Two-Axis Quantum Control of a Fast Valley Qubit in Silicon

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Motivation

- Silicon as a leading contender for hosting qubits
  - Usually spin qubits
  - Nearly degenerate valley states are a possibility for information loss

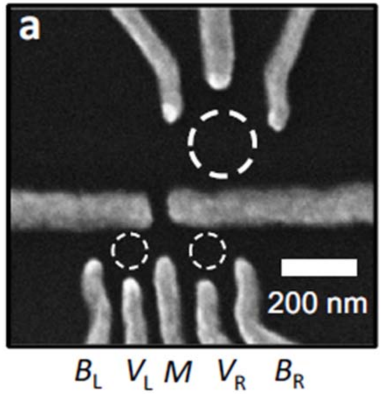
- Idea: Use of valley states as the qubit
  - Fully electrically controllable (no magnetic field needed)
  - Measured through valley-orbit coupling
  - Large gate voltage space which does not change the valley splitting
    - Could have protection against charge noise
  - Fast gate operation (in order of 10 GHz)

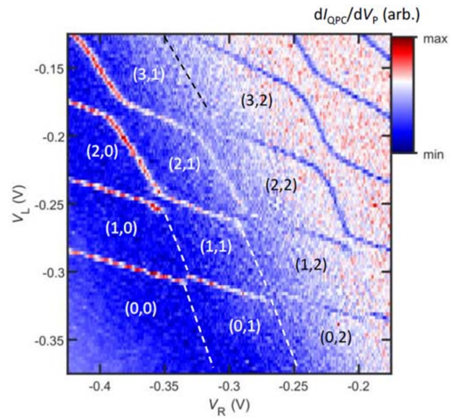
- In this paper
  - Mapping of the surface of the Bloch sphere with sub-nanosecond gate operations

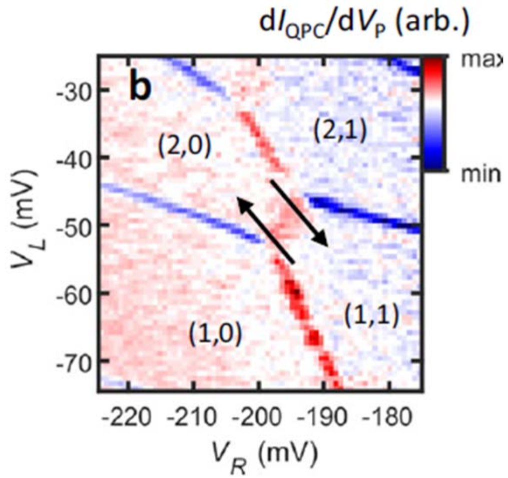
Device

- Double Quantum Dot on a Si/SiGe heterostructure
  - Density: $4 \cdot 10^{11}$ cm^{-2}
  - Mobility $7 \cdot 10^{5}$ cm^2/Vs
  - Gate Material: Ti/Au
  - Dielectricum: Al2O3
  - Global Top Gate: Aluminium

- Measurements
  - Dilution Refrigerator, base T = 36 mK
  - Voltage Pulses: Agilent 81134 A pulse generator
    - Repetition rate 7.5 MHz





