Sci. Bull.
DOI 10.1007/s11434-015-0941-6

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Article

Physics & Astronomy

Concentration and distribution of entanglement based on valley qubits system in graphene

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Received: 1 September 2015 / Accepted: 30 October 2015

Abstract Exploiting the optical excitation selection rules in graphene quantum dots, we investigate theoretically the entanglement generation process and entanglement concentration process of valley qubits. Our protocol shows that the graphene-based quantum dots can be distributed in a maximally entangled state through the interaction with single photons. In our proposed scheme, the setups are simplified as only single-photon detection is required. This provides a fast, all-optical manipulation of on-chip qubits, which gives an effective way for quantum information processing in graphene-based solid qubits.

Keywords Entanglement concentration · Entanglement distribution · Valley qubits

1 Introduction

Quantum information processing (QIP) based on solid-state systems is a dynamically developing field of research [1]. The central challenge of QIP is maintaining the abilities to control the qubits and to preserve their strong isolation from the environment. In the past decades, there are various technologies on qubits that are currently employed to meet this challenge, such as the trapped atoms [2–4], superconductors [5], quantum dots (QDs) [6], nitrogen-vacancy centers [7]. As discussed in Ref. [8], the single-layer graphene is a two-dimensional and gapless material in which two independent energy valleys exist. Here, we denote $|K\rangle$ and $|K'\rangle$ as the two inequivalent Dirac points in the first Brillouin zone in the graphene band structure. This valley state can be used to encode quantum information [9] as a two-level qubit for QIP. In 2012, Rohling and Burkard [10] illustrated an universal quantum computing protocol using the spin and valley states and designed the controlled NOT operation on the spin degrees of freedom. Wu et al. [11] proposed a quantum computation protocol with the valley qubits in the double quantum dot (DQD) model of graphene. Later, another quantum communication protocol is proposed based on the valley states by the same group. As discussed in Ref. [12], the valley qubit is realized by utilizing two coupled QDs in gapped graphene. Quantum state transfer from a photon qubit to a valley qubit could be realized in the same system. Moreover, a static tilted magnetic field is used to manipulate the valley state of the electron in the above protocols, where the in-plane field is used to freeze the electrons spin and the normal field creates a valley Zeeman splitting between the $|K\rangle$ and $|K'\rangle$ valleys. Thus, the valley qubit exhibits the similar energy level structure with a two-level artificial atom. Graphene-based QD system provides us a novel platform for the potential applications for quantum memory [13] and quantum repeaters [14]. Entanglement has been a powerful resource to realize various aspects of QIP. In particular, the distribution of entanglement between distant users is an important process to establish the QIP resources. And the key ingredient of the distribution process depends on the realization of generation and distillation of entanglement.

The key ingredient of these implementations is the distribution of maximal entanglement between the valley states, which includes the generation and distillation of entanglement. However, the environment noise is a major obstacle in realistic process which will reduce the fidelity of entanglement [15]. In order to improve the entanglement

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Published online: 25 November 2015

fidelity of the quantum systems, we can recur to entanglement concentration. The concept of entanglement concentration (EC) was first proposed by Bennett et al. [16] in 1996, which could distill a subset system in a maximally entangled state from a set of system in a less entangled pure state. Later in 2001, Yamamoto et al. [17] demonstrated an EC protocol for entangled photonic qubits with linear optical elements. In 2003, Zhao et al. [18] and Yamamoto et al. [19] experimentally demonstrated the EC process using linear optics independently. During the past decades, these EC protocols were developed from photons with the help of cross-Kerr nonlinearity [20–24] to solid entangled systems, such as the EC protocol for artificial atoms and microcavity coupling system [25–27]. Also, the EC has been theoretically realized in optomechanical systems [28].

In this paper, a novel scheme for maximal entanglement distribution using graphene-based DQD valley qubit is proposed. By utilizing single-photon input–output process, the quantum state could be transferred from flying qubit to the DQD and cavity coupled system. More importantly, we consider the entanglement concentration on the solid qubits as the entanglement distribution process would be effected by the noisy channel. Thus, the proposed scheme can be used to obtain ideal maximal entanglement between nonlocal solid qubits. And our scheme shows the possibility of implementation of QIP in DQD valley qubits system.

2 Model and Hamiltonian

The model of the DQD system is shown in Fig. 1a, and the energy levels structure of the DQD system is described in Fig. 1b.

