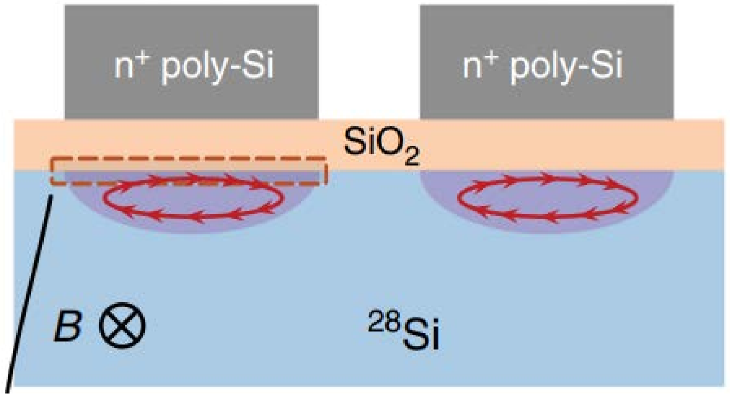
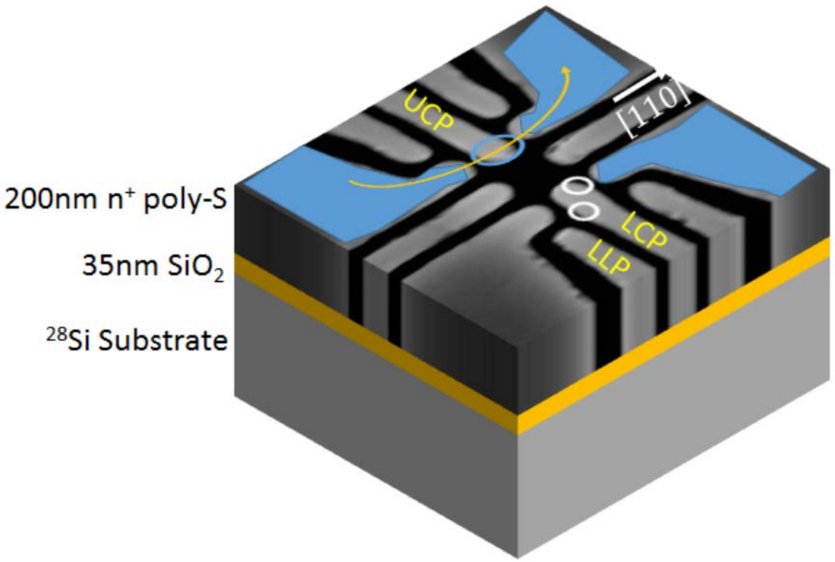
A Silicon Metal-Oxide Semiconductor Electron Spin-Orbit Qubit





Kris Cerveny

FAM talk 12.10.2018

Jock et al., Nature Comm. **9**, 1768 (2018)

Outline

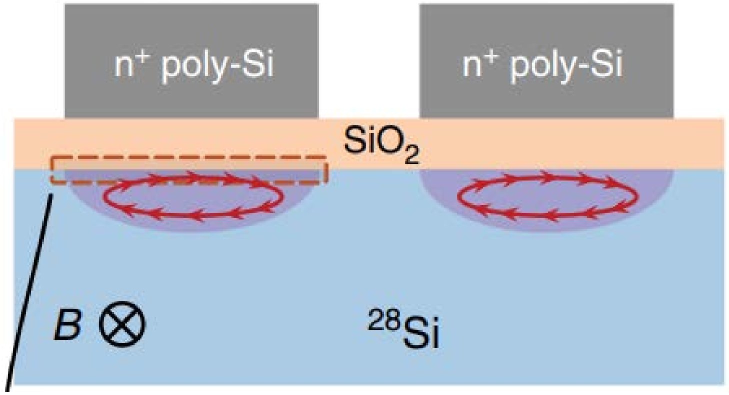
- Motivation
- Their system
- What they have done
  - Use g-factor difference from the SO coupling at the Si/SiO_2 interface to get second axis of control for DQD S-T qubit
  - Study qubit noise and SO interaction at interface
  - Quantitative characterization of charge noise in MOS qubit (quasi-static detuning variance and Hahn-echo time)
  - Demonstrate that MOS interfaces have inherent properties for two-axis qubit control
- Conclusion

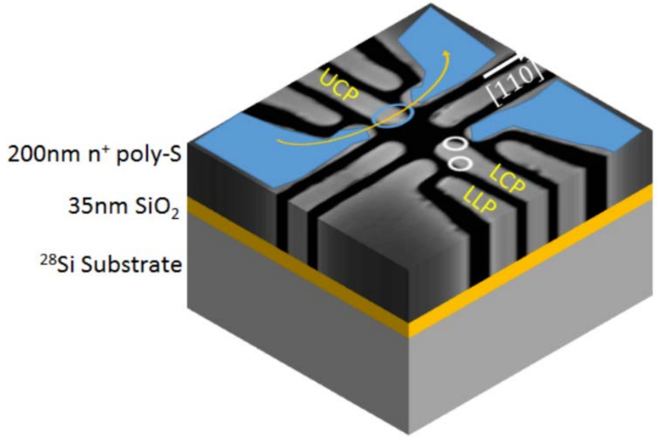
Motivation

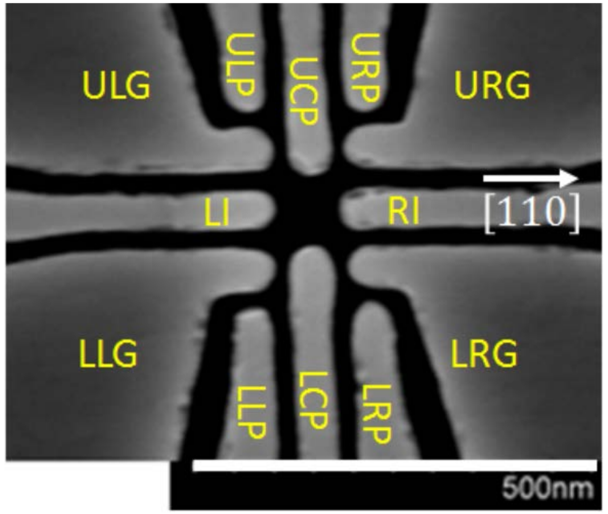
- Persistent concerns about disordered Si/SiO_2 interface leading to
  - Additional charge noise
  - Variable g-factors
- Many have used Si/SiGe heterostructures to move interface away
  - Results in small and/or variable valley splitting
- Want a direct characterization of charge noise at MOS interface
- Means to characterize a SO S-T qubit and its coherent qubit rotations
- See full magnetic field angular dependence
- *Spend more time with spin qubits, particularly at Si interface to SiO_2*

