Low Disorder Coulomb Blockade and Charge Sensing in Double Top Gated Si MOS Nano-Structures

Si QC Workshop 2009

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Sandia National Laboratories

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

THE UNIVERSITY of WISCONSIN MADISON

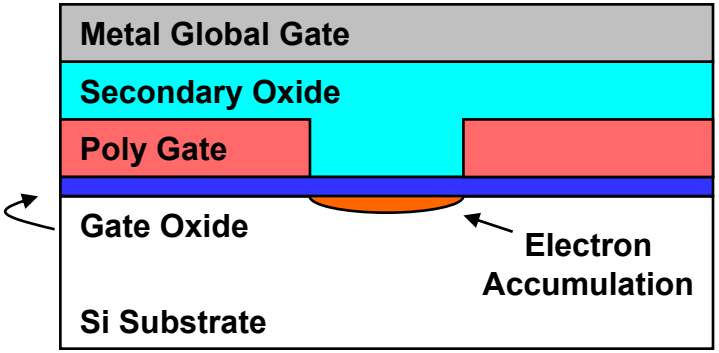
- Goal:
  - Coupled Few-Electron Quantum Dots in a Silicon/Silicon Dioxide Inversion Layer

- This Talk:
  - Process Characterization, Damage Mitigation
  - Low Disorder MOS Quantum Dots
  - Integrated Charge Sensing

Quantum Dot Spin Qubits in Si

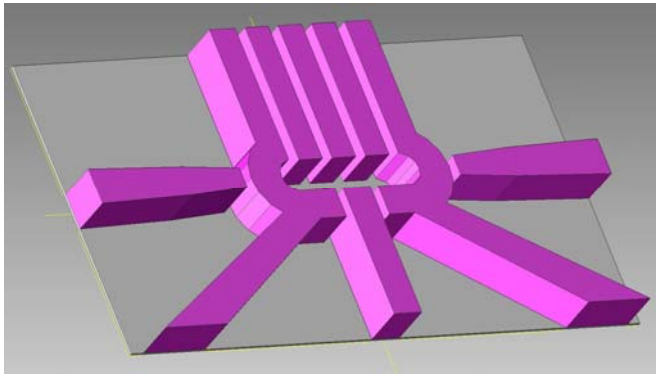
Advantages Si Material:

- Low spin-orbit coupling
- High percentage Si^{28} reduces nuclear spin coupling

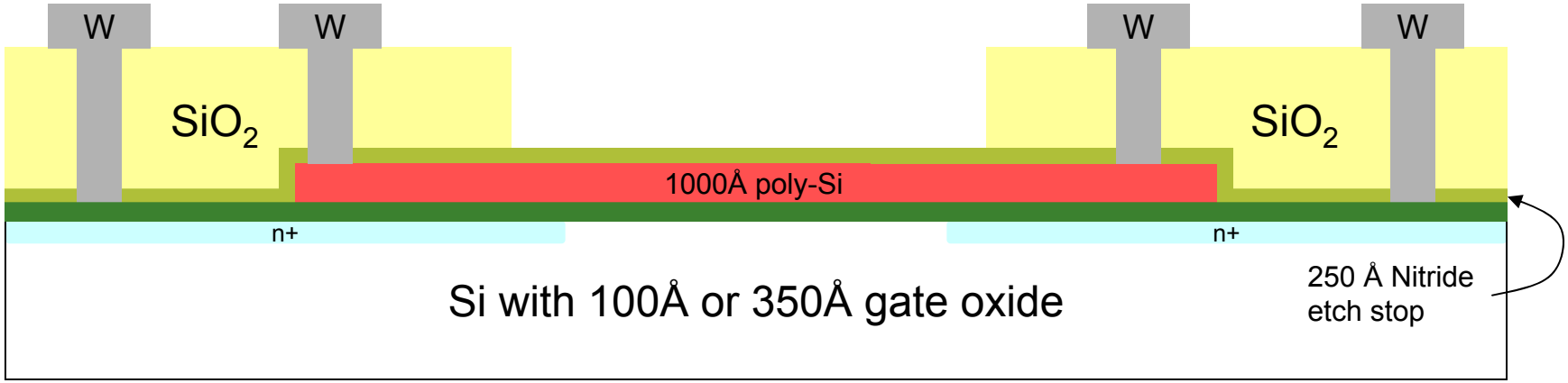


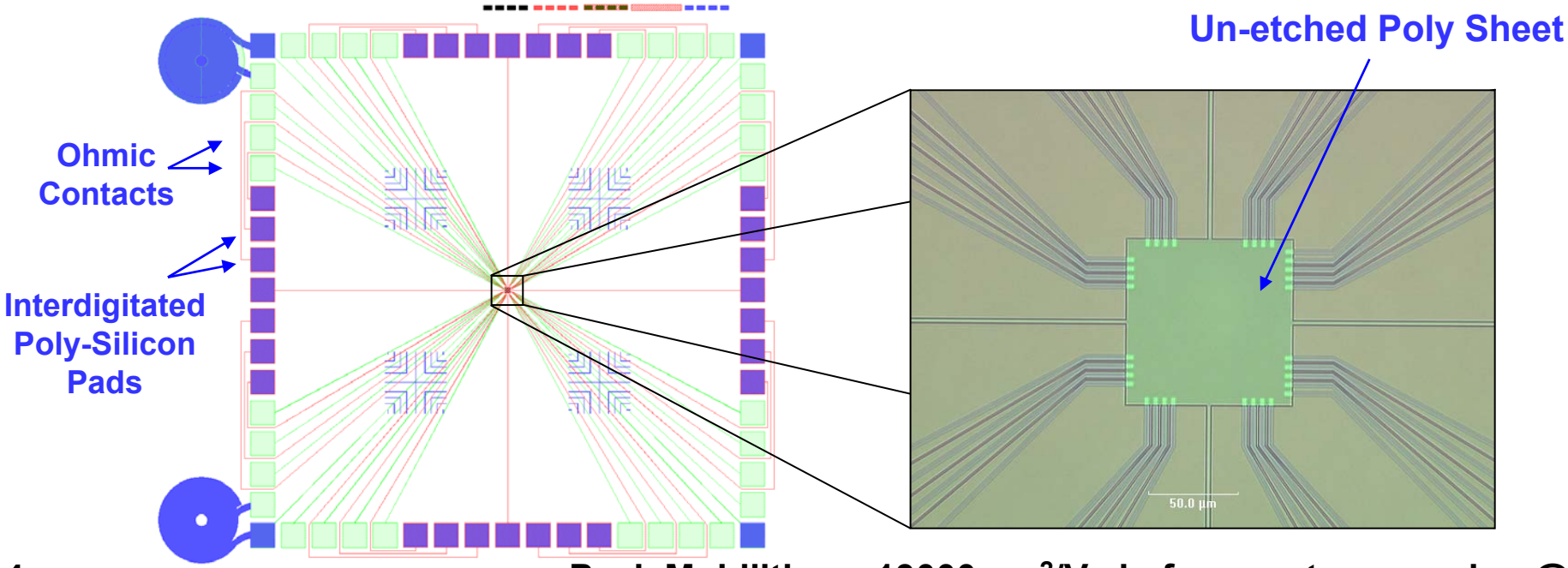
Advantages of the MOS System:

- Highly tunable densities
- Scaling advantage due to gate proximity to electrons
- No δ-dopants required for transport
- Readily CMOS compatible
- Polysilicon depletion gates allow for donor integration



