Nonadiabatic quantum control of a semiconductor charge qubit

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Friday Morning Meeting

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Lucas Casparis
Motivation

• Several solid state qubits are explored
  – Single spin qubit
  – Singlet/Triplet qubit
  – Superconducting qubit (flux/phase/charge qubit)
  – Semiconductor charge qubit

• SC Charge qubit is worth studying, because
  – it is a possible qubit itself
  – other qubits will be also affected by processes which decohere charge qubit
Solid state implementation of qubits

Petta et al. Science, 2005


Spin qubits: charge noise susceptible

In electrically controlled spin qubits, precession frequency noise can be induced by charge noise.

- Noise spectral density
- Ramsey and echo decoupling techniques

Nowack et al. Science 2011

Petta et al. Science, 2005
The charge qubit

- Charge position → two level system
- Initialize in right dot
- Apply pulses to left gate of DQD
- Readout again at large detuning

- Larmor frequency depends on detuning

$$\hat{H} = \frac{1}{2} \varepsilon \hat{\sigma}_z + \Delta \hat{\sigma}_x$$

$$f = \sqrt{\varepsilon^2 + 4\Delta^2}/\hbar$$

Petersson et al. PRL 2010
The charge qubit

- Large negative detuning → rapid decay, due to charge noise
- At $\epsilon_p=0$ strong enhanced coherence → Insensitive to charge noise
- At positive detuning coherent oscillations are strongly suppressed
- Larmor frequency at $\epsilon_p=0$ agrees with tunnel coupling
• $V_R$ is kept constant

• $V_P$ is applied on $V_L$ for time $\tau_p$

• They probe in the regime, where the (1,0) state can decay into a (0,0) state $\rightarrow$ increased visibility

• Again best coherence at zero detuning

• But they look at non-zero detuning with ramsey fringes
...but different

- Ramsey experiment
- $2 \pi/2$ pulses separated by a delay $\tau$
- Depending on $\tau$, electron ends up in $(0,1)$ or $(1,0)$ state
- Precession frequency depends on detuning and tunnel coupling

$$f = \sqrt{\epsilon^2 + 4\Delta^2} / h$$
Quantum Control: Ramsey fringes

- Look at fringes for a fixed detuning
- Fit cuts with the expression:

\[ \Delta P_L = A_0 \exp \left[ -\left( \frac{\tau - \tau_0}{T_2^*} \right)^2 \right] \cos \left[ 2\pi f (\tau - \tau_0) \right] \]

\( f \) taken from tunnel coupling & lever arm

\( T_2^* = 60 \text{ps} \)
Simulation

• Use time dependent Schrödinger equation

• Account for charge noise with a Gaussian

• Fit T2 to be roughly 60ps at sweet spot

\[
f(t_p) = \exp \left[ - \left( \frac{\eta}{\hbar} \right)^2 \int_{\omega_0}^{\infty} S(\omega) \frac{\sin^2(\frac{t_p\omega}{2})}{(\omega/2)^2} d\omega \right]
\]

\[
T_2 = \sqrt{2\hbar/\eta\sigma_\varepsilon}
\]

\[
\eta = \frac{d\Omega}{d\varepsilon}
\]
Charge-echo

- Precession frequency depends on noisy detuning
  → Try to cancel out different frequencies
  → Charge echo

- $\tau_{\pi/2} = 122$ ps / $\tau_\pi = 190$ ps

- Should exhibit oscillations as a function of $\delta t$ (twice the Larmor frequency)

- No echo observed

- Simulation: 4ps period, too small!

- Smaller tunneling coupling would be a possible solution
Requirements for successful charge echo

- Frequency of the echo signal occurs at twice the Larmor frequency precession

- To observe the echo, oscillations must be spaced by an interval larger than the limit given by the detector.. (QPC charge noise)

  - \[ \rightarrow \text{Smaller Larmor precession} \rightarrow \text{Smaller tunnel coupling} \]

  - \[ \rightarrow \text{Better detector} \rightarrow \text{Charge sensing dot} \]

  - \[ \rightarrow \text{Everything has to happen within 10 ns (given by } T_2) \]

  - \[ \rightarrow \text{Extremely fast rise times} \]
Conclusion

• Ramsey fringes are observed in a charge qubit $\rightarrow T_2^* \sim 60$ ps

• Charge-echo fails

• Higher quantum control could be achieved with further technical improvements