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Tunable-correlation phenomenon of single photons emitted from a self-assembled quantum dot

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HIGHLIGHTS

- The continuously tunable correlation property of the single photons is observed in experiment.
- A defect state model is proposed to explain this tunable correlation phenomenon.
- The tunable mechanism discussed in paper can be used to check whether such defects exist in the QD samples.

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ABSTRACT

Deterministic single-photon source plays a key role in the quantum information technology. Thus, research on various properties of such kind of light source becomes a quite necessary task. In this work, we experimentally observe that the second-order correlation properties of single photons can be continuously tuned from pulsed excitation configuration to continuous-wave excitation configuration under the near resonant photoluminescence excitation. By increasing the power of pulsed excitation laser, the effective excitation time of quantum dot can be extended with assistance of the defect states, and more continuous-wave excitation characteristics will gradually appear in the second-order correlation functions. This abnormal power-induced tunable-correlation mechanism can affect the temporal property of the single-photon source but maintain its antibunching property.

1. Introduction

Quantum mechanics provides original and powerful tools for information processing, which can not be implemented in its classical counterparts. As a promising light source, single photon source have been extensively applied in quantum information technology, such as quantum computation processes [1–3], quantum cryptography technology [4] and quantum information transmission [5–7]. Meanwhile, various properties of single-photon source have been studied, for instance, its efficiency [8], temporal [9,10] and spectral [11] characteristics are presented in the literatures recently.

The antibunching property of single photons can be revealed by second-order correlation measurements, which are realized via the Hanbury-Brown and Twiss (HBT) experiment [12–14]. Considering the deterministic single photons emitted from a semiconductor self-assembled quantum dot (QD), both the intrinsic structures of QD, such as the defects [11,15] and dark states [10], and the external excitation configurations can affect their statistical properties substantially. As for the continuous-wave (cw) excitation configuration, a lot of theoretical and experimental results have been studied [16–18]. In Ref. [19], Wang et al. have already derived the second-order correlation function under pulsed excitation configuration using master equation and quantum regression theorem. Moreover, this correlation function also suitable for cw excitation configuration, and their results are consistent with the experimental outcomes [12,19–21]. The intermediate stages between the cw and short-pulsed excitation configurations, which acts an important part of the statistical properties of the single-photon source, have also been observed but on different QDs in the InP sample [17]. However, the continuous transition phenomenon in a same single QD has not been experimentally observed yet.

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In this paper, we fill this gap by introducing an abnormal phenomenon which is observed in the second-order correlation measurements on a same self-assembled InAs/GaAs QD. By increasing the power of the short-pulsed near resonant excitation laser, we find the second-order correlation properties of single photons can be continuously tuned to cw excitation configuration. We subsequently provide a defect state model to explain why this effect can be observed during the variation of the excitation power.

2. Experiment and results

The QD sample we used here is grown on a semi-insulating GaAs substrate using the molecular beam epitaxy (MBE) technique. This sample consists of a distributed Bragg reflector (DBR) with 20 pairs of $Al_{0.9}GaAs/GaAs$ (77.4 nm/65.33 nm) as the bottom mirror, a 4λ-thick cavity in the center, and 8-pairs DBR as the top mirror. The structure of sample and the photoluminescence (PL) spectra are illustrated in Appendix A.

The experimental setup is shown in Fig. 1(a), which includes a coupled QD-cavity system, spectral filters and a HBT setup for the correlation measurements. The QD sample is placed in a liquid-Helium-free cryostat (7 K). The near resonant excitation source is a 3 ps pulsed light at 923 nm provided by a mode-locked Ti:sapphire laser. To construct an orthogonal excitation-detection geometry, we use a DBR microcavity which is grown in the sample to guide the pulsed excitation laser between the cavity mirrors to excite the QD and meanwhile enhance the single photon collection efficiency in the perpendicular direction [22]. In order to eliminate the residual excitation laser optimally, we choose its wavelength to be 923 nm, which is right outside the vertical transmission band of the DBR microcavity and also near to the resonant wavelength (920 nm). The single photons are collected and coupled into a single-mode (SM) fiber. The Fabry–Perot (FP) cavity and the grating with a slit act as filters to isolate the single photons by filtering out the fluorescence emitted from other QDs and the background. The photoluminescence excitation (PLE) spectra before and after the filtering are shown in Fig. 2(b) and (c). Then the time correlation measurements are performed using a HBT setup, which consists of a fiber splitter, two single photon avalanche diodes (SPADs) and a picosecond time analyzer [13].

