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Reweighting of charge occupation in charge stability diagrams due to finite temperature effect and asymmetric tunnel rates in a silicon MOS double quantum dot

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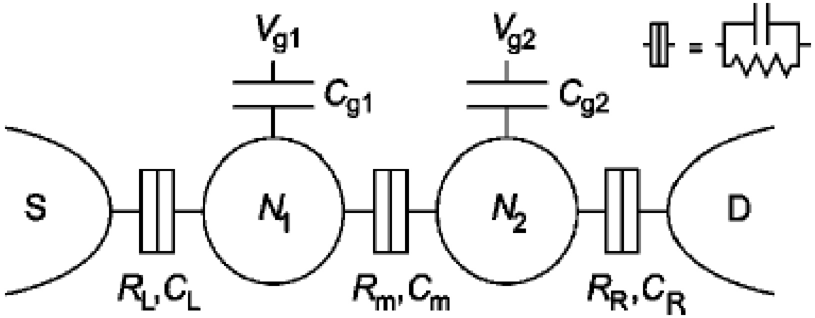
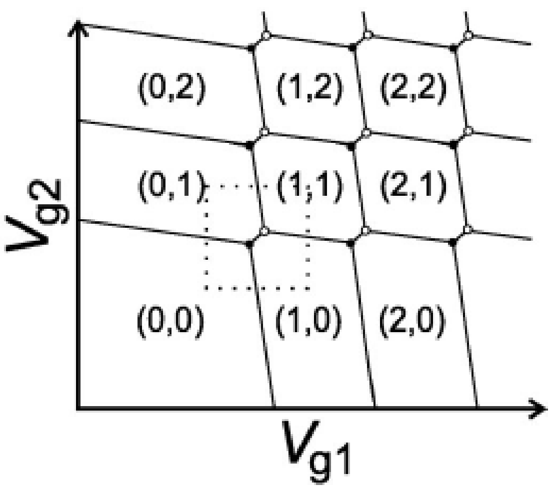
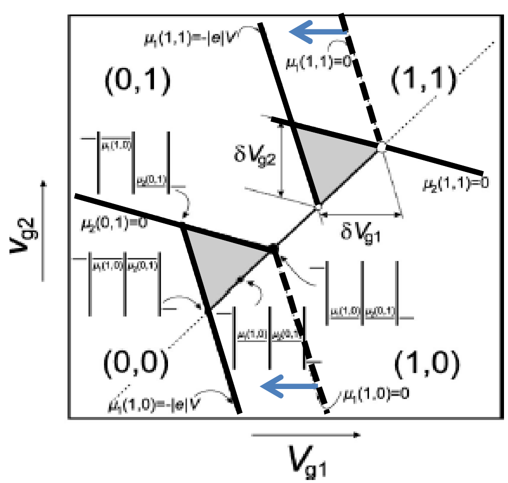
Bias triangles: Nonlinear transport vs. Differential charge sensing







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
- Optimizing charge sensor sensitivity by software feedback
- Importance: Lever arm
  Charging energy
  Tunnel coupling
  Singlet-triplet splitting

- This talk focuses on deviations of bias triangles

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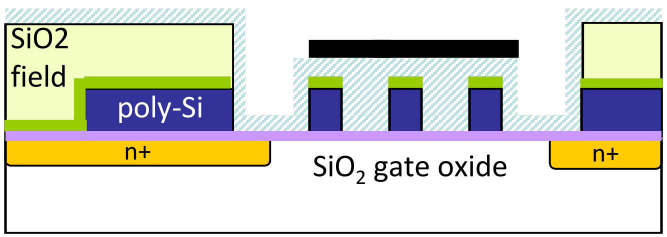
MOS devices

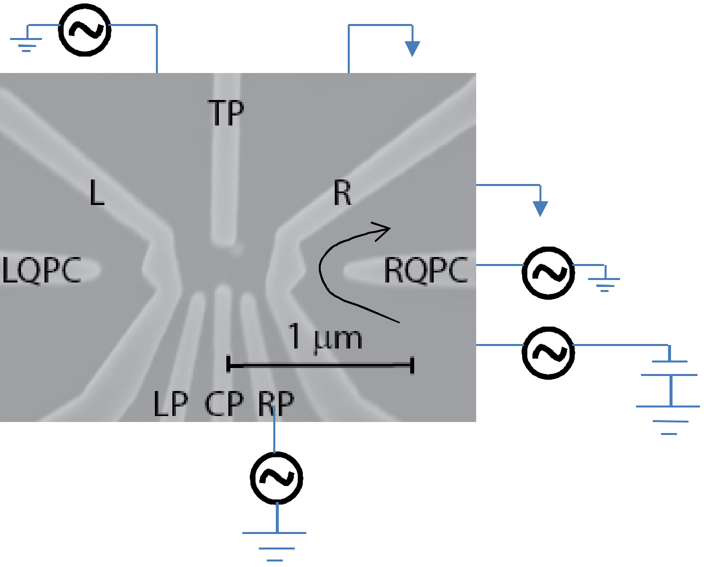
Details of MOS device

- Double top gate process – poly for depletion, Al for top gate
- Barriers are non-monotonic, as with most MOS devices
- Stability is acceptable when gate voltages are not changed significantly

