SAND2012-1015 C

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Quantum Information S&T

Detection of charge transitions in Sb implanted poly-silicon split gate point contact

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Albuquerque, New Mexico, USA

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LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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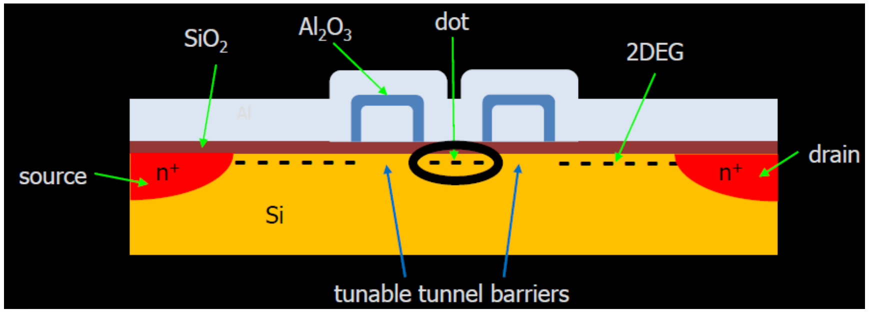
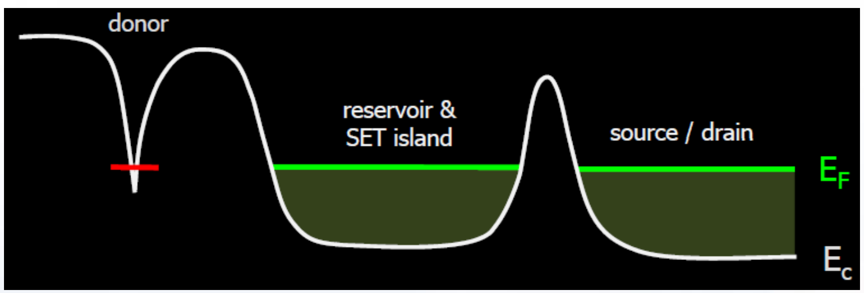
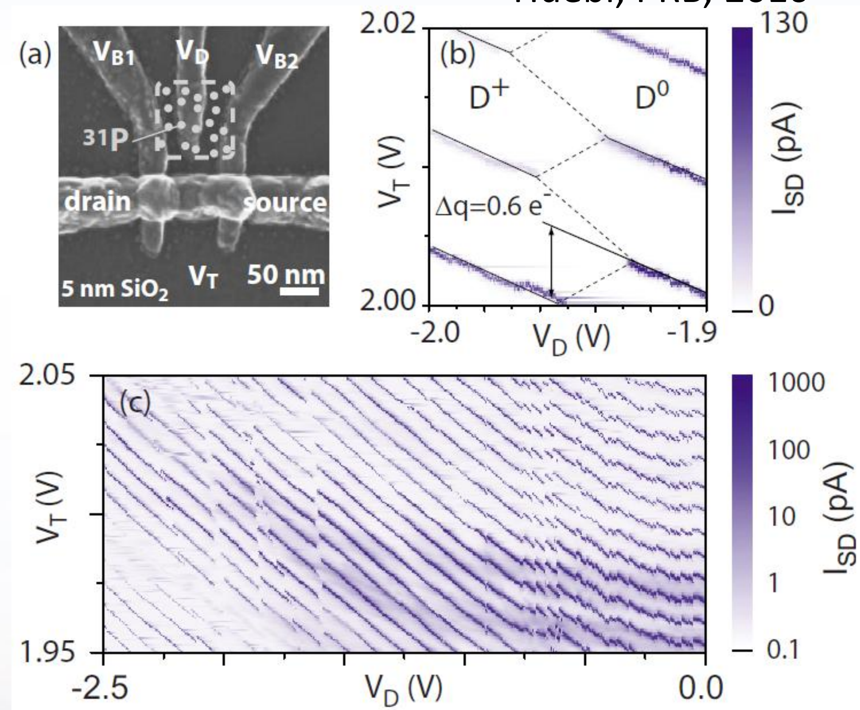
CQC2T donor charge sensing geometry

Morello, PRB, 2010





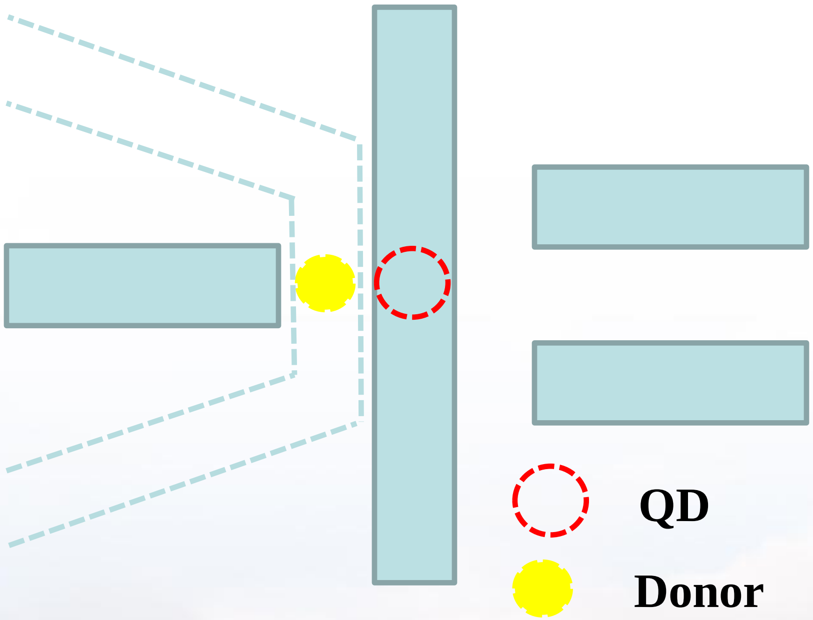
Huebl, PRB, 2010

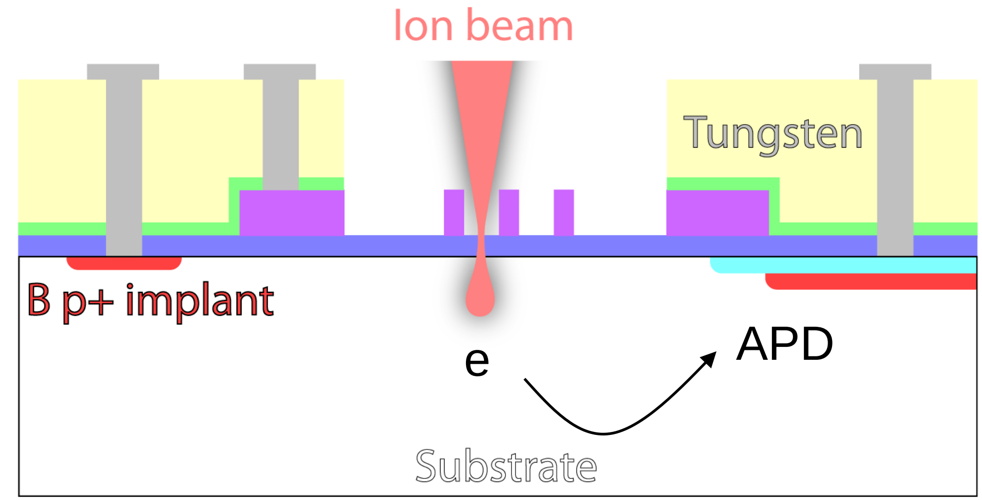


- Concept: SET detects nearby charge center ionization
- Observations:
  - Shifts correlate with donor implant
  - Shift positions are thermally stable
  - Observation: long T1 correlates with phosphorus

Gated Self-Aligned Poly-Si Wires

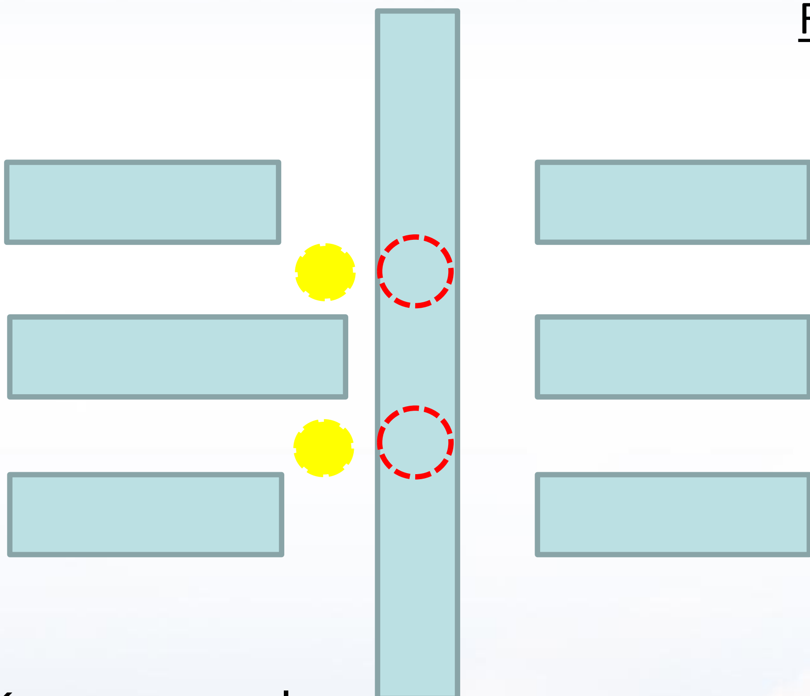
Similar approach



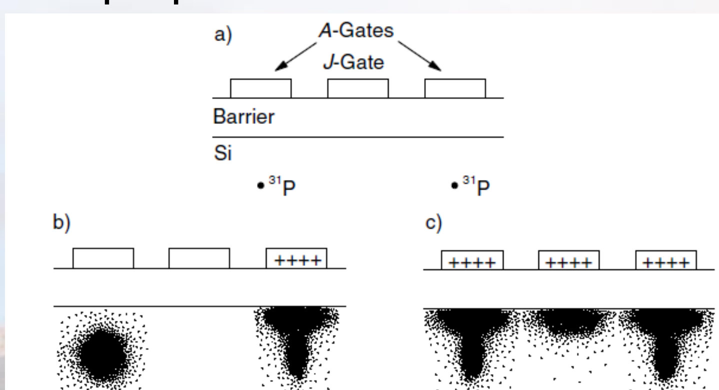


SNL version of the CQC^{2}T AL-SET architecture using Self-Aligned Poly-Si (or Al)

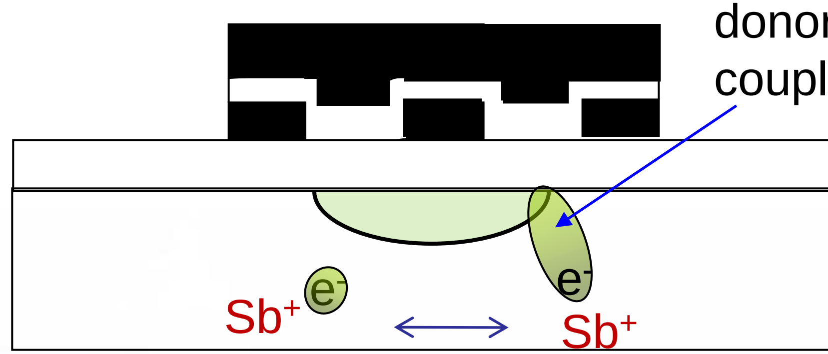
Long term motivations



Kane proposal

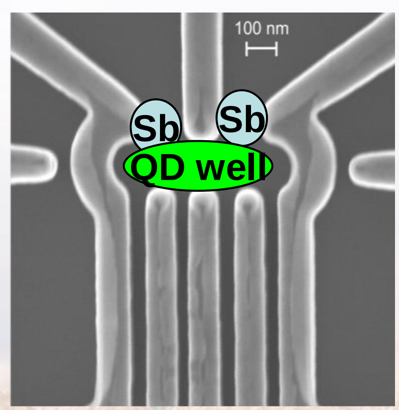


Relax coupling constraints: QD-donor coupling (DQD)

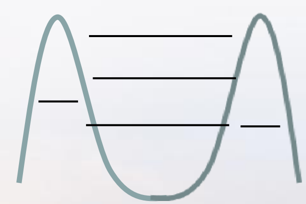


donor-QD coupling?

100 nm straggle tolerance?

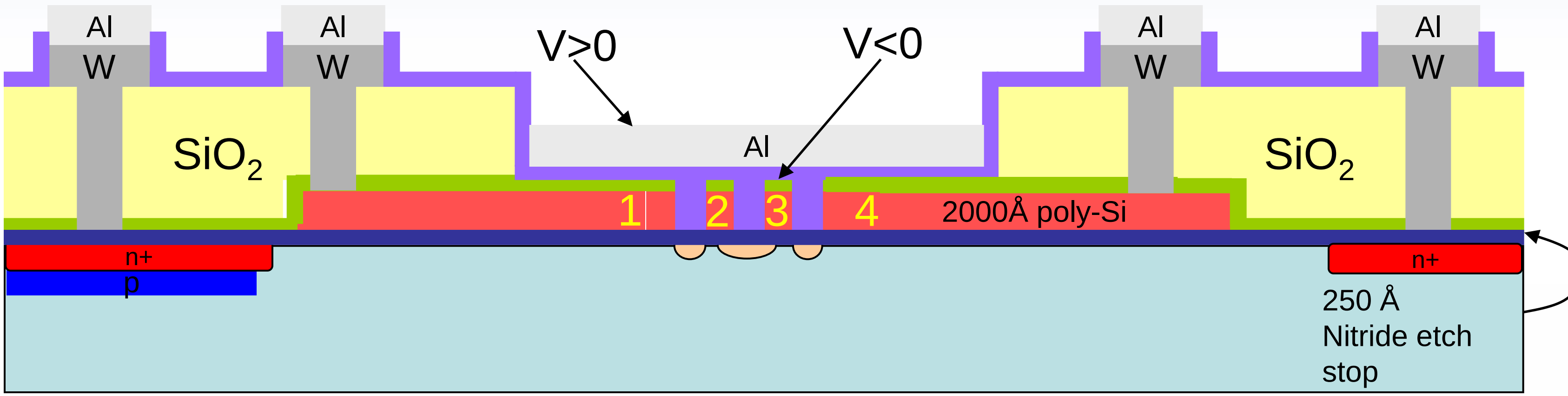


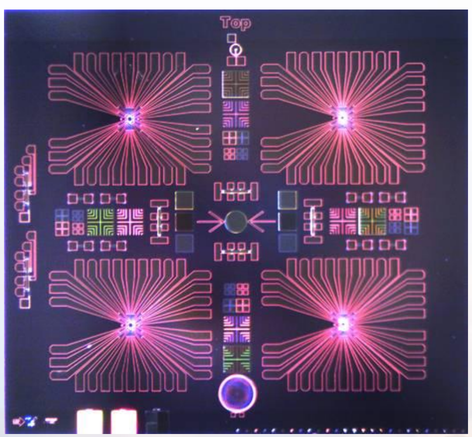
Resonant coupling of donors to dot

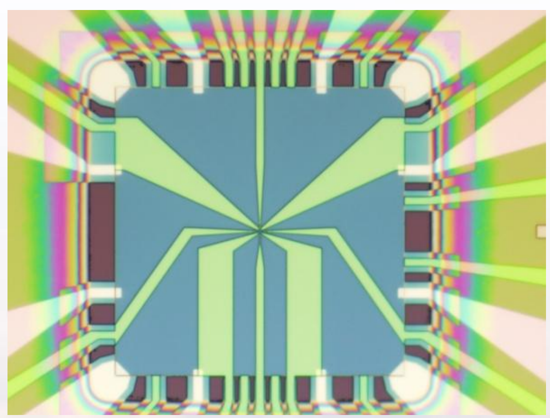


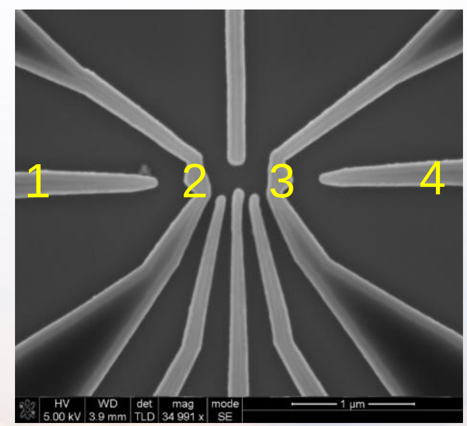
Shift fabrication challenge to tuning challenge

