Quantum-Dot-Based Resonant Exchange Qubit

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We introduce a solid-state qubit in which exchange interactions among confined electrons provide both the static longitudinal field and the oscillatory transverse field, allowing rapid and full qubit control via rf gate-voltage pulses. We demonstrate two-axis control at a detuning sweet spot, where leakage due to hyperfine coupling is suppressed by the large exchange gap. A $\pi/2$-gate time of 2.5 ns and a coherence time of 19 $\mu$s, using multipulse echo, are also demonstrated. Model calculations that include effects of hyperfine noise are in excellent quantitative agreement with experiment.

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As originally conceived, the two-level system that forms the basis of the semiconductor spin qubit is the electron spin itself, with pulsed exchange between two confined electrons forming a two-qubit gate [1]. Generalizations to two-electron [2–6] and three-electron [7–13] qubits make use of multielectron states as the quantum two-level system. These qubits offer ease of initialization, control, and readout, or speed of operation, in exchange for the complexity of controlling more than one electron per qubit. An attractive feature of the original single-spin proposal is that qubit rotations are implemented as Rabi processes, driven by a small resonant transverse field, rather than Larmor processes, which use pulsed Larmor precession around larger nonparallel fields. Rabi rotations allow narrow-band wiring away from dc, precession rates controlled by the amplitude of the oscillatory field, and straightforward two-axis control (needed for arbitrary transformations) implemented using the phase of the oscillatory field [14,15].

In this Letter, we introduce a new quantum-dot-based qubit—the resonant exchange qubit—that captures the best features of previous incarnations, with qubit rotations via Rabi nutation using gate-controlled exchange both for the static longitudinal field and the oscillatory transverse field, as described in Ref. [16]. The large exchange field suppresses leakage from the qubit space. However, because rotations are driven by a resonant transverse field, the large longitudinal field does not impose unrealistically fast evolution between qubit states. Moreover, the qubit is operated at a “sweet spot” of the exchange gap, making it insensitive, to first order, to electrical noise in the detuning parameter [16–19].

The resonant exchange qubit was realized in a triple quantum dot formed by surface gates 110 nm above a two-dimensional electron gas (density $2.6 \times 10^{15}$ m$^{-2}$, mobility 43 m$^2$/Vs) in a GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructure [see Fig. 1(a)]. Gate voltages $V_l$ and $V_r$, controlled detuning, $\varepsilon = (V_l - V_1^0)/2 - (V_r - V_2^0)/2$, measured relative to the center of the 111 charge region, while $V_m$ controlled the size of the 111 region (111 and other number triplets denote the charge occupancy of the triple dot) [20]. An adjacent multielectron quantum dot operated in a Coulomb blockade regime served as a radio frequency (rf) charge sensor [21,22].

Tunneling between adjacent quantum dots gives two exchange splittings, $J_i(e)$, associated with the electron pair in the left and middle dots, and $J_r(e)$, associated with the electron pair in the middle and right dots. Away from zero detuning, defined as the center of 111, the qubit ground state, $|0\rangle=(1/\sqrt{6})(|111\rangle + |122\rangle - 2|211\rangle)$, connects continuously to a singlet state of the left pair, $|s_l\rangle=(1/\sqrt{2})(|111\rangle - |211\rangle)$ in charge state 201, and to a singlet state of the right pair, $|s_r\rangle=(1/\sqrt{2})(|111\rangle - |111\rangle)$ in charge state 102. [see Fig. 2(a)]. The excited qubit state, $|1\rangle=(1/\sqrt{2})(|111\rangle - |111\rangle)$, maps into triplet states, which, in contrast to the singlets, cannot tunnel into charge states

![FIG. 1 (color online). (a) False color micrograph of lithographically identical device with dot locations depicted. Gate voltages, $V_l$ and $V_r$, set the charge occupancy of left and right dot as well as the detuning, $\varepsilon$ of the qubit. A neighboring sensor quantum dot is indicated with a larger circle. (b) Triple-dot charge occupancy as a function of $V_l$ and $V_r$ in and near the 111 regime; $\varepsilon=(V_l-V_1^0)/2-(V_r-V_2^0)/2$, $\delta=(V_l-V_1^0)/2+(V_r-V_2^0)/2+(V_l-V_1^0)/2+(V_r-V_2^0)/2+\gamma(V_m-V_m^0)$. Measurements give $\gamma \sim 3$. The operating position is marked with a star, which is larger than the amplitude of voltage modulation used in rotations. Color scale is sensor dot reflectometer output, $\Delta V_{ref}$, relative to output at (1,1,1), in arbitrary units.](https://example.com/fig1.png)
201 or 102. This allows the qubit state to be detected with a charge sensor that distinguishes 201, 111, and 102. A third state, \(|Q_+\rangle = |\uparrow\uparrow\rangle\), intersects the qubit ground state at two anticrossings whose position depends on Zeeman splitting from an external magnetic field. By sweeping the magnetic field, the qubit ground-state energy can be measured as a function of detuning [Figs. 2(c) and 2(c)]. The fourth state in Fig. 2(a), \(|Q\rangle = (1/\sqrt{3})(|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)\), is separated from the qubit states by a sizable gap (half the separation between \(|0\rangle\) and \(|1\rangle\)), suppressing leakage out of the qubit space. The gap to \(|Q\rangle\) is deliberately large by setting tunneling rates, hence \(J_l\) and \(J_r\), to be large throughout the 111 charge region.

