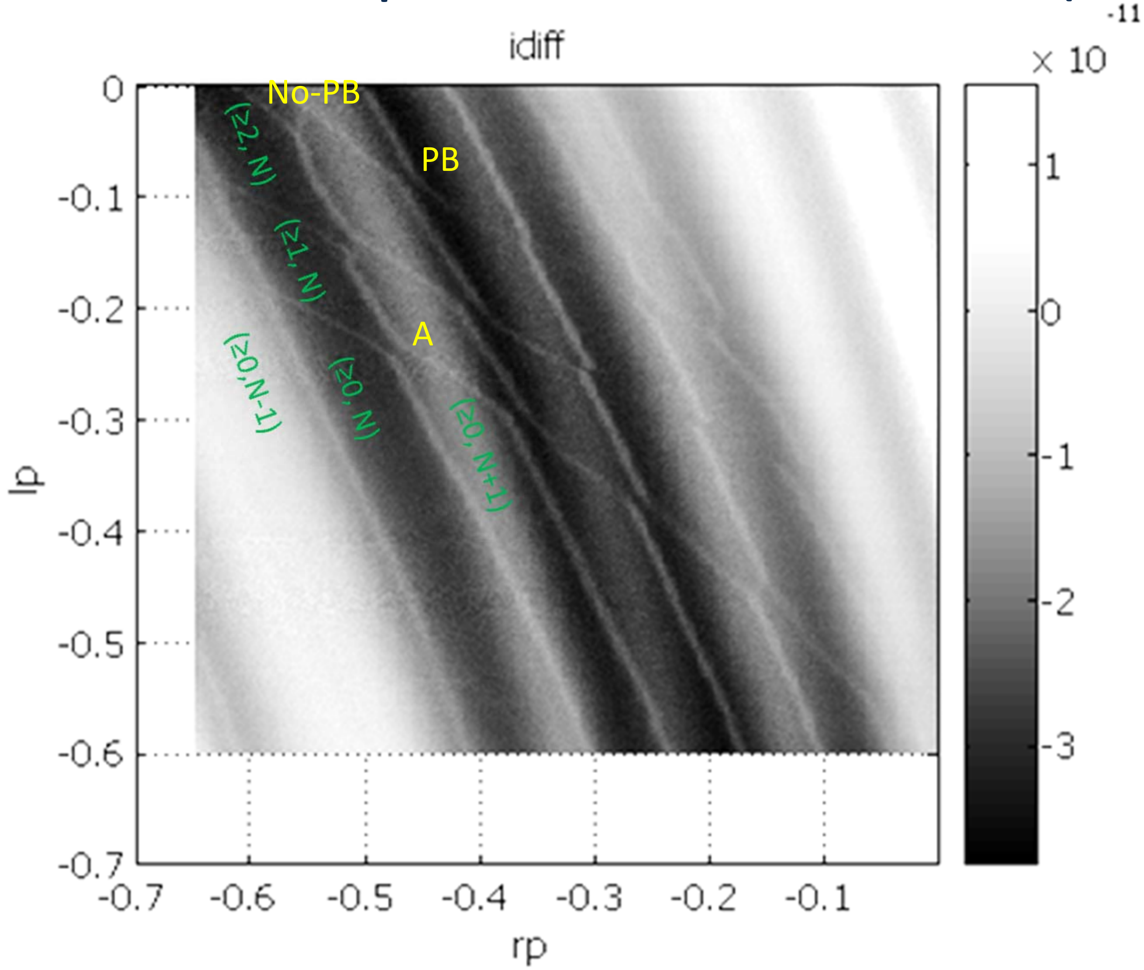
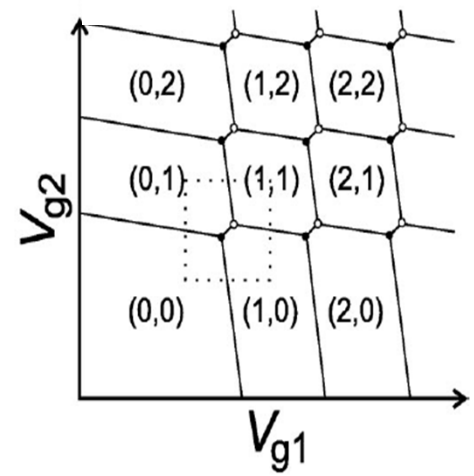
Double quantum dot behavior (charge sensed)