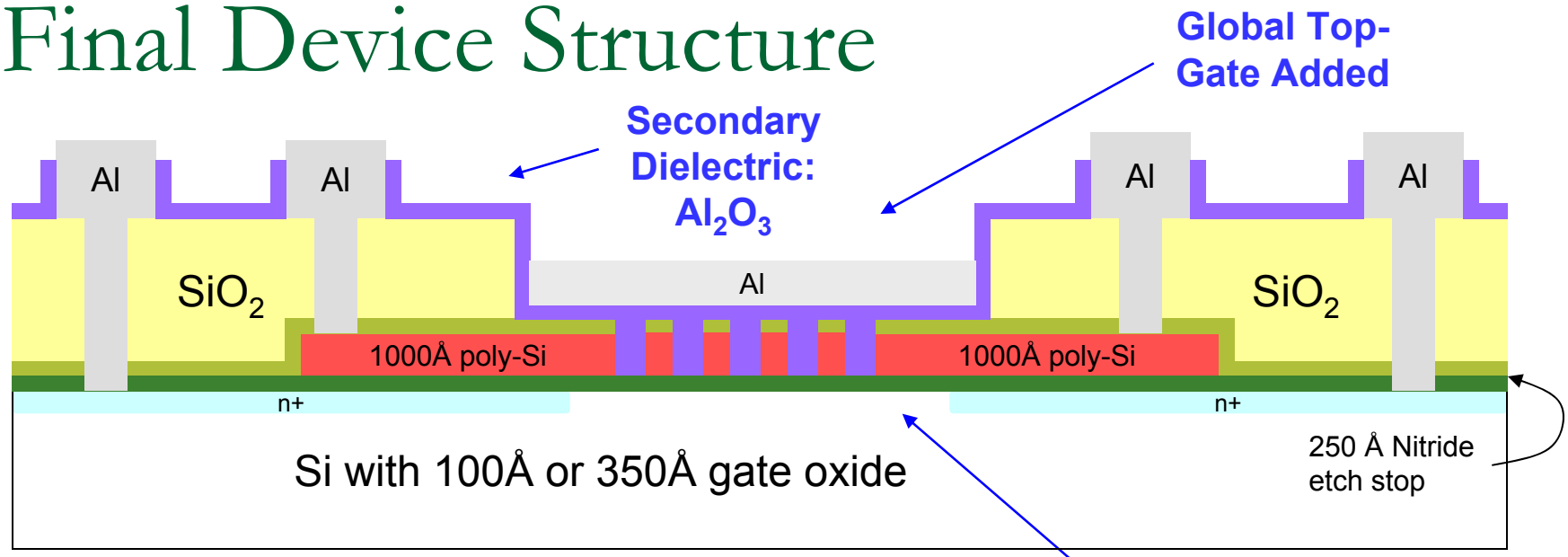
Initial Device Structure



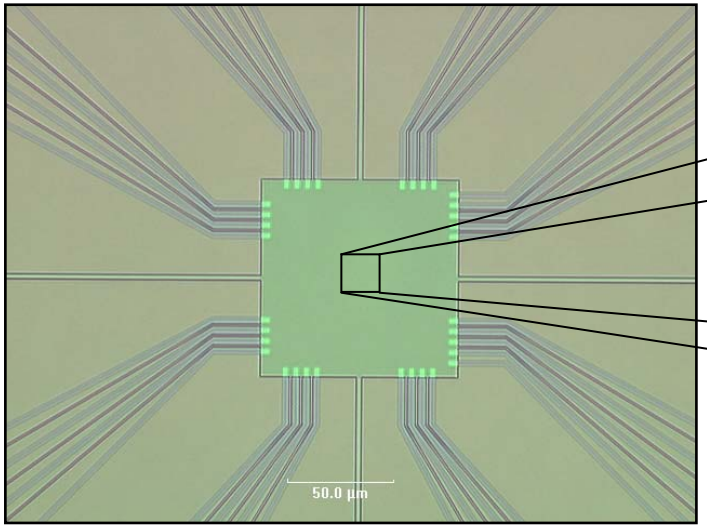


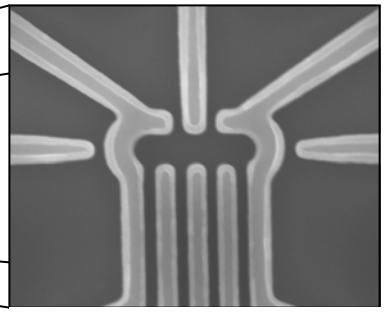
Peak Mobilities ~ 13000 cm^2/Vs before post processing @4K

