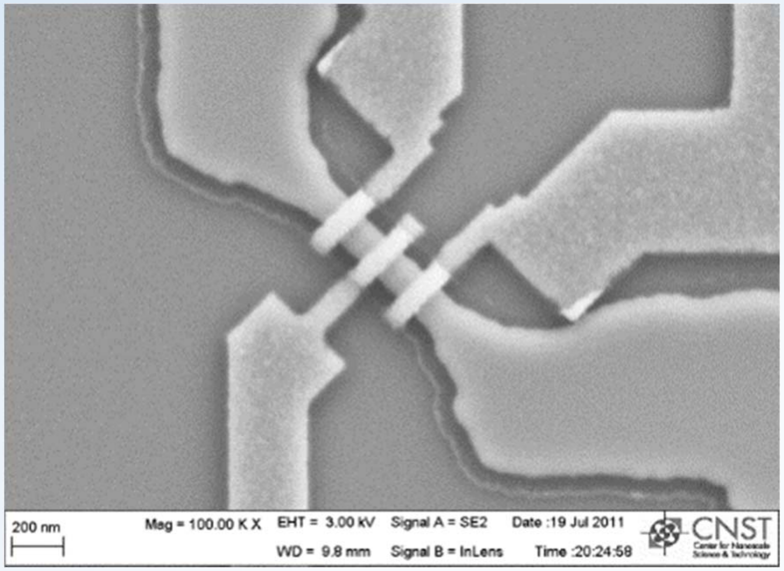
Transport through single electron transistors

Insight into carrier states



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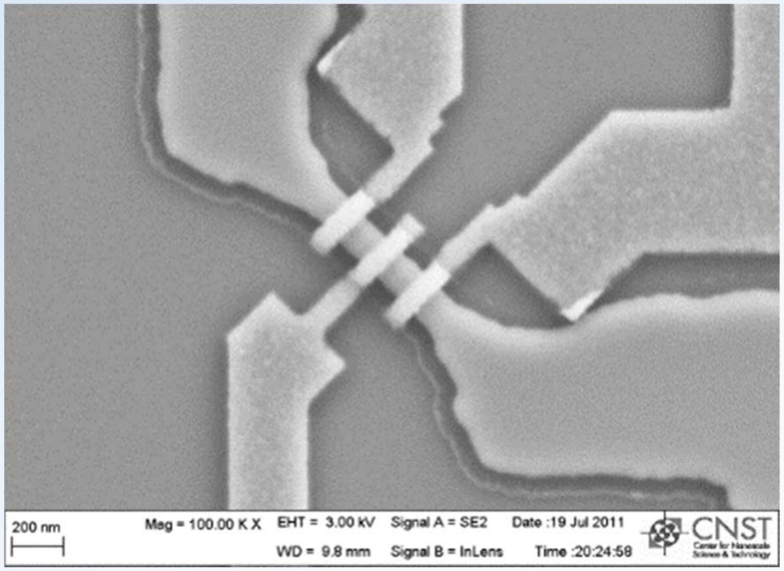
Outline

1. Introduction:
   i. Why is this interesting?
2. Device operation
   i. Single electron effects/transistors
   ii. Single island measurements
   iii. Double island measurements
   iv. Quantum mechanical effects
3. Devices:
   i. Our devices
4. Recent measurements
   i. Triangle asymmetries
   ii. Pauli-spin blockade
   iii. Possible model
5. Future work



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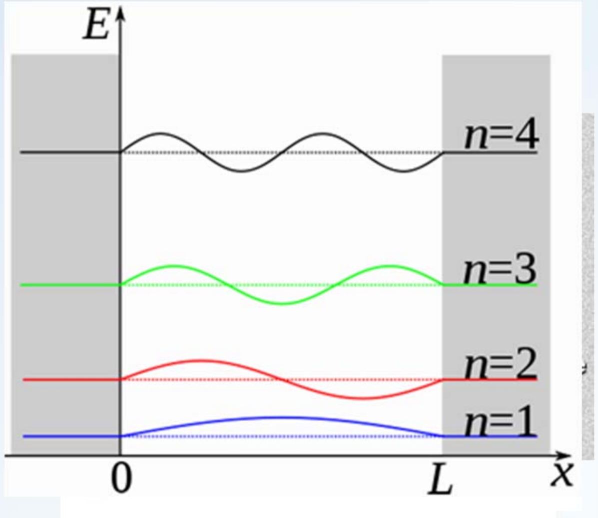
Why is this interesting?

Textbooks frequently describe individual electrons and their properties

- Sub-atomic particle
- Fundamental charge of -1.6 x 10^{-19} C
- Wavelike properties
- Particle in a box



Very abstract ideas with references to complicated experiments

- Millikan oil drop experiment
- Double slit experiment

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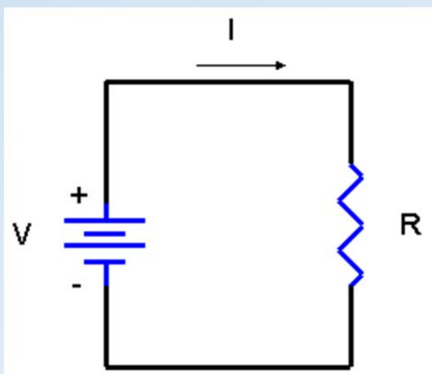
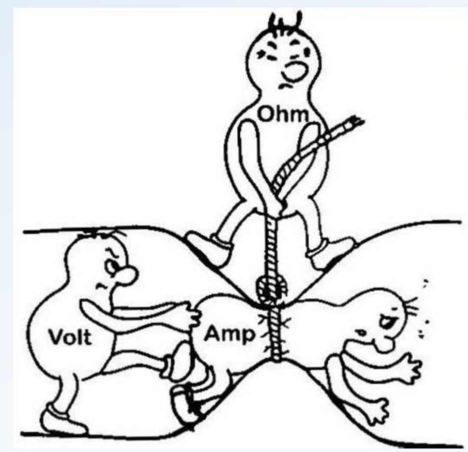
Why is this interesting?

Electric circuits taught without paying much attention to the electron

- Quantities: Current, Voltage etc.
- Principles: Kirchoff's laws, Ohm's law etc.

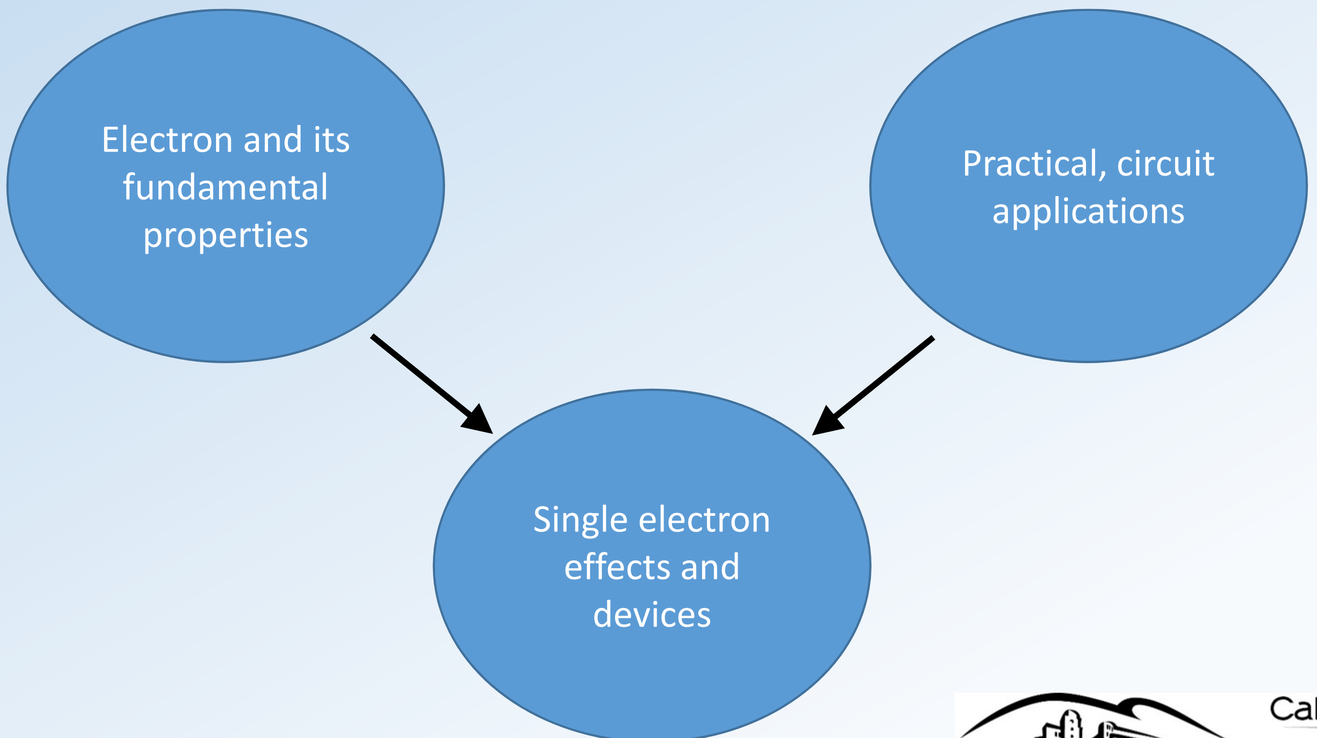


Ohm's Law V = I R
R = 1 kΩ
V = 1 V
→ 1 mA



Why is this interesting?

Single electron devices merge these two ideas



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Single electron effects

Q: If we know electric charge is quantized, why don't we see any evidence of it in all our everyday applications of electric charge?

1) Usual measurements of these quantities involve extremely large numbers of electrons so effects of individual electrons are not observable.

    Example: 1 A ≈ 6.2 x 10^{18} electrons/second

2) Charge flow in conductors is continuous, electrons are not localized.

    Example: Capacitor can charge with an arbitrarily small amount of charge

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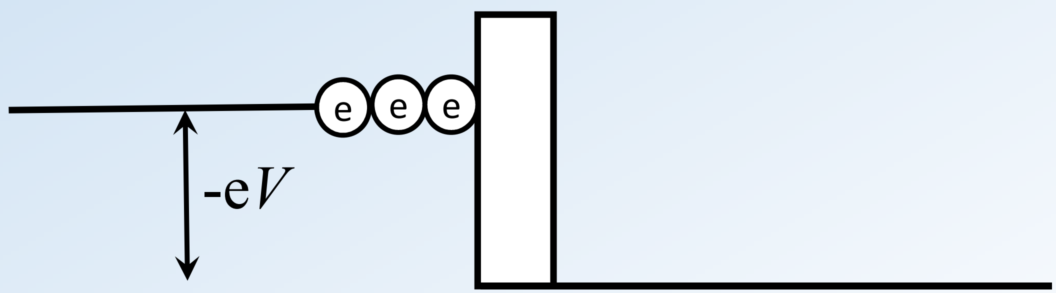
Single electron effects

Tunneling provides a way to isolate individual electrons

Tunnel Junction: Thin oxide/insulator between two conductors

- Classically → no charge allowed to pass
- Quantum mechanics → finite probability electron will tunnel



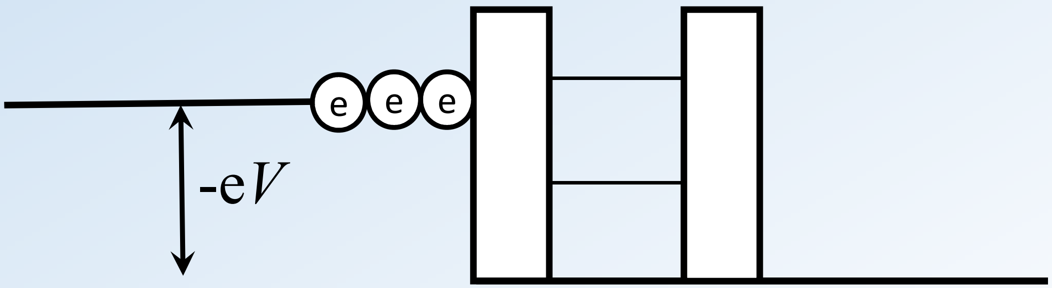
A tunnel barrier splits the sea of electrons into two.
Electrons are on a definite side

Single electron effects

Coulomb repulsion

An electron will tunnel if it is going to a lower energy

- Dropping a voltage V lowers energy by eV
- Coulomb repulsion between electrons increases energy



