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Manipulating single electrons in semiconductor devices for quantum computing

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Sandia National Laboratories

Outline

- Quantum computing with semiconductors
- Silicon MOS double quantum dots
- Donors as a natural single electron potential

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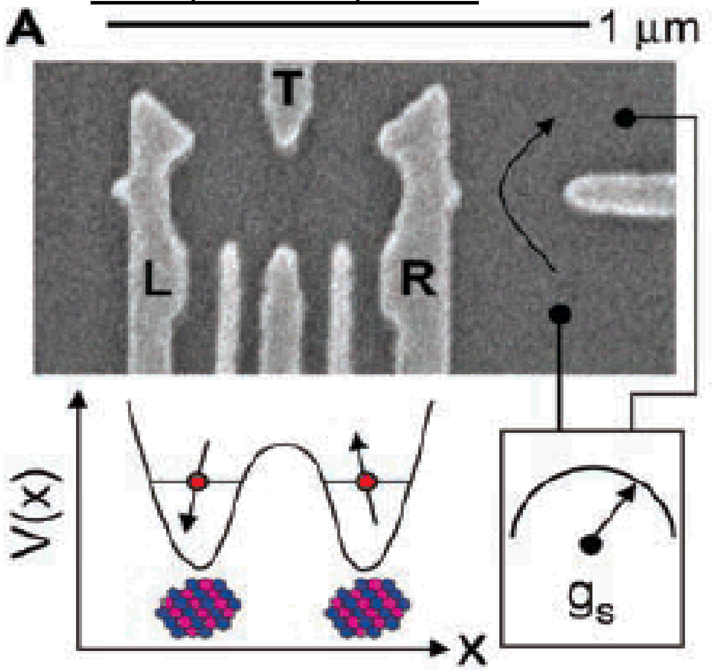
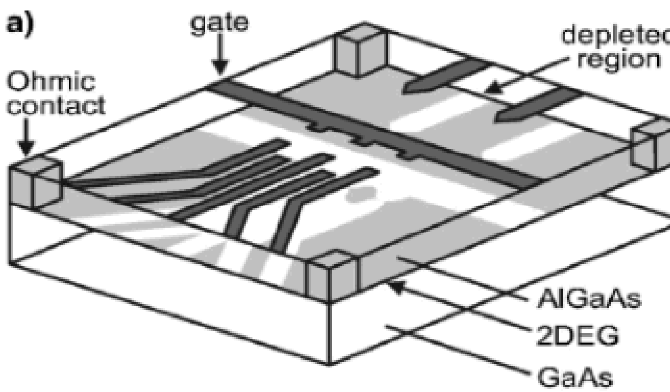
Double Quantum Dot Qubit in GaAs

- Demonstration of GaAs qubits has spurred quantum do semiconductor qubit research (e.g., Petta et al. in 2005)

Petta, Science, 2005



Hanson, Rev. Mod. Phys. 2007



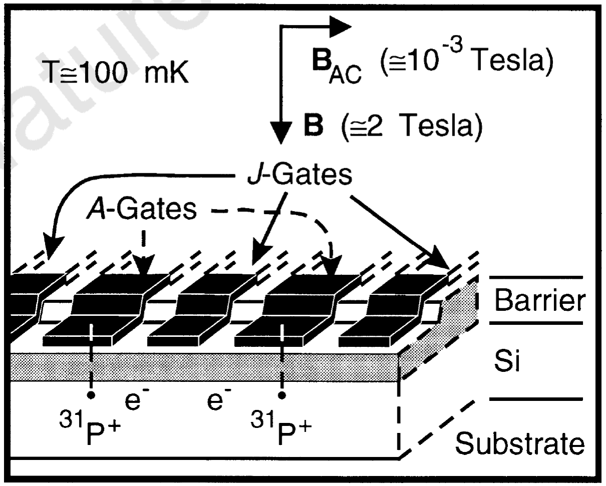
Need
- Isolate singlet triplet system
- Electrically tunable rotations
- Charge sense (fast is desirable)

Donor qubit

In silicon, the natural potential defined by a donor provides an alternative to surface dot approaches in semiconductors.

Kane architecture

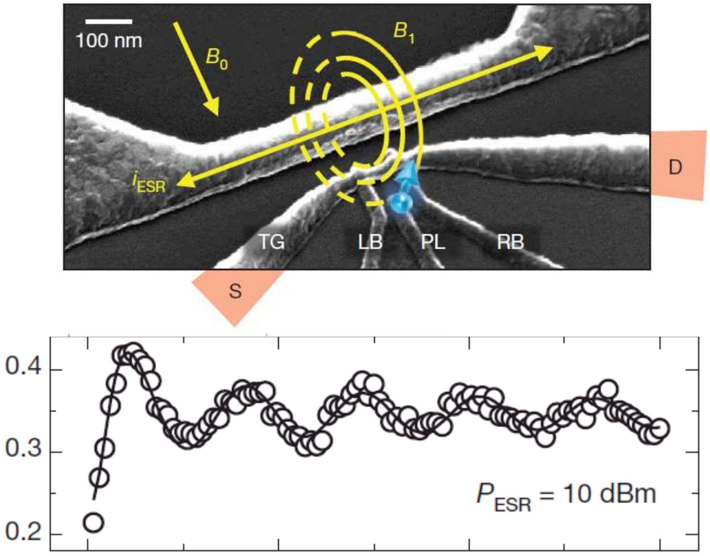
*B. E. Kane, Nature **393**, 1998*



Silicon donor research efforts

Australian CQC2T group (MOS, STM)

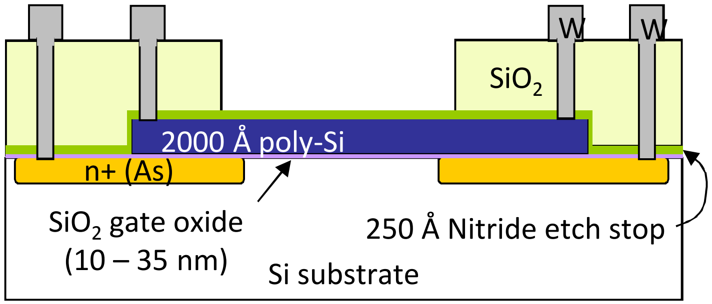
*J. Pla, Nature **489**, 2012*

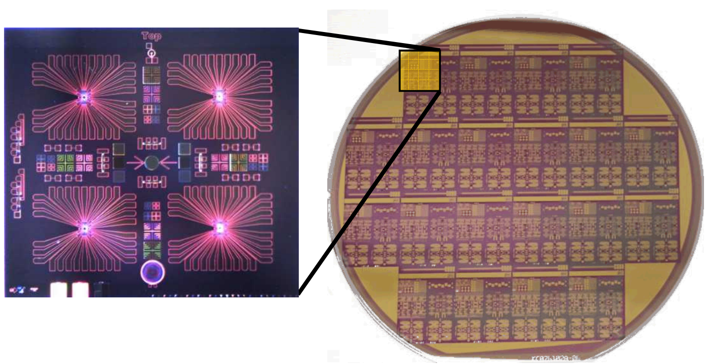


Much of the work in the silicon qubit field is supported by NEMO from Purdue group lead by Gerhard Klimeck)

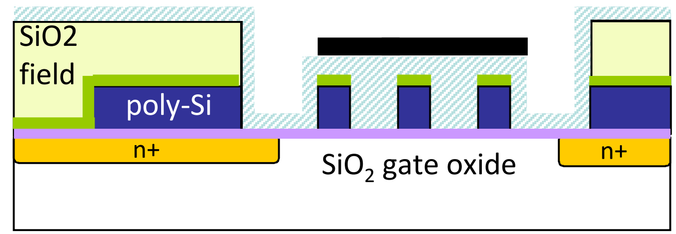
Si MOS Fabrication

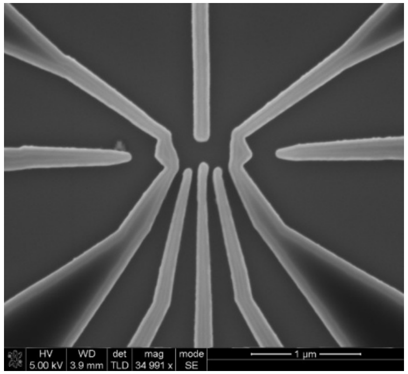
Front-end in silicon fab





Back-end nanolithography





MOS devices

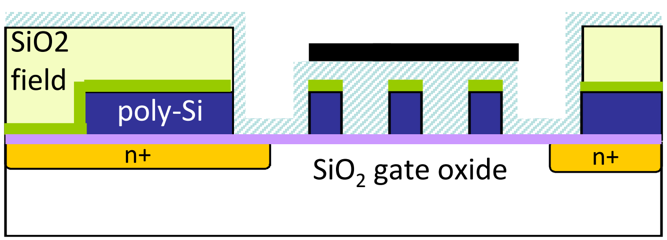
Details of MOS device

- 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

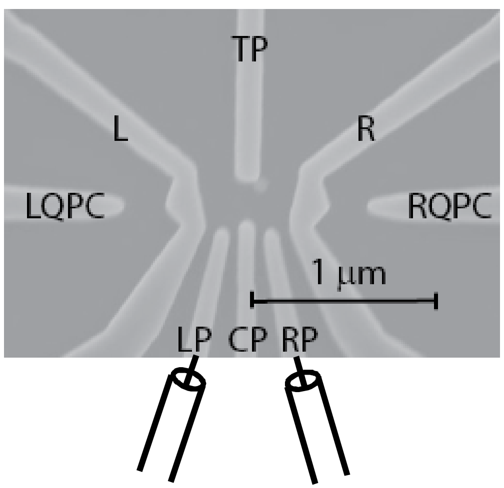
Device variations

- Donor implant in either dot or barrier regions
- Accumulation mode sSi/SiGe with poly depletion gates

Cross-section of MOS device



Ottawa flat 270 double quantum dot

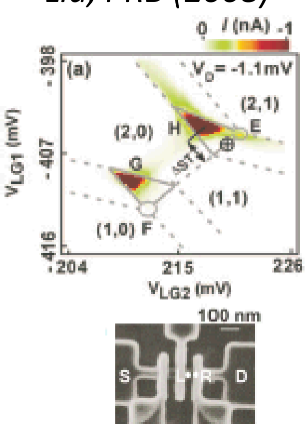


Spin blockade in MOS double quantum dots

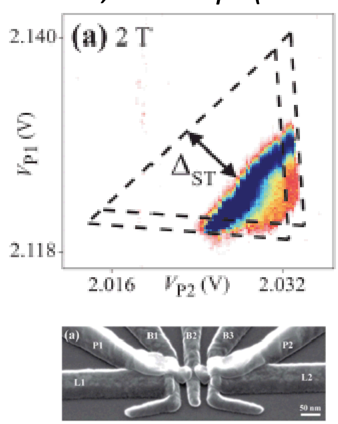
- Many electron DQD regime
    - regime of device operation
    - potential screening of defects
- Charge sensing will be used to measure DQD
- Many electron singlet-triplet is a path to begin qubit measurements

Transport measurements of Pauli blockade in silicon MOS

Liu, PRB (2008)

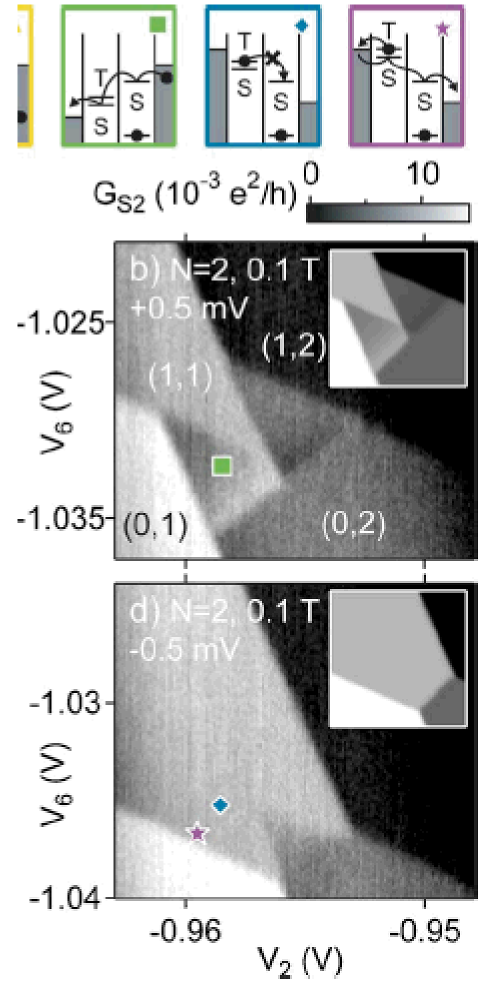


Lai, Sci. Rep. (2011)



Charge sensing for bias triangles in GaAs

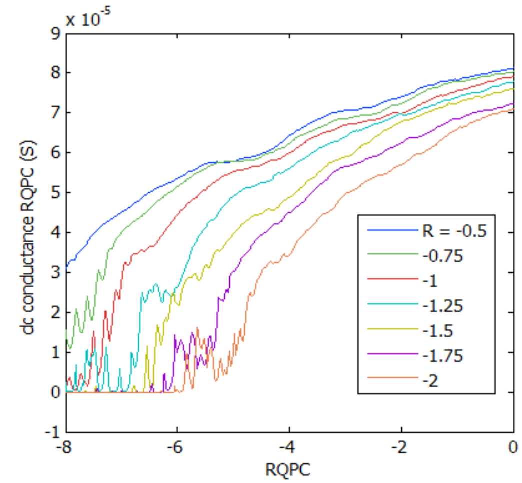
Johnson, PRB (2005)



