SAND2016-0454PE

Fabrication and Characterization of a Single Hole Transistor in p-type GaAs/AlGaAs Heterostructures

Lisa A. Tracy[1], J. L. Reno[2], T. W. Hargett[2]

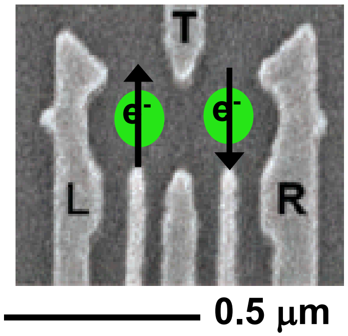
[1)] *Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

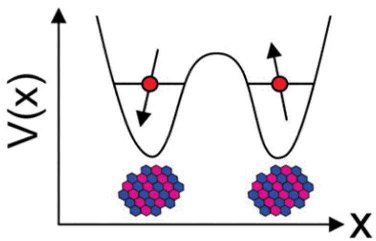
[2)] *Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

 Feb. 10, 2015

Hole Spins in GaAs

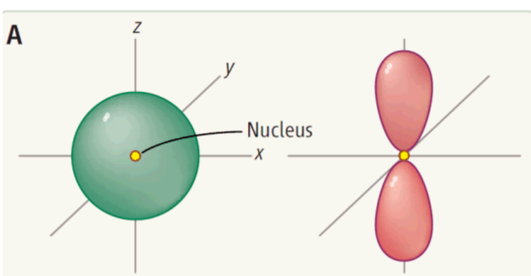
Electron Spin as a Qubit:





- Coherent manipulation of electron spins shown in quantum dot in high-mobility GaAs/AlGaAs heterostructure (*Petta et al., Science 2005*)
- However, coherence time $T_2^* \sim 10$ ns due to background nuclear spins.

Hole Spins in Quantum Dots:



3 JULY 2009 VOL 325 **SCIENCE**

- Hole spins in GaAs have reduced coupling to nuclear spins as compared to electrons

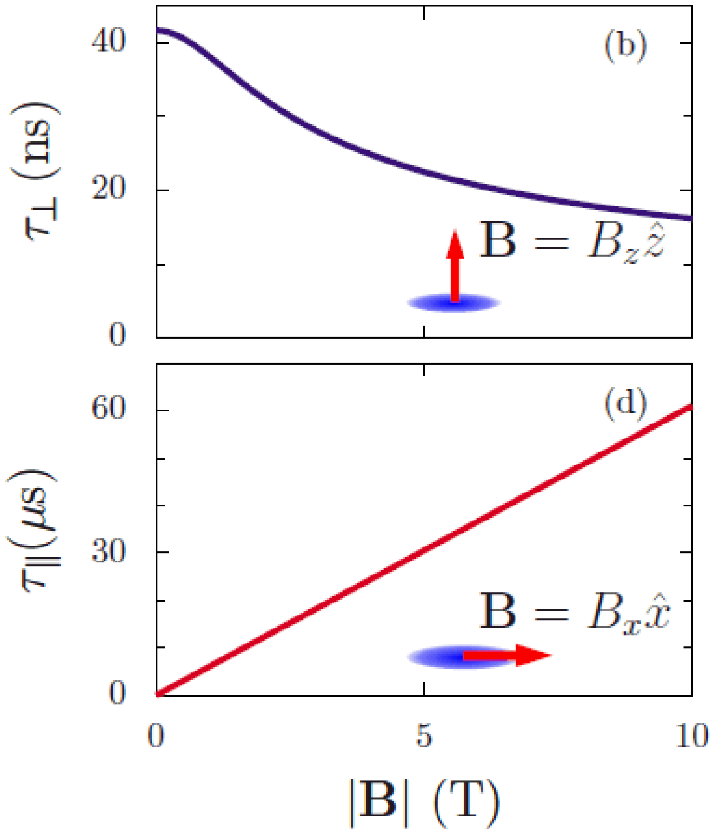
Coherent Holes in a Semiconductor Quantum Dot

Michael H. Kolodrubetz and Jason R. Petta

Quantum states of positive charge carriers may be more stable to information loss than those of electron-based systems.

Hole Spin Coherence (T_2^*)

Theoretical estimates from Loss group, *PRB 2008:*

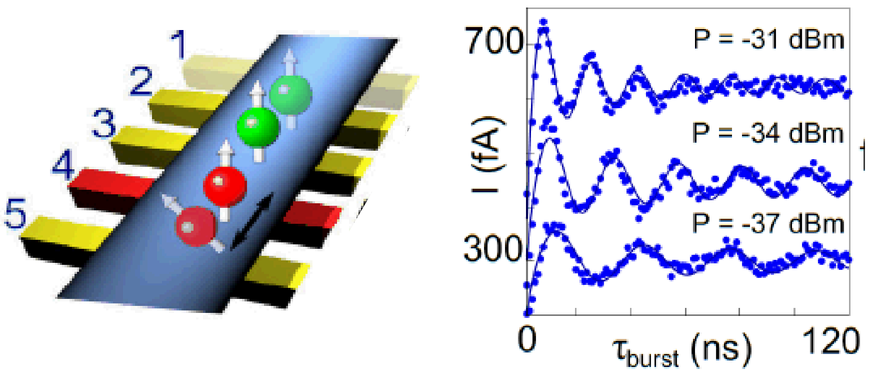


- Nuclear spin – hole spin interaction is anisotropic
- Coherence time T_2^* for B⊥ is somewhat better than for electrons, possibly much better for B∥
- With dynamical decoupling pulses, T_2 will presumably be longer than current state of the art for electrons in GaAs (T_2 ~ 200 μS).

Spin-Orbit Interaction

- Second advantage for using hole spins: spin-orbit interaction can be used to manipulate spin with electric fields
- Example: In plane ac E-field on resonance with Zeeman splitting can create ns π pulses with ~ mV across dot
- Possible disadvantage: spin-orbit coupling can decrease T_1. However, still expect $T_1 > T_2$.

Example: coherent manipulation of single spin using spin-orbit interaction and electric fields, InAs electron spin-orbit qubit.

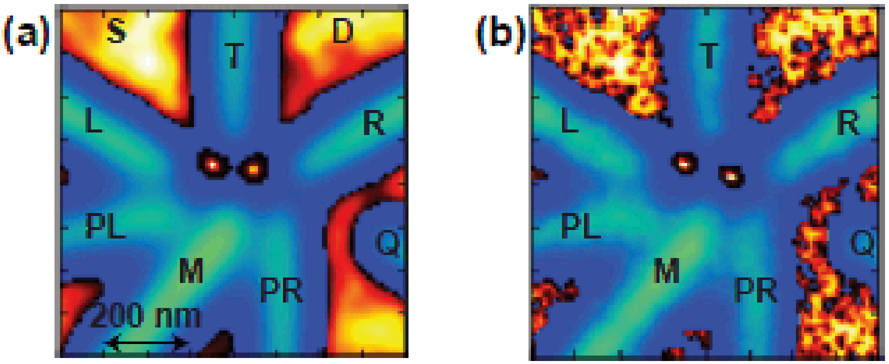


Delft group, Nature 2010.

Why GaAs?