Nguyen, Lilly

- Double quantum dot behavior formed (charge sensed)
- Charge transition between |L> and |R> observable at some triple points
- Avoid Pauli-blockade cases for this measurement (bias triangles used to check)
- Lack of crossings in lower left corner: left dot appears to be N=0 in this voltage range

Future experiments for single qubit characterization: attempt PAT

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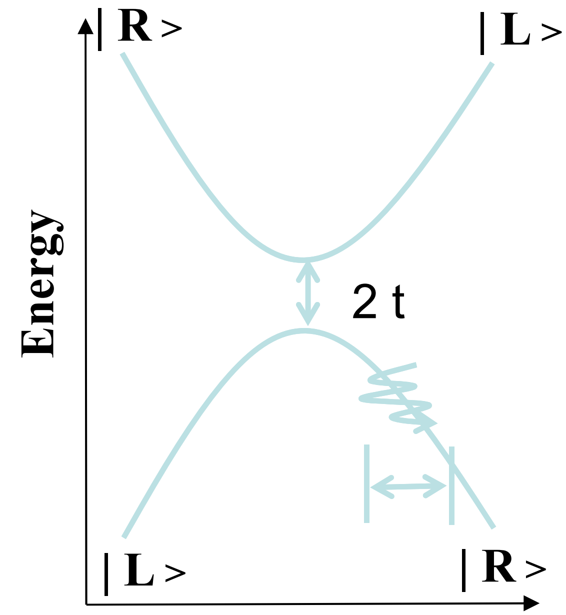
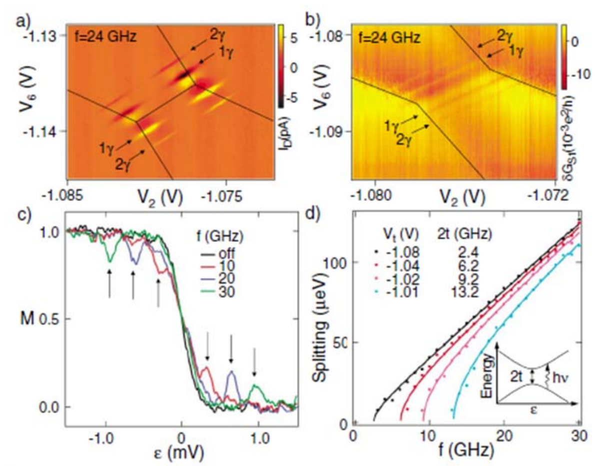
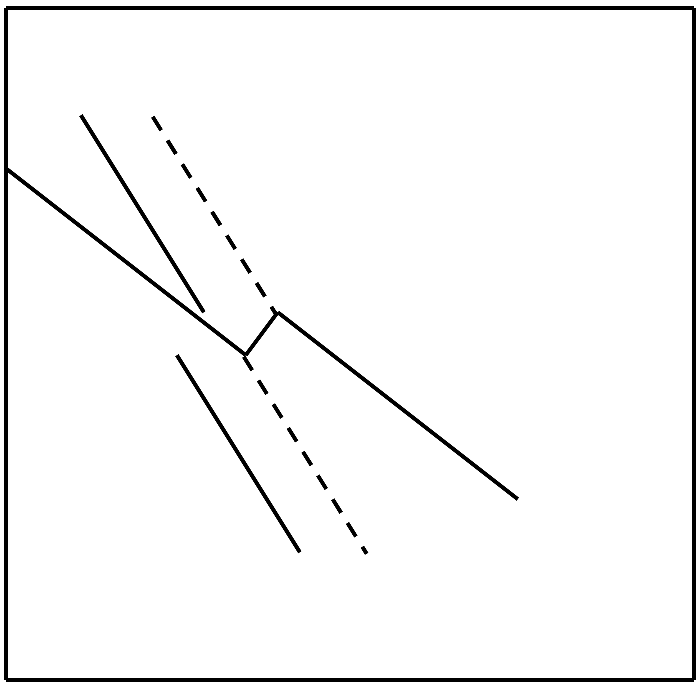
- <u>Error mechanisms</u>
  - **1/f noise** (Z and possibly X)
  - **Phonons** (Z & X)
  - Johnson noise (X and Z)
  - External electronics noise on static gates (X & Z)
  - **Control noise on dynamic gates (X & Z) (tbd)**
  - **Non-adiabatic evolution (X)**
  - Measurement error
    - Weak measurement during evolution (Z)
    - Inaccurate measurement due to S/N
    - Projection error due to imperfect computational basis
- <u>Relaxation (self-correction) mechanism</u>
  - Phonons & tunneling (inelastic tunneling)
  - Photons, plasmons, …