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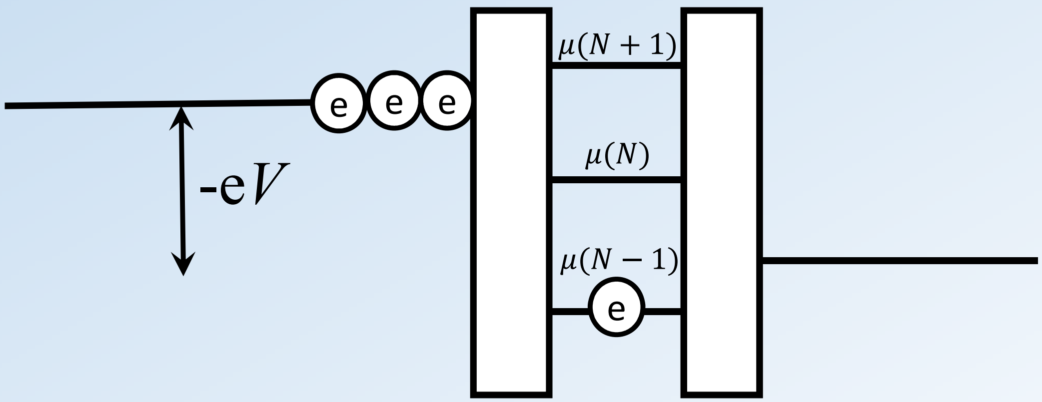
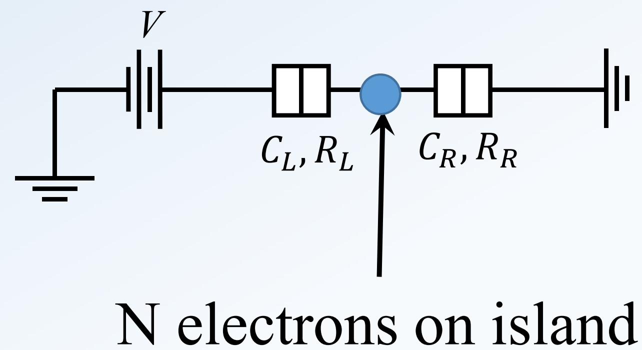
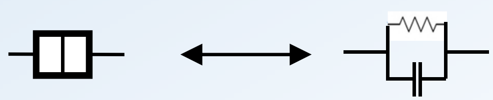
Single electron effects

- Quantitatively, we look at the energy required to add an electron to the small island, the chemical potential $\mu(N) = E_N - E_{N-1}$
- E_N can be determined by modelling the tunnel junctions as leaky capacitors and creating a circuit model



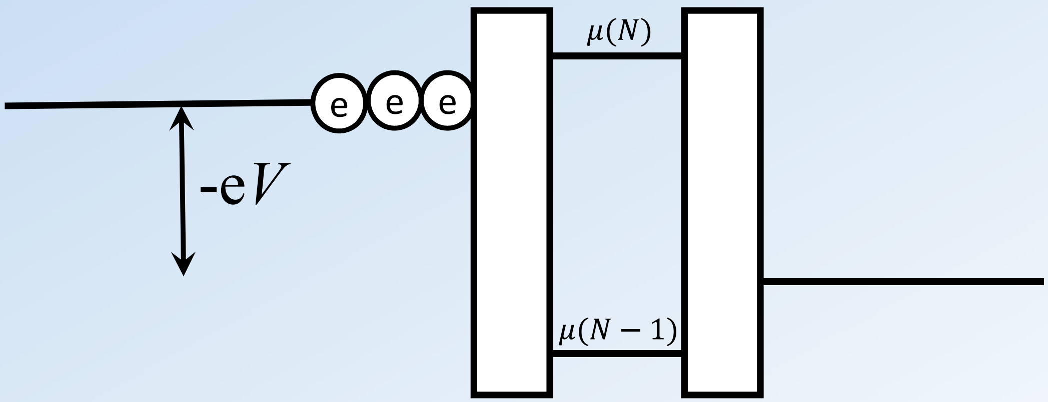


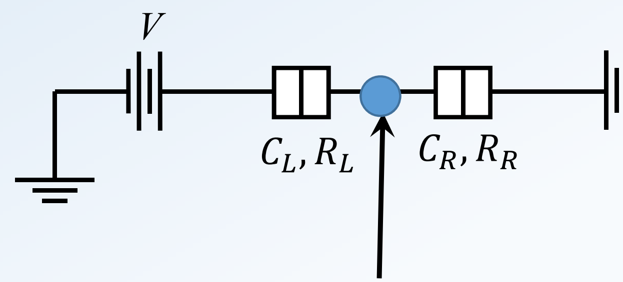


Single electron effects

Coulomb blockade

- If $\mu(N) - \mu(N-1) > eV$ (very small islands)

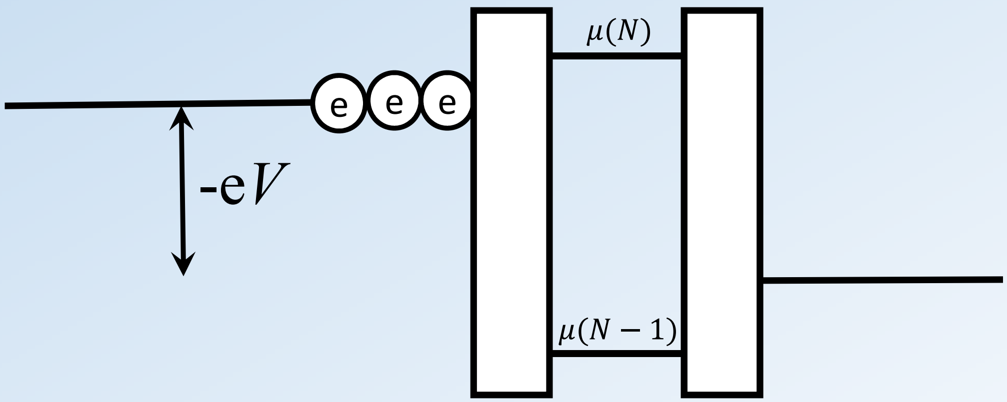


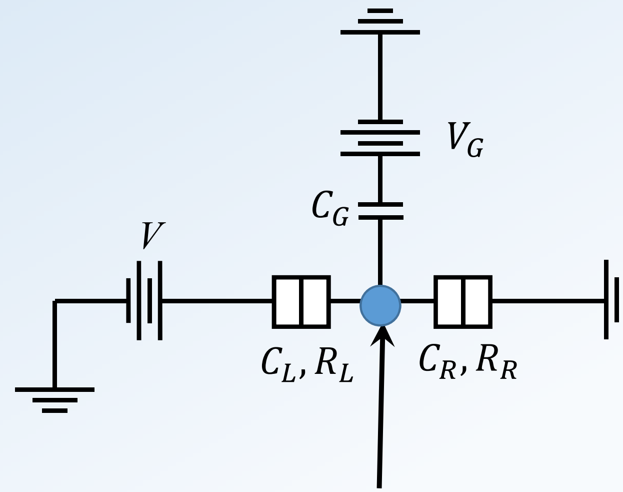


N electrons on island

Single electron transistors

- We need control, so we add a gate
- Gate changes electrostatic potential on island which changes μ_N

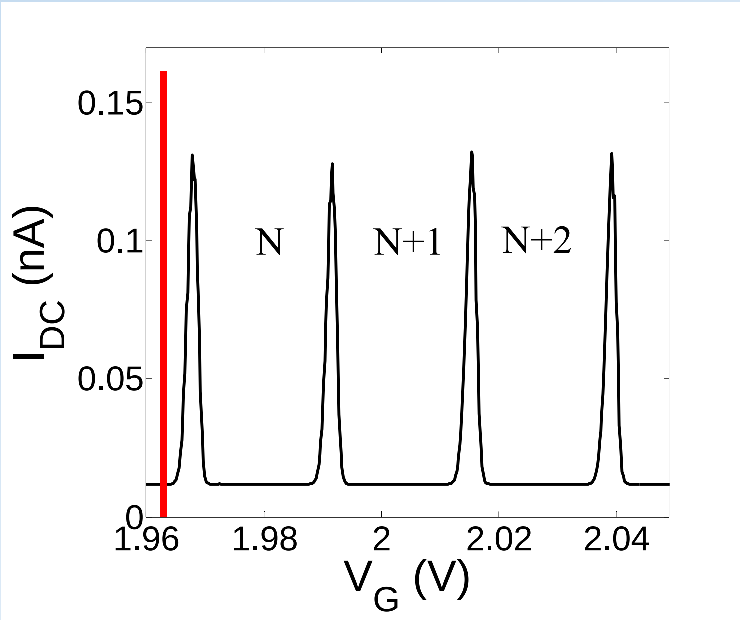


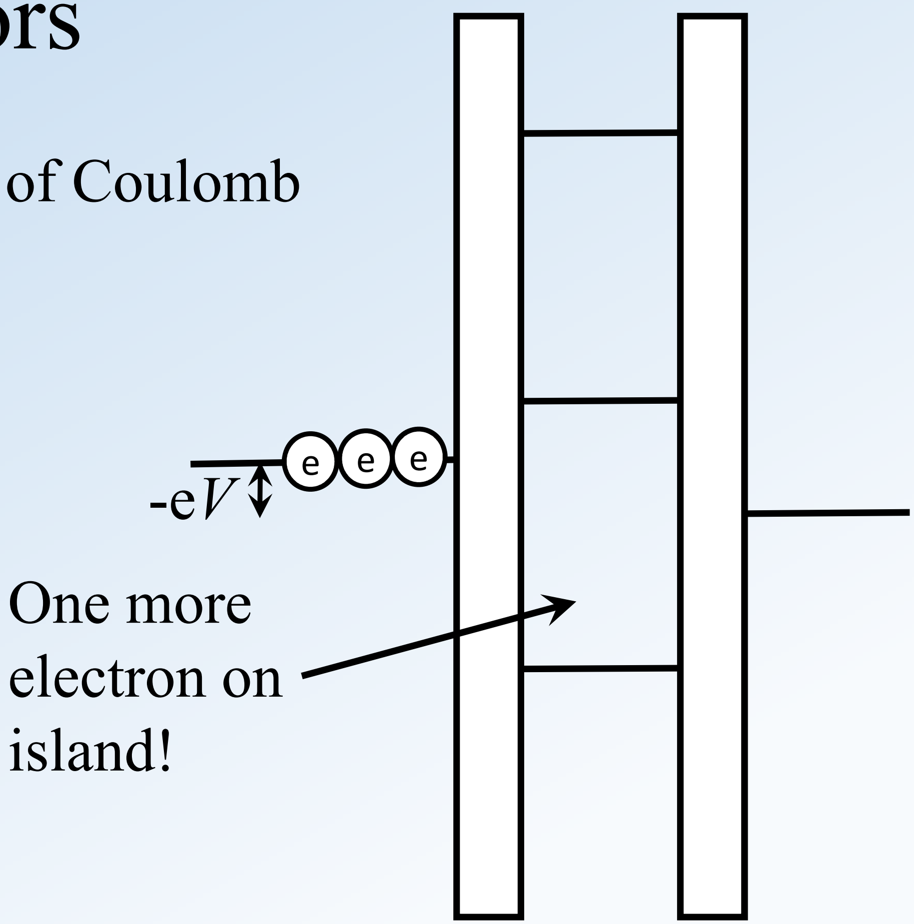


N electrons on island

Single electron transistors

Sweeping V_g we can move in and out of Coulomb Blockade





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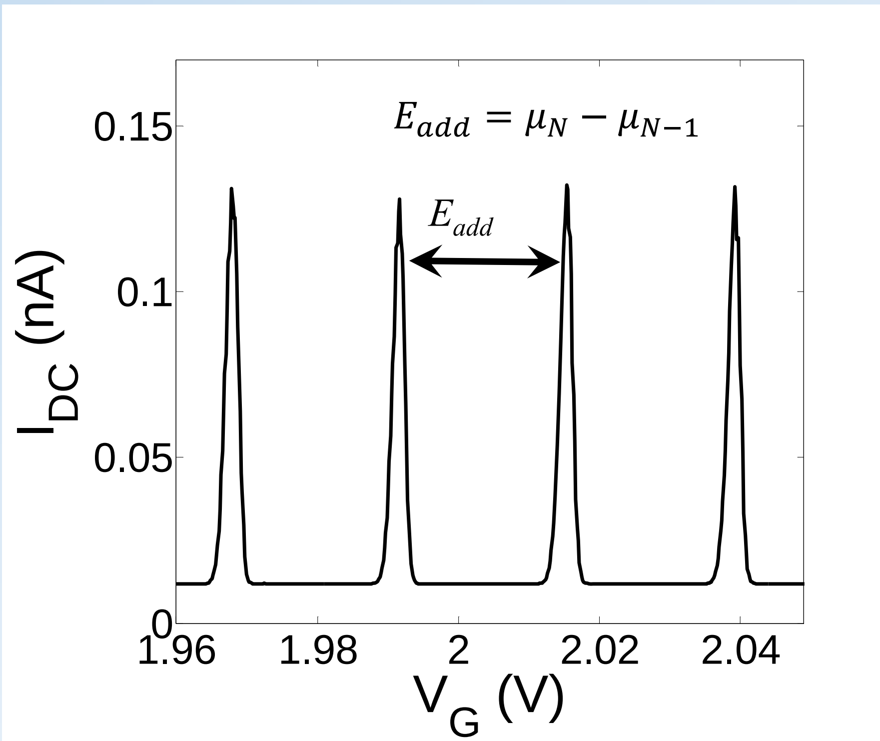
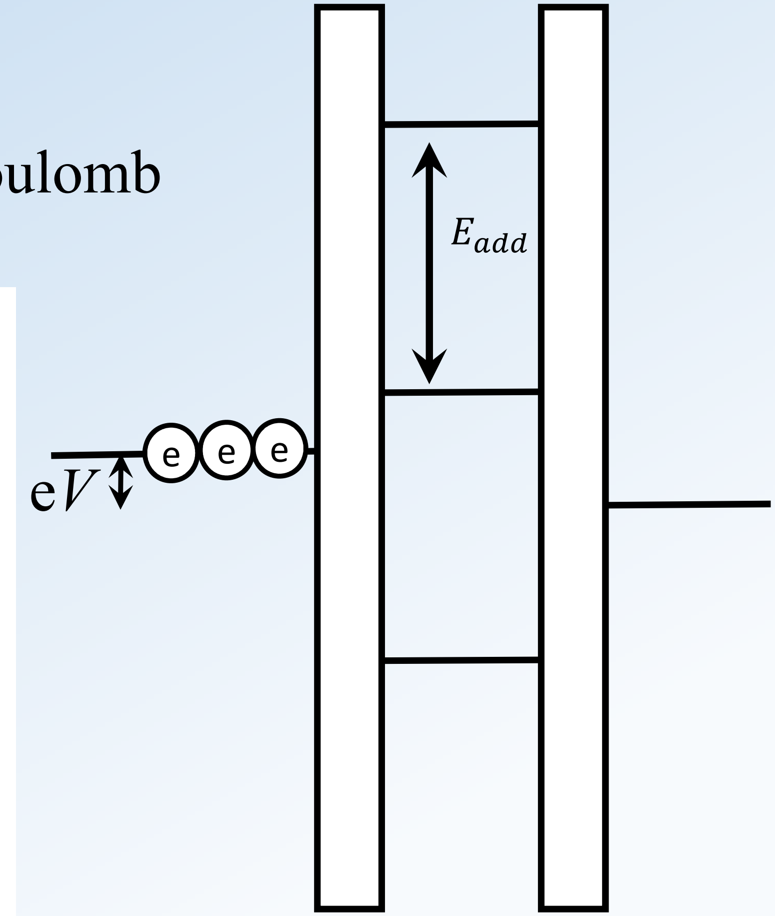
Single electron transistors