Device processing at SNL









<u>**Micro-fab facility**</u>

Rapid turn-around EBL

Poly-silicon etch

Aluminum oxide & Al gate

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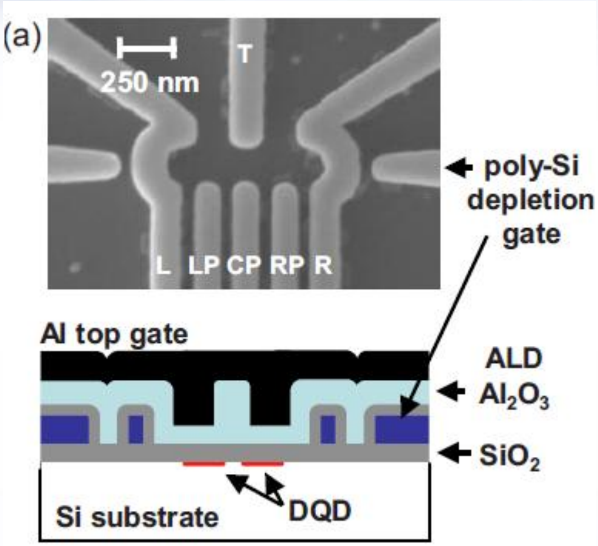
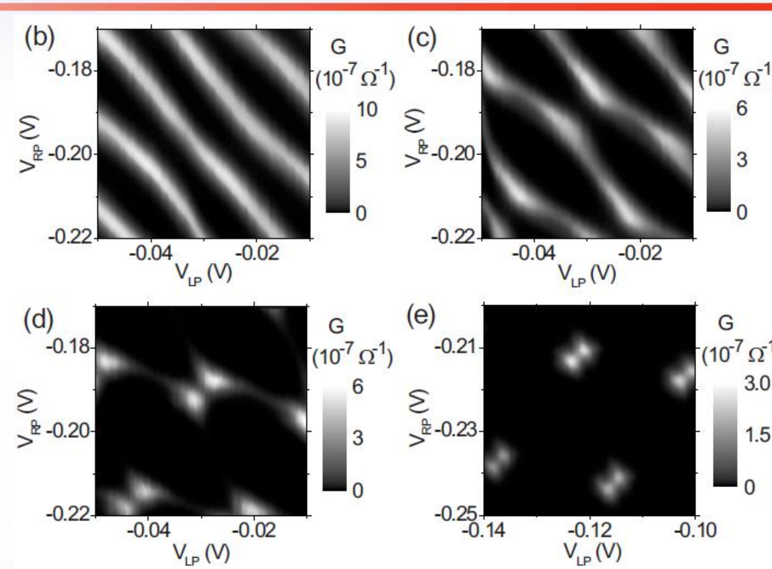
E. Bielejec: talk on integration of Geiger mode detector

Enhancement mode nanostructures for QC (e-mode)





L. Tracy, et al. APL (2010) [SNL]

Charge sensed periodic CB also possible

- Poly-silicon structures can produce regular and tunable DQD behavior
- Lateral charge sensing also possible with the structures

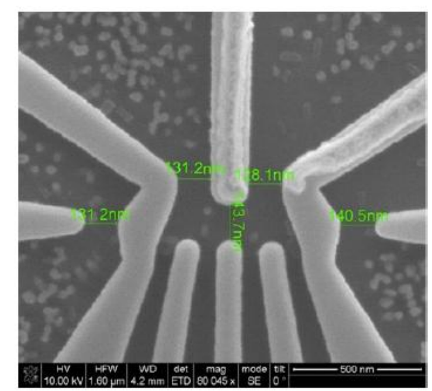
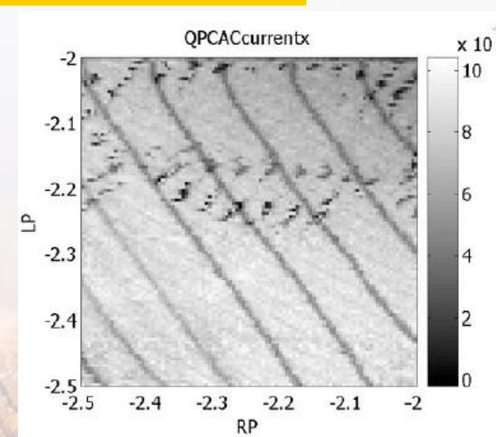


Image of fabricated device: SEM after Poly-Silicon Etch



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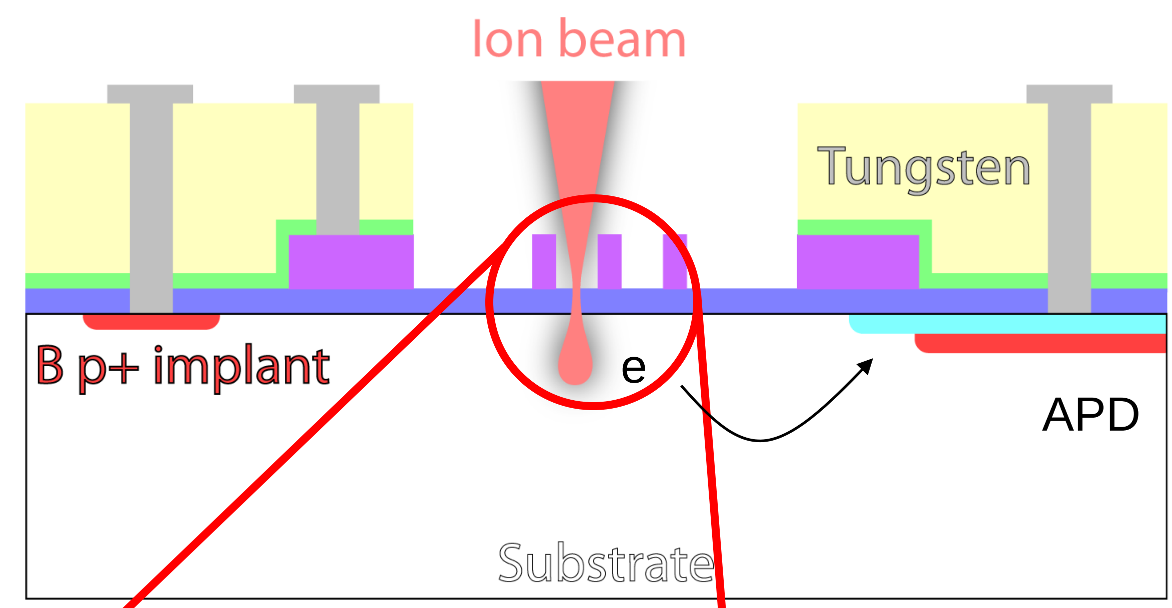
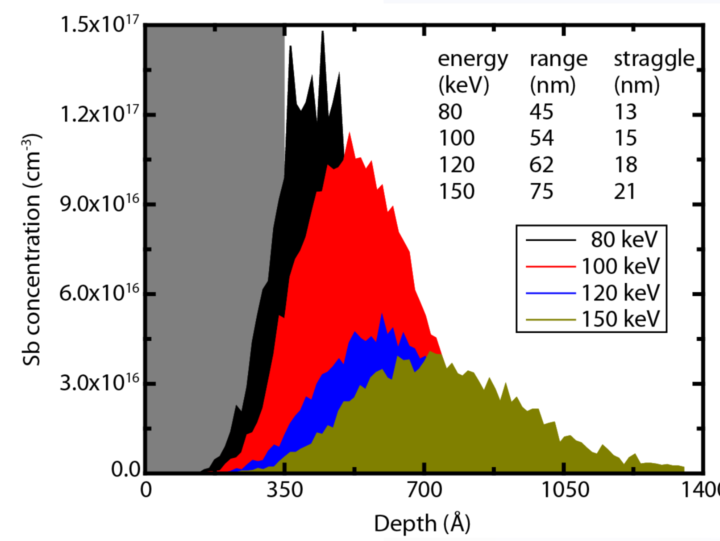
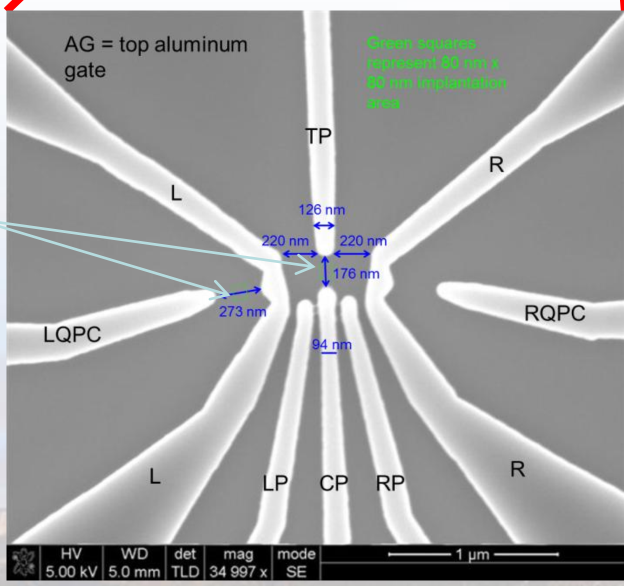
Self-aligned implant of donors with poly-silicon





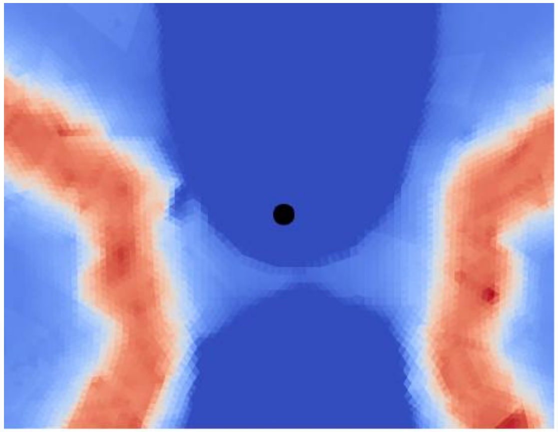


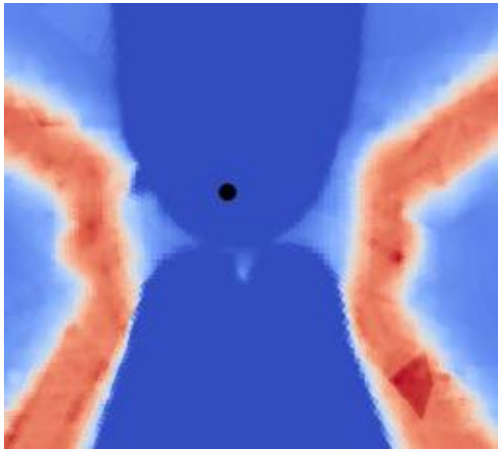
<u>Donor-DQD process</u>

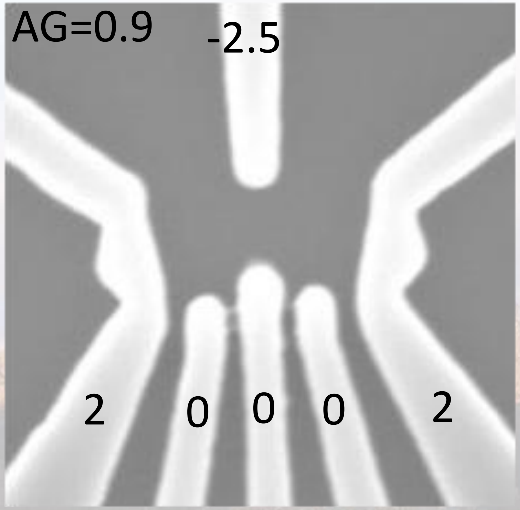
- Baseline to poly-etch
- EBL for implant window
- Implant
- Strip metal
- Anneal (RTA or reoxidation)
- Rest of the baseline process

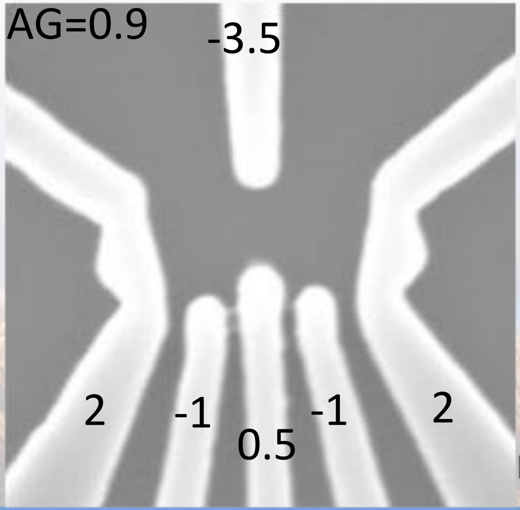
Simulation

Look at split gate configuration first.
Centered dot predicted for positive CP









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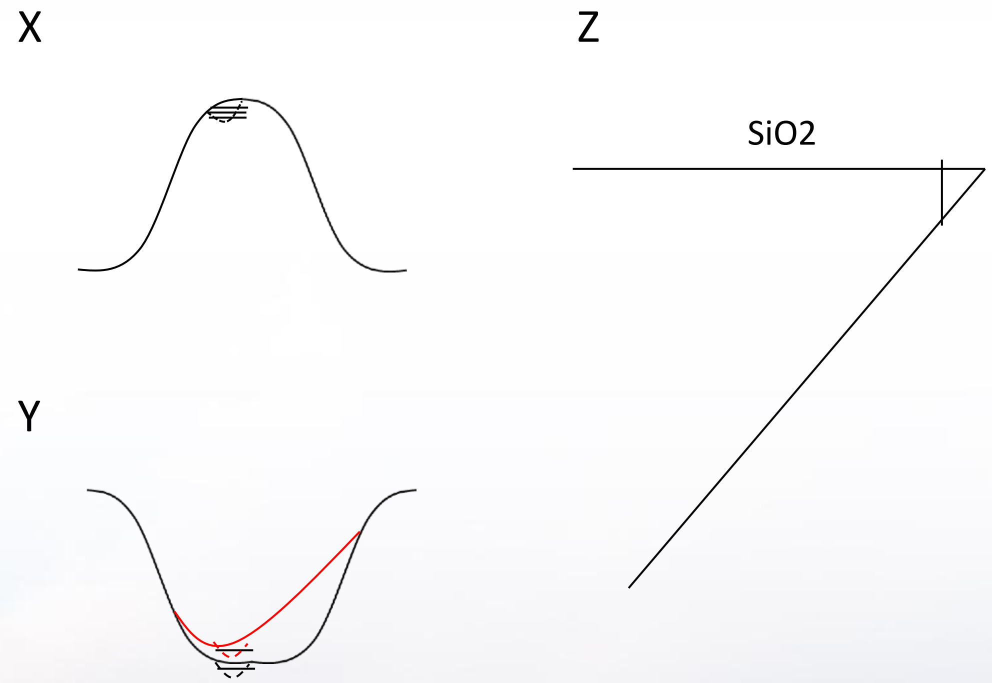
Point contact case (control)

