On-demand electric control of spin qubits

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Spin Journal Club

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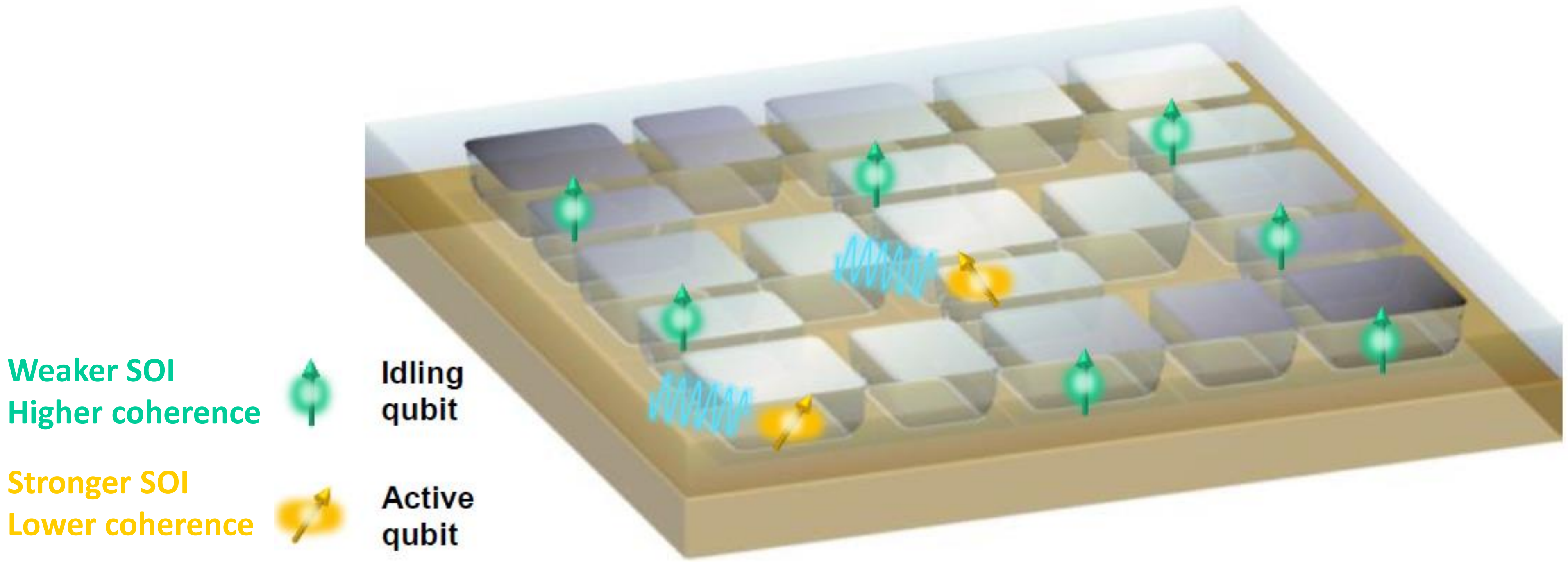
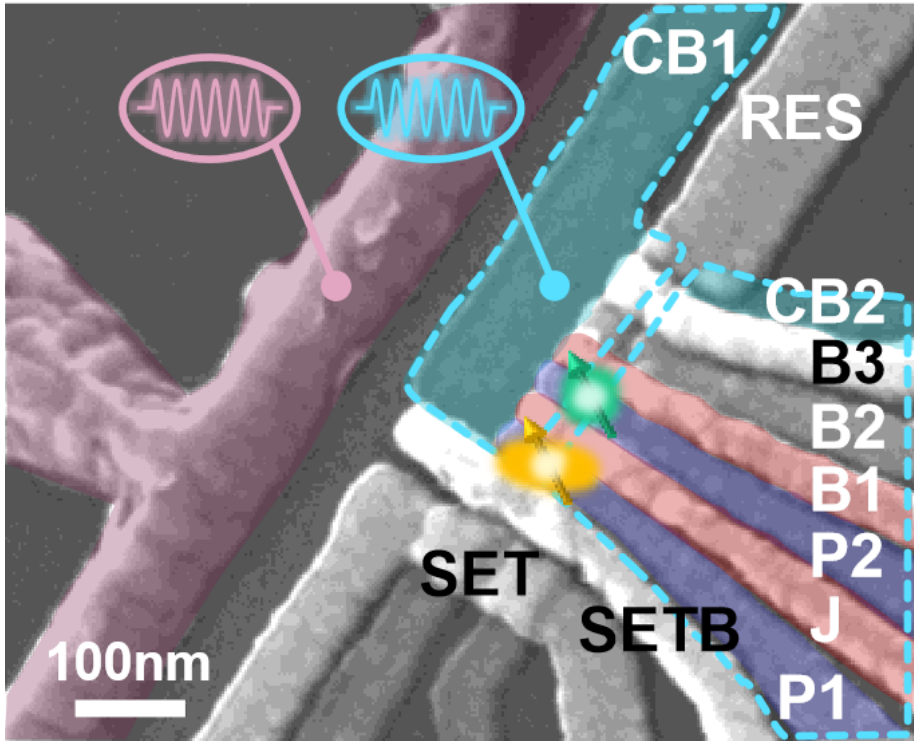
Idea: Spin-orbit switch for electrons in Si

