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Fast and high-fidelity optical initialization of spin state of an electron in a semiconductor quantum dot using light-hole-trion states

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ABSTRACT

We theoretically show that under the Faraday geometry fast and high-fidelity optical initialization of electron spin (ES) state in a semiconductor quantum dot (SQD) can be realized by utilizing the light-hole (LH)-trion states. Initialization is completed within the time scale of ten nanoseconds with high fidelity, and the initialization laser pulse can be linearly, right-circularly, or left-circularly polarized. Moreover, we demonstrate that the time required for initialization can be further shortened down to a few hundreds of picoseconds if we introduce a pillar-microcavity to promote the relaxation of a LH-trion state towards the desired ES state through the Purcell effect. We also clarify the role of heavy-hole and light-hole mixing induced transitions on the fidelity of ES state initialization.

1. Introduction

Spin states of an electron or heavy-hole (HH) confined in a SQD are considered to be a promising candidate of qubit for quantum information processing (QIP) because of their long spin coherence times [1–5]. In particular, the spin coherence time of an electron in a SQD has been measured to be in the microsecond range [6–8], which offers an opportunity to perform a subsequent quantum manipulations of the initialized spin–qubit using short laser pulses with a few picosecond duration. Undoubtedly, fast and high-fidelity initialization of spin state of an electron or HH in a SQD is essential for many QIP protocols. Ideally the time required for initialization of the spin state must be much shorter, at least few orders-of-magnitudes, than the spin coherence time [9,10], since the quantum error corrections for fault-tolerant quantum computing needs an additional time after the initialization and before the next quantum operation of the spin–qubit.

Initialization of spin state can be realized using exciton ionization [11–15] or optical pumping schemes [10,16–21]. In the exciton ionization scheme a HH-exciton (electron-HH pair) is created in a neutral SQD, which is followed by the electric-field-induced tunneling of HH (electron) to initialize the electron (HH) spin state. Very recently, fast and high-fidelity initialization of the HH spin state in a SQD has been demonstrated using the exciton ionization scheme [11,12]. This scheme is also employed, under the Faraday geometry, to initialize the electron spin (ES) state in a SQD by introducing the blockade immediately underneath the SQD layer to prevent the electron from tunneling out faster than the HH [13]. The drawback of the exciton ionization scheme, regardless of the fast initialization of the spin state in the picosecond time scale, is that the fidelity of ES state initialization is quite low due to the small g-factor of exciton [13]. Alternatively, the optical pumping scheme enables us to initialize the electron as well as HH spin state in a SQD under the Faraday as well as Voigt geometry. In the Voigt geometry, fast and high-fidelity initialization of the electron and HH spin state has been demonstrated utilizing the cross-transitions, which are fully allowed due to the mixing of spin states, between the ES and HH-trion states [10,16–19]. In contrast, under the Faraday geometry, cross-transitions are forbidden under the ideal situation due to the polarization selection rules. In practice, however, they are weakly allowed because of the HH–LH mixing effect. As a result, in spite of the high fidelity, initialization of the electron as well as HH spin state in optical pumping scheme under the Faraday geometry takes a few microseconds, which is too slow for implementing the quantum error corrections [20,21].

Note that the HH-trion or HH-exciton states are used for initialization of the electron as well as HH spin state in all the studies mentioned above, and there is no known scheme for the fast and high-fidelity initialization of the ES state under the Faraday geometry. This is because the quantum confinement and strain in conventional semiconductor quantum dots (SQDs) usually result in the ground state of the hole state to have a predominantly HH character. Some recent proposals, however, suggest that the use of a LH state as the ground state can be more beneficial for QIP [22–25]. For example, quantum manipulations of the ES states in SQD

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with LH ground states can be realized under the Faraday geometry [23,26]. Therefore the study of ES state initialization becomes more relevant in such SQD systems. Moreover, it is nowadays possible to convert the ground state of the hole with a predominantly HH character to that with a predominantly LH character using strain engineering in SQDs [27,28]. Thus, the use of LH-trion or LH-exciton states is now open for the quantum manipulation in SQDs.

In this paper, we theoretically show that the fast optical initialization of ES sate in a SQD can be realized with high fidelity under the Faraday geometry by making use of the LH-trion states, instead of the HH-trion states, as the lowest states. The incident laser can be either linearly, right-circularly, or left-circularly polarized pulses. In the scheme we propose, the cross-transitions between the ES and LH-trion states are not forbidden anymore, which allows us to complete the initialization within the nanosecond time scale. Moreover, we demonstrate that the initialization time can be further shortened down to a few hundreds of picoseconds with the aid of Purcell-promoted relaxation of a desired LH-trion state.