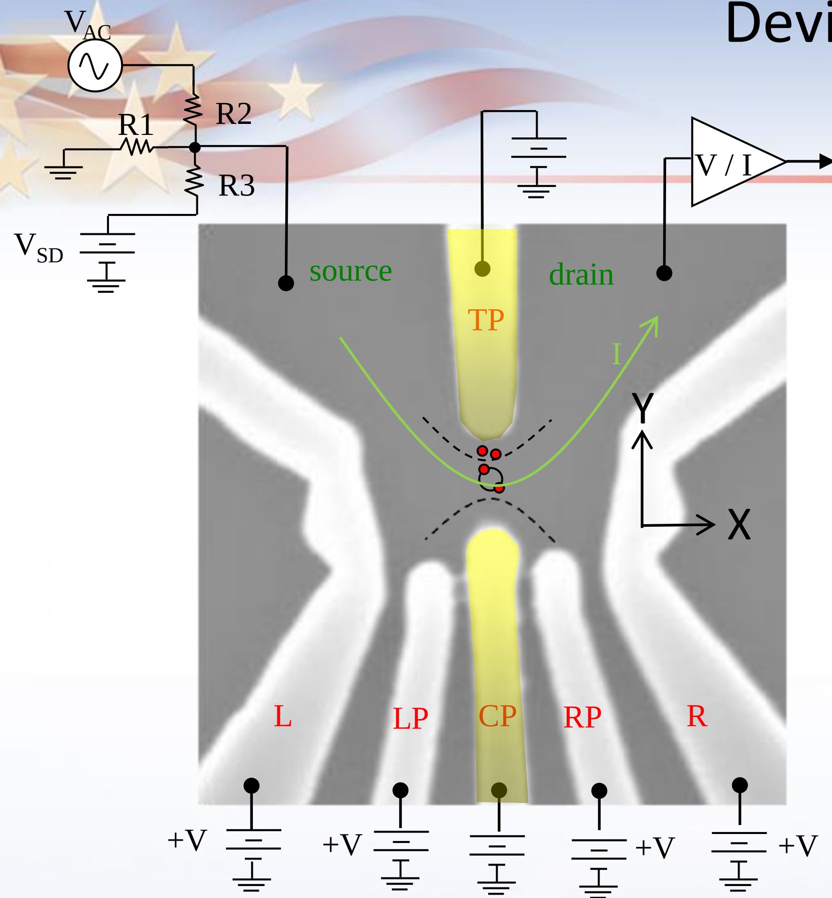
Look at split gate configuration first

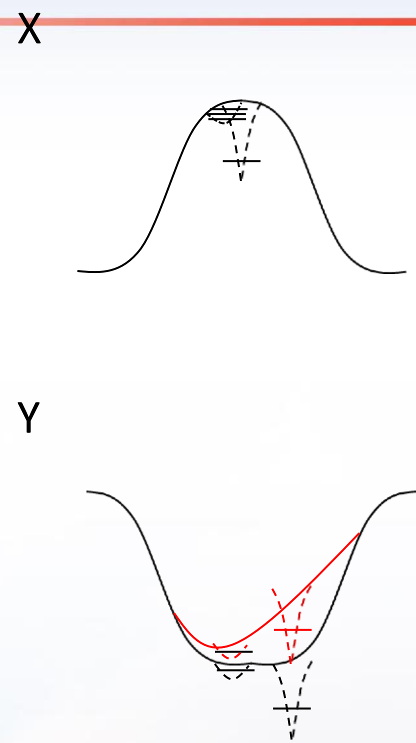
Threshold

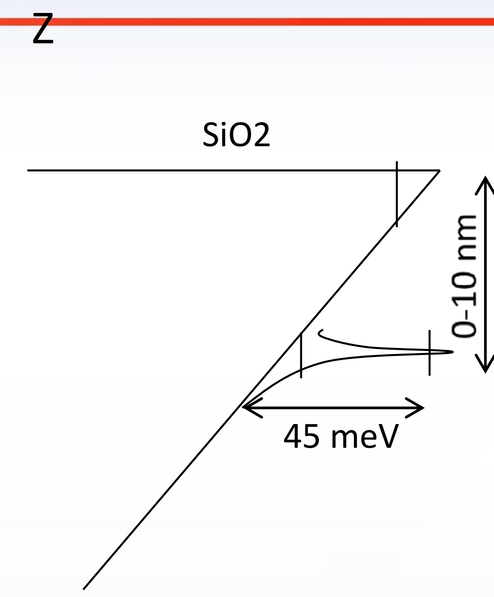
Stability plot



Device geometry



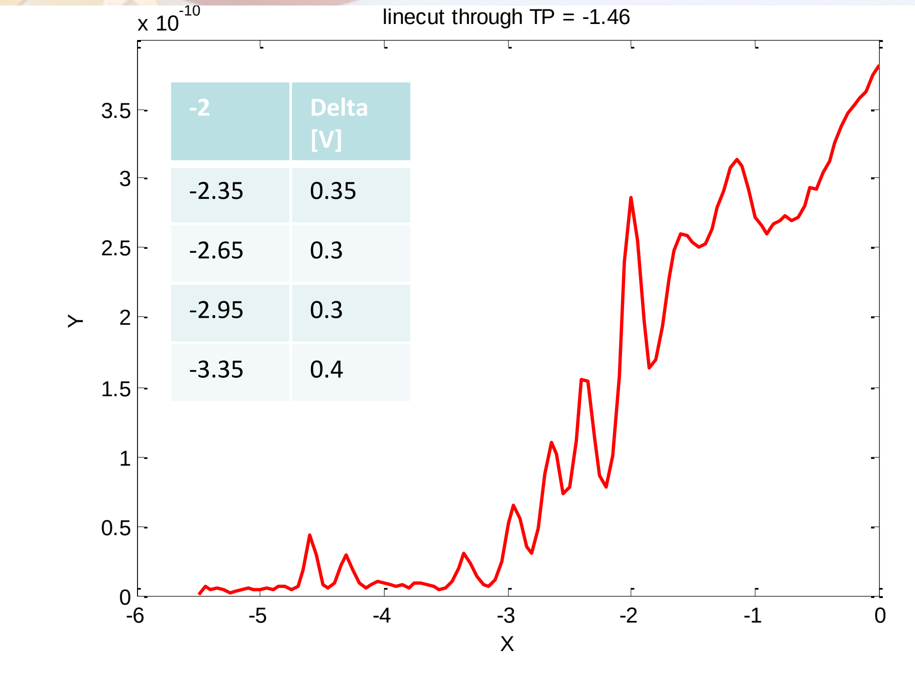




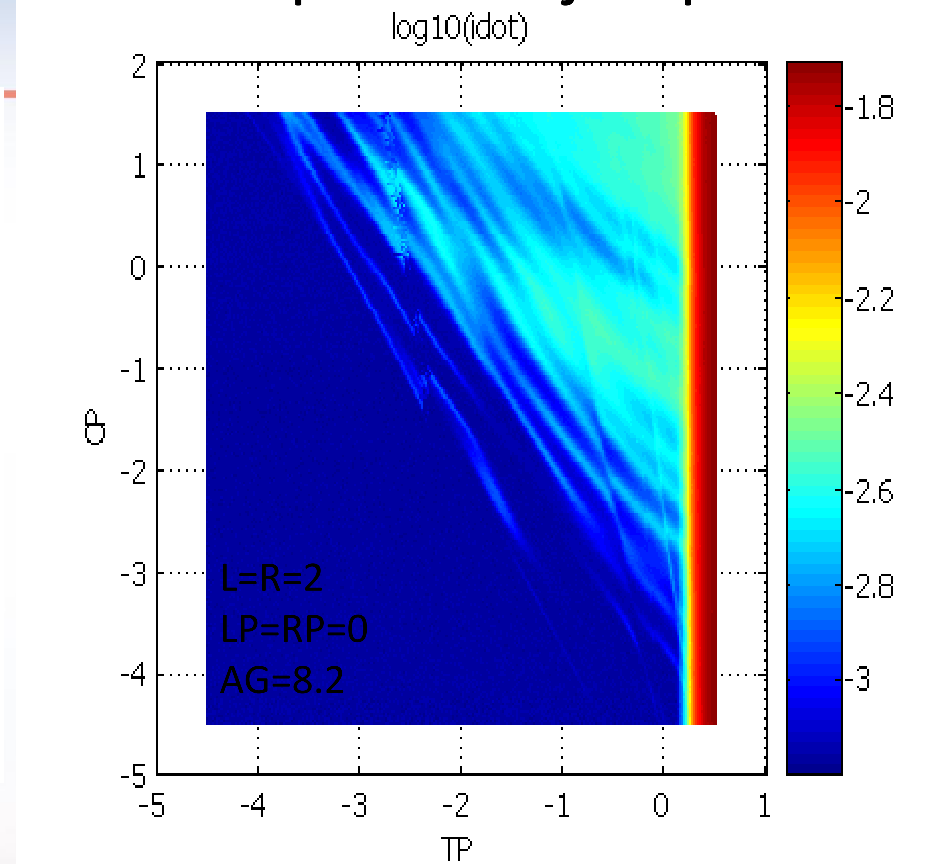
n_dot_region=(1-10)e11/cm^2
E_field = 5-50 MV/m
Max bound depth ~ 1-10 nm

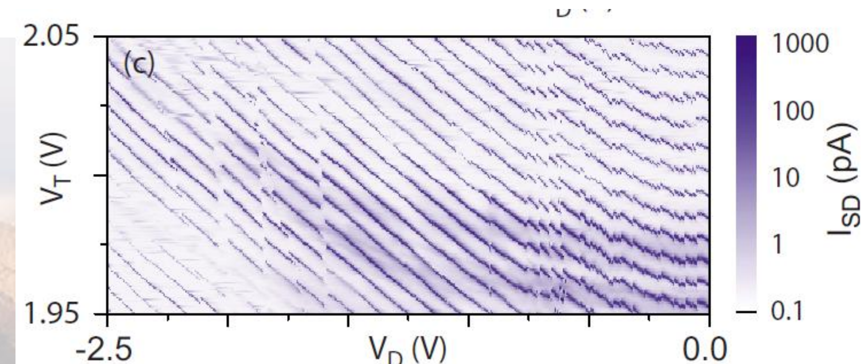
- Concept:
  - Use polysilicon lateral QD for charge sensor
  - Dot is self aligned to position of donors
  - Do we see coupling when dot is nearly in same position as donors?
    - Geometry provides some control over vertical field and lateral barrier with top gate configuration (tunnel coupling gate)
    - Geometry introduces potential parallel path conduction (simultaneous donor spectroscopy

Disorder dot and charge-state dependent jumps



-2	Delta [V]
-2.35	0.35
-2.65	0.3
-2.95	0.3
-3.35	0.4



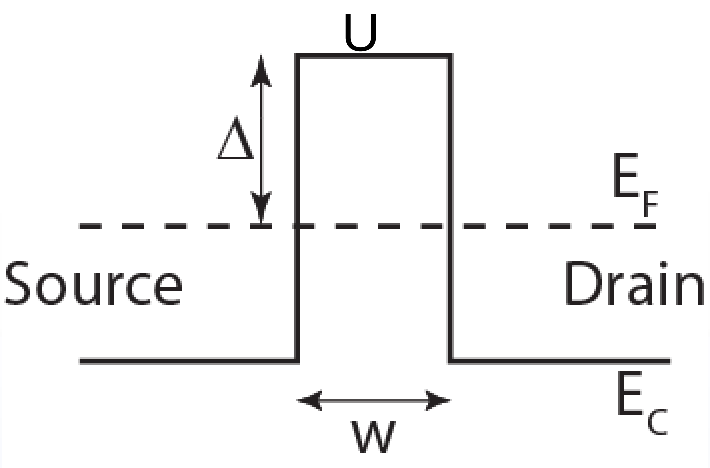


- Observations:
  - Disorder observed in constriction
  - Plunge disorder with TP and CP
  - Several repeatable jumps observed in disorder resonances
  - Strong coupling to TP
  - Possible causes
    - Series disorder dots
    - Parallel disorder dots
    - Series dot-donor
    - Parallel dot-donor

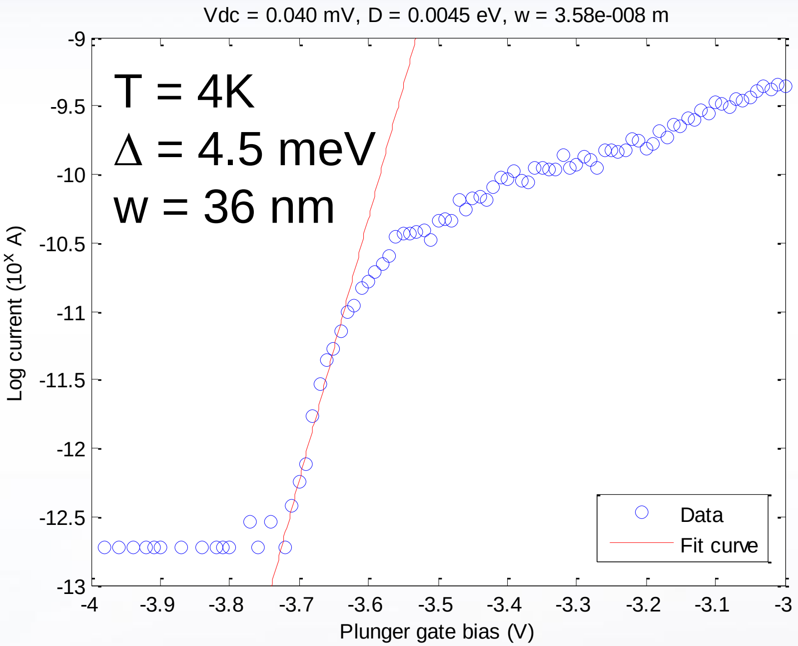
Improve modeling: tunnel barrier model for realistic optimization parameter