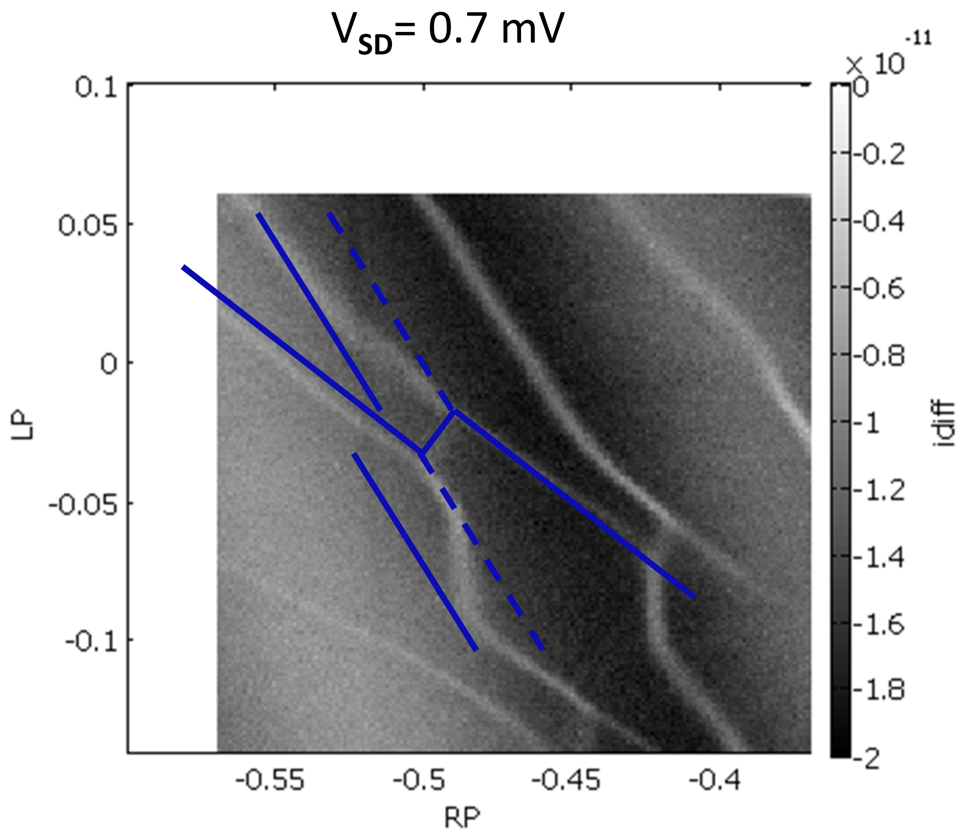


Non-adiabatic limit (Petta et al.)