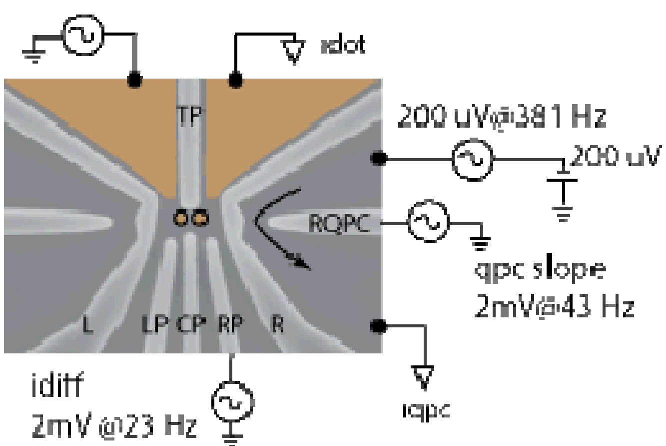
Measurement technique

- All of the following results emply 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

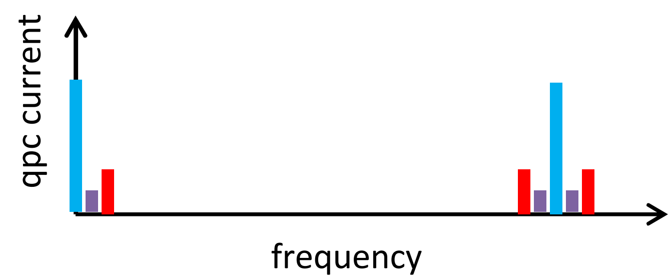


Measurement setup



- lock-in amplifier measurements using 1211 current preamp

Multiple signals enables simultaneous information

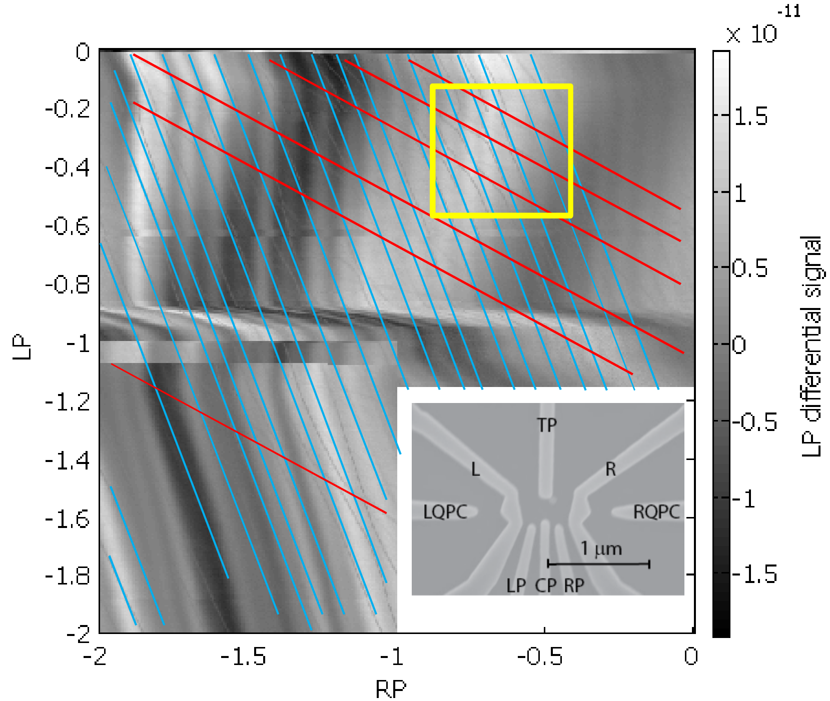


- transport, direct CS, differential CS
- QPC sensitivity for adaptive code
- AM modulation technique demonstrated

Honeycomb in many-electron regime

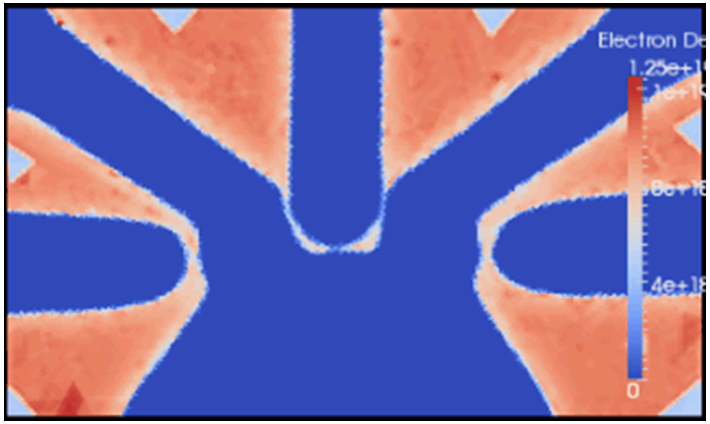
- Focus on many electron regime where triple points are visible with charg sensing
- In the low electron regime, eventually even low frequency ac signals (~10 Hz) lead difficulty in measuring charge sense features

Charge sense for many (R,L) transitions



QCAD calculated electron density for (10,10)

Poisson calculation of density optimized for 10 electrons in each dot



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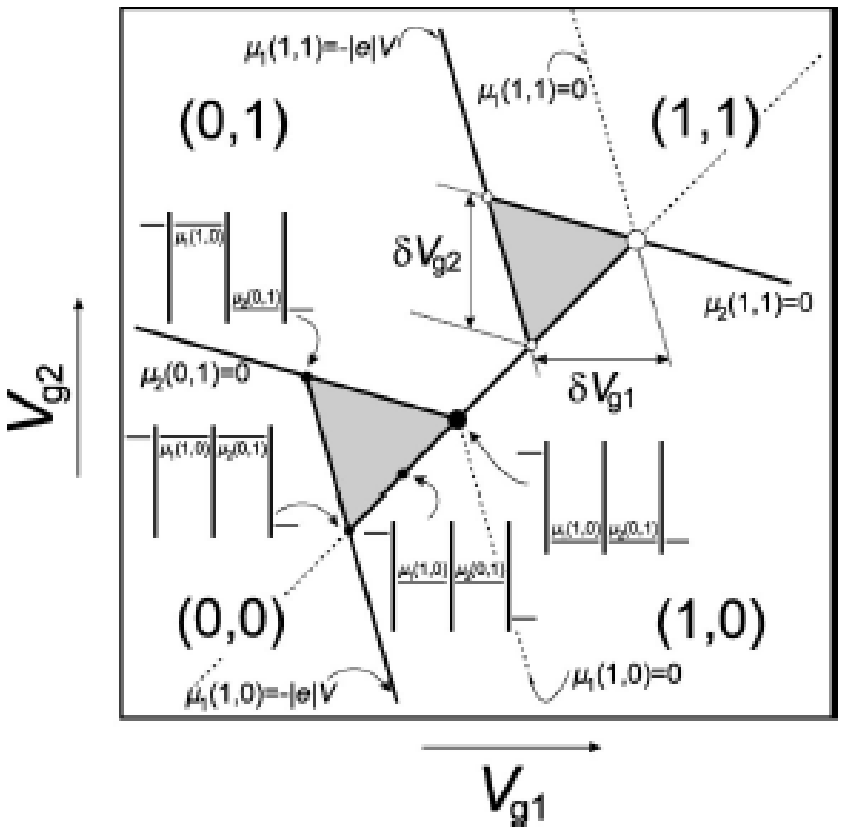
Nonlinear transport overview

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



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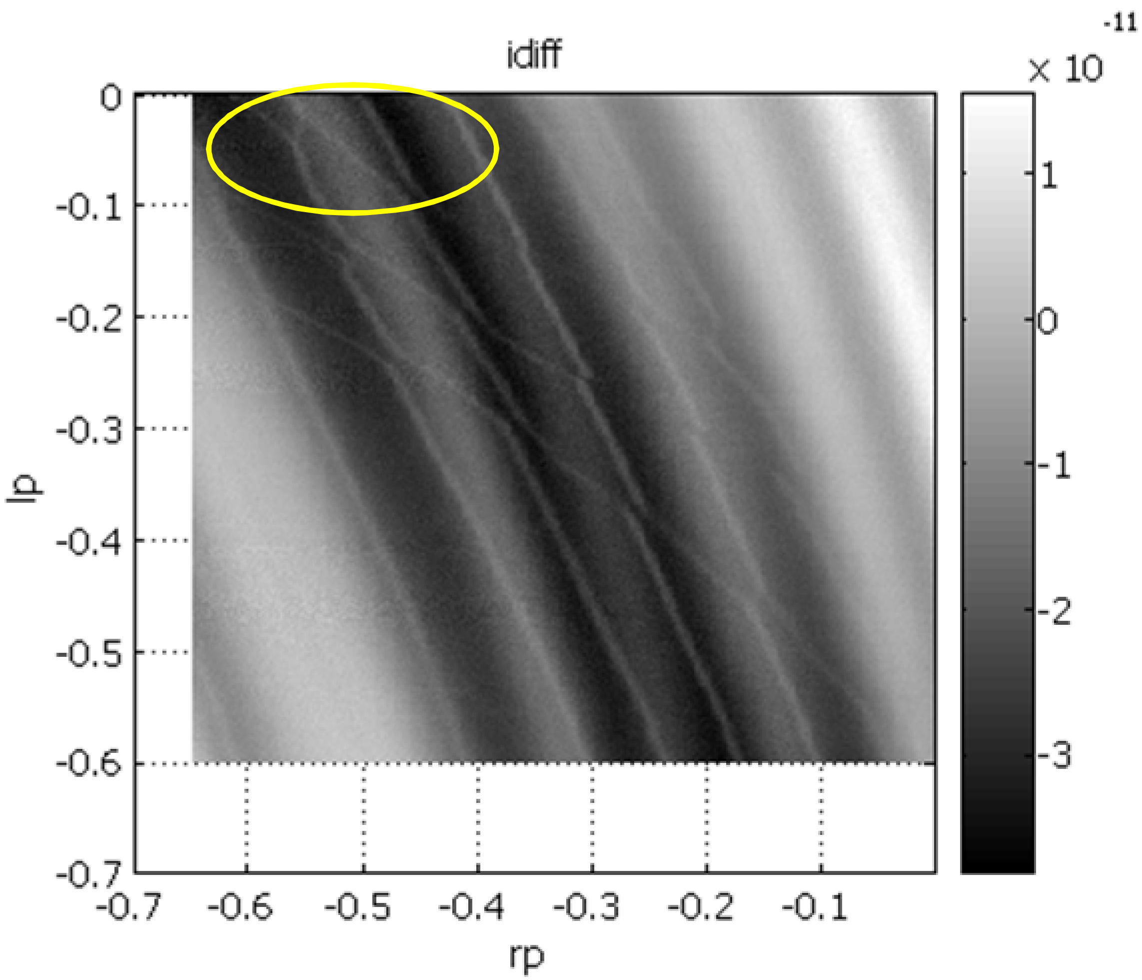
Triple points to measure bias dependence

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



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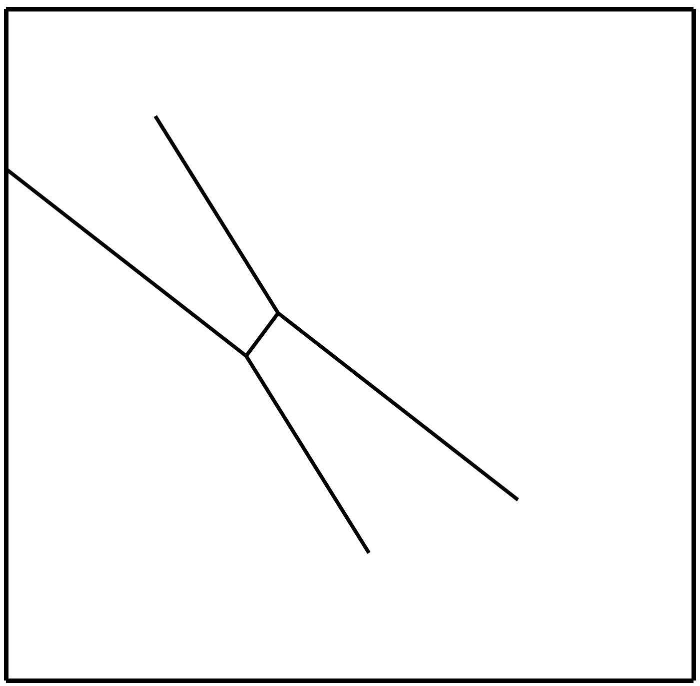
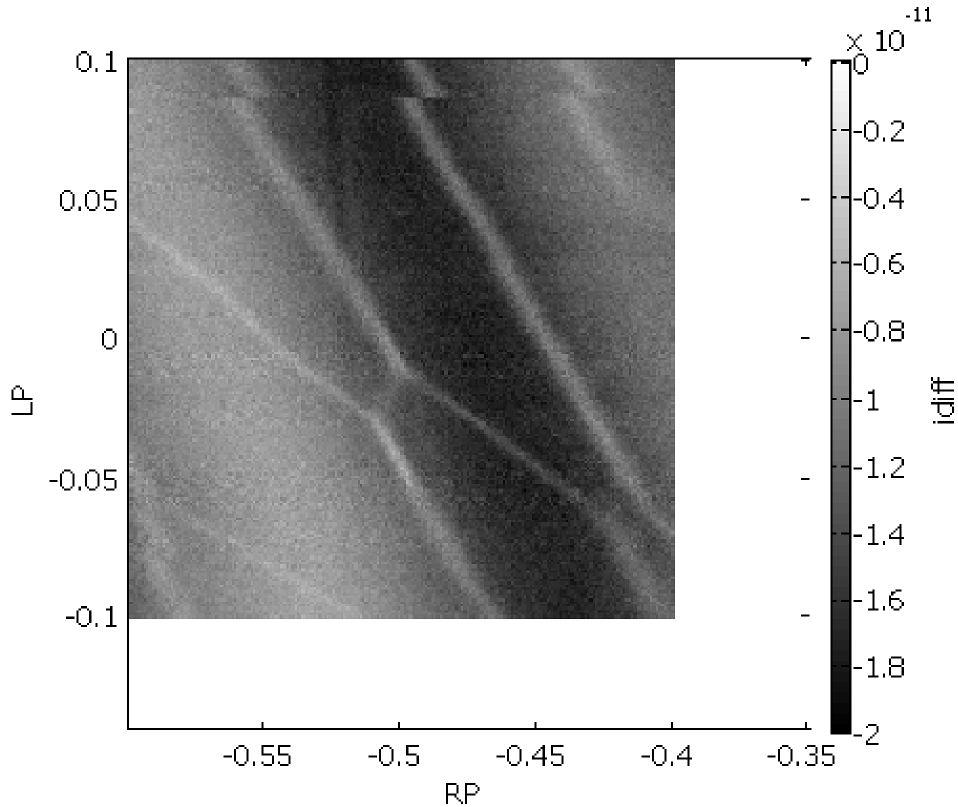
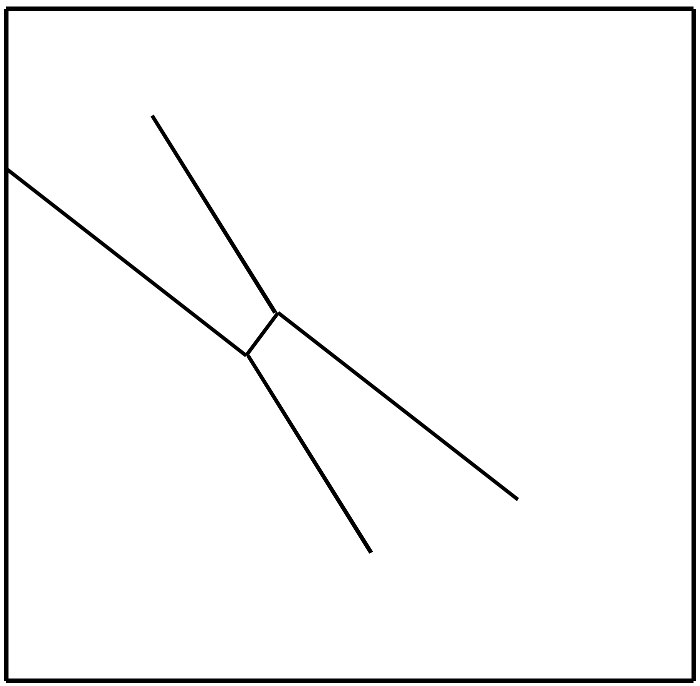
No source-drain bias