The System

- Fully foundry-compatible process with single gate layer MOS poly-silicon gate stack on an epitaxially-enriched ^{28}Si epilayer with 500 ppm residual ^{29}Si
- Hall bar measurements on same wafer yield
  - $n = 5.7 \times 10^{11}\ cm^{-2}$
  - $\mu = 4500\ cm^2 V^{-1} s^{-1}$
  - $V_{th} = 1.1\ V$
  - $T_e \sim 150\ mK$
- Accumulation mode using highly-doped n+ poly-silicon gates
- Tune lower half of device to form DQD (one tunnel-coupled to LRG)
- Upper half used as SET charge sensor







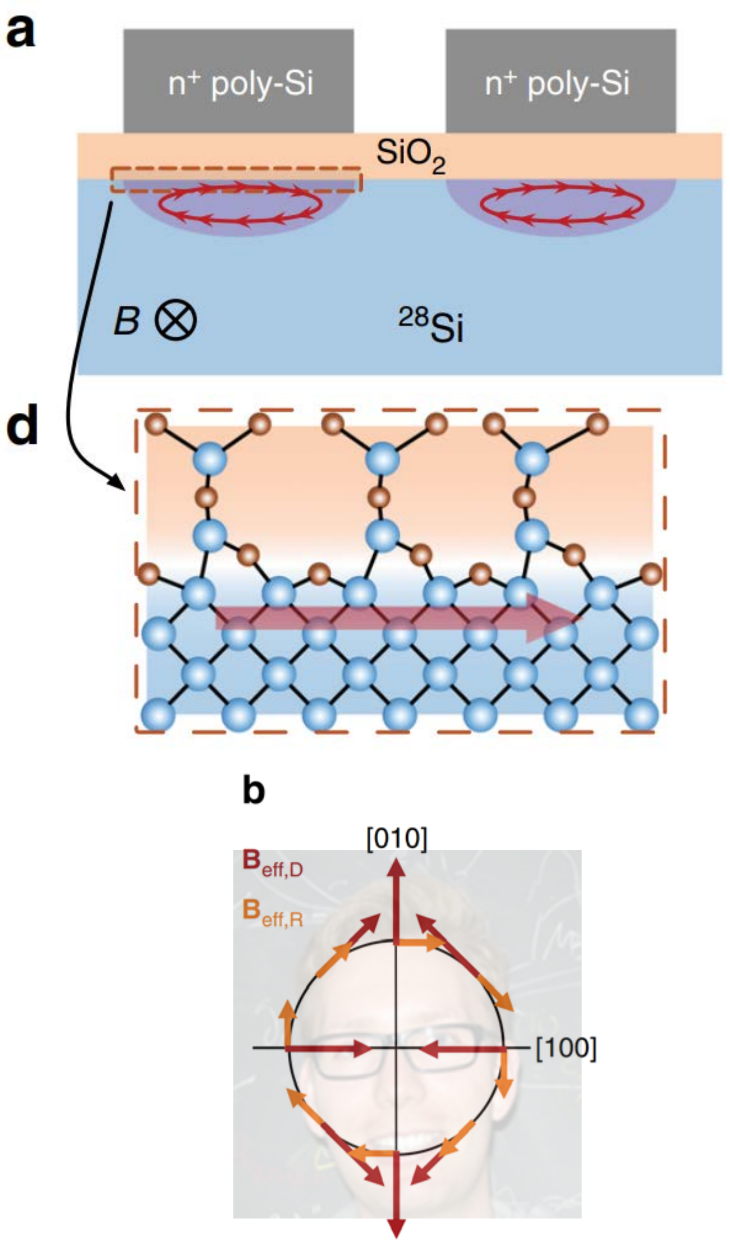
Spin-Orbit Interaction

- Interface leads to SOI:
  - B field parallel to interface leads to cyclotron motion of electrons establishing net momentum along interface
  - Coupling of this momentum perpendicular to the electric field at the interface produces the SOI

- Rashba due to vertical electric potential at interface (structural inversion asymmetry)
- Dresselhaus due to microscopic interface inversion asymmetry (potentially variable interatomic fields)

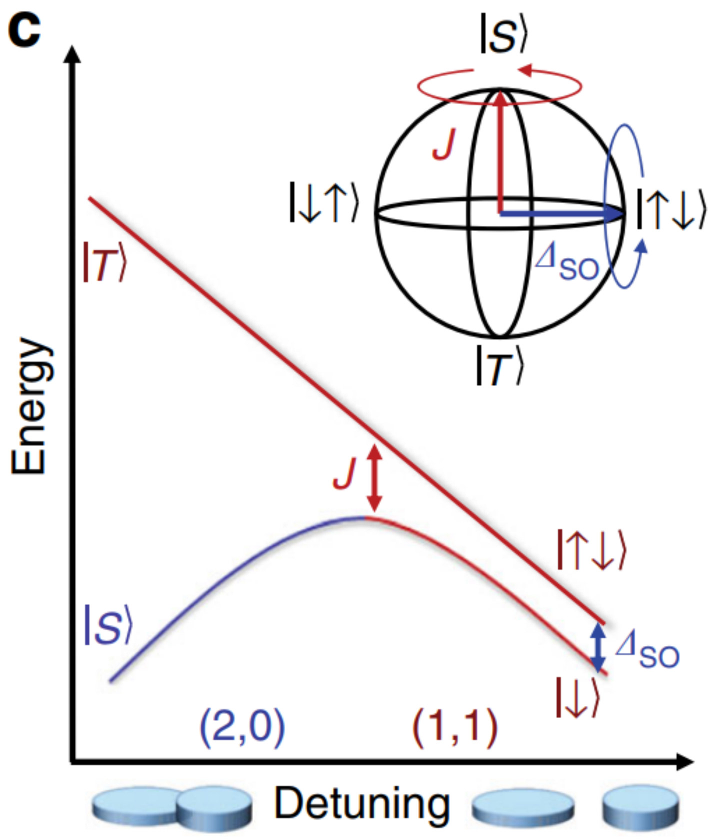
- Not unique to this system
  - Analysis of interfacial effects on g-factor variability useful in other systems

$$H_R \propto \gamma_R (P_y \sigma_x - P_x \sigma_y) \qquad H_D \propto \gamma_D (P_x \sigma_x - P_y \sigma_y)$$

