Abstract

Coherent time evolution of a charge qubit in a semiconductor double quantum dot is demonstrated by means of electrical pulse experiments. The qubit state is manipulated with a rectangular or tailored voltage waveform that controls the energy of the system. The initialization, rotation gate, phase-shift gate, and measurement process are sequentially performed just by changing the voltage in a short time.

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1. Introduction

Studies on coherent quantum dynamics for single particles, such as Larmor precession and Rabi oscillation, as well as for more than two particles have been initiated from various experiments on excitation processes in atoms, and have been applied to small-scale quantum computers [1]. Nano-fabrication technology allows us to design semiconductor artificial atoms (quantum dots, QDs) and molecules (double quantum dots, DQDs), in which atomic (molecular)-like electronic states can be designed and controlled by external voltages [2–5]. The eigenstates of interacting electrons in quantum dots and the transitions between them can be well understood in terms of atomic physics language. These artificial atoms (molecules) may have advantages for flexible control on their states and for large-scale integration. At least, it has been demonstrated that stationary eigenstates can be tailored by adjusting static gate voltages. In order to test their potential for application to quantum information technology, coherent manipulations of non-stationary superposition state are required.

Here, we describe electrical manipulation of a charge qubit in a DQD in the Coulomb blockade regime. The qubit state is manipulated by applying a rectangular or tailored voltage pulse between the source and drain electrodes. The qubit state is effectively initialized by injecting an electron into one of the localized states. The rotation gate, which
modulates the population of each QD, is obtained by adjusting the system at the resonant tunneling condition. The phase-shift gate, which gives a phase difference between the computational bases, is executed at an off-resonant condition in a very short time. Finally, the qubit state is measured by using a tunneling process.

2. Charge qubit in a DQD

We consider a DQD (left and right dots) connected to the source and drain electrodes in series (see Fig. 1(a)). The electrical current, which flows through the DQD via three tunneling barriers, is strongly affected by the on-site and inter-dot Coulomb interactions. In the weak coupling regime, finite current is only observed when all the tunneling processes through three tunneling barriers are allowed. Under an appropriate condition, where the inter-dot tunneling is allowed but tunneling into and out of the DQD is blocked, the DQD is effectively isolated from the electrodes, which are required for the initialization and measurement processes. In this case, we can consider two charge states, in which an excess electron occupies the left dot or the right dot. In practice, each charge state involves many-body ground and excited states due to orbital and spin degrees of freedom. When the energies $E_L$ and $E_R$, respectively, for two particular states $|L\rangle$ and $|R\rangle$, are energetically close to each other and the excitation to other states can be neglected, the system can be approximated by a two-level system (qubit), which is more convenient for quantum computing applications. It should be noted that $|L\rangle$ and $|R\rangle$ can be any excited state of each QD, if the population of other states can be neglected. We chose one of the excited state resonances in the experiments. The system is characterized by the energy offset $\varepsilon \equiv E_R - E_L$ and interdot tunneling, whose energy splitting is $\Delta$. The effective Hamiltonian is

$$ H = \frac{1}{2} \varepsilon \sigma_z + \frac{1}{2} \Delta \sigma_y, $$

where $\sigma_x$ and $\sigma_z$ are the Pauli matrices for pseudo-spin as bases of $|L\rangle$ and $|R\rangle$. The eigenstates of the system are bonding and anti-bonding states, whose energies ($E_a$ and $E_b$) are schematically shown in Fig. 1(b). The system can also be mapped onto the Bloch sphere of a pseudo-spin in a fictitious magnetic filed ($\varepsilon$ and $\Delta$), as shown in Fig. 1(c).

The DQDs used in this work are defined by metal gates on top of a GaAs/AlGaAs heterostructure with a two-dimensional electron gas (2DEG). Each dot contains about 25 electrons with on-site charging energy $E_c \sim 1.3$ meV. The interdot charging energy is $U = 200$ µeV. The qubit parameters, $\varepsilon$ and $\Delta$, and tunneling rates, $\Gamma_L$ and $\Gamma_R$, respectively, for left and right
barriers, can be roughly estimated from elastic tunneling current and tuned by gate voltages [4,6]. In the region of interest, |ε| ≤ 50 μeV and Δ = 5–10 μeV is smaller than U and smaller than the typical level spacing of each dot, ~100 μeV, where the system can be approximated by a two-level system. The experiments were performed at lattice temperature of T\text{lat} < 20 mK in a magnetic field of 0.5 T applied perpendicular to the 2DEG. The effective electron temperature, which is estimated from the line width of a single electron tunneling current through a single quantum dot, remained at T\text{elec} ~ 100 mK, probably due to high-frequency noise. In the following experiment, we only changed ε in a short time with a quasi-constant Δ.