Sweeping V_g we can move in and out of Coulomb Blockade





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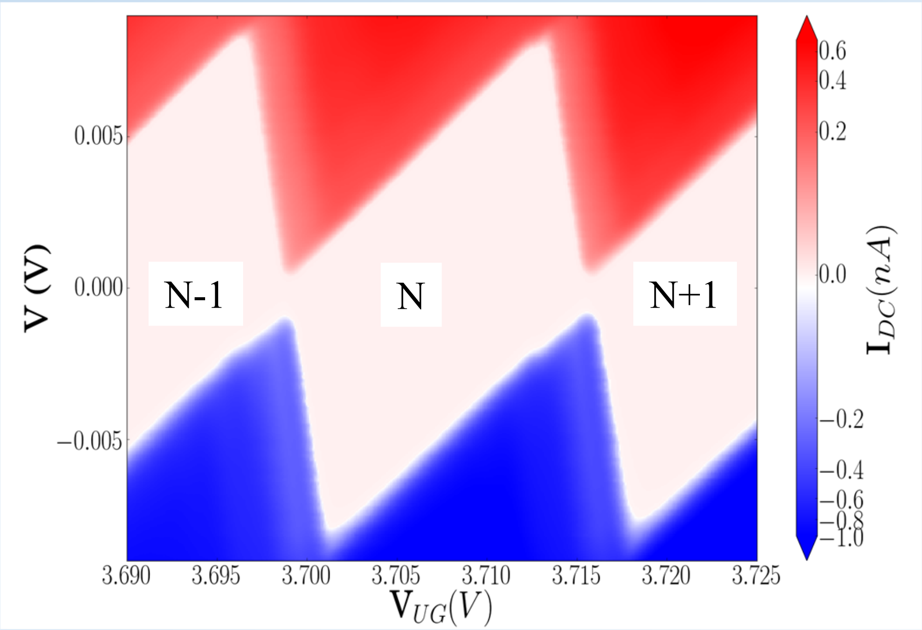
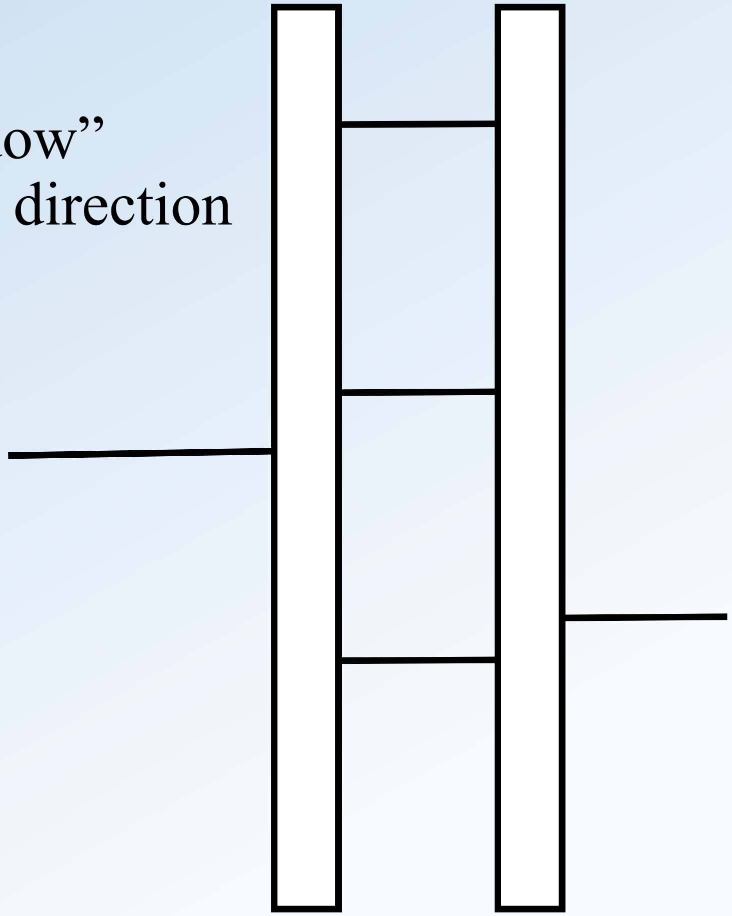
Single electron transistors

Sweeping V_{bias} we can change the "bias window" where current is allowed to flow, and change direction of current.

→ Coulomb diamonds





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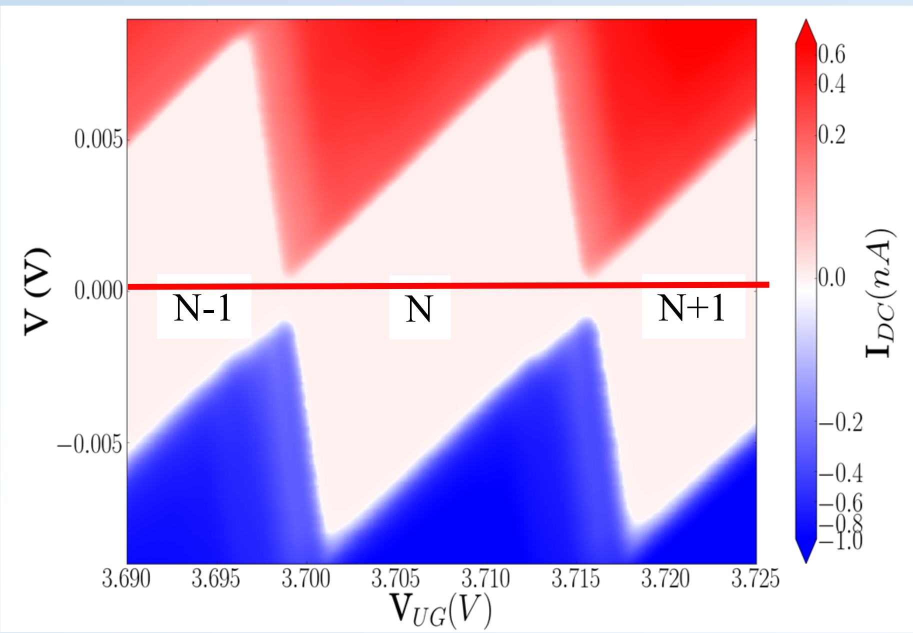

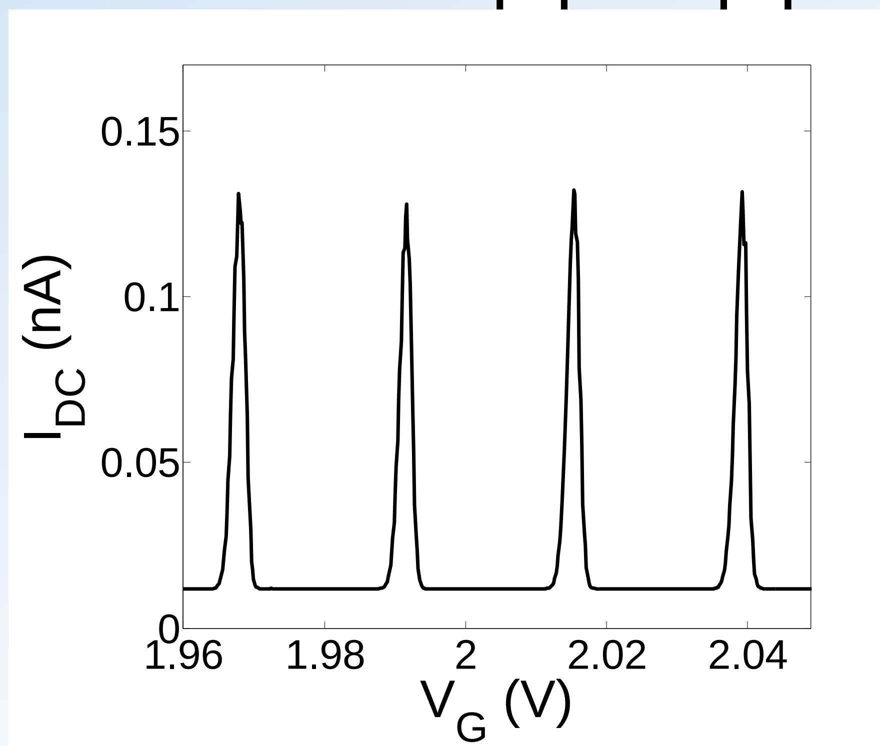

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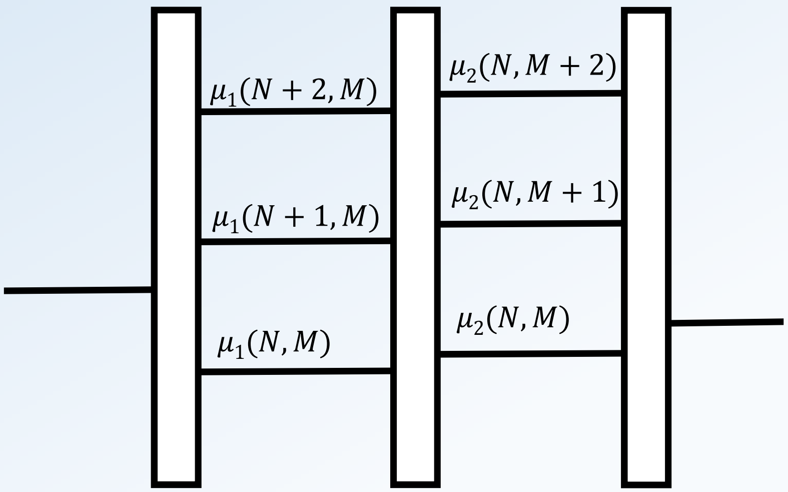
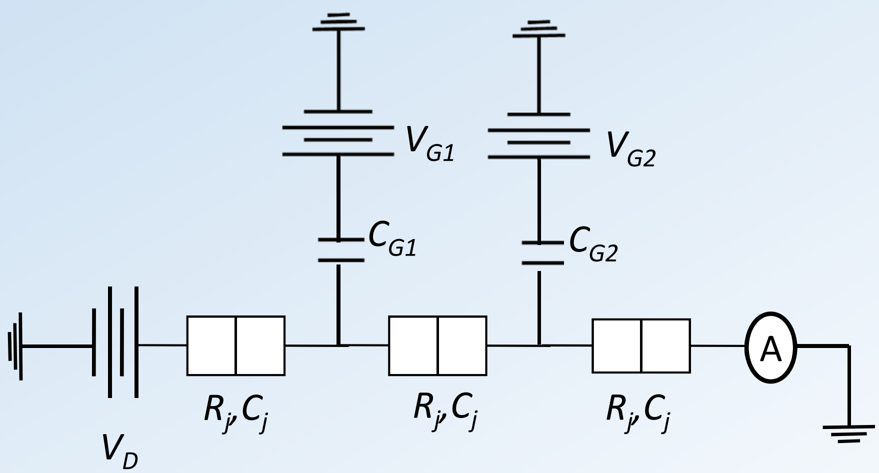
Double quantum dots

- We can add another tunnel junction and make two islands
- Current is blocked when any single dot is in Coulomb blockade
- μ_L and μ_R now depend on how many electrons are on both dots