Present tunneling target MIT ~ $1.5x10^{11}$ cm^{-2}

Stalford et al., IEEE Trans. on Nanotech. (2011)



MacLean et al., PRL 2007



$$I = q\Gamma \approx f_0 e^{-\frac{2w}{\hbar}\sqrt{2m^*\Delta}}$$

$$\ln(I) = \ln(qf_0) - \frac{w}{\hbar}\sqrt{\frac{2m^*}{\Delta}}\left(2\Delta + q\frac{C_{gate}}{C_\Sigma}(V_0 - V)\right)$$

- Square barrier & WKB
- Linearize the radical

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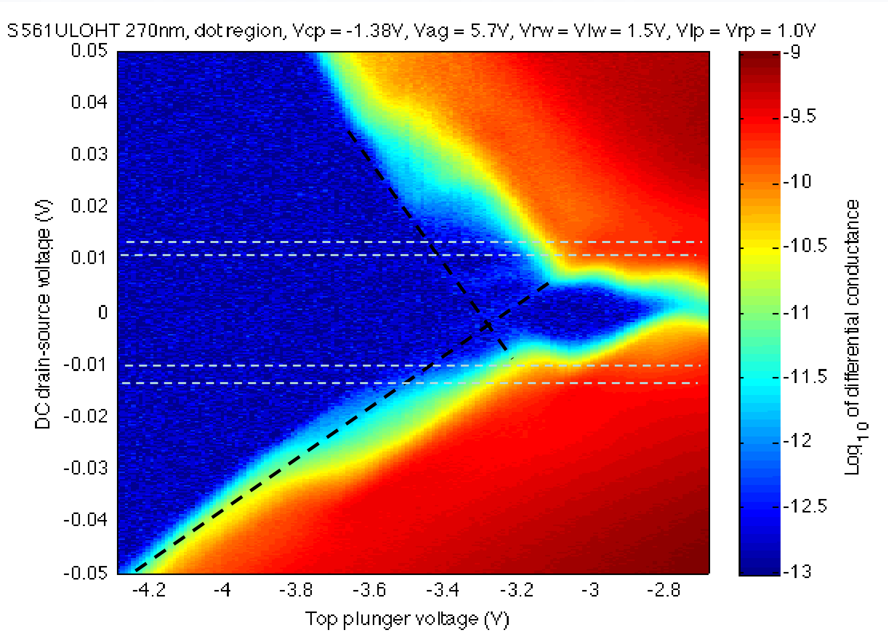
Self consistency of WKB model



Vds (mV)	Vg (V)	Δ (meV)	W (nm)	Δ@ Vds = 0V Vg = -3.4V (meV)
-11	-3.26	4.63	21.9	15.6
-10	-3.24	4.42	22.9	13.7
10	-3.12	2.79	26.8	13.8
11	-3.13	2.69	26.7	13.7

<u>Extrapolate to Vsd = 0</u>

$$dU = \frac{\partial U}{\partial V_{sd}} dV_{sd} + \frac{\partial U}{\partial V_{gate}} dV_{gate}$$

$$dU = \Delta - \Delta_0 - q|V_{sd}|$$

$$\Delta = \Delta_0 + q|V_{sd}| + \frac{C_S}{C_\Sigma} dV_{sd} + \frac{C_G}{C_\Sigma} dV_{gate}$$

<u>Next step is to compare to simulation</u>

Shirkhorshidian, et al.

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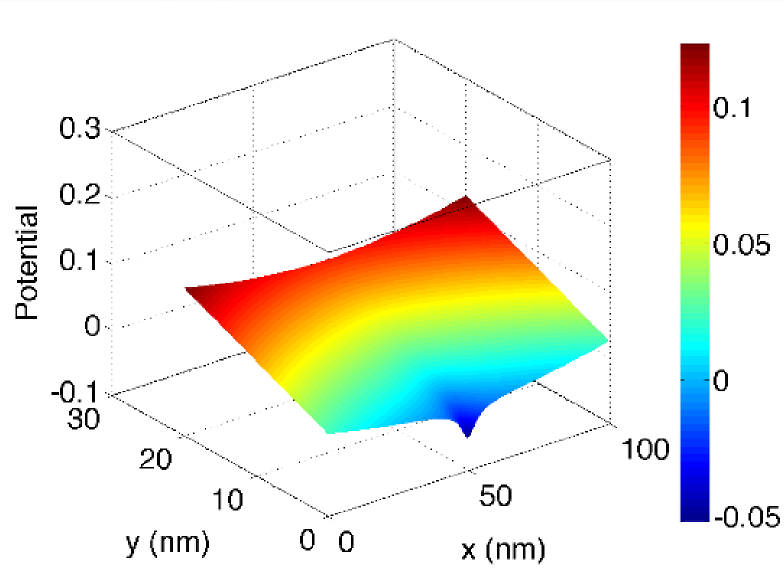
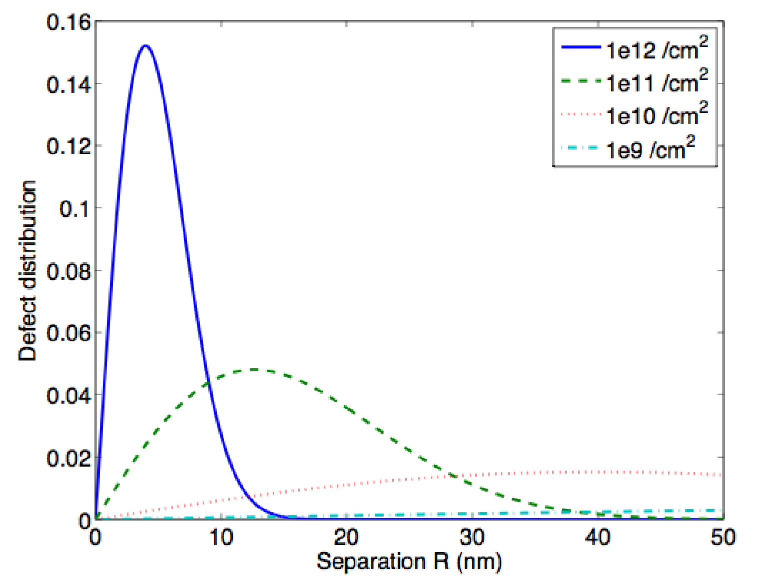
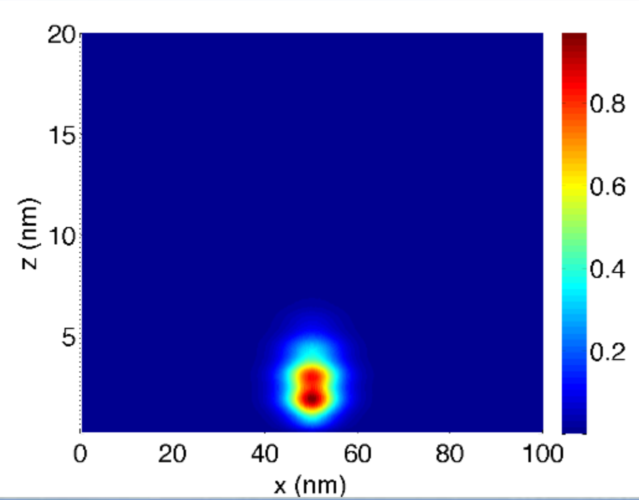
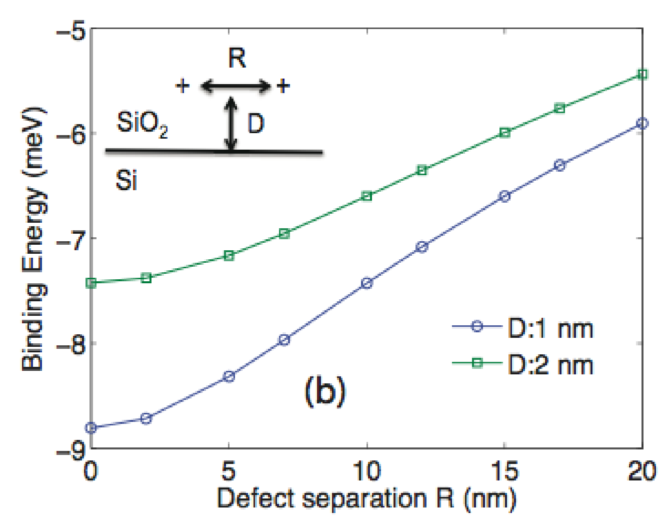
Implications of positive fixed charge (defect center detection?)



