SAND2013-2873P

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Pulsed Electron Transition Measurements in a Silicon Double Quantum Dot

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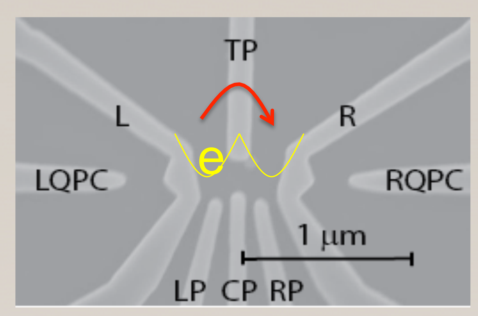
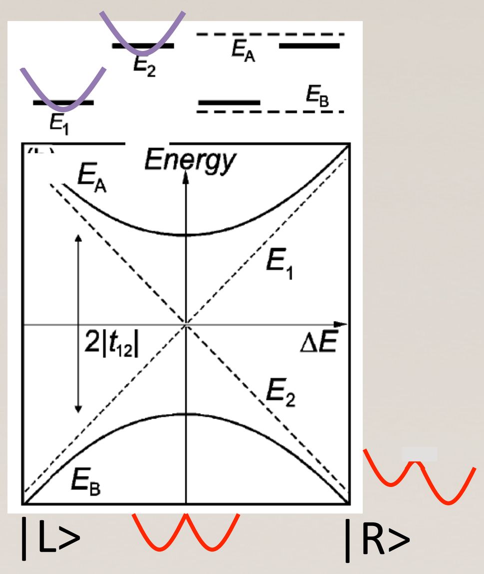
Charge qubit encoding for QUBO

At the triple points of semiconductor double quantum dots, a charge qubit can be formed with an electron on the left or right side of the dot forming the 2 level system. The tunneling between the dots (for initialization) and the electric field on the double well potential (either positive or negative) are the experimental parameters for QUBO.

Si MOS gated double quantum dot



Use QD technology as learning platform



- Measurement technique (e.g., initialization, evolution, read-out)
- Test negative exchange design & DQD-DQD coupling
- Characterize material issues

Motivations:

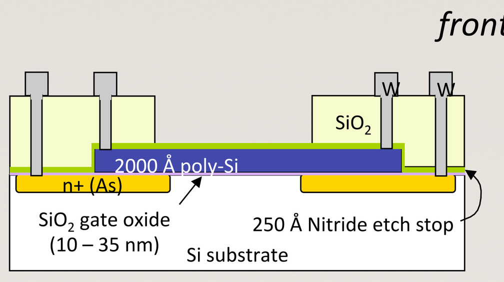
- Charge qubit encoding is easier to experimentally implement
- Stable ground state (relaxation self-corrects excitation errors)

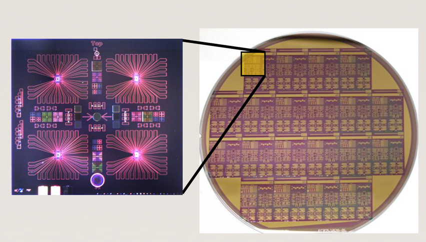
Semiconductor double quantum dots

Silicon metal-oxide-semiconductor (MOS) dots

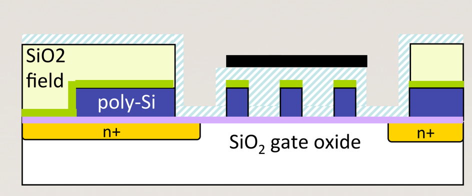
MOS devices are started in a silicon fab, and completed with electron beam lithography, ALD aluminum oxide and a final metal step for the accumulation gate.