Final Device Structure



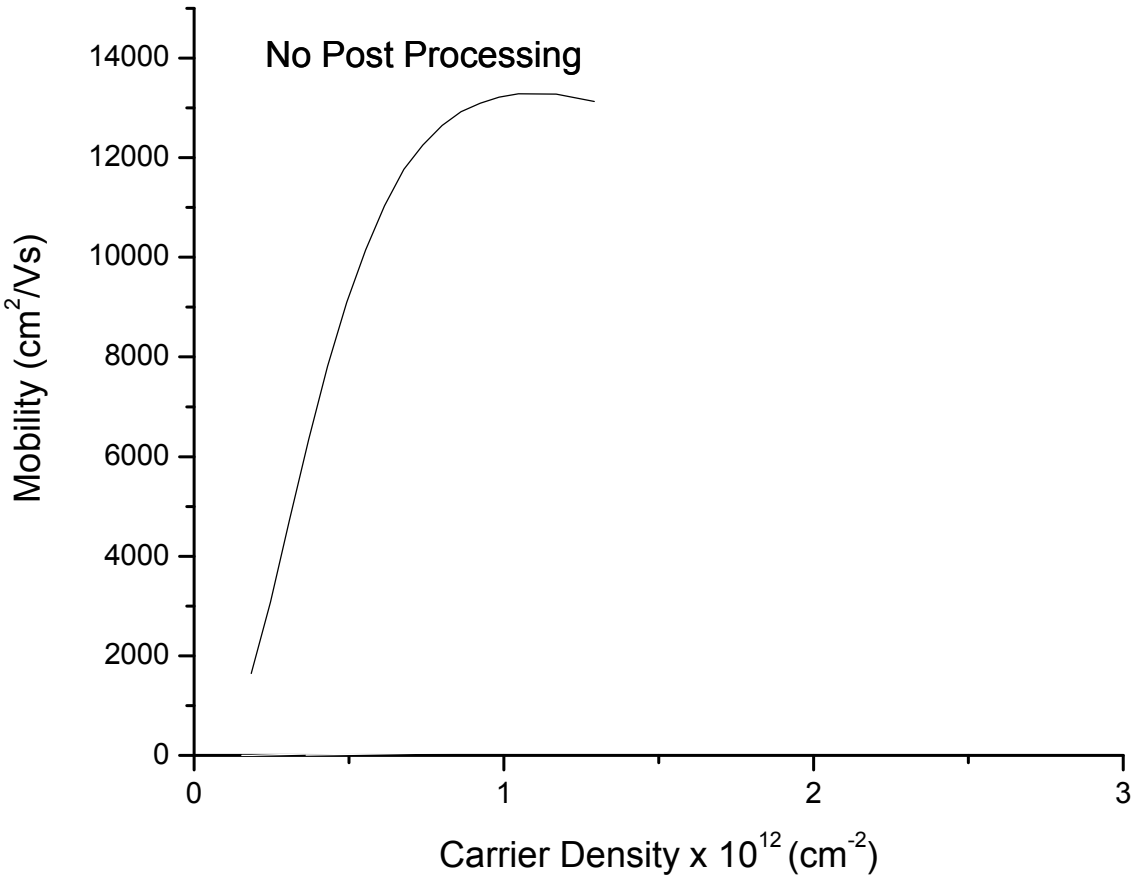
Etched poly-Gates





1µm

Sources of Disorder Inducing Process Damage

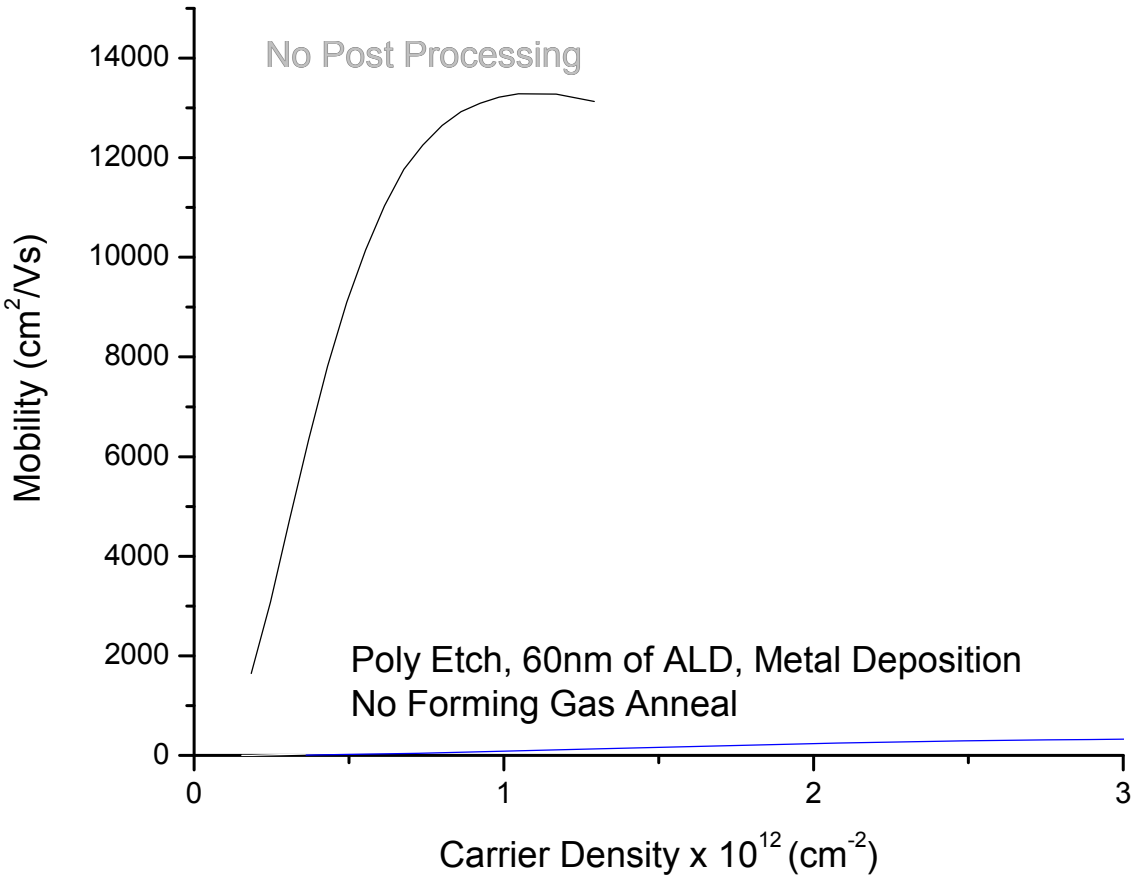


Process Steps Examined:

- Electron Beam Lithography
- Poly Silicon Plasma Etch
- Dielectric Atomic Layer Deposition (ALD)
- Metal Evaporation
- Forming Gas Anneal

Data taken at 4K

Sources of Disorder Inducing Process Damage



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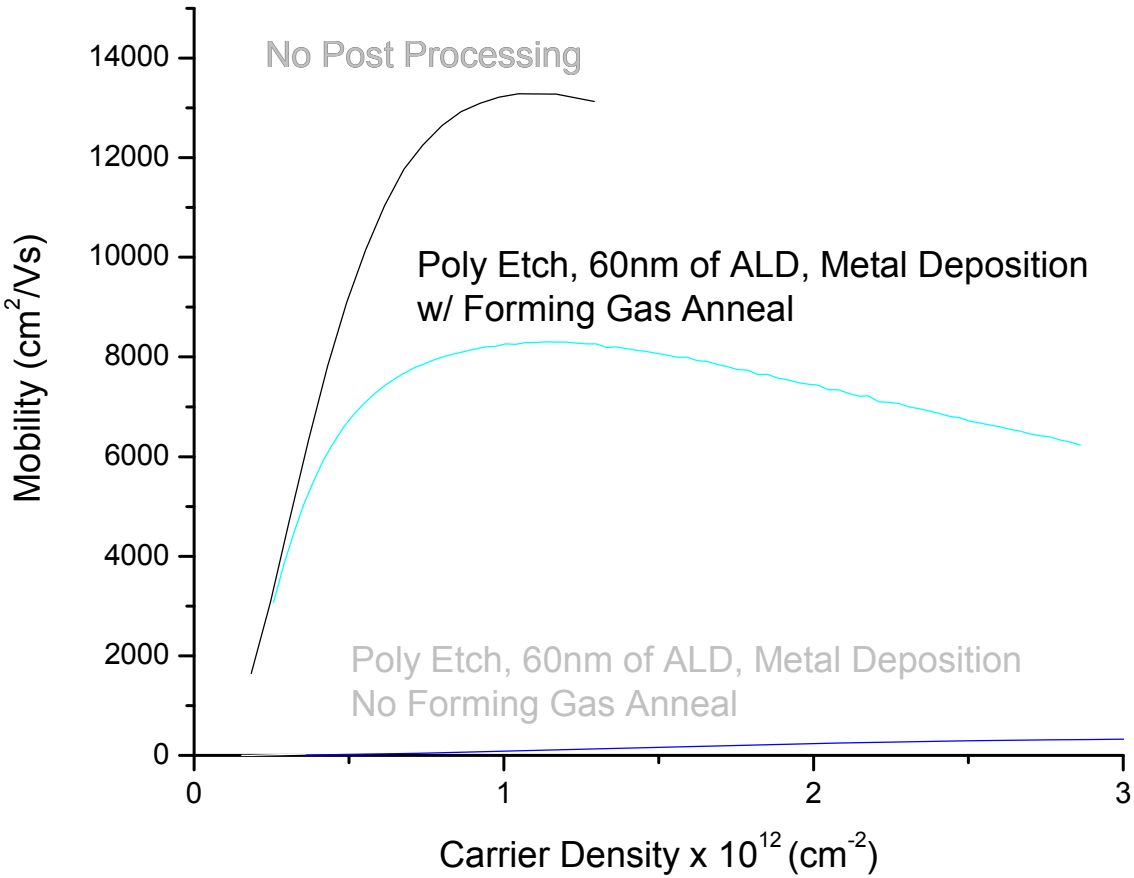

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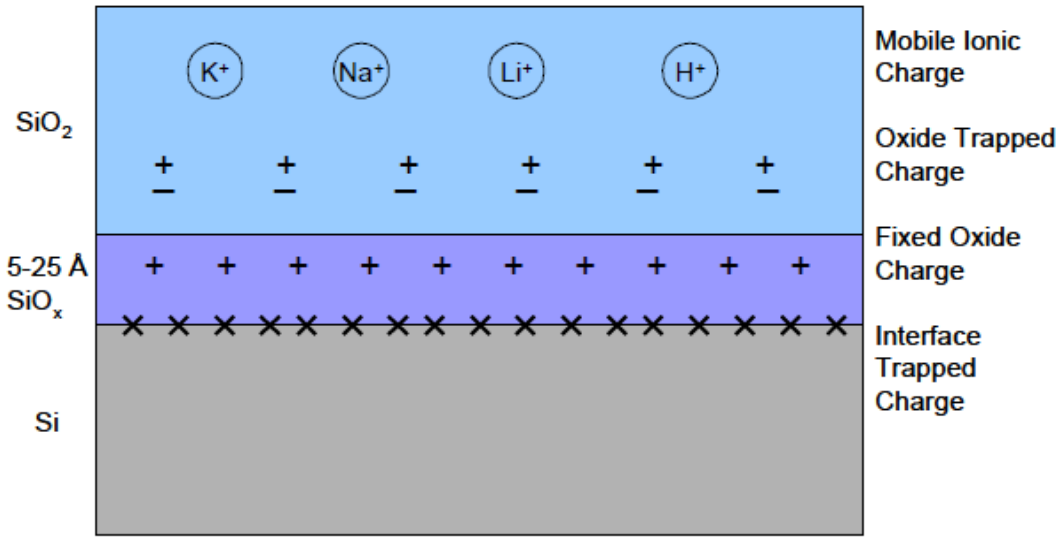
Data taken at 4K

CV Measurements

- Disorder at the Si-SiO_2 interface influenced by oxide charge and trap density
- Damage from individual process steps can increase each density



350Å Si-SiO_2 w/
e-beam Al:

Qf = 3.51 x 10^{10} q/cm^2

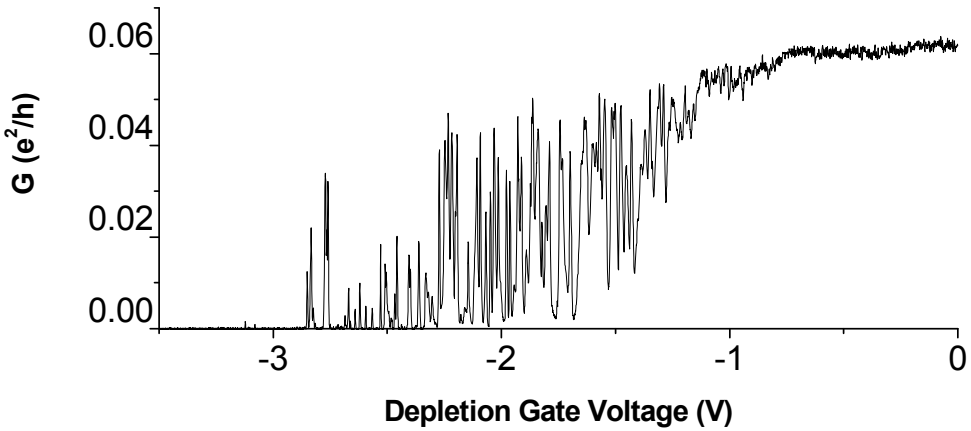
D_{it} = 6.58 x 10^{10} q/cm^2eV

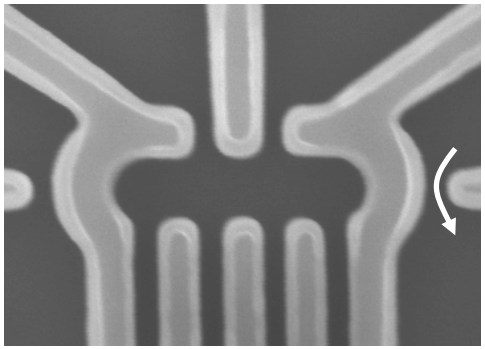
- With forming gas anneal, Dit values remain roughly process independant
- Qf can very from process to process