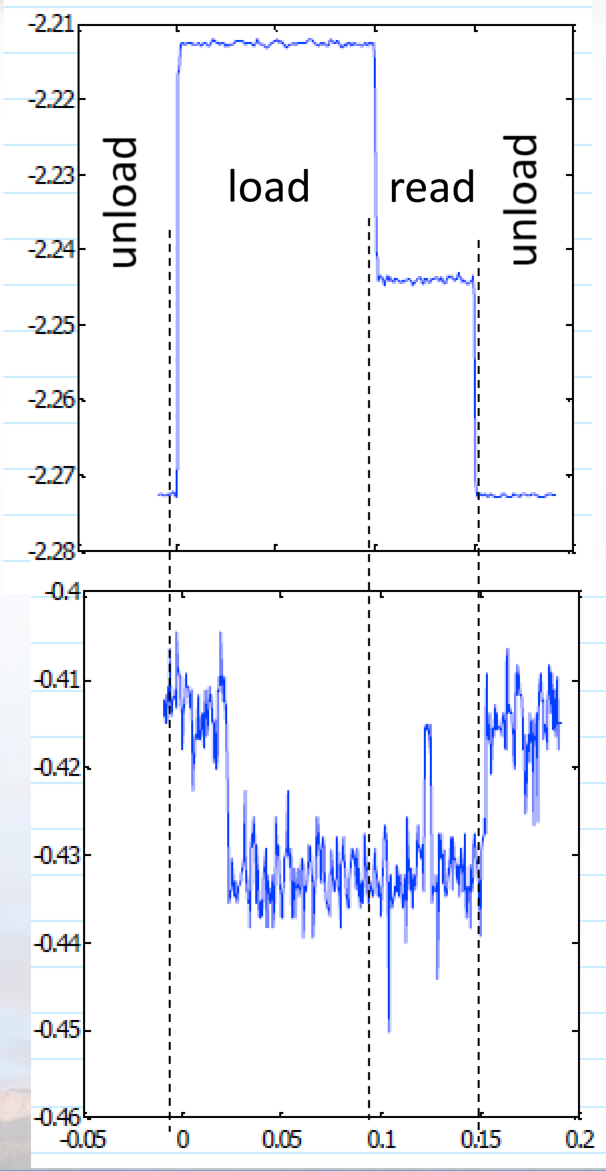


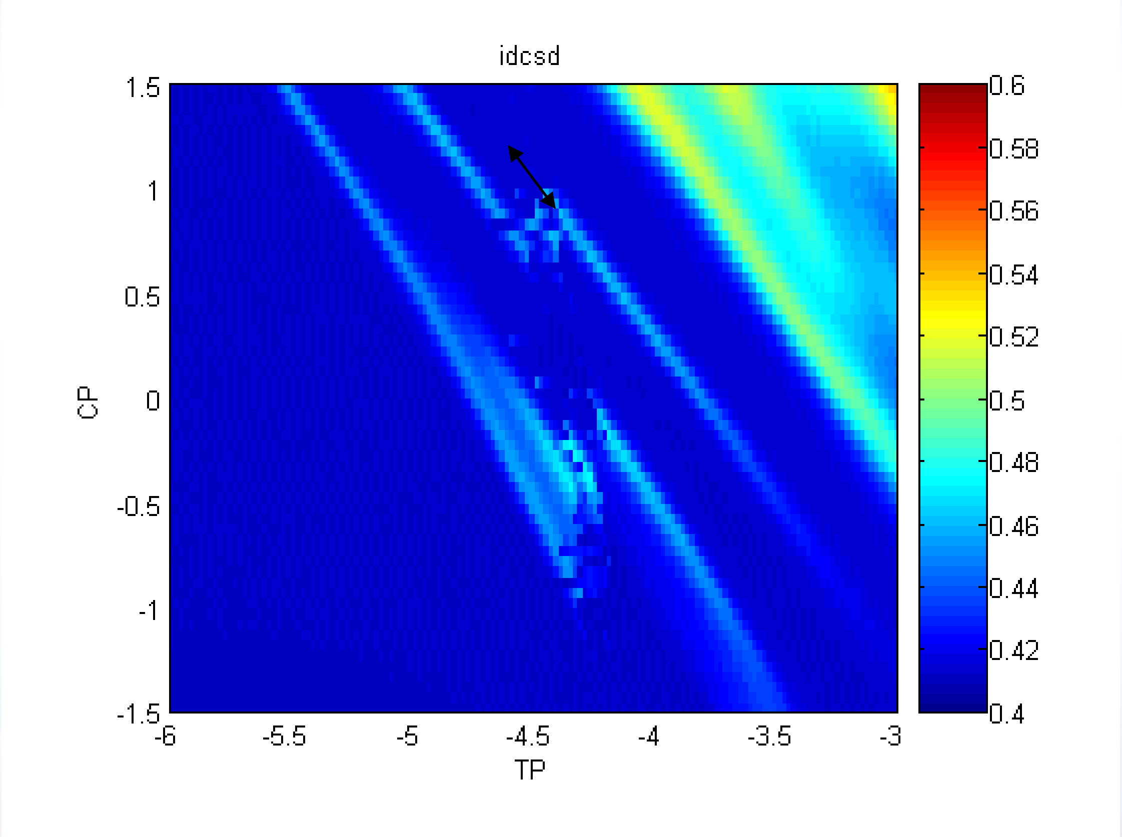




Rahman & Muller

Run 6, 1K pot, real time measurements





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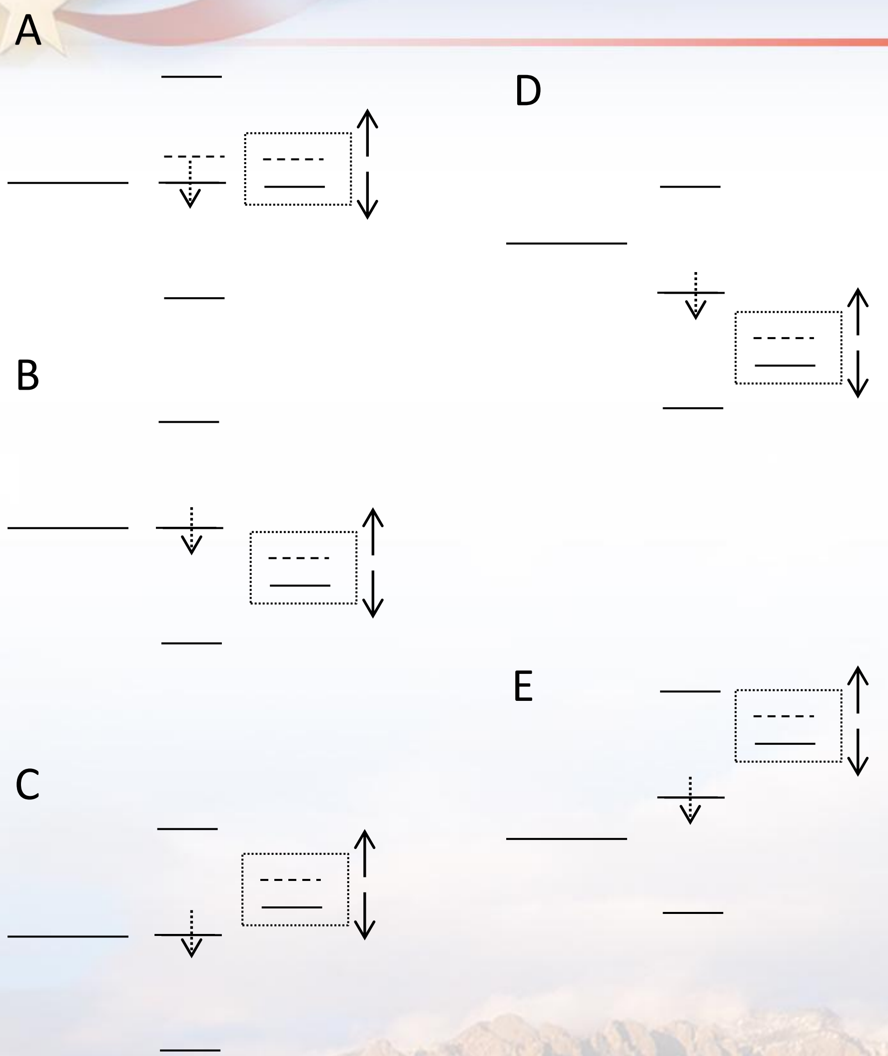
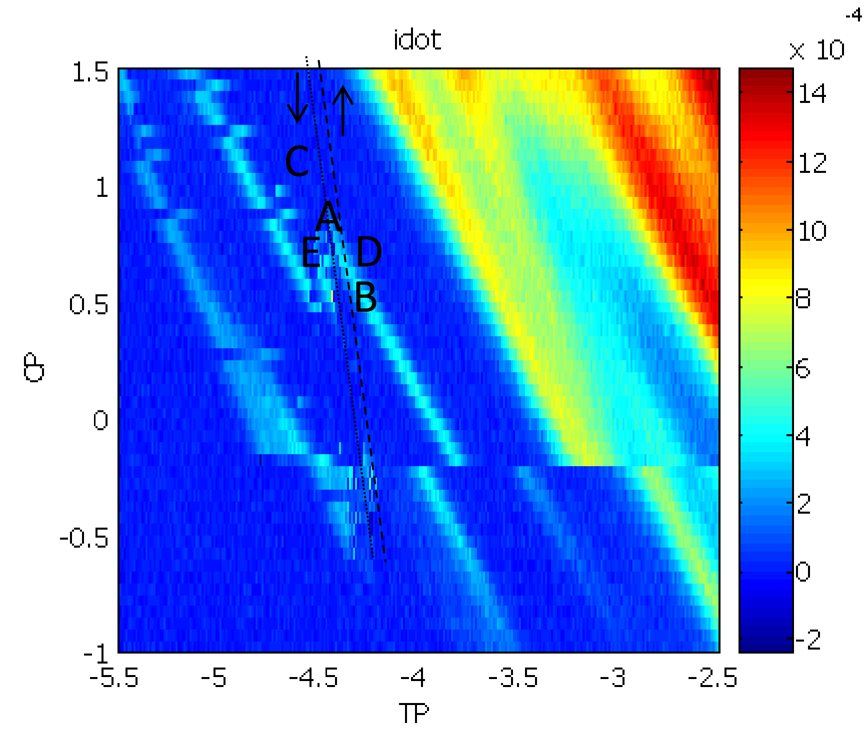
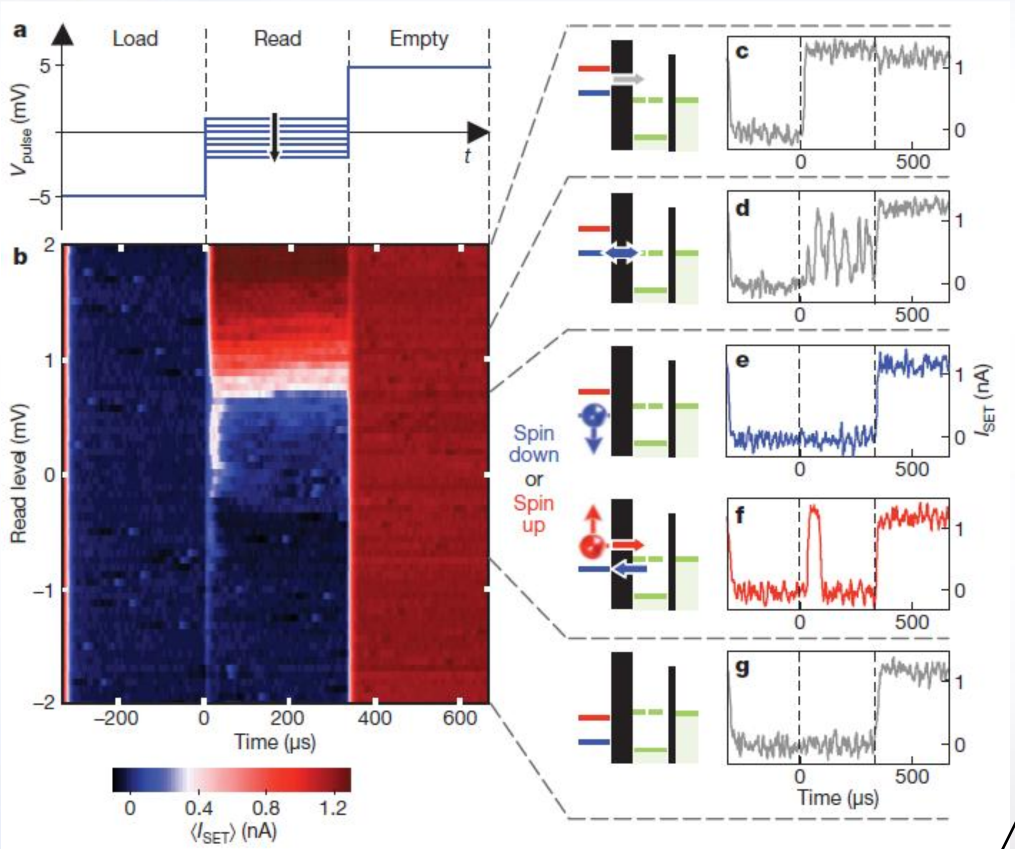
Cartoon of energy diagram and stability plot regions

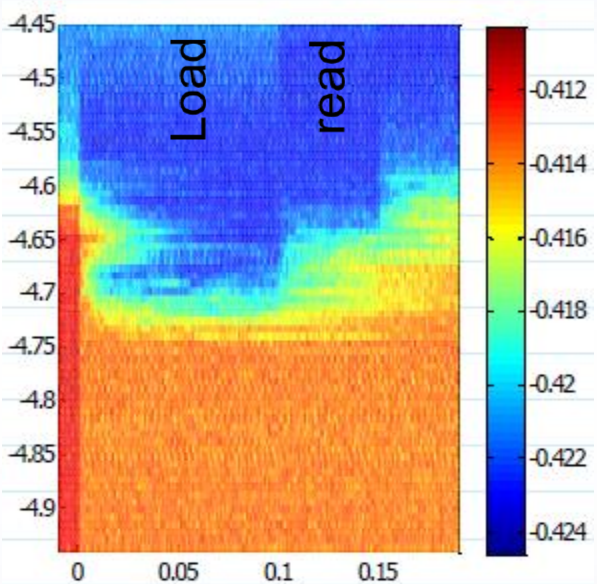


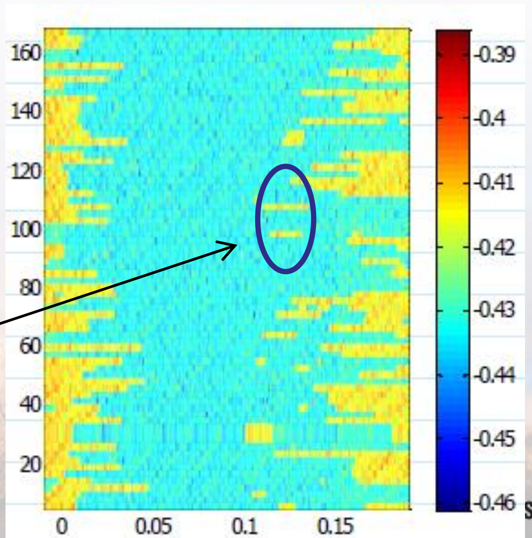


- asd

Run 6, 1K pot, real time measurements

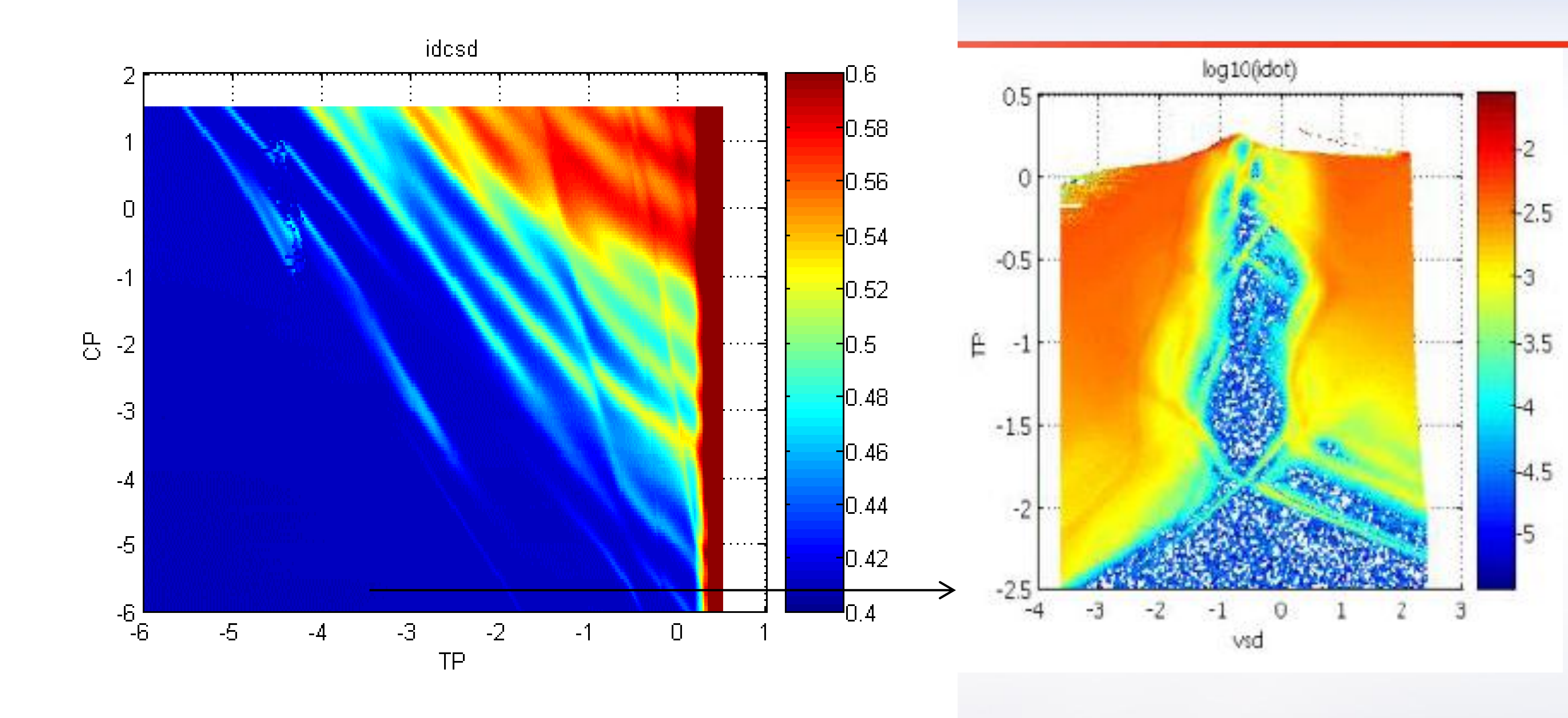






- Need to find right read level
- Approach demonstrated in recent Nature paper shifts only read level
- For reasons of set-up simplicity, we keep levels constant and shift position
- Single shots at TP = -4.63

Few electron regime



- Last resonances observed by transport
- Diamond plots do not reveal additional transport beyond the last visible
- Coupling of charge centers is to few electron dots
- Implications?
  - Complications related to density of states?
  - Opportunity to couple to N=0 or N=1 dot?

Summary

- Near term motivations:
  - Develop poly-silicon read-out for donor qubit
  - Poly-silicon structures provide path to self-aligned implants (e.g., assure J-gate between donors)
  - Integrated detector development progressing in parallel (see E. Bielejec talk)
- Sb implanted split gates show unintentional dot behavioe
- Resonances show charge offsets qualitatively similar to that used for donor read-out in previous work
- Three level pulsed measurements in progress to examine T1
- Split-gate unintentional dots appear to be few electron leading to open questions
  - Additional challenge for read-out due to discrete DOS?
  - Opportunity to examine coupling to few electron dot?