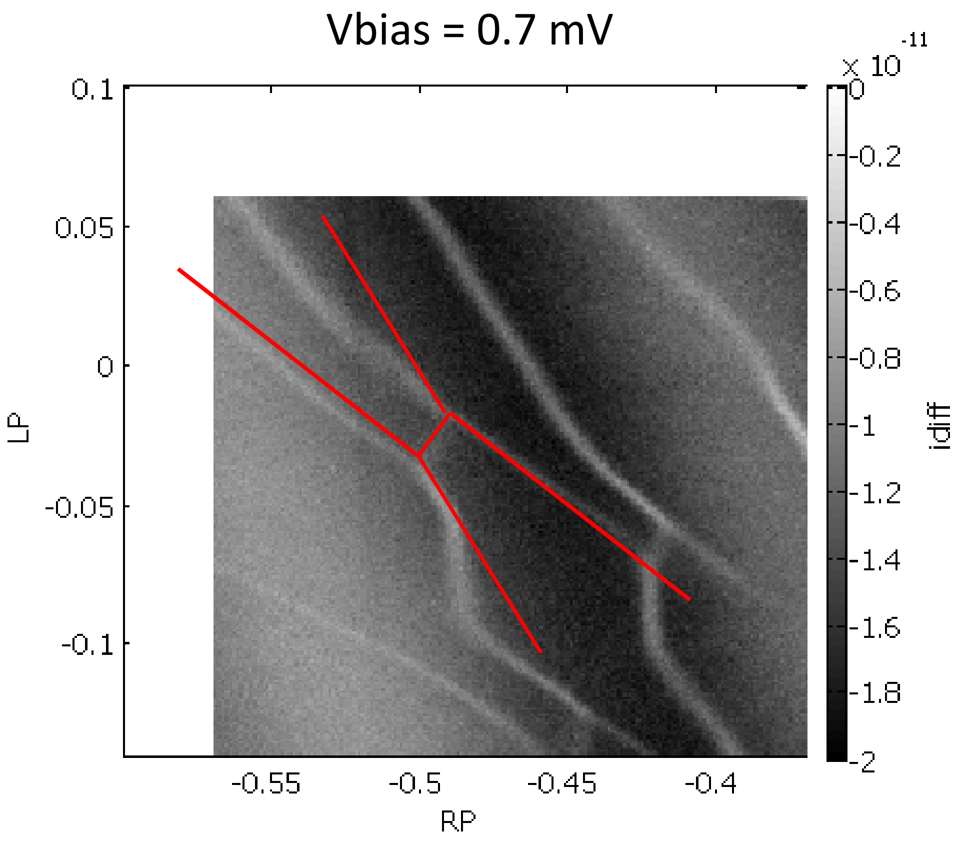




1. Identify charge sense transitions for the left and right dot.
2. Identify connection line for the triple point.

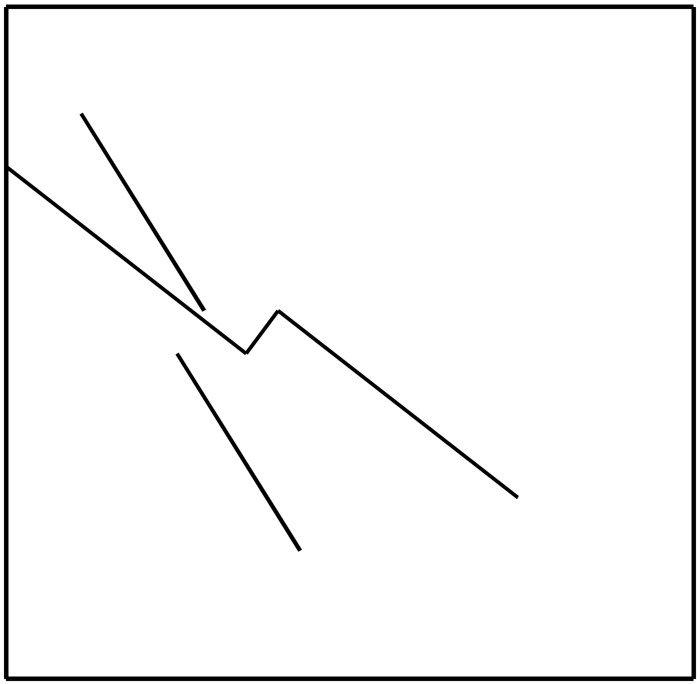
Determine the bias triangle, step 1

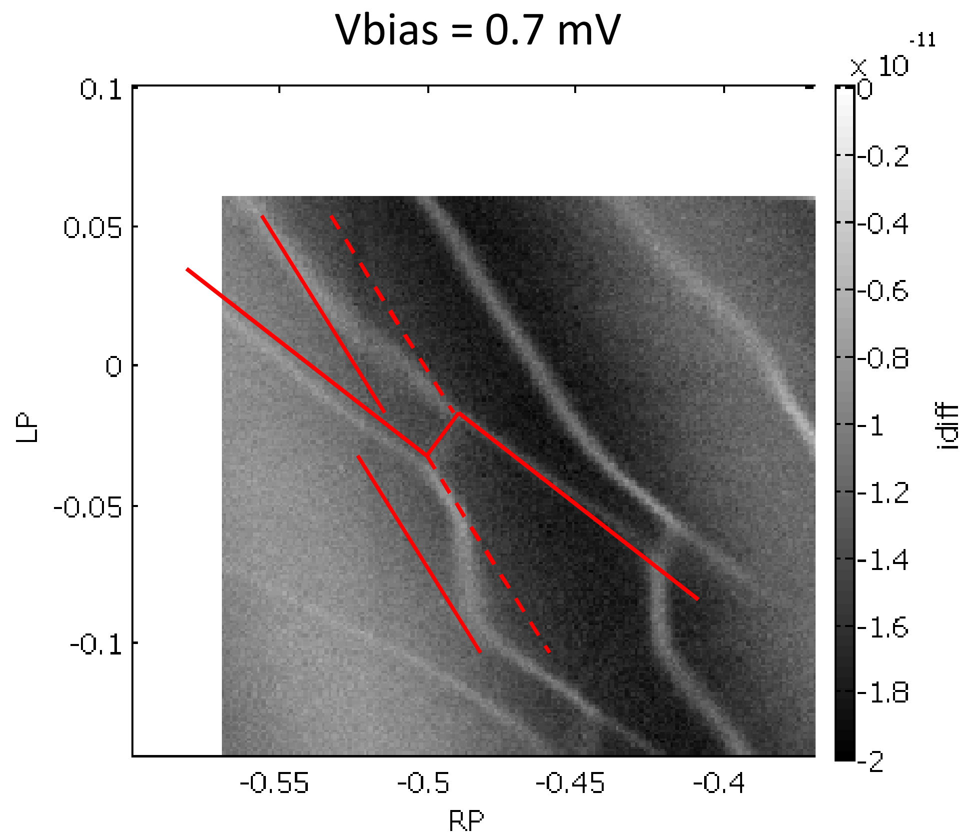




3. Line up the charge sense line for the left dot and the connection line.

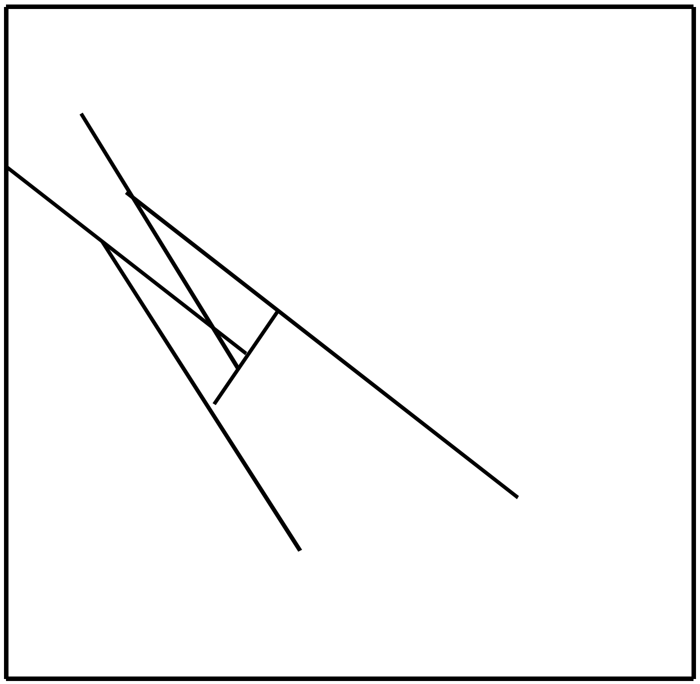
Determine the bias triangle, step 1

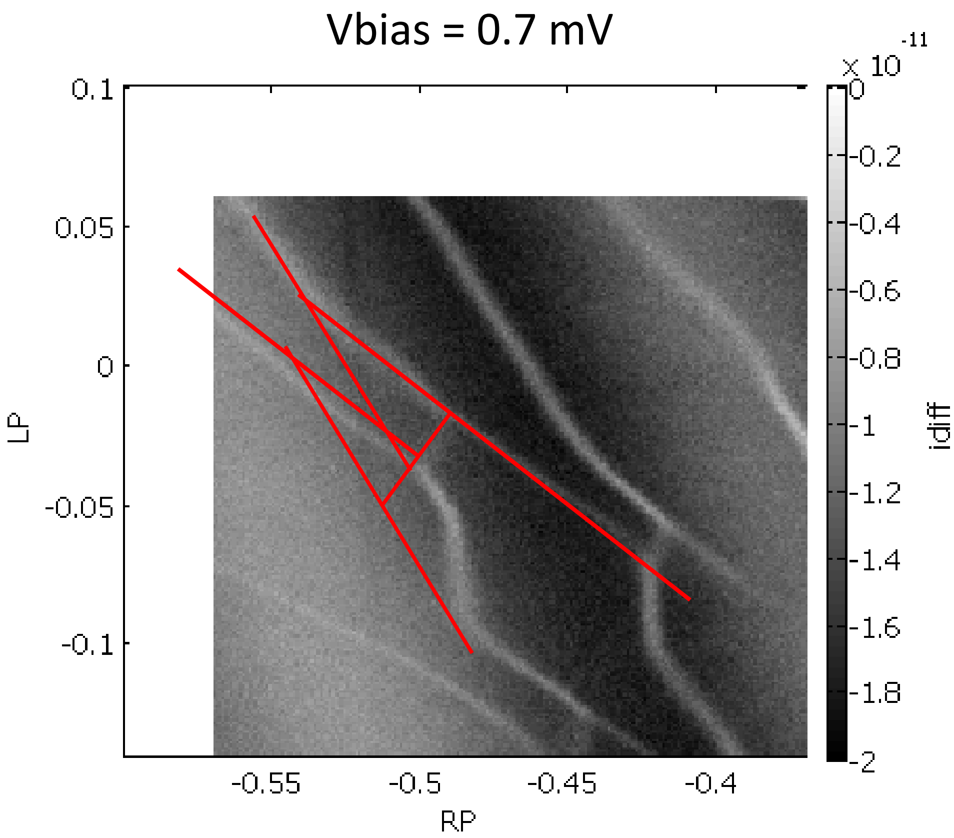




3. Line up the charge sense line for the left dot and the connection line.
4. Shift the charge sense lines for the right dot to match the upper left region.

