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Sensitivity of charge detection techniques in electrostatically defined MOS quantum dots

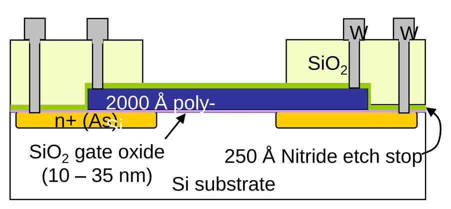
M. P. Lilly[1], M. S. Carroll[1], N. Bishop[1], L. Tracy[1], K. Nguyen[1], S. Carr[1], T. M. Lu[1], J. Wendt[1], J. Stevens[1], R. Grubbs[1], T. Pluym[1], J. Dominguez[1], R. Young[1], H. Stalford*, R. Muller[1] and E. Nielsen[1]; [1]Sandia National Laboratories, [2]University of Oklahoma

Quantum Information S&T

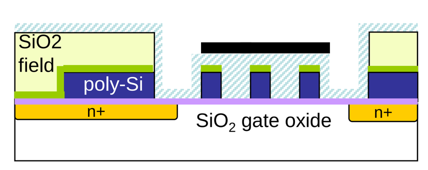
MOS double quantum dot with charge sensors

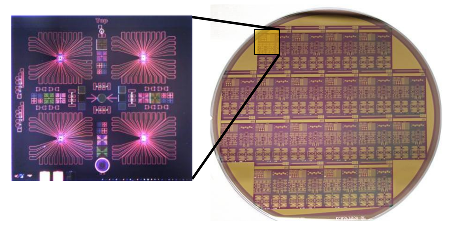
MOS devices are started in a silicon fab, and completed with electron beam lithography, ALD aluminum oxide and a final metal step for the accumulation gate. The critical interface is a thermal SiO_2 that results in a mobility of 7-15 x 10^3 cm^2/Vs.

front-end: silicon fab

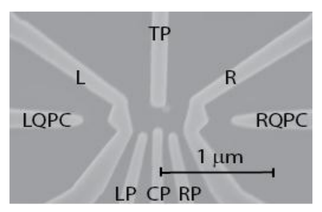


back-end: nanolithography





Ottawa hybrid flat 270 nm design (top gate not shown)

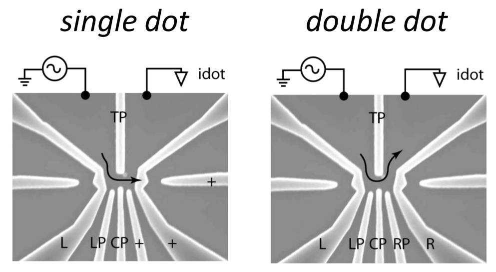


The gate pattern here has 270 nm tunnel and point contact openings. This allows low threshold voltages on the top gate and better control of the dot occupation.

Measurement techniques

Single or double quantum dots

single dot *double dot*



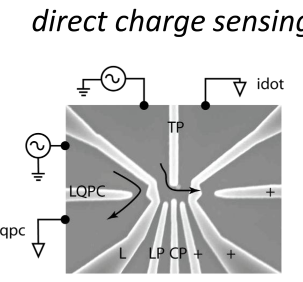
The full double dot structure is used for both single and double dot experiments. In single dot operation, a positive bias is applied to gates that are not required for confinement.

Quantum dot and charge sensor transport

Transport through the dot is measured using lock-in techniques. A bias voltage of 25 µV (100 µV for T = 0.3K) is applied to an ohmic. The current is converted to a voltage with a DL instruments 1211 preamp (gain 10^6-10^8 V/A) and measured with a either an SRS830 or ziHF2LI lock-in amplifier.

- frequency ranges from 13 Hz to 381 Hz
- measurement bandwidths from 7 Hz to 0.3 Hz

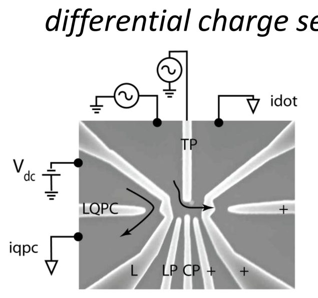
direct charge sensing



For direct charge sensing, two ac bias voltages with two different frequencies are applied to the dot and charge sense channel. The current is measured resulting in a conductance measurement in each channel.