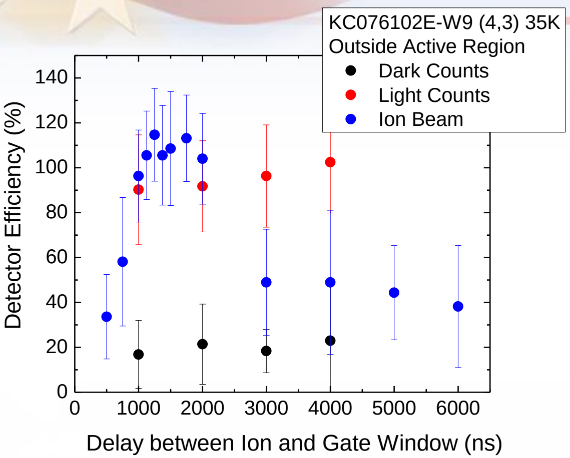
Acknowledgements

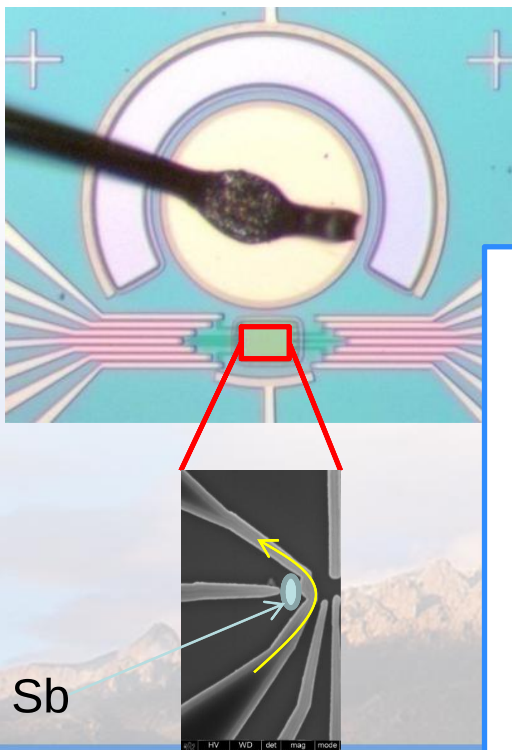
- Thanks to the organizers for hosting the Si workshop

- The technical teams
  Silicon quantum dot: M. Lilly, N. Bishop, S. Carr, T.-Z. Lu, L. Tracy, K. Nguyen, T. Pluym, J. Dominguez, J. Wendt, J. Stevens, B. Silva, E. Bower, R. Gillen
  Donor and donor-dot: E. Bielejec, E. Bussmann, D. Perry, B. McWatters, A. MacDonald
  Device modeling: R. Muller, R. Young, W. Witzel, E. Nielsen, R. Rahman, K. Young, J. Verley
  Cryogenic electronics: T. Gurrieri, J. Levy, R. Young, J. Hamlet, K. Barkley
  Architecture and quantum error correction: A. Ganti, M. Grace, W. Witzel, U. Onunkwo, A. Landahl, C. Phillips, R. Carr, T. Tarman

- Joint research efforts with external community:
  - U. Wisconsin (M. Eriksson, D. Savage, M. Friesen, R. Joynt)
  - Australian Centre for Quantum computing Technology (L. Hollenberg, D. Jamieson, M. Simmons, A. Dzurak, A. Morello)
  - Princeton University (S. Lyon)
  - NIST (N. Zimmerman)
  - U. Maryland (S. Das Sarma, M. Peckerar)
  - Lawrence Berkeley National Labs (T. Schenkel)
  - National Research Council (A. Sachrajda)
  - U. Sherbrooke (M. Pioro-Ladriere)

Status of the Donor Sample and Immediate Path Forward

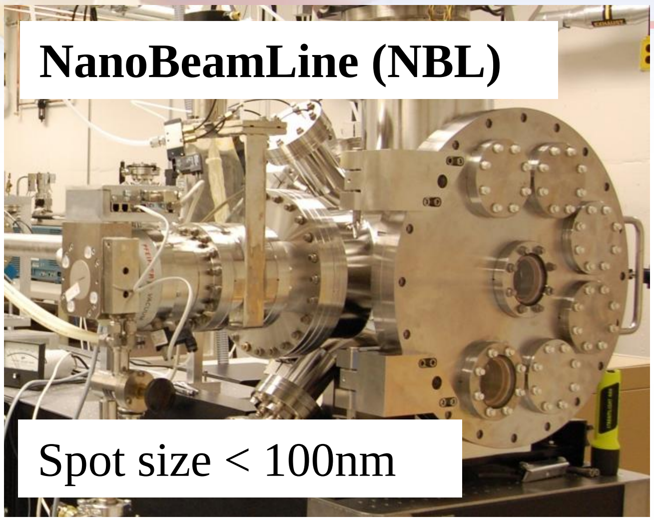




- 100% Detection Efficiency with new generation of integrated ion detectors – opens door to new devices
- Next step is hand off the working detectors to fab folks to pattern into self-aligned poly-Si gate structures
- Then we are ready for deterministic single ion implantation into self-aligned poly-Si nanostructures
- In parallel we will do timed implants following CQC2T approach with poly-Si

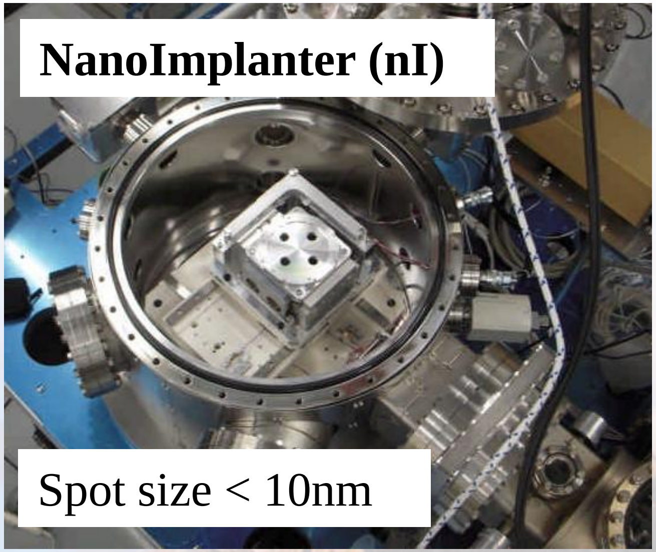
- Path forward to reproducibility building 1 + 2 donor qubits
    - Potentially higher yield for single donor devices
    - Path forward for 2 donor qubits
- High precision donor placement with top-down approach
    - Sensitivity for low energy ion implants
    - Focused ion beam approach for scalability
- Flexibly of Design and materials (sSi/SiGe or Si MOS)

Focused Ion Beam Development at the IBL



NanoBeamLine (NBL) on 400 kV HVEE Implanter

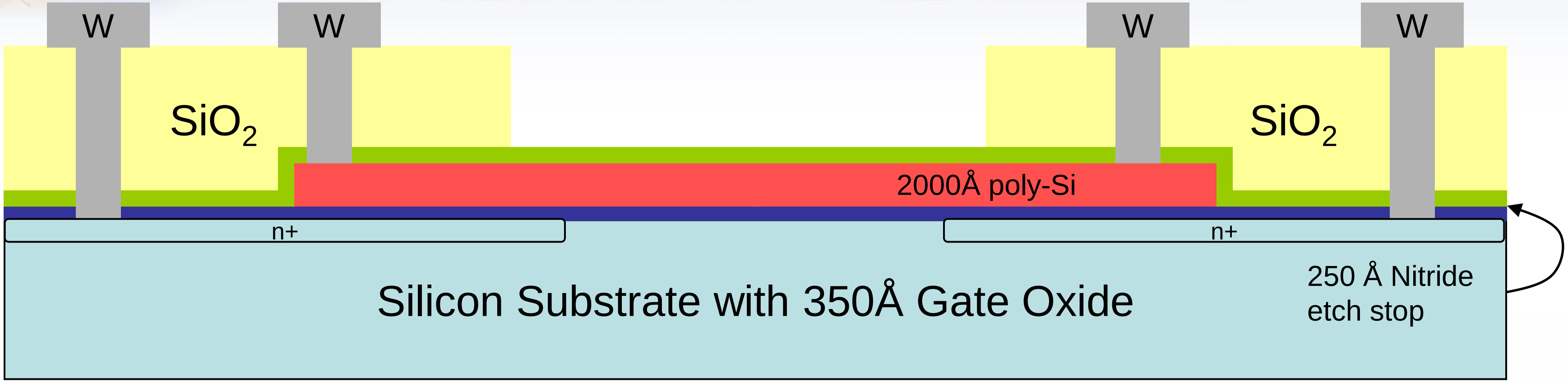
- Attached to standard semiconductor implanter
- ***Wide range*** of ion energies 10-400 keV
- ***Variable Current*** from mAs to ***Single Ion***
- Broad Range of ***Ion Sources*** (Ion Species)
- Targeting a spot size of <100 nm in the third version of this beam-line - ***On-hold time spent on APD development***



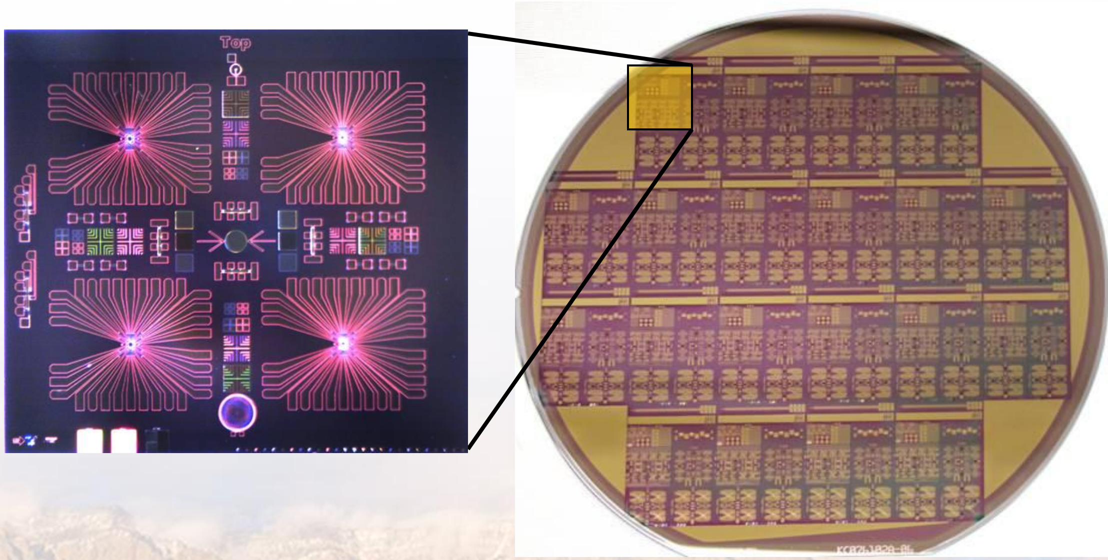
NanoImplanter (nI) 100 kV FIB

- High ***Resolution*** of a FIB
- 100 kV Accelerating Voltage
- ***Variable Current*** from pAs to ***Single Ion***
- Broad Range of ***Ion Sources*** (Ion Species)
- **Ultimate resolution limit** of the top-down approach will be tested using the nI

Silicon foundry

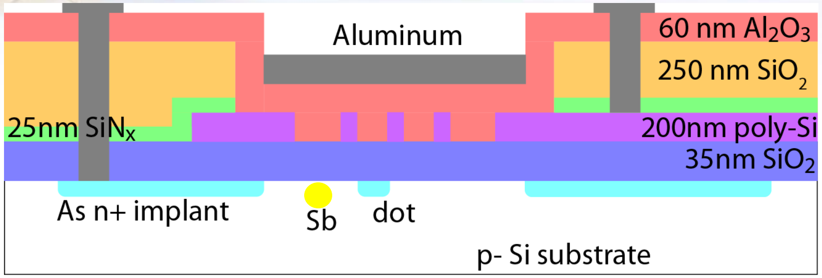


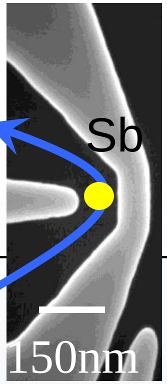
<u>MOS Stack from Si fab</u>
Deep UV lithography (0.18 um)
7,500 – 15,000 mobility cm2/Vs
QDs possible with 0.18 um litho
Smaller features w/ EBL in/out of fab
Standard MOS material set only



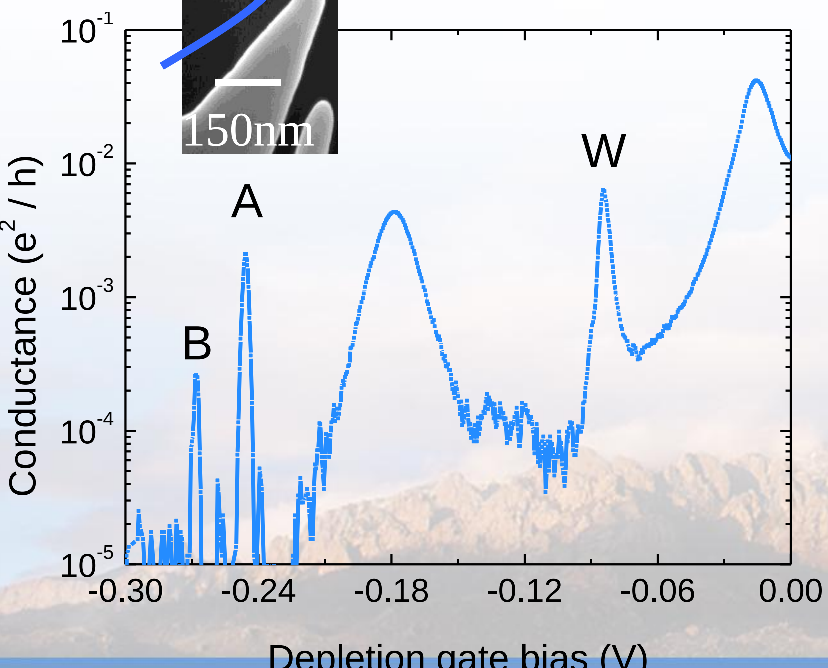
T. Pluym

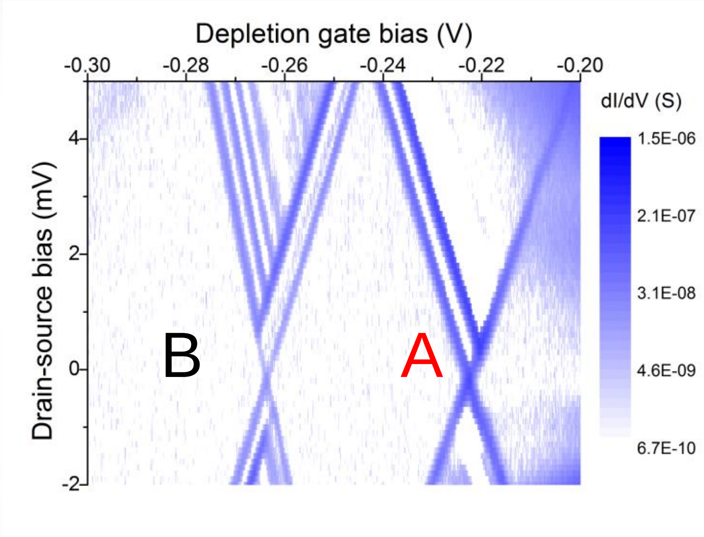
Triangulation of resonances in implanted split-gates

