Nonlinear response and crosstalk of strongly driven silicon spin qubits

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Nonlinear response and crosstalk of strongly driven silicon spin qubits

• Scaling: Multiplexed driving field to address individual, spectrally separated qubits

• Challenge: Maintaining high fidelity operations if qubit dynamics are affected by off-resonant tones

• Here: Experimental characterization of crosstalk for single-qubit rotations

• System: Electron QD in $^{28}$Si/SiGe QW, with Co micromagnet placed on top for «synthetic» SOI

[1] X. Xue et al., Nature 2022
Initialization, readout and control

- Readout: Spin-selective tunneling to electron reservoir

[1] X. Xue et al., Nature 2021

[2]
Nonlinear Rabi frequency scaling (I)

- Gate-defined QDs in Si: EDSR mediated by orbit-like or valley-like hybridized states

- In either case, linear scaling of Rabi frequencies with drive amplitude is expected

- Driving tones for either Qubit 1 or 2 are applied (not simultaneously):
  
  - Nonlinearity distinct to each qubit frequency
  
  - Rule out
    - Micromagnet gradient: nearly constant over QD length scale
    - Resonance frequency shift: Would increase $f_{Rabi}$
Nonlinear Rabi frequency scaling (II)

• Shape of nonlinearity changes with $B_{\text{ext}}$ and driving gate

• Change of Q2 occupancy only weakly affects Rabi scaling of Q1:

![Graphs showing Rabi frequency scaling](image-url)
Single-qubit crosstalk

• Both qubit driving tones applied simultaneously; one of them at a fixed drive amplitude (arrow)

• Effect on $f_{Rabi}$ is stronger when resonant tone amplitude is smaller than off-resonant tone (atleast for Q1 this seems to be the case...)

→ Crosstalk would become more severe as single-qubit operations are more densely multiplexed
Phenomenological model (I)

\[ H(t) = H_0 - \frac{E_Z}{2} \sigma_z + b'_{SL} \hat{x} \vec{n} \cdot \vec{\sigma} + E'_{ac}(t) \hat{x} \]

Orbital and valley degrees of freedom of charge state

Zeeman energy \( E_Z = g \mu_B B_{tot} \)
with \( B_{tot} \) along \( \sigma_z \) spin quantization axis

Electric drive: \( E'_{ac}(t) = e \sum_k E_{ac,k} \sin(\omega_k t) \)

Harmonic confinement: \( \tilde{H}_0 = \hbar \omega_0 (\hat{a}^\dagger \hat{a} + \frac{1}{2}) \rightarrow \Omega_{\text{rabi}} \propto E_{ac} \) (does not explain nonlinearity)

Anharmonic confinement: \( H(t) = -\frac{\Delta_0}{2} \tau_z + E'_{ac} \sin(\omega t) \hat{x} - \frac{E_Z}{2} \sigma_z + b'_{SL} \hat{x} \sigma_x \)

(\( \Delta_0 \): energy splitting between ground/excited state, e.g. orbital-mediated or valley-mediated; acted on by set of Pauli operators \( \{ \tau_i \} \))

Eigenstates \( |VO_0 \rangle \) and \( |VO_1 \rangle \) may contain transverse/longitudinal terms: \( \hat{x} = r \tau_x - p \tau_z \) (r: dipole transition element; p: influence of asymmetric confinement)
Phenomenological model (II)

Anharmonic confinement: 

\[ H(t) = -\frac{\Delta_0}{2} \tau_z + E'_{ac} \sin(\omega t)\hat{x} - \frac{E_z}{2} \sigma_z + b'_{SL} \hat{x} \sigma_x \]  

(\( \Delta_0 \): energy splitting between ground/excited state, e.g. orbital-mediated or valley-mediated; acted on by set of Pauli operators \( \{\tau_i\} \))

Eigenstates \( |VO_0 \rangle \) and \( |VO_1 \rangle \) may contain transverse/longitudinal terms: 

\[ \hat{x} = r\tau_x - p\tau_z \]  

(r: dipole transition element; p: influence of asymmetric confinement)

Orbital-mediated:

\[ \Delta_0 = 1 \text{ meV}, r = \frac{20}{\sqrt{2}} \text{ nm}, \text{ and } E_z = 60 \text{ meV} \]

Valley-mediated:

\[ \Delta_0 = 150 \text{ meV}, r = 2 \text{ nm}, \text{ and } E_z = 60 \text{ meV} \]

\( \rightarrow \) Captures saturation effect, but not full breadth of nonlinear features observed in experiment
Phenomenological model (III)

- Electric driving term in $H(t) = H_0 - \frac{E_Z}{2}\sigma_z + V_{SL}\hat{x}\hat{\sigma}_x + E_{ac}'(t)\hat{x}$ is extended by prefactor: $E_{ac}'(t)\hat{x} \rightarrow f(P_k, \omega_k)E_{ac}'(t)\hat{x}$

- Dependence on microwave power $P_k$, frequency $\omega_k$

- Prefactor included: Rabi saturation + crosstalk as in experiment

Possible origins of nonlinearity:

- **Electric drive distortion**: Driving on same gate gives different nonlinear response depending on which qubit is addressed → Points to microscopic origin of nonlinearity (though, driving frequencies differ as well)

- **Device heating**: Microwave drive may induce change to QD confinement, modifying orbital structure (e.g. via device strain or filling of charge traps)
Summary

• Measurements of nonlinear Rabi frequency scaling and crosstalk effect

• EDSR Hamiltonian (harmonic&anharmonic confinement) doesn’t capture full breadth of nonlinear effects

• Nonlinearity possibly caused by drive distortion and/or device heating

• Observed crosstalk poses a challenge for scaling via multiplexed qubit control