Poster: Greg Ten Eyck

Process Induced Disorder

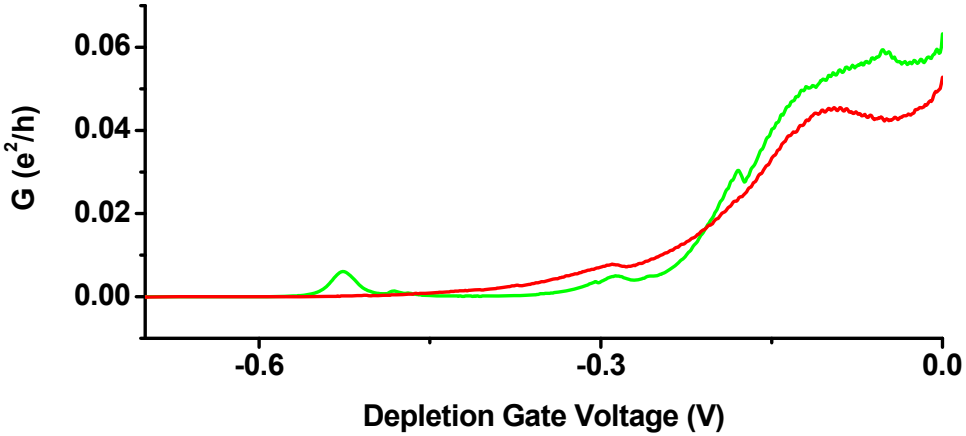
Disorder Dominated Conduction

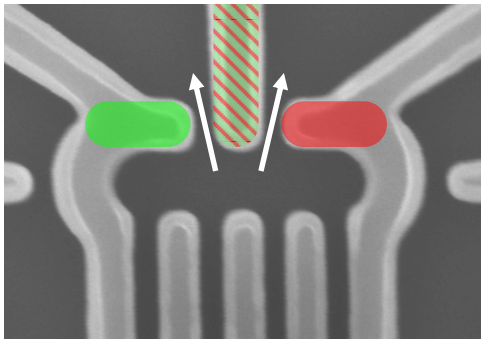




Top Gate Voltage: 8V

Constriction Dominated Conduction

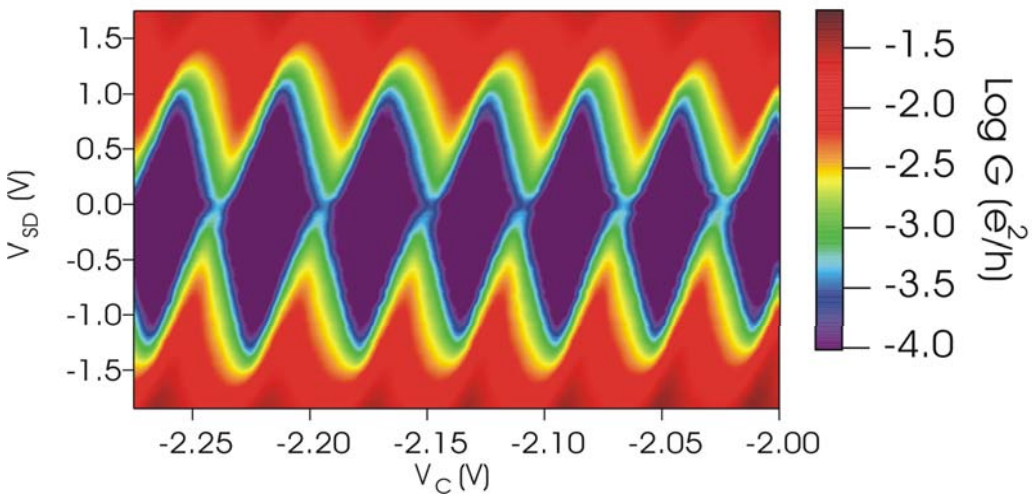


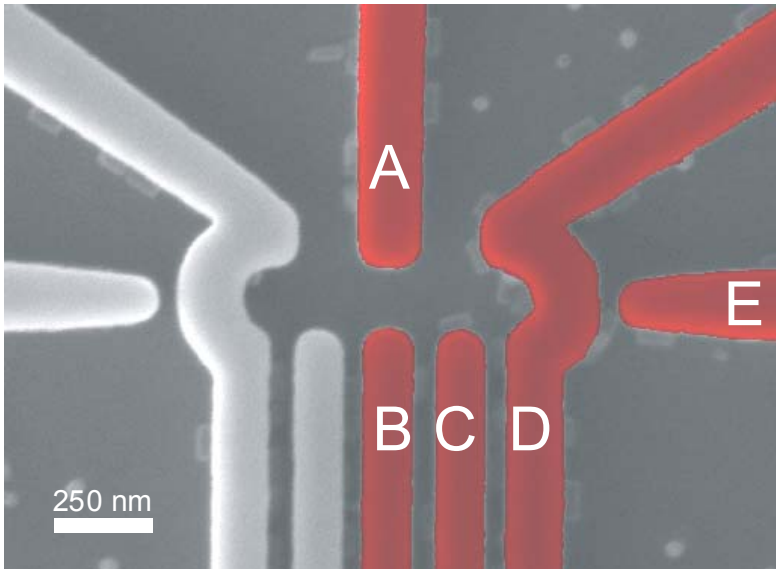


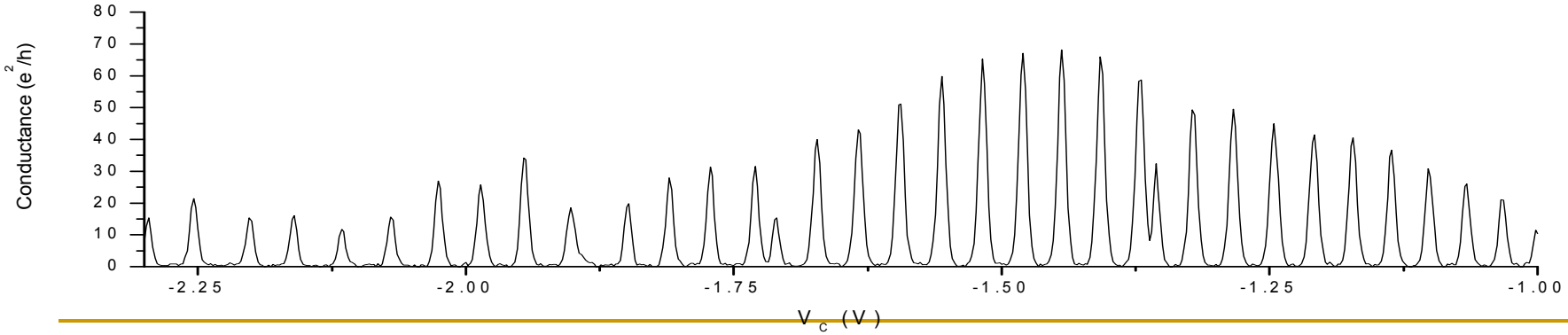
Top Gate Voltage: 25V

Data taken at 300mK

Coulomb Blockade within a Lateral Non-Collinear Geometry



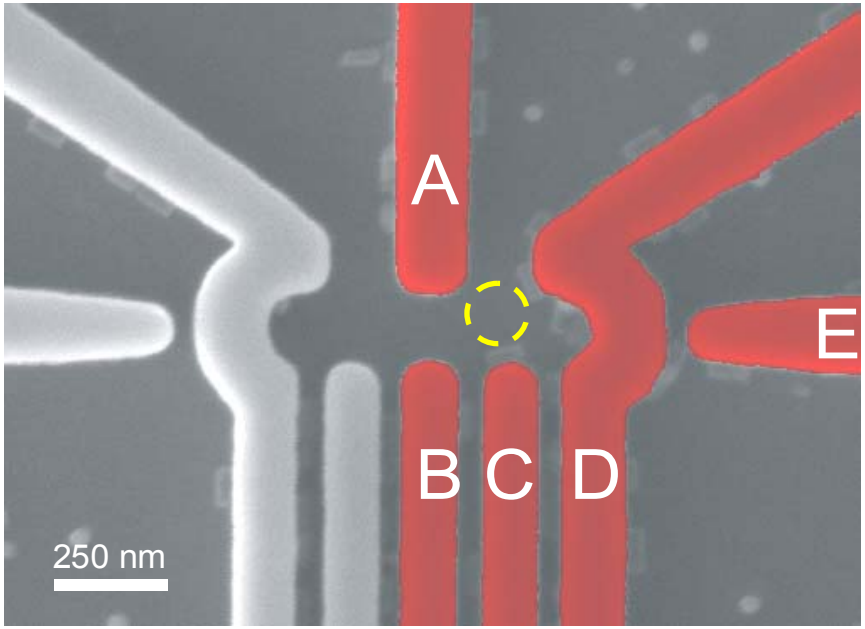




Data taken at 300mK

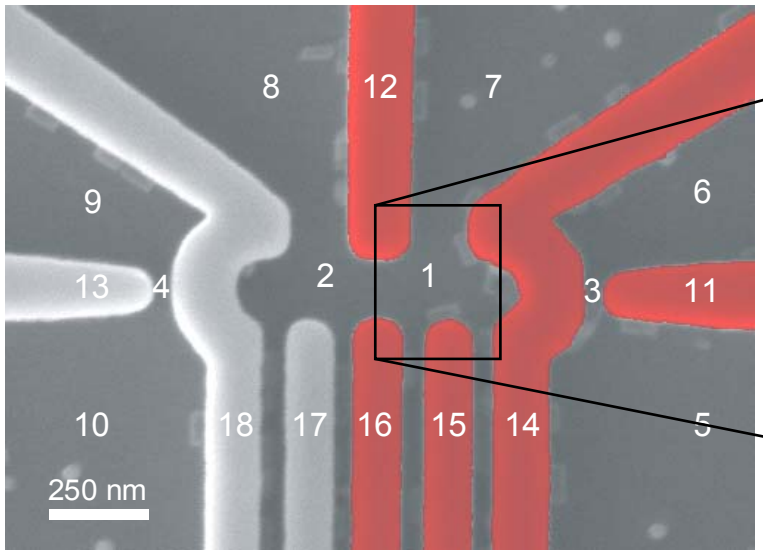
Quantum Dot Capacitances

Gate:	C to Dot
Top Gate	14.7 aF
A	6.12 aF
B	3.24 aF
C	3.36aF
D	7.23 aF

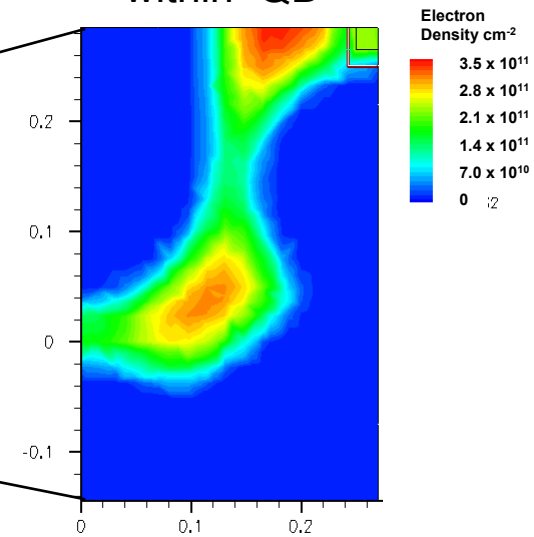


- Capacitances can be extracted experimentally by measuring the period of the Coulomb blockade while each gate is swept
- These experimental capacitances can be compared to electrostatic simulations