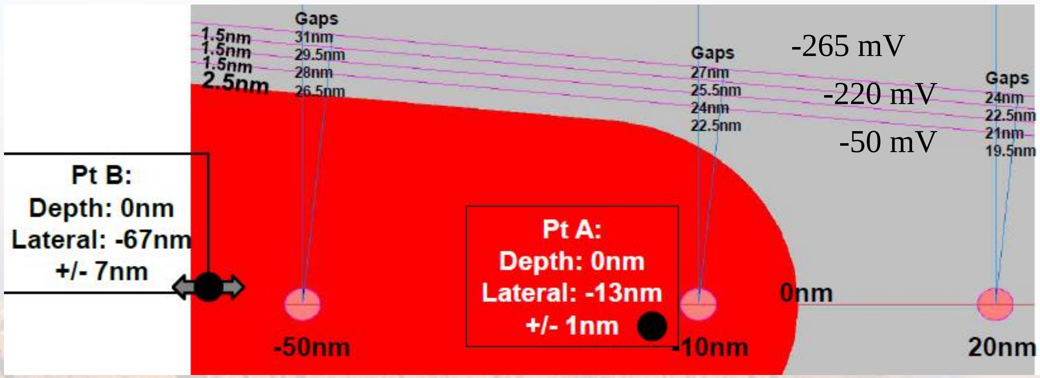




100 keV Sb
4 x 10^{11} cm^{-2} dose
implanted through 80 nm
PMMA mask







Bishop, arXiv. 1107.5104

Tunnel width comparison: WKB & triangulation

Resonance B

Vsd (mV)	Vg (V)	Δ (meV)	W (nm)
25	-0.3805	2.21	48.4
22	-0.3745	2.53	45.6

For V_{SD}= 0V and V_g = -0.27V, Δ = 9.12 meV

dU/dV_{SD} = -0.4203 eV/V (C_s/C = 0.4468)

Resonance A

Vsd (mV)	Vg (V)	Δ (meV)	W (nm)
25	-0.353	1.65	39.1
22	-0.345	1.82	38.6

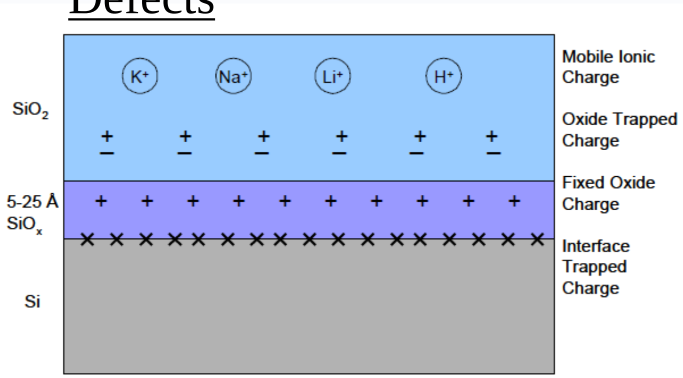
For V_{SD}= 0V and V_g = -0.24V, Δ = 6.05 meV

dU/dV_{SD} = -0.3825 eV/V (C_s/C = 0.3899)

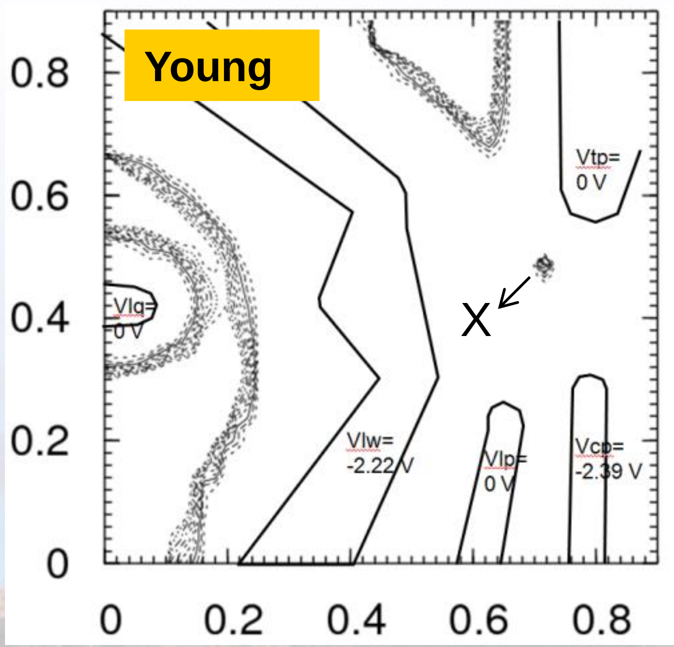
Method	Width (A) [nm]	Width (B) [nm]
Triangulation to 1.5x10^11 cm^2 edge	32	34
Square barrier	38.9	47

Persisting doubts about MOS for qubits

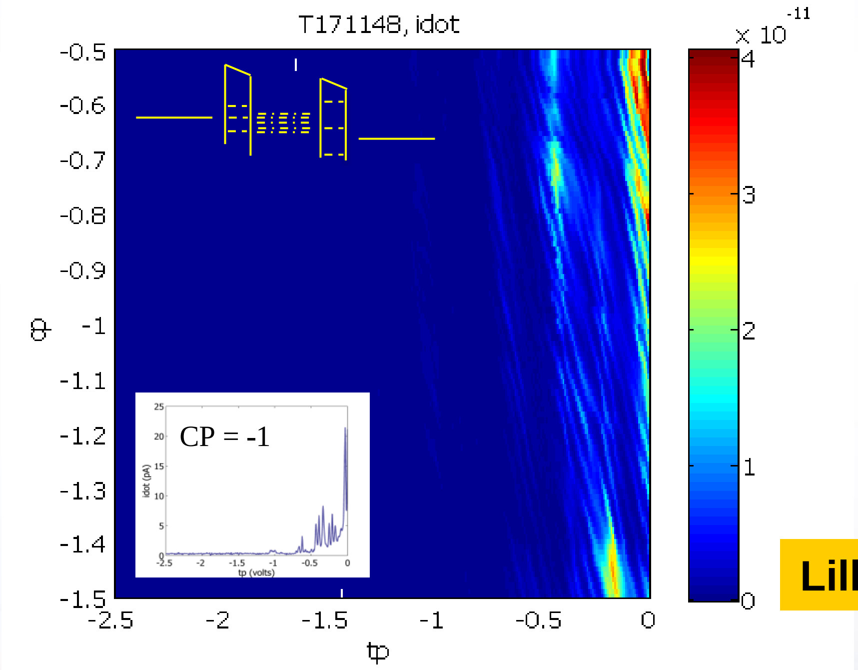
Defects



Uncontrolled localization



Coulomb blockade with disorder



Assume: DQD Area ~ 100 nm x 25 nm

Number of defects in DQD area

1×10^{10} → 0.25 per QD

1×10^{11} → 2.5 per QD

1×10^{12} → 25 per QD

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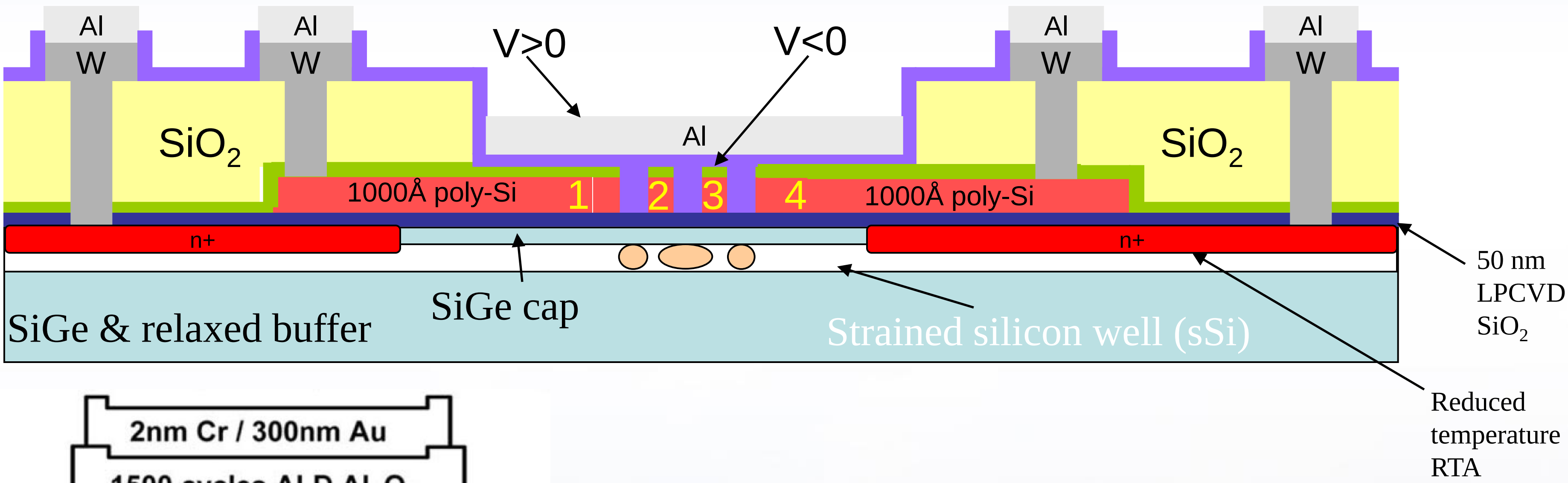
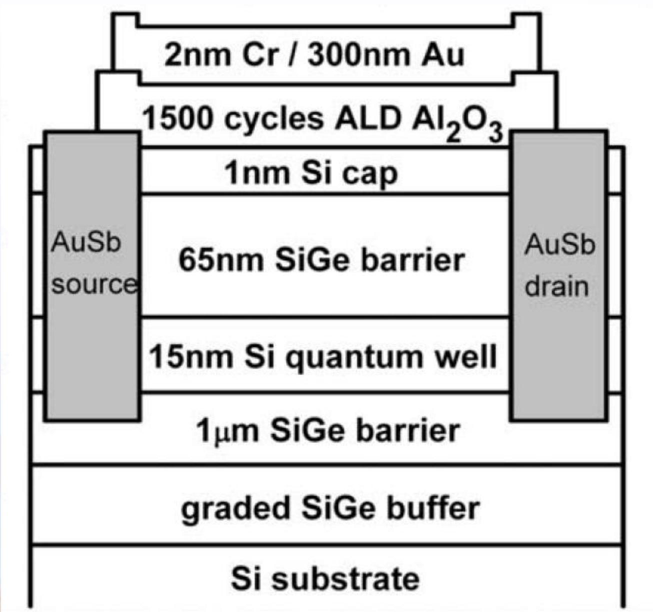
Enhancement Mode SiGe/sSi: High Mobility & Modular Change to MOS Flow





Undoped SiGe Heterostructure

Lu et. al., APL **94**, 182102 (2009)

Mobility ~1.6×10^6 cm^2/Vs

Get the spin away from the surface and defects related to dielectric/crystal interface

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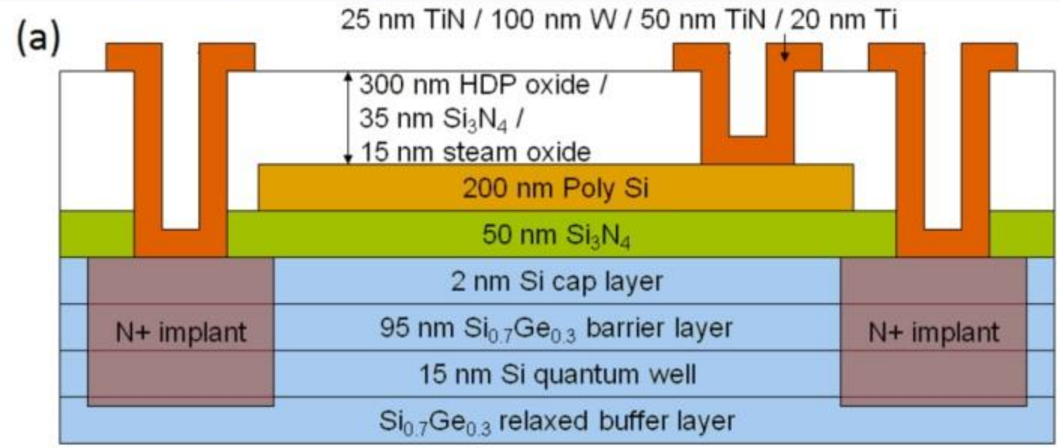
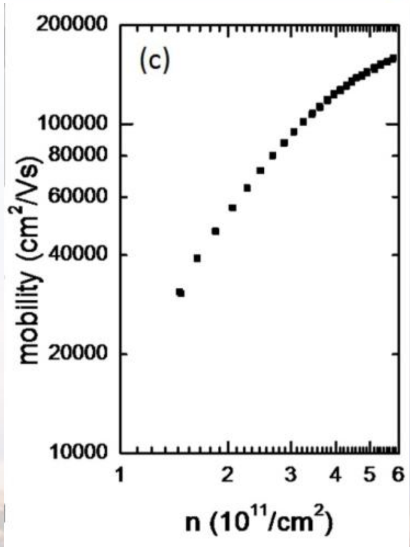
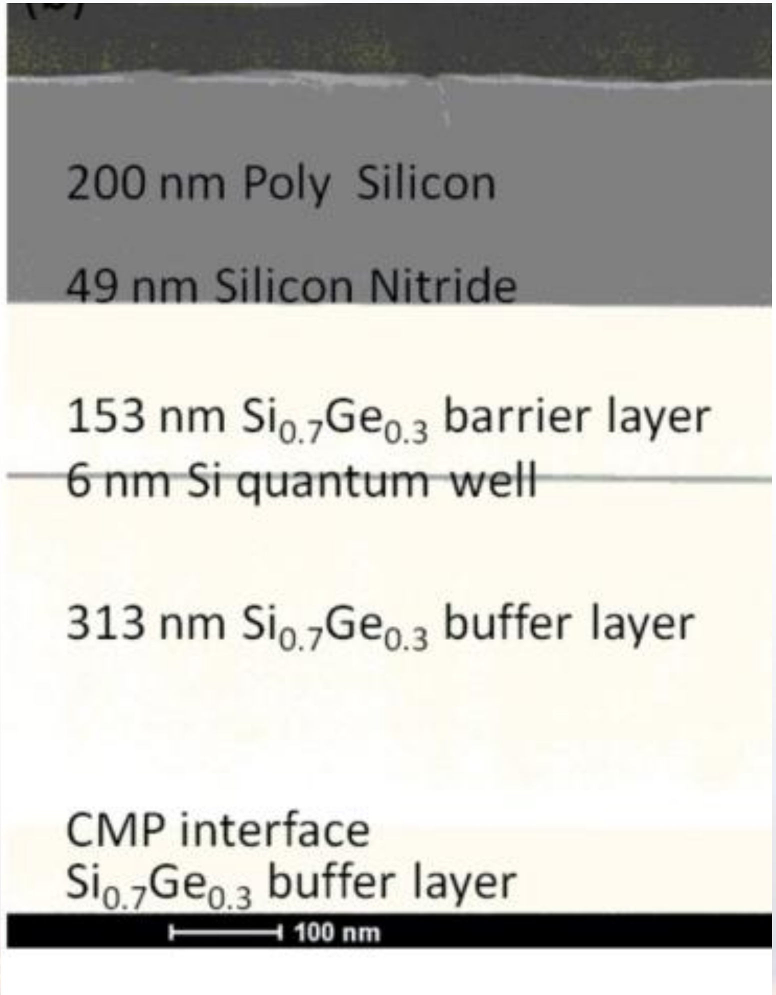
Back to the fab: SiGe/sSi