- Beneficial for creating nanostructures where transport is not impeded by defects.
- Example: unintentional dots can form due to nearby charged defects
- Modulation-doped GaAs/AlGaAs heterostructures hold record for low temperature 2D mobility, both for electrons and holes. Mfp ~ 100 μm!
- Pioneering experiments in coherent single spin manipulation done in GaAs

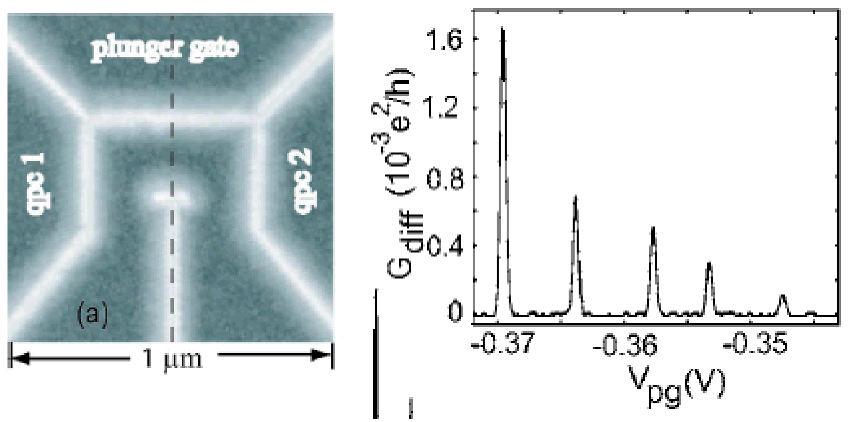
Simulation of electron density in a semiconductor quantum dot with 3 x 10^{11} cm^{-2} randomly distributed charges, a) 30 nm away from 2D layer, b) 10 nm. *Borselli et al., APL, 2011*



modulation-doped GaAs/AlGaAs heterostructure

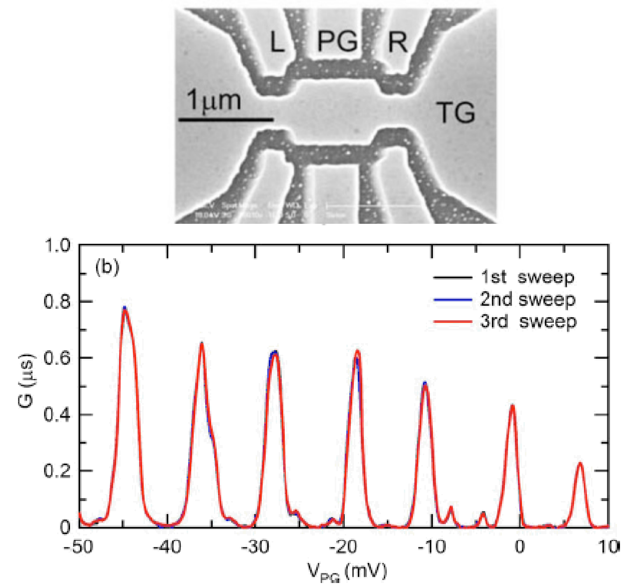
Previous work on hole QD in GaAs

Gates formed with AFM oxidation lithography



Ensslin group, 2005

Undoped structure with single layer of gates (wet etch)



Hamilton group, 2010

- P-type quantum dots in GaAs formed with surface depletion gates previously plagued by instability problems
- Few-hole limit had not yet been achieved

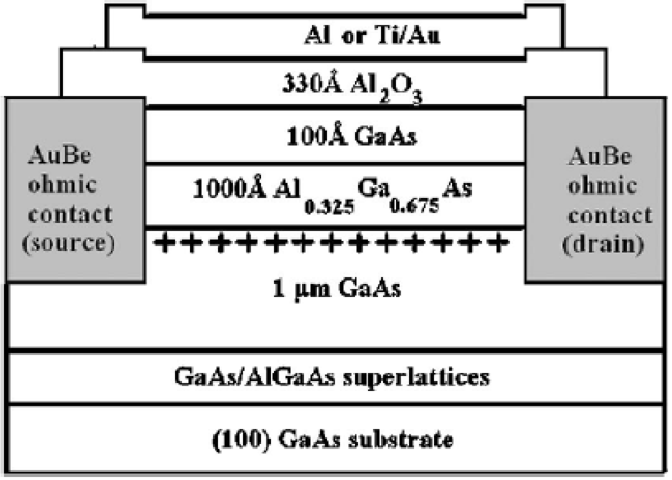
Undoped Heterostructures

Undoped high mobility two-dimensional hole-channel GaAs/$Al_xGa_{1-x}As$ heterostructure field-effect transistors with atomic-layer-deposited dielectric

T. M. Lu,[a] D. R. Luhman, K. Lai,[b] and D. C. Tsui
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

L. N. Pfeiffer and K. W. West
Bell Laboratories, Lucent Technologies, 700 Mountain Avenue, Murray Hill, New Jersey 07974

- Charge movement in doping layer or between doping layer and 2D layer leads to charge noise?
- Doping layer can be eliminated using enhancement mode device.
- Challenge is maintaining good mobility despite surface states and preventing gate leakage to channel.



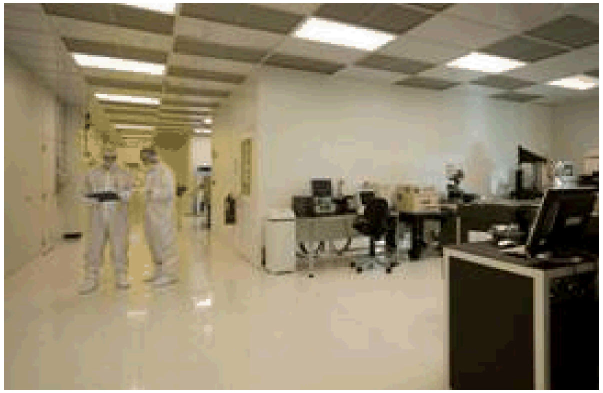
Facilities and Capabilities Used

- This work leverages Sandia's unique, world-class capabilities in MBE growth of GaAs/AlGaAs heterostructures. We also use Sandia nanofabrication facilities (CINT), and low-temperature measurement systems.

- Few groups worldwide have the capability for MBE growth GaAs/AlGaAs heterostructures for high mobility 2D systems.

- MBE of high mobility III-V heterostructures (John Reno)

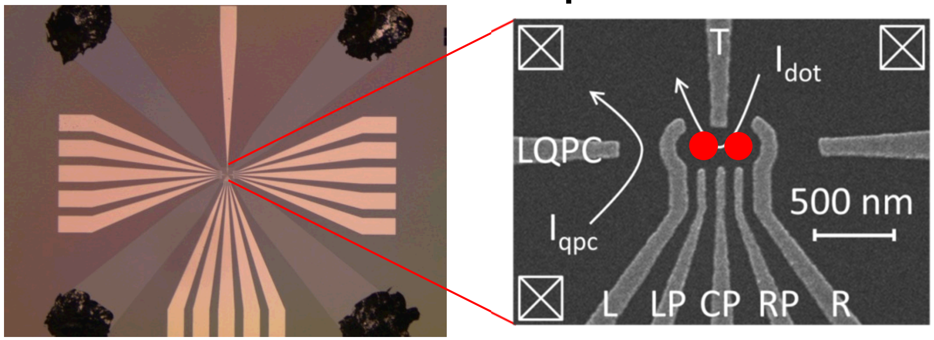
- Integration Lab, Center for Integrated Nanotechnologies (CINT)

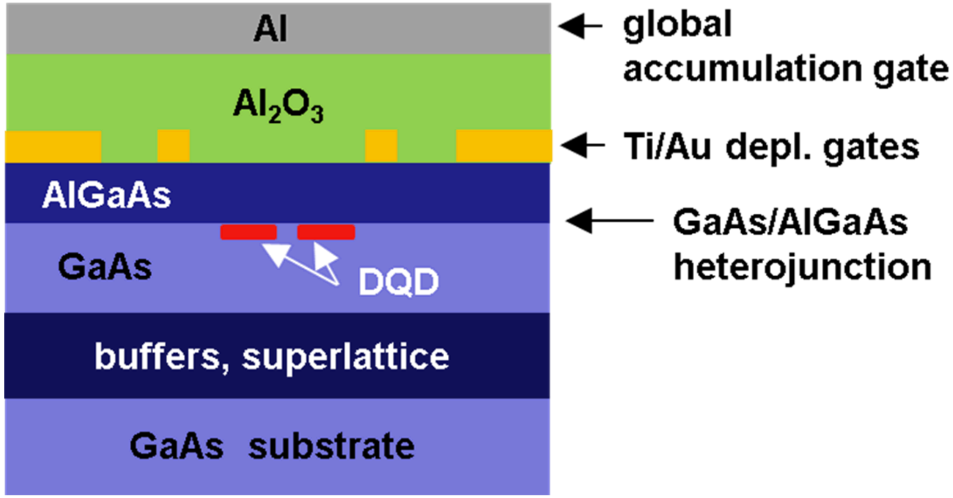


Hole Nanostructure Fabrication

- Start with GaAs/AlGaAs heterostructure capable of forming 2D hole layer (heterojunction or quantum well)
- Surface cleans and AuBe Ohmic contact formation
- Electron beam lithography and TiAu gate lift-off
- Atomic layer deposition of Al_2O_3
- Global Al accumulation gate deposition and lift-off