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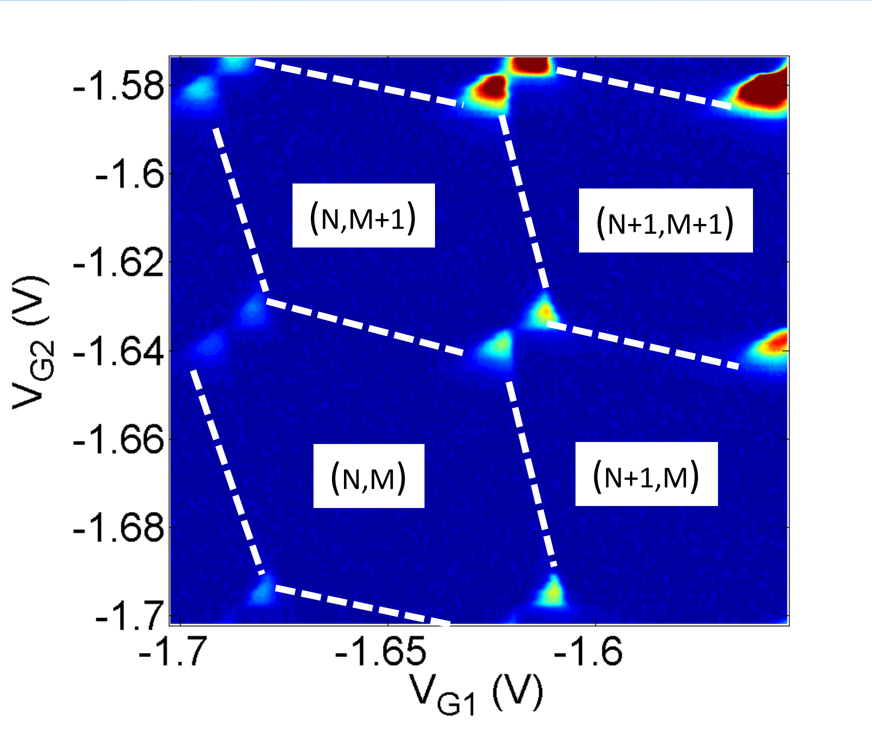
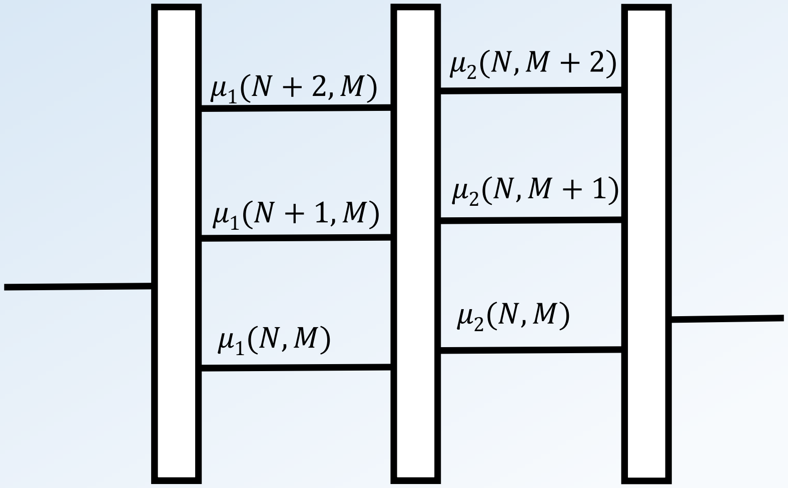
Double quantum dots

Charge stability diagram → honeycomb





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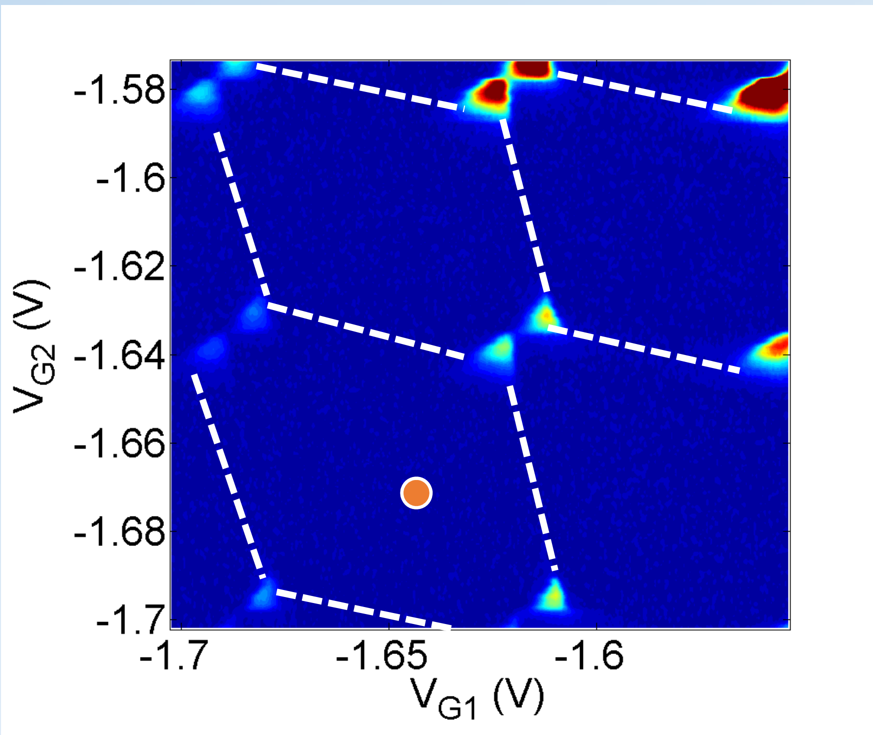
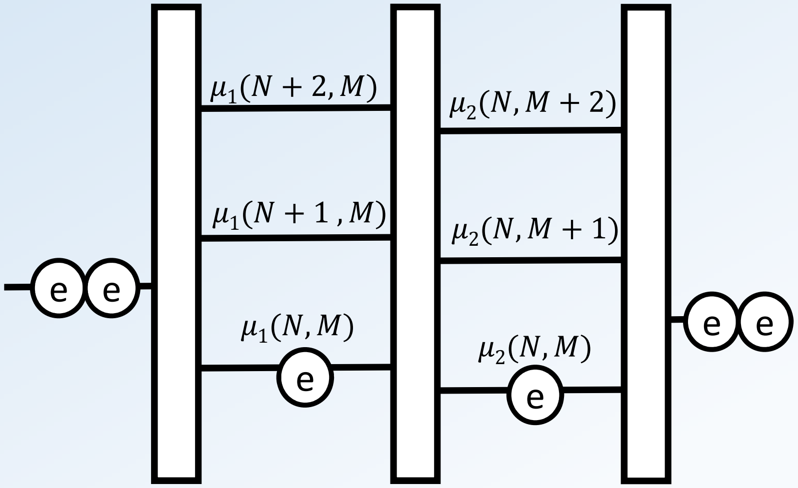
Double quantum dots





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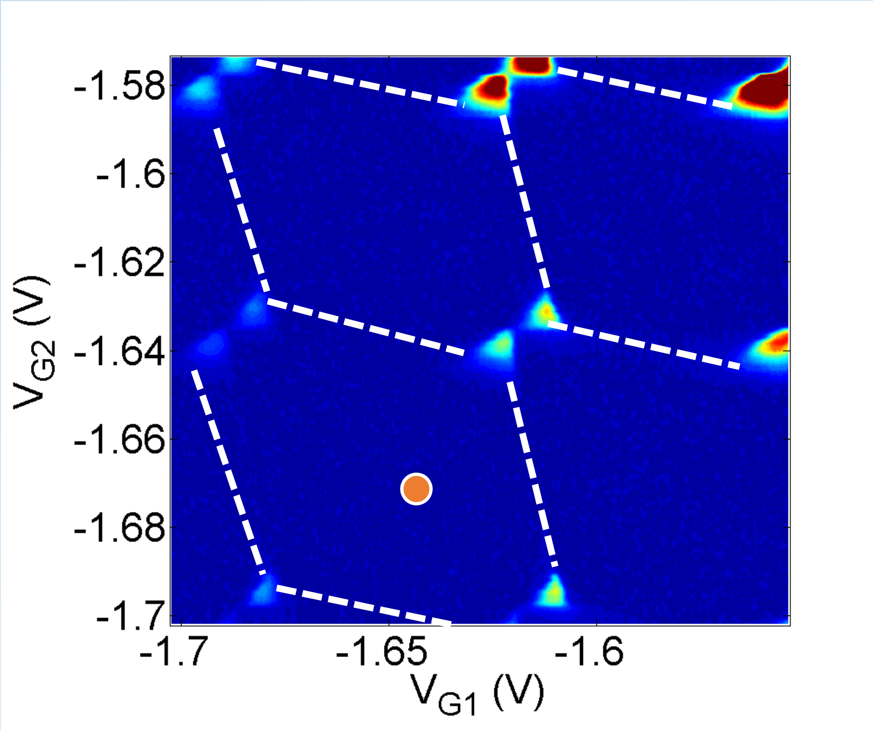
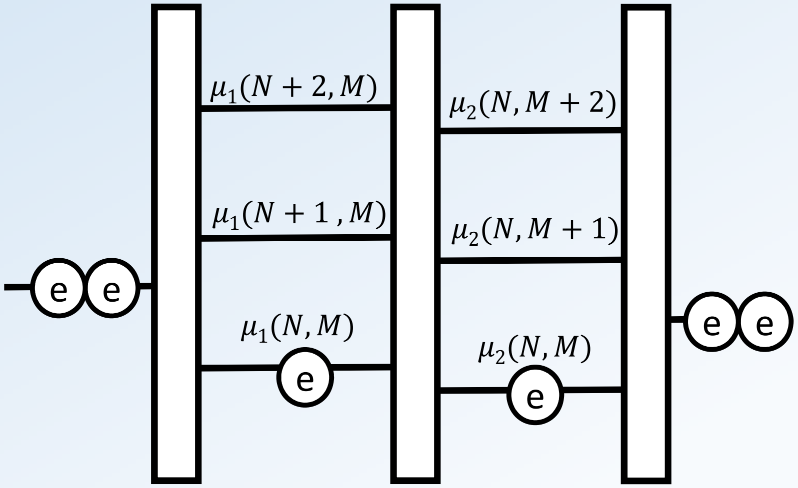
Double quantum dots





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Double quantum dots

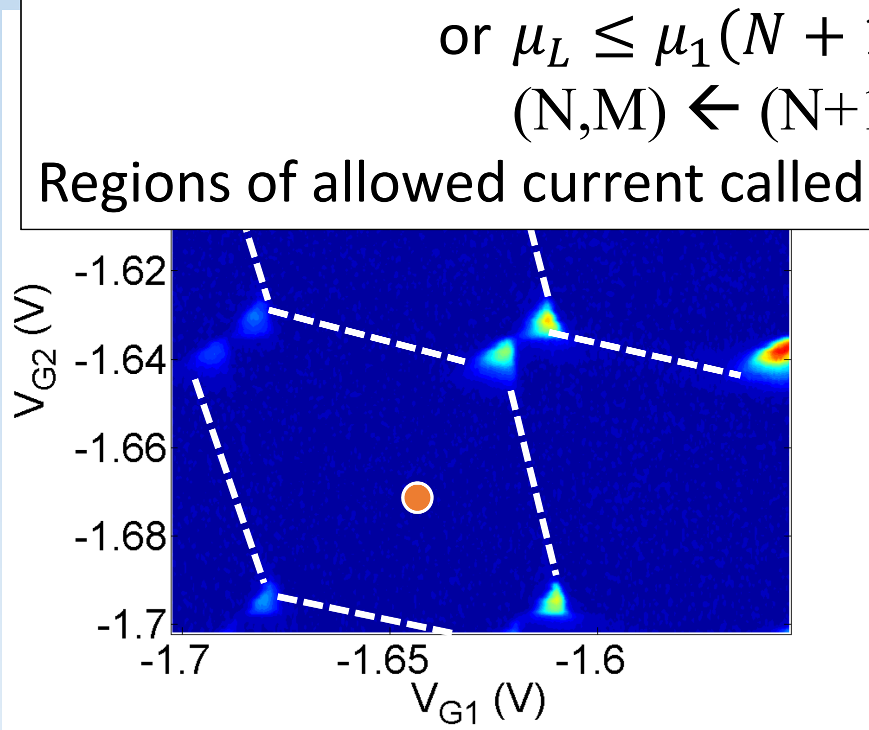
Current allowed if $\mu_L \geq \mu_1(N+1, M) \geq \mu_2(N, M+1) \geq \mu_R$

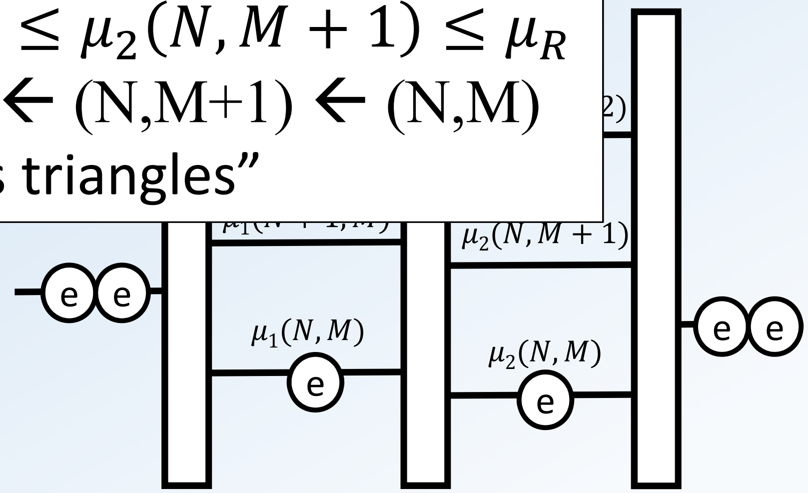
(N,M) → (N+1,M) → (N,M+1) → (N,M)

or $\mu_L \leq \mu_1(N+1, M) \leq \mu_2(N, M+1) \leq \mu_R$

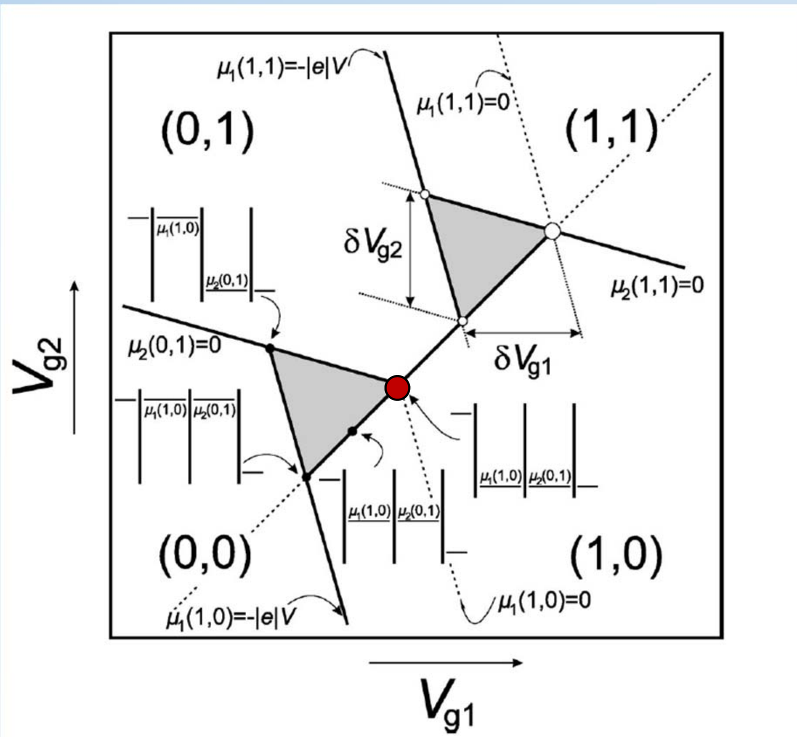
(N,M) ← (N+1,M) ← (N,M+1) ← (N,M)