Cross-section of MOS device



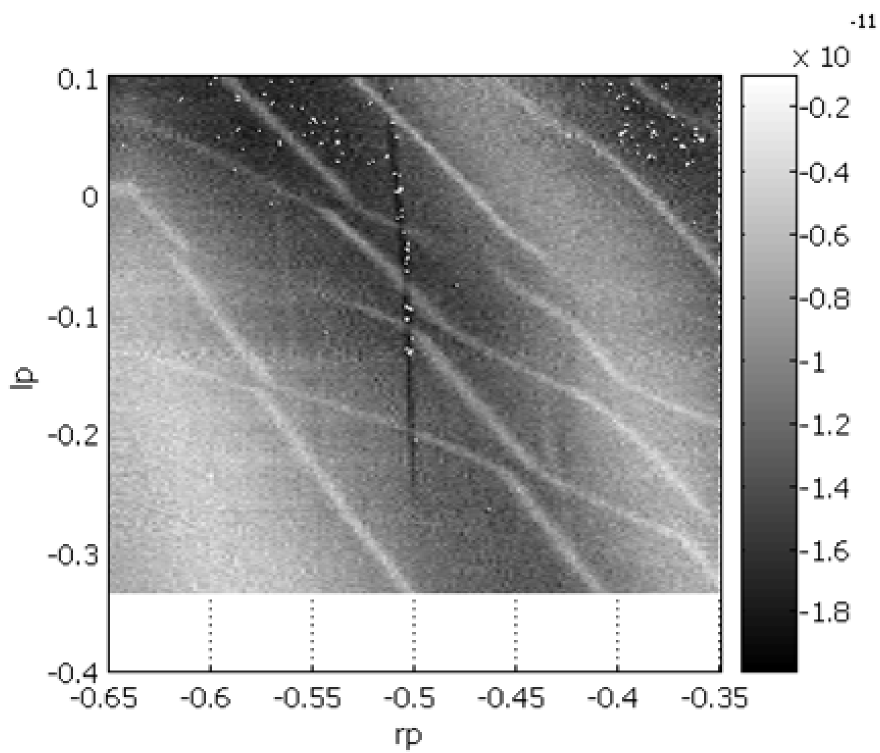
Ottawa flat 270 double quantum dot



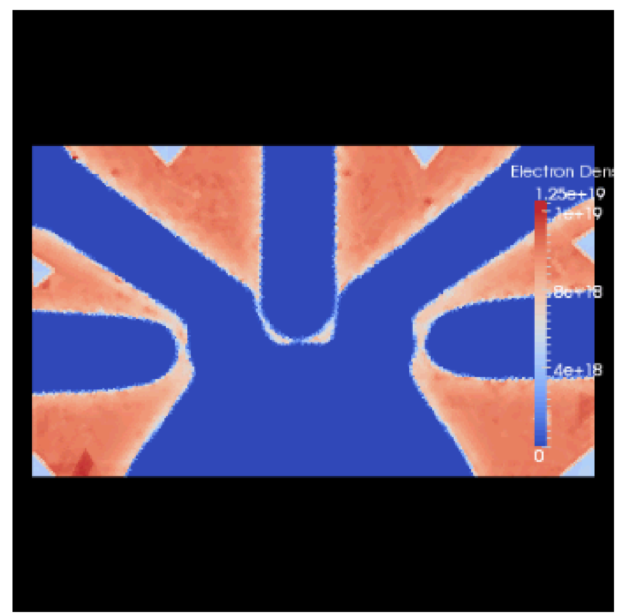
Honeycomb in many-electron regime

- Focus on many electron regime where triple points are visible with charge sensing
- In the low electron regime, eventually even low frequency ac signals (~10 Hz) lead difficulty in measuring charge sense features

Charge sense for many (R,L) transitions

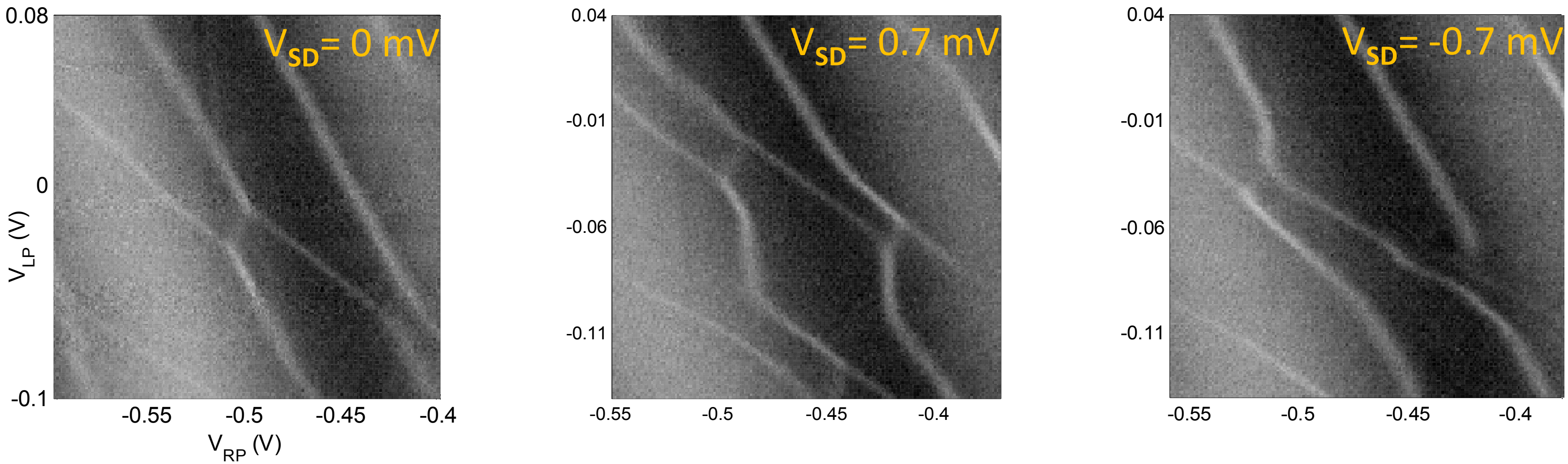


QCAD calculated electron density for (10,10)