SEM of partially processed device

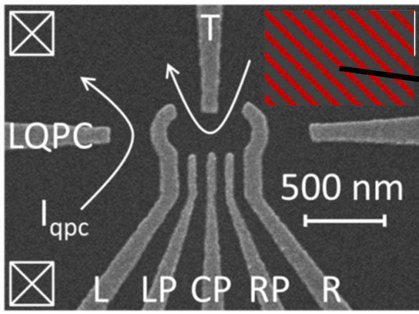


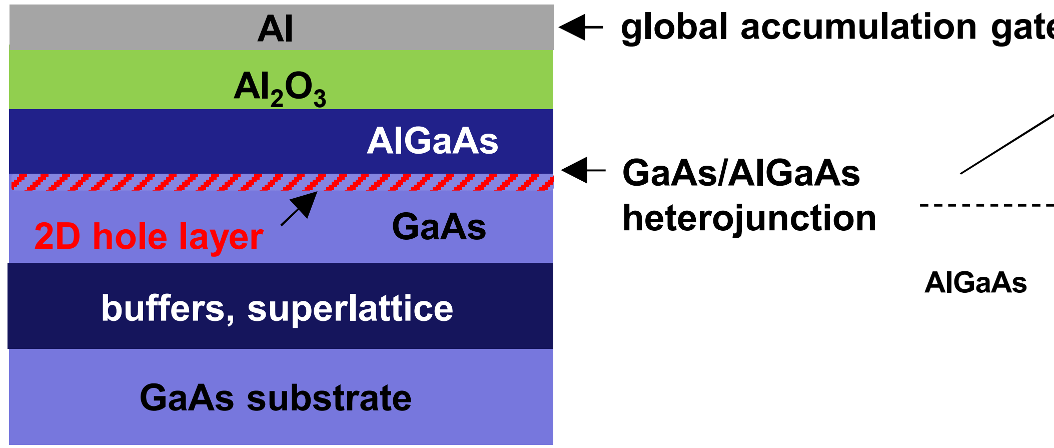


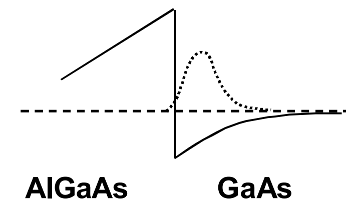
 Feb. 10, 2015

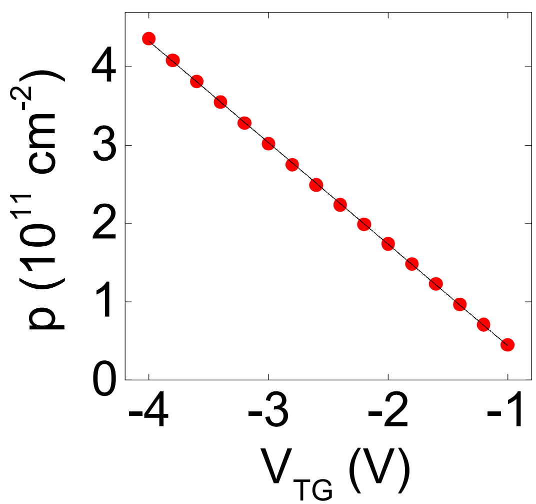
Sandia National Laboratories

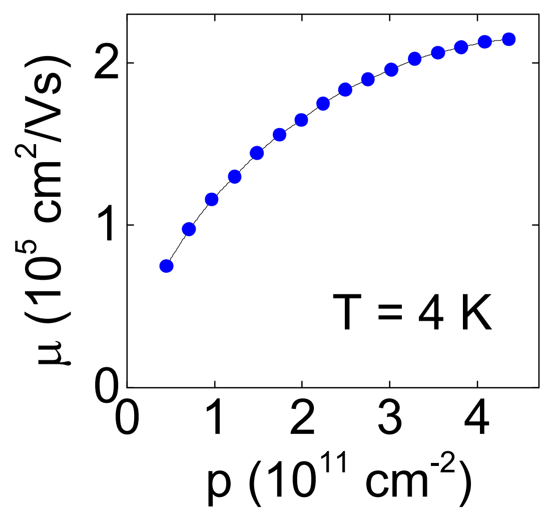
Undoped 2D Hole Layer (Device Field Region)







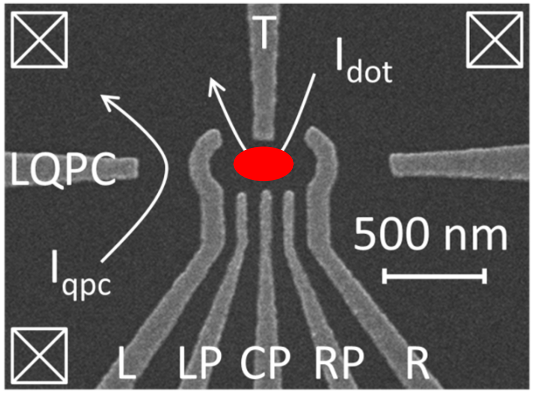


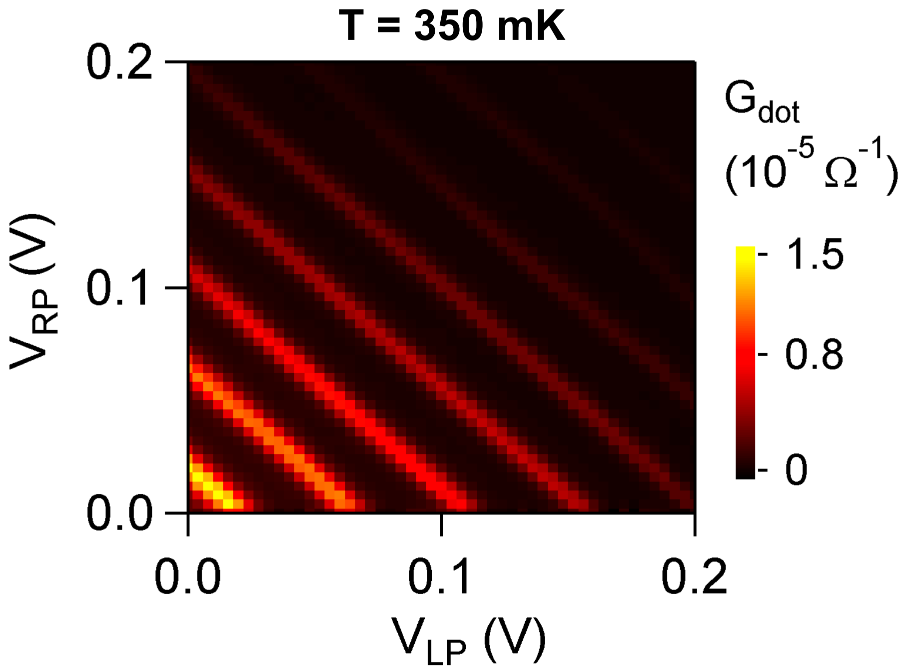


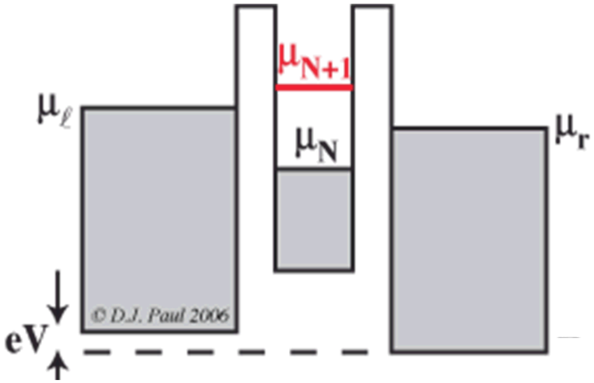
- Accumulation density vs. V_{TG} matches expected layer thicknesses for ε_r = 11.5, 7.2 for AlGaAs and Al_2O_3
- Mobility > 1×10^5 cm^2/Vs, mfp > 1 μm for p > 2×10^{11} cm^{-2}