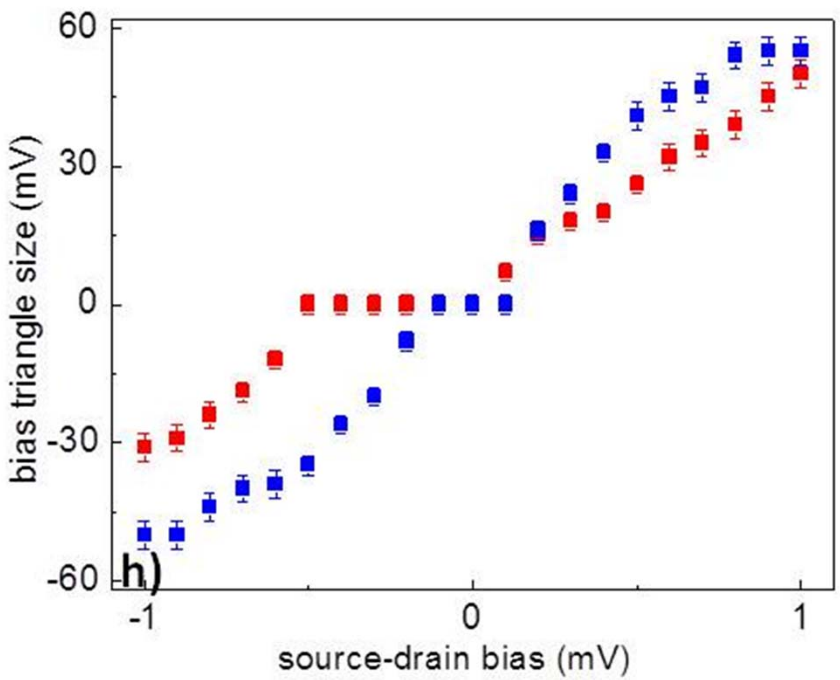
Determine the bias triangle

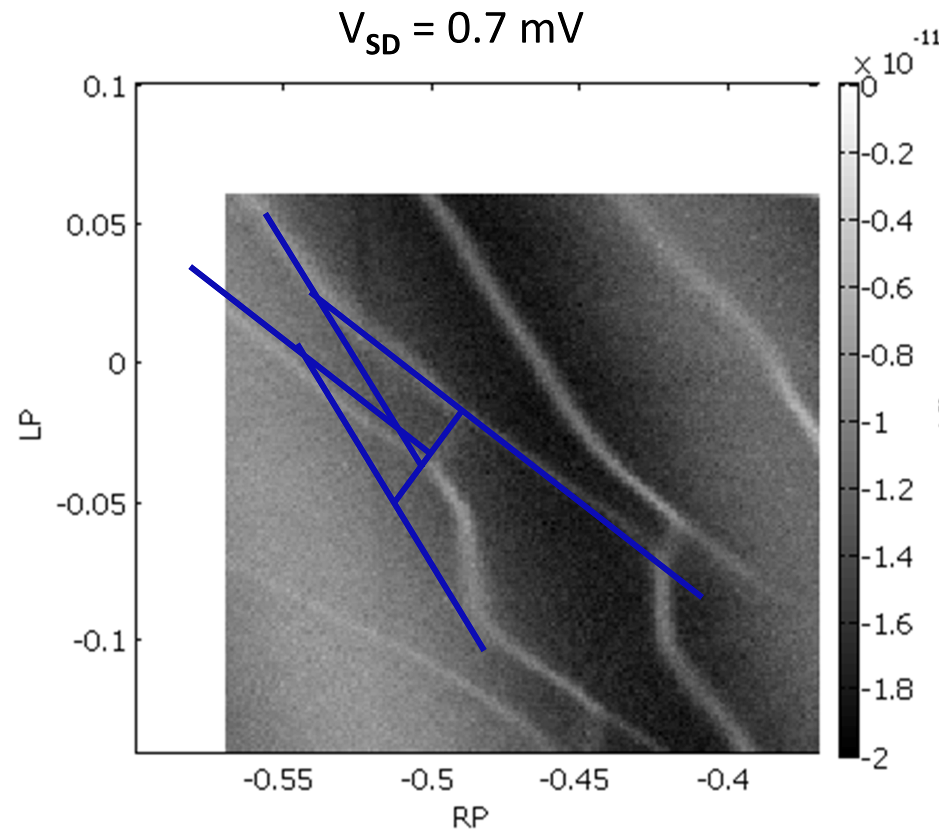




3. Line up the charge sense line for the left dot and the connection line.
4. Shift the charge sense lines for the right dot to match the upper left region.