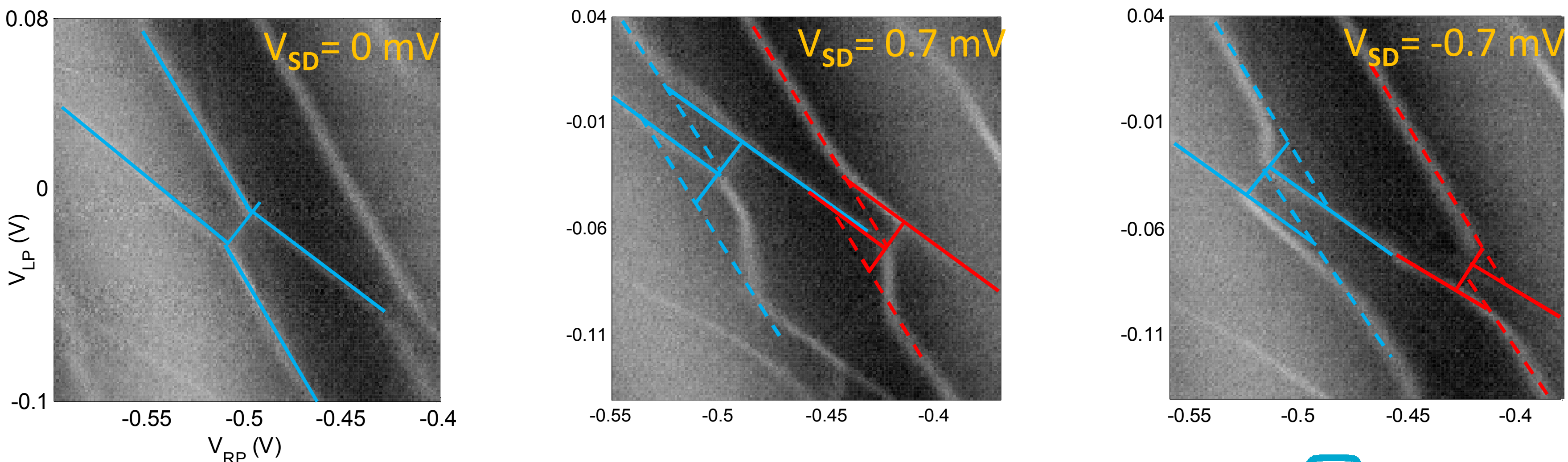


Bias triangle deviations

line vanishing and shifting



Using the slopes of charge sense lines at V_{SD} = 0 to identify bias triangles



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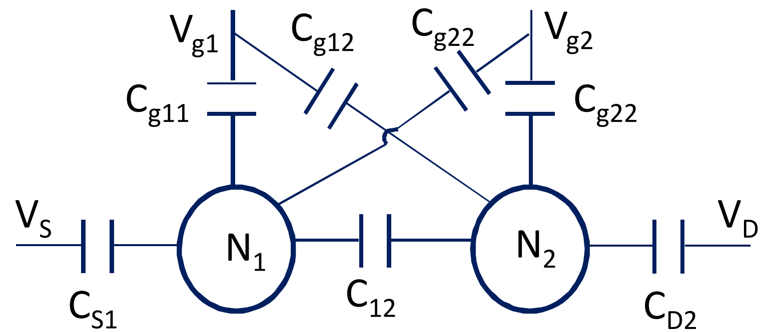
Capacitive network model

Based on the constant interaction model, including cross coupling

Chemical potential of each dot is determined from

$$\begin{cases} \mu_1(N_1, N_2) = U(N_1, N_2) - U(N_1\text{-}1, N_2) \\ \mu_2(N_1, N_2) = U(N_1, N_2) - U(N_1, N_2\text{-}1) \end{cases}$$



Where $U(N_1, N_2) = 0.5\,(V1, V2)\,.\,(Q1, Q2)$

with $Q_{1(2)} = N_{1(2)}e$

and $V_{1(2)}$ are determined by

$$\begin{cases} Q_1 = C_{S1}(V_1 - V_S) + C_{g1}(V_1 - V_{g1}) + C_{12}(V_1 - V_2) + C_{g21}(V_1 - V_{g2}) \\ Q_2 = C_{D2}(V_2 - V_D) + C_{g2}(V_2 - V_{g2}) + C_{12}(V_2 - V_1) + C_{g12}(V_2 - V_{g1}) \end{cases}$$

or

$$\begin{pmatrix} Q_1 + C_1 V_S + C_{g1} V_{g1} + C_{g21} V_{g2} \\ Q_2 + C_2 V_D + C_{g2} V_{g2} + C_{g12} V_{g1} \end{pmatrix} = \begin{pmatrix} C_1 & -(C_{12} + C_{g21}) \\ -(C_{12} + C_{g12}) & C_2 \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$$

In which $C_{1(2)} = C_{S1(D2)} + C_{g1(2)} + C_{12}$

Inputs are capacitances

Simplified rate equation

To obtain steady state occupancy of DQD

For a specified number of charge sectors, we solve sets of equations for each triple point, e.g. the yellow one, taking into account the transition from nearest charge sectors only

$$0 = dP_A/dt = \Gamma_{B\to A}P_B + \Gamma_{C\to A}P_C + \Gamma_{A\to B}P_A$$

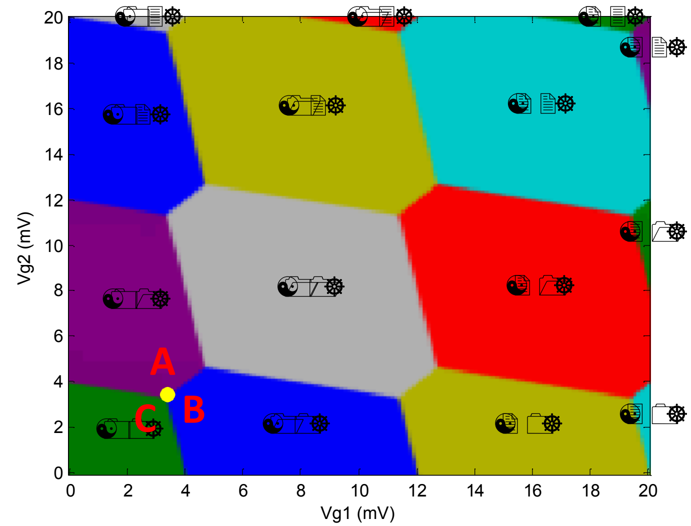
$$0 = dP_A/dt = \Gamma_{B\to A}P_B + \Gamma_{C\to A}P_C + \Gamma_{A\to B}P_B$$

$$0 = dP_A/dt = \Gamma_{B\to A}P_B + \Gamma_{C\to A}P_C + \Gamma_{A\to B}P_C$$

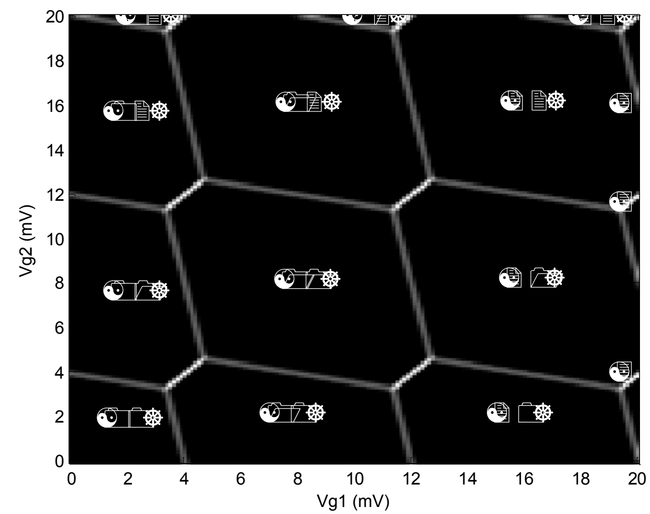
where P_i is the probability of finding an electron in charge sector i and Γ is the tunnel rate between sectors

