Resonantly driven exciton Rabi oscillation in single quantum dots emitting at 1300 nm*

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We report on the resonance fluorescence (RF) from single InAs quantum dots (QDs) emitting at the telecom band of 1300 nm. The InAs/GaAs QDs are embedded in a planar optical microcavity and the RF is measured by an orthogonal excitation-detection geometry for deeply suppressing the residual laser scattering. An ultra-weak He–Ne laser is necessary to be used as a gate laser for obtaining RF. Rabi oscillation with more than one period is observed through the picosecond (ps) pulsed laser excitation. The resonant control of exciton opens up new possibilities for realizing the on-demand single photon emission and quantum manipulation of solid-state qubits at telecom band.

Keywords: quantum dots, resonance fluorescence, single photons, Rabi oscillation

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1. Introduction

Single-photon sources have potential applications in quantum communication, random number generation and quantum information processing.[1,2] Semiconductor quantum dots (QDs) are proved to be a promising candidate as a single-photon emitter due to easily tuning emission wavelength by using growth techniques or electric and stress fields, and also the compatibility with the semiconductor processing techniques.[3,4] Note that the on-demand single-photon sources with the properties of high purity, indistinguishability and extraction efficiency from single QDs have been reported.[5,6] However, these studies mainly focused on single photon emissions with a wavelength of below 1000 nm which could not suitable for a long-distance communication in fiber. Thus the realization of single photon sources emitting at telecom band becomes necessary. There have been reports on the telecom band single emissions from InAs/GaAs and InAs/InP QDs grown by molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), respectively.[7,8] However, at present the on-demand single photon emissions operating at telecom band having properties of high purity, indistinguishability and high emission rate have not been reported yet. Resonant excitation of excitons in QDs, which can eliminate the influences of recapture of carriers and reduce the spectral broadening of exciton emissions, has been proven to be an effective tool of preparing the on-demand single photon sources in a wavelength range of 900 nm–1000 nm.[5,9] Recently, RF from a telecom band QD as well as Mollow triplet excited by cw laser has been reported.[10] However, up to now, the study on RF from a telecom band QD excited by a pulsed laser as well as the related exciton Rabi oscillation is still lacking.

In this paper, we demonstrate a pulse-excited RF from a single InAs/GaAs QD emitting at 1300 nm. A planar optical microcavity is used as a waveguide to guide the excitation laser beam to propagation between the top and bottom mirrors in the sample growth plane. Simultaneously, the cavity can enhance the RF emission in the direction orthogonal to the sample growth plane.[11–14] An ultra-weak He–Ne laser is used as a gate laser for the observed RF.[15] With the excitation of picosecond (ps) pulsed laser, a Rabi oscillation with more than one period is observed.

2. Methods

The sample was grown on a semi-insulating (100) GaAs substrate by molecular beam epitaxy through strain-coupled bilayer InAs QDs.[16] By this method, the QD wavelength can be tuned into around 1300 nm and the QD sample has an extremely low density of QDs ($\sim 1\times10^{8}$ cm^{-2}). It is easier to measure single QDs without the aid of small apertures or mesas by using microscope objective. The planar cavity consists of a distributed Bragg reflector (DBR) with 20

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(8) pairs of AlGaAs/GaAs as the bottom (top) mirror and a λ-thick GaAs space in the center as schematically shown in Fig. 1. The quality factor of the studied planar cavity is approximately 200. The sample is cooled down to 10 K in an optical cryostat. A single mode fiber, mounted on a three-axis precision position stage, is used to guide the excitation laser into the planer cavity from the cleaved sample edge. The ps pulsed laser with a width of approximately 2 ps is generated by spectral filtering of a Ti:sapphire pulsed laser with a pulse width of approximately 120 femtosecond via a 150-mm focal length monochromator. The RF is collected by a near-infrared objective (NA:0.55), then coupled to a single mode fiber which acts as a spatial filter to suppress the residual excitation laser scattering, and last spectrally analyzed by a 300-mm monochromator equipped with a linear InGaAs charge coupled device (CCD). The time-resolved photoluminescence (PL) of the QDs is measured by a time-correlated single photon counting (TCSPC) setup. To confirm single photon emission of the QDs, a conventional Hanbury–Brown and Twiss (HBT) setup with two InGaAs avalanche photodiodes (id230-FR-SMF) is used. Besides the resonant ps pulsed laser, an ultra-weak He–Ne laser is employed to perform as an optical gate for the QD RF.[15]