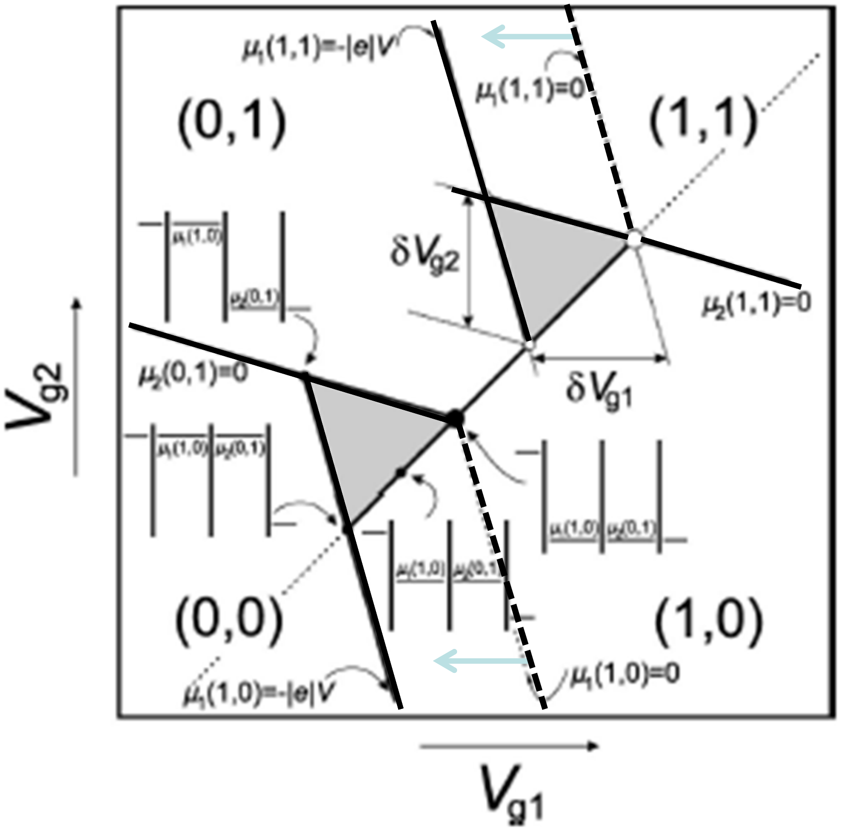
Determine the bias triangle, step 2





5. Extend the lines to make triangles.

Energy calibration (method 1)



W.G. Van der Weil, RMP (2003)

- Triangle regions with fractional charge are measured in transport experiment.
- Differential charge sensing technique is sensitive to the average charge occupation and **edges** of charge sectors show up

Missing charge sense lines

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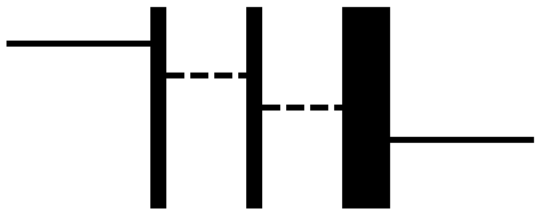
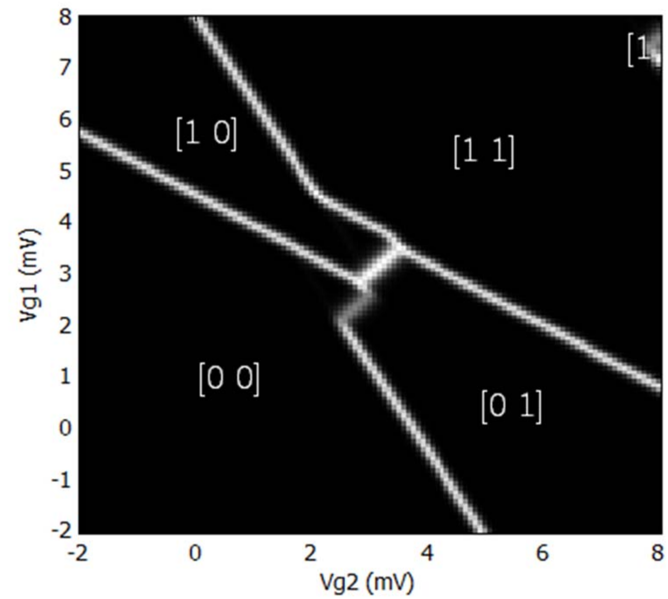
DQD chemical potential