$$\Gamma_{i\to j} = \alpha_{ij}.\ f[(\mu_i - \mu_j)/kT]$$

with f is Fermi function and α_{ij} is a constant and an input for the model



Charge sensing ↔ taking derivative



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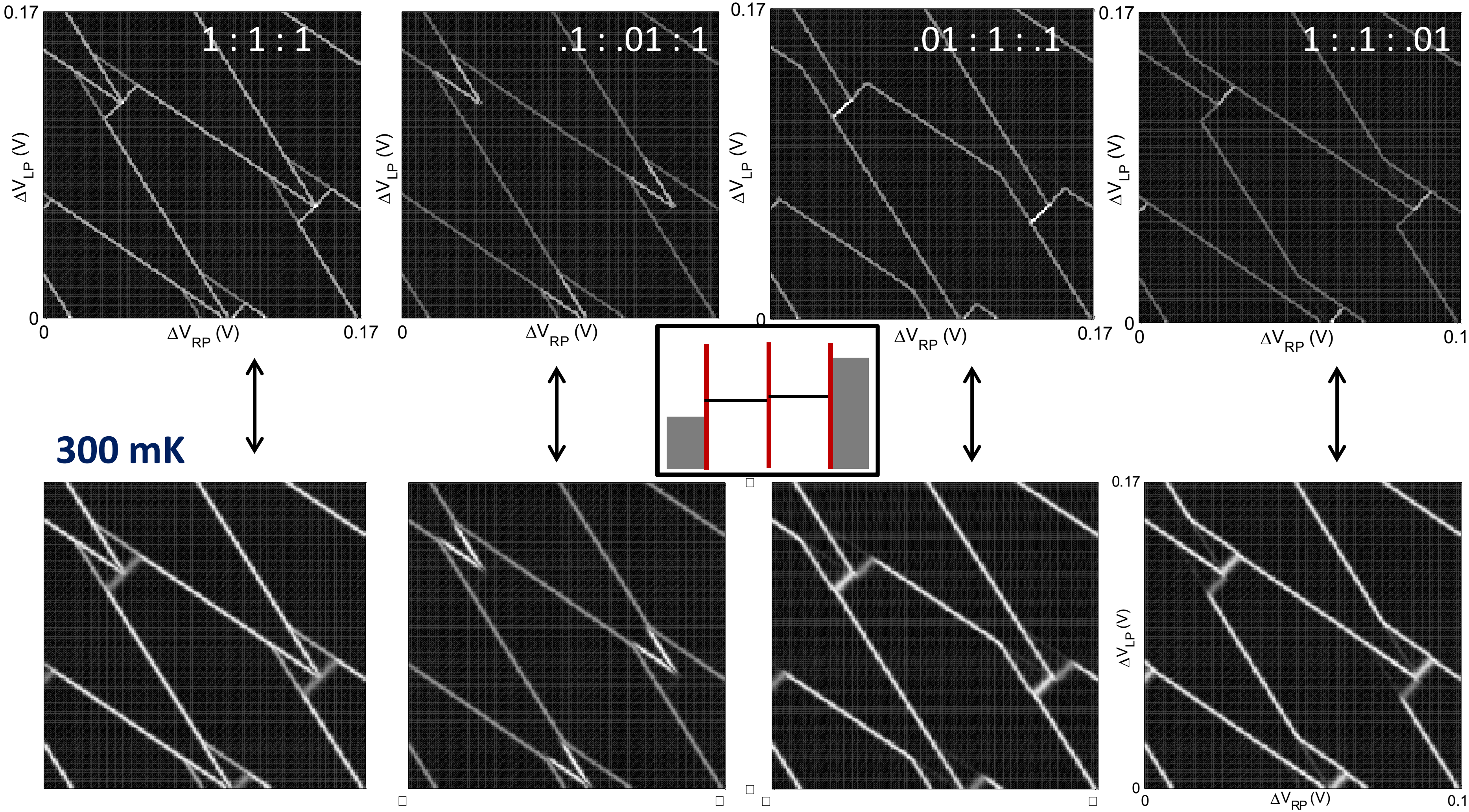
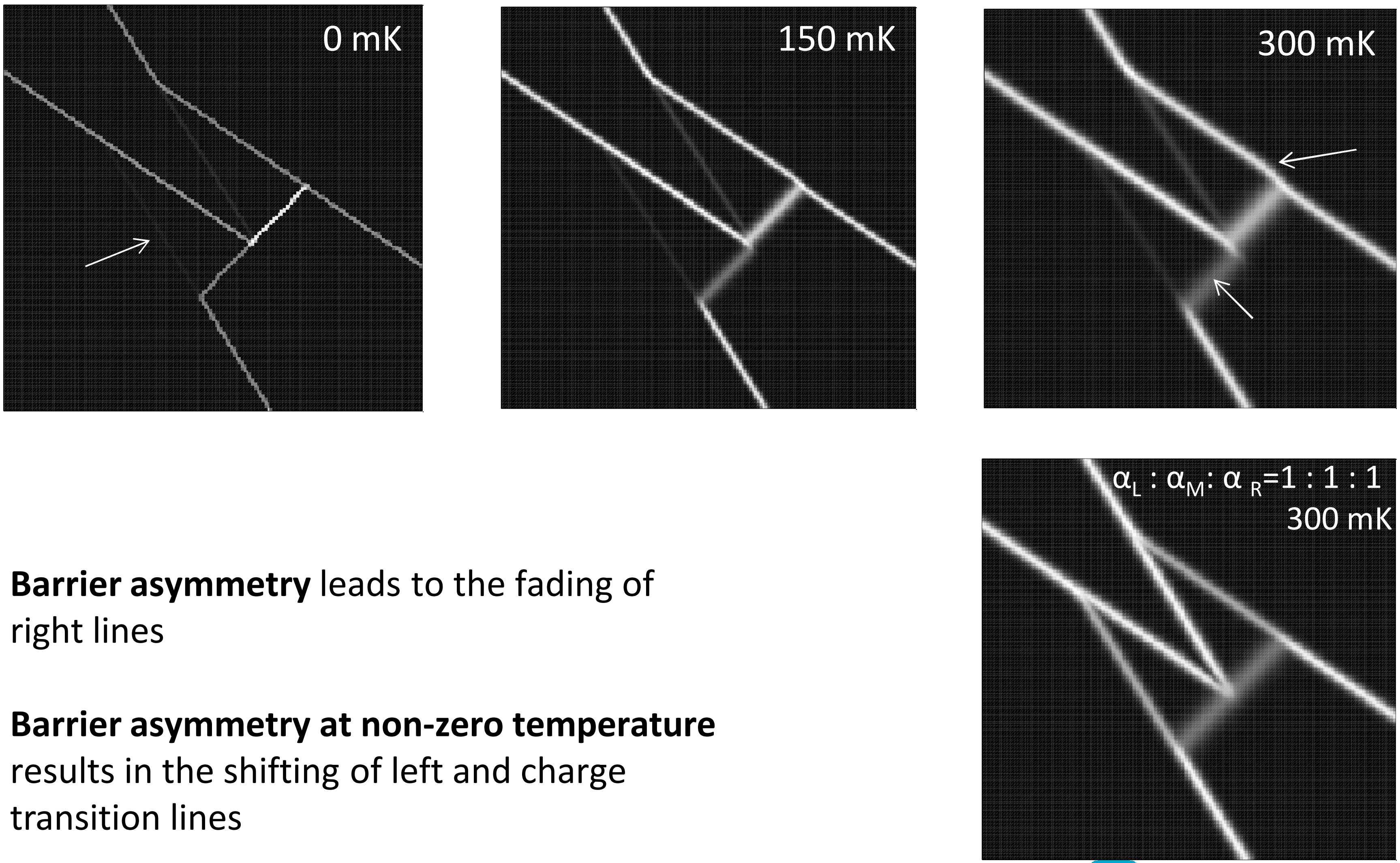
Imbalanced tunnel rates and temperature effects

