Low noise qubit gates in DQD systems

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Quantum Information S&T

Introduction

Singlet-triplet qubits realized by double quantum dot (**DQD**) structures encode quantum information in the lowest lying 2-electron singlet and unpolarized triplet states. Qubit rotations are performed by modulating the exchange energy *J*, defined as the difference in singlet and triplet energies.

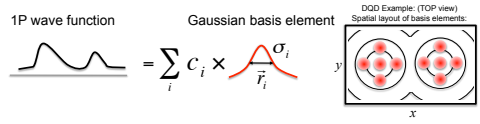
Since coherence of the quantum state must be maintained, the ability to modulate *J* in a way that is robust to charge noise is a crucial concern for singlet-triplet DQD qubits. Similarly, the analogue of the exchange energy which causes a controlled rotation must be robustly modulated in order to implement a controlled phase (C-phase) gate.

We study regimes in which the exchange and C-phase gates are expected to be more robust to charge noise using configuration interaction approaches. We consider dots in GaAs (or single-valley Si), and also report preliminary results for multi-valley Si systems.

Method: Configuration interaction with Gaussian basis

A full configuration interaction method is used to compute the exchange energy where the single particle states are written in a **Gaussian basis**:

1P wave function — Gaussian basis element



Single-valley effective mass Hamiltonian

$$H = \sum_i \left(\frac{(p - eA)^2}{2m} + V(r_i) + \frac{e}{m} B \cdot S_i \right) + \frac{e^2}{\kappa r_{12}}$$

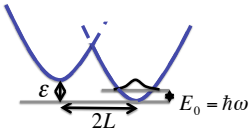
vs. Heitler-London / Hund-Mulliken:
- Variationally **more accurate**
- Captures qualitative differences

vs. mesh-based solvers: Less computational demand, allowing rapid traversal of parameter space

Exchange Gate (single DQD)

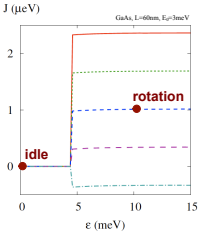
We compute the exchange energy *J* and seek regimes in which the gate is robust to detuning noise (small **Δ/Δε**) and operates over a time interval achievable by current electronics (limits |*J*| to μeV for ns gate times).

Idealized DQD potential (minimum of two quadratic dots)



Two robust regimes

Regime I: (0,2) flat

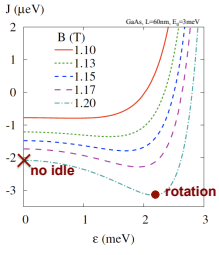


Example robust operation point

B = 1668 mT and
$P_{th} = 10^{-4}$ (QEC error threshold)
(give gate with)
τ ~ 2 ns
Δε ~ 12 meV

- $J \sim \mu eV$ ➡ **ns gate times**
- **can satisfy Δ/Δε requirements** for realistic P_{th} and electronics
- though robust to ε-noise, sensitive to fluctuation in L, E_0, B

Regime II: Magnetic field induced minimum

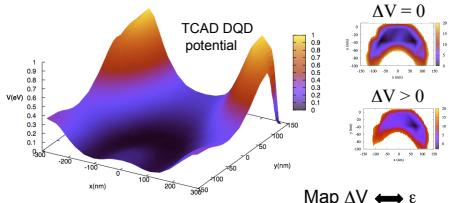


Example robust operation point

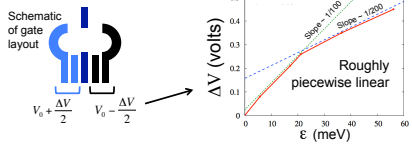
B = 1130 mT and
$P_{th} = 10^{-4}$
(give gate with)
τ ~ 1 ns
Δε ~ 0.2 meV

- Similar characteristics as regime I, but **no idle at ε=0**

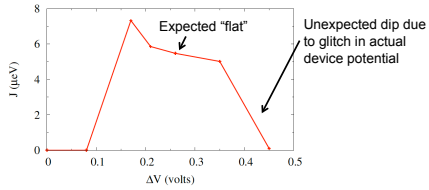
Realistic DQD potential (obtained via Poisson solution of CAD model)