Hole Quantum Dot and Coulomb Blockade

- Fabricated quantum dot devices on shallow 2D hole wafers and characterized at T = 350 mK.
- Able to form single quantum dot. Observed Coulomb blockade in 2 out of 2 devices tested.
- Conductance is stable over time with no noticeable hysteresis.

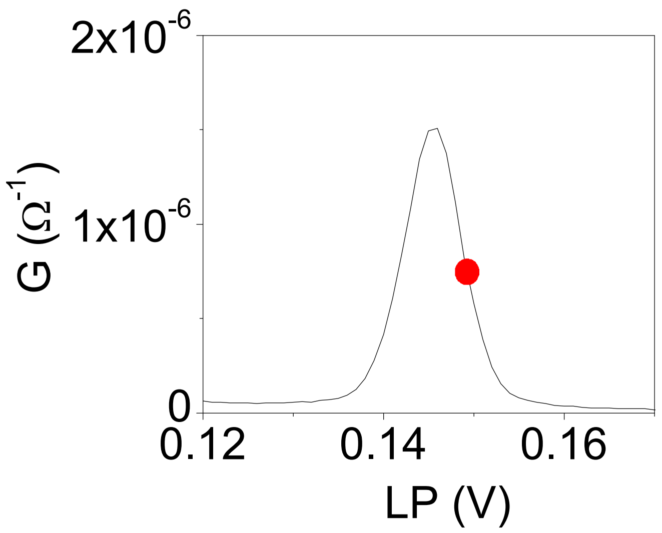


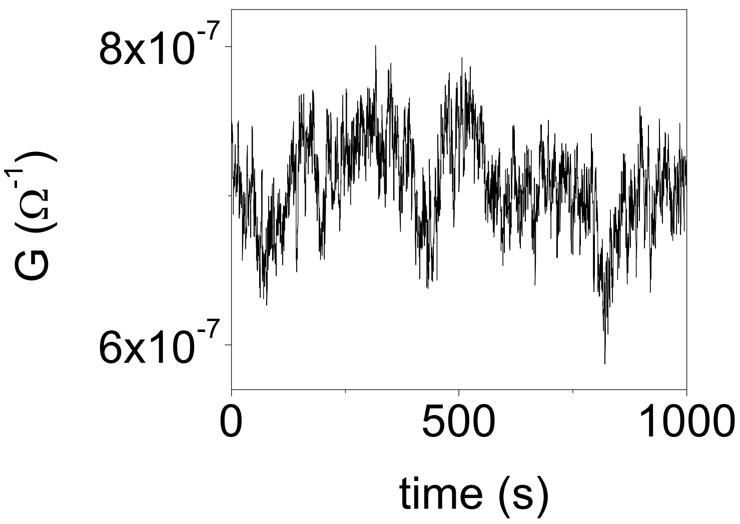


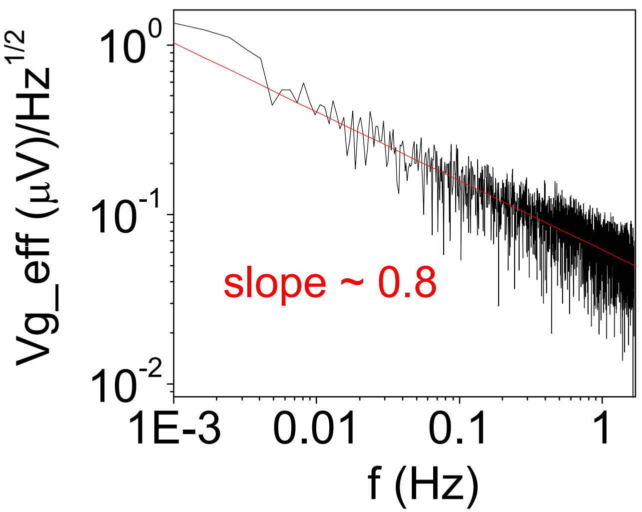


Sandia National Laboratories

Charge Noise



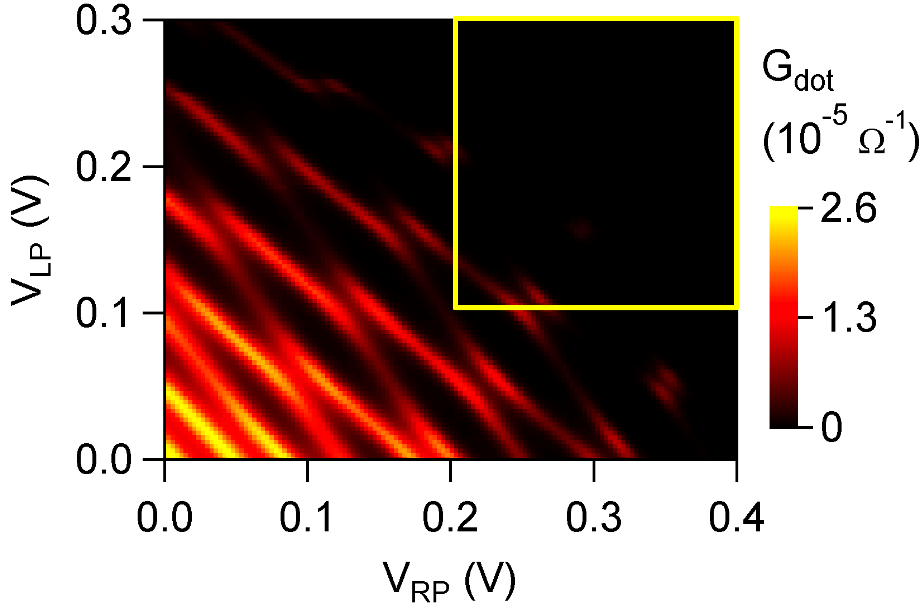


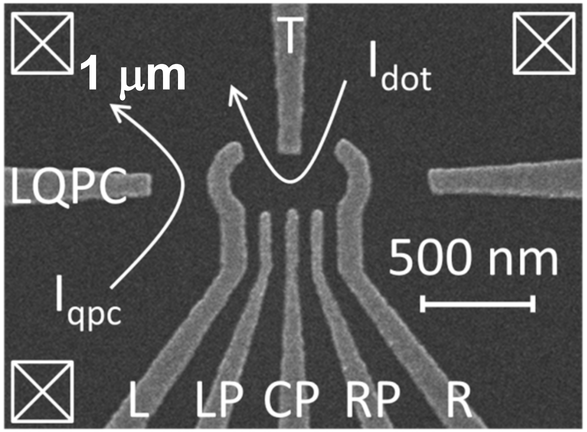


- ✓ Noise is fairly low -- near limit of noise of gate voltage source (battery box)