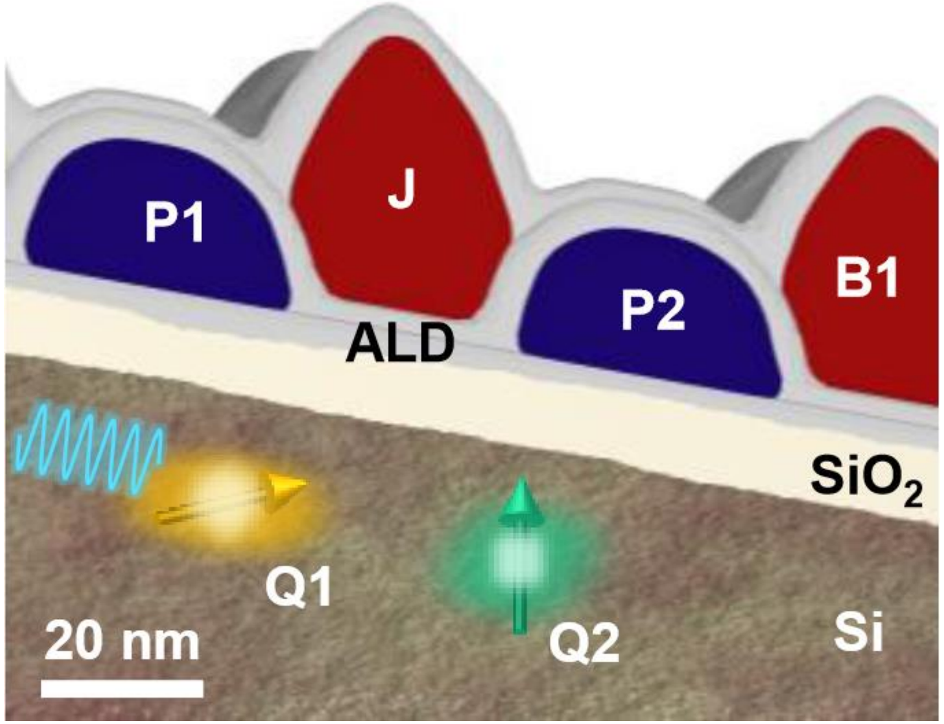
- Electrons in Silicon: Relatively weak spin-orbit interaction without micromagnet
- EDSR via micromagnet or ESR via on-chip transmission line both pose scaling challenges
- SOI effects in Si QDs may become significant if electron is allowed to move between orbital configurations
- In this paper, such sweetspots are accessed via gate voltages to enable switchable spin-orbit interaction:



Device layout

- Enriched ^{28}Si MOS devices with SET charge sensor and (optional) coplanar waveguide antenna
- Experiments carried out with different material stacks (not specified; most of the groups' recent publications have Al gates, sometimes Pd gates; Aluminum oxide as ALD layer)