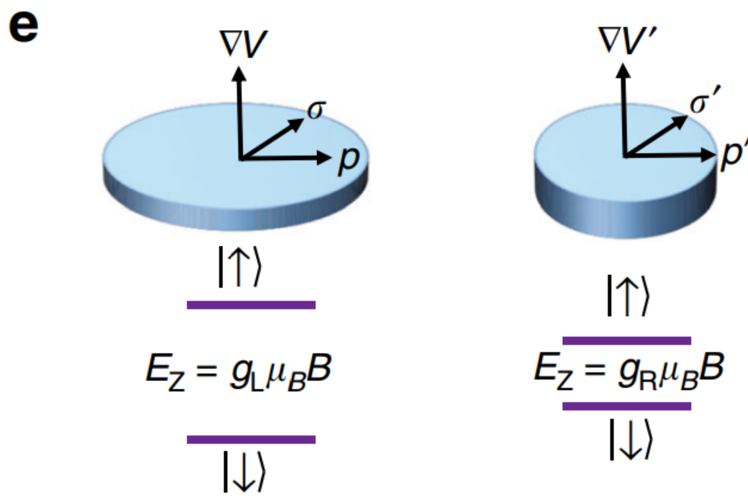


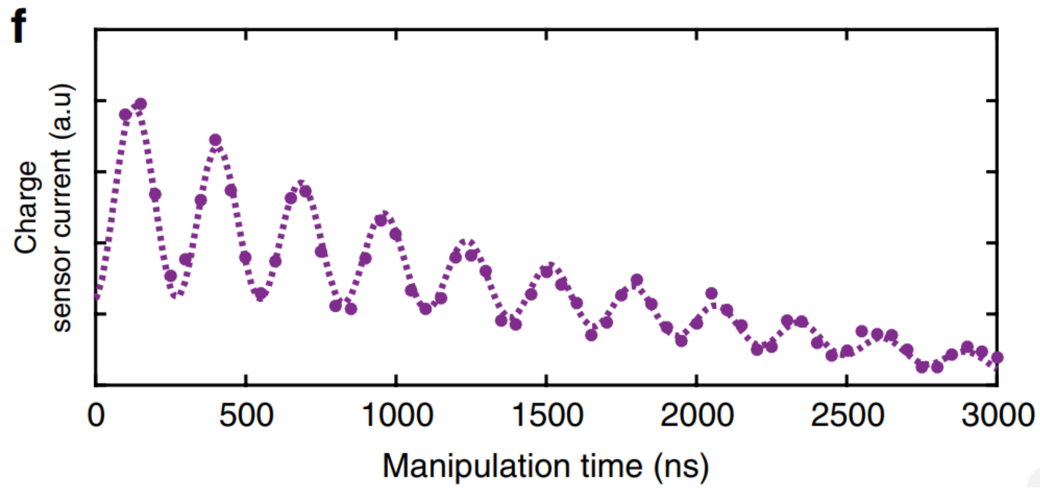
Tuning the DQD

- Near zero detuning ($\epsilon = 0$), *J* dominates → rotations around Z-axis
- Deep into (1,1) charge sector ($\epsilon > 0$), *J* small → rotations around X-axis (different Zeeman energies for the two dots)
    - ➔ use inherent g-factor difference at interface as second axis of control!



$$f(\epsilon) = \frac{1}{h}\sqrt{J(\epsilon)^2 + \Delta_{SO}^2}$$





Operation of the S-T Qubit

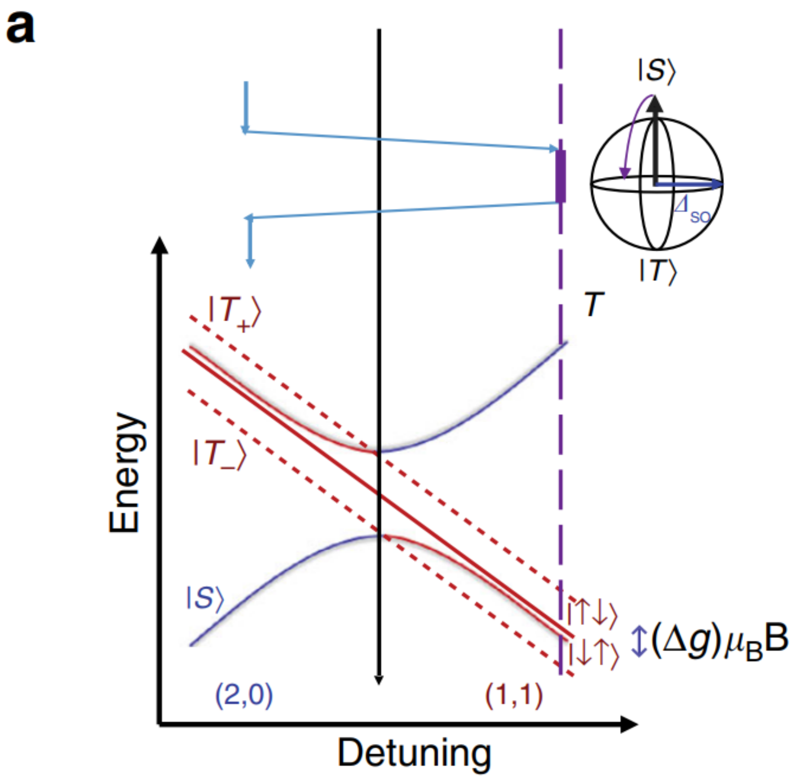
- Basis of eigenstates of the two-spin system in limit of large S-T exchange *J (S & T_0)*
- Small applied B-field splits off $m = \pm 1$ triplet states by $E_z = g\mu_B B$

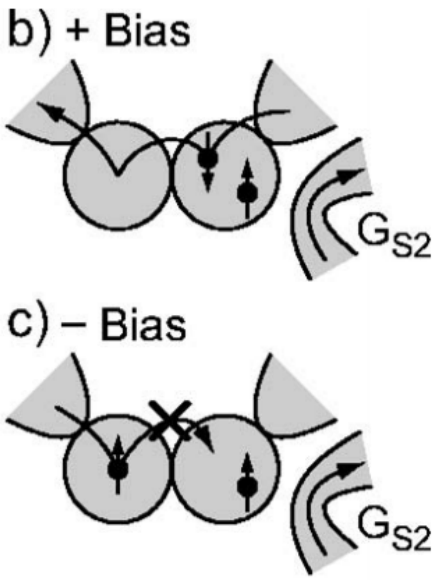
- Initialize in (2,0)
- Rapid adiabatic pulse to (deep) (1,1) state
- Difference in Larmor frequency yields rotations in X-axis between S(1,1) and T_0(1,1)