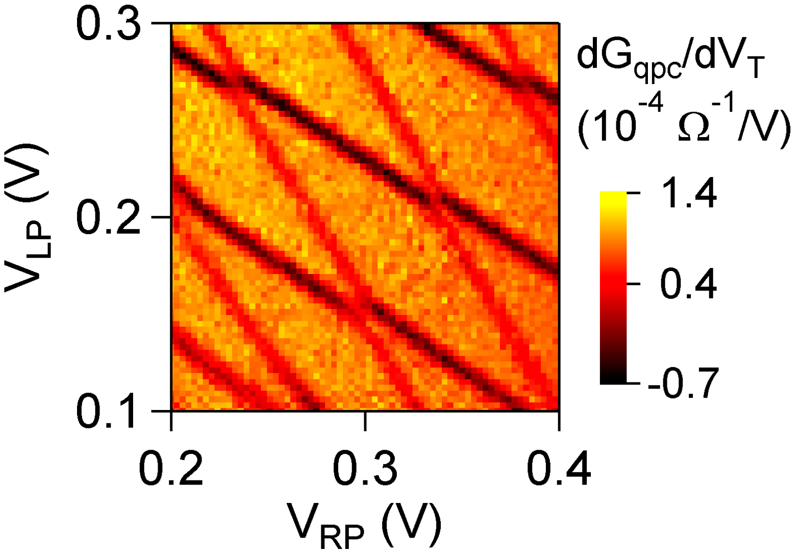
Sandia National Laboratories

Double Quantum Dot and Charge Sensing



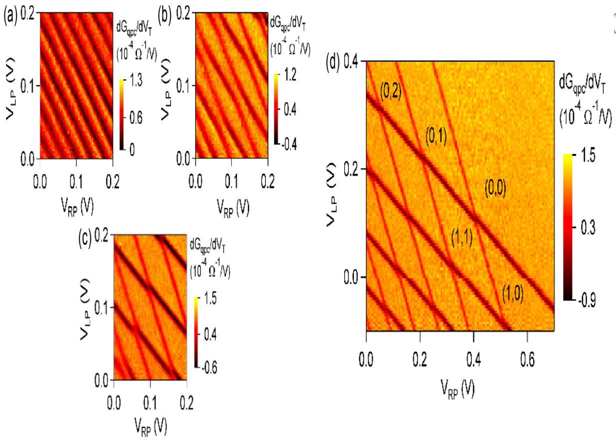


- Can use CP gate to form double quantum dot
- Charge sensing can be used to measure DQD occupation beyond region with transport through dot.