- Charge sense signal is a change in current (conductance) of the charge sensor.
- Features can be brought out with numeric derivative.

differential charge sensing

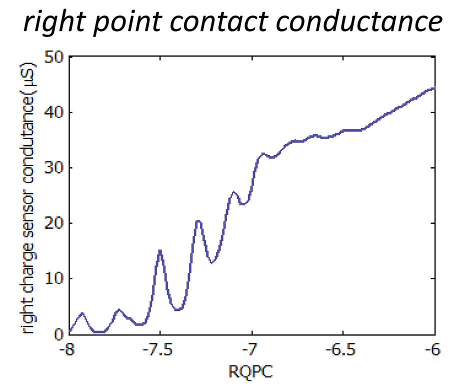


In the differential charge sense technique, the point contact is biased with a dc voltage (100 to 500 µV) and an ac signal is added to one of the gate voltages (2-5 mV).

- ac current is due to a change of the conductance of the channel when the ac signal changes the dot occupation.
- Both ac and dc current are measured.

The conductance of the point contact for this devices exhibits a series of resonances. The resonance structure, probably due to geometric or disorder constrictions in the channel, provides very steep slopes with high sensitivity

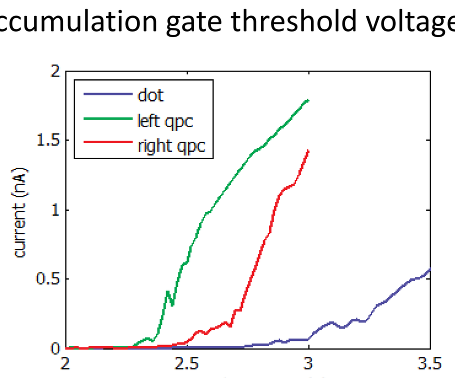
right point contact conductance



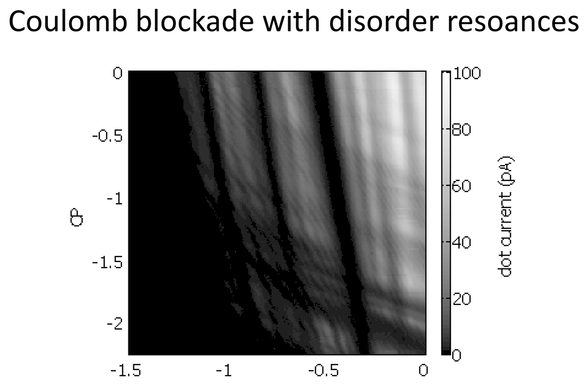
Initial characterization

Rapid testing at room temperature and 4K verifies gate isolation, threshold voltages through the dot and charge sensors, and even can reveal the onset of Coulomb blockade of the electrostatically confined dot.

Accumulation gate threshold voltages



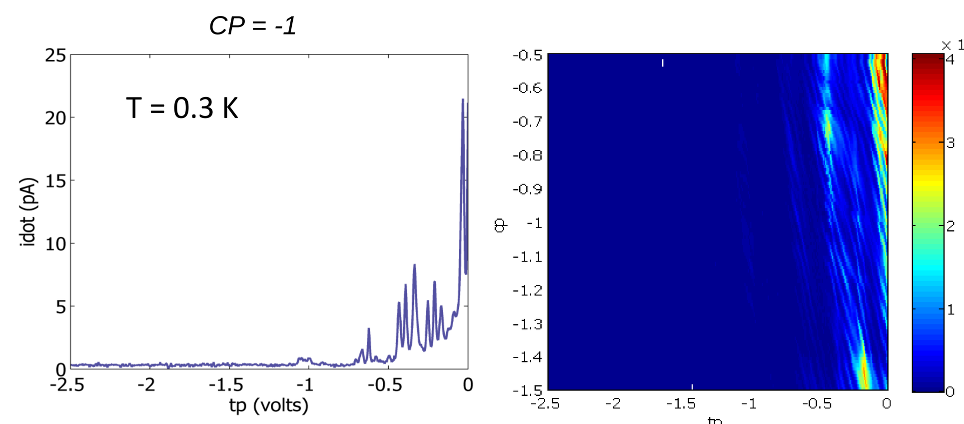
Coulomb blockade with disorder resoances



Charge sensed single quantum dot

Coulomb blockade

Tuning the dot in the presence of disorder is a challenge. The tunnel barrier is not monotonic. Measuring features as a function of two gate voltages allows a separation of the disorder from the electrostatic dot.