Device Modeling



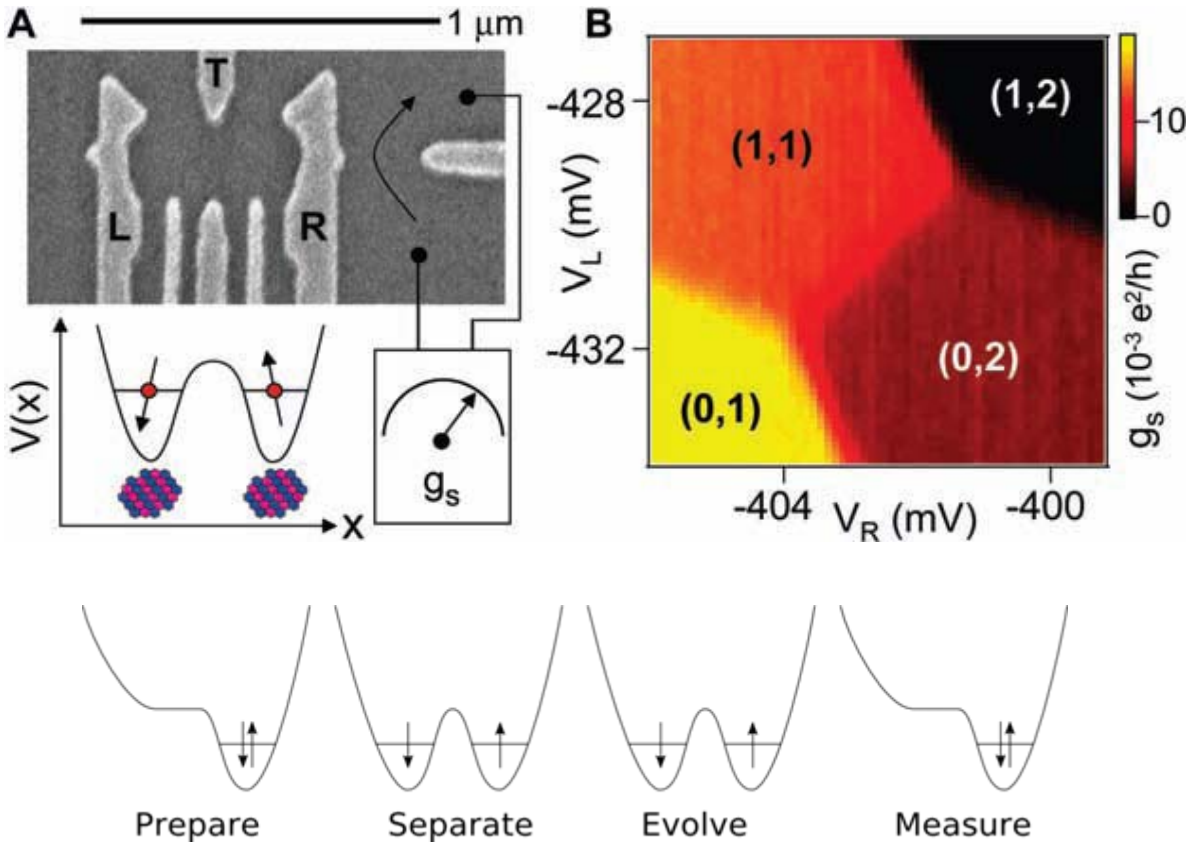
Simulated e^- density within QD



Capacitive Matrix:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	73.498	11.488	0.092	0.028	2.805	1.558	14.712	2.698	0.800	1.601	0.295	6.217	0.150	7.186	3.373	3.242	1.050	1.386	14.818
2	11.488	73.421	0.028	0.092	1.608	0.801	2.700	14.475	1.567	2.816	0.150	6.210	0.297	1.391	1.053	3.260	3.379	7.199	14.882
3	0.092	0.028	7.869	0.001	1.649	1.434	0.288	0.077	0.039	0.080	1.305	0.024	0.007	2.014	0.079	0.051	0.028	0.045	0.629
4	0.028	0.092	0.001	7.922	0.080	0.039	0.077	0.288	1.433	1.656	0.007	0.024	1.322	0.045	0.028	0.051	0.079	2.028	0.643
5	2.805	1.608	1.649	0.080	475.201	34.803	10.974	4.918	3.298	7.943	40.337	1.142	0.647	45.041	8.523	5.480	2.935	4.032	298.983
6	1.558	0.801	1.434	0.039	34.803	319.262	22.655	3.507	1.809	3.296	37.377	0.929	0.322	56.828	1.479	1.312	0.869	1.757	148.423
7	14.712	2.700	0.288	0.077	10.974	22.655	290.716	19.226	3.506	4.916	1.951	32.096	0.565	49.103	1.662	1.676	1.195	3.449	120.043
8	2.698	14.475	0.077	0.288	4.918	3.507	19.226	290.588	22.630	10.977	0.565	32.150	1.953	3.457	1.198	1.678	1.661	49.169	119.964
9	0.800	1.567	0.039	1.433	3.298	1.809	3.506	22.630	319.124	34.873	0.322	0.929	37.419	1.758	0.870	1.314	1.479	56.724	148.285
10	1.601	2.816	0.080	1.656	7.943	3.296	4.916	10.977	34.873	475.438	0.646	1.142	40.398	4.030	2.932	5.476	8.506	45.123	299.031
11	0.295	0.150	1.305	0.007	40.337	37.377	1.951	0.565	0.322	0.646	569.446	0.142	0.059	9.174	0.359	0.296	0.186	0.334	475.955
12	6.217	6.210	0.024	0.024	1.142	0.929	32.096	32.150	0.929	1.142	0.142	503.061	0.142	1.470	0.355	0.546	0.354	1.457	417.668
13	0.150	0.297	0.007	1.322	0.647	0.322	0.565	1.953	37.419	40.398	0.059	0.142	569.012	0.335	0.187	0.297	0.360	9.155	475.446
14	7.186	1.391	2.014	0.045	45.041	56.828	49.103	3.457	1.758	4.030	9.174	1.470	0.335	1350.500	110.369	4.914	1.980	2.398	1049.083
15	3.373	1.053	0.079	0.028	8.523	1.479	1.662	1.198	0.870	2.932	0.359	0.355	0.187	110.369	365.775	94.507	2.782	1.976	134.150
16	3.242	3.260	0.051	0.051	5.480	1.312	1.676	1.678	1.314	5.476	0.296	0.546	0.297	4.914	94.507	381.870	94.478	4.905	158.447
17	1.050	3.379	0.028	0.079	2.935	0.869	1.195	1.661	1.479	8.506	0.186	0.354	0.360	1.980	2.782	94.478	365.298	110.398	133.618
18	1.386	7.199	0.045	2.028	4.032	1.757	3.449	49.169	56.724	45.123	0.334	1.457	9.155	2.398	1.976	4.905	110.398	1351.939	1050.347
19	14.818	14.882	0.629	0.643	298.983	148.423	120.043	119.964	148.285	299.031	475.955	417.668	475.446	1049.083	134.150	158.447	133.618	1050.347	5060.414

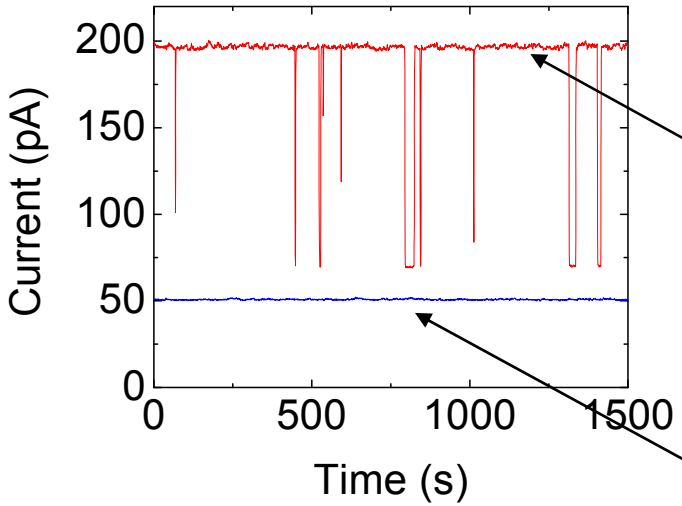
Integrated Charge Sensing

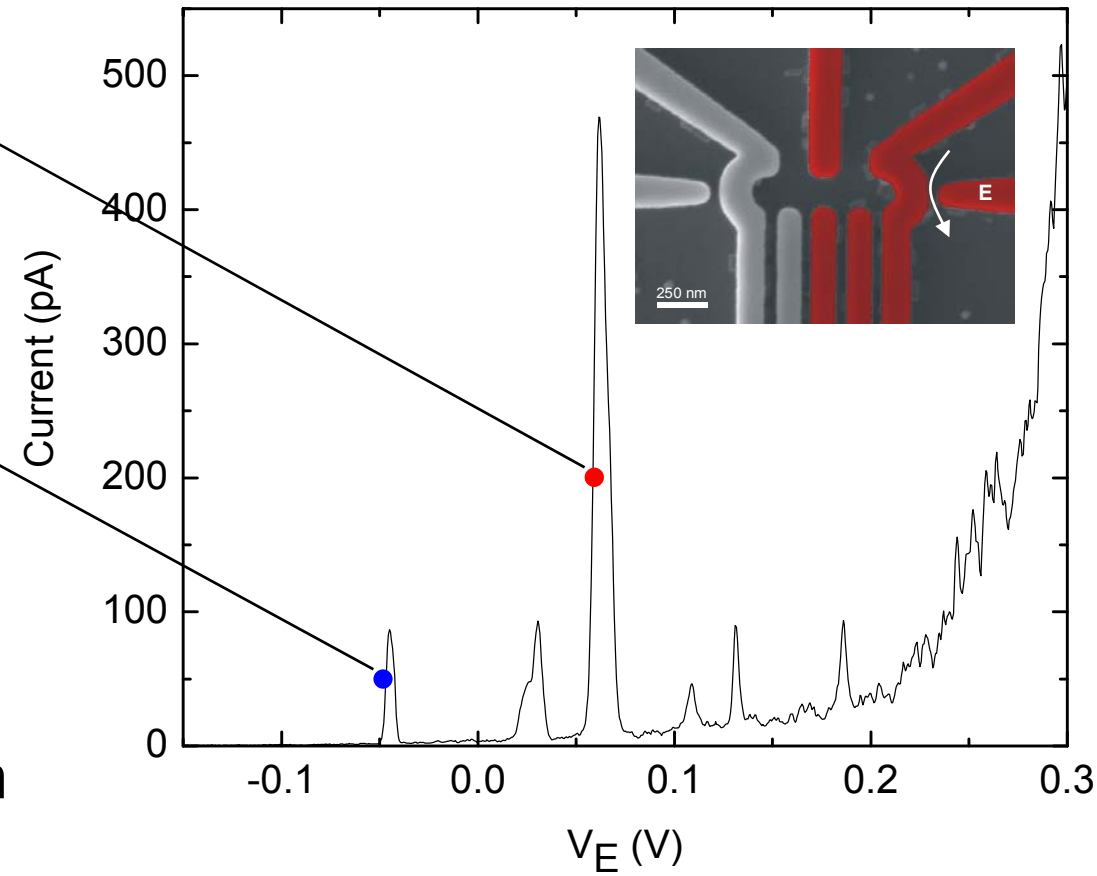


- Noninvasive charge sensing key to obtaining and verifying few electron occupation, and spin-to-charge conversion