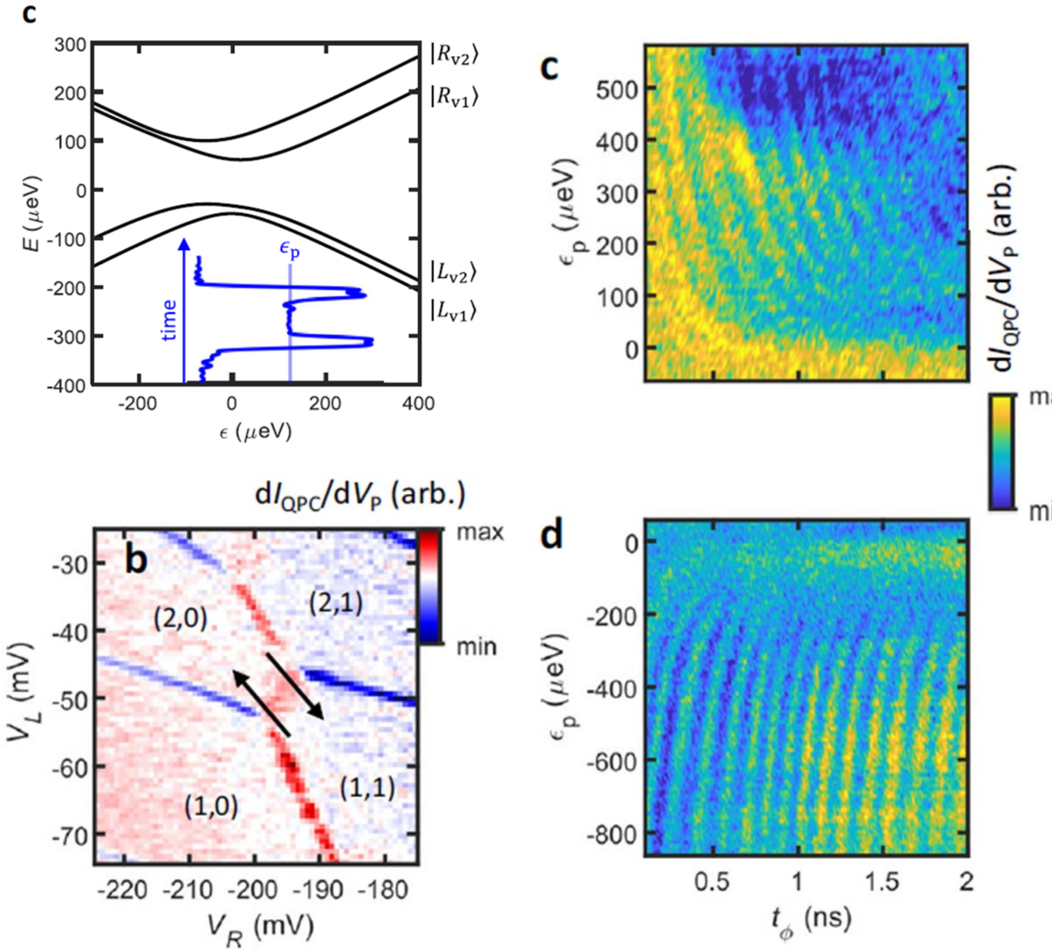


Coherent Valley Oscillations

- Initialization in (1,1) charge configuration ($= |R_{V1}\rangle$)
- Trapezoidal pulse (rise time 200 ps) modifies system detuning $\epsilon = V_R - V_L$

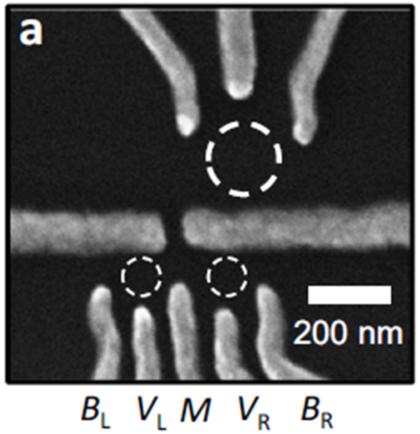
- Anticrossing at $\epsilon \approx 0$ $\rightarrow$ superposition of two lowest energy states $\psi = 1/\sqrt{2}(|L_{V1}\rangle + e^{i\phi}|L_{V2}\rangle)$
- At maximum detuning: Larmor precession (frequency determined by valley splitting)
- Phase difference mapped to charge states
- Projective readout relies on dot occupation
  - ➢ Small valley splitting transformed into large energy difference
- Note: valley splitting modified by spin states, but does not affect charge-based read-out sensitivity

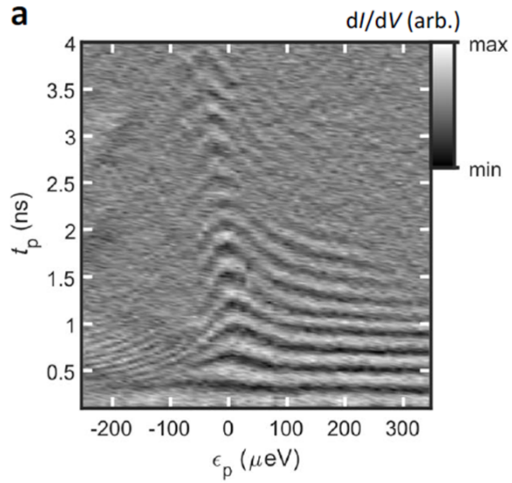
- Lower bound for $T_2^* > 7$ ns (decay of oscillations)