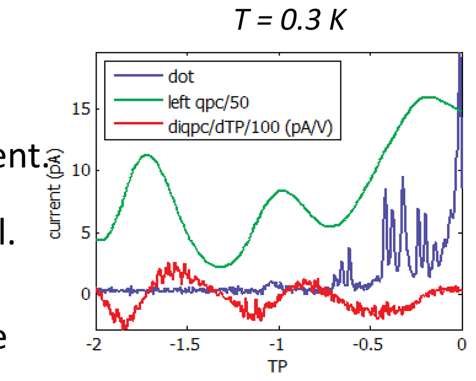


- Single period CB is observed (65 mV, 2.5 aF)
- For many bias conditions, end of CB likely related to tunnel barriers

Direct charge sensing

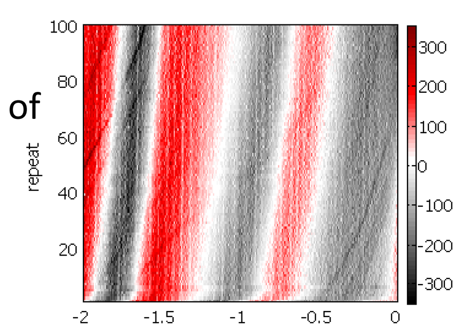
Top: For direct charge sensing, separate voltages (and frequencies) are used on the point contact and dot. Changes in the dot occupation are expected to lead to discontinuities in the QPC current.

- The LQPC conductance varies as TP is coupled to the left channel.
- No obvious steps are visible in the LQPC current. The derivative signal has spikes that will be shown to be charge sensing, but are not convincing as a single trace.



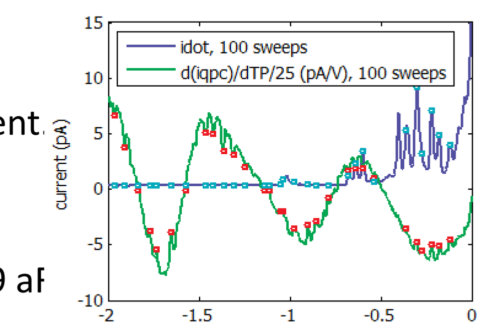
Middle: For direct charge sensing, separate bias voltages (and frequencies) are used on the point contact and dot. The derivative of 100 repeated TP sweeps show a charge sense signal in the large positive (red) and negative (black) slope regimes.

- The vertical lines are charge sensing of the left dot.
- The dot is very stable since the charge sense lines do not drift.
- The QPC regions drifts slowly (drift of sensitive regions).



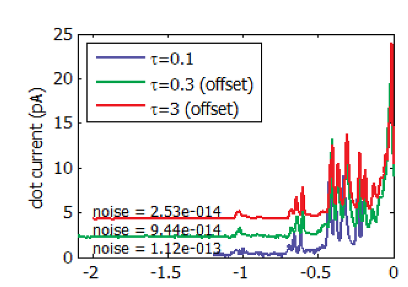
Bottom: Average of 100 sweeps. Each charge sense feature is identified, and the corresponding point is plotted on the dot current.

- The charge sense and Coulomb blockade agree well where dot transport can be observed.
- Peak spacing is ~55 mV corresponding to a TP capacitance of 2.9 aF

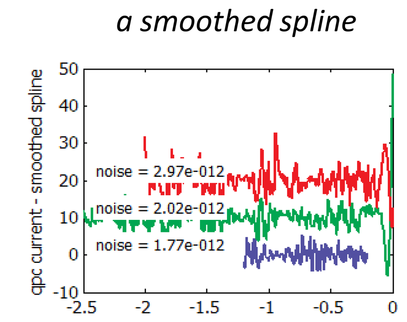


Noise

dot current for several lock-in time constants



LQPC current after removing a smoothed spline



- Left: Increasing lock-in time constant improves idot noise roughly as 1/sqrt(tau).
- Right: Lock-in time constant has very little effect on noise of the QPC channel.

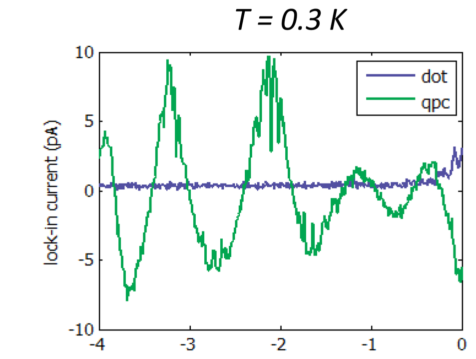
For direct charge sensing, multiple averages with a short time constant is more effective than using a long averaging time per point. It makes using a single sweep very difficult for direct charge sensing in this device.

Differential charge sensing

In the differential charge sense technique[1], the change in resistance of the QPC is detected when an electron transition occurs in the dot. While the data look very similar to the numeric derivative of the direct charge sense technique, far less averaging is required to detect charge transitions.