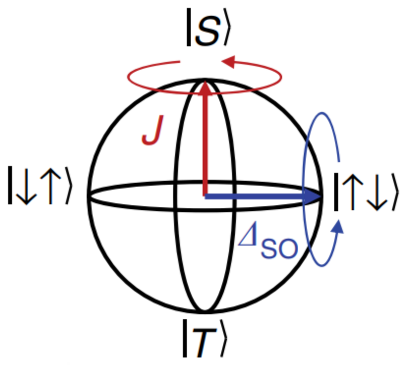
$$2\pi f = \Delta\omega = \Delta g \mu_B \, {}^{B}/_{\hbar}$$

- Driving closer to the anticrossing lets *J* dominate and drives the Z-axis rotations

- Detection using Pauli spin blockade [1] and the remote charge sensor to determine if state passed through (2,0) or was blockaded in (1,1) during readout

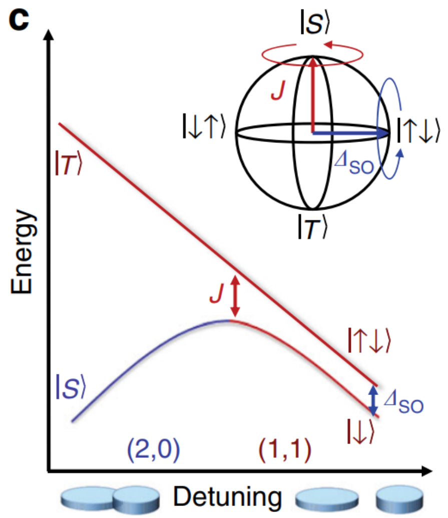




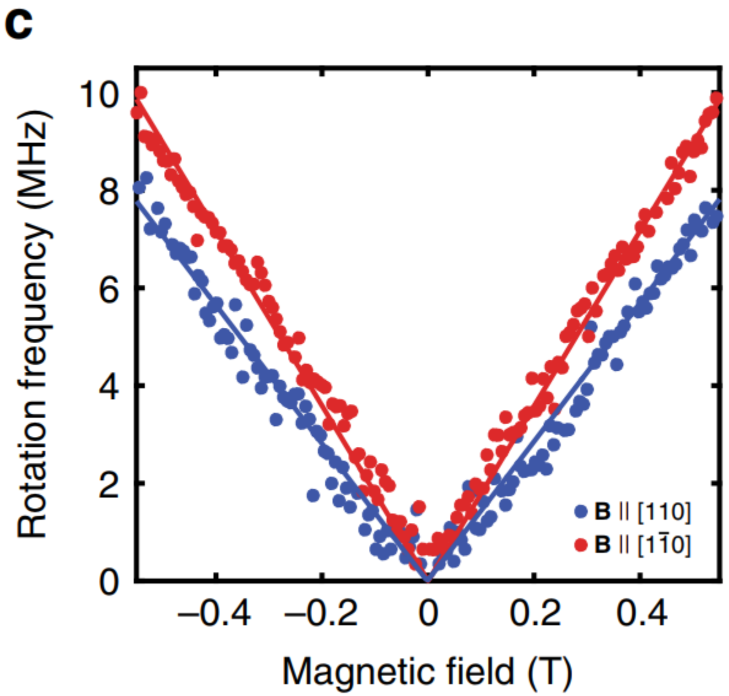


[1] Petta, Marcus et al., PRB **72**, 165308 (2005)

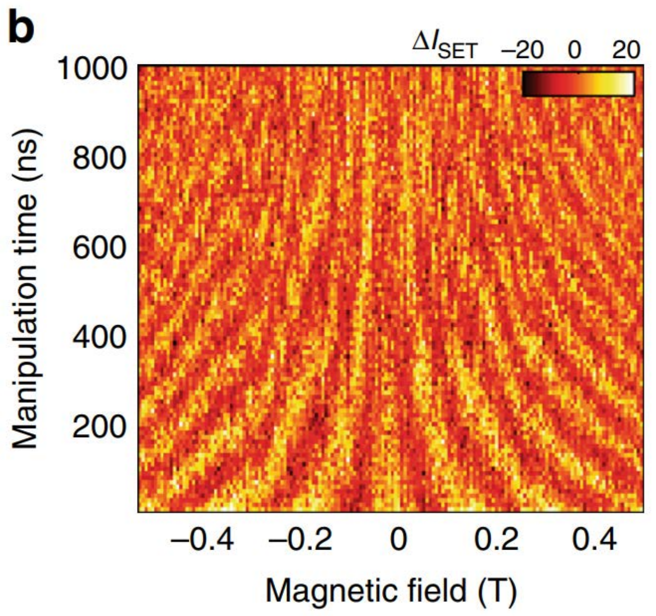
Coherent Rotations



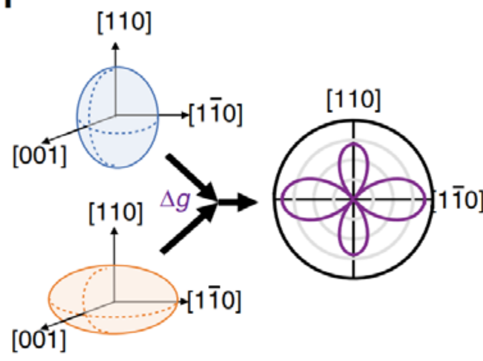
- Clear oscillations (X-axis) at large detuning to (1,1) manipulation point
- Difference in slopes indicative of angular dependence of Δg
    - Qualitatively consistent with different SOI in each dot
- Extract $\Delta\alpha = 1.89\ MHzT^{-1}, \Delta\beta = 15.7\ MHzT^{-1}$