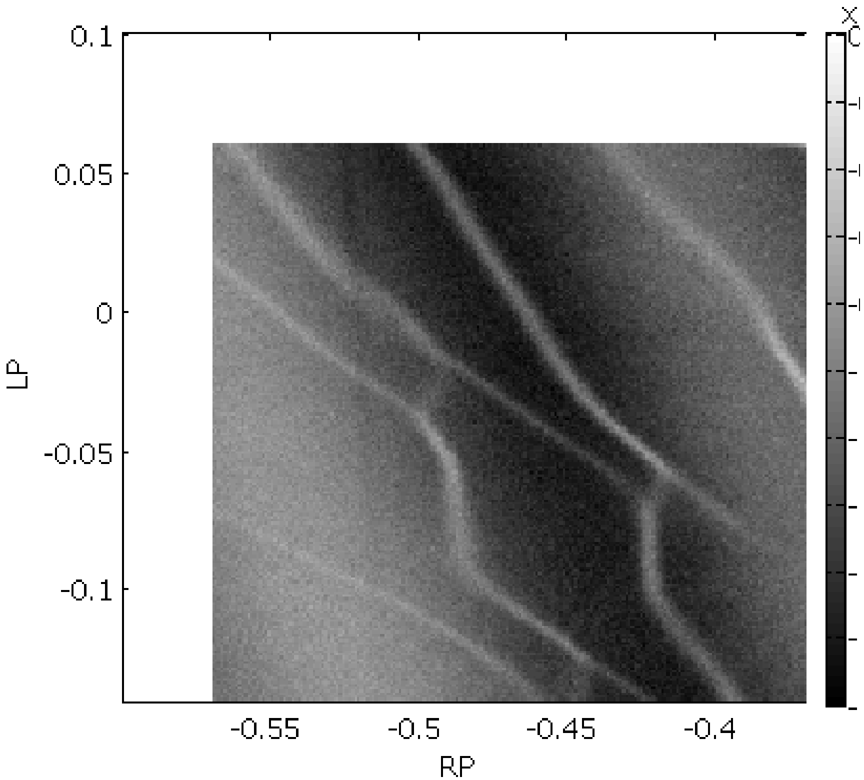
Determine the bias triangle, step 2



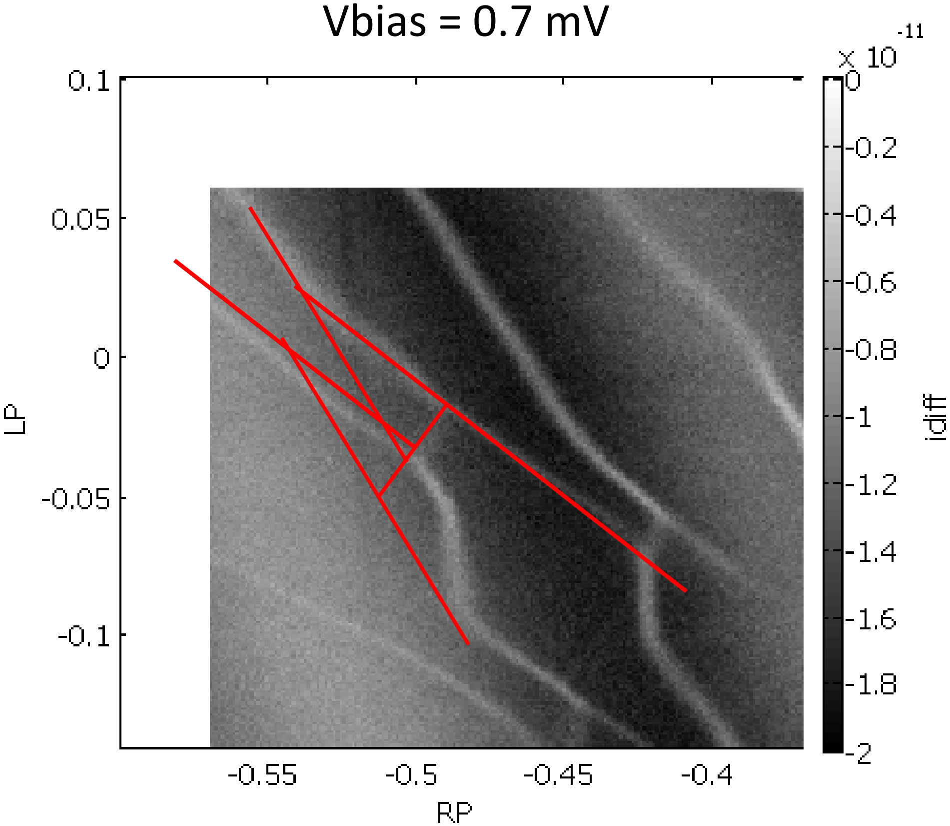


5. Extend the lines to make triangles.

Determine the bias triangle



Vbias = 0.7 mV

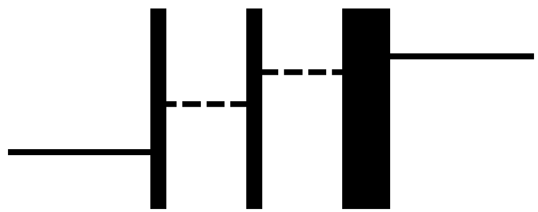


Charge sensing lines do not provide complete information on bias triangle

Missing charge sense lines

Transport in electron triangle

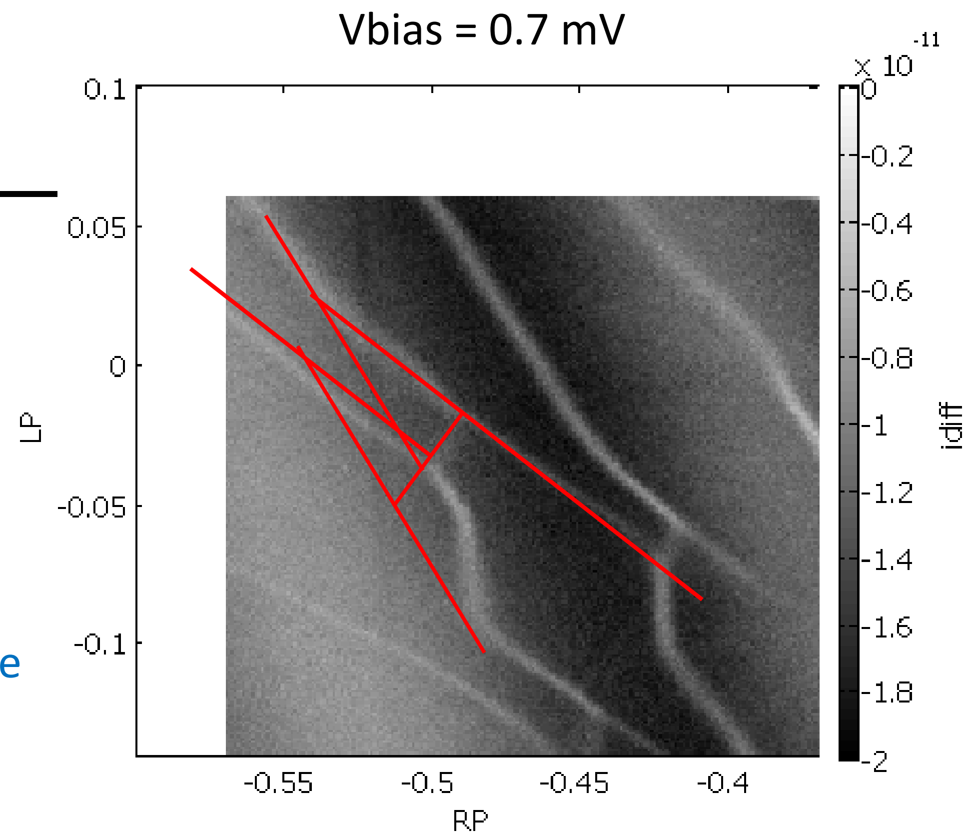
DQD chemical potential



tunnel rates — fast fast slow

DQD last electron occupation — mostly empty

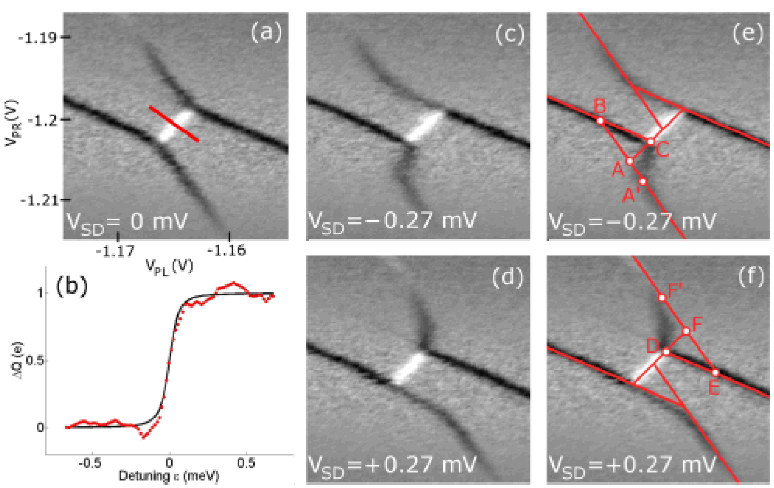
Strongest CS feature — upper line of triangle

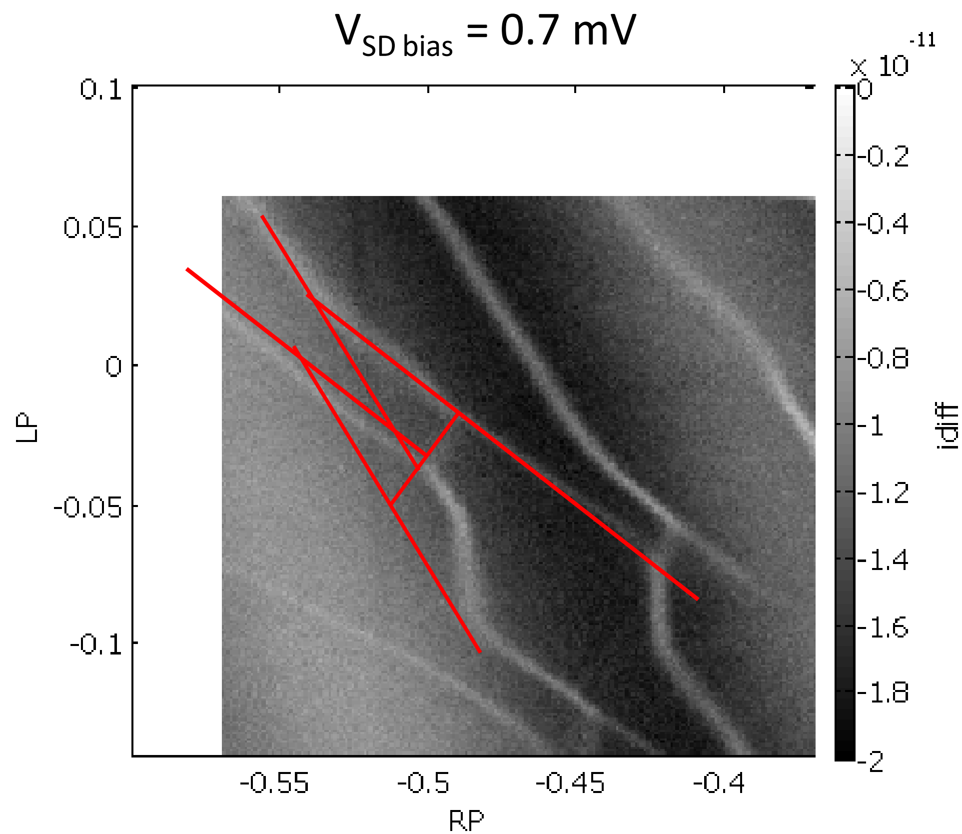


- Charge sensing depends in average occupation
- For unbalanced tunnel barriers, some of the lines will be below our signal to noise and appear to be missing.