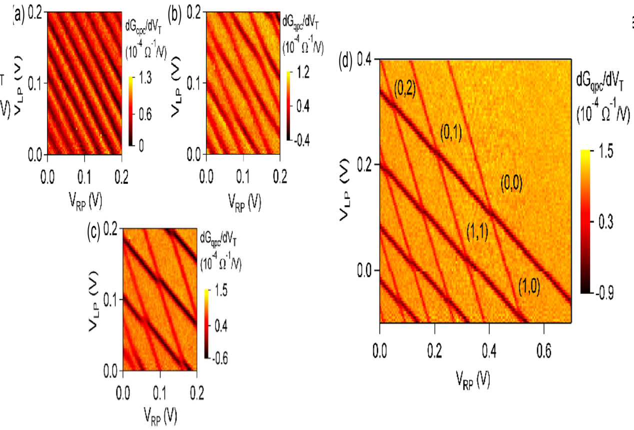


Tuning and Emptying of DQD

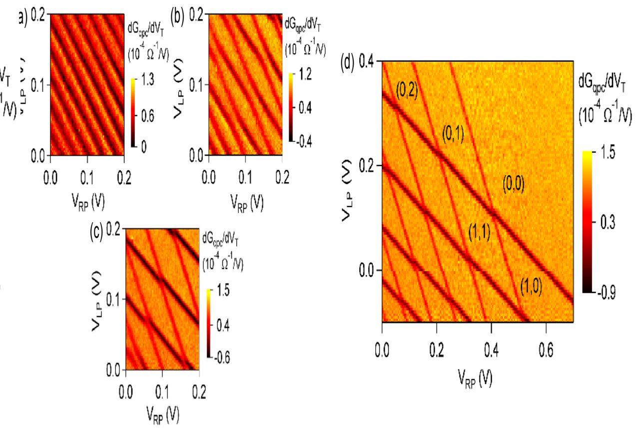
CP = 0 V

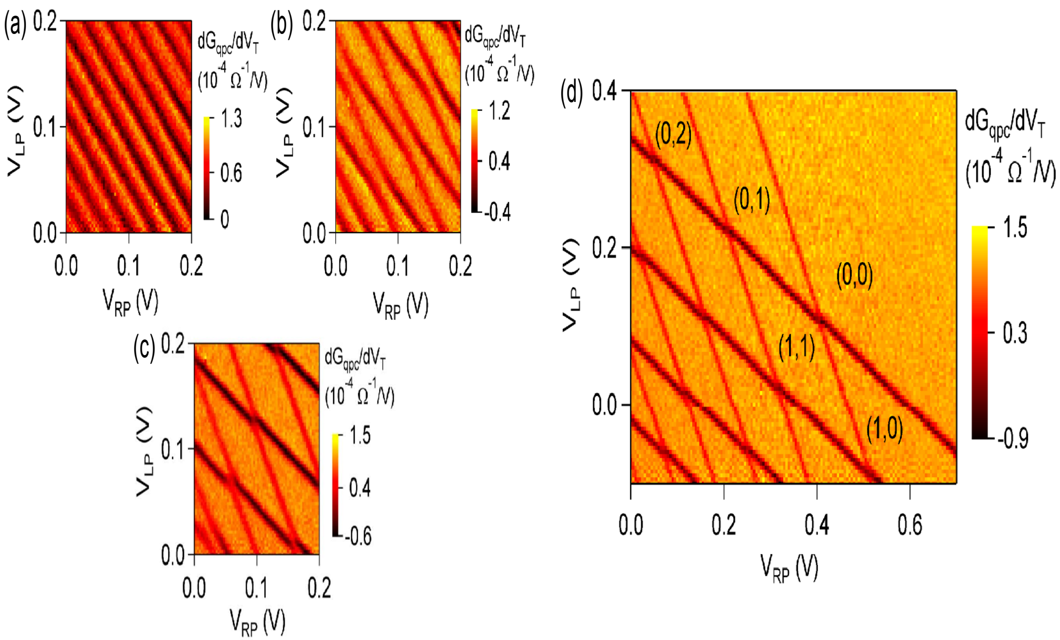


CP = 0.2 V



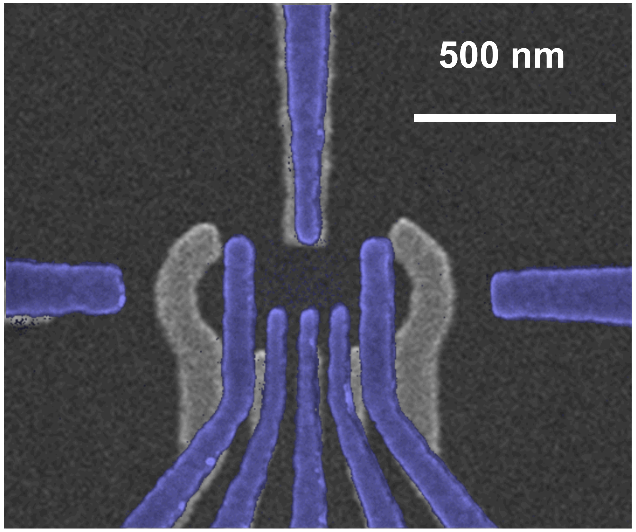
CP = 0.4 V

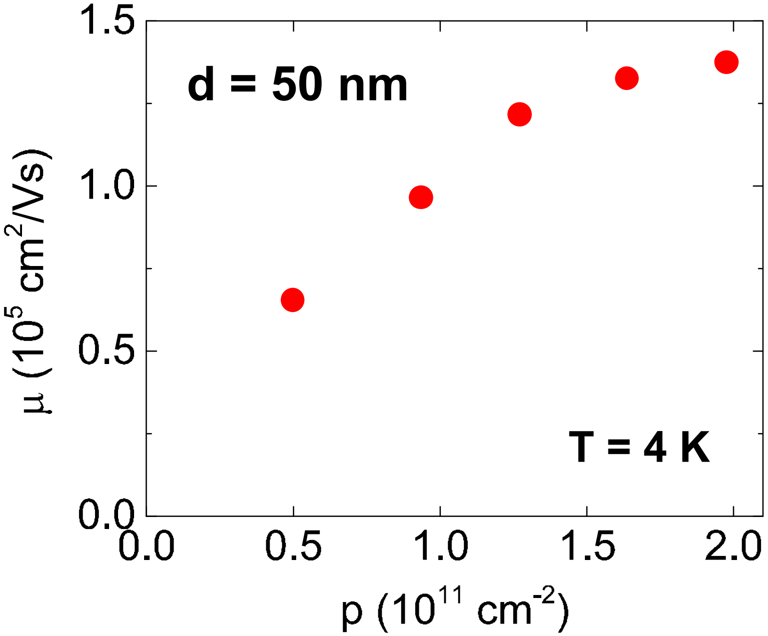




- Can use CP gate to tune interdot coupling
- DQD occupation can be determined for few-hole occupation (down to empty dot) using charge sensing

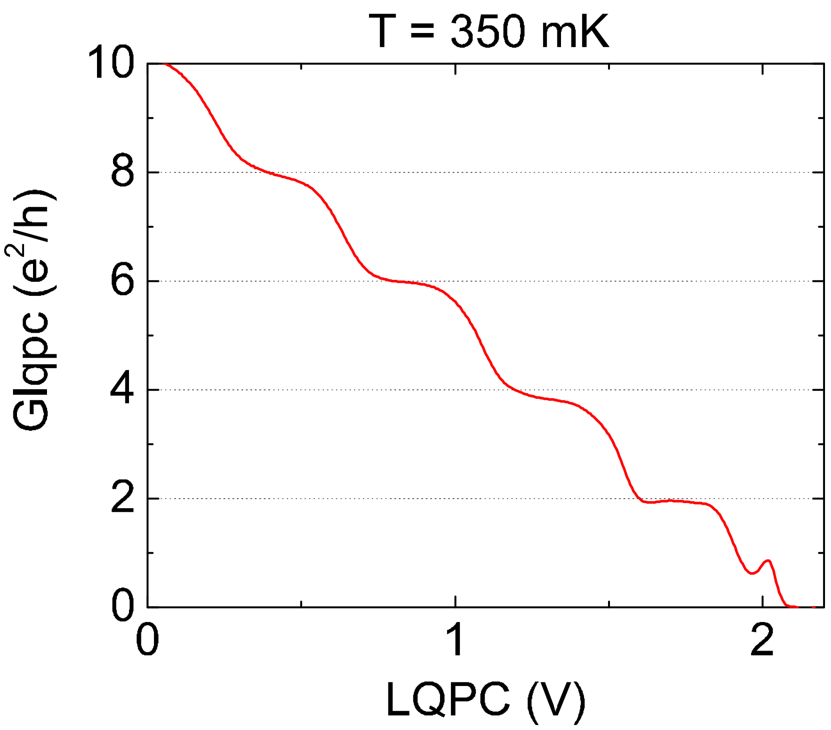
New Gate Geometries and Shallow Heterostructures

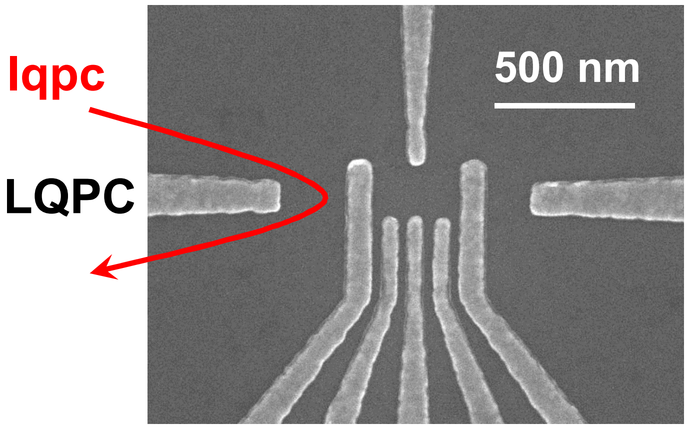




- Goal: Pauli spin blockade in DQD at few-hole occupation. Requires transport through dot when dot is nearly empty → reduce distance between two dots and between dots and leads.
  - Shrink and modify gate geometry.
  - Shallow 2D layers. Minimum feature size in 2D layer is set by distance to gates. Reduced 2D layer depth to 50 nm (2x reduction). Mobility > 10^5 cm^2/Vs for p > $1\text{x}10^{11}$ cm^{-2}.

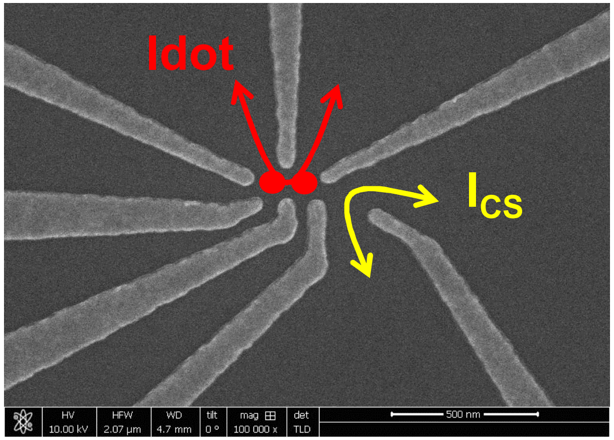
Charge Sensor QPC and Ballistic Transport