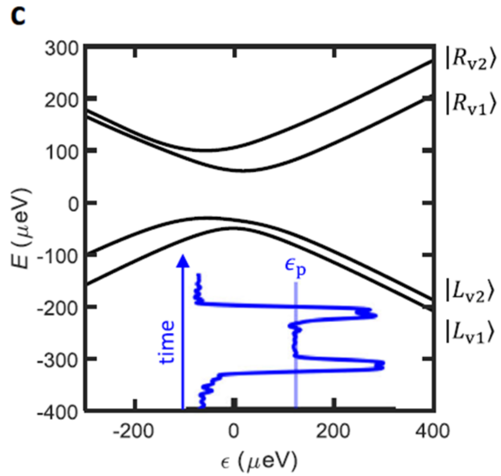


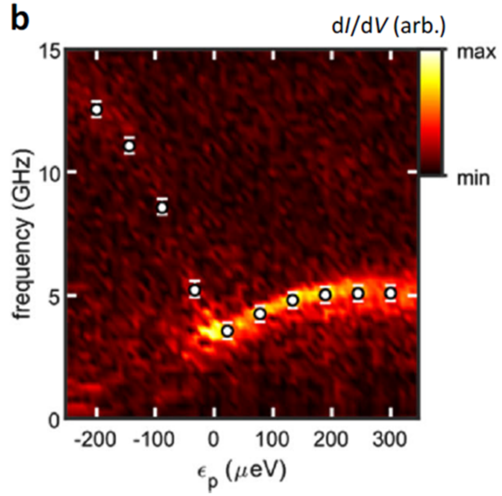
Ramsey Spectroscopy

- Three-stage pulse only on V_R (+ no tunneling out or into dot)
  - High visibility precession
  - Frequency directly convertible to energy gap
  - Valley splittings: $\delta_L = 4.55$ GHz and $\delta_R = 15.7$ GHz
- Sweet spots at $\epsilon = 20\ \mu$eV (first order insensitive to charge noise) and at large detuning (splitting independent of gate voltage)
- Valley splitting varies from dot to dot ($10\ \mu$ev to $60\ \mu$eV)
  - Gate voltages modify up to 20%