0 mK



Imbalanced tunnel rates and temperature effects

$\alpha_L : \alpha_M : \alpha_R = 1 : .1 : .01$



Barrier asymmetry leads to the fading of right lines

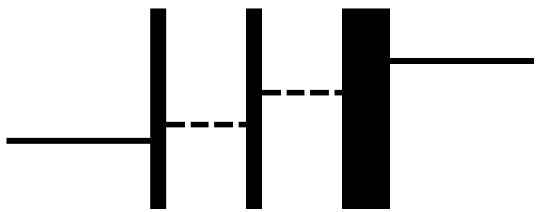
Barrier asymmetry at non-zero temperature results in the shifting of left and charge transition lines

Charge sense line vanishing

imbalanced tunnel rates

Transport in electron triangle

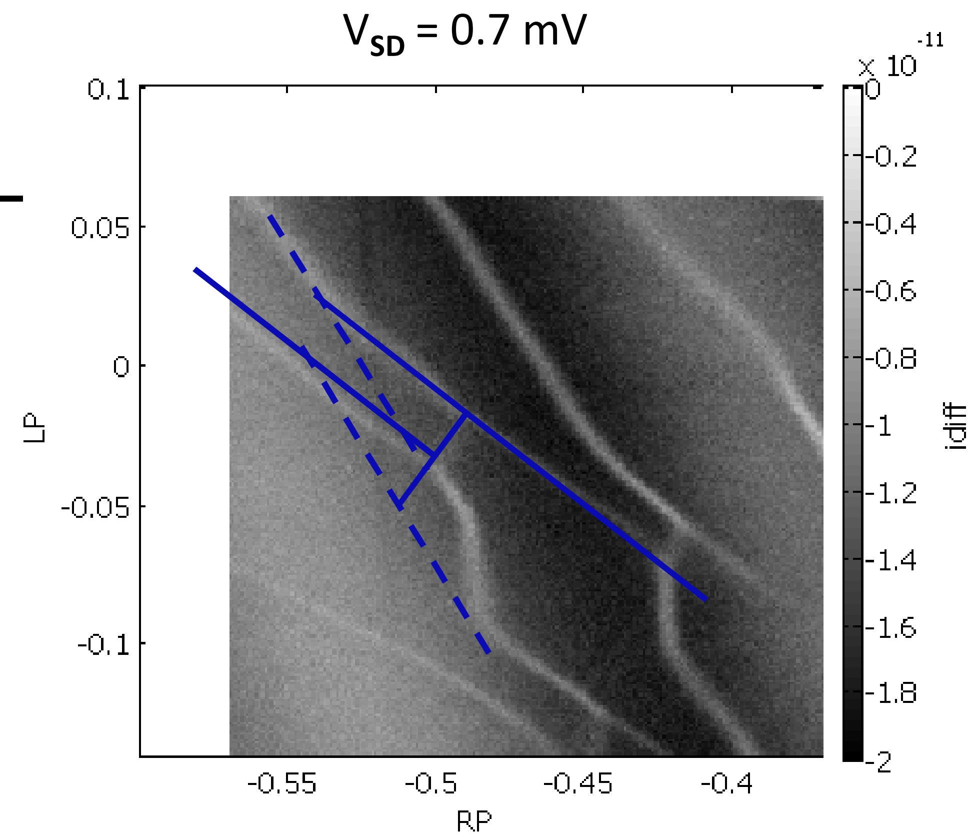
DQD chemical potential



Tunnel rates	fast	fast	slow

DQD last electron occupation: right lead, mostly

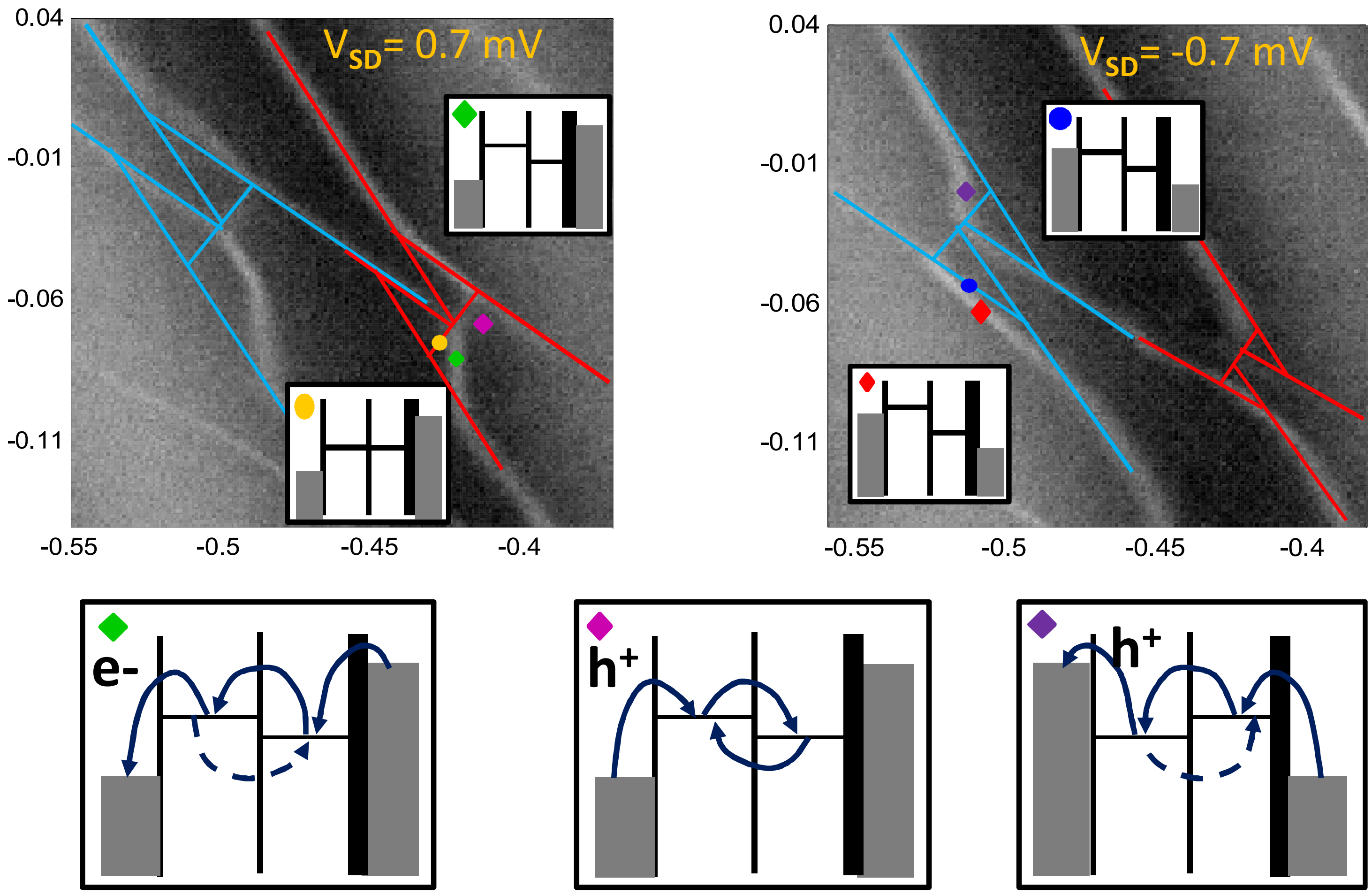
Strongest CS feature: left line of triangle



- 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.