Additional charge sense features

House, et al., APL (2011)



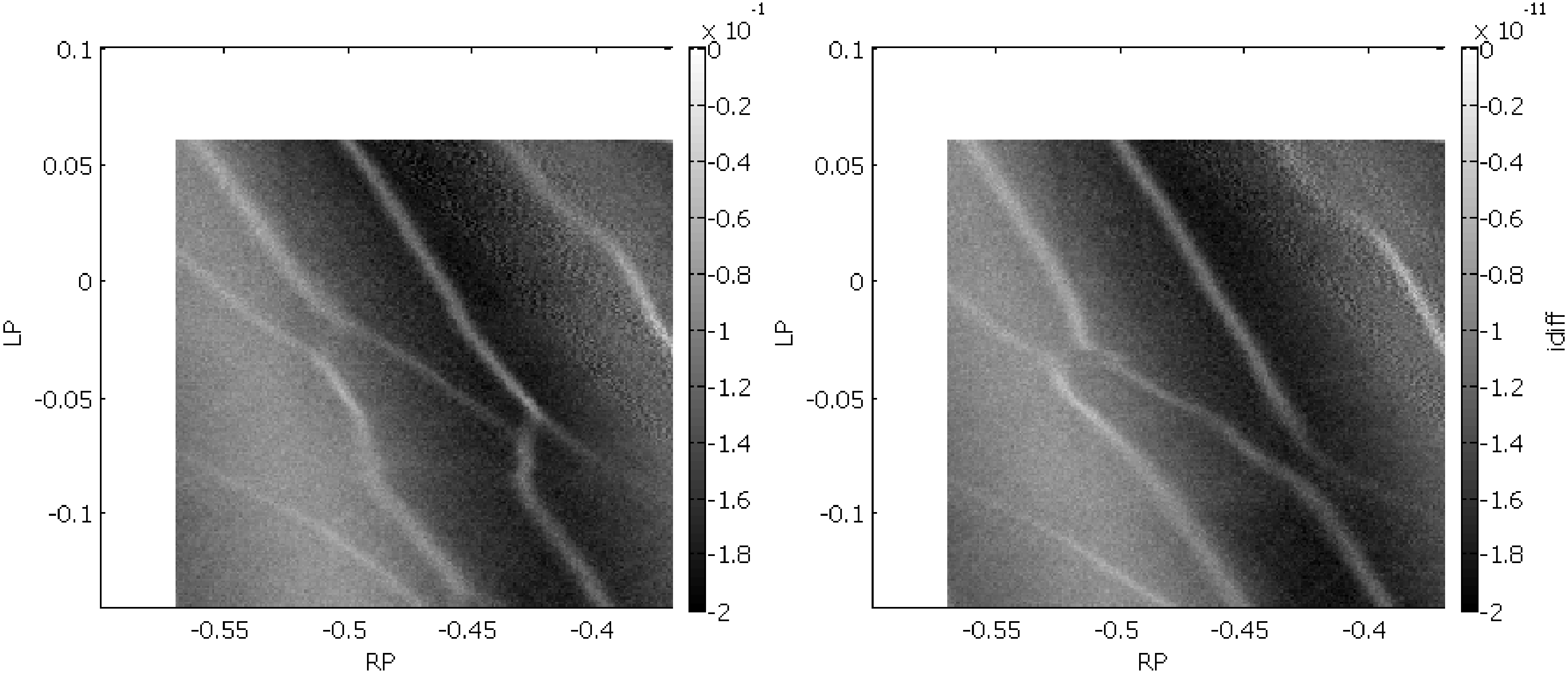


- Observed charge sense bias triangle is very similar to UCLA result
- Additional features may be due to a combination of co-tunneling, tunnel rates and overlap with nearby triple points

Bias triangle asymmetry

$V_{SD\ bias}$ = 0.3 mV

$V_{SD\ bias}$ = -0.3 mV



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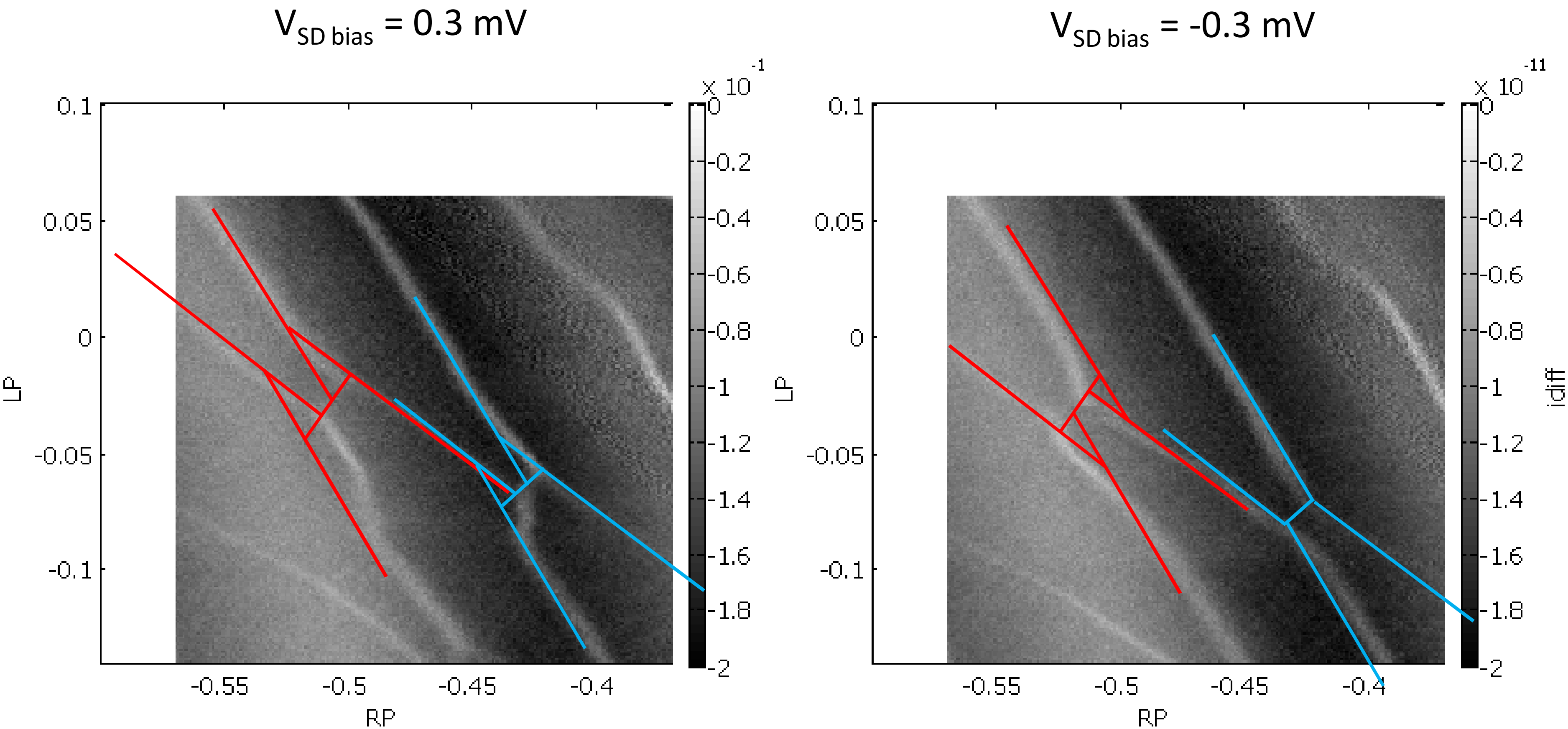
Bias triangle asymmetry



- Upper left: bias triangles form for both positive and negative source drain voltage
- Lower right: no bias triangle can be determined for negative bias

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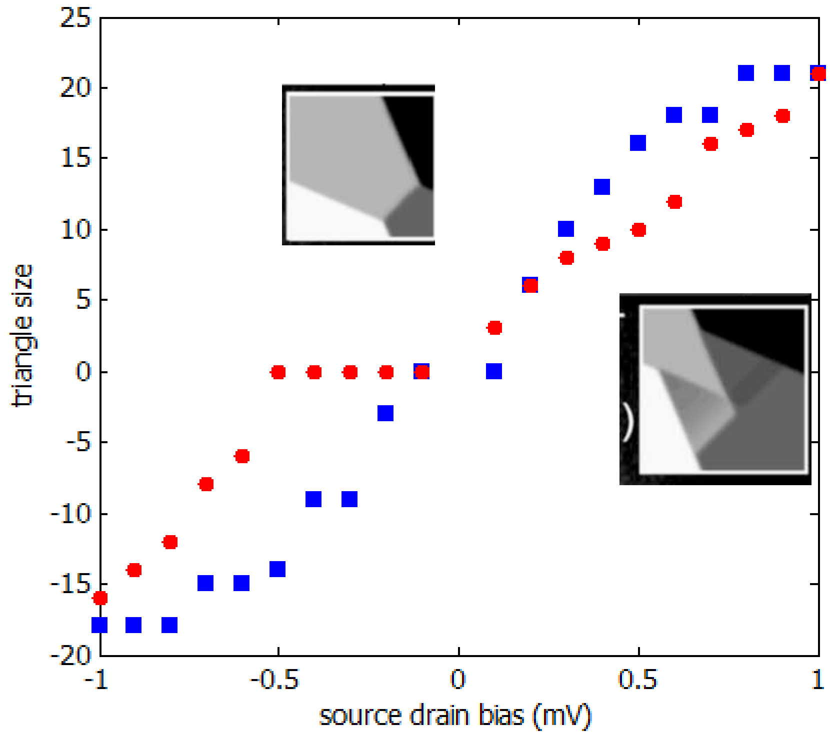
Bias triangle size for many SD bias

- Upper left triple point shows a smooth evolution of the bias triangle as the source drain voltage is varied.
- Lower right triple point has a dramatic asymettry with bias:
  - smooth variation for positive
  - no bias triangle until negative value exceeds (-400 uV)
- Results are qualitatively consistent with a *Johnson, PRB (2005)* model charge sensed spin blockade occurring in lower right triple point.



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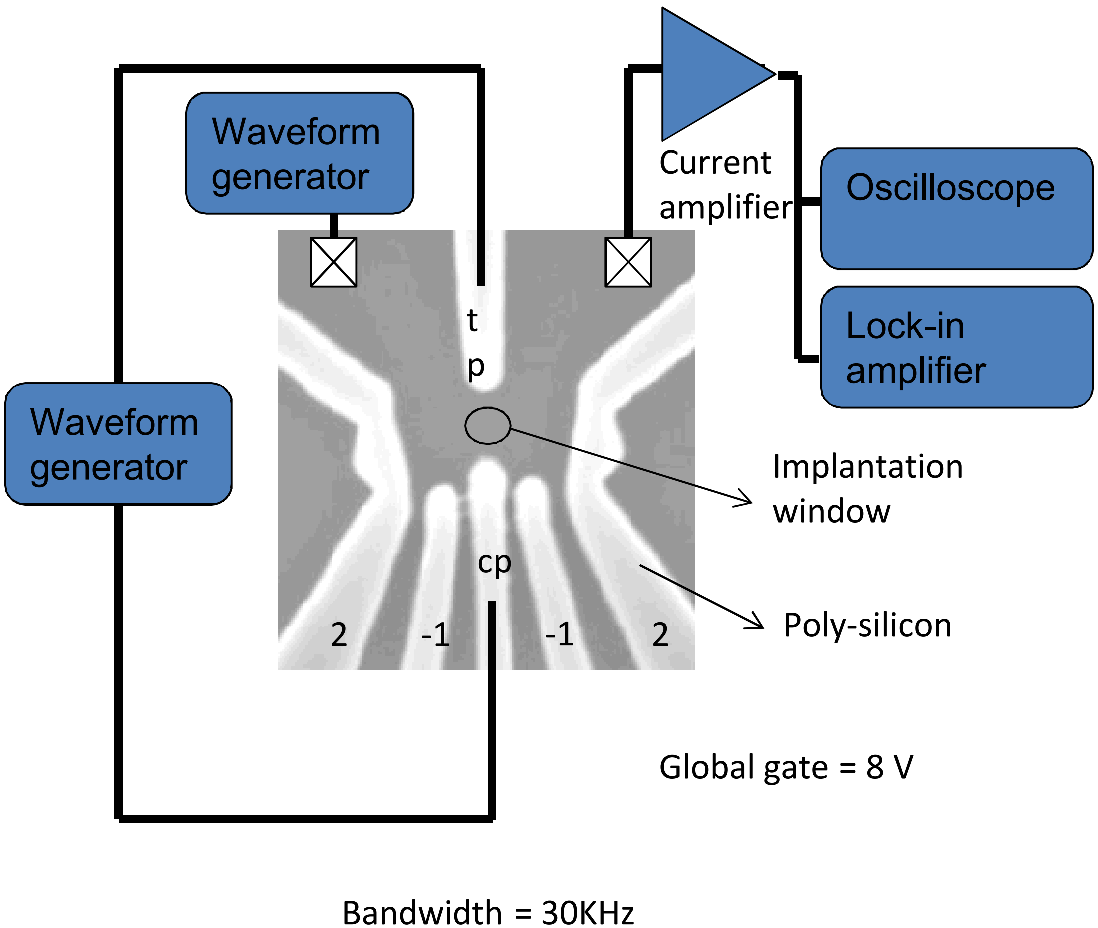
Simple Approach to Addressing Donor

Device fabrication

1. Wafer level processing of front-end.
2. Nano-patterned poly-silicon gates were defined by e-beam lithography and etching.
3. Implantation window was defined, followed by timed implantation of Sb at 120 KeV. Estimated number donors in the window ~ 5.
4. Second dielectric and global gate were deposited.

