Understanding Sensitivity of Entangled Qubit Logic Operations in Electrode-driven Semiconductor Quantum Dot Platforms

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Electron spin in isotopically enriched Silicon (Si) has beeb known as a promising mechanism for encoding quantum bits (qubits) as the coherence time can be extremely long (> 30 seconds) even though electrons are subjected to strong quantum confinement [1]. Here, we examine the behaviors of quantum bits (qubits) encoded to electron spins in gate-driven Si double quantum dot (DQD) systems with a multi-scale modeling approach that combines Thomas-Fermi calculations and electronic structure simulations based on the effective mass approach [2]. Covering the full functionality of DQD structures from charge controls to time responses of spin-qubits, we study the sensitivity of exchange interaction between initialized spin-qubits and investigate how it affects the fidelity of 2-qubit entangled logic operations (represented with controlled-NOT (CNOT) logic operations in this work) to understand the reported features of experimental devices [3]. This preliminary study not only presents theoretical clues for figuring out the major control factors that directly affects the robustness of entangled qubits encoded to electron spins, but also opens the possibility for further exploration of the engineering details for designs of higher-degree quantum logic gate blocks (*e.g.*, 3-qubit Toffoli (CCNOT) gate) that are not easy to be procured solely with experiments due to time and expense.

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References

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[4] The NURION high performance computer in Top500 site, https://www.top500.org/system/179421/

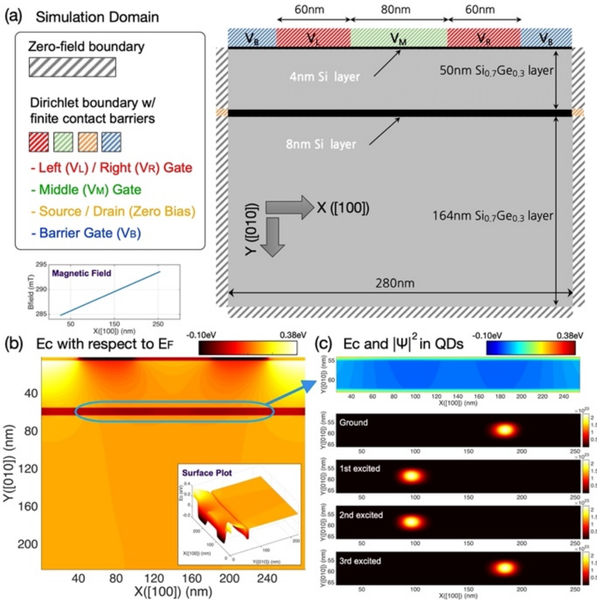

Fig.1: **Si DQD systems and electronic structures.** *(a) A 2D representation of Si double quantum dot (DQD) structure that is assumed to be very long along the [001] direction as the reported experimental device is (~200nm along the [001] direction). Quantum confinement along the [100] direction is formed by controlling top-gate biases (V_L, V_M, V_R). (b) Local bandstructure (E_C, spatial distribution of conduction band minimum) of the DQD system that is simulated at V_L = 400mV & V_L,= V_R = 542mV, and (c) corresponding electron density profiles at the four lowest conduction band states. Doe the magnetic field gradient along the [100] direction, Zeeman-splitting in the right QD is slightly larger than the one in the left QD.*