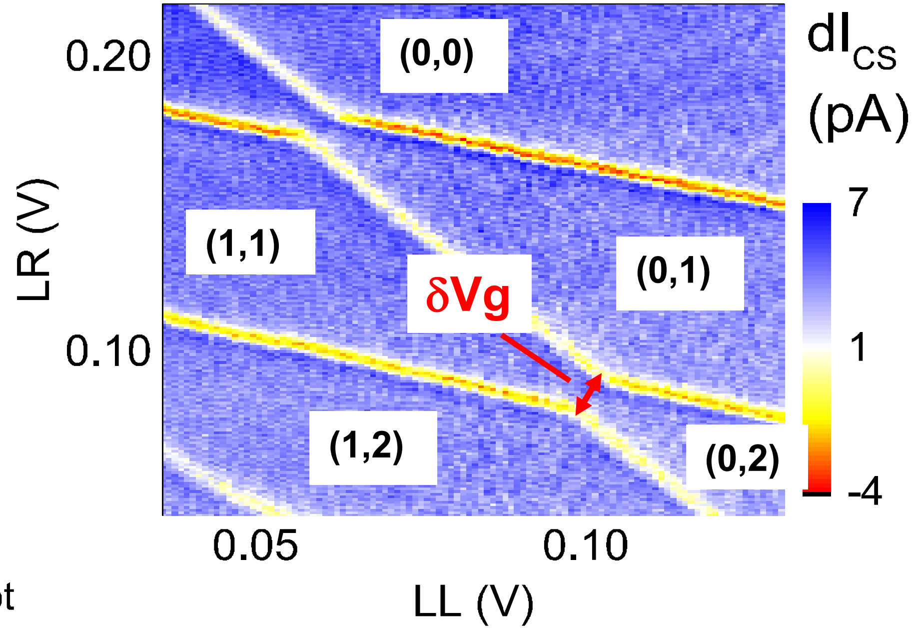


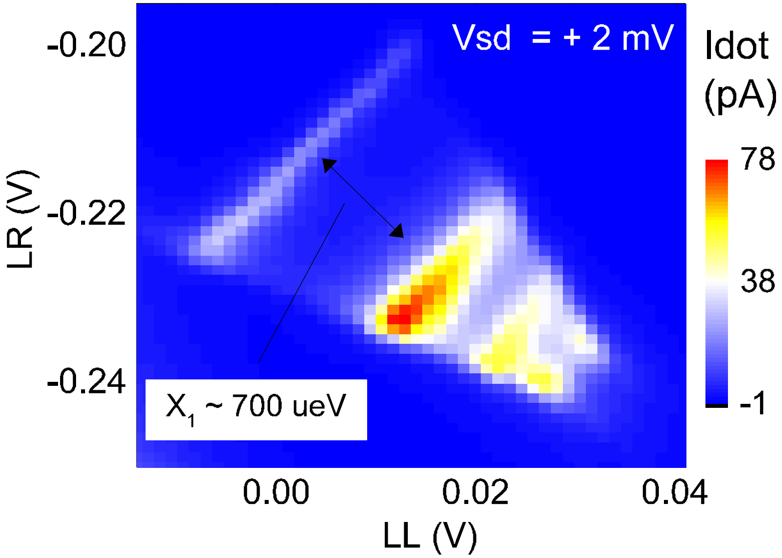


- Plateaux near multiples of $2e^2/h$ indicates ballistic transport → low disorder
- Feature below $2e^2/h$ likely due to “0.7 structure”

Transport and Charge Sensing at (1,1) – (0,2)



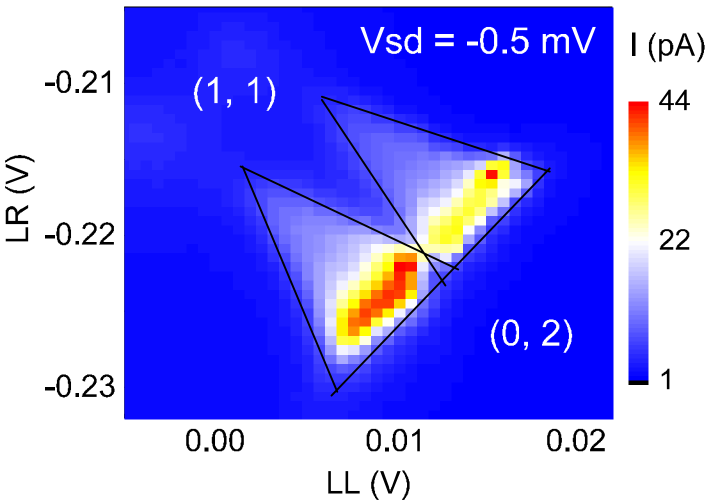


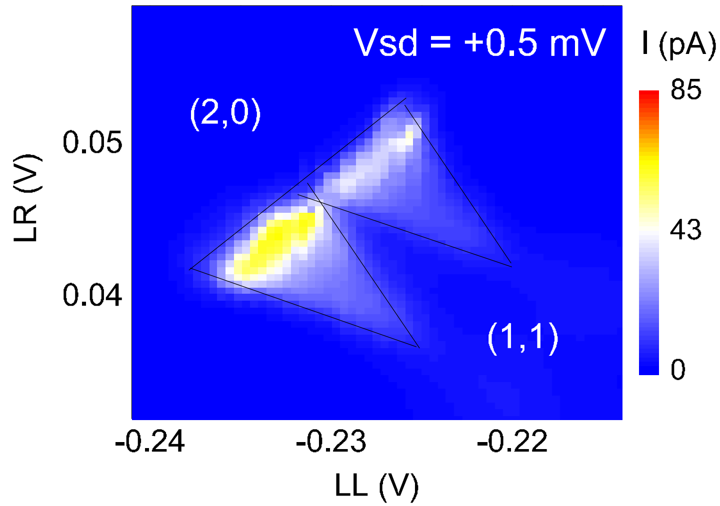


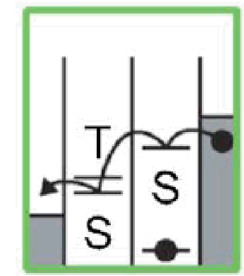
- New gate design allows transport through double dot in few-hole regime
- Large interdot coupling now appears possible in few-hole regime.

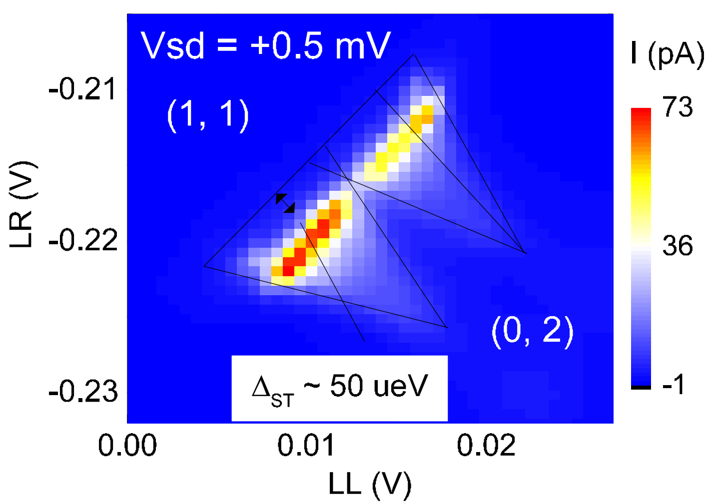
Sandia National Laboratories

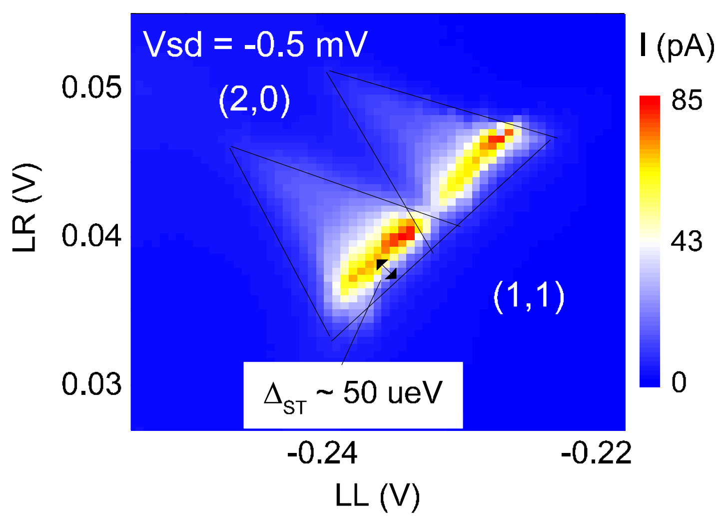
Pauli Spin Blockade?