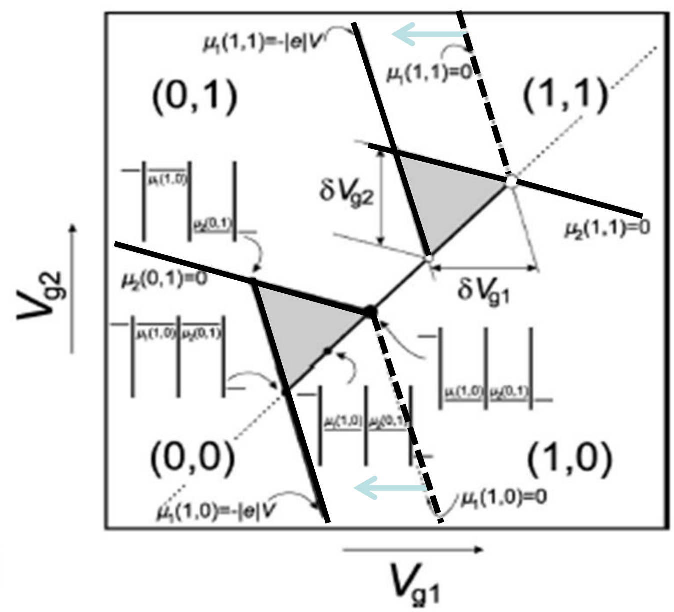
tunnel rates — fast, fast, slow

DQD last electron occupation — right dot, mostly

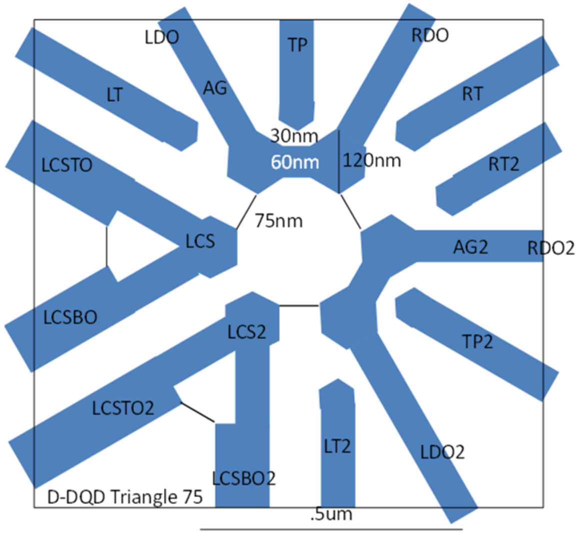
Strongest CS feature — Largest contrast in occupation (right to lead & left to right)

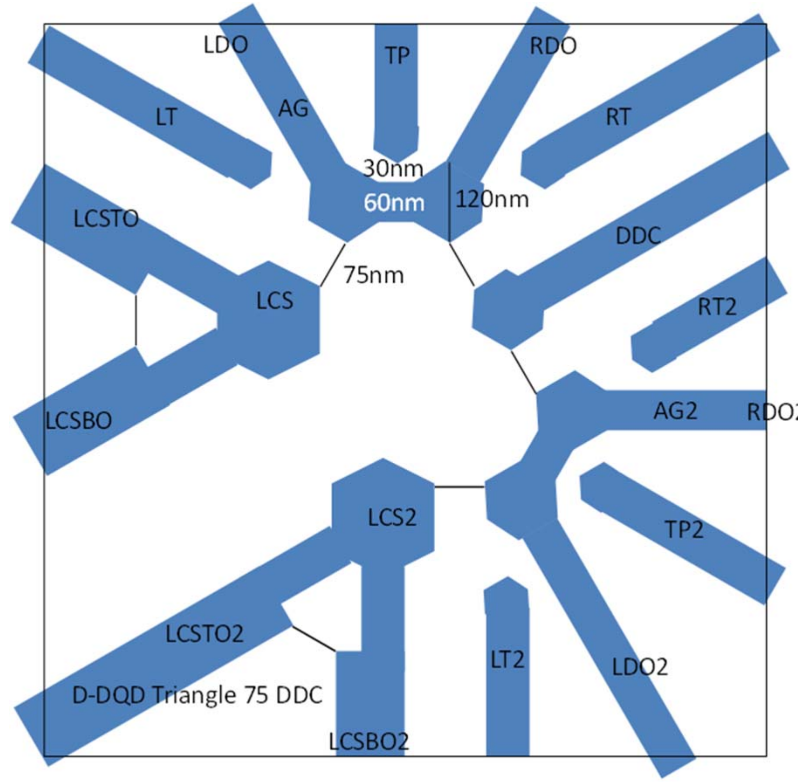


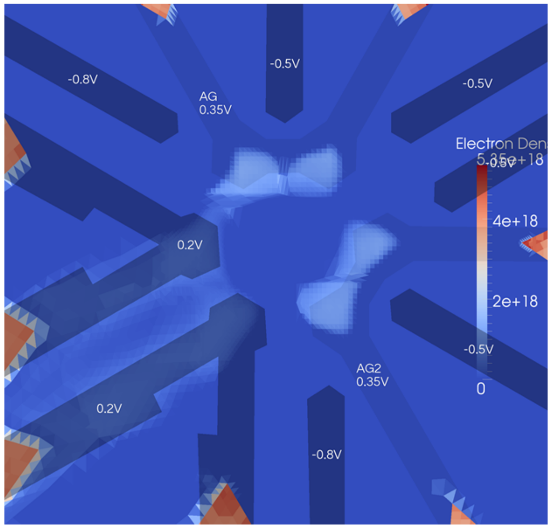
- Tunnel barriers have complex dependence on V
- Charge sensing depends on average occupation
- For unbalanced tunnel barriers, some of the lines will be below our signal to noise and appear to be missing.