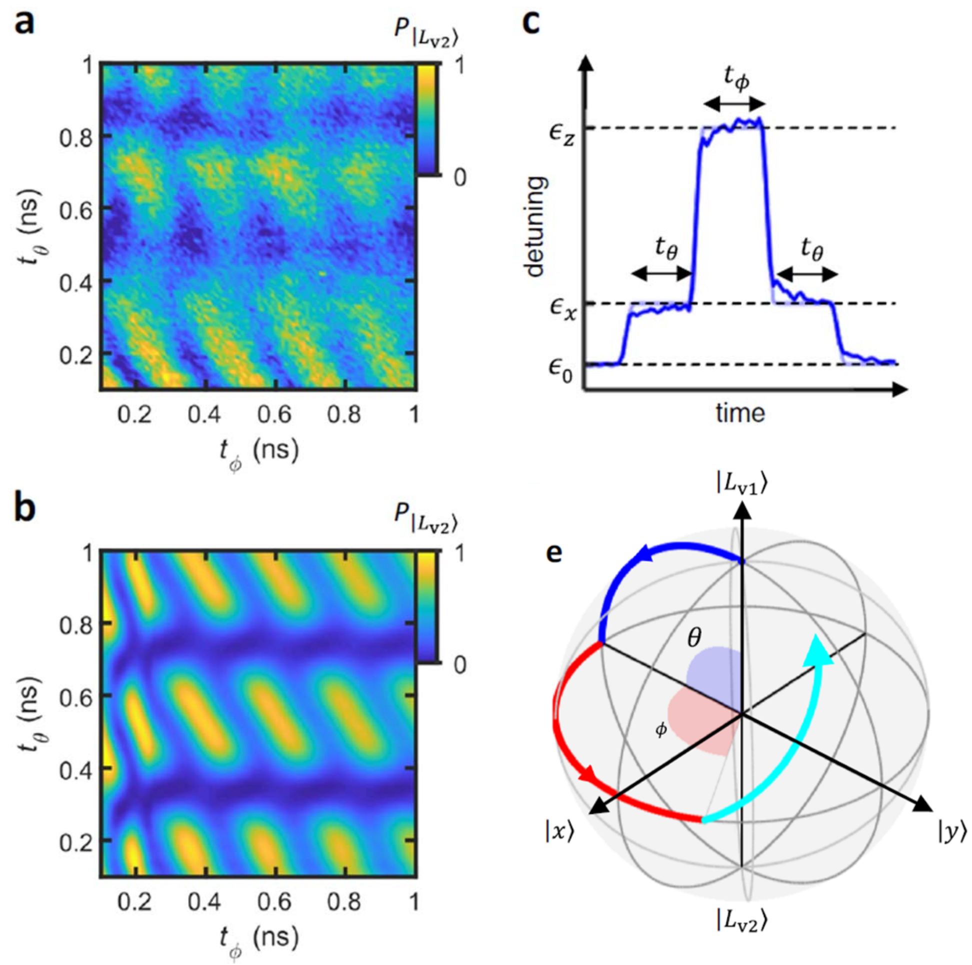




Fast Two-Axis Control I

- Three-stage pulse scheme
  - Initialization at $\epsilon_0 = |R_{V1}\rangle$
  - 1. Pulse to ϵ_x = anticrossing, precess for time t_θ
  - 2. Pulse to ϵ_z, precess for time t_ϕ
  - 3. Pulse to ϵ_x, precess for time t_θ → maps valley state to charge state
- Rise time of 200 ps not fast compared to state evolution
  - Rotation occur at an angle $\alpha \sim \pi/4$
- Mapping of the entire surface of Block sphere possible [1]

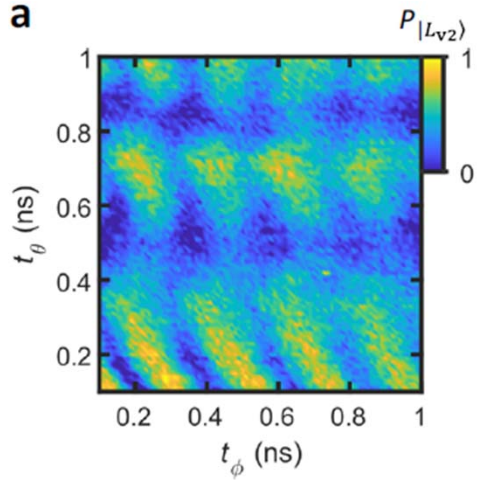
- Note: Mapping is dependent on t_θ due to finite rise time
  - Probablity of finding excited state vanishes at even multiples of π (in θ)
- Trace with fixed ϕ: projective measurement of state with initialization and measurement axis determined by t_θ

