Low Noise Exchange Gates in Double Quantum Dots

by Erik Nielsen, Malcolm Carroll, and Richard Muller

Motivation—Quantum computation relies on the coordinated operation of quantum bits, or qubits. In many solid-state qubit architectures, the exchange interaction is tuned in order to perform quantum operations (rotations) on the qubit. This requires precise control of the energy splitting between a spin-0 singlet state and a spin-1 triplet state, which is called the exchange energy and denoted by J. It is therefore important to understand and minimize the coupling between noise in the gate voltages and noise in J.

Accomplishment—We model a solid-state qubit formed by a pair of coupled quantum dots, called a double quantum dot (DQD), and compute the exchange energy J using a newly developed configuration interaction (CI) technique. The dots are approximated as parabolic, and the electrostatic potential is parameterized by the bias between the dots ε, half the dot spacing L, and the dot confinement energy E_0. This captures the general features of a DQD potential, and allows the technique to be easily applied to different dot materials (such as silicon and gallium arsenide) within the effective mass approximation. By applying our physical understanding of the DQD system along with the CI's ability to search large regions of parameter space quickly, we have identified regimes in which the exchange energy is relatively insensitive to variation in one or several of the electrostatic parameters determining the potential. These regimes are ideal locations for operating the qubit, since J is more robust against charge noise. We focus on regimes robust to variation in the bias energy ε, since one finds that varying ε independently of L and E_0 is more experimentally feasible than for other parameters. We have found that, within our approximation for the potential, multiple regimes exist in where J can be controlled on the energy scales necessary to perform a successful qubit rotation.

The configuration interaction method we use is more general than the Heitler-London, Hund-Mulliken, and effective Hubbard model approaches that have been used in past studies, yielding a more accurate exchange energy and capturing qualitative features that these more approximate methods miss. By using Gaussian basis functions, the CI possesses a substantial performance advantage over methods which require a large mesh, while still retaining semi-quantitative accuracy.

Significance—Understanding and mitigating the effects of charge noise in double quantum dot systems is crucial to the successful operation of a solid-state qubit. Using the CI method we have developed, it has been possible to identify the physical effects relevant to the coupling between charge- and exchange-noise, and to find specific regimes where this coupling is suppressed. The flexibility of the method makes it amenable to treating many solid-state systems, and its semi-quantitative accuracy can be used to suggest the design of qubit devices.

Sponsors for various phases of this work include: Laboratory Directed Research & Development

Contact: Erik Nielsen, Semiconductor Material and Device Sciences
Phone: (505) 844-6912, Fax: (505) 844-3211, E-mail: enielse@sandia.gov

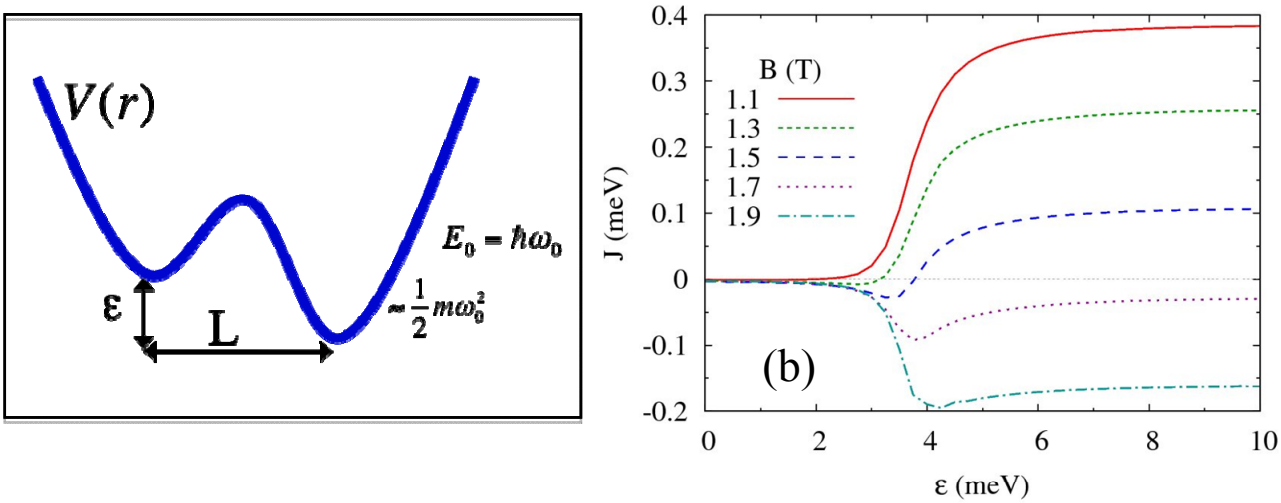

Figure 1. (a) DQD potential along x-axis showing parameters ε, L, and E_0. (b) Exchange energy as a function of bias for E_0=3meV and L=30nm. For a range of magnetic field the curve has a local minimum as well as two "flats" at high and low ε.

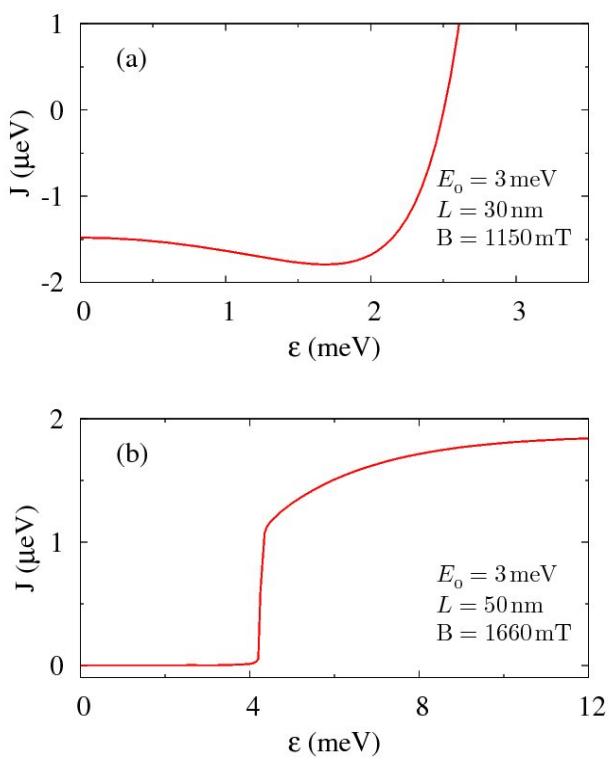

Figure 2. Exchange energy J as a function of bias in cases for where J is sufficiently robust to ε-noise that current electronics technology could produce operational quantum gates. In (a), these robust points are at ε=0 and 1.7meV, and in (b) at ε=0 and 12meV.