J. Petta, et al. Science ***309****, 2180 (2005)*

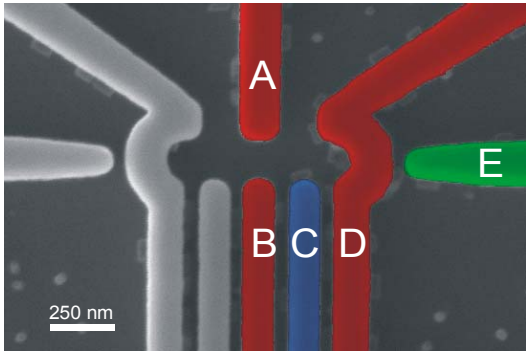
Charge Sense Channel Characteristics

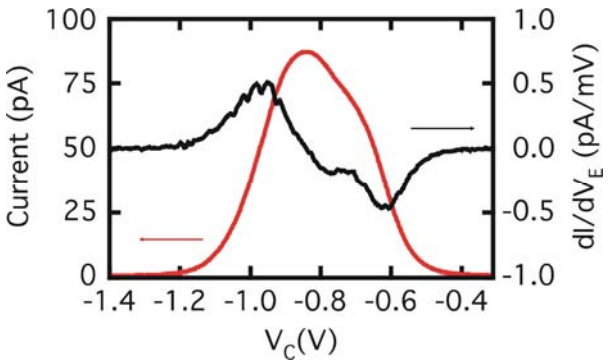


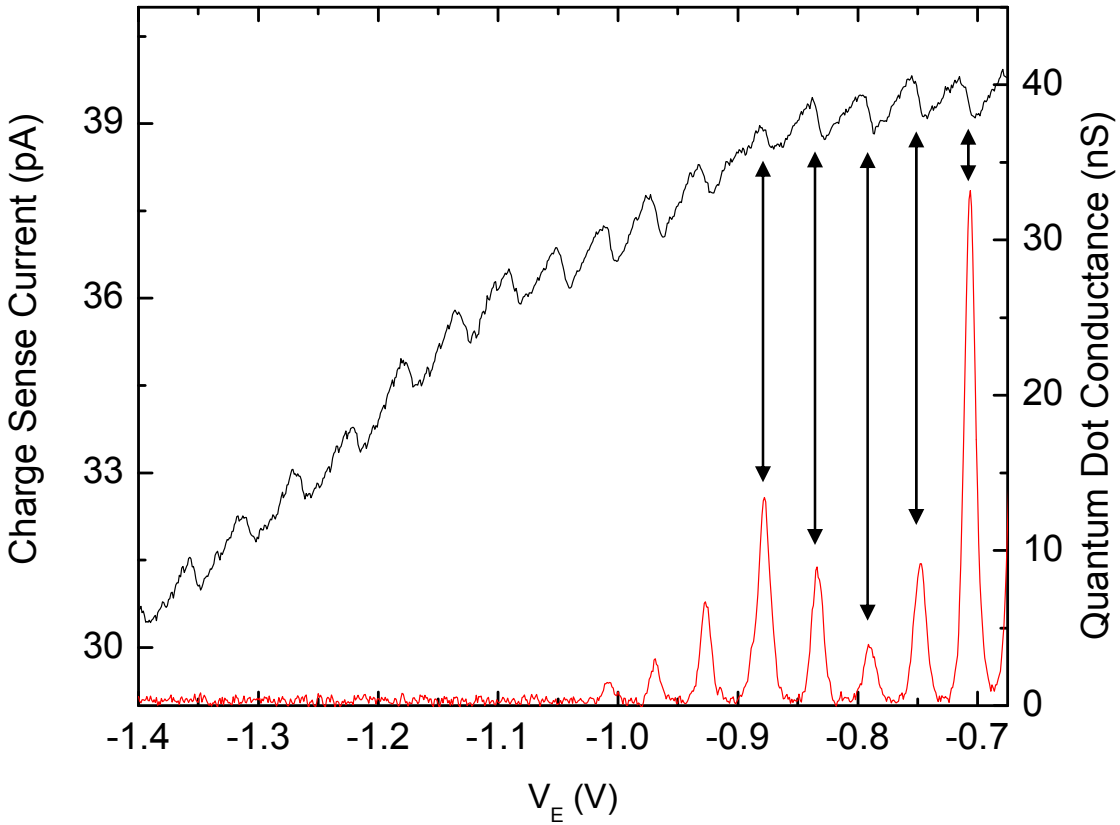


- Device geometry restricts conduction range within the charge sensor

Compensated Charge Sensing

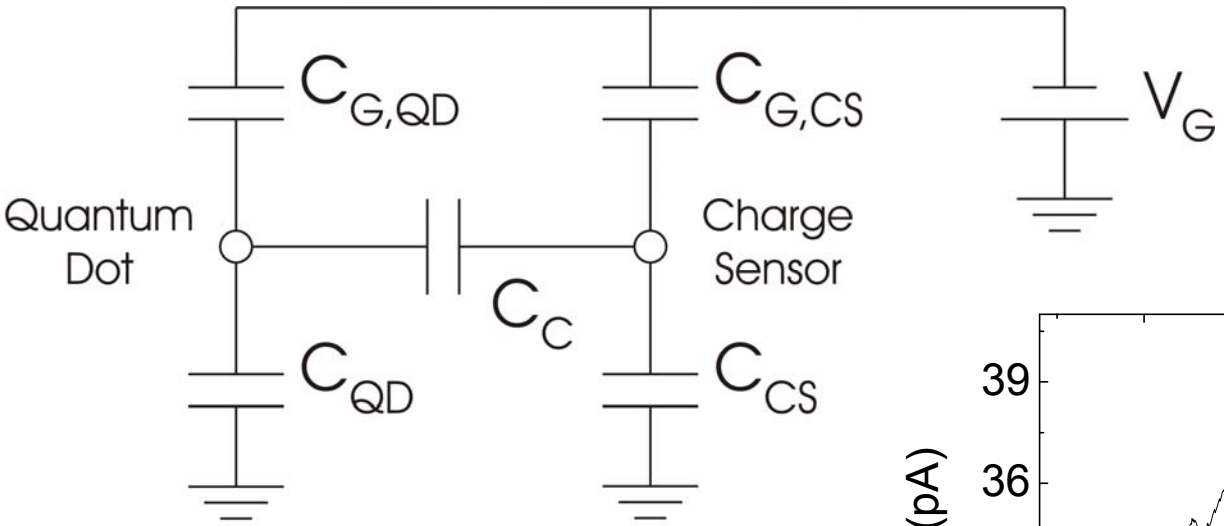






- As V_C ramps from -0.7 V to -1.4 V, V_E is smoothly ramped from -50.57mV to -42.46mV.