Qubit rotations are implemented by applying an oscillatory voltage to gate \(V_l\), which moves the operating point around \(\epsilon = 0\), in turn creating an oscillatory transverse field \(J_x\) [see Fig. 2(b)]. When the oscillation frequency \(\omega\) matches the longitudinal exchange frequency, \(f_l/\hbar\) [see Fig. 2(b)], the qubit nutates between \(|0\rangle\) and \(|1\rangle\). Figure 2(c) maps the positions of the \(|Q_+\rangle\) anticrossings with the lower qubit branch as a function of field and detuning without applied microwaves, along with a model calculation of the exchange splittings \(J_l\) and \(J_r\). This spectroscopy is performed by preparing a \(|S_+\rangle\) state in 102, then pulsing into 111 for 300 ns before returning to 102 to project the resulting state back onto \(|S_+\rangle\).

The data in Fig. 2(d) show two features, a vertical line corresponding to the crossing of \(|Q_+\rangle\) and the center of the lower qubit branch (circle), and a curved feature reflecting a driven oscillation between qubit states \(|0\rangle\) and \(|1\rangle\), marked with a star. The curved feature shows that the qubit splitting is controlled by gate voltage \(V_{m_1}\), here covering a range from 200 MHz to 2 GHz. Using fast gating, we have demonstrated control of this frequency on nanosecond time scales. The dashed line in Fig. 2(d) is a model of \(\omega (V_{m_1})\) that assumes a linear dependence of \(J_l\) and \(J_r\) on \(V_{m_1}\).

The resonant exchange qubit can be modeled by the Hamiltonian,

\[
\mathcal{H}(\epsilon) = -J_1 \sigma_z/2 - J_x \sigma_z/2, \tag{1}
\]

where \(J_1 = (1/2)[J_l(\epsilon) + J_r(\epsilon)]\) and \(J_x = (\sqrt{3}/2)[J_r(\epsilon) - J_l(\epsilon)]\), where \(\sigma_z = |0\rangle\langle 0| - |1\rangle\langle 1|\) and \(\sigma_x = |0\rangle\langle 1| + |1\rangle\langle 0|\) are the Pauli operators of the qubit [see Fig. 2(b)]. Exchange fields \(J_l(\epsilon) = -(\epsilon + \epsilon_0)/2 + \sqrt{\epsilon^2 + (\epsilon + \epsilon_0)^2}/4\) and \(J_r(\epsilon) = (\epsilon - \epsilon_0)/2 + \sqrt{\epsilon^2 + (\epsilon - \epsilon_0)^2}/4\) are modeled in terms of the tunnel coupling, \(t\), which is taken to be the same for both the 201-111 and 111-102 transitions, and \(\pm \epsilon_0\), the detunings of these charge transitions. At \(\epsilon = 0\), this gives \(dJ_1/d\epsilon = 0\) and \(dJ_x/d\epsilon = (\sqrt{3}/2)(1 - \epsilon_0/\sqrt{4\epsilon^2 + \epsilon_0^2})\). For small detuning, \(\epsilon \ll \epsilon_0\), \(J_x\) is unchanged to first order while \(J_1 \sim \epsilon\). This system is equivalent to a spin 1/2 in a large static field with a small transverse field. While \(J_1\) is insensitive to detuning noise to first order, it is not insensitive to noise on gate \(V_{m_1}\) or other gates. However, other gates, including \(V_{m_1}\), do not need to operate at high frequency, and so can be heavily filtered.