Structures for simulation w/ charge sensors & couplers







Preparing initial qubit designs

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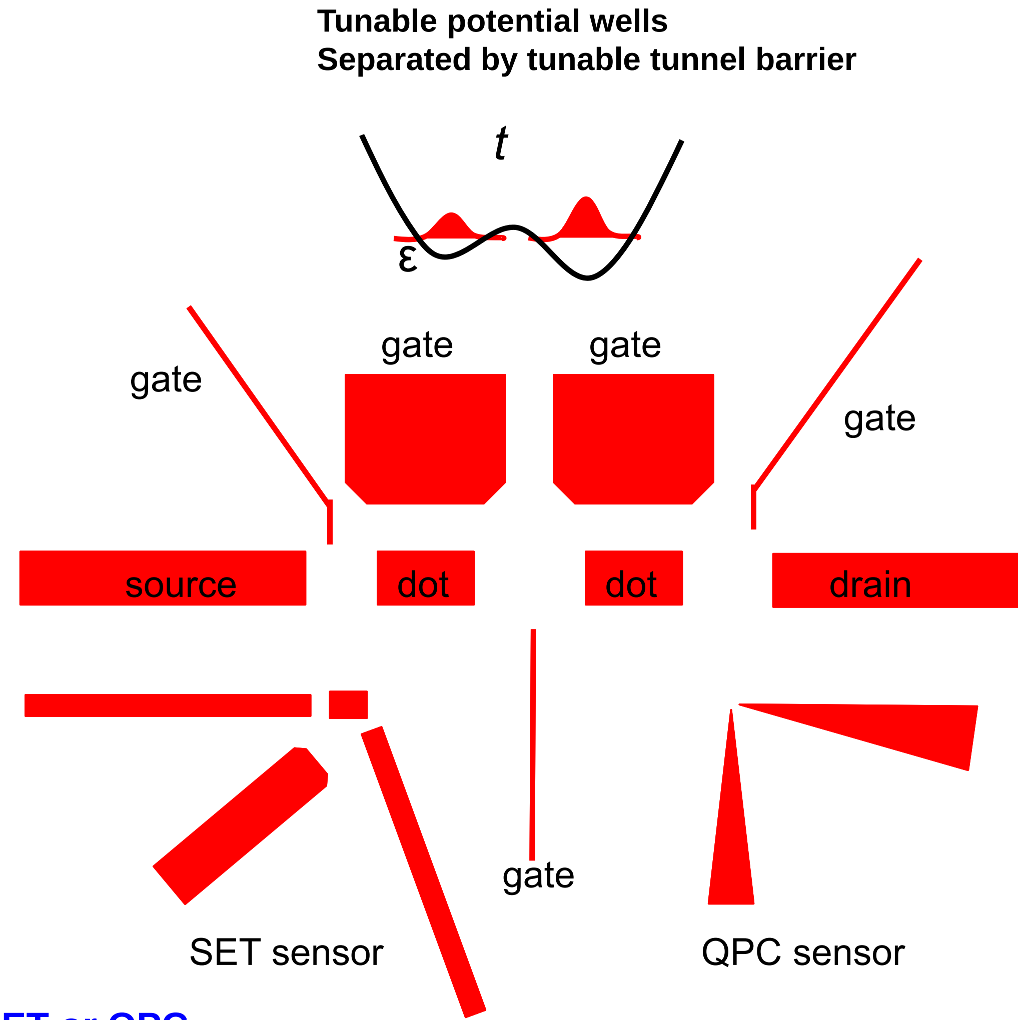
Brainstorm on what we need for device

1. Tunable tunnel barriers
   (ideally tunnel rates from 0 to >10^9 Hz)

1. Tunable ε and dot occupation—few electron

3. A charge sensor



Charge qubit components

1. **Quantum dots (possibly single donor)**
2. **Source/drain leads**
3. **Tunneling gaps**
4. **Gates**
- Plungers to tune chemical potentials (definitely)
- Barrier gates to tune tunnel barriers/rates
5. **A passive charge-state readout circuit e.g. SET or QPC**

All elements are coplanar → crowding limits number of device elements