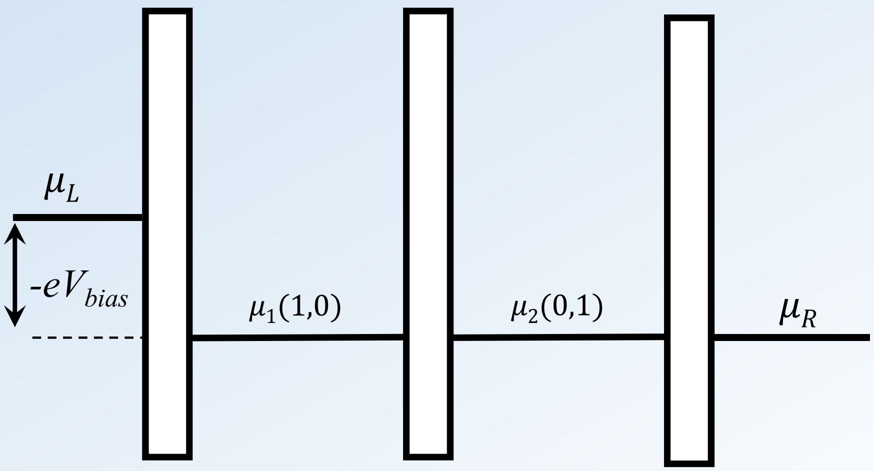
Regions of allowed current called “bias triangles”





Bias triangles





Larger bias → Larger triangles

Van der Wiel *et al.* *Rev. Mod. Phys.* **75,** 1 (2003)

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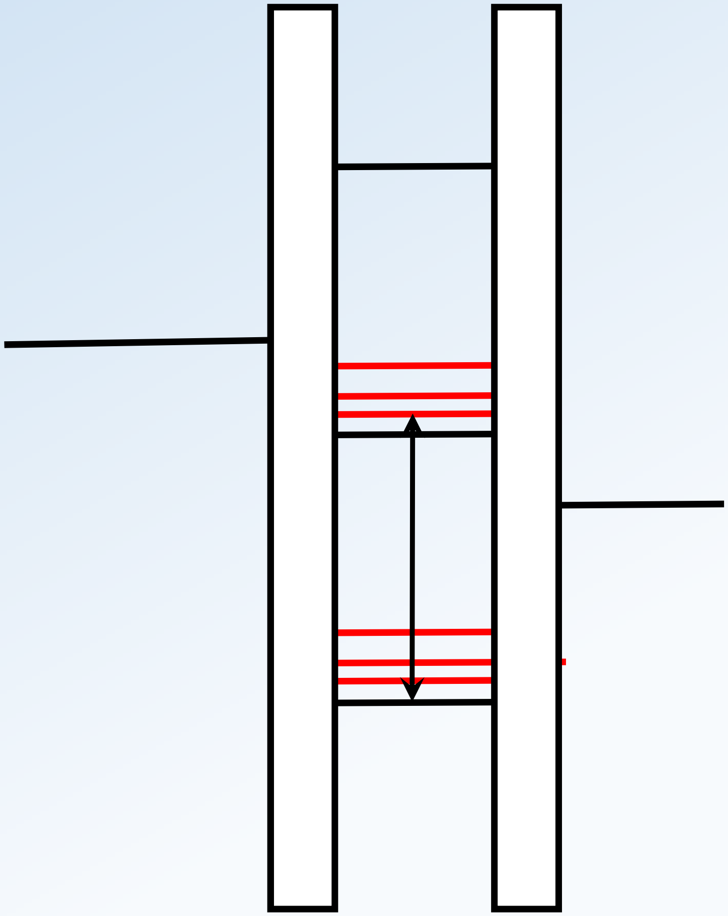
Quantum effects

- Up to now, only classical effects considered.
- Energy should also have a quantum term
$$E_N = E_{Electrostatic} + E_{quantum}$$
- This means *μ(N)* will also have a quantum term
$$\mu(N) = E_{charging} + \Delta E_{quantum}$$
- Transport measurements become very enlightening



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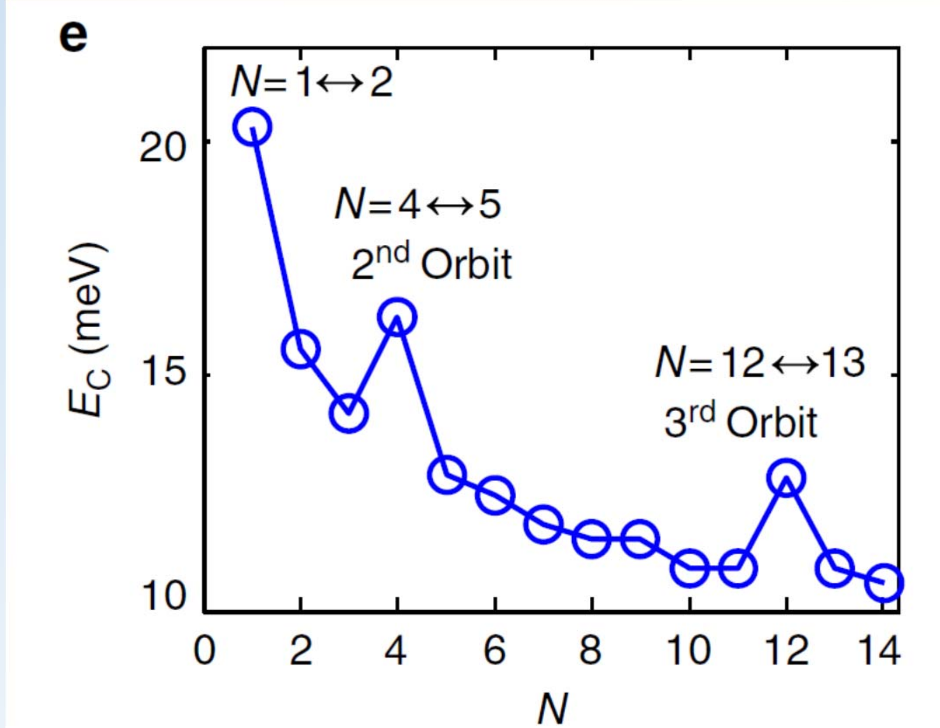
Quantum effects

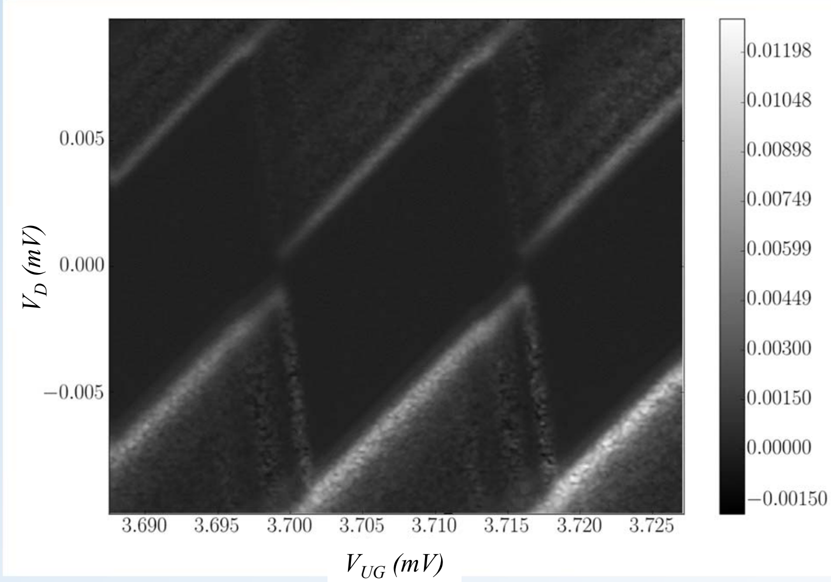
- Spacing between current peaks can show shell filling

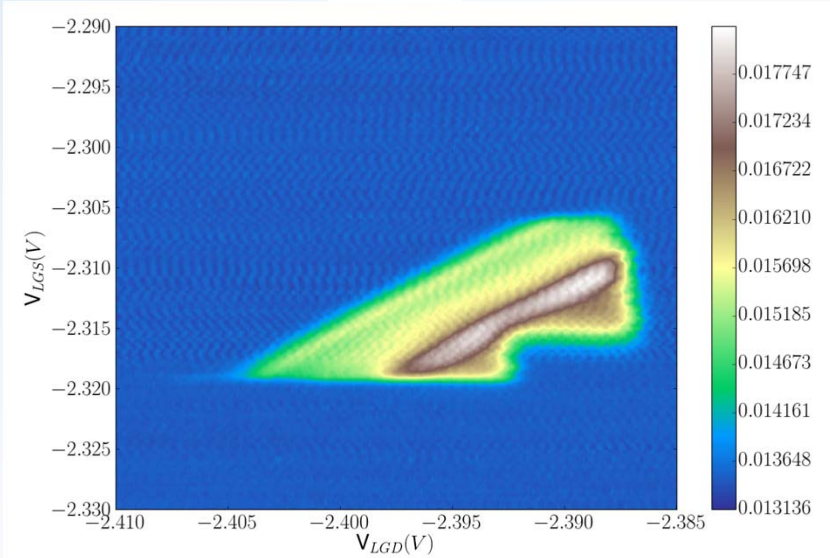


C.H. Yang et al. *Nat. Comm* **4,** 2068 (2013)

Quantum effects

- Spacing between current peaks can show shell filling
- Resonances at larger S-D bias also reveal level spacing

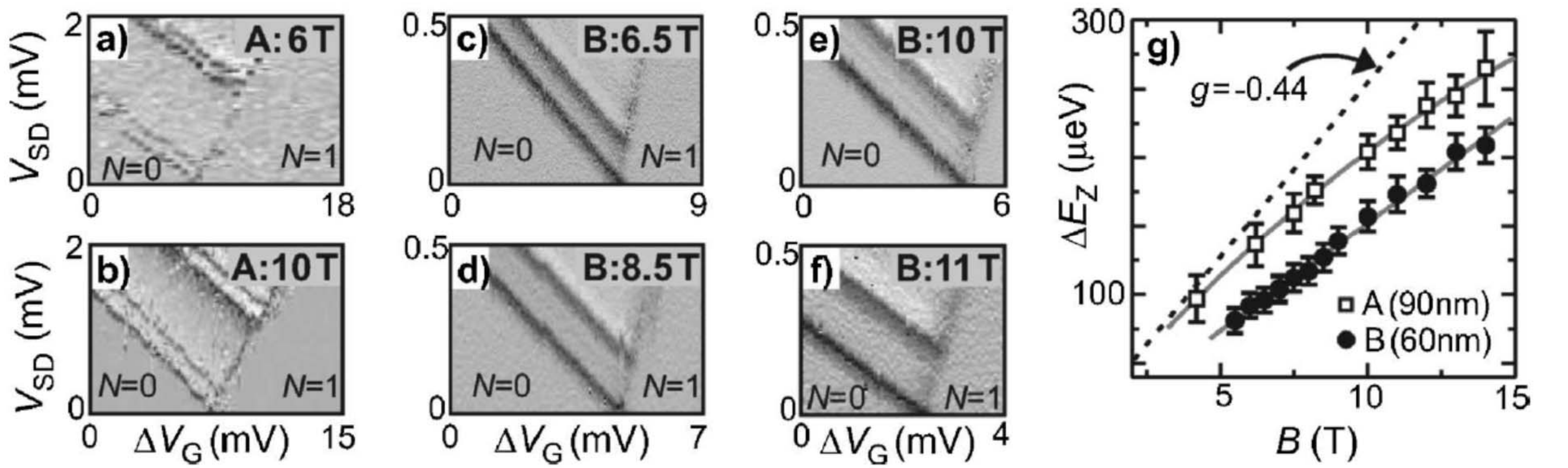




Quantum effects

- Spacing between current peaks can show shell filling
- Resonances at larger S-D bias also reveal level spacing
- Magnetospectroscopy

Hanson *et al.,* Rev. Mod. Phys. **79,** 1217 (2007)