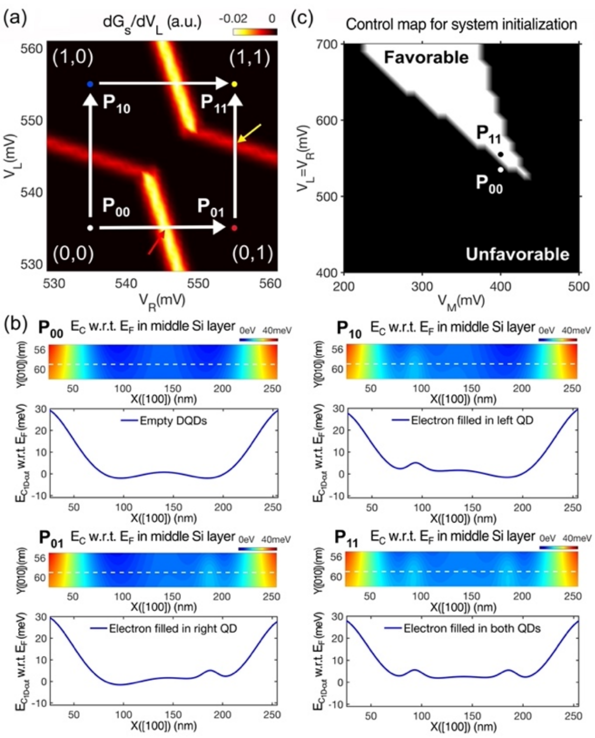

Fig.2: **Electrostatic charge control and qubit initialization in Si DQD system.** *(a) Charge stability diagram modelled at V_M = 400mV. (b) 1D-cut potential profiles that are plotted along the [100] direction in the middle Si layer at each charge state. (c) Range of top gate biases that can initialize the DQD system, which is marked with a white color.*

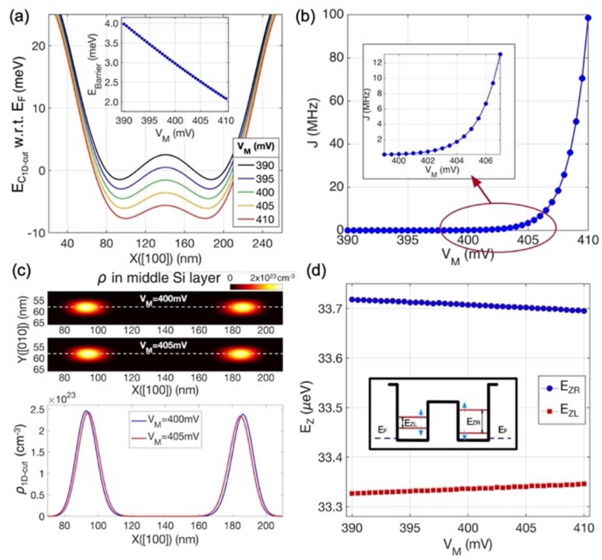

Fig.3: **Effects of the middle gate (V_M) control.** *(a) The 1D potential profile cut along the [100] direction in the middle Si layer, which is given as a function of V_M varying from 390mV to 410mV. The barrier height between two QDs reduces as V_M increases, and the lever-arm of the middle electrode on the top turns out to be about 10%. (b) Even though variation in the barrier height is a few mVs in the V_M range of our interest, corresponding change of the exchange interaction (J) is extremely huge, and (c) this huge change is mainly due to the change of charge distribution. (d) The Zeeman-splitting energy of the ground state in each QD turns out to be almost independent of V_M, which is good because the result indicates that the control of J and electron spin resonance frequency can be independent.*

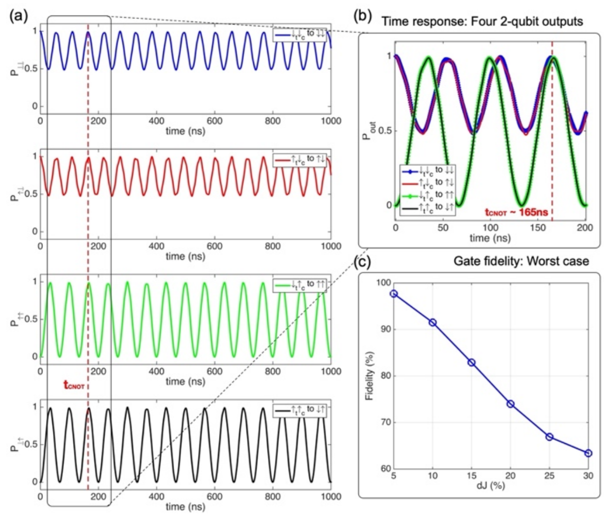

Fig.4: **Entangled 2-qubit logic operation and its sensitivity to the top gate controls.** *(a) 2-qubit time responses that are simulated for the four input qubits (|↓↓⟩, |↓↑⟩, |↑↓⟩, |↑↑⟩). Top gate biases are set to initialize the DQD system to the (1,1) charge state, where J (exchange coupling) between two QDs becomes about 10MHz. (b) Controlled-NOT (CNOT) operation is achieved at t = multiples of 165ns. (c) The state fidelity of CNOT operations at t=165nm is plotted as a function of ΔJ, which indicates the percentile deviation of J with respect to the reference value. Note that just 15% deviation of J already lowers the state-fidelity under 80% (the best state-fidelity reported for single-pulse CNOT operation so far is around 78%). So, the precise control of J is the key to improve the fidelity of entangled qubit logic operations that are represented by the CNOT gate in this work.*