Device top view and electronics setup



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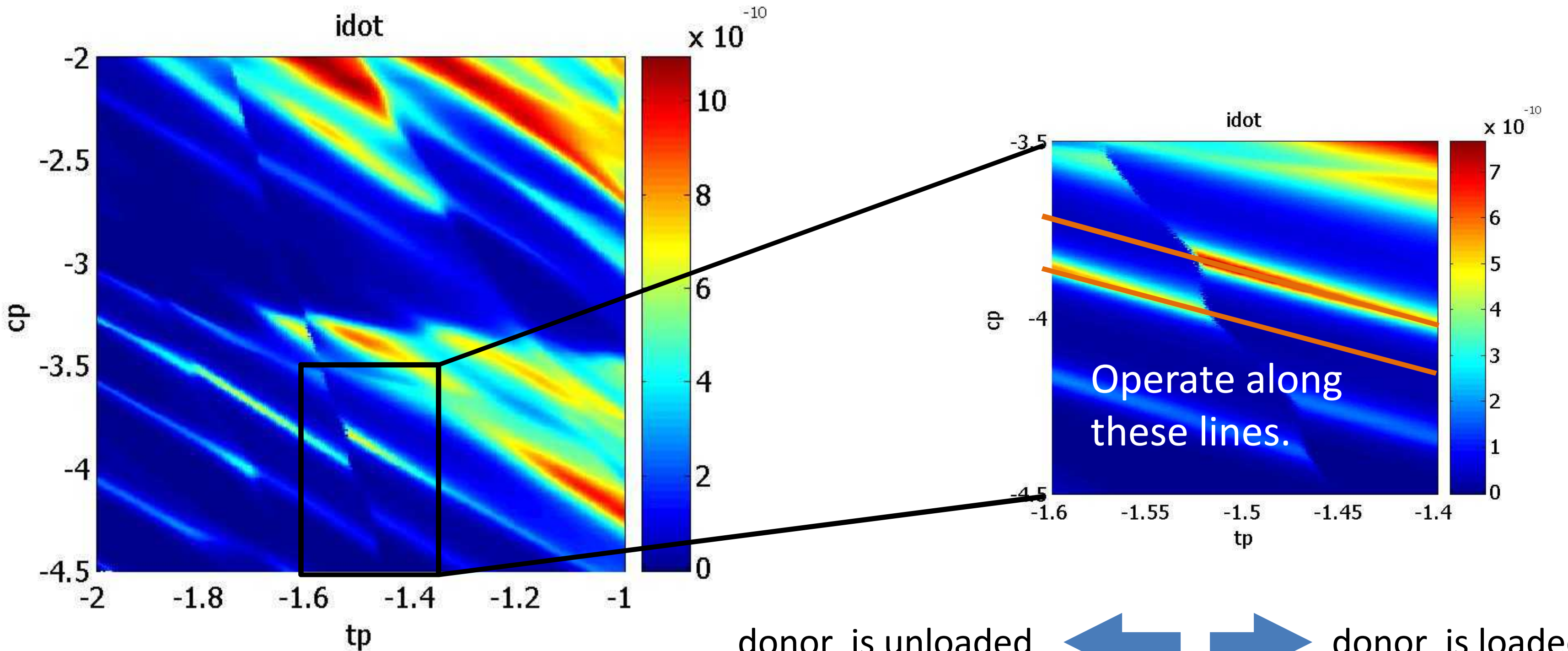
Quantum Dot Electrometer

Donor induced charge offset observed in transport through the quantum dot



donor is unloaded ⟵ ⟶ donor is loaded

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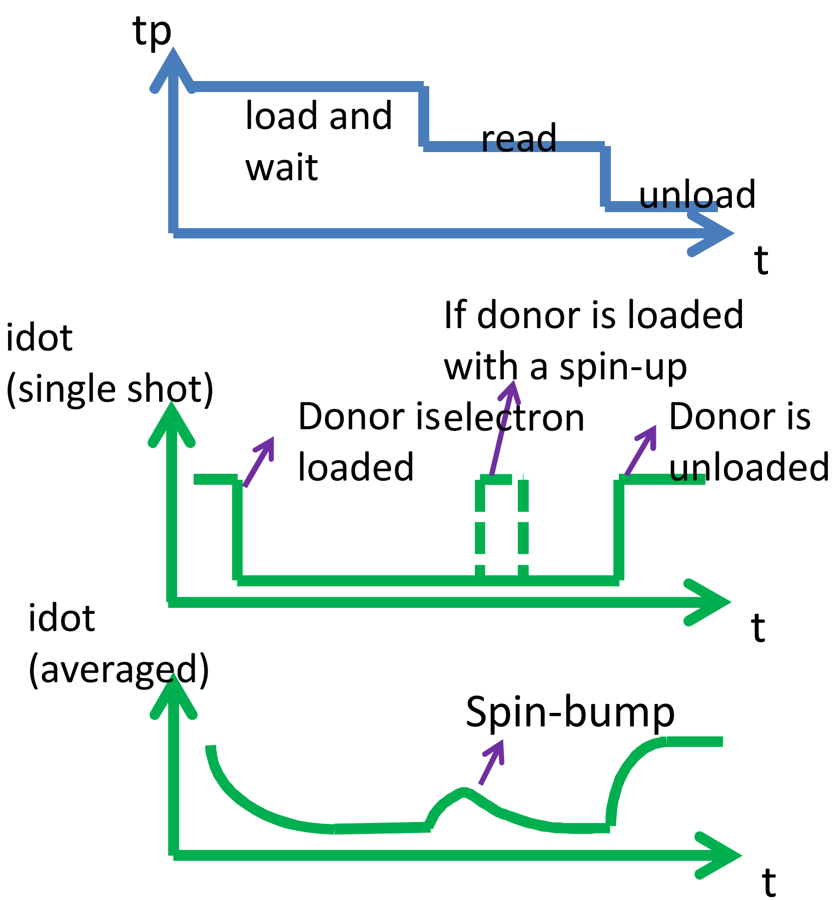
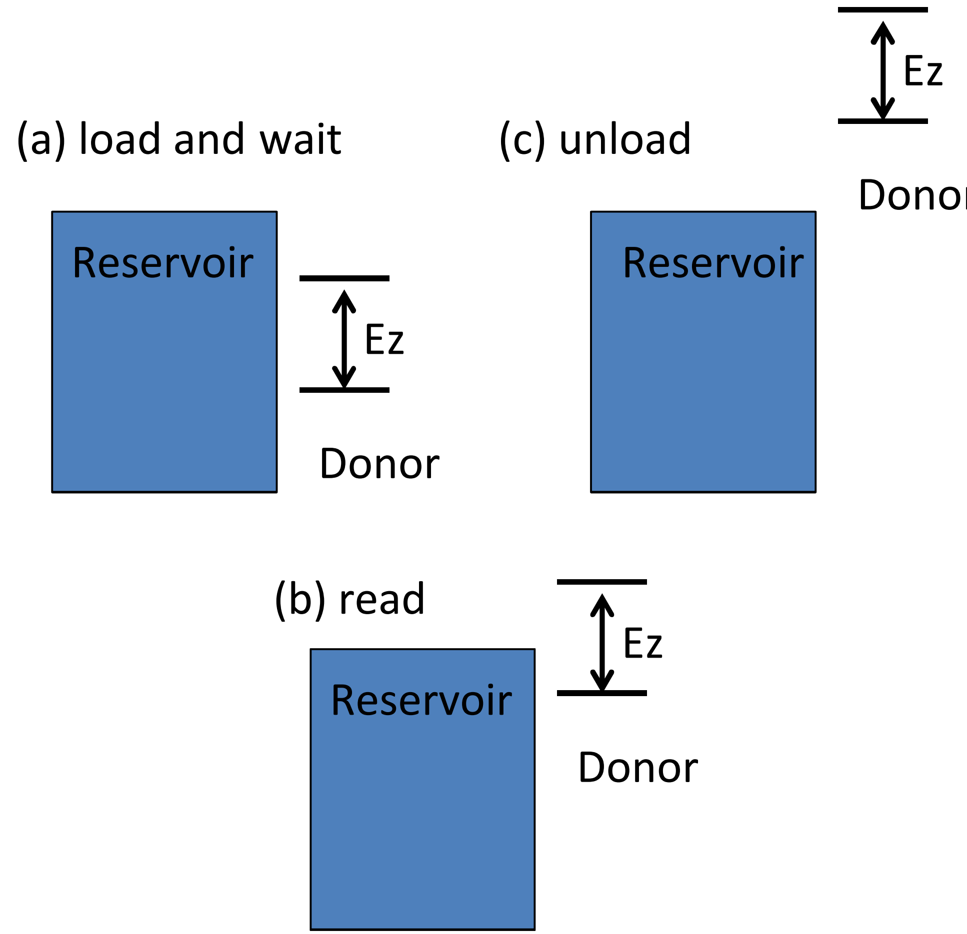
Pulse Sequence

Three-level probing sequence



Energy level alignment



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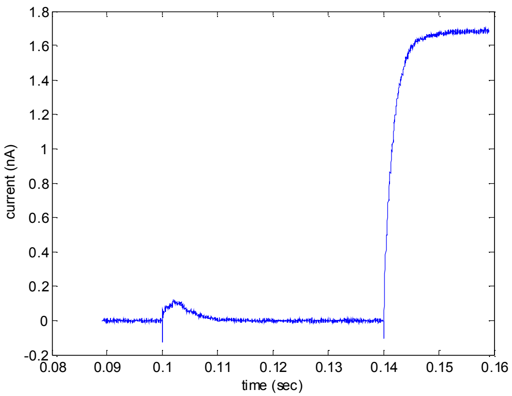
Spin Signals

Example of averaged current response

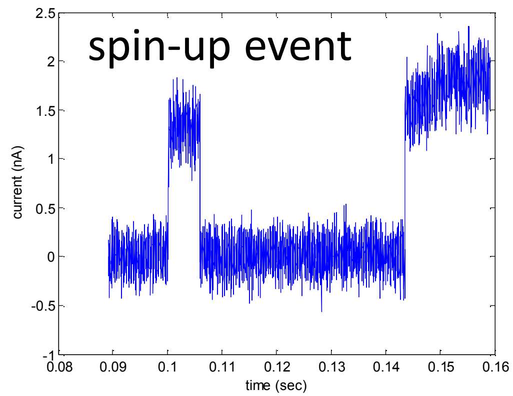
(read = 0.1-0.14 sec)

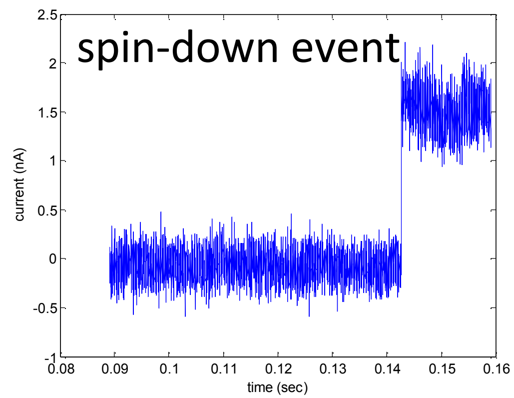


The bump between t = 0.10 sec and 0.11 sec is due to a spin-up electron hopping off the donor, followed by a spin-down electron hopping onto the donor.

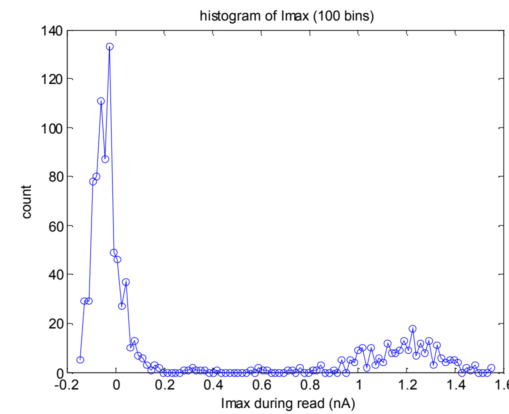
Examples of single-shot current response

(read = 0.1-0.14 sec)





The distribution of the maximum current during the read period show two well isolated peaks. The right one corresponds to spin-up events.



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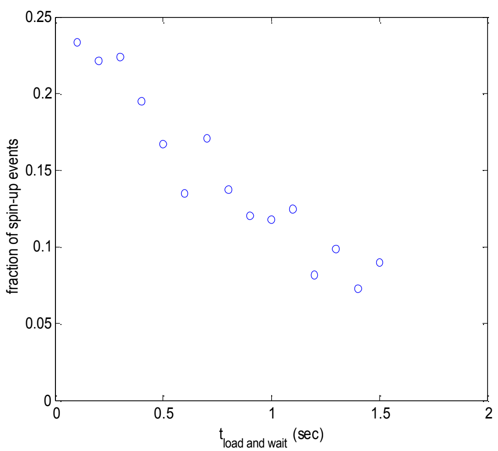
Relaxation Time

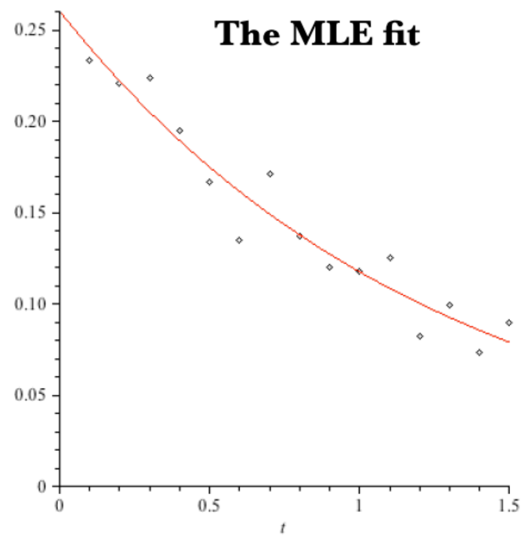
N single-shot traces are recorded at each load and wait time. The fraction of spin-up events decays exponentially with a time constant T_1.