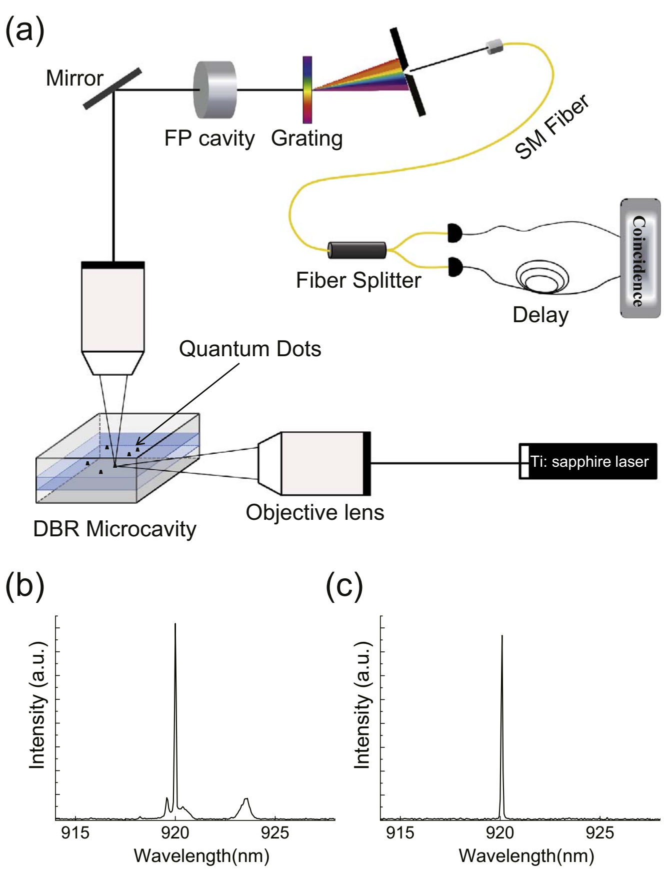

Fig. 1. (a) Experimental setup. A mode-locked picosecond Ti:sapphire laser is operated at 923 nm with repetition frequency 76 MHz. An orthogonal excitation-detection geometry is applied to reduce the noise from the excitation light and enhance the collection efficiency of signal light. Single photons are collected after filtering by FP cavity and grating. The HBT setup which consists of a fiber splitter, two SPADs and a picosecond time analyzer is employed to perform the time correlation measurements. (b) Signal light PLE spectrum before filtering. The small peak at the right side of the signal peak is caused by the excitation laser which is primarily removed by the DBR cavity. (c) Signal light PLE spectrum filtered by the FP cavity and grating.

Six different excitation powers are employed here and the measurements are performed on a same single QD in the sample. The time correlation data are shown in Fig. 2(a)–(f) are associated with the results for 3.2 mW, 4.5 mW, 5.5 mW, 6.0 mW, 7.0 mW and 8.4 mW, respectively (Due to the orthogonal excitation–detection geometry, the power density actually felt by the quantum dot is not as large as we provide, same phenomenon also have been reported in Ref. [23]). The blue dots are the normalized coincidence counts . The black lines are the fitted second-order correlation functions calculated by the method mentioned in Appendix B and will be discussed in the next section).

As shown in Fig. 2, when the power of the excitation laser increases, the second-order correlation function gradually transits from the pulsed excitation configuration to the cw excitation configuration. The period of the correlation peaks in the $g^{(2)}(\tau)$ is equivalent to the period of the excitation laser pulse. When the power of the excitation laser increases, the heights of the correlation peaks become lower and generate higher offset in the correlation functions. The single photon behavior is demonstrated by the dips at $\tau = 0$. The results show clear antibunching properties with the minimum at $\tau = 0$, which indicates that the photons indeed come from a single QD [24]. The transition phenomenon is not unique and occurred in a similar way on a multitude of quantum dots in this sample, which suggests that our result is repeatable and it is not an isolated case.

3. Defect state model and discussion

We attribute this phenomenon to a recapture process with assistance of defect states in the QD sample. This mechanism makes the excitation time t_0 not able to be represented by the excitation laser pulsewidth t_p simply. As a matter of fact, t_0 here should be replaced by the effective excitation time t_{eff}, which is greatly influenced by the power of the pulsed excitation laser according to the defect-state model. These defects in our sample are generated due to the nonintentional MBE condition. They usually locate in the vicinity of the QD and the energy levels of them are very close to the excited state. At this aspect, these defects have some similarities with the ones reported by Ref. [11], but they are different defects in nature. For example, the defects in our sample do not show chargeability, and this can be confirmed by the PL spectra in which no trion state is found (Appendix A). The carriers can be trapped in these defects first for a certain time and after that there is a recapture process from defect states into the QD following the initial recombination [17,22]. Then, two or more photons can be created between two neighboring laser pulses. Yet, they are not simultaneously emitted. Namely, these sample defects will strongly impact the temporal property of single photon source, but do not prevent to achieve a low $g^{(2)}(0)$.