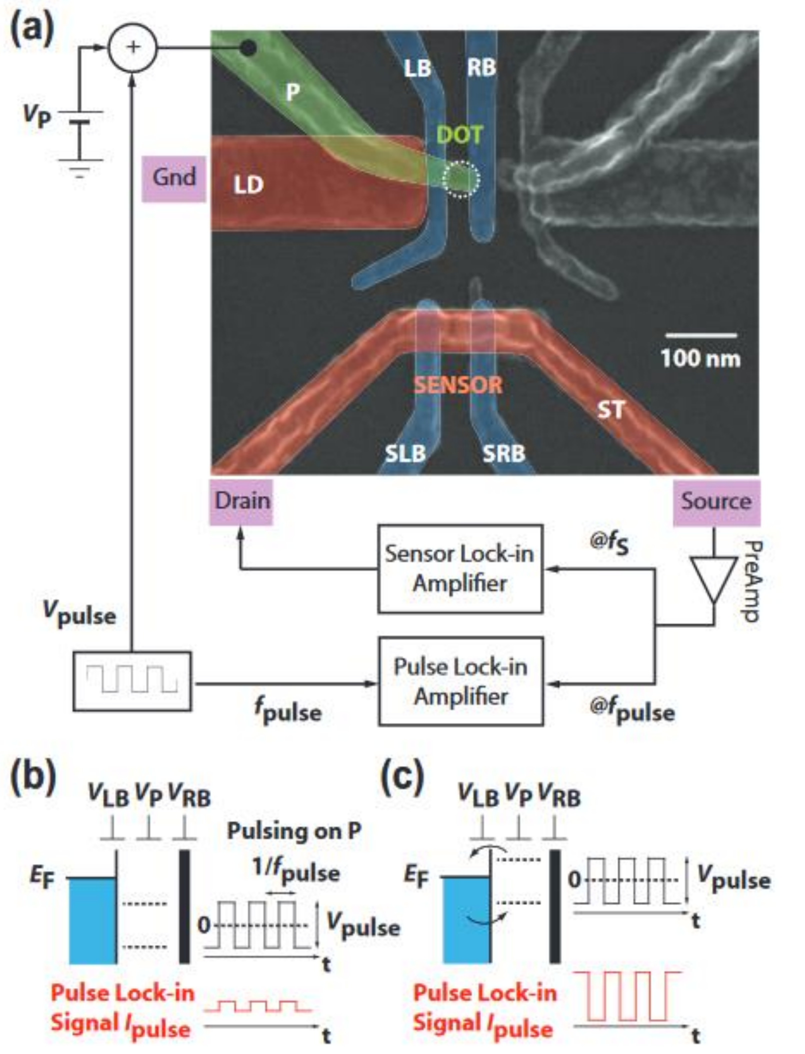




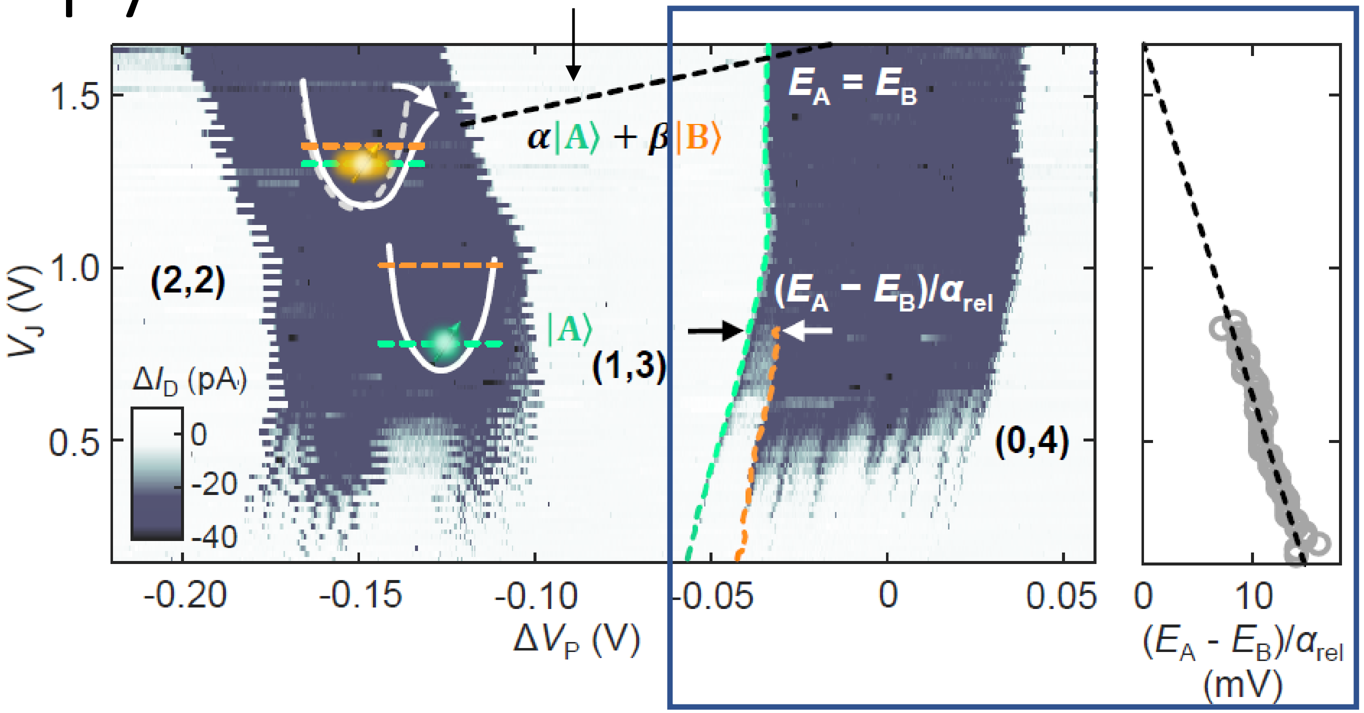
CB: Lateral confinement barriers
RES: Reservoir gate