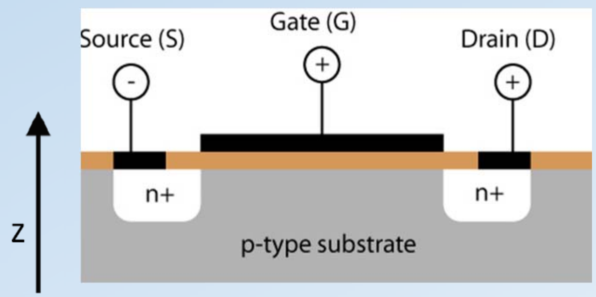


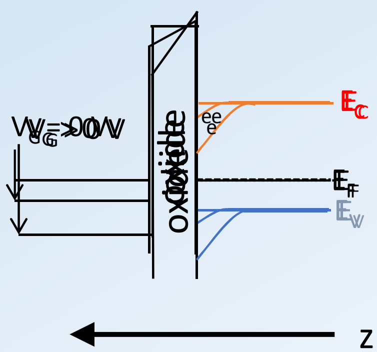
Quantum effects

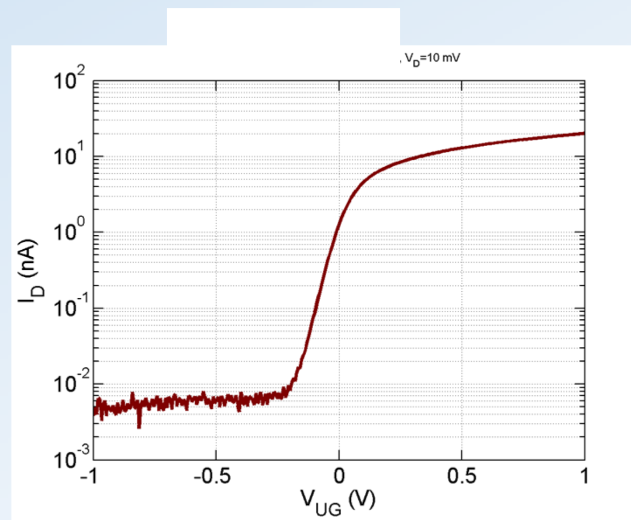
- Spacing between current peaks can show shell filling
- Resonances at larger S-D bias also reveal level spacing
- Magnetospectroscopy
- Current blockade

Our devices

- Functionally just multi-gate MOSFETs (metal on semiconductor field effect transistors)







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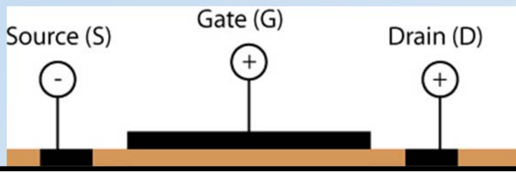
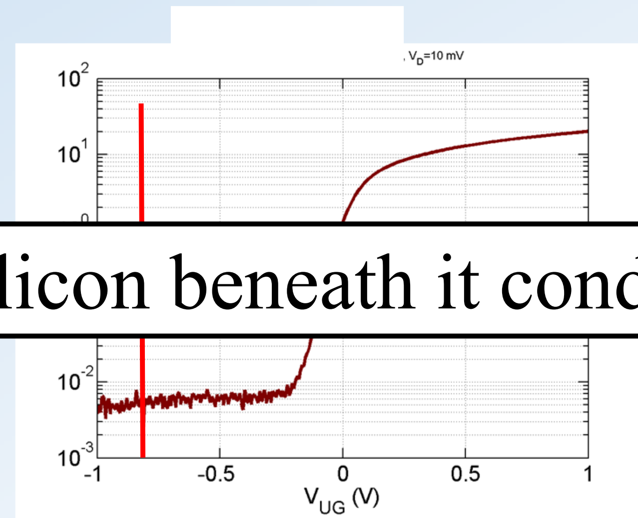


Voltage on Gate determines if silicon beneath it conducts



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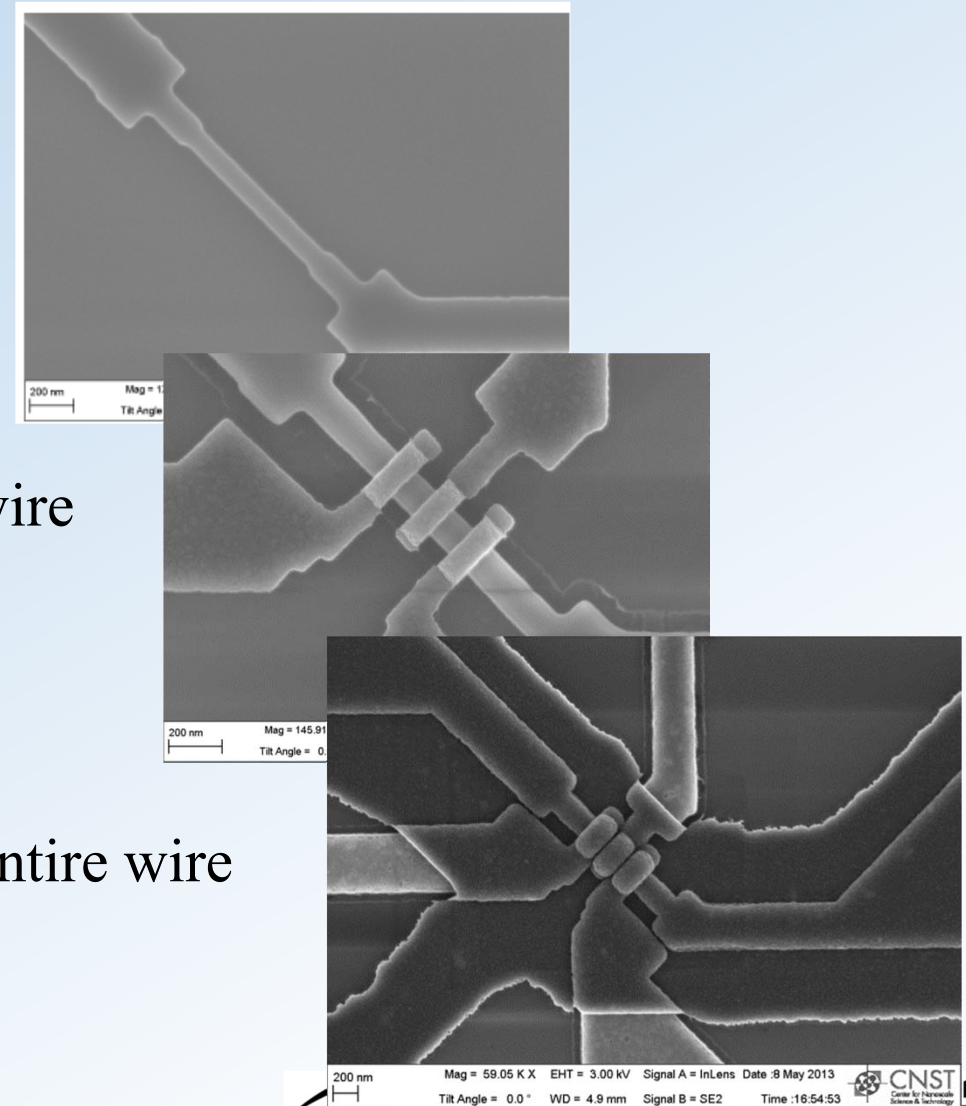
Our devices

Fabricate a nanowire of silicon

Add three very small gates across wire

Add global upper gate that covers entire wire



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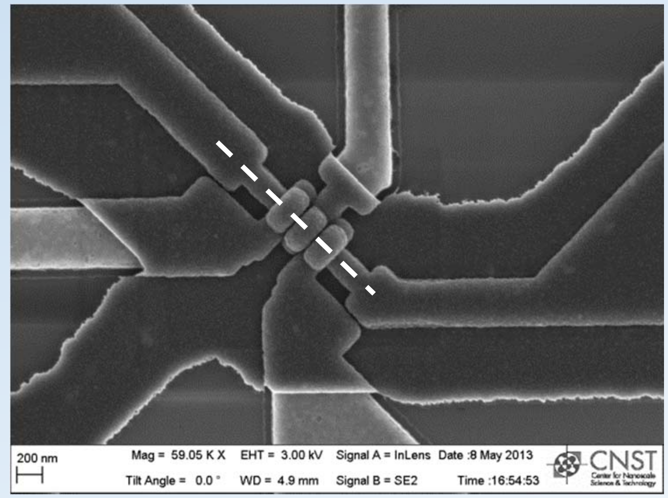
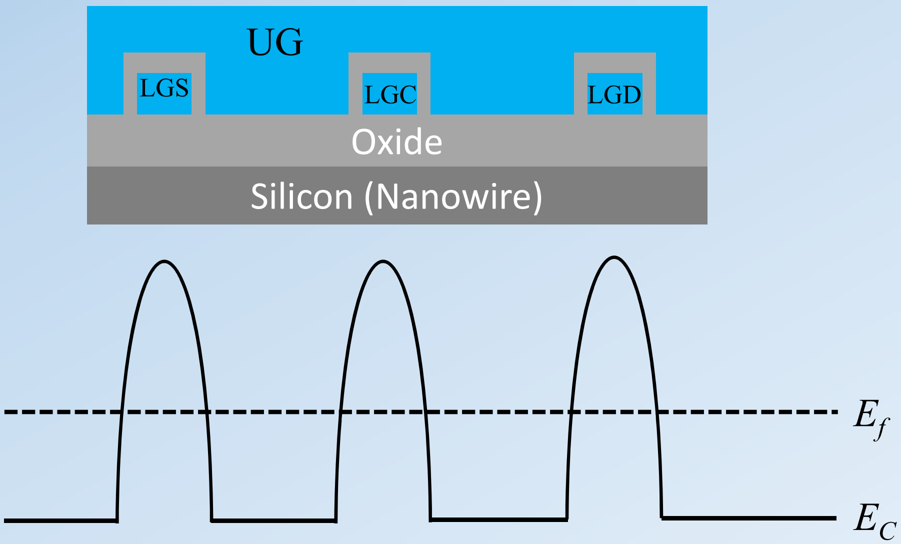
Our devices

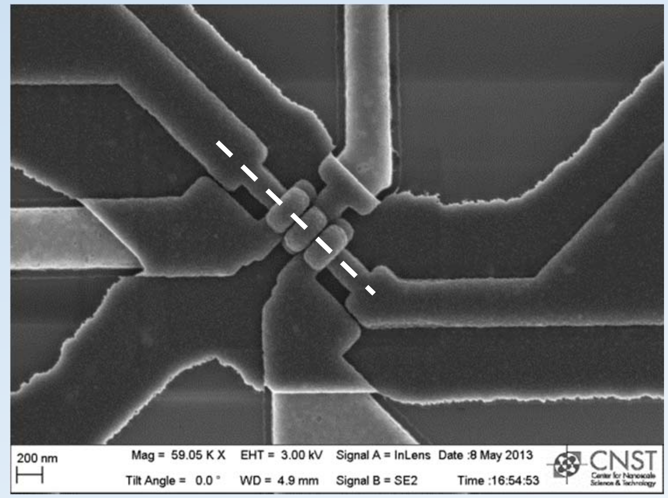

UG
LGS
LGC
LGD
Oxide
Silicon (Nanowire)


E_C
E_f


200 nm
Mag = 59.05 K X
Tilt Angle = 0.0 °
EHT = 3.00 kV
WD = 4.9 mm
Signal A = InLens
Signal B = SE2
Date :8 May 2013
Time :16:54:53
CNST

Our devices





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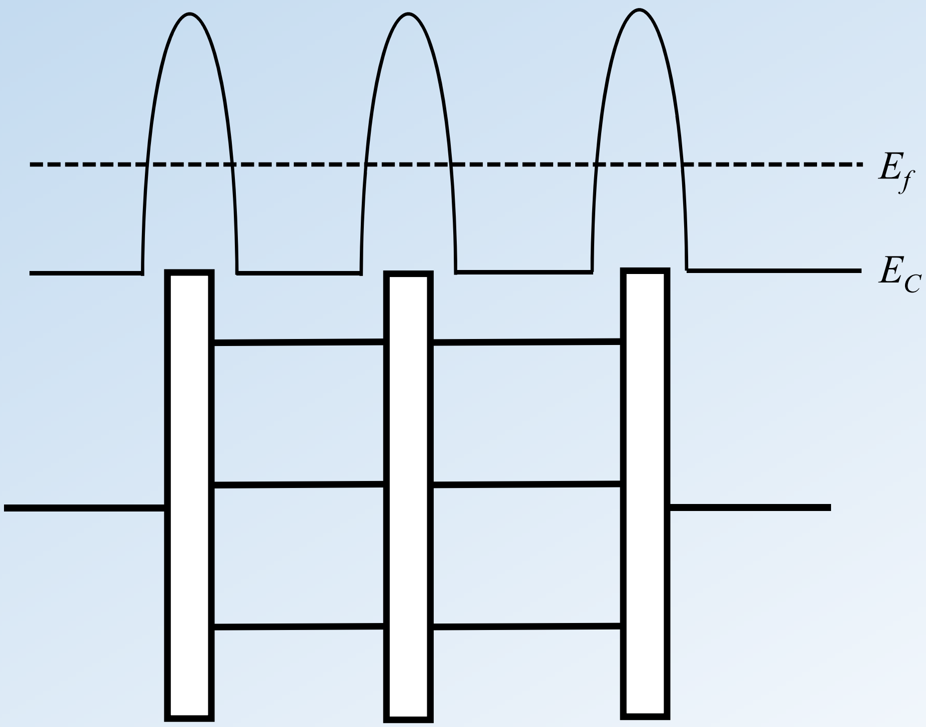
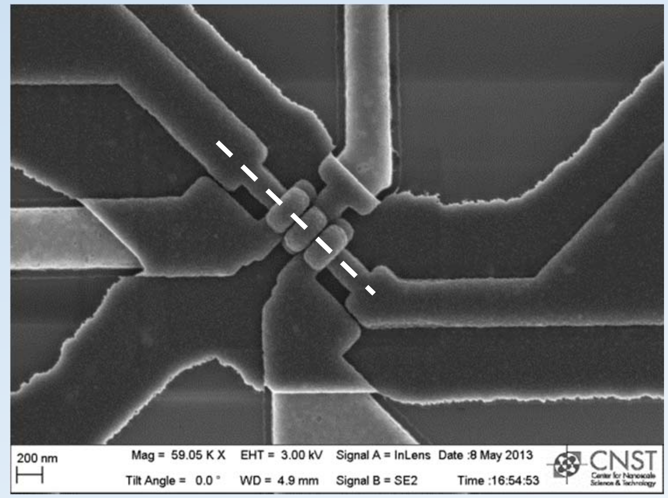
Our devices