front-end: silicon fab





back-end: nanolithography

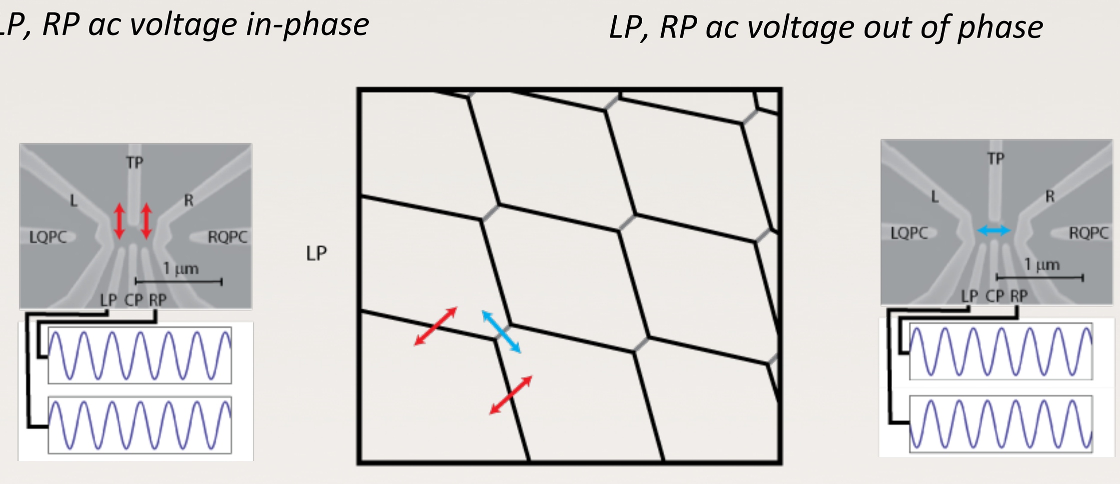


Measurement techniques

Charge sensing

The charge occupation of the double dot is measured using a differential technique. The signal indicates a change in DQD occupation.

LP, RP ac voltage in-phase *LP, RP ac voltage out of phase*

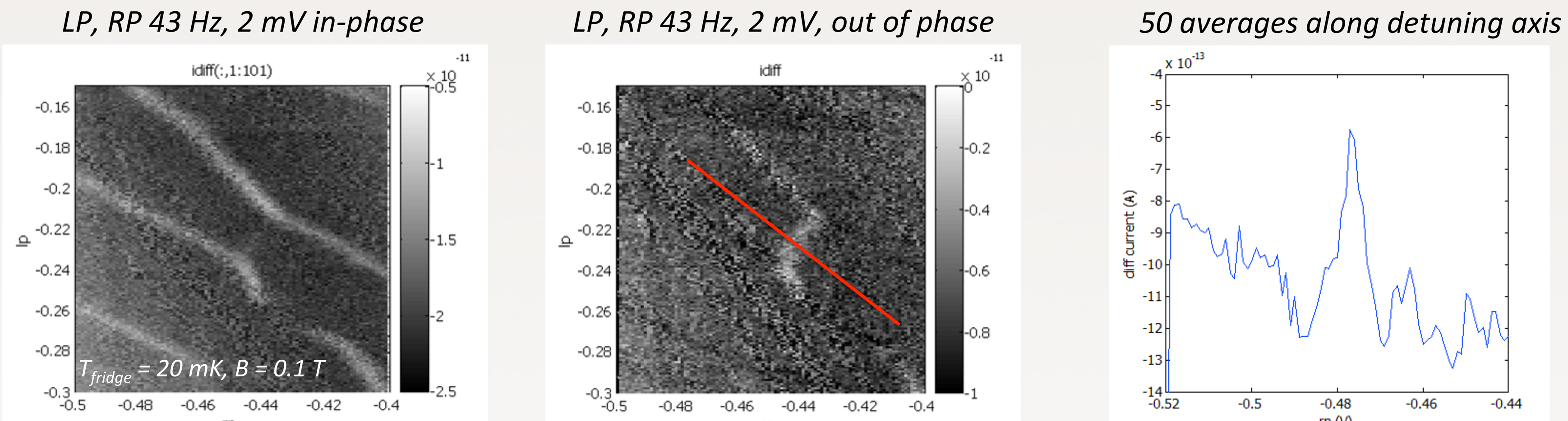


- In the differential charge sense technique, the point contact is biased with a dc voltage (100 to 500 μV) and an ac signal is added to one of the gates (2-5 mV).
- ac current is due to a change of the conductance of the channel when the ac signal changes the dot occupation.

Both ac and dc current are measured.