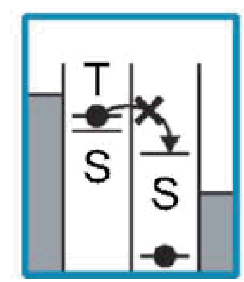






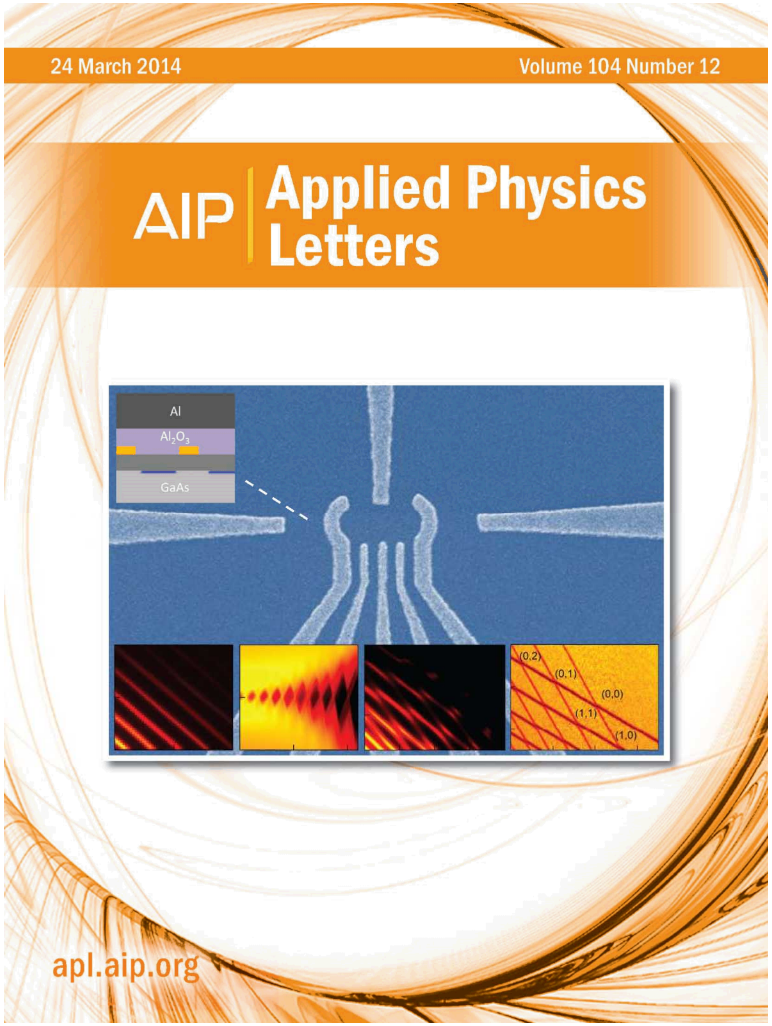






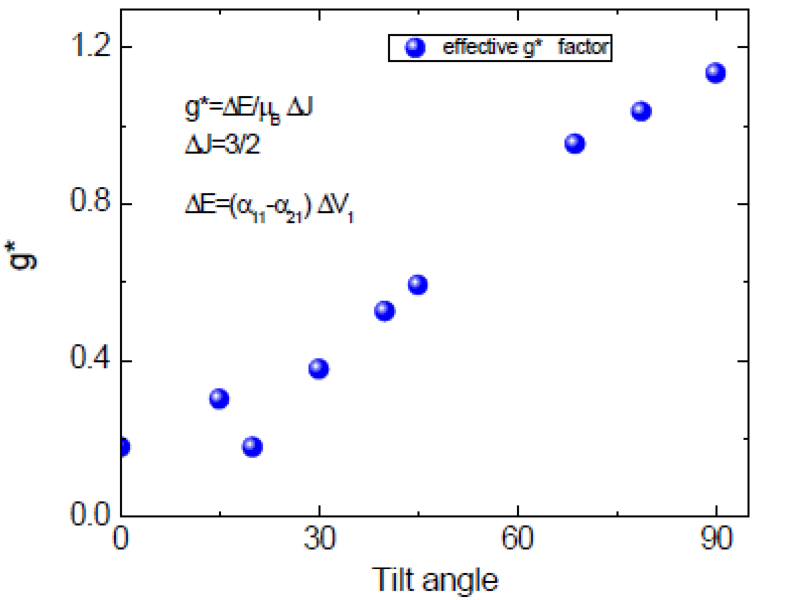
Publications, Collaborations

- "Few Hole Double Quantum Dot in an Undoped GaAs/AlGaAs Heterostructure", Appl. Phys. Lett. 104 (2014) (cover article)
- External collaboration developed with Andrew Sachrajda and co-workers at the National Research Council Canada. Investigate physics of single hole spins in magnetic field + dilution refrigerator with RF lines.



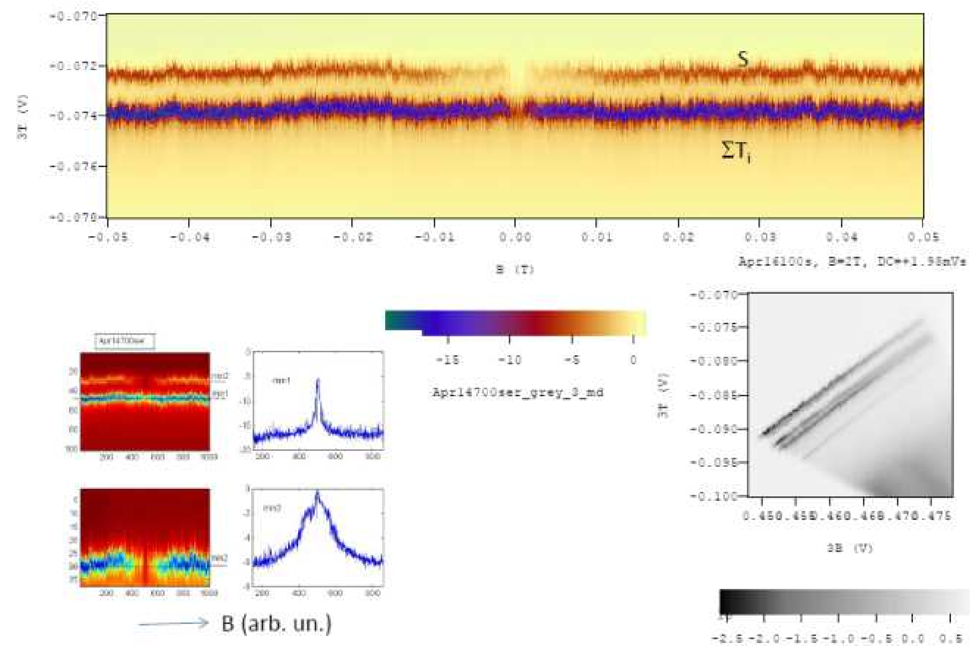
Initial NRC Measurements on p-type DQD device

Heavy-hole g-factor and anisotropy



- Initial results reasonable when compared to bulk 2D values from literature

DQD magnetospectroscopy at (1,1) – (0,2) transition



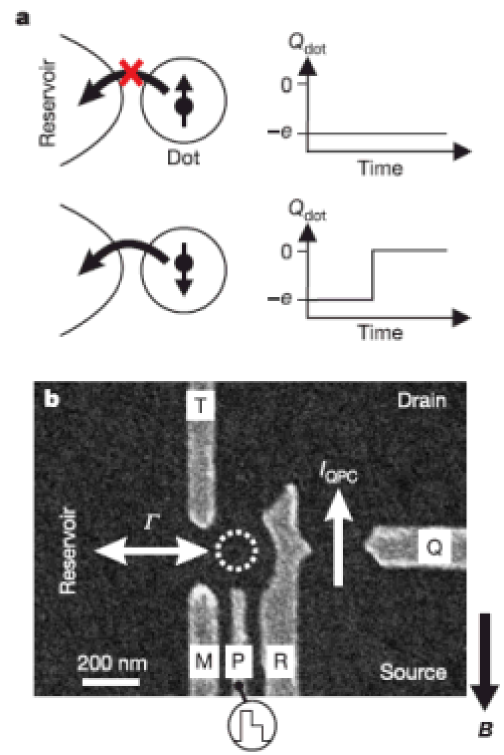
- Reminiscent of data for nanowire DQDs in systems with spin-orbit coupling (InAs Ge-Si core-shell wires)
- NRC offering theory support

Future Directions

Long-term goals (collaboration with NRC Canada, RF measurements in dilution fridge):

- Manipulation of spin degree of freedom using spin-orbit interaction
- Experiments to measure spin lifetime and coherence time
- Investigate interactions between hole spins (Pauli blockade, …)

Ex: Spin-dependent tunneling and T_1 measurement for e^- QD in GaAs
Elzerman *et al*., Nature, 2004



New quantum dot designs
for NRC collaboration