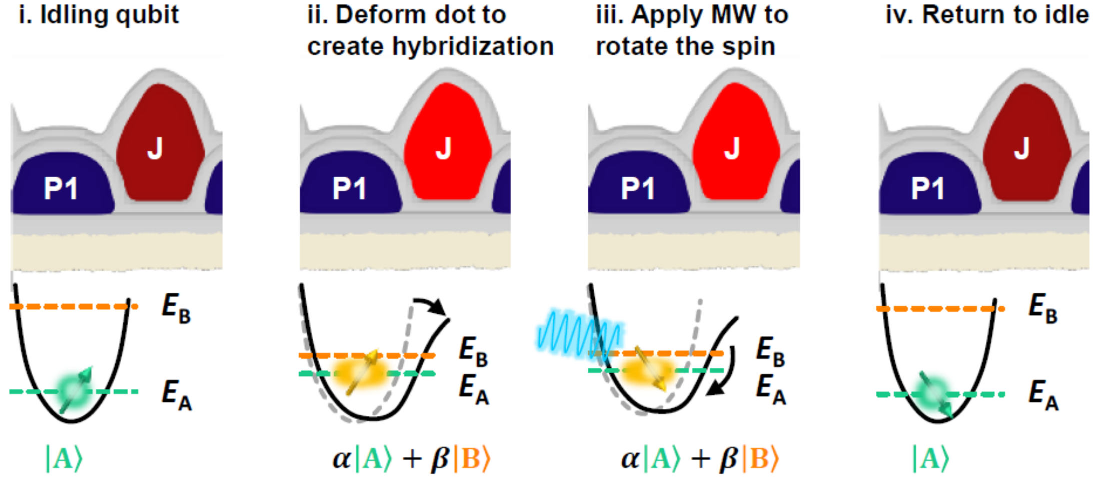
Excited state spectroscopy

Principle (from C. H. Yang et al., PRB 2012, older device layout):



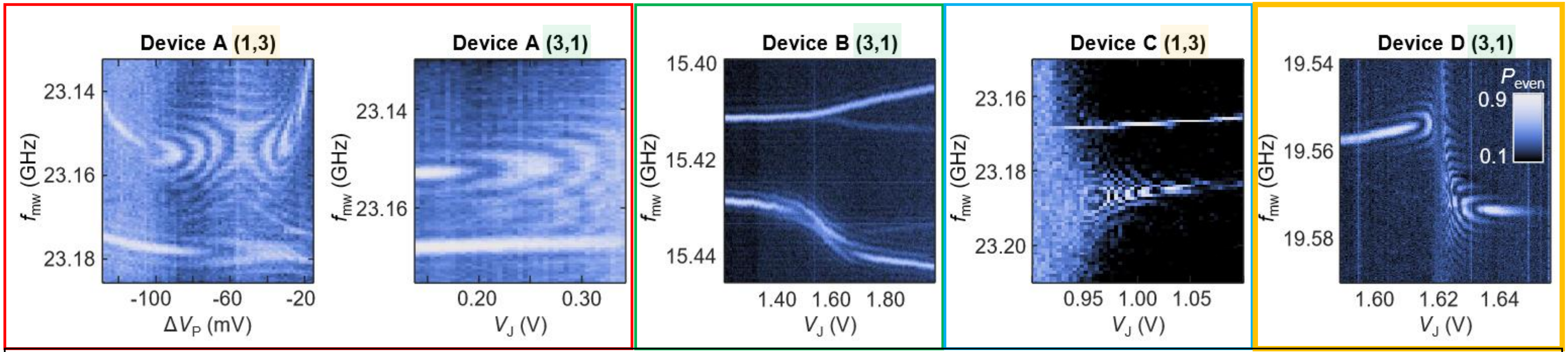
Black dashed line: Points with maximum SOI driving





Pulsed electron spin-orbital spectroscopy (PESOS)

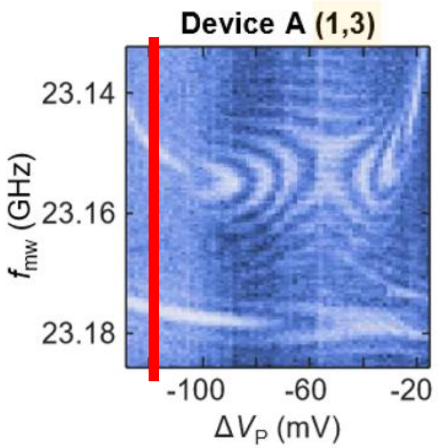
- Protocol: Apply microwave pulse of fixed duration/power as function of f_{mw} and gate voltages
- PESOS maps for spins initialized&measured using parity readout (A. Seedhouse et al., PRX Quantum 2021):