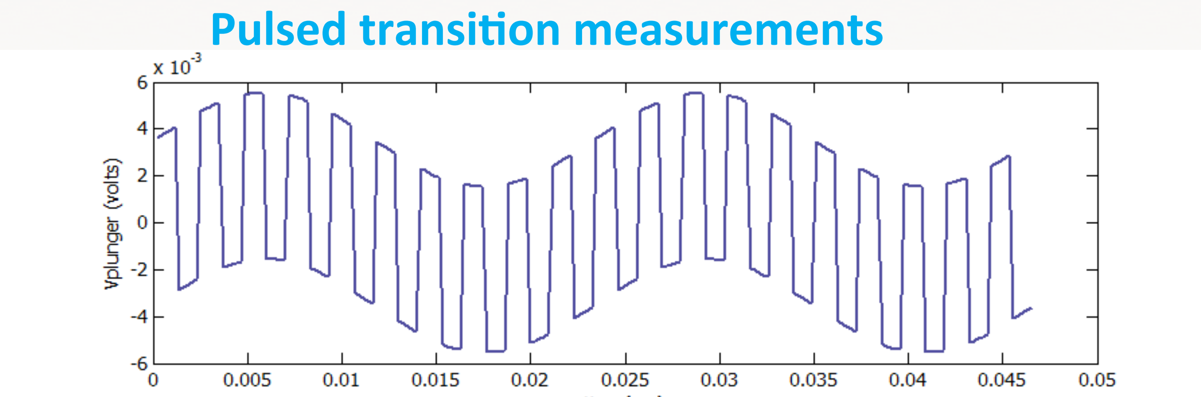
Interdot transitions

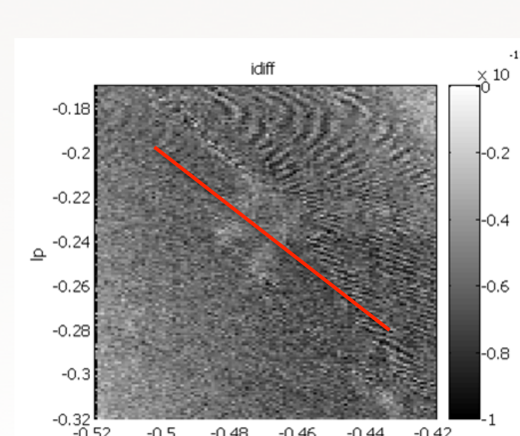
LP, RP 43 Hz, 2 mV in-phase *LP, RP 43 Hz, 2 mV, out of phase* *50 averages along detuning axis*



Varying RP and LP, we can move an electron from one dot to the other. This detuning sweep moves electrons from $|L\rangle$ to $|R\rangle$ in the energy diagram above. A single peak is observed at the transition

Pulsed transition measurements





In addition to the sine wave for charge sensing, we can also superimpose a rapid change of position using a square wave with a tunable risetime. For long wait time (slow square wave frequency), the connection line in the triple point is doubled.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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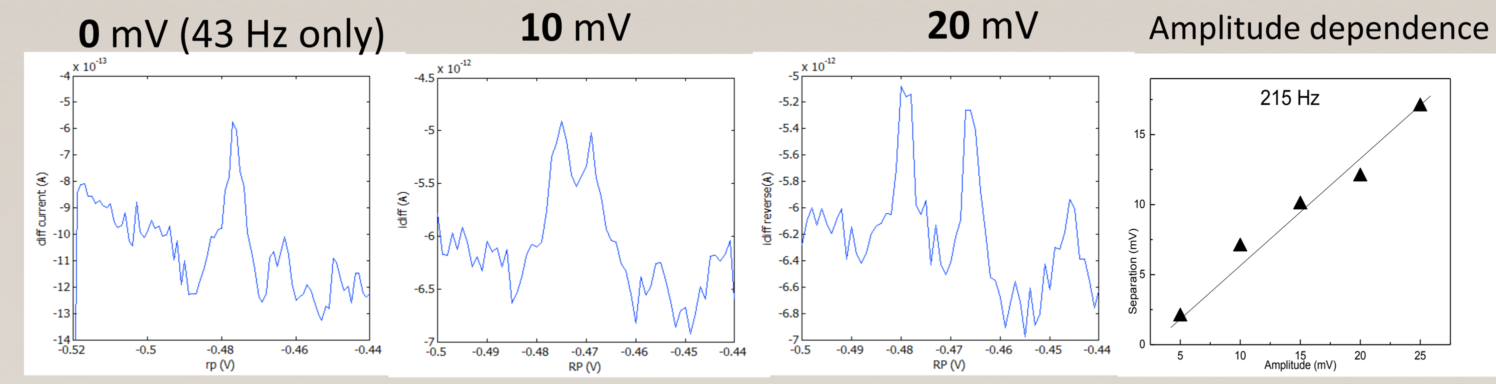
Interdot transtion dynamics probed with pulsing

Pulsed transitions: amplitude dependence

Shown below are 50 averages of a detuning sweep for a slow square wave of 215 Hz, 16 ns risetime.