A rectangular voltage pulse was applied to the drain electrode via a low-distortion coaxial cable. The pulse switches the source–drain bias voltage between high (600 μV) and zero. Due to the mutual coupling between the QDs and electrodes, the pulse also shifts the energy offset from ε = ε0 to ε1 by ε1 − ε0 ~ 40 μeV. We design the pulse sequence that performs initialization, coherent manipulation, and measurement in the following way. Although the basic idea is borrowed from experiments on a superconducting island [7], our qubit is effectively isolated from the electrode during the manipulation, while it is influenced by strong decoherence during initialization.

3. Rotation gate

The rotation gate is obtained by applying a rectangular voltage waveform. Fig. 2(a) shows a typical waveform (pulse length of 400 ps) for the rotation gate. The actual waveform at the sample is deformed by the frequency-dependent loss of the coaxial cable.

For initialization, we applied a relatively large source–drain voltage, V\text{sd} ~ 600 μV (Fig. 2(b)). We also adjusted the gate voltages so that |L⟩ and |R⟩ would be out of resonance in the transport window (μS < E_L > E_R > μD = μS − eV\text{sd}, ε = ε0 ~ −40 μeV). Elastic and inelastic current flows through the DQD, but the current is always limited by the central barrier when the outer tunneling barriers have higher tunneling rates (ℏΓ_L ~ ℏΓ_R ~ 30 μeV > Δ, ℏΓ_i), where Γ_i is the inelastic tunneling rate between the two dots (ℏΓ_i ~ 0.1–4 μeV). In this case, the DQD is effectively initialized to |L⟩.

For coherent manipulation, we immediately change the source–drain voltage to zero, and shift the energy offset to ε = ε1 ~ 0 (Fig. 2(c)). In this case, the inter-dot charging energy prevents electrons tunneling in and out of the DQD within the first-order tunneling process, and no current flows through the DQD. The qubit is effectively isolated from the electrodes. Therefore, the system is well approximated by Eq. (1). The rise time of voltage pulse was about 100 ps, which is fast enough to change the system non-adiabatically. The system first prepared in |L⟩, goes back and forth between the two dots. In the Bloch sphere representation, the pseudo-spin state rotates about the total fictitious magnetic field (Larmor precession). We maintained zero bias voltage for a duration, t_p = 80–2000 ps.

Then, the large bias voltage is restored for measurement process (Fig. 2(d)). The large tunneling rate (ℏΓ_L, ℏΓ_R) and off-resonant condition effectively ceases the coherent precession, and provides a strong measurement. If the electron ends up in the right QD, it tunnels out to the right electrode and contributes to the excess pulse-induced current. If the electron end up in the left dot, however, it cannot do so. The system automatically goes to the initial state after waiting longer than Γ_L^{-1} + Γ_R^{-1}.

In practice, we repeatedly apply many pulses with repetition time t_{\text{rep}} = 10 ns ≫ Γ_L^{-1} + Γ_R^{-1}, and measured the average DC current, I_p. In order to improve the signal-to-noise ratio, we employed lock-in amplifier technique to measure the pulse-induced current, I_p, by switching the pulse train on and off at a modulation frequency of 100 Hz. We evaluate the average number of pulse-induced tunneling electrons, ⟨n_p⟩ = I_p/ef_{\text{rep}}.

Fig. 3(b) shows a color plot of the pulse-induced current I_p as a functions of pulse length t_p and energy offset ε1 during the manipulation. In this experiment, ε0 and ε1 were simultaneously swept by changing a gate voltage, V_R. The condition ε0 = 0 was determined at the resonant tunneling peak in the absence of the pulse, while the condition ε1 = 0 was determined at the current peak in I_p for t_p > 1 ns. Clear oscillations were observed in the time domain at ε1 ~ 0. The trace at ε1 = 0 is also shown in Fig. 3(a). The oscillation can be fitted very well with the exponential decay of the cosine function and a linearly decreasing term,

$$\langle n_p(t_p) \rangle \simeq A \exp(-t_p/T_2) \cos(\Omega t_p + \phi) - \Gamma_i t_p$$

(2)
Fig. 2. (a) The rectangular pulse waveform used for the rotation gate. The rise time of the pulse was about 40 ps at the pulse generator, but degraded to about 100 ps at the sample. Energy diagrams of the DQD during (b) initialization, (c) coherent oscillation, and (d) measurement process.