2. Theory

We consider a negatively charged SQD with the growth direction taken as the *z*-axis. The magnetic field is applied along the growth direction (Faraday geometry). Fig. 1 shows the scheme we consider in this paper. In Fig. 1(a), we show the in-plane and out-of-plane excitation of a SQD embedded in a pillar-microcavity using linearly and circularly polarized laser pulses, respectively. Fig. 1(b) shows the allowed respective transitions between the ES and mixed LH-trion states. Here, $|\pm1/2\rangle_Z$ and $\widetilde{|\pm 1/2\rangle}_Z^{LH}$represent the ES and mixed LH-trion states polarized parallel or antiparallel to the z axis, respectively. The numbers $(\pm1/2)$ represent the total angular momentum along the *z*-axis. Since the LH-trion and mixed HH-trion states are energetically well separated by a few tens of meV, which can be spectrally resolved by the employed laser pulses, we can safely neglect the mixed HH-trion states (which contain some LH-trion-state character) and consider the mixed LH-trion stats only. Under the externally applied magnetic field in the Faraday geometry, the ES as well as LH-trion states are split into the spin-up and spin–down states by the Zeeman frequencies; $\delta_e = \left|\frac{g_Z^e \mu_B B}{h}\right|$ and $\delta_e = \left|\frac{g_Z^{LH} \mu_B B}{h}\right|$, respectively, where g_Z^e and $g_Z^{LH}$are the ES and LH-trion g-factors, μ_B is the Bohr magneton, *h* is the Planck constant, and B is the magnetic field strength. In Fig. 1(c), we show all the longitudinal relaxation rates of the mixed LH-trion states. These include the natural relaxation rate (Γ), additional relaxation rates ($\eta^2\Gamma$ and $\beta^2\Gamma$) due to the HH-LH-mixing-induced transitions, and pillar-microcavity-induced Purcell-promoted relaxation rates of the right-circularly ($\eta^2\Gamma F_P^{14}, \Gamma F_P^{24}$, and $\beta^2\Gamma F_P$) and left-circularly ($\beta^2\Gamma F_P^{24}$, ΓF_P, and $\beta^2\Gamma F_P^{23}$) polarized transitions with F_P being the Purcell factor. For simplicity we assume that the natural longitudinal relaxation rates are in the relation of $\Gamma'_{13} = \Gamma'_{23} = \Gamma'_{14} = \Gamma'_{24} = \Gamma$. Here Γ'_{nm} denotes the natural longitudinal relaxation rate from state *m* to state *n*. The physical meanings of F_P^{14}, F_P^{24}, F_P, and F_P^{23} will be explained later in the text.

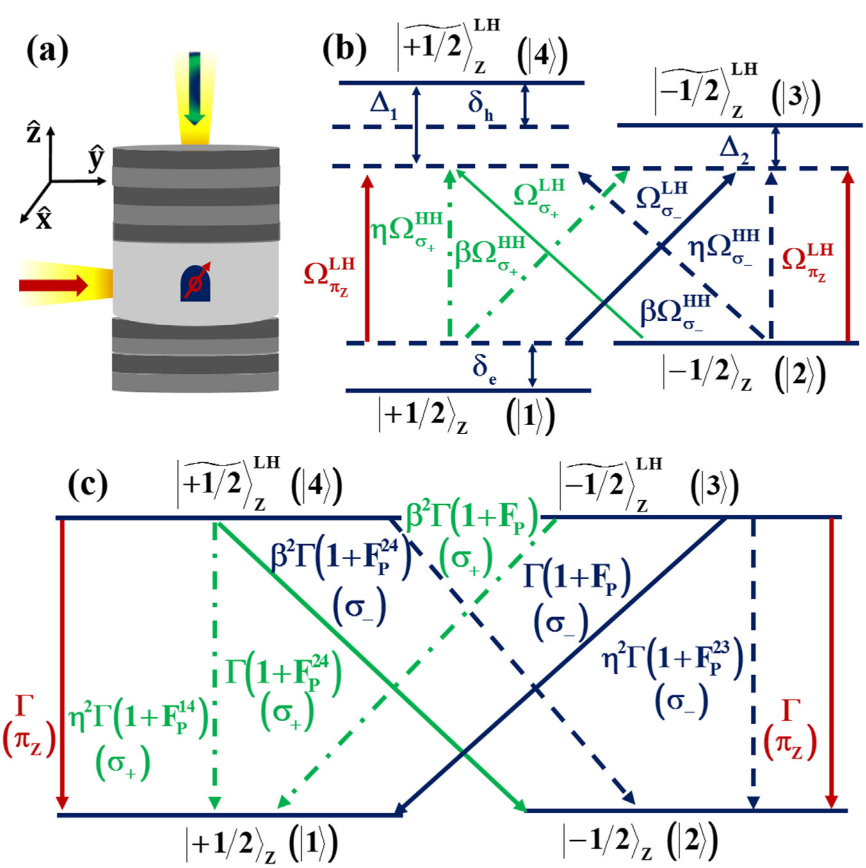

Fig. 1. Proposed scheme. (a) In-plane and out-of-plane excitation of SQD embedded in a pillar-microcavity interacting with linearly and circularly polarized laser pulses, respectively. (b) Allowed transitions between ES and mixed LH-trion states. (c) Longitudinal relaxation rates of the mixed LH-trion states through the linearly (red line), right-circularly (green solid and dash-dotted line), and left-circularly (blue solid and dashed line) polarized transitions. π_Z, σ_+, and σ_- stand for the linearly, right-, and left-circularly polarized transitions. F_P is the Purcell factor to be explained later in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)