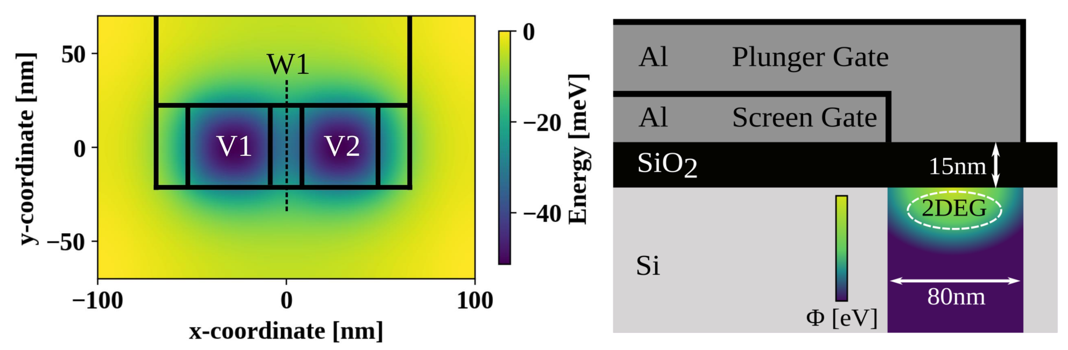
Simulated Control of Spin Qubits in MOSFET Quantum Dot Linear Arrays

ZACH D. MERINO, BOHDAN KHROMETS, XINNING WANG, JONATHAN BAUGH

QuDiPy

Introduction

We present a comprehensive simulator of electron spin qubits in electrostatically-defined quantum dots (QDs) to address challenges in designing quantum information processors.



Finite element solutions to Poisson's equation of realistic Silicon MOS are leveraged:

- Determine charge stability regions for various voltage configurations
- Engineer voltage pulses for spin qubit control
- Simulate gate operations on spin qubits in quantum circuits

Hubbard Hamiltonian

Hubbard parameters calculated from electrostatic potential [1]:

- Chemical potential
- Tunnel coupling
- Coulomb repulsion: onsite & interdot

$$H_{Hubbard} = H_\mu + H_t + H_U + H_u$$

$$H_\mu = -\sum_{\sigma=\uparrow,\downarrow}\sum_{i=1}^{N} \mu_i \hat{n}_{i,\sigma}$$

$$H_t = -\sum_{\sigma=\uparrow,\downarrow}\sum_{i<j} t_{ij}(\hat{c}^\dagger_{i,\sigma}\hat{c}_{j,\sigma} + h.c.)$$

$$H_U = \sum_{i=1}^{N} U_{ii}\hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

$$H_u = \sum_{\sigma_1,\sigma_2\in\{\uparrow,\downarrow\}}\sum_{i<j} U_{ij}\hat{n}_{i,\sigma_1}\hat{n}_{j,\sigma_2}$$

$$\left[-\frac{\hbar^2}{2m}\nabla^2{}_{2D} + V_i(\vec{r})\right]\psi_i(\vec{r}) = \epsilon_i\psi_i(\vec{r})$$ 2D Schrödinger

Effective Spin Hamiltonian

Spin Hamiltonian in rotating frame [2]:

- Stark shift: g-factor deviation
- Exchange interaction: Heitler-London/ Hund-Mulliken approximation

$$H_{Spin} = H_Z + H_J$$

$$H_Z = \hbar\sum_{j=1}^{N}\frac{1}{2}\left[\left(1+\frac{\delta g_i(t)}{2}\right)\omega - \omega_{RF}\right]Z_j + \frac{\Omega(t)\hbar}{2}\left(\cos\phi(t)\,X_j + \sin\phi(t)\,Y_j\right)$$