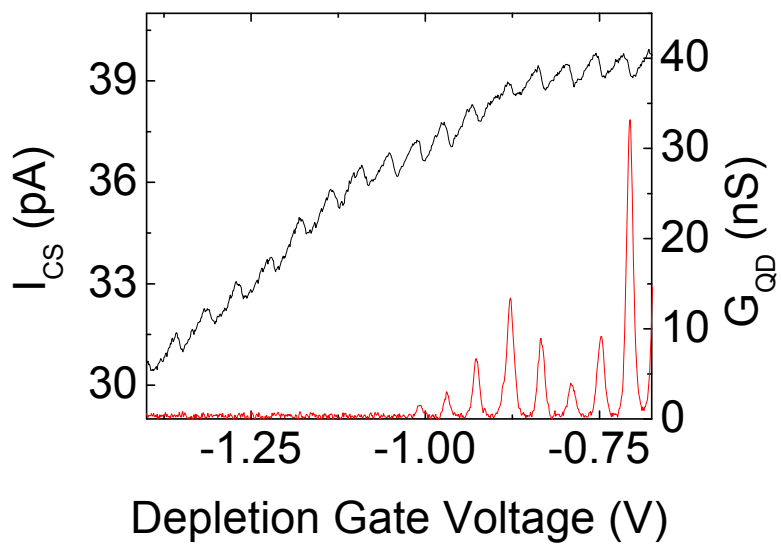
Capacitive Model – Expected Results



Experiment:
$C_C = 0.09 \pm 0.01$ aF

Capacitive Model:
$C_C = 0.092$ aF

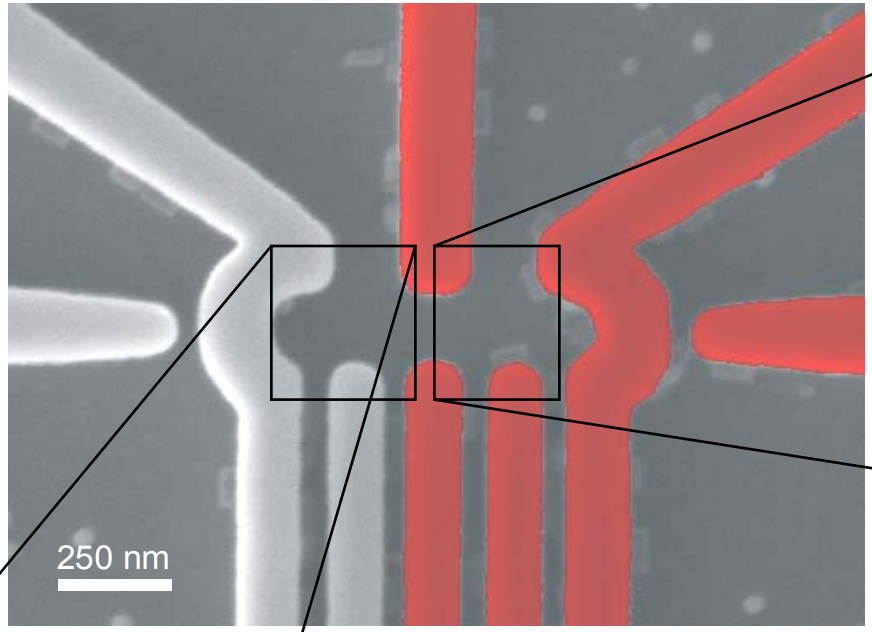
2	11.488	73.
3	0.092	0.02
4	0.028	0.

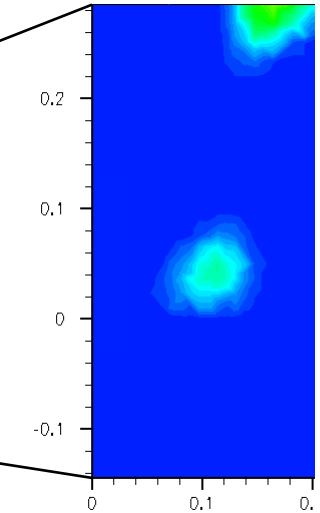


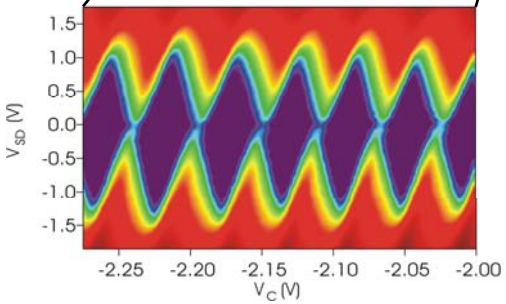
- Using measured gate capacitances, the charge sense signal magnitude, and dI/dV_G, C_C can be found experimentally
- Confidence exists that we can predict the magnitude of a charge sense signal in similar geometries with a capacitive simulation

Device Directions

Simulated e^- density within QD: Single Electron Conditions

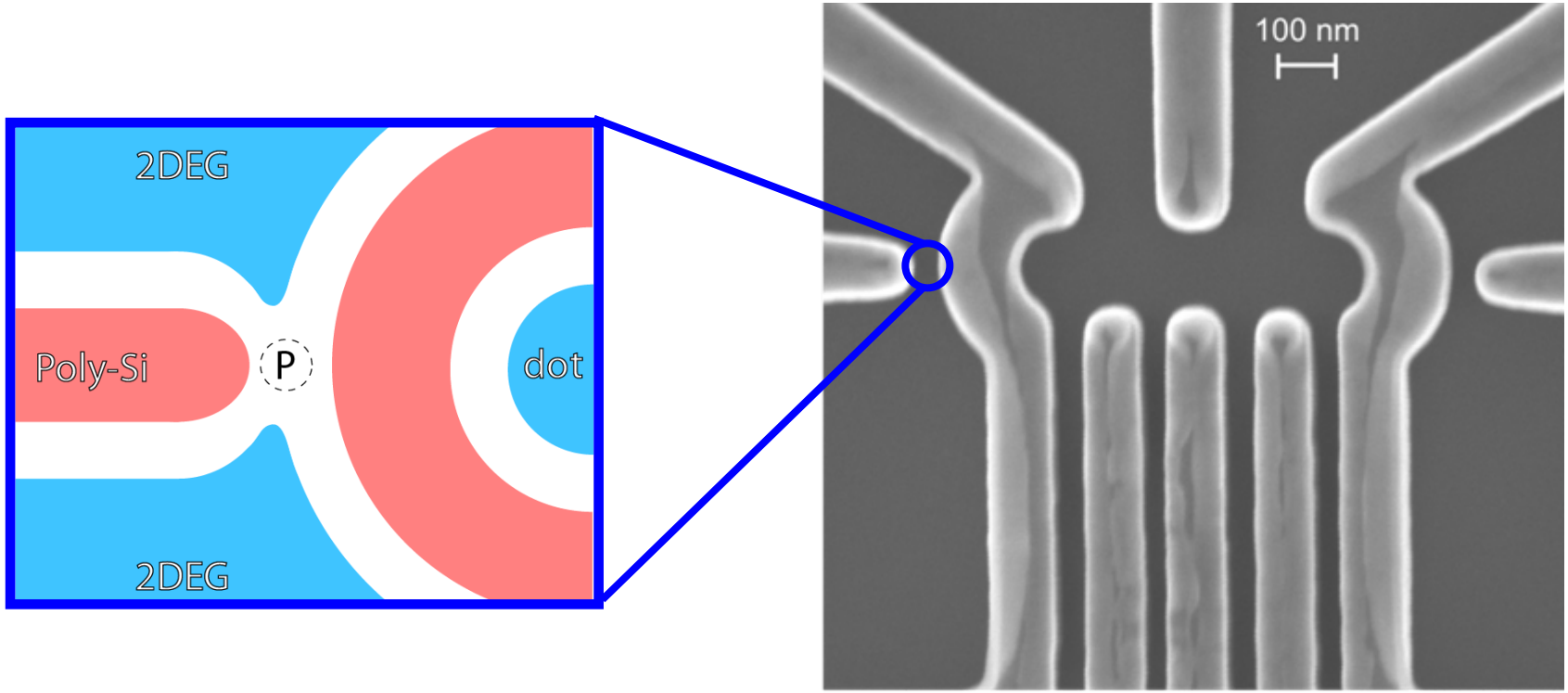






- Simulation suggests few electron occupation achievable within available voltage range (current occupation ~ 100 e^-)
- Explore double dot device functionality

Donor Integration



- Poly silicon gates allow for activation anneals *after* nanolithography

Summary

- Stable, repeatable Coulomb blockade observed within a non-linear, tunable, Si-MOS structure with the possibility of donor integration
- Integrated, high visibility, charge sensing shown
- Capacitance simulations consistent with expected dot geometry, and observed charge sense signal
- Process damage able to be overcome to create measurable nanostructures w/ sensitivities similar to those in other material systems
- Future directions:
  - Push towards few electrons
  - Couple with neighboring dot
  - Modify forthcoming structures for greater charge sensitivity