Physica E 72 (2015) 53–57

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Correlated dynamics of a Rabi oscillation and a quantum tunneling in coupled quantum dots

Weidong Xie [a,b,d], Bingxin Chu [c], Suqing Duan [b], Yan Xie [b,*], Weidong Chu [b,**], Ning Yang [b], Xian-Geng Zhao [b]

[a] Department of Modern Physics, University of Science and Technology of China, 230026 Hefei, China
[b] Institute of Applied Physics and Computational Mathematics, P.O. Box8009(28), 100088 Beijing, China
[c] School of Information Science and Engineering, Shandong University, 250100 Jinan, China
[d] Department of Electronic Science, Huizhou University, 516007 Guangdong, China

HIGHLIGHTS

- We couple a Rabi oscillating electron and a quantum tunneling one in a four-quantum-dot system.
- We show the correlated dynamics of Rabi oscillation and quantum tunneling.
- We reveal that the Rabi oscillation and the quantum tunneling can be synchronized under specific condition.
- We propose a possible way to accomplish a gang control of two electrons by a single optical signal.

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
17 April 2015
Accepted 22 April 2015
Available online 24 April 2015

Keywords:
Correlated dyanmics
Rabi oscillation
Quantum tunneling
Quantum dots

ABSTRACT

We couple the Rabi oscillation in a double quantum dot (DQD) with the quantum tunneling in another DQD by Coulomb interaction between the neighboring dots. Such a coupling leads to correlation of the Rabi oscillating electron and the quantum tunneling one, and gives a tendency of synchronizing them under appropriate Rabi frequency Ω_R and tunneling rate T_c. The correlated oscillation is shown clearly in the tunneling current. As $\Omega_R = T_c$, the Rabi oscillation and the quantum tunneling reach their strongest correlation and the two electrons finish their complete transitions simultaneously. And then, a single optical signal accomplishes a gang control of two electrons. This result encourages superior design of two-qubit quantum gates based on correlated DQDs.

1. Introduction

Correlated dynamics of electrons is a fundamental quantum physical problem. It describes characteristics of many-body systems [1–3], and attracts many attentions on potential application to transmission of quantum information [4,5]. In semiconductor quantum dots (QDs), the tunable electronic structure makes them a well platform to design and control various correlated quantum physical processes. In a double quantum dot (DQD) system coupled to a strongly biased quantum point contact, a quantum ratchet phenomenon originating from Coulomb correlation has been observed [6]. In a coupled DQD system, correlated quantum tunnelings from each pair of DQD are observed [7,8]. Theoretical studies propose various schemes to carry out Coulomb drag effect induced by electron correlation in a capacitively coupled DQD [9] and quantum circuits [10]. Conditional dynamics of two optical excitations is demonstrated in two coupled QDs, which represents a substantial progress toward realization of an optically effected controlled-phase gate between two solid-state qubits [11]. These results suggest exciting prospects of various applications in quantum information and new photo-electric devices.

The above-mentioned correlations occur among the same kind of dynamic processes. Recently, Cristofolini et al. coupled optical excitation of an exciton with quantum tunneling of its electron in a double quantum well, observing the coherent behavior of different dynamic processes of one particle [12]. In this paper, we study how these two different kinds of couplings make two spatially separated electrons oscillating coherently and collectively. A similar result has been accomplished by correlating two quantum tunnelings in Shinkai's experiments, and the observed coherent oscillations were interpreted as various two-qubit operations

* Corresponding author
** Corresponding author.
E-mail addresses: xie_yan@iapcm.ac.cn (Y. Xie), chu_weidong@iapcm.ac.cn (W. Chu).

http://dx.doi.org/10.1016/j.physe.2015.04.019
1386-9477/

under the same coupling [8]. Compared with the all-electric manipulation, the joint physical process is expected to involve more pure coherent dynamics and less decoherence process. Here, we couple the Rabi oscillation of one electron with the quantum tunneling of another one in a four-QD structure. Our results show the coherent dynamics of synchronous transition for the two electrons. This effect provides a viable way to implement correlated control of two electrons by a single optical signal, which is useful for designing fundamental quantum qubit operation.

2. Physical model and calculation

The studied correlated dynamics occurs in a system of two DQDs coupled by electrostatic interaction as schemed in Fig. 1(a). One is the optical DQD with QDs 1 and 2, the other is the tunneling DQD with QDs 3 and 4, each of which possesses an excess electron in an orbital of the either dot $|i\rangle$ ($i = 1, 2, 3, 4$). Electron 1 resides in the optical DQD, performing a Rabi oscillation driven by an optical field. And electron 2 is the tunneling one, making a coherent oscillation under the condition of resonant tunneling. Since the two dynamic channels are coupled by electrostatic interaction, electron tunneling between the DQDs is not allowed. In experiments, this can be done by applying an appropriate voltage on the isolation gate between DQDs [7,13]. This configuration is similar to the experimental sample in Ref. [13], where the capacitive coupling between two near neighbor dots correlates the charge-state of electron spins. Here, the electrostatic interaction between the two electrons correlates coherent dynamics of optical excitation and quantum tunneling. And then, the correlated couplings of this system can be described by the Hamiltonian on the basis of double-electron states $|ij\rangle$ ($i=1,2$ and $j = 0, 3, 4$):

$$H(t) = \sum_{i=1,2;j=0,3,4} \varepsilon_{ij}|ij\rangle\langle ij| + \frac{1}{2}\hbar T_c(|13\rangle\langle 14| + |23\rangle\langle 24|) + \hbar\Omega(t)(|20\rangle\langle 10| + |23\rangle\langle 13| + |24\rangle\langle 14|) + h.\,c.$$