Driving:	ESR	Not specified	ESR	All-electrical EDSR

- Maps for 4 devices differing in operation modes, material stacks, MW excitation strategies, 2 different fridges
- Hybridization points: Interference fringes due to enhancement of EDSR efficiency

Fit to theoretical model (I)



- From PESOS maps, one can extract vertical line traces of P_{even} in dependence of f_{mw}:

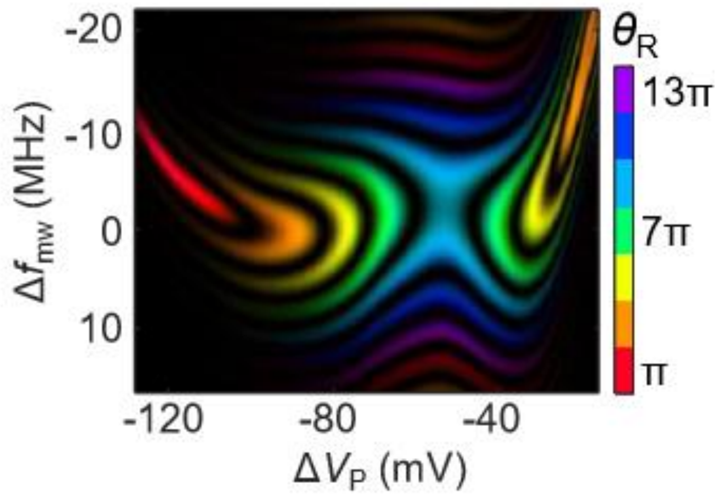
$$P_{\rm even} = \frac{A f_{\rm Rabi}^2 \left[1 - \cos\left(\tau\sqrt{f_{\rm Rabi}^2 + (f_{\rm mw} - f_0)^2}\right)\right]}{f_{\rm Rabi}^2 + (f_{\rm mw} - f_0)^2} + \delta A \qquad (1)$$

A: oscillation amplitude, τ: total time of driving pulse, δA: Amplitude offset of oscillations

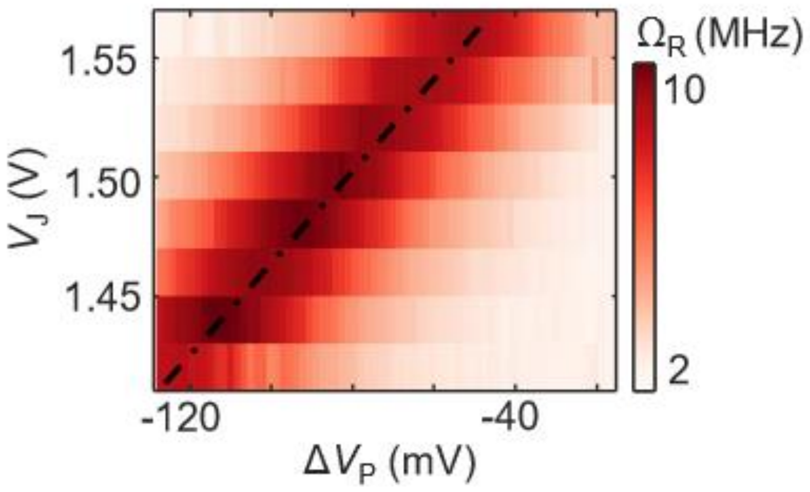
- From fit to Rabi equation (1), Rabi frequency $f_{\rm Rabi}$ and qubit frequency f_0 can be extracted

- Rabi equation for each voltage value can be used to simulate PESOS maps:

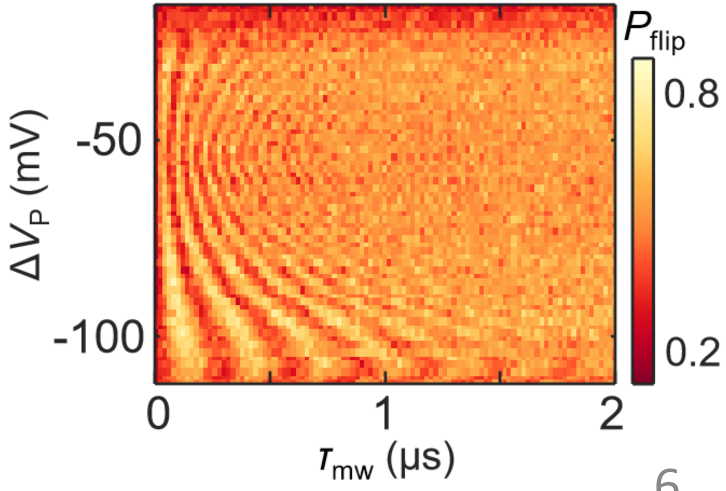
Simulation of PESOS map for A:



$f_{\rm Rabi}$ from simulation vs. gates:

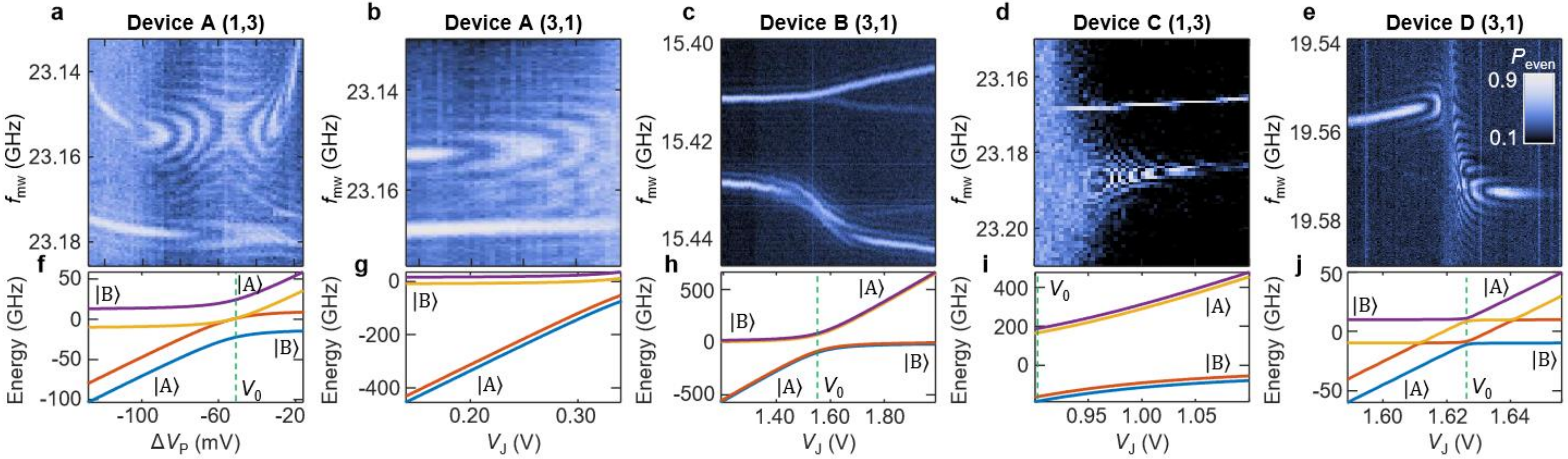


Measured $f_{\rm Rabi}$ vs. ΔV_P



Fit to theoretical model (II)

- f_{Rabi} and f_0 as function of gate voltage are then target fit values for 4-level Hamiltonian:

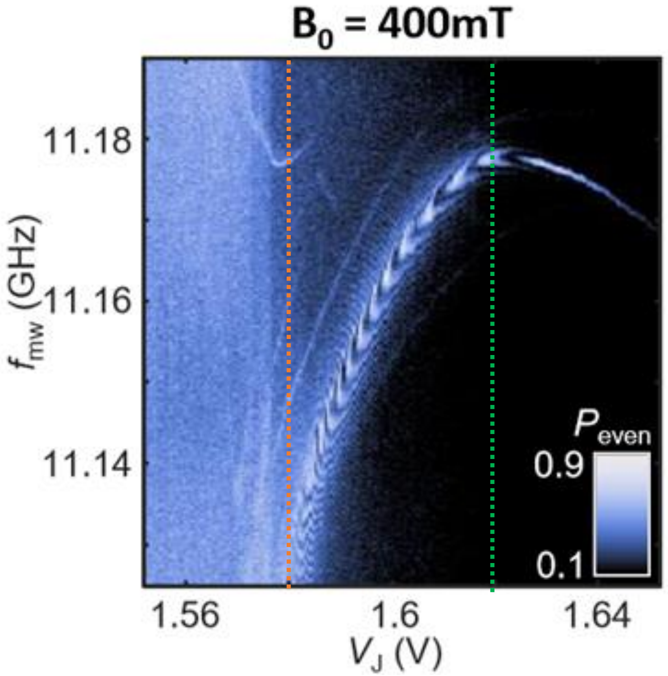


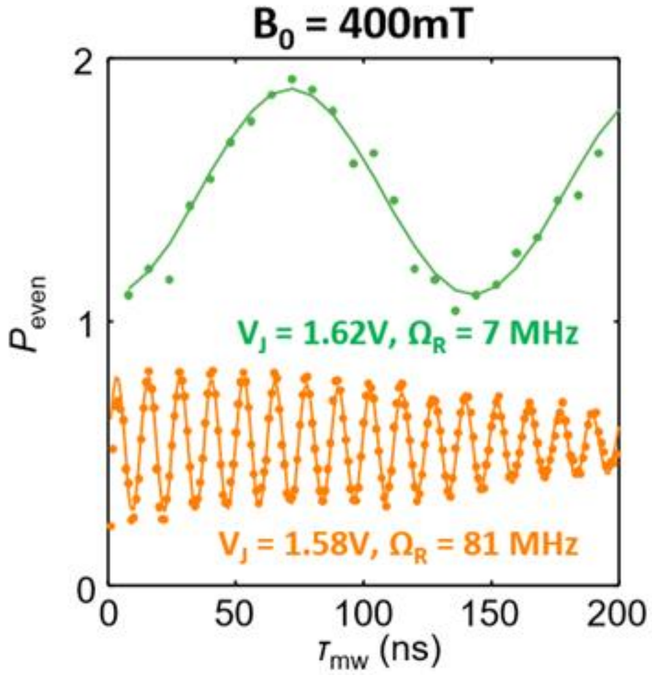
- Hybridization gap energy compares differently to spin splitting energy for each of these configurations

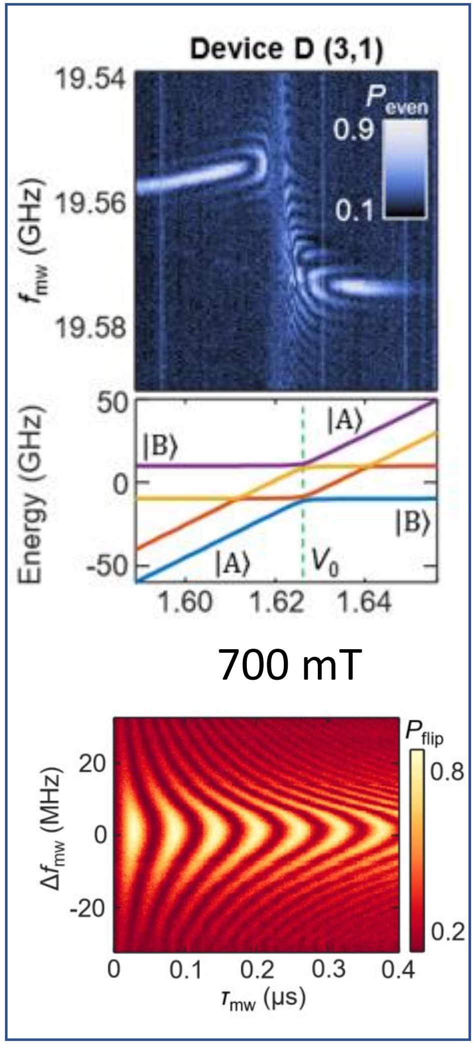
- Hybridization may involve states with e.g. different valley configurations, in-plane orbitals, …

Enhancement of Rabi frequency

- **Device D**: Driven all-electrically, with strongest observed effects of orbital degeneracy on spins
- At 400 mT: Largest enhancement of f_{Rabi} across all experiments
- f_{Rabi} decreases to below 125 kHz for V_J > 1.65 V