Charge sense line shifting

imbalanced tunnel rates and finite temperature



Additional charge sense feature may be due to the overlap between triangles and the fact that tunnel rate Γ is also a function of voltages.

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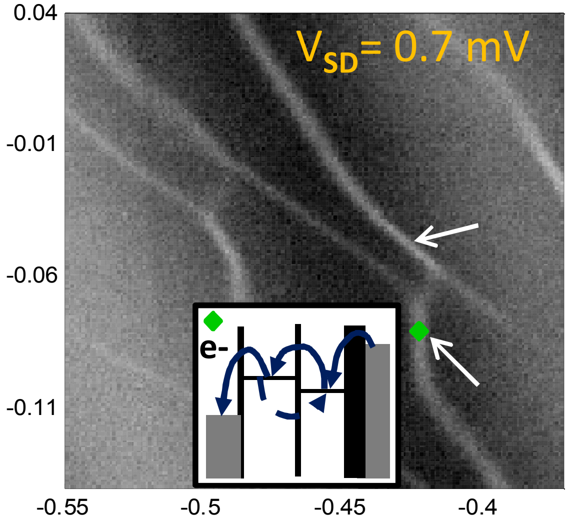
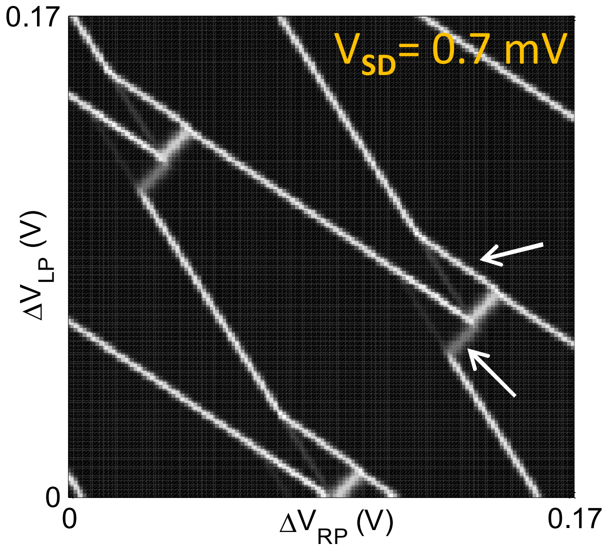
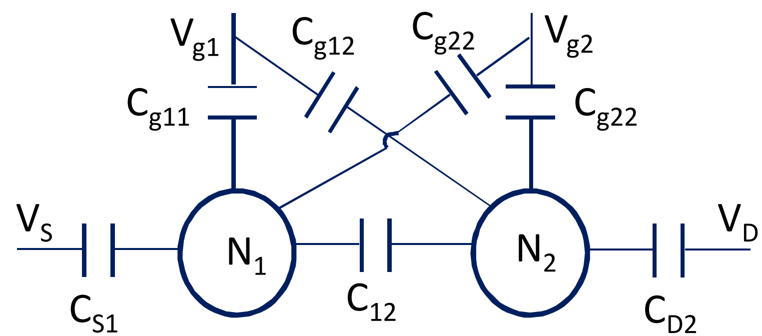
Summary







We show the missing and shifting of charge sense lines of bias triangles in Silicon MOS DQD.

While line vanishing is due to the imbalanced tunnel rates, the shifting is caused by both tunnel barrier asymmetry and finite temperature effects.