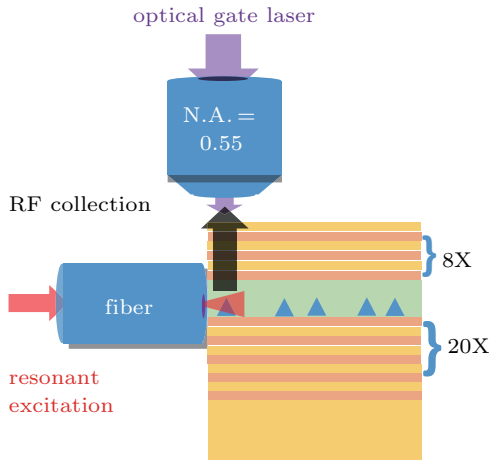


Fig. 1. (color online) Sample structure of InAs/GaAs QDs with top and bottom DBRs and RF measurement setup of orthogonal excitation-detection geometry. The resonant laser guided by single mode fiber enters the QD planner waveguide through the cleaved edge of the sample, propagates along the waveguide and excites the QDs. RF is collected from the sample surface with an objective. He–Ne laser is used as an optical gate and focused on the QD through the collection objective.

3. Results and discussion

The PL spectrum of the QD, nonresonantly excited by He–Ne laser, is shown in the inset of Fig. 2(a). Exciton emission line is located at a wavelength of 1301.11 nm. For observing RF, the ps pulsed laser wavelength is tuned to the position of 1301.11 nm (here the laser linewidth is approximately 0.4 nm) in order to avoid phonon-assisted processes.[17] The RF spectrum of the QD is shown in Fig. 2(a), where an obtained exciton emission linewidth is approximately 0.2 nm which is limited by the spectral resolution of the spectrometer. It is known that the resonant emission signal consists of the superposition of the coherent resonant Rayleigh scattering (RRS) and the incoherent resonant photoluminescence (RPL). Note that although a spectral width of the ps pulsed laser covers the QD emission line, RF cannot be observed without an additional He–Ne laser as an optical gate due to the Coulomb blockade in QDs.[15] Figure 2(b) shows the RF intensities with (•, gate on) and without (○, gate off) additional He–Ne laser as a function of laser detuning $\Delta\lambda$ from the central wavelength of 1301.11 nm. This experimental method has been reported previously in InAs QDs emitting at a wavelength of about 900 nm,[15,18] the so-called optical gate-effect. Here, the power of the additional He–Ne laser is approximately 39 nW, which is too low to excite the QDs for observing PL emission. When the He–Ne laser gate is off, the scale of peak intensity is 600, which is due to the residual resonant laser scattering. After the He–Ne laser gate is on, the peak intensity increases up to 2600, which includes the components of the QD RF and the residual laser scattering. As a result, the signal-to-background ratio of the RF from the QD is approximately 3.33.

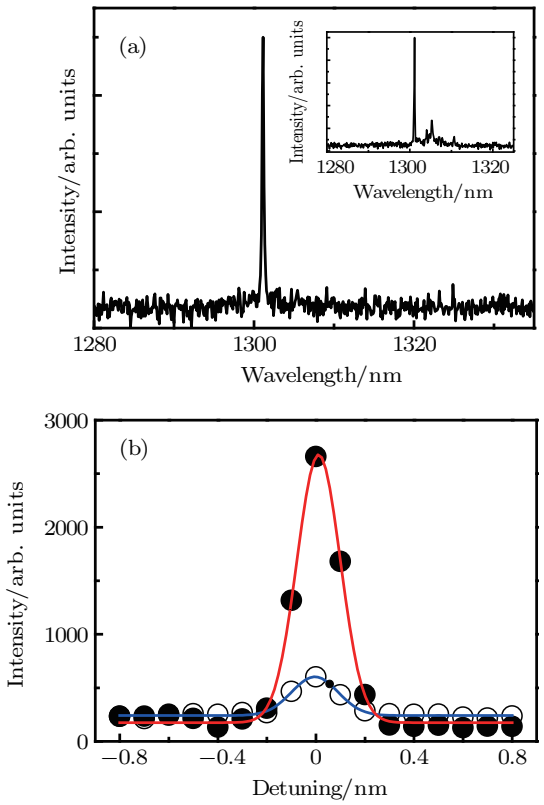


Fig. 2. (color online) (a) RF spectrum of single InAs/GaAs QD excited by picosecond pulsed laser at 10 K, with an optical gate. The inset shows nonresonant PL spectrum excited by He–Ne laser. (b) RF intensity with (•, gate on) and without (○, gate off) optical gate of ultra-weak He–Ne laser with a power of 39 nW, as a function of pulsed laser wavelength detuning from QD exciton wavelength.