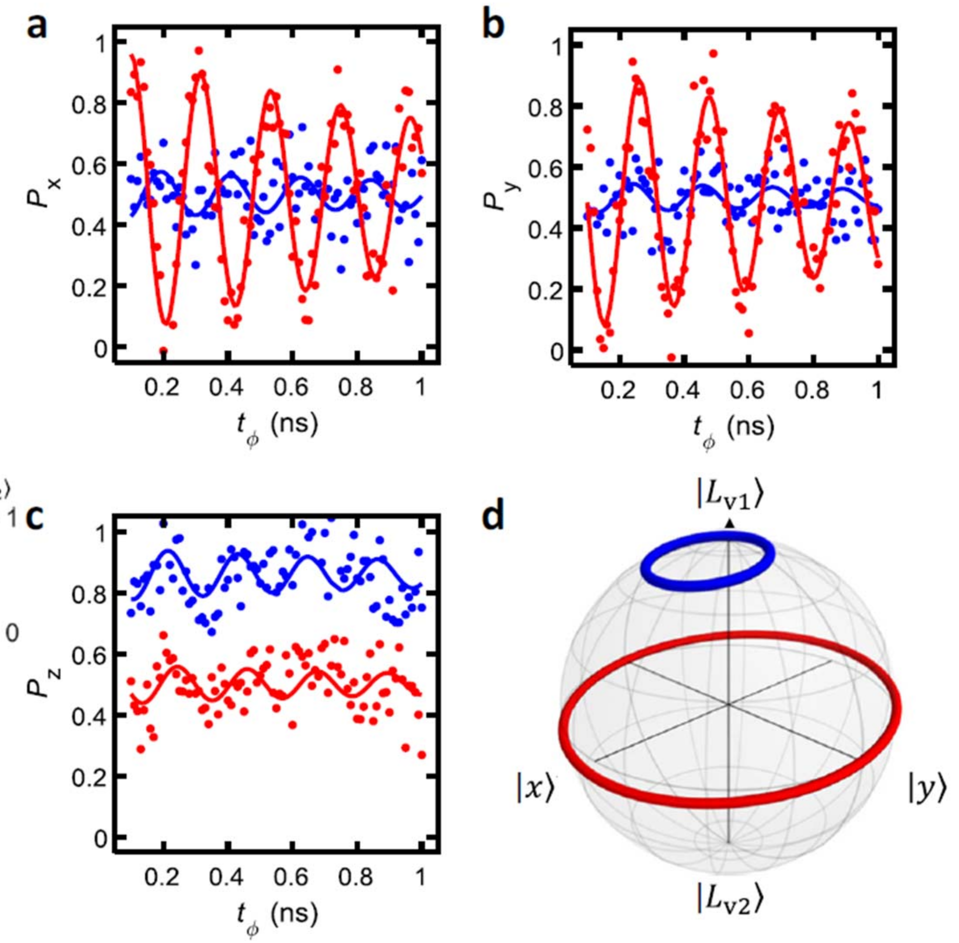


[1] Previously shown in self assembled quantum dots (Press *et al*.Nature 456, 218-221 (2008), but here the first time in gate defined quantum dots

Fast Two-Axis Control II

- Fixing t_θ at 0.22 ns with variable t_ϕ = Z rotation in equatorial plane
  - Z rotations have maximum amplitude
- Fixing t_θ at 0.5 ns with variable t_ϕ = Z rotation at north pole of bloch sphere
  - Z rotations have minimal amplitude
- Frequencies of rotation agree with energy splitting at operation points

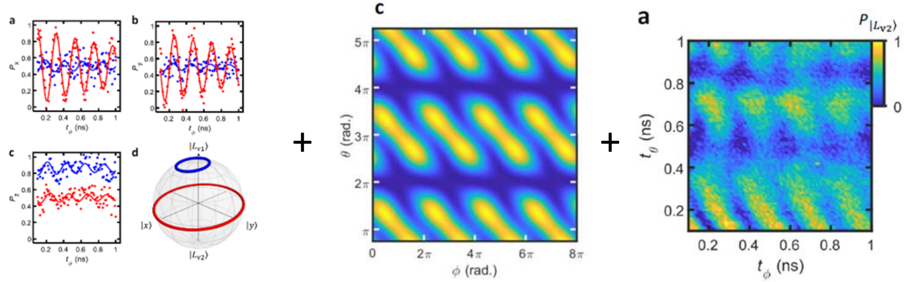


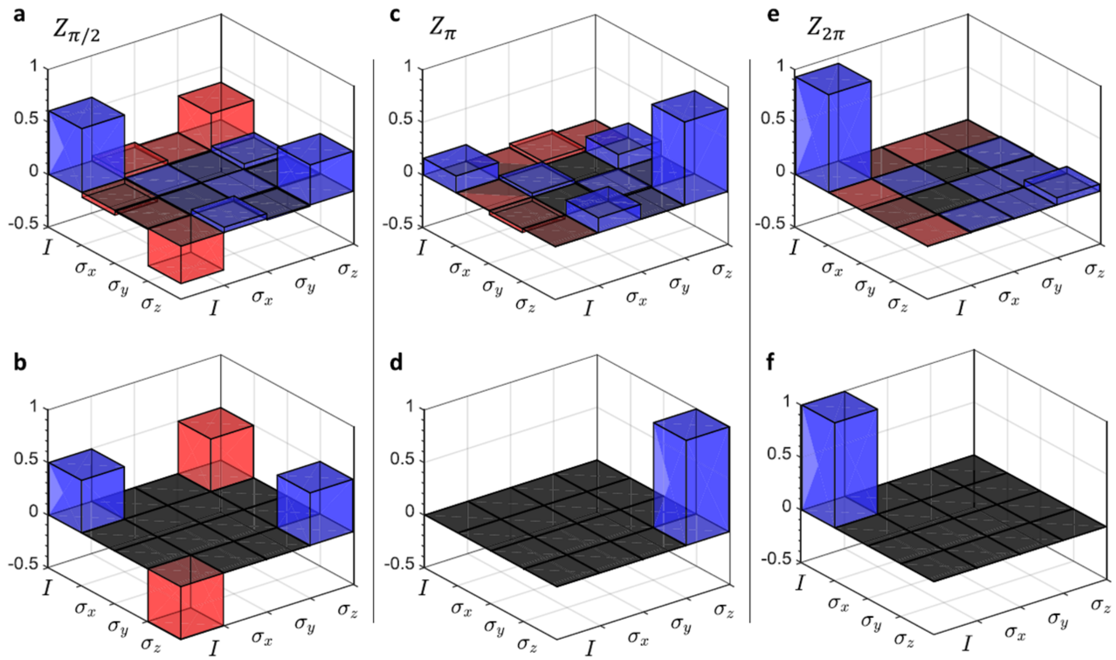


Valley Qubit Operation Fidelities

- Fidelities from quantum process tomography (QPT)
- True QPT not possible due to dynamical projection approach
- Still possible with comparison to theory and reconstruction of states (missing components are approximated)
- $F_{\pi/2} = 85\%,\ F_{\pi} = 79\%,\ F_{2\pi} = 93\%$