The capacitive network model including rate equation provide qualitatively agreements with experimental data

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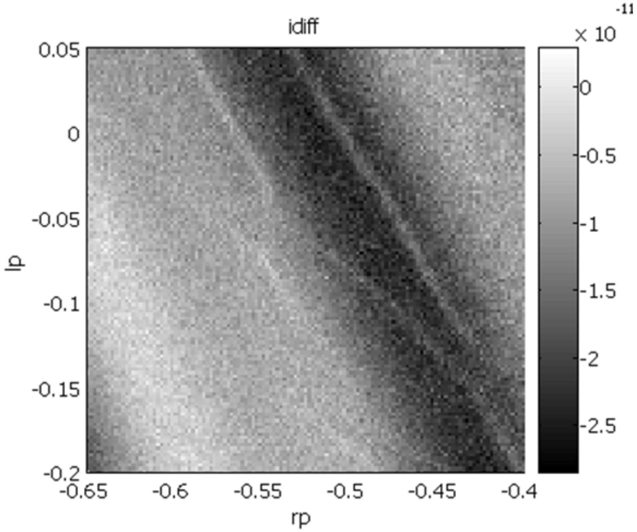
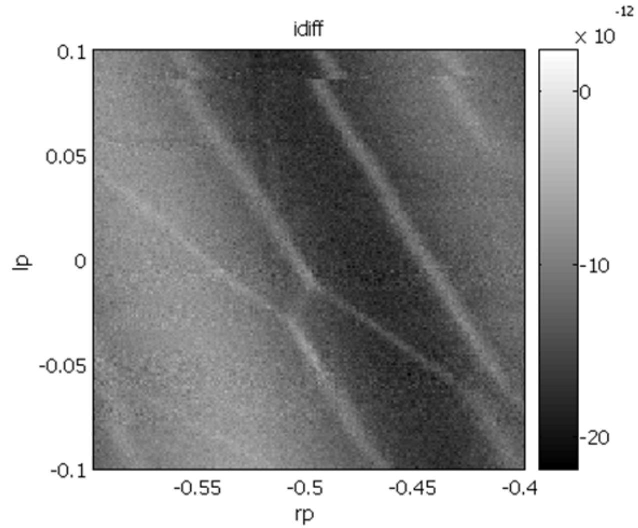
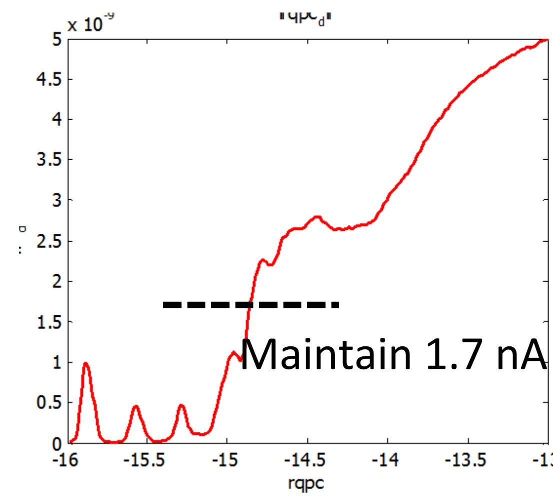
Adaptive charge sensing

No adapting **Adapting** **Charge sensor**







Software feedback for optimizing charge sensor sensitivity

- Adapting maintains sensitivity at triple points more reliably over long times
- We adapt to fix the ac current through the qpc
  - sweep back and forth to avoid sudden jumps
  - adjust RQPC by a single step at each point
- Remaining background variations are due to the variations CS curve

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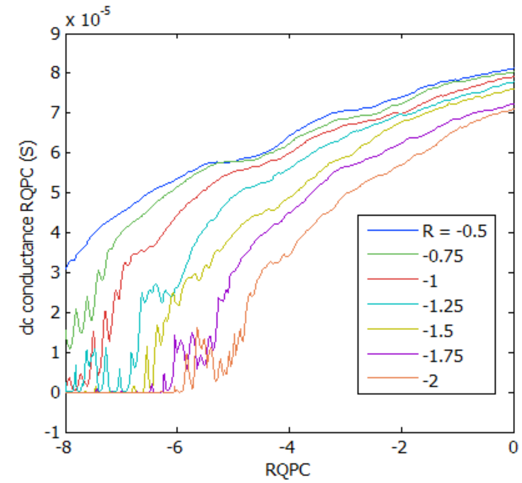
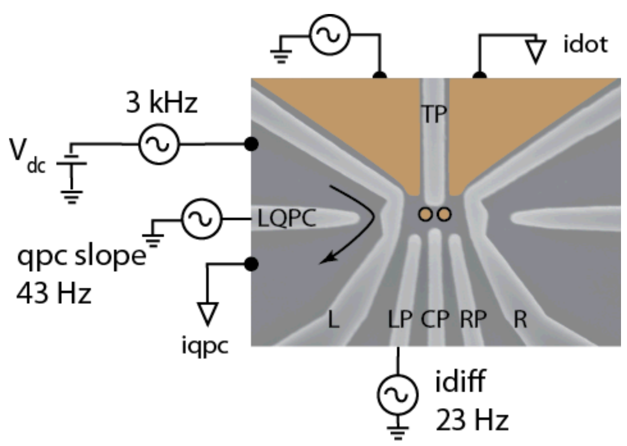
Measurement technique

- All of the following results employ a differential charge sense measurement
- The measurement is similar to the MOS DQD measured by the UCLA group (House, et al., PRB (2011)).
- Approach is also similar to the DELFT pulse gate technique used by many groups.

Charge sensor conductance

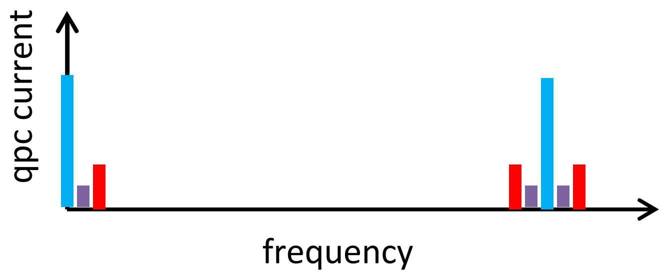


Measurement setup



- lock-in amplifier measurements using 1211 current preamp

Multiple signals enables simultaneous information



- transport, direct CS, differential CS
- QPC sensitivity for adaptive code
- AM modulation technique demonstrated