Charge sensor current as function of B field along [1-10] direction



B-Field Dependence

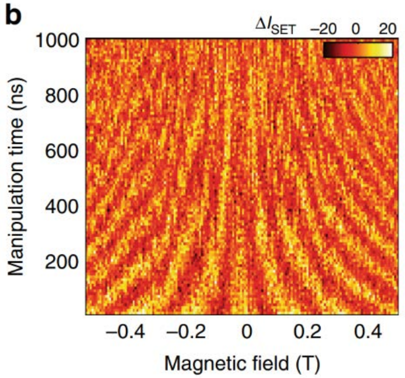


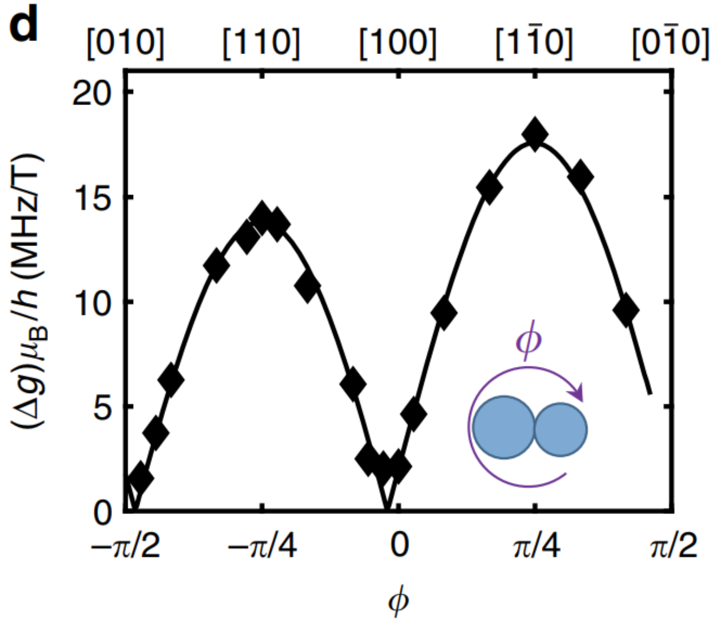
- Choice of B-field direction utilized to maximize SOI to drive spin rotations, or cancel them out
  - Potentially important for uniform spin-splitting between multiple QDs in devices

- Out-of-plane field with respect to [001] (θ) suppresses SOI difference
- In-plane field with respect to [100] (ϕ) can maximize SOI difference

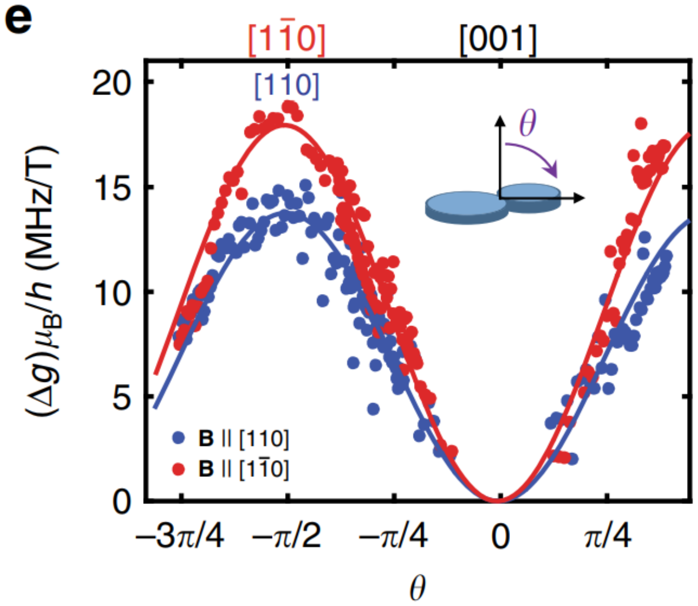
$$
\begin{aligned}
f_{\text{rot}}(\theta,\phi) &= \Delta_{\text{SO}}(\theta,\phi)/h \\
&= (\Delta g(\theta,\phi))\mu_{\text{B}}B/h \\
&= \tfrac{2}{h}|\langle S|H|T_0\rangle| \\
&= |\mathbf{B}|\underbrace{|\Delta\alpha - \Delta\beta}\sin(2\phi)|\sin^2(\theta)
\end{aligned}
$$

Difference in Rashba and Dresselhaus g-tensor perturbations between two QDs





$\theta = \dfrac{\pi}{2}$

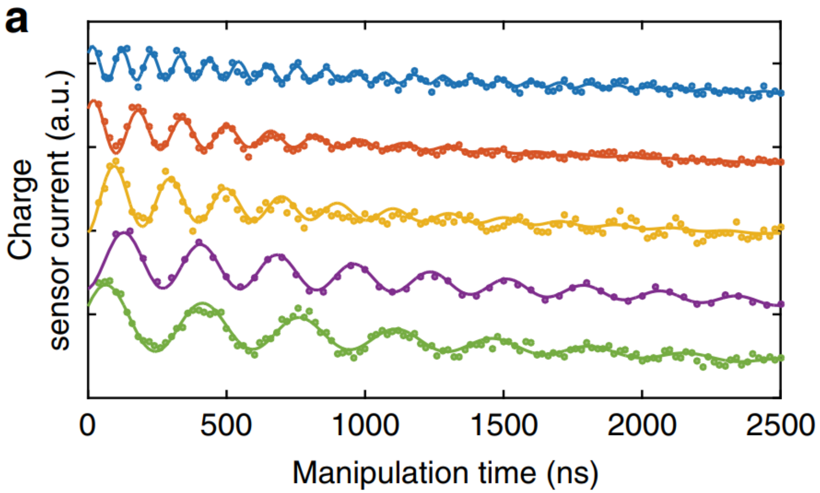


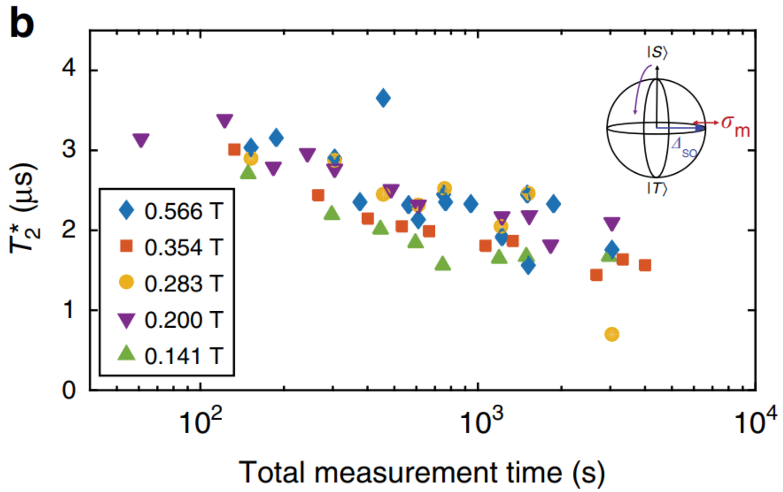
$\phi = \dfrac{3\pi}{4}$ $\phi = \dfrac{\pi}{4}$