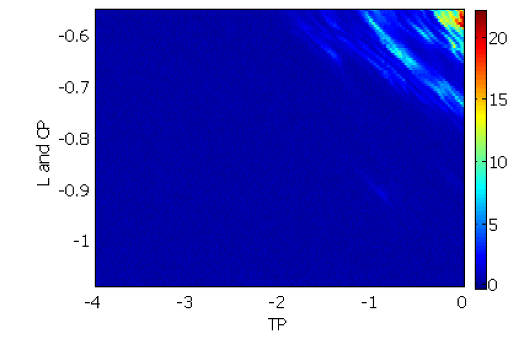
[1] Discussed by House and Jiang at the last Silicon Workshop

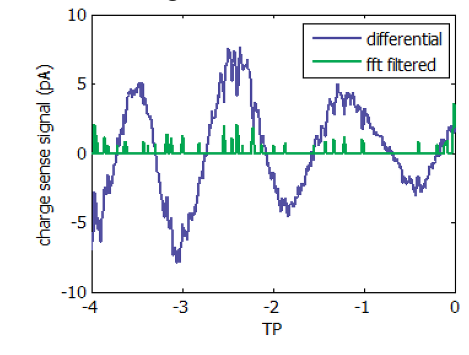
Right: single sweep with a lock-in time constant of 100 msec.

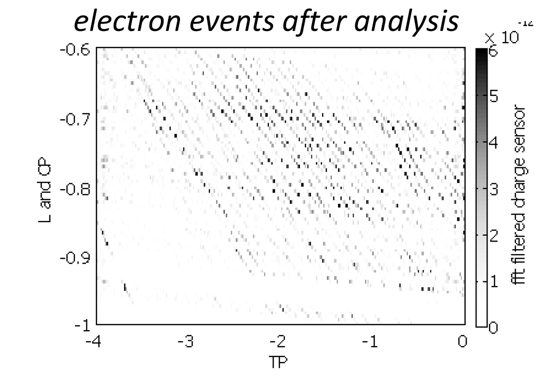


With improved charge sensing, the depletion gates can be pushed more negative.

- Left: dot transport as a function of LP (dot occupation) and both L and CP (tunnel barriers).
- Middle: charge signal (blue); low frequency background is removed using fft analysis (green).
- Right: electron evens are more visible after fft technique. The signal is modulated by the sensitivity. Charge sensing match with dot transport in the upper right. In the lower left, there is an abrupt reduction in the charge sense features.





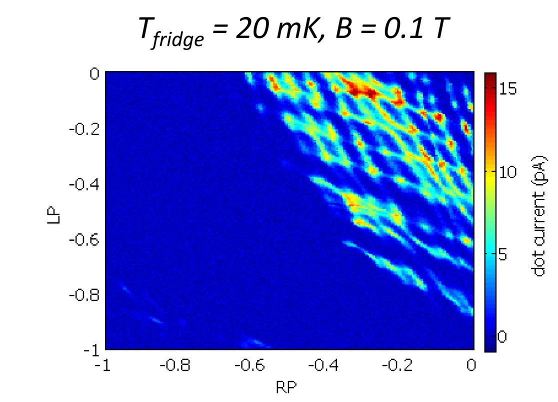


Charge sensed double quantum dot

Double dot transport

The same device can be operated as a double dot. Here, L=0, R=-0.5, TP=0 and CP =0. A honeycomb structure is visible.

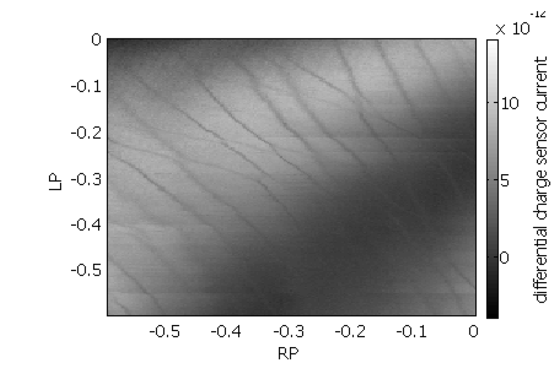
- The lack of transport at negative values of RP and LP is due to low device conductance.
- A number of regimes have been explored to decrease the tunnel barriers, but
- With charge sensing more negative, LP/RP can be made much more negative.