UG
LGS
LGC
LGD
Oxide
Silicon (Nanowire)


E_f
E_C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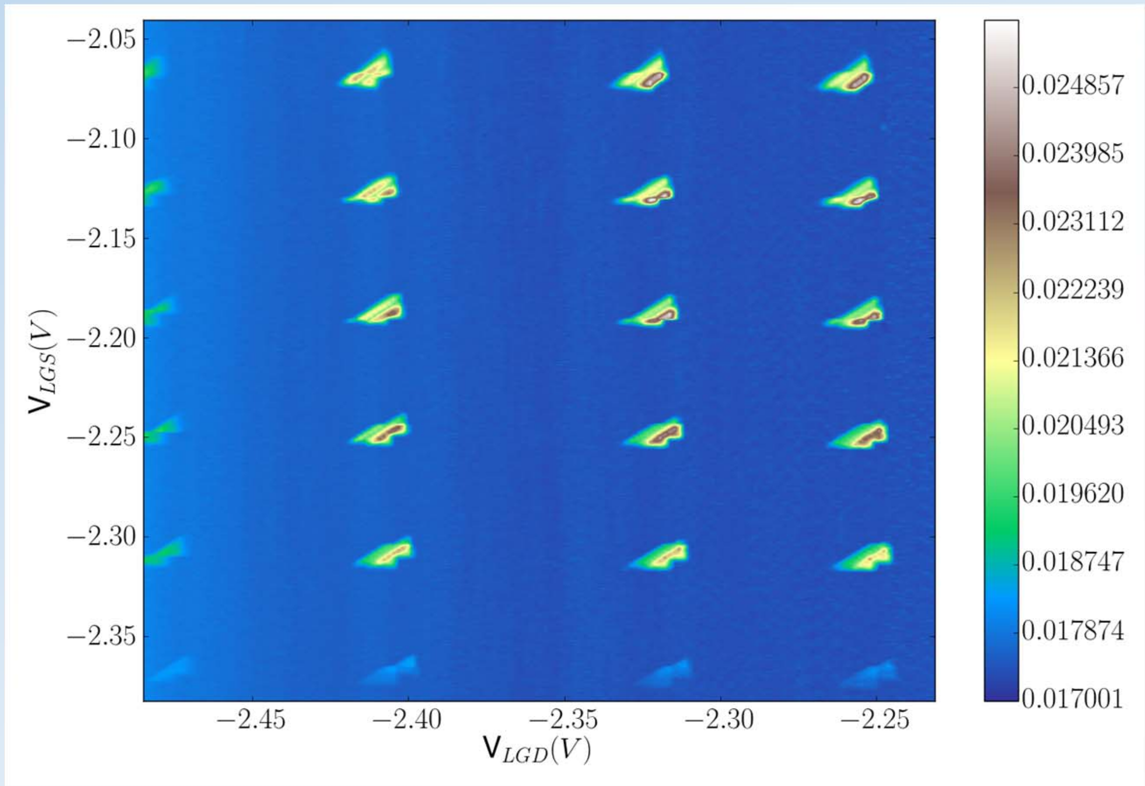
Recent results

Charge stability diagram



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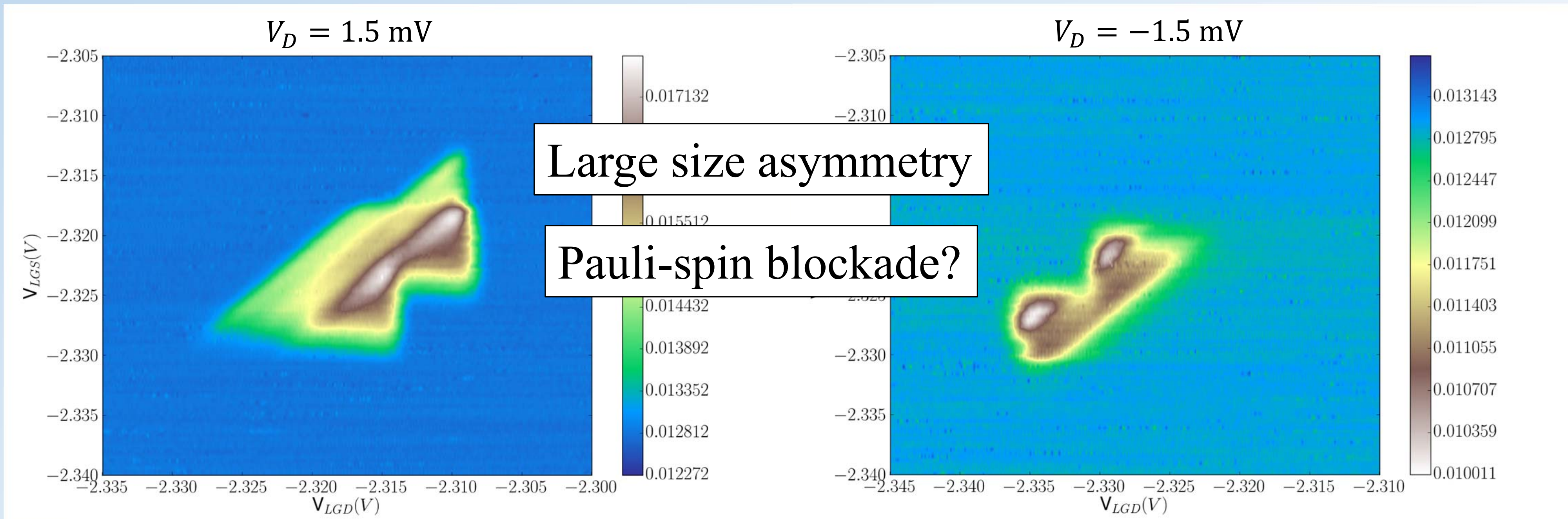
Recent results

Bias triangle data



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Pauli-spin blockade

Quantum mechanics

- Pauli-spin blockade results from the spin states of the electrons on the double quantum dots.
- Spin conserved in tunneling
- Certain transitions are forbidden

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Pauli-spin blockade

- Consider the bias triangle where current flows through the (0,1)↔ (1,1) ↔(0,2) ↔(0,1) charge states
- Two electron spin states
- 4 possible states

$$|S\rangle = (|\downarrow,\uparrow\rangle - |\uparrow,\downarrow\rangle)/2$$
$$|T_+\rangle = |\uparrow,\uparrow\rangle$$
$$|T_-\rangle = |\downarrow,\downarrow\rangle$$
$$|T_0\rangle = (|\downarrow,\uparrow\rangle + |\downarrow,\uparrow\rangle)/2$$

- $|S\rangle$ is lower in energy than the $|T_x\rangle$ states due to the exchange energy *J*
- *J* scales with the wave function overlap between the two electrons (how close they are)
- Therefore → *J*(0,2) > *J*(1,1)

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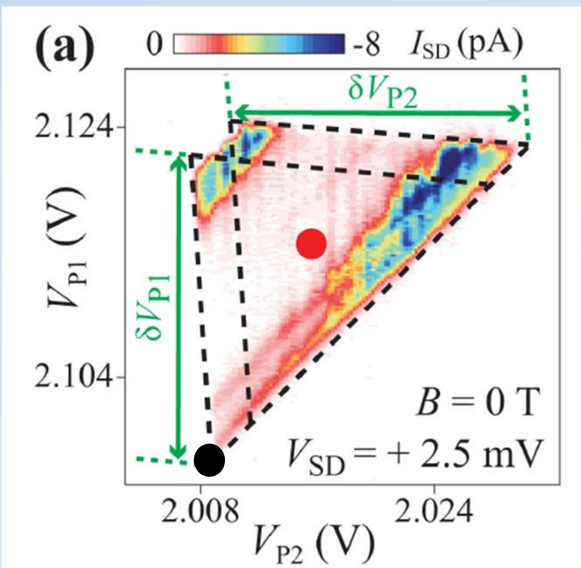
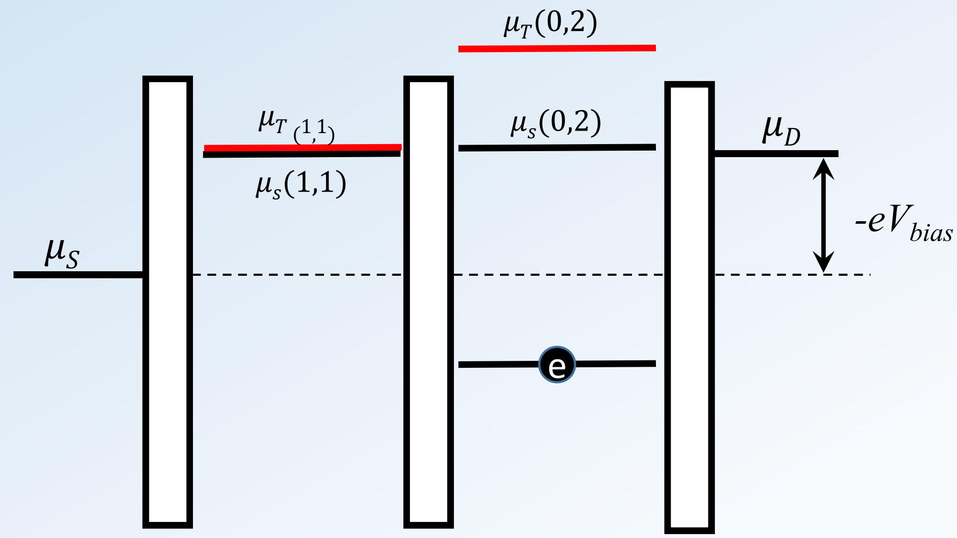
Pauli-spin blockade

- Consider the triple point where current flows by repeating the (0,1)→(0,2)→(1,1)→(0,1) transitions



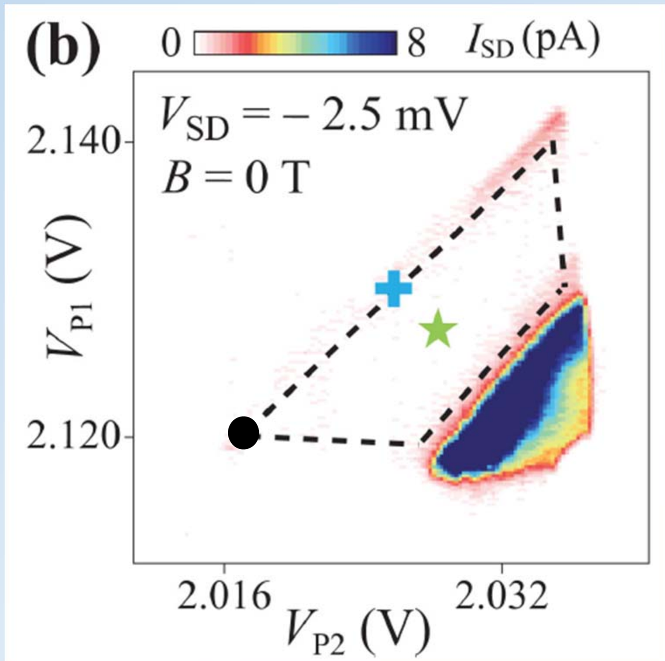
N. S. Lai *et al. Sci. Rep.* **1,** 110 (2011) [UNSW]



(0,2) → (1,1) direction results in a standard bias triangle

Pauli-spin blockade

- Consider the reverse direction where current flows through the (0,1)→(1,1)→(0,2)→(0,1) transitions



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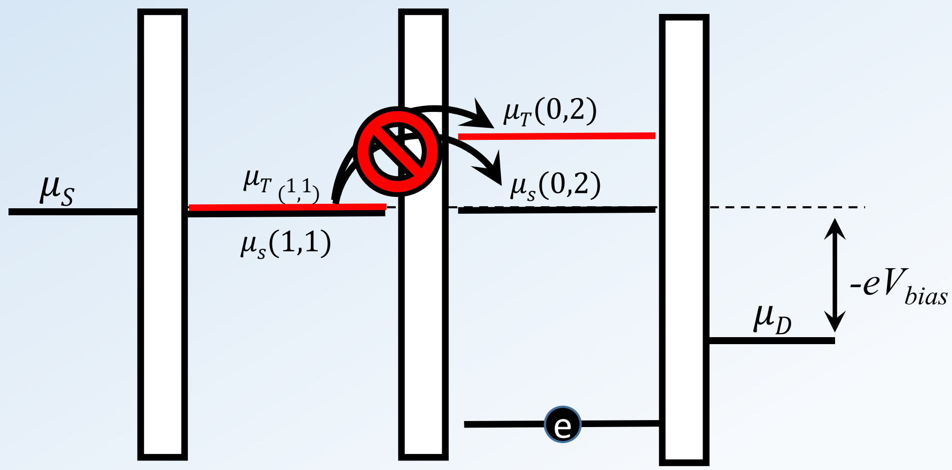