Timescales

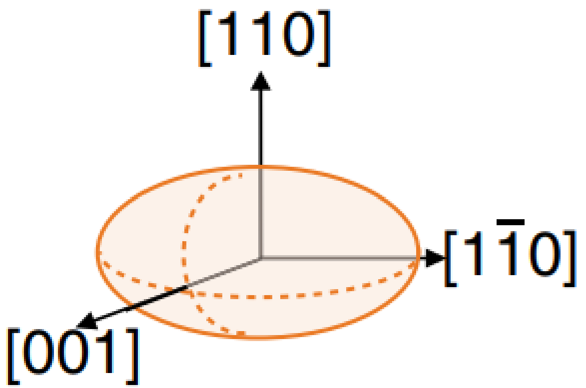
- Nuclear spin flips (background ^{29}Si) lead to time-variation of Overhauser field, which results in decay in time of coherent oscillations *(here: X-axis)*.
- Decay in oscillation amplitude fits a Gaussian consistent with quasi-static noise
  - T_2^* = 1.6 μs extracted for long-averaging timescales assuming decay like $\exp[-(t/T_2^*)^2]$
- Relative absence of B-field dependence suggestive that the interface SOI doesn't contribute to T_2^* ➔ no additional noise due to MOS interface (consistent with bulk ^{29}Si)

50 min averaged measurements

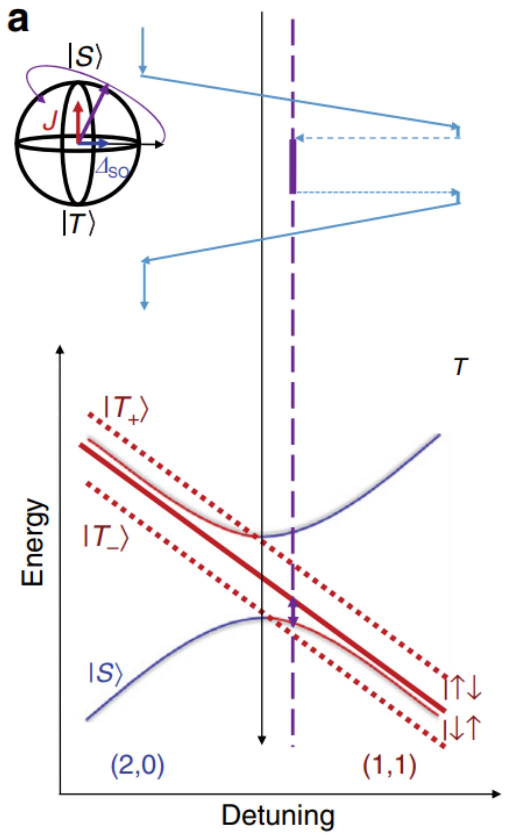




B fields along [1-10]



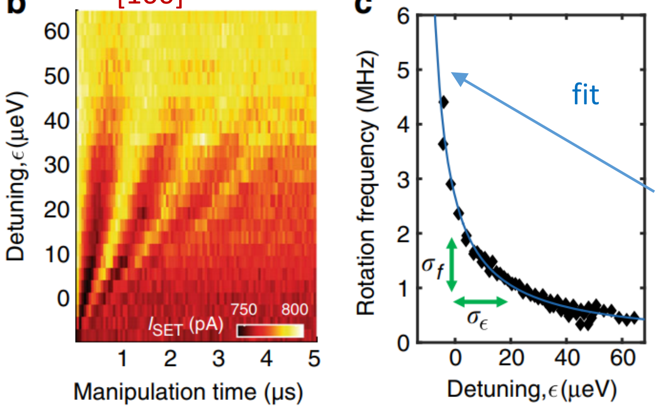
Charge Noise Characterization



- Initialize in S(0,2) state then drive to S(1,1) near J(ϵ) ≈ 0, then drive to and from J(ϵ) around $\epsilon = 0$ for a waiting time, rotating qubit around Bloch sphere

- Associate saturation of T_2^* at deep detuning with dominant noise mechanism going from charge noise on the confinement gates to magnetic noise due to residual ^{29}Si

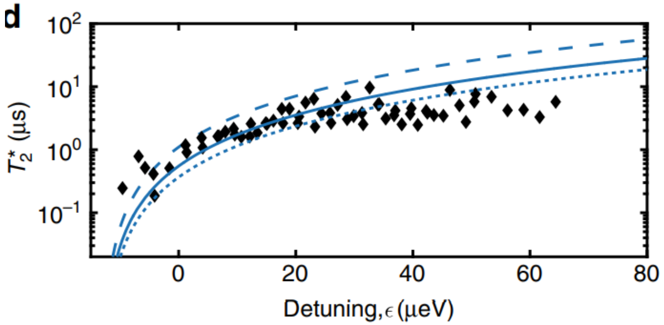
$B_{[100]}$ = 0.2 T



$\sqrt{J(\epsilon)^2 + \Delta_{so}^2}$

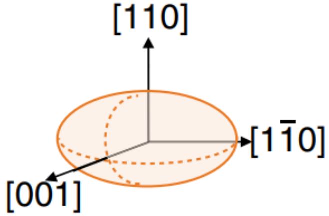
$J(\epsilon) \propto \epsilon^{-1}$

Fit rotation frequency to ${}^{df(\epsilon)}/_{d\epsilon}$, then the ratio of T_2^* to $|\,df(\epsilon)/d\epsilon|^{-1}$ gives rms charge noise [1] of $\sigma_\epsilon = 2 \pm 0.6\ \mu eV$



$$T_2^* = \frac{1}{\sqrt{2}\pi\sigma_\epsilon}\left|\frac{df}{d\epsilon}\right|^{-1}$$

[1] Dial et al., PRL **110**, 146804 (2013)