0 mV (43 Hz only) **10** mV **20** mV Amplitude dependence

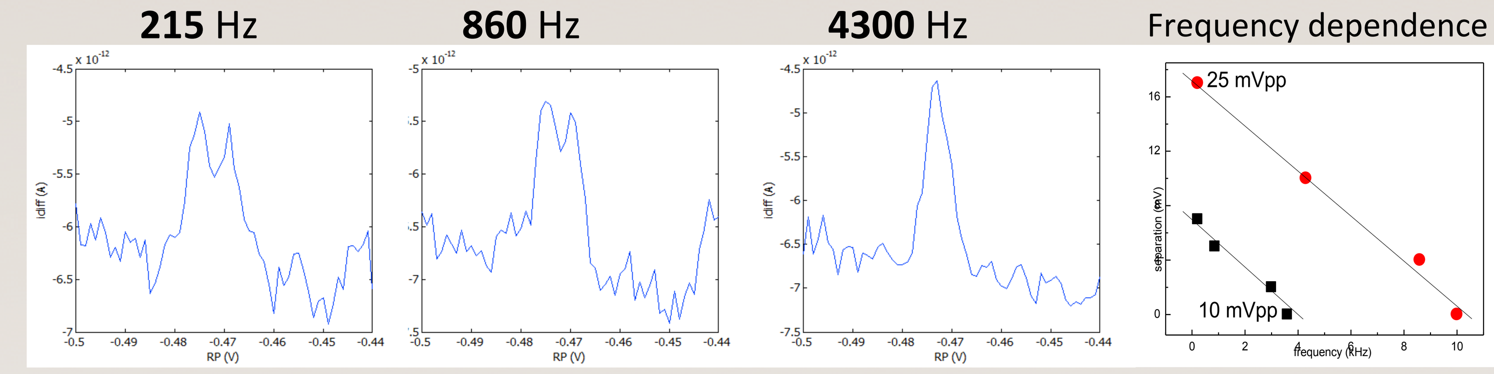


- For this slow transition, the electron has plenty of time to move to move back and forth between the dots, and there is a peak for each side of the square wave.
- The peaks are broadened by the amplitude of the 43 Hz sine wave used for charge sensing. Other broadening effects (i.e. temperature) are involved for lower CS signals.
- For large enough pulse amplitudes, we would expect to see occupation of excited states. While other features are present in the data, they do not consistently appear.

Pulsed transitions: frequency dependence

Detuning sweeps for 10 mV square wave amplitudes at different frequencies show an evolution from two peaks to a single peak.

215 Hz **860** Hz **4300** Hz Frequency dependence

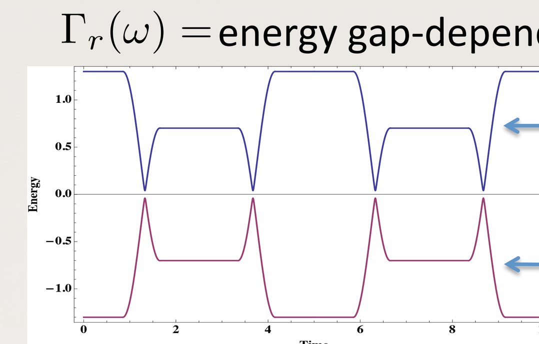


- As the transition rate increase, the two peaks merge and form a single peak.
- Using longer risetimes, the qualitative peak merging effect shown here is very similar.
- The merged peak indicates that the electron cannot make interdot transitions at these fast rates.
- Measurement-induced dephasing rate, $\Gamma_d = \frac{1}{2\pi e}(\sqrt{I_1} - \sqrt{I_2})^2 \sim \mathrm{Hz}$, with QPC current I_1 = 2 nA, I_1-I_2 = 0.25 pA, is insignificant. The double peak structure, hence, does not result from back action.

Modeling

Assuming relaxation dominated by coupling to acoustic deformation phonons (spin-boson model)

$\Gamma_r(\omega)$ = energy gap-dependent relaxation rate (gap = $\hbar\omega$)