Figure 3(a) shows the time-resolved PL spectra of the QD for nonresonant (•) and resonant (○) excitations on a semi-logarithmic scale. By linearly fitting experimental data (red lines), the obtained exciton radiative times are 1.05 ns and 0.75 ns for nonresonant and resonant excitations, respectively. The fast decay time of 0.25 ns for the resonant excitation stems from the residual pulsed laser scattering (blue line), which reflects the time response of the spectral measurement system. The observed decrease of exciton radiative time of the QD means that the spontaneous emission rate can be increased by resonant excitation.[19] Figure 3(b) shows the intensity-correlation histogram measurement by using HBT setup. The obtained second-order correlation function $g^2(0)$ at zero delay time is a 0.19±0.02, showing the single photon emission of the QDs under resonant excitation.

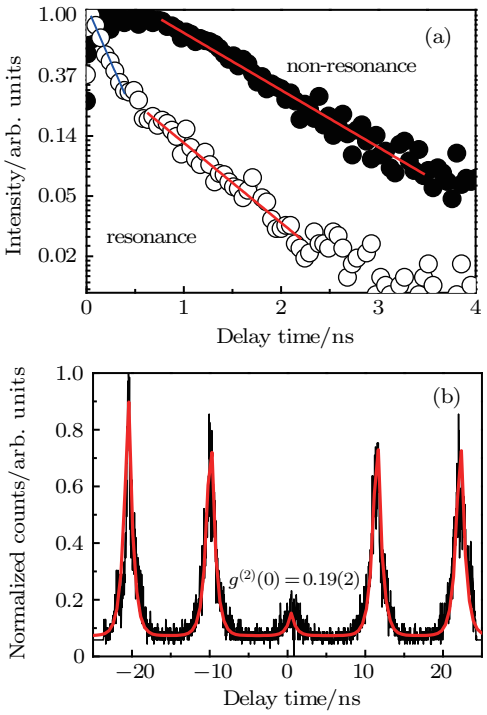


Fig. 3. (color online) (a) Time-resolved PL spectra of the QD for non-resonant (•) and resonant (○) excitations on a semi-logarithmic scale, and linear fittings are used to fit the experimental data, shown by red and blue lines. (b) Intensity–correlation histogram of the RF obtained using an HBT setup. The second-order correlation function $g^2(0) = 0.19(2)$ at zero delay time, showing the single photon property of the QD emission.

The well-known Rabi oscillation is due to the nonlinear interaction between the two-level system and the resonant electromagnetic field.[20] Under strong pulsed laser excitation, Rabi oscillation occurs as a function of the square root of the excitation laser power, or the so-called input pulse area (the time-integrated Rabi frequency), $\theta = (\mu/\hbar)\int_0^{\infty} E(t')\mathrm{d}t'$, where $E(t)$ is the pulse envelope and μ is the transition dipole moment.[21] Figure 4 shows the measured RF intensity as a function of pulse area after the background scattering laser intensity has been deducted, which is proportional to the square root of the incident laser power. The obtained result shows that the Rabi oscillation with more than one period is observed through the picosecond (ps) pulsed laser excitation. From the RF experiments, we note that it is difficult to observe many periodic Rabi oscillations due to the acoustic phonon and carrier scatterings which can cause the exciton dephasing.[17,20] Furthermore, the RF component can be influenced by the residual laser scattering. When the excitation power is increased, the influence of residual laser scattering on the RF becomes more intense, resulting in difficultly in separating the RF component from the residual laser scattering.

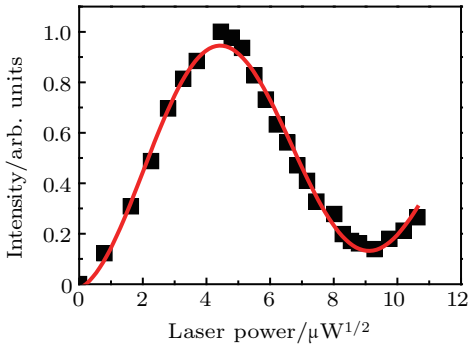


Fig. 4. (color online) Intensity of RF as a function of the square root of the picosecond pulsed laser power. The red curve is a fit to the experimental data.

4. Conclusions

In summary, we observed resonantly driven Rabi oscillation in single QDs emitting at 1300 nm by orthogonal excitation–detection geometry. It is found that an ultra-weak He–Ne gate laser is necessary for suppressing Coulomb blockade and observing RF. The resonant excitation leads to an increased exciton spontaneous emission rate. The results pave the way for realizing the QD on-demand single photon source and quantum information process via resonant excitation at telecom band.

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