Double dot charge sensing

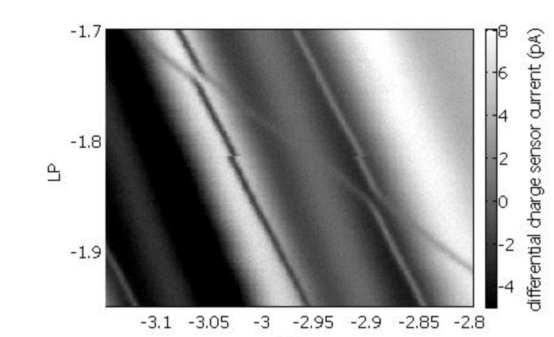
Top: Using the right quantum point contact, charge sensing can be measured in the double dot. A dc bias of 200 µV and ac signal of 2 mV @ 83 Hz for the differential charge sense technique is used.

- The lines with high slope are electron transitions in the right dot and are strong due to close proximity to the right charge sensor.
- A few transitions with anti-crossings are observed for the left dot.

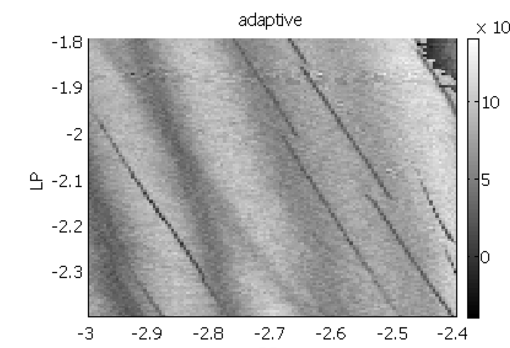


Bottom: Charge sensing of two triple point regions.

- Here 500 µV dc bias is applied to the dot.
- More negative values of LP result in only transitions in the right dot.
- The discontinuity at LP = -1.81 only affects the dot, and is probably a local potential fluctuation. Other bias regimes can avoid (or increase) such events.



Adaptive control

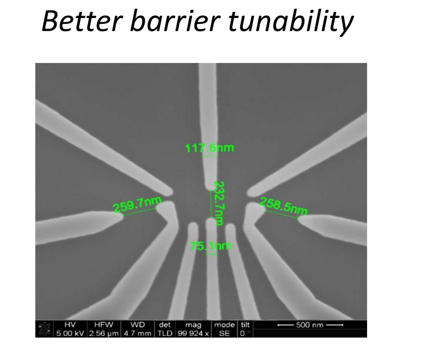


The variation in the quantum point contact sensitivity can mask important features. In this and other devices we can use the dc current through the point contact with software feedback on RQPC to increase the range of sensitivity. While this simple approach assumes the sensor is independent of the dot (clearly not true), more advanced control can be implemented that will maintain high sensitivity.

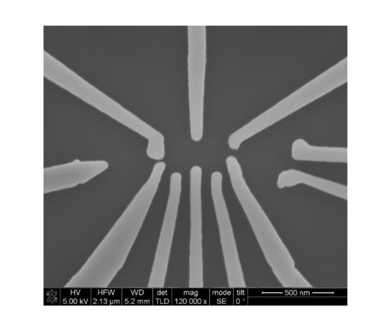
New device designs

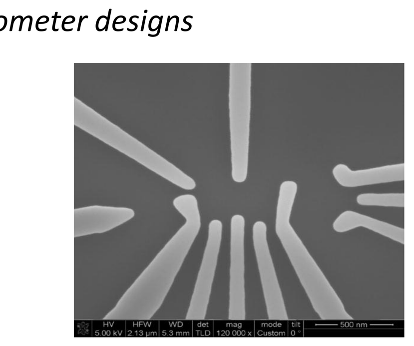
The non-colinear lateral design used here allows for significant control over dot occupation, interdot coupling and transport paths. The challenge with MOS devices is to tune the tunnel barrier and charge sensor sensitivity in the working regime. New device designs are aimed at improved tunnel barrier control and charge sensor operation.

Better barrier tunability



New electrometer designs





Conclusions

- Surface gate enhancement mode devices are a good platform for double quantum dot experiments. The Sandia silicon foundry process is producing MOS devices with stable dots and effective charge sensing.
- For single quantum dots, the direct and differential charge sensing are used to detect changes in the dot occupation. The quantum dot transport is very stable. The quantum point contact has many resonant features leading to high sensitivity but also a variation in sensitivity as the dot is controlled. For negative plunger voltages, we observe an abrupt decrease in charge sensing, which indicates low electron number in the dot.
- Charge sensing is observed in a double quantum dot. The right charge sensor is used to detect transitions in both the right and left dot. Honeycomb structures are seen in both transport and charge sensing.
- The double dot is current in the dilution refrigerator with coax lines connected to LP and RP. Next experiments will include reducing electron number, Pauli blockade and pulsing experiments.

Sandia National Laboratories

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