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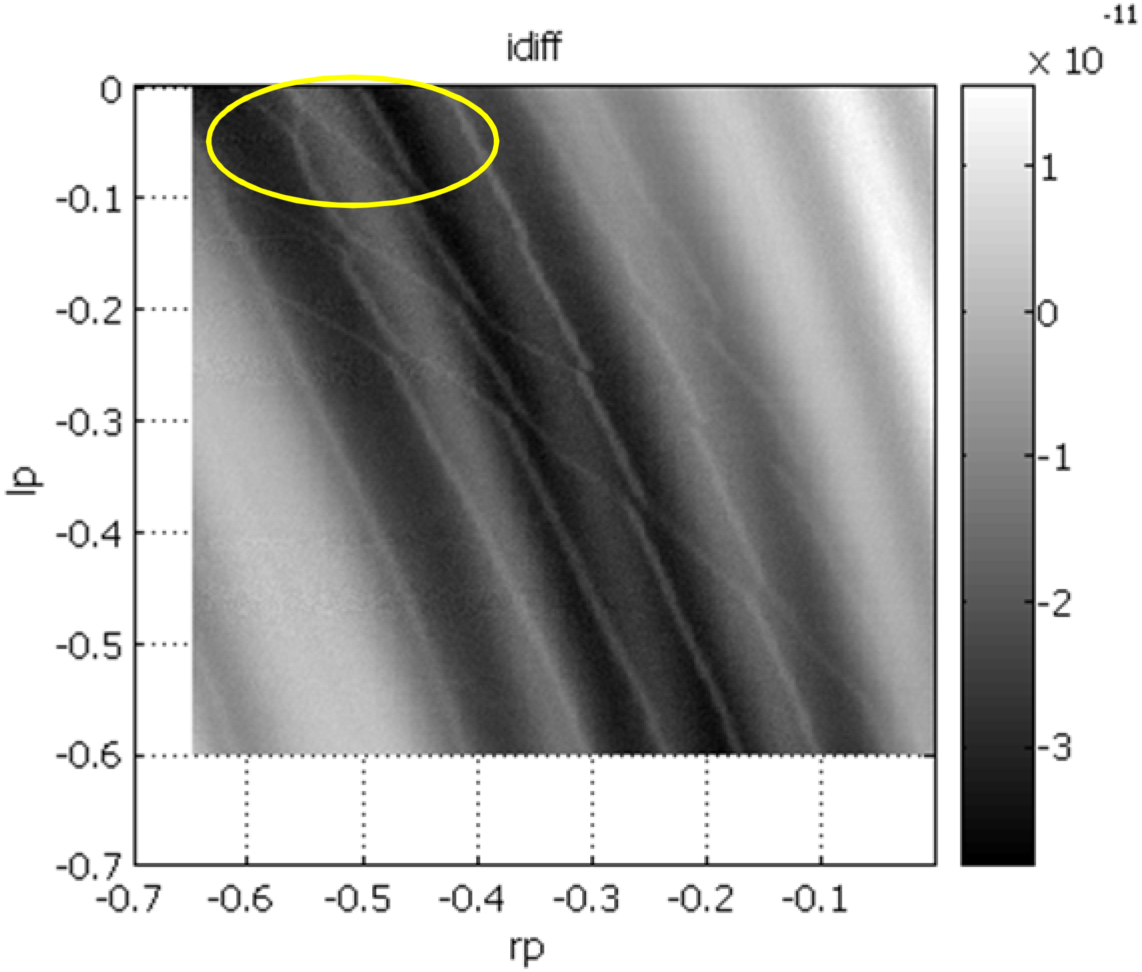
Triple points to measure bias dependence

- Focus on two triple points
- Visibility of the connection lines (m+1,n) -> (m,n+1) is very important



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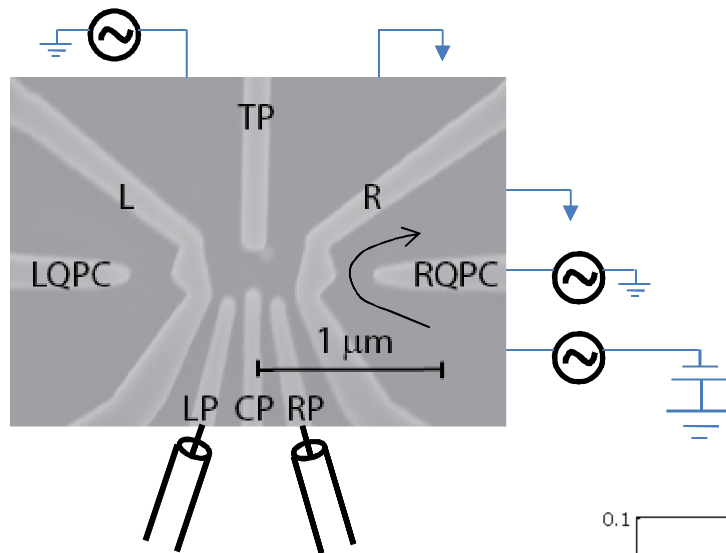
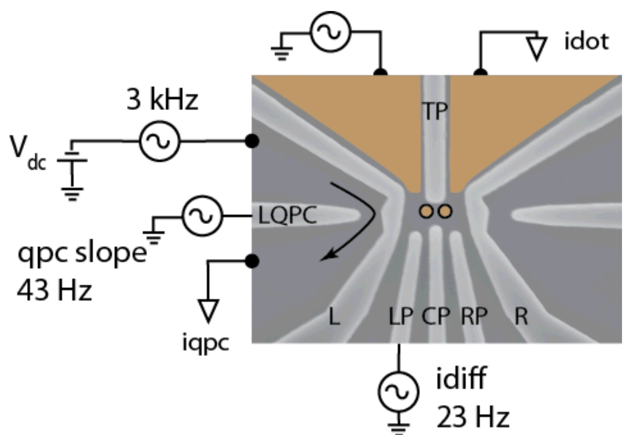
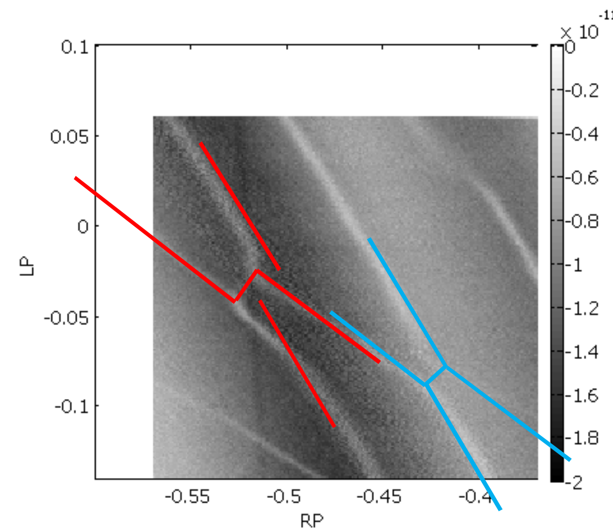
SEM



TP
L
R
LQPC
RQPC
1 µm
LP CP RP



idot
3 kHz
V_{dc}
TP
LQPC
qpc slope
43 Hz
iqpc
L
LP CP RP
R
idiff
23 Hz



0.1
0.05
0
-0.05
-0.1
LP
-0.55
-0.5
-0.45
-0.4
RP
x 10^-11
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
idiff