In Fig. 3, \(|S_+\rangle\) is prepared in 102 and adiabatically evolved to \(|0\rangle\) at \(\epsilon = 0\), taking care to move rapidly through the \(|Q_+\rangle\) anticrossing. A microwave burst is then applied to \(V_l\) for a time \(\tau_B\) before returning adiabatically to 102 for measurement. The color plot shows the probability, \(P_0\), of detecting the ground state through a charge measurement (see Sec. I, Supplemental Material [23]). By sweeping frequency and power, we see patterns characteristic of Rabi nutation subject to low frequency noise in the splitting frequency, \(\omega_{01}\) due to hyperfine gradients (see Sec. VI, Supplemental Material [23]). In the rotating frame, the amplitude of the oscillation gives the strength of the \(\mathcal{H}(\epsilon)\)
rotation, while the frequency detuning, $\delta = \omega - \omega_{01}$, gives the strength of the $\hat{z}$ rotation. As seen in Fig. 3(b), as the power increases, effects of $\delta$ errors due to hyperfine gradients decrease. At $\omega_{01}/2\pi = 0.355$ GHz, the nutation frequency scales with voltage as $d\Omega_R/dV_i \sim 2\pi \times 70$ MHz/mV. This scaling increases with $dJ_x/d\epsilon$, which grows as the 111 region is shrunk ($\epsilon_0 \rightarrow 0$) to increase $\omega_{01}$. At $\omega_{01}/2\pi = 1.98$ GHz, this scaling was measured to be $\sim 2\pi \times 5$ GHz/mV, demonstrating a way to increase coupling to external voltages.

On resonance in the rotating frame, the Hamiltonian takes the form $\hat{H}_{rt} = \cos(\Phi)\sigma_x + \sin(\Phi)\sigma_y$, where $\Phi$ is the relative phase of the carrier wave with respect to the first pulse incident on the qubit. Controlling phase relative to the initial pulse thus allows full two-axis qubit control. To test the qubit response, we prepare a $|0\rangle$ and drive a rotation on resonance for a time $\tau_x$, then apply a second pulse at relative phase $\Phi$ to drive a $3\pi/2$ rotation in a time $3\pi/2\omega_R$. Figure 4 shows data for $\Phi = 0^\circ$, $90^\circ$, and $180^\circ$, along with model curves using an optimized, though reasonable, value for hyperfine couplings as a fit parameter.

Phase control was sufficient to implement a Carr-Purcell-Meiboom-Gill (CPMG) dynamical decoupling sequence, where $\pi$ pulses are applied along the $\hat{y}$ axis in the rotating frame, partially decoupling rotation errors [15]. Figure 5 shows resulting coherence time, $T_2$, for CPMG sequences up to 64 $\pi$ pulses, which gave $T_2 = 19 \pm 2$ $\mu$s. Values for $T_2$ were extracted from Gaussian fits to $P_0/\tau_D$, where $\tau_0$ is the total dephasing time (see inset of Fig. 4). Between 2 and 16 pulses, the scaling of coherence time with (even) pulse number, $n_\pi$, appears well described by the power law, $T_2 = A(n_\pi)^\beta$, where $\gamma = 0.84 \pm 0.05$. Within a classical power-law noise model [24,25], this implies $S(\omega) \sim \omega^{-\beta}$ with a $\beta = 5 \pm 1$. The inconsistency of this result with recent studies of electrical noise in the singlet-triplet qubit, where $\beta \sim 0.7$ [26], may reflect first-order insensitivity of the resonant exchange qubit to detuning noise. However, a detailed model for dynamical decoupling that distinguishes voltage noise from hyperfine noise has not been developed to date. Moreover, pulse sequences designed to decouple hyperfine noise for exchange-only qubits [27] may also be adaptable to the resonant exchange qubit.

For $n_\pi > 16$, $T_2(n_\pi)$ falls below the steep power law, and appears to saturate around 20 $\mu$s. The measured $T_1$ for a splitting $\omega_{01}/2\pi = 0.33$ GHz was $\sim 40$ $\mu$s, and decreased monotonically with increasing $\omega_{01}$, consistent with phonon-based relaxation, which suggests that $T_1$ was not limiting $T_2$ at $\omega_{01}/2\pi = 0.2$ GHz. Pulse errors are likely
The number of pulses was well described by $n/C_2^5$, each sequence contains $n/C_1^3 = \pi/2$. Limiting $T_2$ in this measurement, though extending coherence much longer will require extending $T_1$.

In summary, we have introduced and demonstrated the operation of a new quantum-dot-based qubit that uses exchange for both the longitudinal and oscillatory transverse fields. A large exchange gap prevents state leakage, and the operating point is insensitive to first order fluctuations in gate-controlled detuning. Two-axis control and a large ratio ($\sim 10^4$) of coherence time to gate operation time were demonstrated. Implementation of a two-qubit gate is the next experimental challenge.

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[20] $V_m^0 = (-588 \text{ mV}, -452 \text{ mV}, -145 \text{ mV})$.
[29] The theory curve is a plot of $\omega_{01} = (-\beta V_m^0 + \sqrt{\beta^2 (V_m^0 - V_0^m)^2 + 4 \hbar^2 / 4}) / 2$, where $\beta = 20 \mu \text{ eV/mV}$, $I = 16.9 \mu \text{ eV}$, and $V_0^m = -4.05 \text{ mV}$. A constant tunnel coupling was used here rather than a Gaussian dependent tunnel coupling, because $V_I$ and $V_r$ were constant.