Here, ε_{ij} are energies of $|ij\rangle$ including Coulomb interactions, which can be precisely controlled by engineering the dot size, inter-dot distance, and tunneling in experiments [13–15]. The optical coupling between $|1j\rangle$ and $|2j\rangle$ is induced by a field $\mathbf{E}(t) = Ff(t)\sin(\omega t)\mathbf{e}$ with amplitude F and angular frequency ω. The corresponding Rabi frequency is $\Omega(t) = \boldsymbol{\mu}\cdot\mathbf{e}Ff(t)\sin(\omega t)/\hbar = \Omega_R f(t)\sin(\omega t)$ with $\Omega_R = \boldsymbol{\mu}\cdot\mathbf{e}F/\hbar$, and the dipole moment can be calculated by $\boldsymbol{\mu} = e\langle 1j|\mathbf{r}_1|2j\rangle$. T_c is the strength of tunnel coupling. The states $|i0\rangle$ represent electron 2 tunneling out of QDs 3 and 4.

Due to the weak interdot tunnel coupling in each DQD, its single-electron states have little change from the ground state in each component dot [16]. We adopt parabolic model to describe the confining potential of each dot as $V_i(\mathbf{r}) = \frac{1}{2}m^*\omega_{di}^2(\mathbf{r} - \mathbf{r}_{di})^2$, and calculate each ground state with energy ε_i and wave function ψ_i, which is approximately considered as the single-electron state in each DQD. Here, m^* is the electron effective mass, ω_{di} and $\mathbf{r}_{di}$ are the confining frequency and the central position of the ith dot, respectively. Because there is no electron tunneling between the DQDs, the exchange Coulomb interaction of the two electrons is ignored. The energies of direct Coulomb interactions $U_{ij} = \langle ij|\frac{e^2}{|\mathbf{r}_1 - \mathbf{r}_2|}|ij\rangle = \int d\mathbf{r}_1 d\mathbf{r}_2 \psi_i^*(\mathbf{r}_1)\psi_j^*(\mathbf{r}_2)\frac{e^2}{|\mathbf{r}_1 - \mathbf{r}_2|}\psi_i(\mathbf{r}_1)\psi_j(\mathbf{r}_2)$ $(i=1,2,\ j=3,4)$ based on double-electron states can be calculated. And the energies of double-electron states can be obtained by $\varepsilon_{ij} = \varepsilon_i + \varepsilon_j + U_{ij}$. For the optical and tunnel coupling strengths Ω_R and T_c, we take them as adjustable parameters in the calculation.

Either DQD's tunneling current can be used to monitor the correlation where the charge state of one DQD is changed by the state of the other DQD via the electrostatic coupling. Here, we weakly couple the tunneling DQD to the source and drain, and set it in the Coulomb blockade region, as shown in Fig. 1(a). The conductance through the device is only allowed by compensating the energy difference between states $|3\rangle$ and $|4\rangle$ with Coulomb energy of electron 1 in QD 2. The dynamics of the system can be described by master equation $\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}[H, \rho] + \Lambda\rho$, where ρ is the density matrix of the system, $\Lambda\rho$ is the irreversible term presenting the tunneling between electronic reservoirs and the QDs, whose rates are Γ_s and Γ_d, and the electron damping due to the phonon effects of solid environment, whose rate is γ. By numerically solving the master equation, we obtain the occupation probability $P_{ij}(t)$ for each state $|ij\rangle$, and then calculate the current by $I(t) = e\Gamma_d[P_{14}(t) + P_{24}(t)]$.

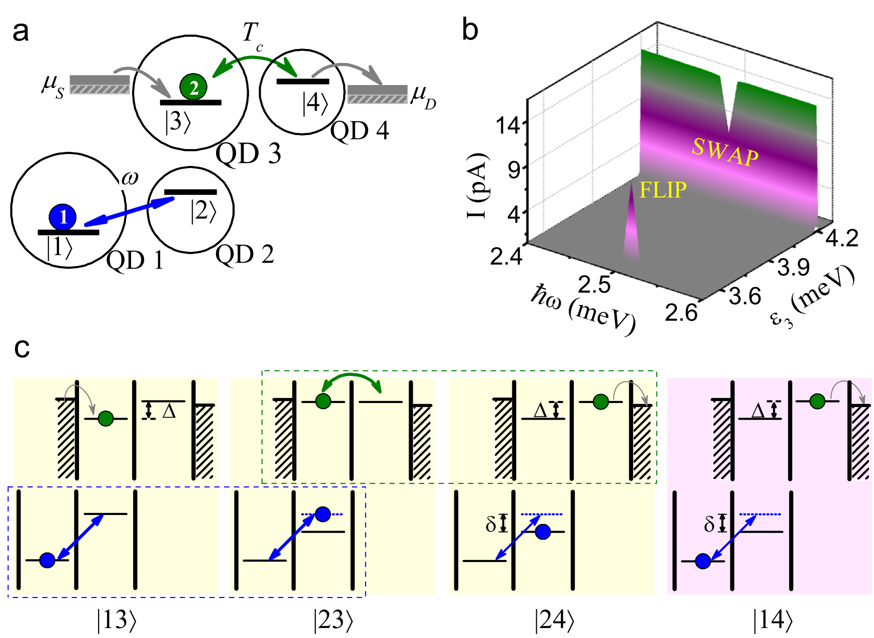

Fig. 1. (a) Schematic representation of a four-dot structure with an electron in Rabi oscillation and another one in quantum tunneling. (b) Time-average current spectrum as functions of $\hbar\omega$ and ε_3 for $T_c = \Omega_R = 0.4$ GHz. (c) Schematic diagrams of FLIP operation.