$$\delta g_i(t) = \eta\,\langle\psi_i(t)|\mathcal{E}_z(t)^2|\psi_i(t)\rangle$$

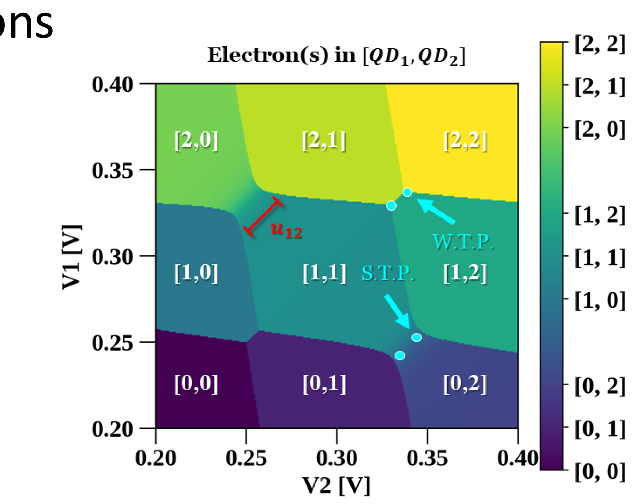
$$H_J = \sum_{i<j}\frac{J_{ij}(t)}{4}\vec{\sigma}_i\cdot\vec{\sigma}_j$$

Results

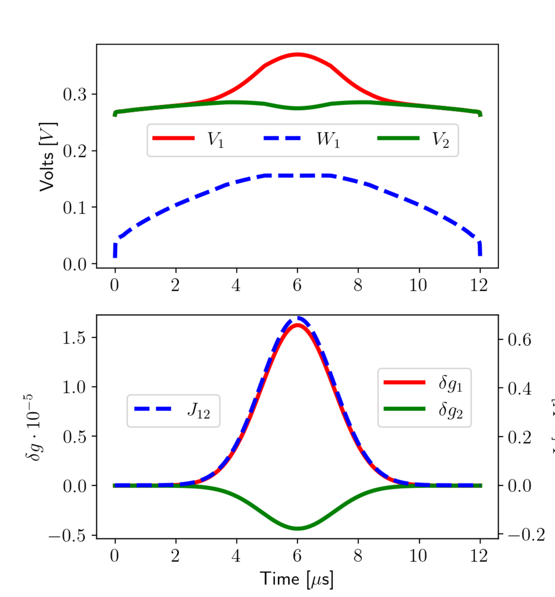
Charge Stability Regions

Charge stability regions for a double QD device. Coulomb repulsion and tunnel coupling features:

- Inform optimal control: pulse engineering & experiment



Qubit Gate Operations

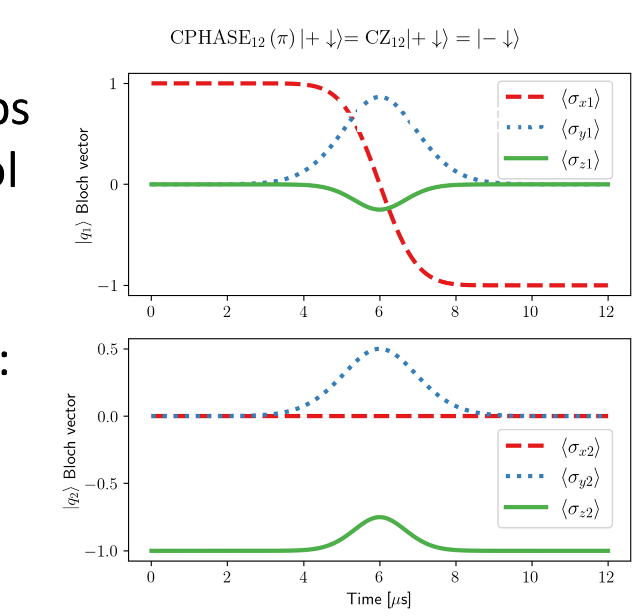


Global Electron Spin Resonance (ESR) field with gate voltage control enables effective parameter control:

- ESR 1-qubit gates
- Voltage-only 2-qubit gates

A novel, custom control method maps experimental control pulses from the expected effective parameter behavior:

- Incorporation of realistic device geometries
- Account for electrostatic cross-talk between QDs
- Universal set of gates & quantum algorithms



Hadamard

SWAP

GHZ

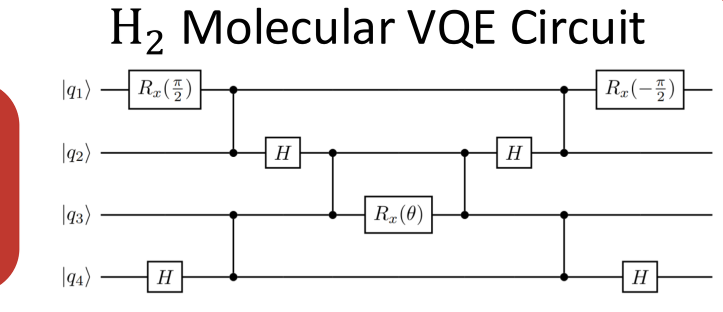
Application

Variational Quantum Eigen-Solver (VQE)

VQE sets an upper bound on ground state energy for a molecular electronic system. Approximating the multi-electron wavefunction is crucial in capturing correlation features in a many-electron system. With proper choice of Ansatz and optimization routine, a multi-electron wavefunction can be computed efficiently and accurately [3].