(1,1) → (0,2) direction results in a standard bias triangle

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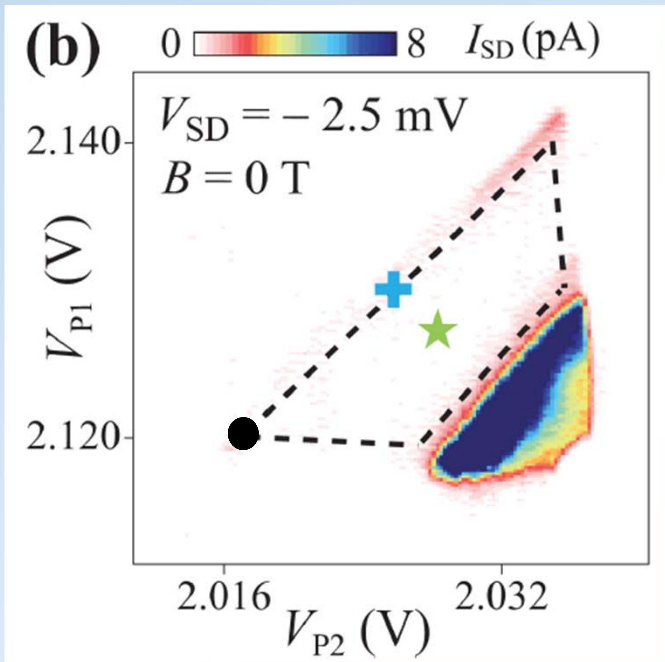
Pauli-spin blockade

- Useful for spin physics
- Quantum information



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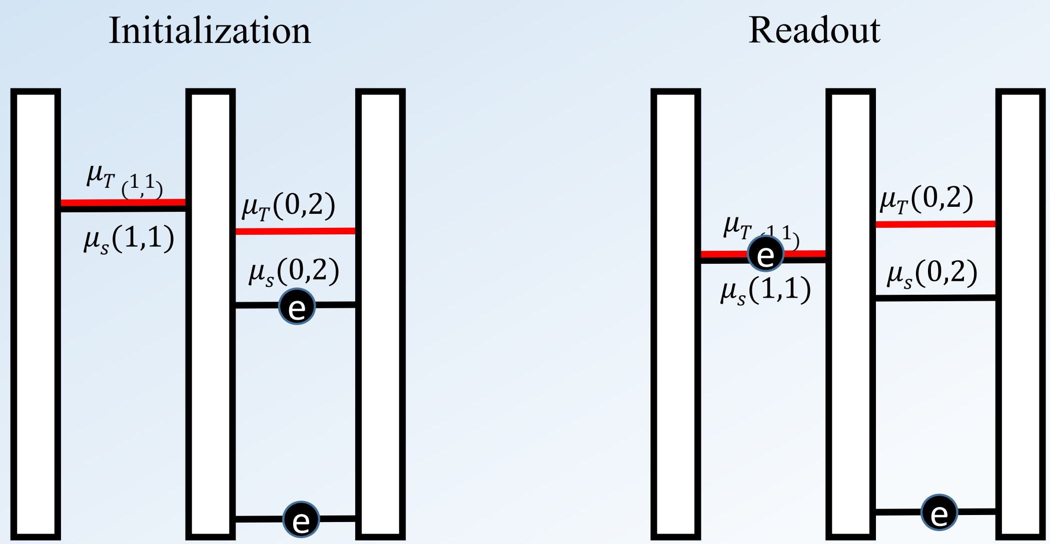

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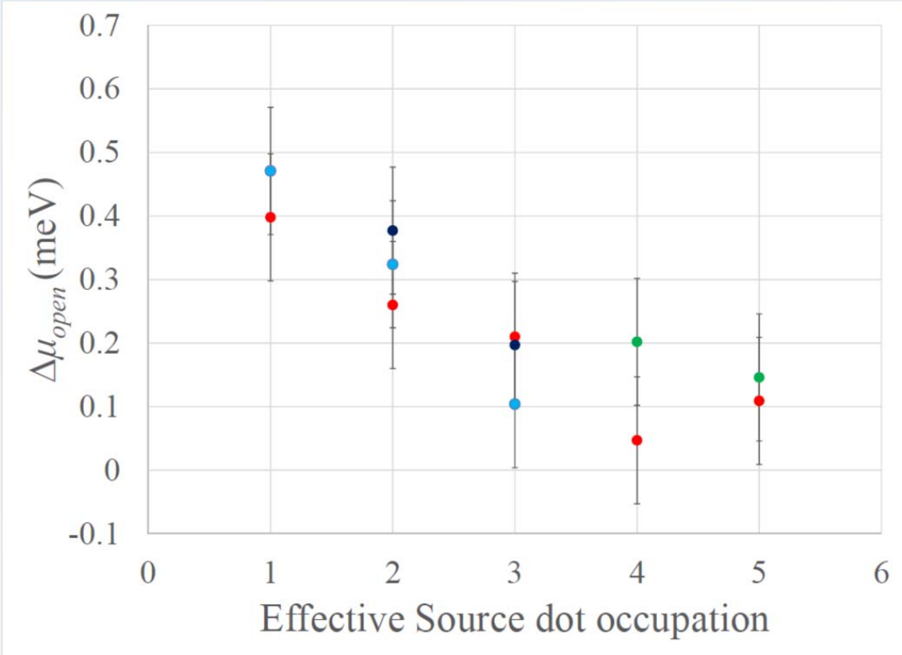
Recent results

- Pauli-spin blockade has certain expected features
  1. Systematic magnetic field dependence due to Zeeman splitting and ΔJ
  2. Odd-even filling effect → only observe every other set of bias triangles
  3. Should change polarity every other set of bias triangles

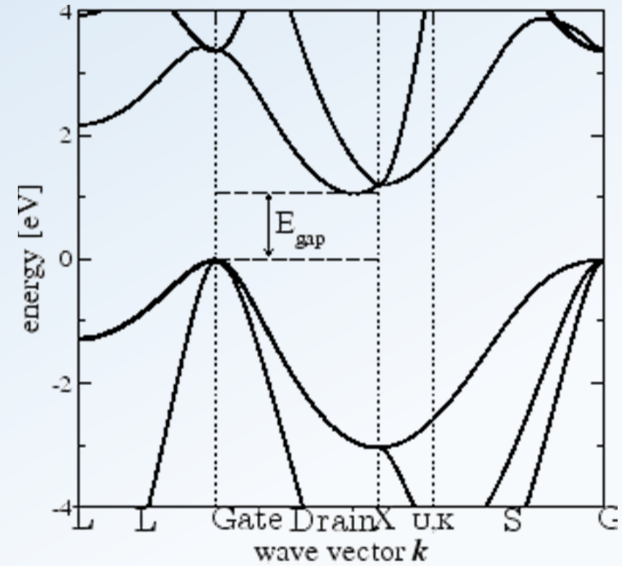
- What we observe
  1. No systematic dependence on B
  2. Asymmetry over consecutive triangles
  3. Same polarity of all asymmetries
  4. Dependence on electron occupation

Not Pauli-spin Blockade!



Recent results

- What then?
- Natural to look at a different quantum number → "Valley" degree of freedom
- Possible that valley states are leading to blockade in similar way to the spin states of Pauli-spin blockade?



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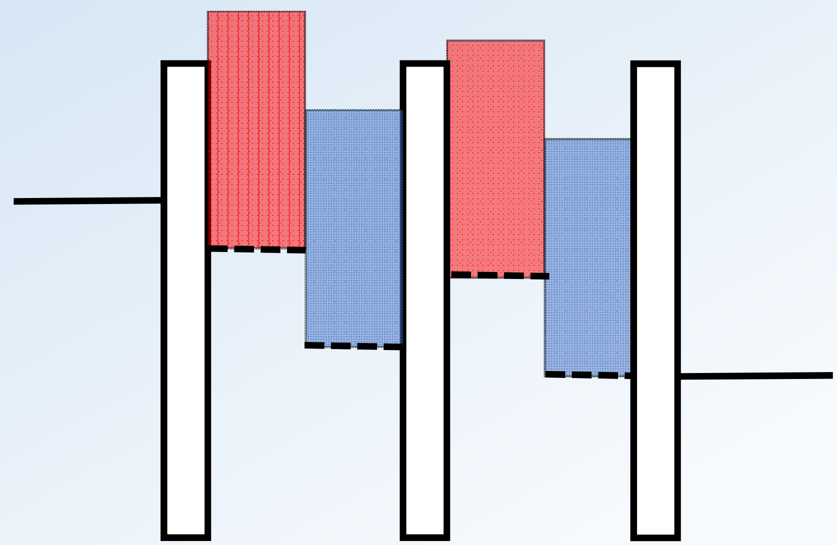
Model

- Electrons in one of two valley states.
- Band of states of each valley type
- Ground state of each band split by Δ_v
- Significantly different electron fillings



Valley type 1

Valley type 2

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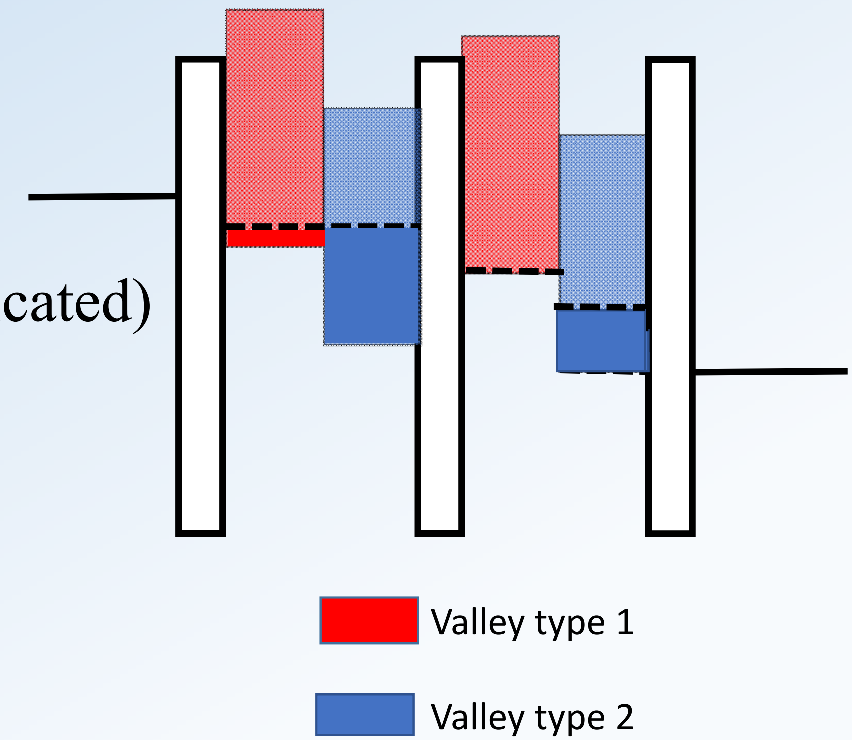
Model

The asymmetric filling this leads to blockade and qualitative agreement with our observations

- B dependence → not systematic (complicated)
- Sequential transitions with blockade
- Same polarity of asymmetry
- Dependence on electron occupation



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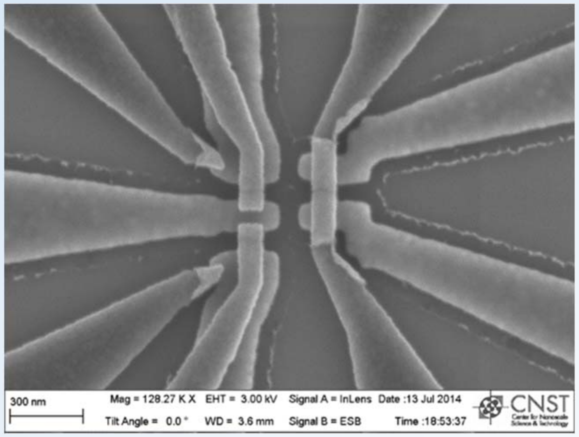
Summary

	Experiment	Pauli spin blockade	Valley blockade model
Magnetic field dependence	Complicated, non monotonic	Monotonic	Complicated
Observed at	Multiple consecutive transitions	Alternating transitions	Multiple consecutive transitions
Polarity of asymmetry	Single polarity across multiple transitions	Alternating transitions	Single polarity across multiple transitions
Dependence on electron occupation	Decreasing size asymmetry with electron occupation	No dependence	Decreasing size asymmetry with electron occupation

Future work

1. Fabricate devices with increased functionality
   - Charge sensing
   - Independent plunger gates
   - Few electron limit

   } True N & M



2. Finer B and E field spectroscopy
3. Examine surface properties (roughness etc.)

Thank you

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Neil Zimmerman – analysis
Josh Pomeroy, Garnett Bryant, Mark Stiles – discussions

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Michael Gullans and Jacob Taylor – Theory

CNST Center for Nanoscale Science & Technology

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NIST National Institute of Standards and Technology U.S. Department of Commerce

jqi Joint Quantum Institute

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