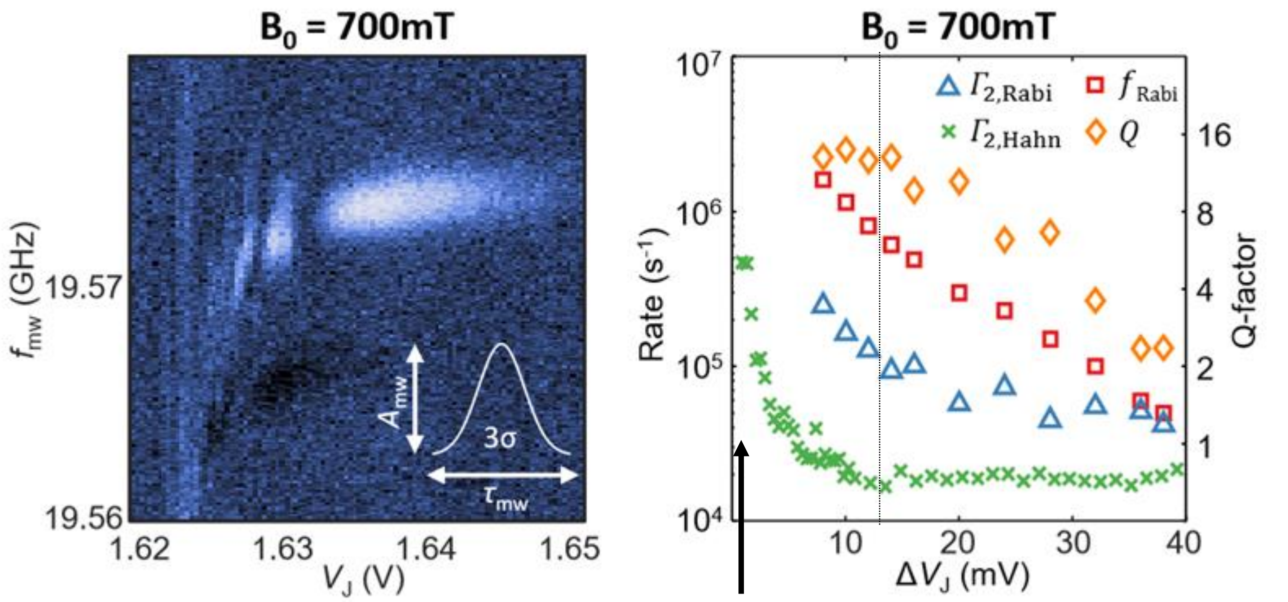






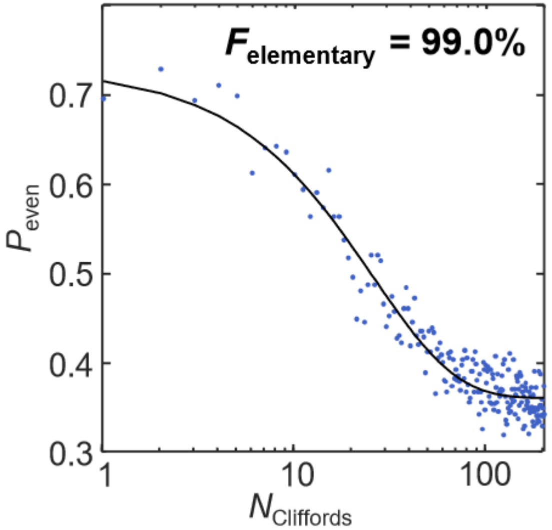
Impact on coherence

- At 700 mT: Qubit states more convoluted, tend to leak into undesired excited states
- Rabi speed-up more modest, but qubit frequency less affected by electric field fluctuations, leading to higher control fidelity
- Echo experiment: Idle wait times are offset by $\mathbf{\Delta V_J}$
- Q = $2 \cdot \Omega_{\mathrm{Rabi}}/\Gamma_{2,\mathrm{Rabi}}$



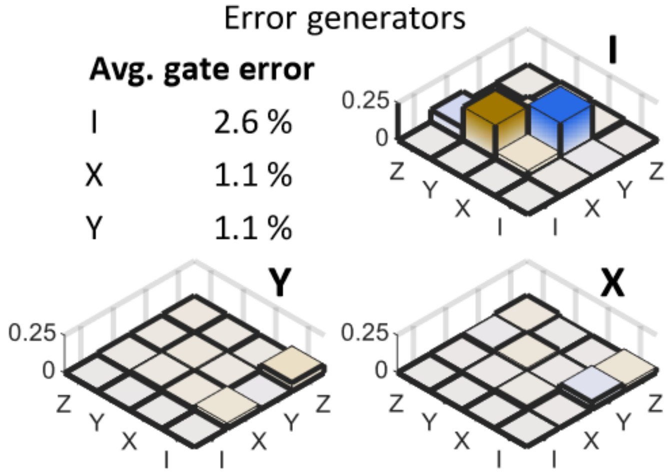
$\Delta V_J \to 0$: Stark shift $\mathrm{d}f/\mathrm{d}V_J$ becomes very large

Clifford gate set randomized benchmarking (ΔV_P = 13.6 mV):



$\pm$ 0.3%

Gate set tomography (ΔV_P = 13.6 mV):



Summary

- Orbital hybridization effect on spin dynamics is shown for 4 different devices
- Excited state spectroscopy guides search for hybridization points
- PESOS maps show the change in spin dynamics at these points
- All-electrically driven device:
  - B_0= 0.4 T: f_{Rabi} tunable from <125 kHz to 81 MHz
  - B_0= 0.7 T: $\mathrm{T}_{2,\mathrm{Hahn}} \approx 50\mu\mathrm{s}$; elementary gate fidelity of 99 $\pm$ 0.3 %
- Open questions:
  - What is the dominant source of control errors?
  - How regularly does the EDSR speed-up occur?