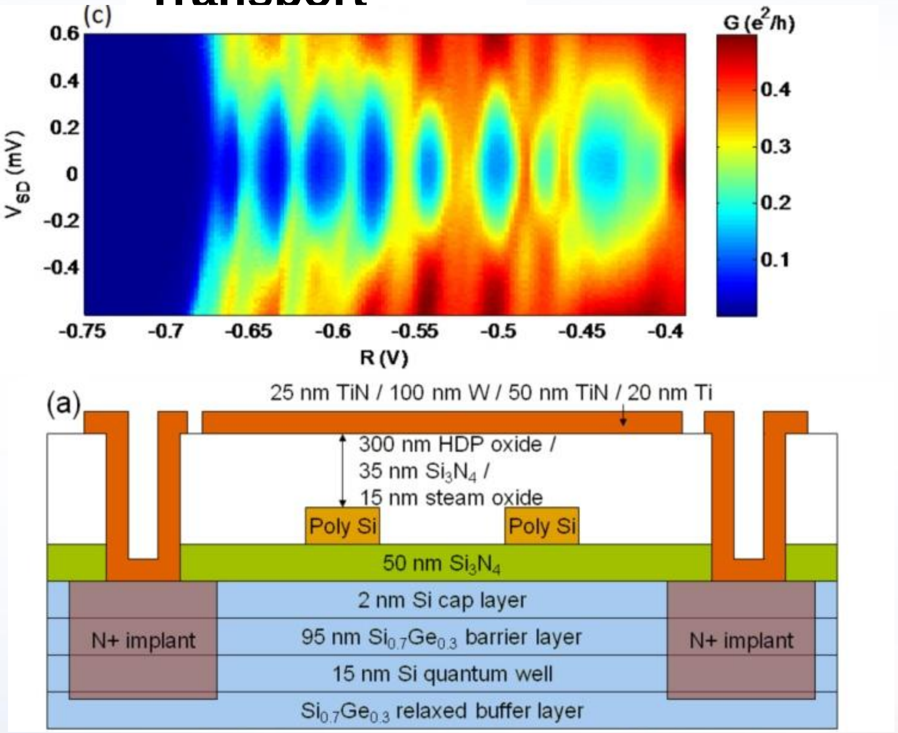
- Modifications:
  1. Substrate
  2. Gate dielectric
  3. Implant & anneals
- Questions:
  1. Ge/Si diffusion
  2. Surface pinning
  3. Mobilty



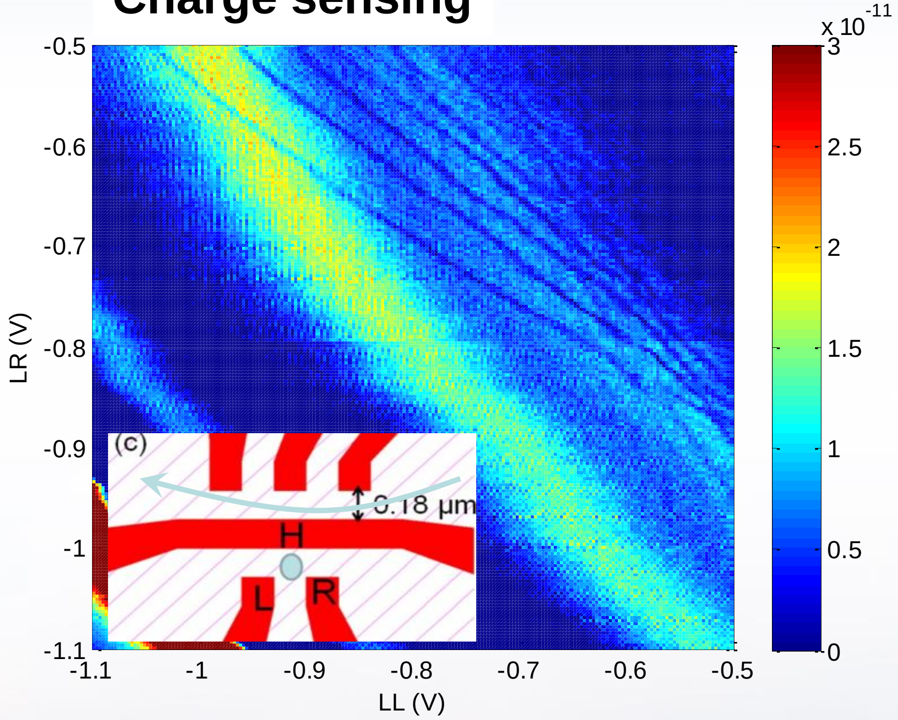


Charge sensing: last transition

Transport



Charge sensing



- Opposite channel used as charge sensor
- Last transition in region of high sensitivity of sensor
  - looks like the last electron

Lu et al., APL 2011

Wafer-level modular process flow

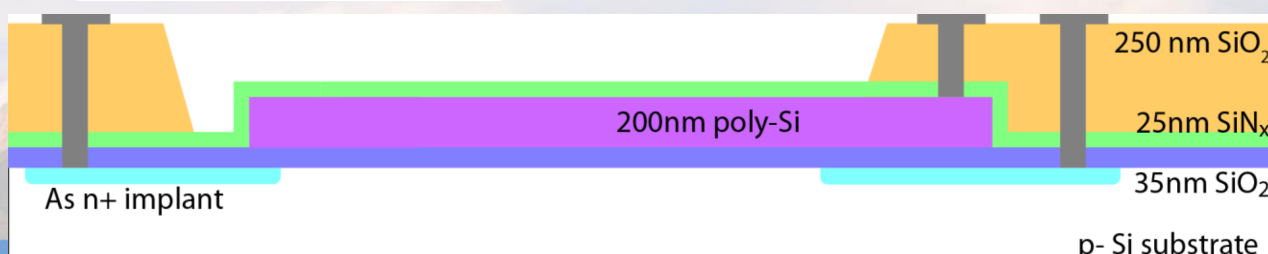
2-3 months

- MOS primary dielectric (SiO_2)
- Gates and ohmic contacts
- Cap and planarize
- Metal bond pads and alignment marks

sSi/SiGe module
- SiGe primary dielectric (SiNx)

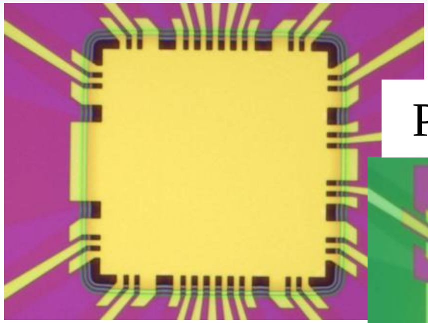
Donor module
- Ion detector formation

Can do both donors and SiGe!

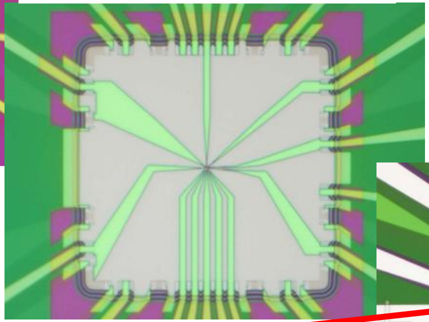


Fast turnaround die-level process

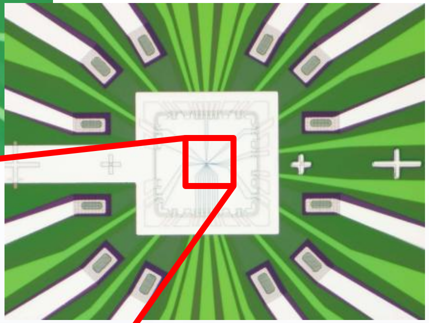
Start

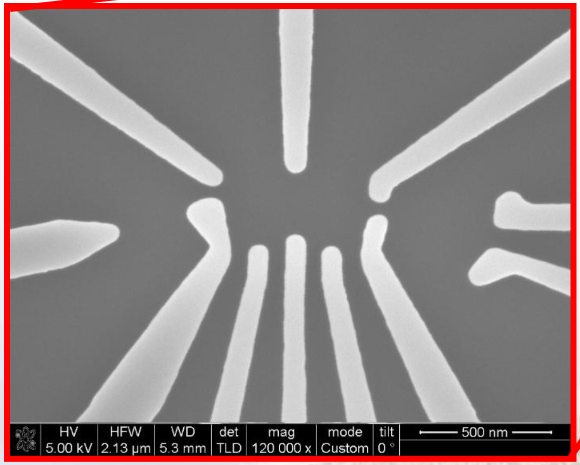


Polysilicon Etch



Finish

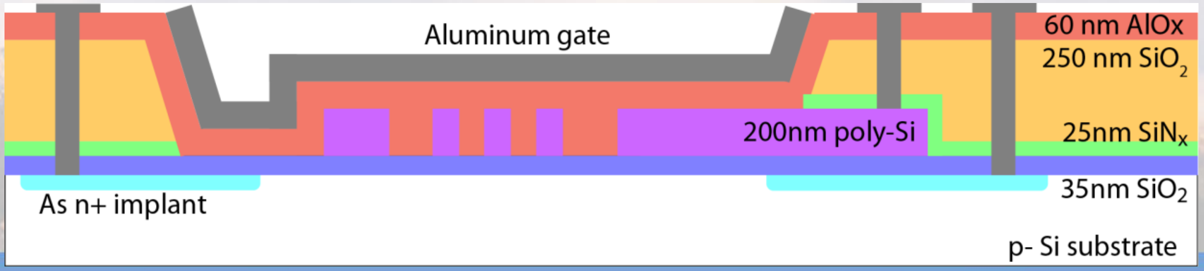




2-3 weeks

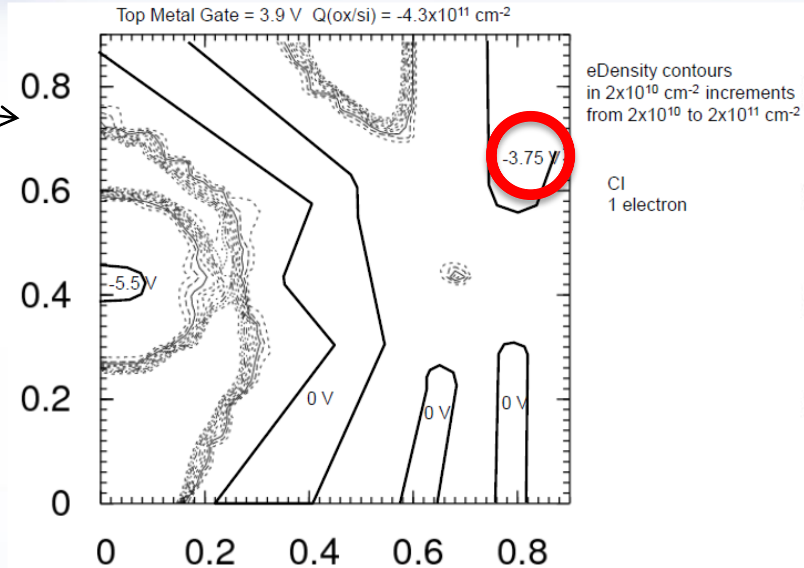
<u>Process flow</u>

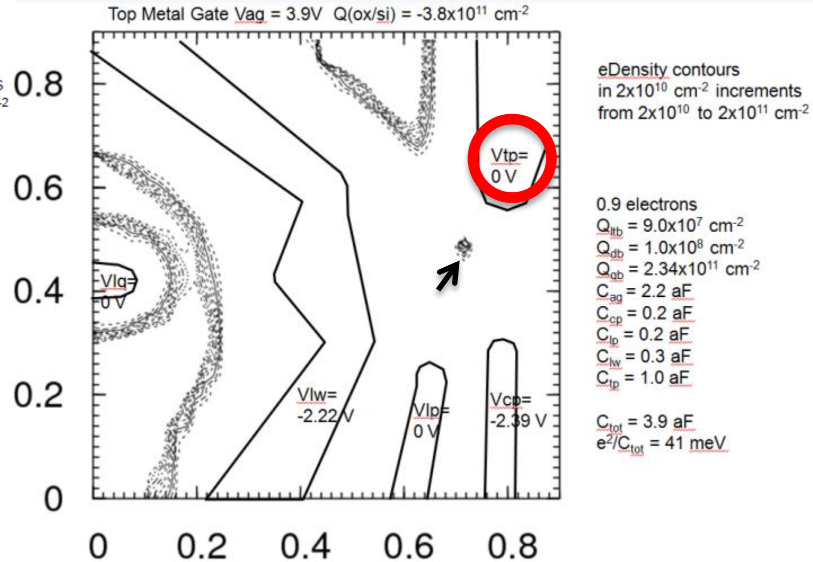
- E-beam litho
- Etching
- Second dielectric ($ALD\ Al_2O_3$)
- Accumulation and bond pad metal



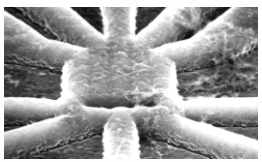
Improve modeling: calibrate simulations

Xpt. Bias w/ Vt offset →

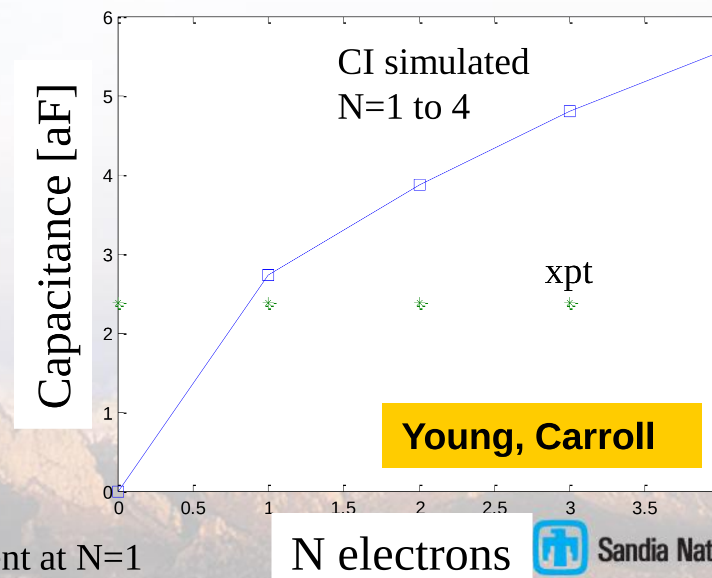




Topography



Gate	Measured [aF]	CI (N=1) [aF] TP=-3.75/ 0	Semi-classical [aF] TP=-3.75
AG	2.37	2.73 / 2.2	3.13
TP	0.48	0.29 / 1.0	0.3
L	0.56	1.56 /0.3	1.9
LP	0.29	0.45 /0.2	0.49
CP	0.54	0.59 /0.2	0.66



Simulation is consistent with observed magnitudes in experiment at N=1

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