Fig. 3. (a) The pulse-induced tunneling electrons, \( \langle n_p \rangle \). The solid line is a damped cosine function with a linearly decreasing term, which is fitted to the data. (b) Color plot of the pulse induced current, \( I_p \).

except for the rise time of the voltage pulse (\( t_p < 100 \) ps). The amplitude of the oscillation, \( A \sim 0.3 \), which is smaller than unity, may arise from the finite rise time of the pulse as well as the non-ideal initialization and measurement processes. The small phase shift \( \phi \) might also arise from the finite rise time. The last term corresponds to the reduction of the inelastic tunneling current, which only flows during
high $V_{sd}$, $I_1$ obtained from this fitting almost agrees with the inelastic DC current amplitude, indicating the validity of the isolated quantum state during the manipulation. We determined the oscillation frequency $\Omega/2\pi$ to be $\sim 2.3$ GHz and the decoherence time $T_2$ to be $\sim 1$ ns from the fitting. The $h\Omega$ should correspond to the energy splitting of the bonding and antibonding states, $\hbar\Omega = \sqrt{\varepsilon_1^2 + \Delta^2}$, from which we can determine $\Delta$.

The oscillation pattern in Fig. 3(b) shows that the amplitude and period decreases when $\varepsilon_1$ is out of the resonance. The asymmetry of the current profile at around $\varepsilon_1 = 0$ arises from the finite rise time of the voltage pulse [7]. A clear oscillation appears if the transient from $\varepsilon_0$ to $\varepsilon_1$ crosses the resonant condition (i.e., $\varepsilon_0 \leq 0 \leq \varepsilon_1$).

We can control $\Delta$ to be from 6 to 12 $\mu$eV by changing the central gate voltage, $V_C$, as shown in Fig. 4. However, the decoherence time is always limited to about 1 ns. Possible decoherence mechanisms will be discussed in a separate paper [8].

### 4. Phase-shift gate

The phase-shift gate is obtained by applying a large source–drain voltage during the manipulation to shift the energy offset to $\varepsilon = \varepsilon_2$. Leaving a state at $\varepsilon_2 \gg \Delta$ for a specific time $t_{\phi}$ produces a phase shift $\phi = \varepsilon_2 t_{\phi}/\hbar$ [9]. Fig. 5(a) shows the pulse waveform for demonstrating the phase-shift gate. The rectangular waveform (i) with pulse length of 200 ps works as a $\pi$ pulse for $\Delta = 10$ $\mu$eV at $\varepsilon_1 = 0$. A single sharp pulse, which we refer to as a tipping pulse, is superimposed at the center of the main pulse [see waveform (ii)]. When we neglect non-ideal factors, the first half of the rectangular pulse ($\pi/2$ pulse, Fig. 5(b)) puts the system in the superposition state $\frac{1}{\sqrt{2}}(|L\rangle - i|R\rangle)$. The tipping pulse gives a phase shift $\phi$, and thus the state becomes $\frac{1}{\sqrt{2}}(|L\rangle + i\exp(i\phi)|R\rangle)$ (Fig. 5(c)). The second half of the pulse [$\pi/2$ pulse, Fig. 5(d)] changes the system...
to $\frac{1}{2}(1 - e^{i\phi})|L\rangle + (1 + e^{i\phi})|R\rangle$. Therefore, the probability of finding the system in $|R\rangle$ oscillates in $\phi$.

However, in our experimental scheme, the high $\varepsilon_2$ requires a large source–drain voltage, which can break the Coulomb blockade condition and induce strong decoherence from the tunneling. Therefore, we minimize the time duration $t_0$ for the phase-shift gate, and change $\varepsilon_2$ to control the phase shift. The tipping pulse is prepared by making a derivative of another rectangular pulse of the same length. This gives an additional negative pulse just after the main pulse. We believe this negative pulse does not affect the following measurements very much.

Fig. 6(b) shows the color plot of the pulse-induced current when $\varepsilon_0$ and $\varepsilon_1$ are simultaneously swept by changing $V_R$ (horizontal axis) and $\delta\varepsilon_2 = \varepsilon_2 - \varepsilon_1$ are changed (vertical axis). The oscillations observed at $\varepsilon_1 = 0$ (Fig. 6(a)) indicate the phase-shift gate operation. The amplitude slightly decays with increasing $\delta\varepsilon_2$, although pulse width remained constant. The maximum $\delta\varepsilon_2$ (2.0 arbitrary unit in Fig. 6) corresponds to about 5 mV in the source–drain voltage, which is much greater than the charging energy of the dots. Additional decoherence might come from enhanced tunneling rates via other excited states at high $\varepsilon_2$.

5. Summary

We have successfully observed coherent charge oscillations of a charge qubit in a double quantum dot. Although the quality of the oscillation is not very good due to decoherence, our observation could stimulate studies on coherent dynamics in semiconductor quantum dots.

References