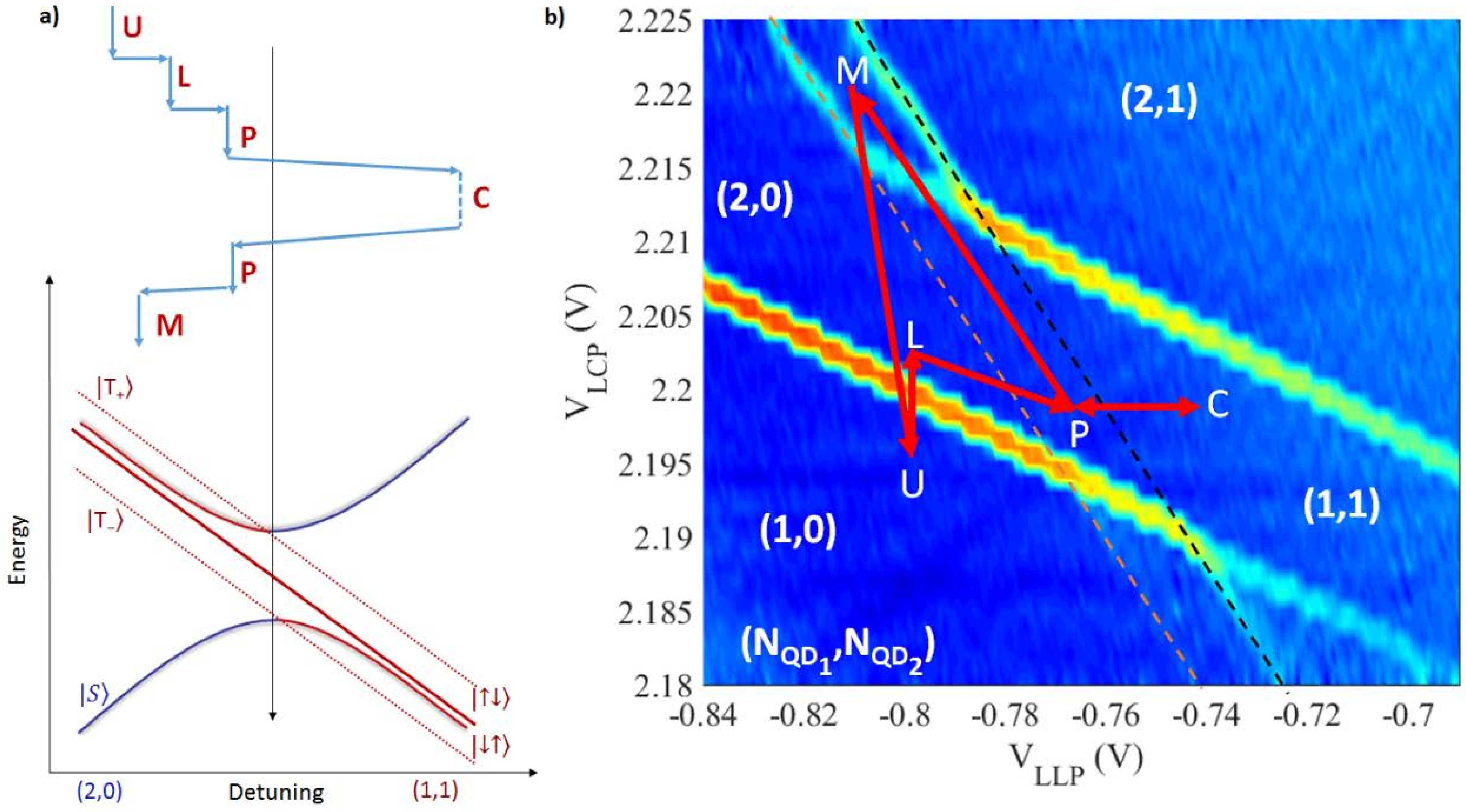
Conclusion

- All-electrical two-axis control of MOS DQD using the intrinsic details of the system at the interface
  - Exploits interfacial SOI + detuning for two axis control

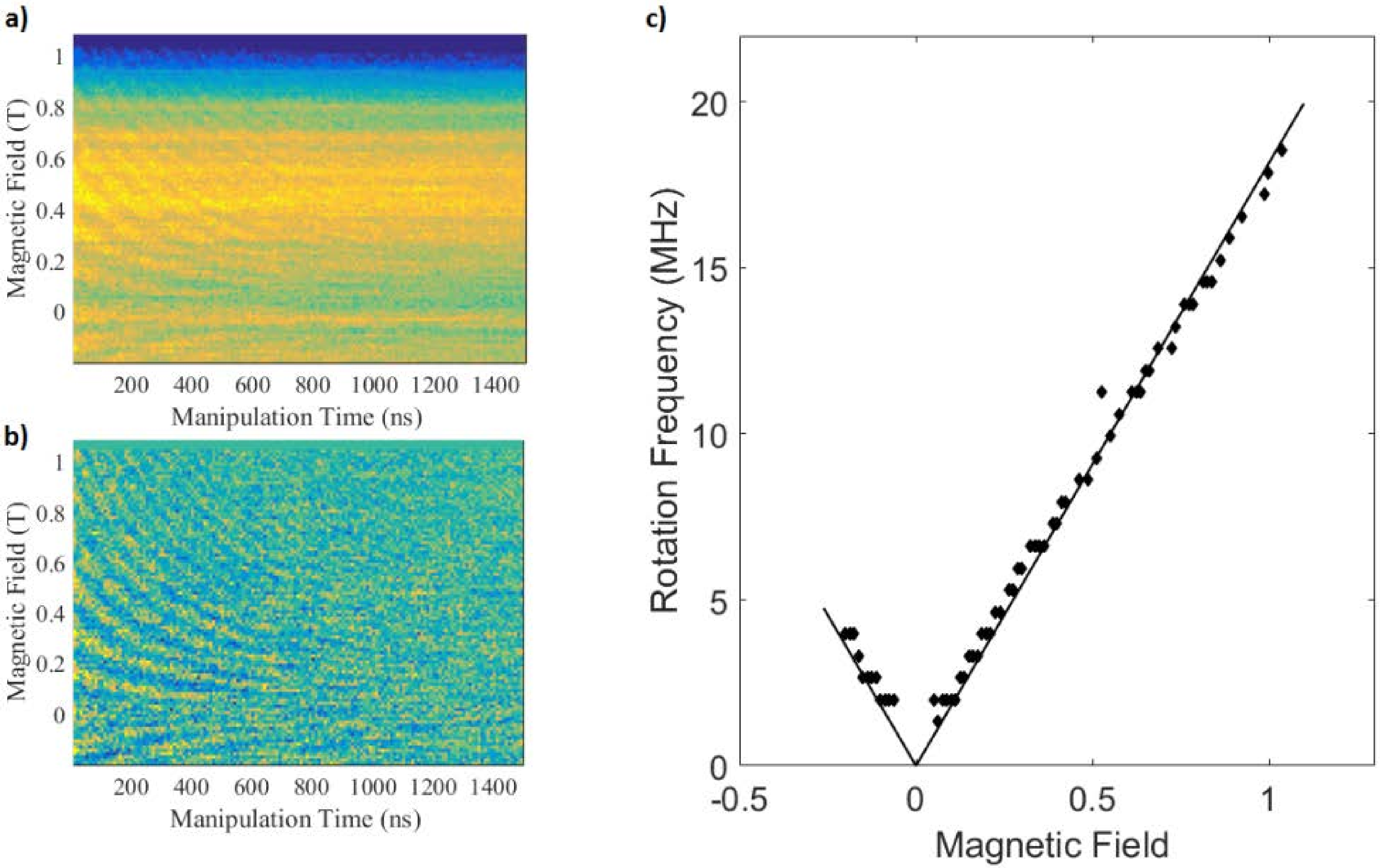
- Charge noise characterized at the interface