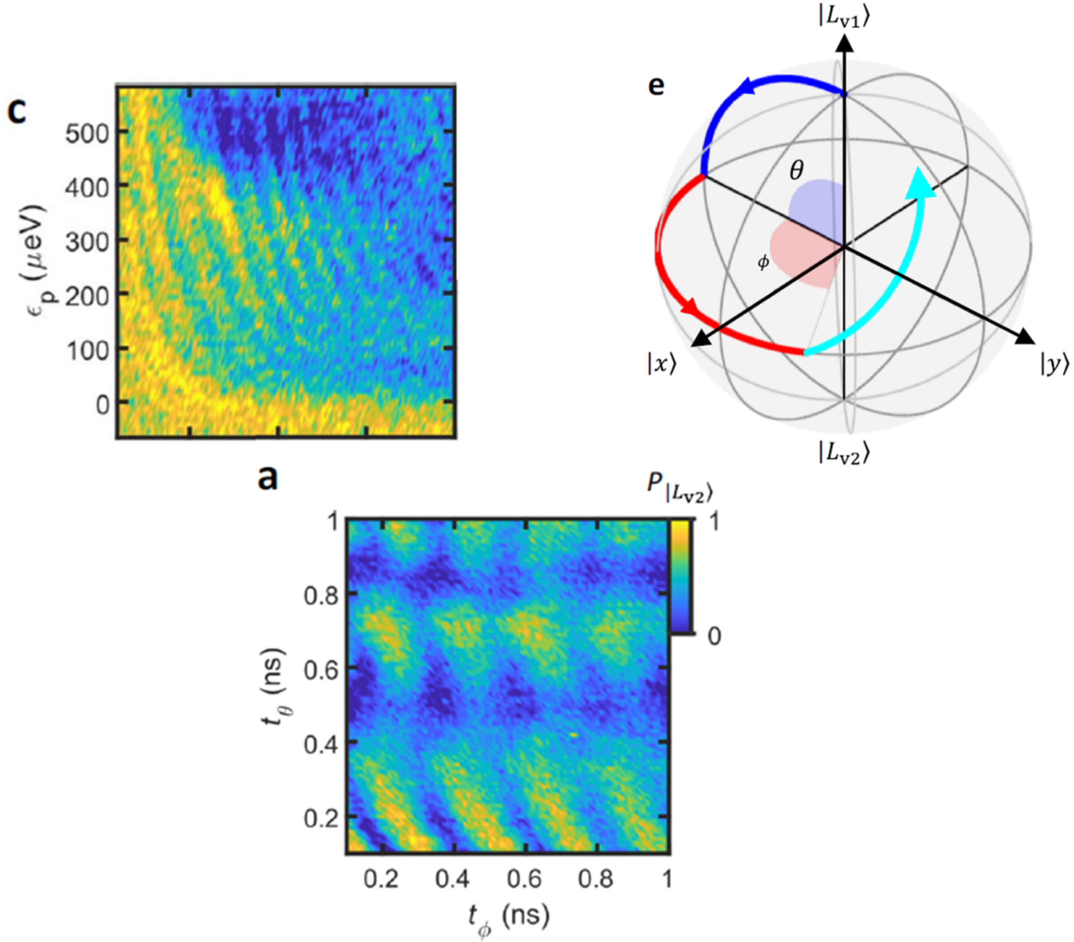
- Fidelities limited by rotation axis errors (not decoherence)
- Can be improved with better pulse shaping
- Choice of ϵ_z has large importance due to converging of energy splitting
    - Charge noise and charge coupling
    - Further supported by coherence time during Z-rotation: 1.5 ns (smaller than typical valley relaxation times)





Summary

- Realization of a valley qubit in a semiconductor
- Fully electrically controlled
- Fast operation (200 – 300 ps)
- Currently inferior to hybrid qubit systems
- Can be improved with proper pulse engineering and detuning



Fast Two-Axis Control III