As shown in Fig. 1a, three electrical gates defined by V_{L}, V_{R} , and V_{C} are used to produce the DC and AC field, and tune the potential barrier, respectively. The valley pair qubit is exhibited in a DQD structure defined electrostatically. Each QD can be described by the valley (denoted as τ_{v}) degree of freedom and the spin (denoted as σ) degree of freedom. Considering the excitation process of the electron in QD from valence band to the quantized conduction band, the effective interaction between the electrons of the QDs can be described as [12]:

$$H_J = \frac{1}{4} J \tau_{\mathrm{L}} \cdot \tau_{\mathrm{R}}, \tag{1}$$

where J denotes the exchange integral which can be tuned by V_{C} and τ represents the pauli operators for the valley qubits. Considering the excitation process of the electron in QD from valence band to the quantized conduction band, the effective interaction between the electrons of the QDs can be described as: $H_J = \frac{1}{4} J \tau_{\mathrm{L}} \cdot \tau_{\mathrm{R}} = 3\hbar^2/2 + \hbar^2(\sigma_{x,\mathrm{L}} \cdot \sigma_{x,\mathrm{R}} + \sigma_{y,\mathrm{L}} \cdot \sigma_{y,\mathrm{R}} + \sigma_{z,\mathrm{L}} \cdot \sigma_{z,\mathrm{R}})/2$. The density matrix of the system could be written as

$$\begin{pmatrix} 2\hbar^2 & 0 & 0 & 0 \\ 0 & \hbar^2 & \hbar^2 & 0 \\ 0 & \hbar^2 & \hbar^2 & 0 \\ 0 & 0 & 0 & 2\hbar^2 \end{pmatrix}.$$

The Hilbert space of the system is spanned by the eigenvectors of two electrons spin state as $|K'_{\mathrm{L}} K_{\mathrm{R}}\rangle$, $|K_{\mathrm{L}} K'_{\mathrm{R}}\rangle$, $|K_{\mathrm{L}} K_{\mathrm{R}}\rangle$, and $|K'_{\mathrm{L}} K'_{\mathrm{R}}\rangle$, and the eigenvalues could be solved as 0 and $2\hbar^2$. By solving the eigenfunctions of the system, the triplet states $(|K_{\mathrm{L}} K'_{\mathrm{R}}\rangle + |K'_{\mathrm{L}} K_{\mathrm{R}}\rangle)/\sqrt{2}$, $|K_{\mathrm{L}} K_{\mathrm{R}}\rangle$ and $|K'_{\mathrm{L}} K'_{\mathrm{R}}\rangle$ could be solved, which corresponds to eigenvalue $2\hbar^2$, and the singlet

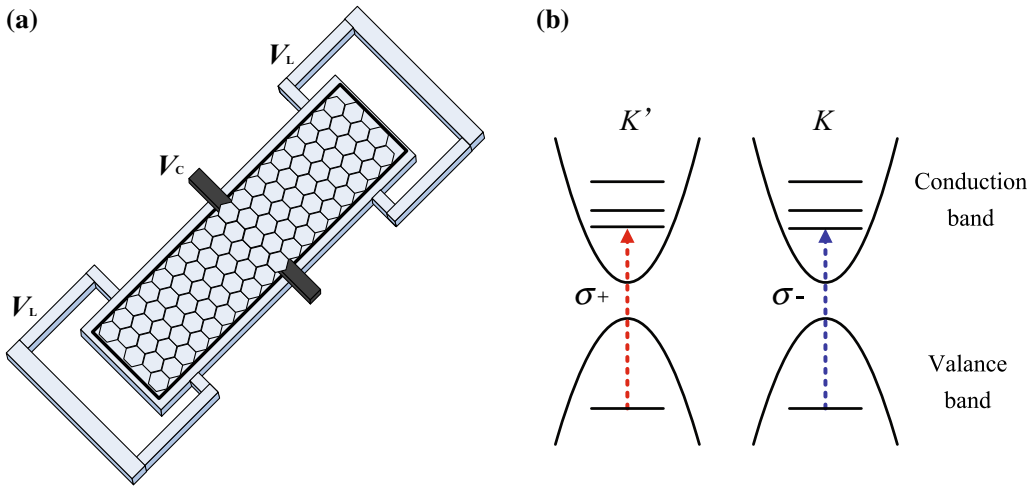

Fig. 1 (Color online) **a** Schematic diagram showing the principle of the double quantum dot system. Here, V_{L}, V_{R} , and V_{C} are the electrical gates that can be used to produce the DC and AC field and tune the potential barrier, respectively. **b** The energy level structure of the DQD system. Here, K' and K represent the valley state denoted by $\tau_{\mathrm{v}} = -1$ and $\tau_{\mathrm{v}} = +1$ QD, and the band-level transition only oscillates by using the single-photon excitation with the polarization σ_- and σ_+