- T_2^* comparable to other systems (Ga/AlGaAs ; Si/SiGe)

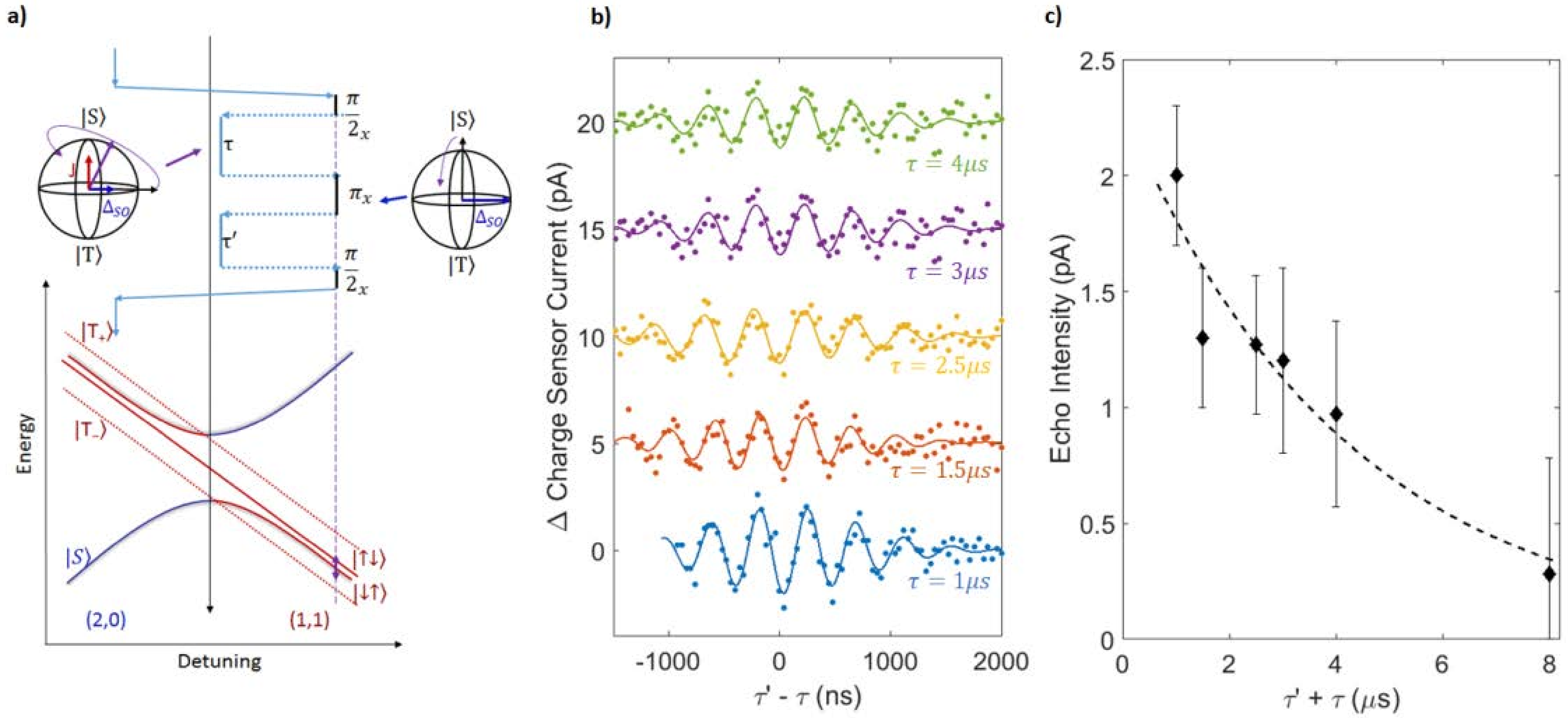
Thanks for listening!


a)
U
L
P
C
P
M
|T+⟩
|T−⟩
|S⟩
|↑↓⟩
|↓↑⟩
Energy
(2,0)
Detuning
(1,1)
b)
M
(2,1)
(2,0)
L
P
C
U
(1,1)
(1,0)
(N_QD1,N_QD2)
V_LCP (V)
V_LLP (V)
2.225
2.22
2.215
2.21
2.205
2.2
2.195
2.19
2.185
2.18
-0.84
-0.82
-0.8
-0.78
-0.76
-0.74
-0.72
-0.7

$$I_{SET} = A \sin(2\pi f t + \phi_0) \exp[-(t/T_2^\star)^2] + Bt + C$$



At (1,1) manipulation point



a)
b)
c)
|S⟩
|T⟩
J
Δ_{SO}
τ
τ'
$\frac{\pi}{2_x}$
π_x
$\frac{\pi}{2_x}$
|S⟩
|T⟩
Δ_{SO}
|T₊⟩
|T₋⟩
|S⟩
|↑↓⟩
|↓↑⟩
(2,0)
(1,1)
Energy
Detuning
Δ Charge Sensor Current (pA)
τ' - τ (ns)
τ = 4μs
τ = 3μs
τ = 2.5μs
τ = 1.5μs
τ = 1μs
Echo Intensity (pA)
τ' + τ (μs)