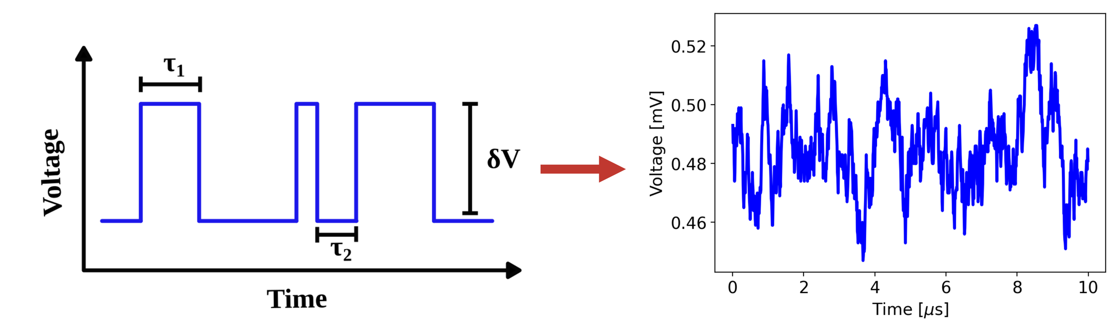
H_2 Molecular VQE Circuit

4 QD spin system mapped to Hydrogen molecule

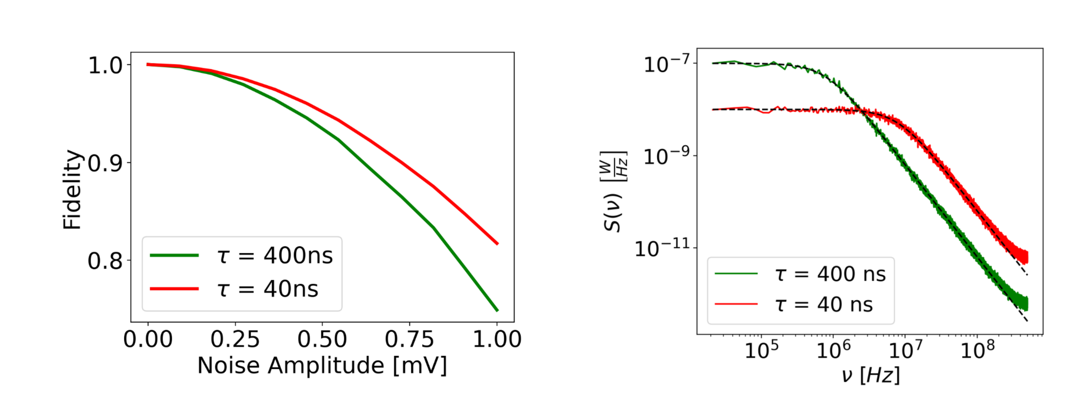


Noisy Intermediate Scale Quantum (NISQ) Devices

Simulation of electrical noise generated by an ensemble of Random Telegraph Noise (RTN) fluctuators for varied switching times τ. A Coupled Cluster (CC) designed VQE is applied to a 4-qubit QD linear array, which optimizes parameter θ for a quantum circuit with gate $R_x(\theta)$ to estimate the ground state wavefunction.



The impact on process fidelity of variational algorithm: RTN with varying electrical amplitudes and switching times → mimic that of experimentally observed values in real QD devices.



[1] Merino et al. AMMCS (2024): URL: https://arxiv.org/abs/2402.15499
[2] Khromets et al. AMMCS (2024), URL: https://arxiv.org/abs/2402.08146
[3] Yuxuan Du et al. npj QI (2022), DOI: 10.1038/s41534-022-00570-y.

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