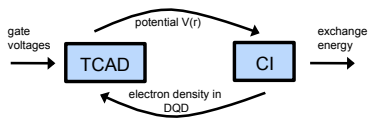
Map ΔV ⟷ ε



- Solution of Poisson and drift diffusion equations are performed using a commercial classical software package (TCAD) using a CAD model of an actual device. The potential solved for is then used in a Gaussian-basis CI yielding the exchange energy as a function of device gate voltages:

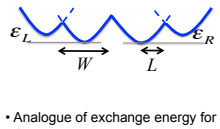


- **Current work: iterative solution**. More accurate inclusion of the specific environment will be obtained by iterating TCAD and CI solutions for the potential and charge distribution respectively:



C-phase gate (two DQDs)

Two idealized DQD potentials
(minimum of four quadratic dots)

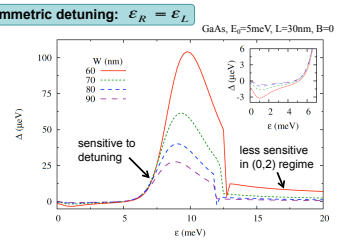


E_{TS} = energy for left DQD in triplet, right in singlet

$$\Delta = (E_{TT} - E_{ST}) - (E_{TS} - E_{SS})$$

- Analogue of exchange energy for C-phase is Δ
- Can **utilitze analog of (0,2) flat in single DQD to be less sensitive to detuning noise.**
- More robust mode of operation to get to (0,2) flat is to detune one DQD, then the other (not symmetric biasing)

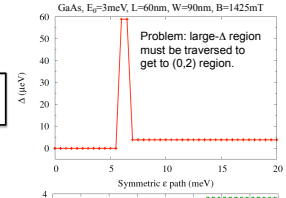
Symmetric detuning: $\varepsilon_R = \varepsilon_L$



Symmetric vs. right-then-left detuning at operating point with good DQD exchange curve:

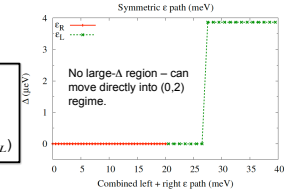
Case 1

Symmetric $\varepsilon_R = \varepsilon_L$



Case 2

Detune right DQD then left DQD (ε_R then ε_L)

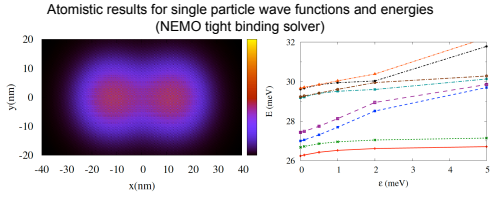


Tight-binding (atomic lattice) Configuration interaction

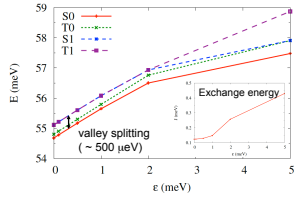
- **Inclusion of valley effects** by coupling CI to a tight-binding solver (NEMO). Results account for valley energy splitting and the possibility of exchange oscillations.

Compute two-particle Coulomb integrals using a discrete mesh and diagonalize CI Hamiltonian.

Atomistic results for single particle wave functions and energies (NEMO tight binding solver)



Many-body energies and exchange energy (CI)



Summary

We have analyzed the behavior of exchange and C-phase gates constructed with one and two double quantum dot(s), respectively, using a full configuration interaction method. We find that the physics of the system can be used to realize an exchange gate that meets the requirements set by current electronics technology (gate time, jitter), quantum error correction strategies (QEC threshold), and adiabatic transitioning. Specifically, we find that at finite magnetic field the noise due to detuning error or fluctuation can be suppressed in an exchange gate at usable qubit operating points. We also find an analogous regime where a C-Phase gate may be less sensitive to detuning noise, and suggest a sequence for biasing the constituent DQDs to perform the gate. The primary method used is a CI with a Gaussian. Although it has several advantages with respect to Heitler-London, Hund-Mulliken and mesh-based techniques, it cannot capture the physics of multiple valleys. Because of this, we have begun atomistic simulations which incorporate these effects (for silicon devices).

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