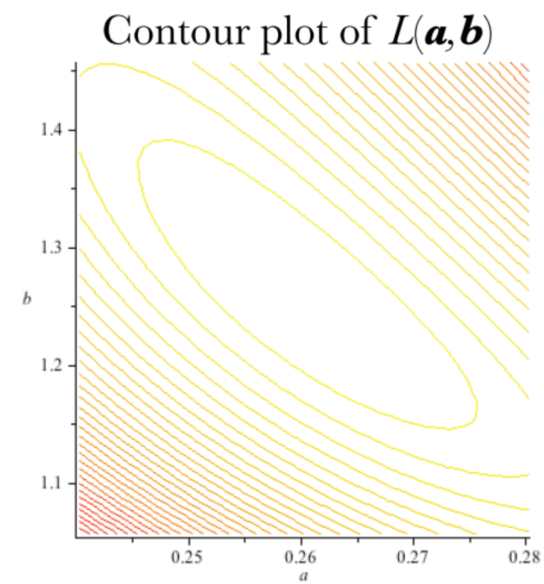
Model: $p(t) = a\, e^{-t/b}$

Likelihood function L(a,b) = Pr(Data | a,b)

Example: B = 3.25T, N = 1000







T1 = b = 1.27±0.15 sec (with 95% confidence)

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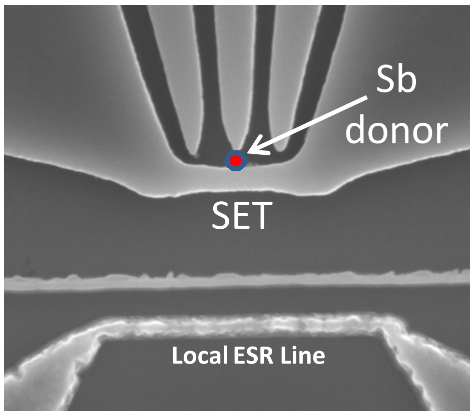
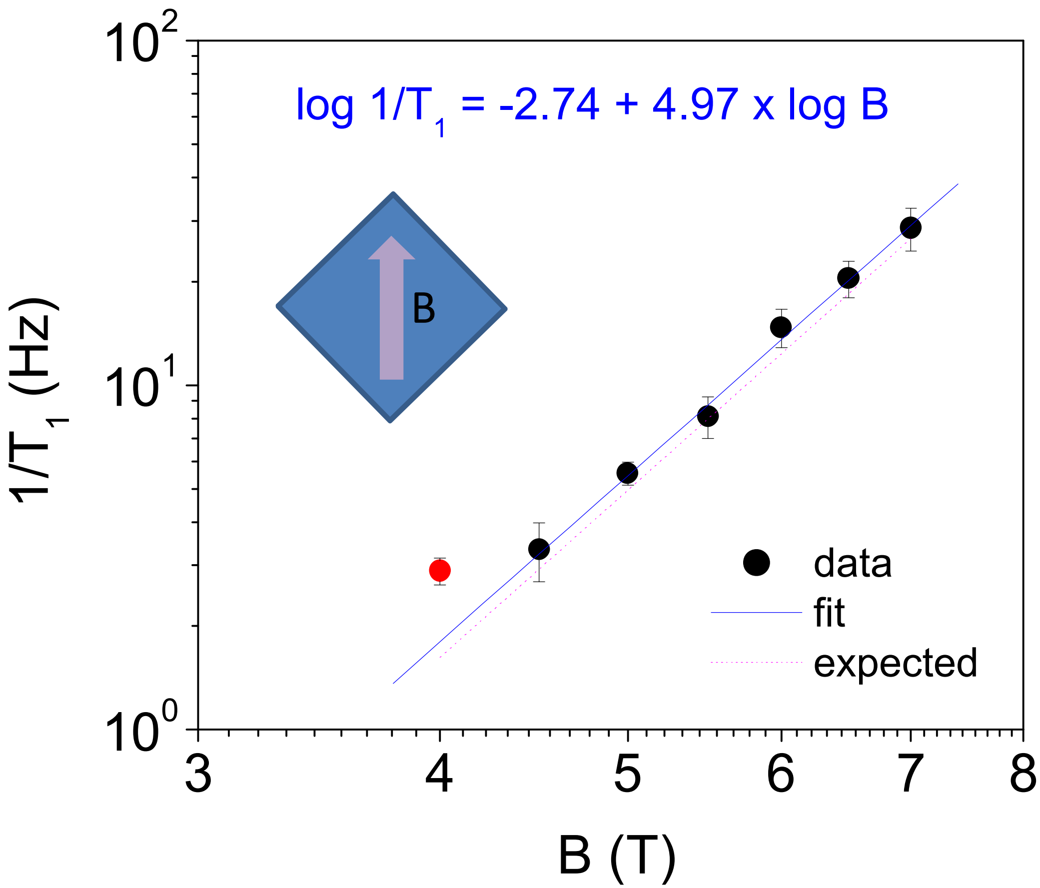
Magnetic field dependence of T1

Sb donors implanted near silicon SET



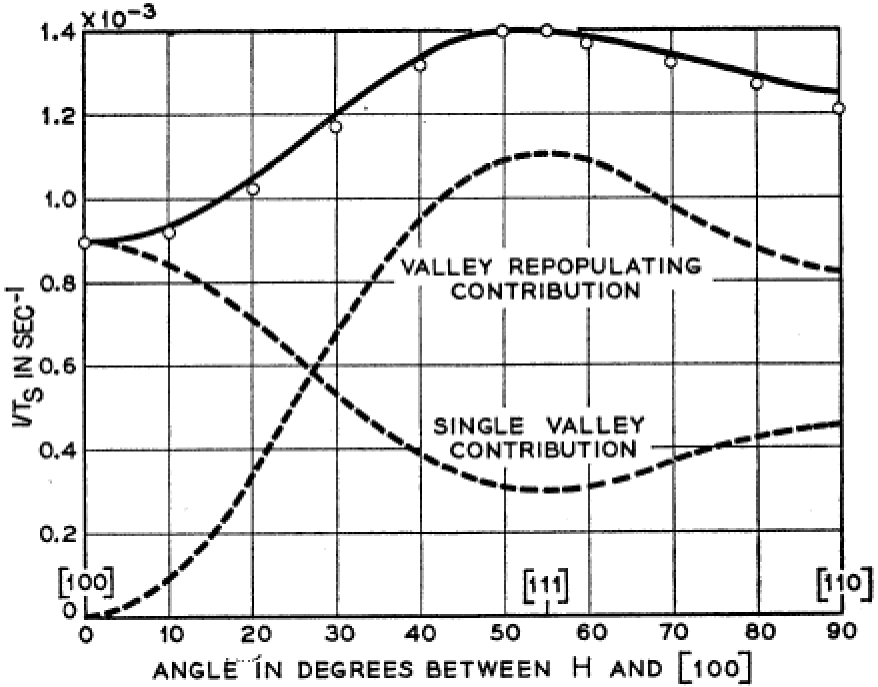
- B5 dependence expected for electron on donor
- Long T1 times beneficial for silicon qubit.

T1 decreases with increasing field



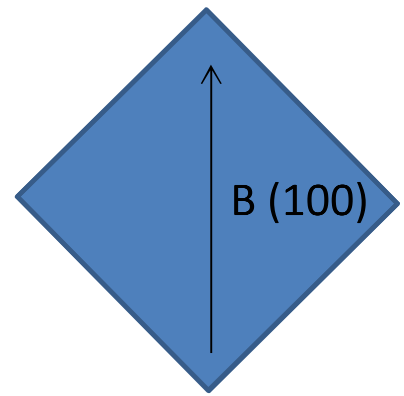
Lisa Tracy

Spin relaxation in silicon



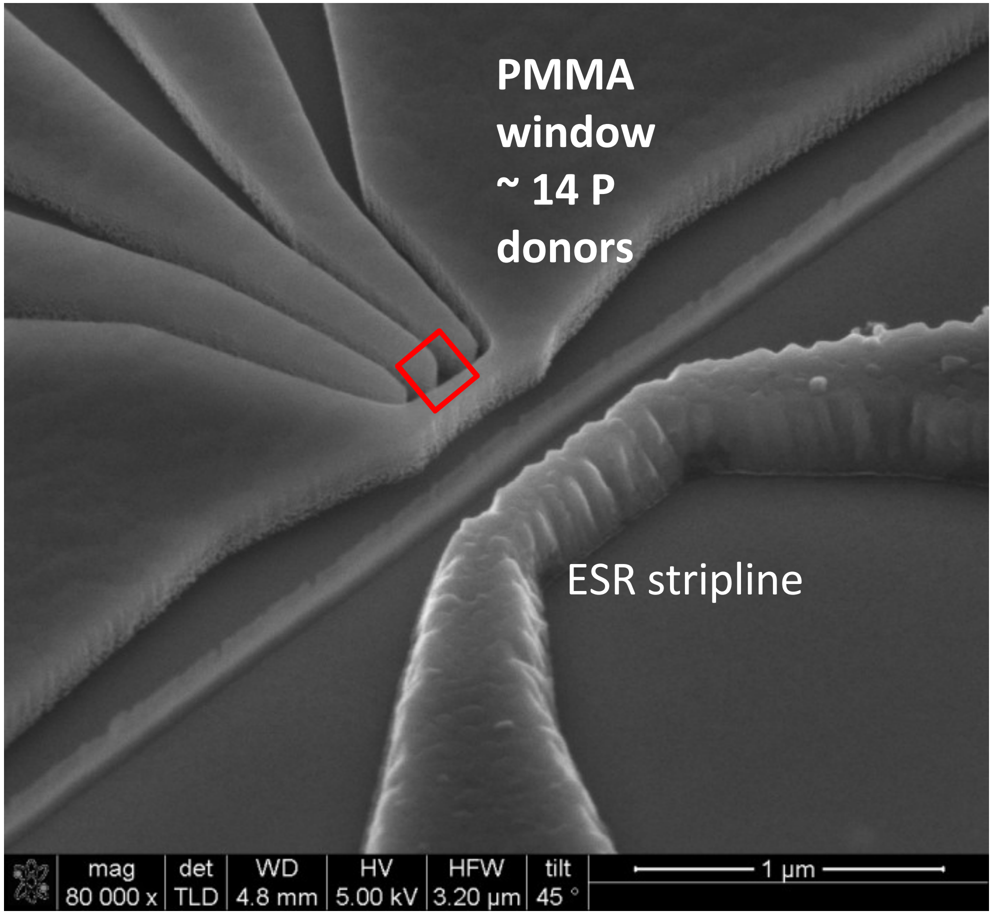
Phys. Rev. 124, 1068 – 1083 (**1961**).

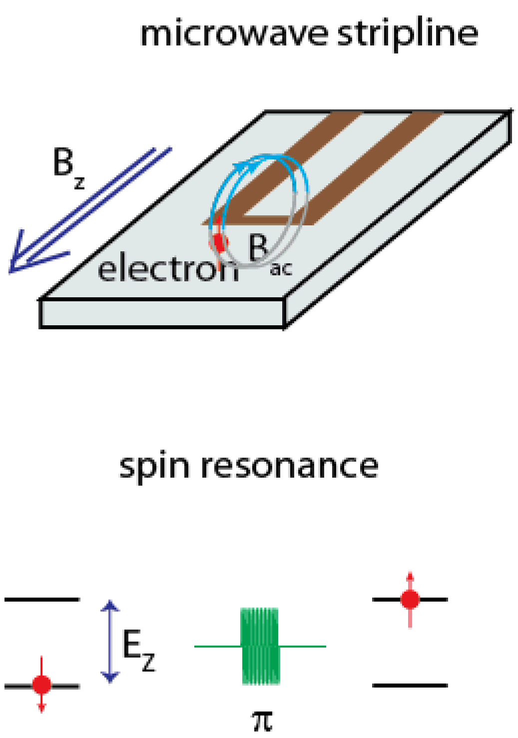
Sample orientation in dry fridge



For B in (100) direction, expect single valley contribution only to T_1 relaxation.
Due to change in g-factor from mixing between bands with strain.

Next Steps: Local Electron Spin Resonance

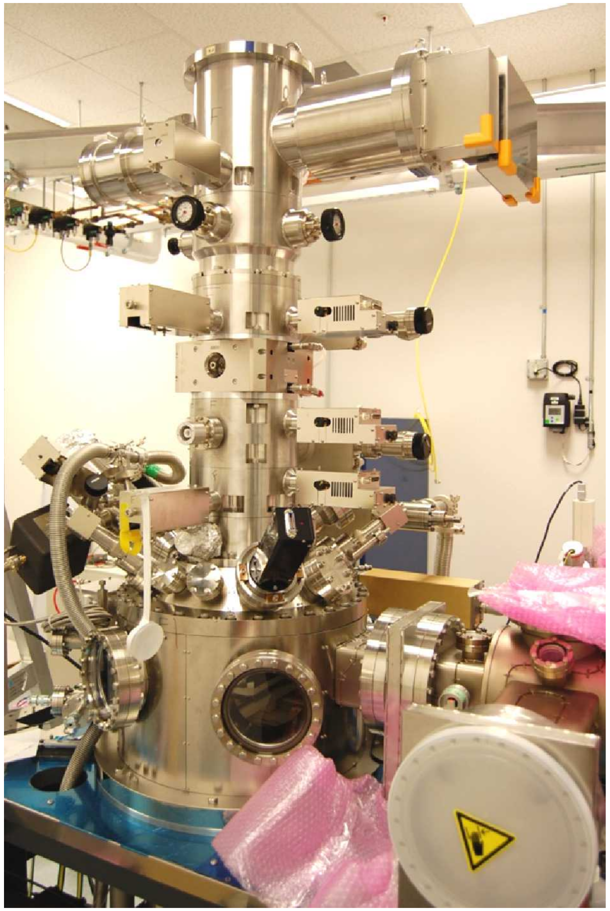




Lisa Tracy, Dwight Luhman, Khoi Nguyen

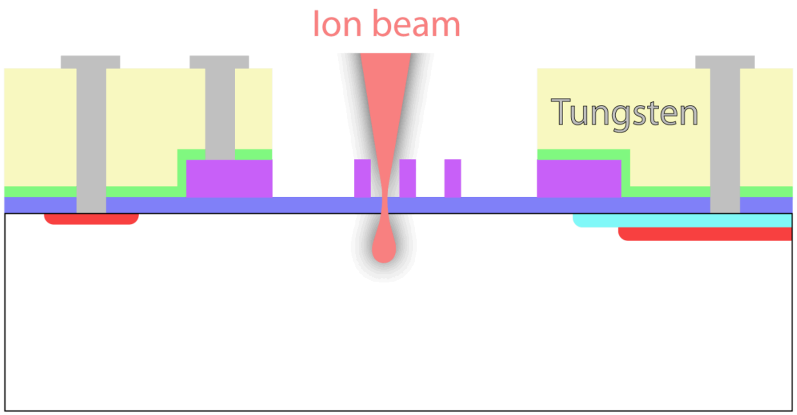
Deterministic implants using ion detection

nanoImplanter



- AuSiSb source
- ExB filter to select ion species and ionization
- Super-FIB for focus and steering donor ions
- Built in detectors surround silicon nanostructure regime