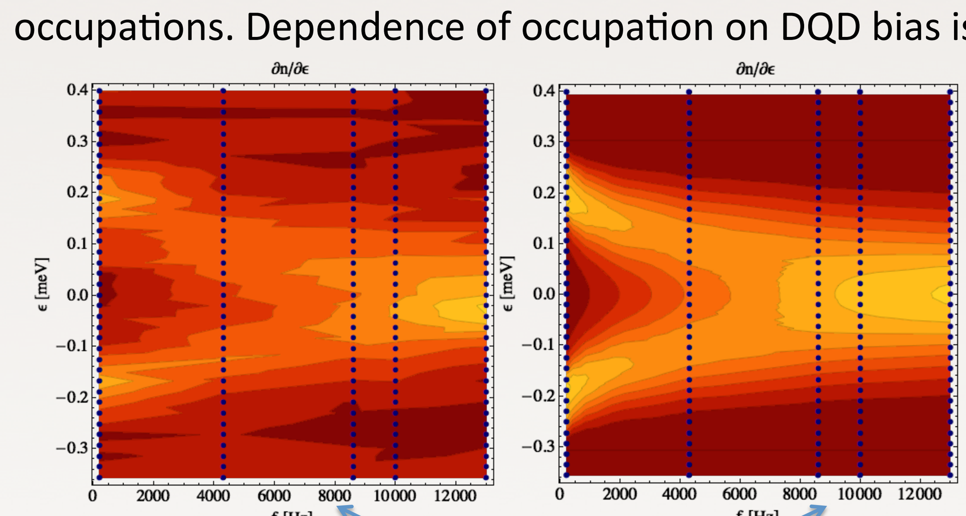
Rate equation for ground/excited state occupations:

$$\dot{\rho}_{00}(t) = \langle E_0|\dot{\rho}(t)|E_0\rangle = \Gamma_r(\omega)\left[\frac{1}{1+e^{-\beta\hbar\omega}} - \rho_{00}(t)\right]$$

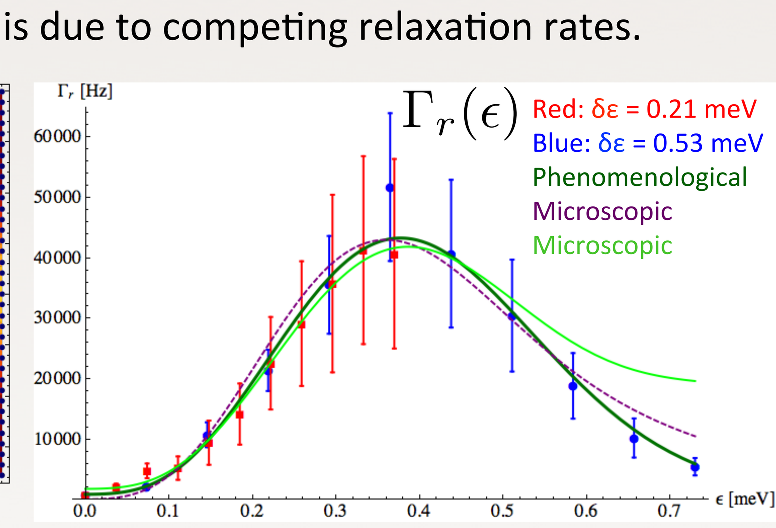
$$\dot{\rho}_{11}(t) = \langle E_1|\dot{\rho}(t)|E_1\rangle = \Gamma_r(\omega)\left[\frac{e^{-\beta\hbar\omega}}{1+e^{-\beta\hbar\omega}} - \rho_{11}(t)\right]$$

$$(\beta \equiv (k_B T)^{-1})$$

Take long-time average (dynamical equilibrium) of this master equation to compute time-averaged occupations. Dependence of occupation on DQD bias is due to competing relaxation rates.



Differential time-averaged occupation $\partial\bar{n}/\partial\epsilon$ for 25 mV peak-to-peak switching amplitude



Relaxation rate agrees with coupling to deformation acoustic phonons

Summary and Collaborations

- Using charge sensing, we explore the dynamics of interdot transitions.
- As a function of frequency, we observe two charge sense peaks for long wait times merging to a single peak for short wait times and this is independent of measurement setup as proved in other experiment.
- A relaxation model indicates super-Ohmic relaxation.
- Pulsed techniques provide a possible way to probe slow inelastic relaxation times.

National Research Council (A. Sachrajda)

Australian Centre for Quantum computing Technology (L. Hollenberg, D. Jamieson, M. Simmons, A. Dzurak, A. Morello); U. Wisconsin (M. Eriksson, D. Savage, M. Friesen, R. Joynt) ; Princeton University (S. Lyon); NIST (N. Zimmerman);U. Maryland (S. Das Sarma, M. Peckerar)

Lawrence Berkeley National Labs (T. Schenkel)

U. Sherbrooke (M. Pioro-Ladriere)

Carleton College (D. Luhman); U. New Mexico (L. Lester)

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