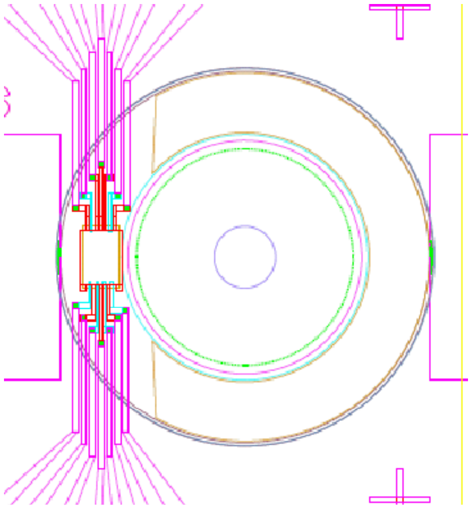
Detector schematic



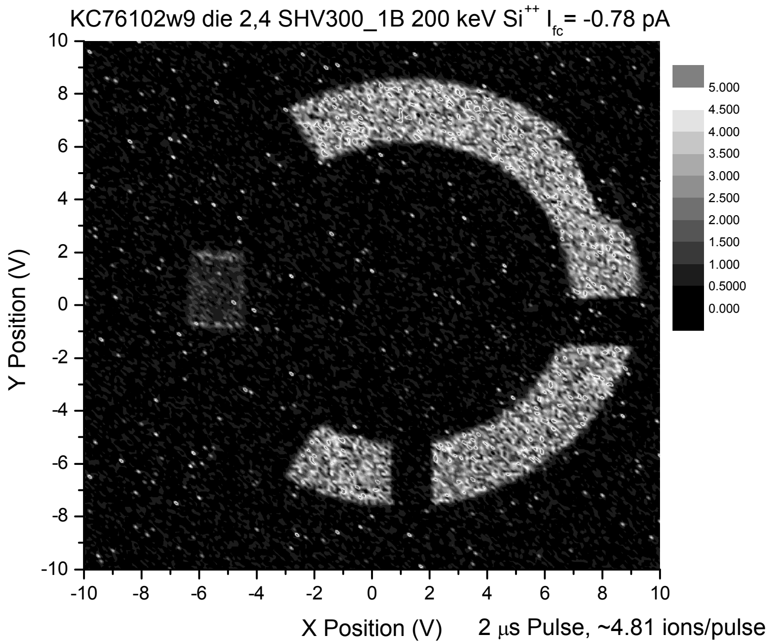
Ed Bielejec, Eli Garratt

Ion detector operation

CAD for detector and nanostructure construction zone



200 keV silicon

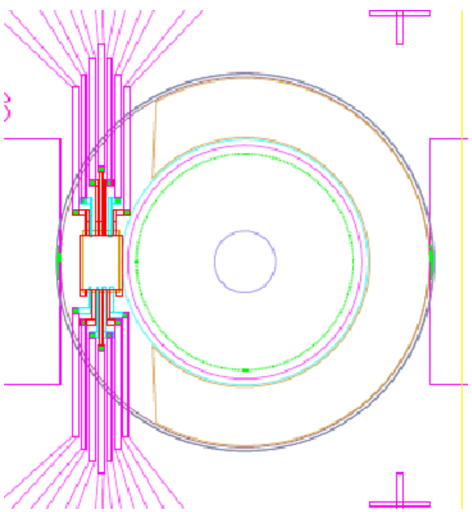


Ed Bielejec, Eli Garratt

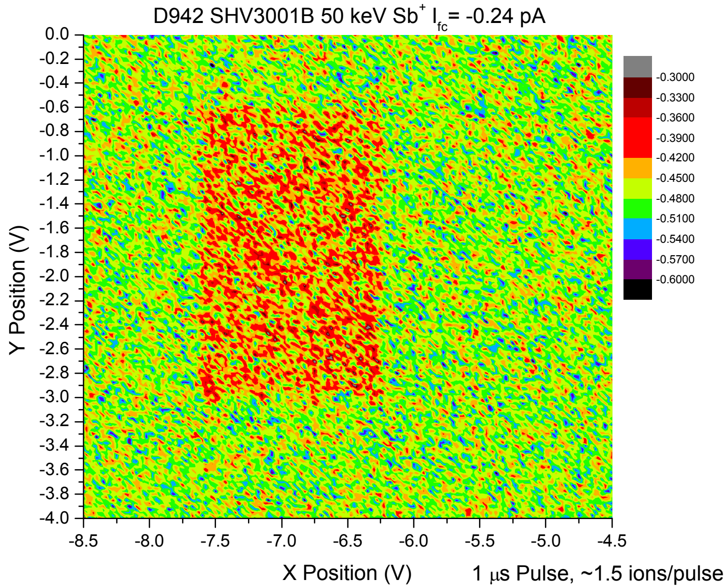
Ion detector operation

Detected single donor implantation of Sb ions allows multi-donor devices

CAD for detector and nanostructure construction zone



50 keV Sb, 1.5 ions/pulse

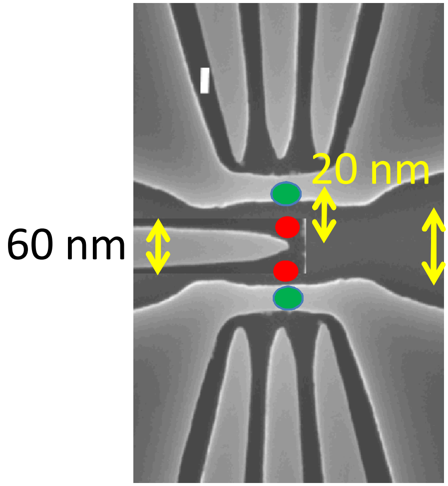


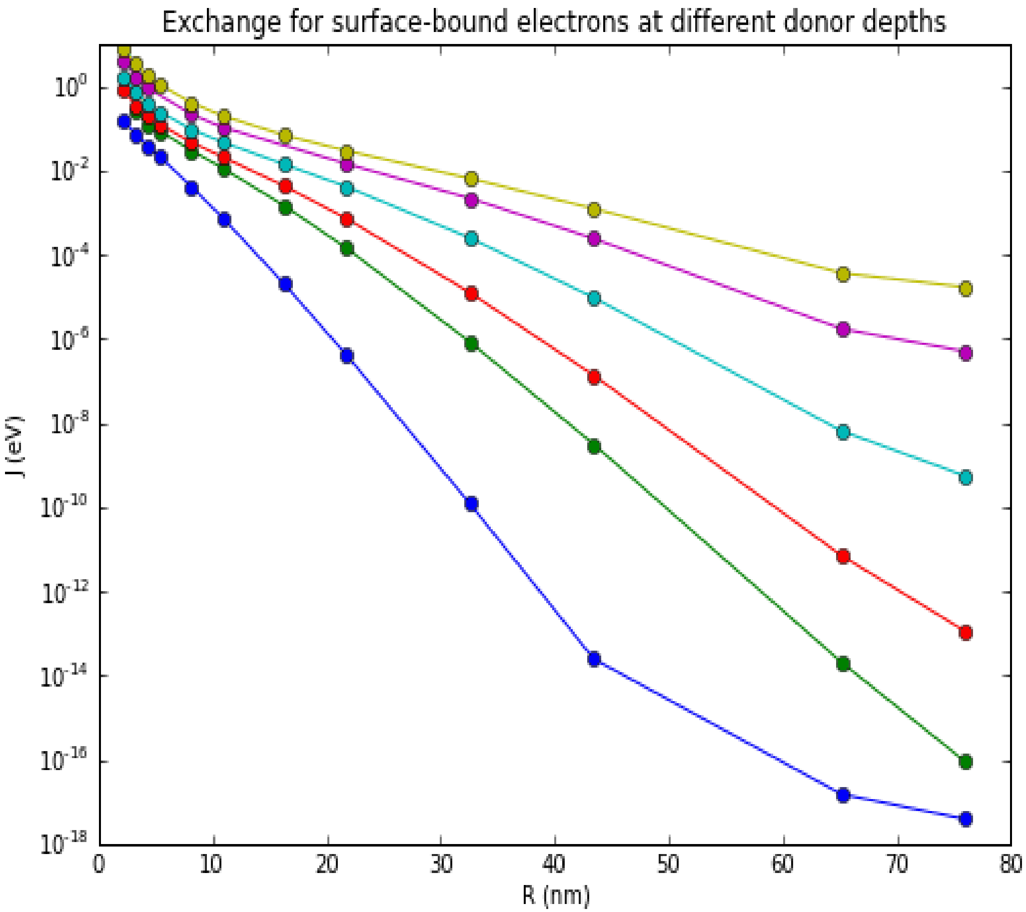
Ed Bielejec, Eli Garratt

Two qubit structures

Exchange interaction due to electron wavefunction overlap is one technique for demonstrating a two-qubit device.

Photoshop lay-out





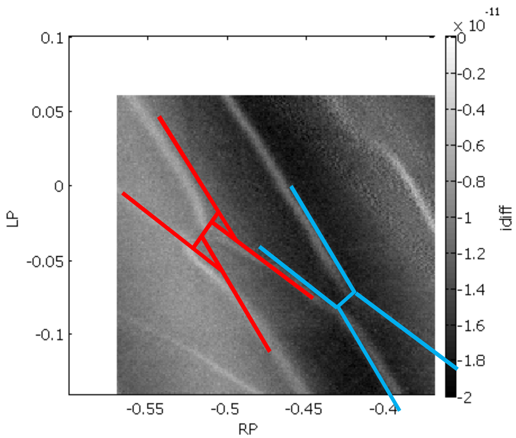
Rick Muller

Sandia National Laboratories

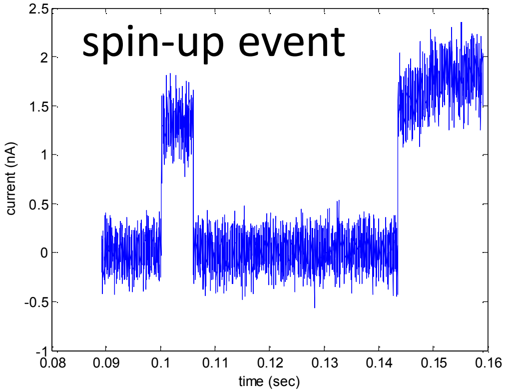
Summary

- Silicon nanoelectronics devices can be used control and measure the quantum properties of single electrons.
- Integrated charge sensors allow an all electrical readout of spin states in both double quantum dots and electrons on a single donor.
- Future work on ESR will enable direct control of the electron spin state.

Pauli Blockade



Single-shot spin readout



Center for Integrated Nanotechologies

CINT is a US Department of Energy user facility open to the international research community. Our measurement lab is based in CINT, and we welcome user proposals from this community. More information is at http://cint.sandia.gov

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Sandia Co-workers

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Princeton University (S. Lyon)

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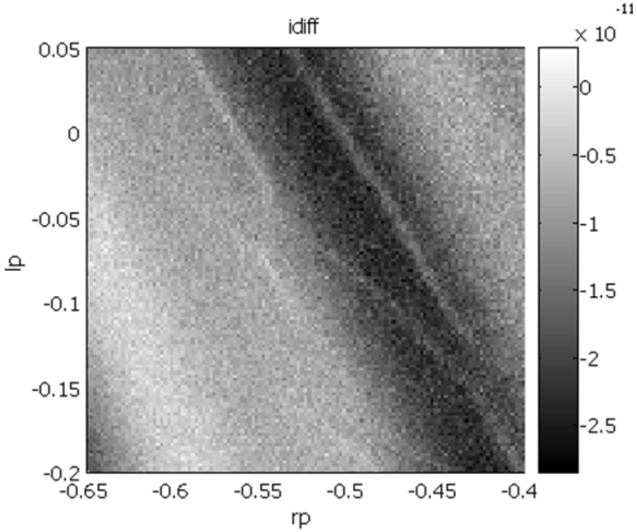
Lawrence Berkeley National Labs (T. Schenkel)

National Research Council (A. Sachrajda)

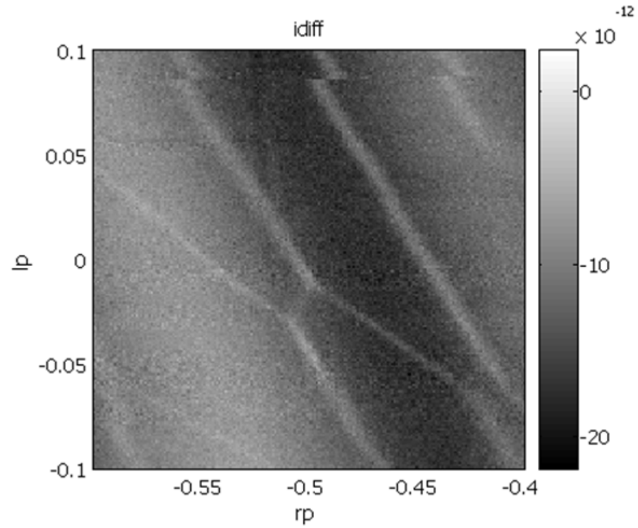
U. Sherbrooke (M. Pioro-Ladriere)

Adaptive charge sensing

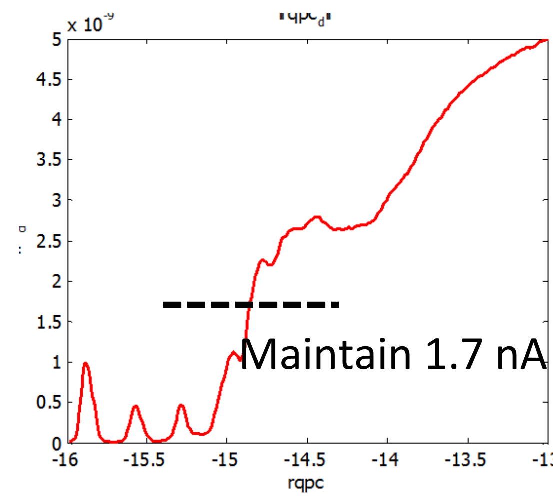
No adapting



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