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Single photon emission with high degree of circular polarization from a single quantum dot under zero magnetic field

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Abstract

Single photon emission with high degree of circular polarization (DCP) from a positively charged exciton (trion) state in a single quantum dot (QD) is demonstrated under zero magnetic field. Obtained high DCP as large as 0.6 is a clear manifestation of highly effective mutual polarization conversion between single photon and single electron spin. This finding also reveals that the spin relaxation is strongly suppressed during capture and thermalization processes and also in trion ground states in a quantum dot. Moreover, exciton charging state control is shown to be possible by modifying the electron capture probability through the excitation energy tuning, which leads to an exclusive formation of the positive trion in a QD. © 2001 Elsevier Science. All rights reserved

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Keywords: Polarization conversion; Single quantum dot; single photon; charged exciton; spin flip

1. Introduction

In recent years, quantum key distribution (QKD) is attracting much more attention due to its highly secure nature [1]. Since it is based on physical principles such as indivisibility and non-cloning of single photons instead of mathematical complexity, completely secure communication which is free from eavesdropping will be possible in principle. One of the most important protocols for implementing the QKD is BB84 [2]. Since the BB84 is based on photon polarization states belonging to two non-orthogonal bases, generation of single photons from quantum dot (QD) with arbitrary polarization state is prerequisite. When the QD is taken as a “photon-state converter” from *coherent state* of excitation laser to single photon train in *number state*, polarization fluctuation between emitting photons after each excitation events will strongly reduce the consequently available bit rate of quantum-optical devices since the specific photon polarization is

filtered for the subsequent polarization modulation for coding in the BB84 protocol. Therefore, suppression of spin flip during whole processes including absorption, capture, relaxation, and radiative recombination is a crucial issue. In case of neutral exciton, long-range electron-hole exchange interaction stems from an anisotropic confinement potential [3-5] will lead to a simultaneous spin flip of electron and hole [6]. Singly-charged exciton (trion), on the other hand, is free from the exchange interaction owing to the presence of spin-paired carriers. Therefore, spin flip between trion ground states will be well suppressed during its lifetime. Since the trion is a half spin system, its ground states are degenerated due to Kramer’s theorem in the absence of a magnetic field [7,8], and the trion couples to circular-polarized photons guaranteed by a selection rule [9,10]. Therefore, the trion in a QD is quite promising for the efficient photon state converter, where its spin state formed by the

circularly-polarized excitation in coherent state will be transferred into photons in number state through a recombination with the incident polarization being preserved.

In this paper, single photon emission from a positive trion with high degree of circular polarization (DCP) which is defined by $(I_{\sigma^+} - I_{\sigma^-}) / (I_{\sigma^+} + I_{\sigma^-})$ is demonstrated without magnetic field. Resultant DCP amounts to ~ 0.6 , which indicates that mutual polarization conversion between single photon and single electron spin is realized with high efficiency. Control of the exciton charging state dominating the spectrum is also discussed via excitation energy tuning, as reported for neutral excitons [11,12].

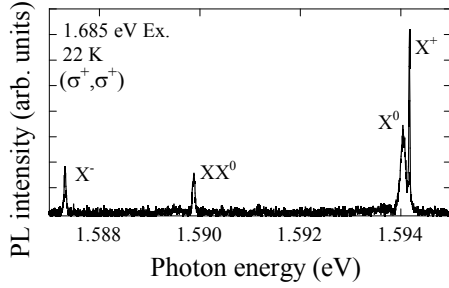


Fig. 1 High-resolution PL spectrum from a InAlAs single QD. Positively charged exciton (X^+), neutral exciton (X^0), neutral biexciton (XX^0), and negatively charged exciton (X^-) dominate the spectrum.

2. Experimental

The $\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ QDs sample was grown on a semi-insulating (001)-GaAs substrate by molecular-beam epitaxy. The QDs were prepared in Stranski-Krastanow (S-K) growth mode on $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layers and were sandwiched with $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layers. The topmost surface was terminated with a GaAs cap layer. All the grown layers were nominally undoped, but the QDs are naturally *p*-doped. After the growth, the sample was etched into mesa structures with diameters of ~ 150 nm for isolating single QD from the dot ensemble with the density of around 5×10^{10} dots/cm².

In a single dot spectroscopy, the sample was held in a closed-loop He cryostat and was kept at 22 K. A continuous-wave Ti: sapphire laser was used as a circular excitation source (σ^+) using a quarter-wave plate. An objective lens with the numerical aperture (NA) of 0.42 focused the laser beam on one of the mesa structures and collected luminescence emitted

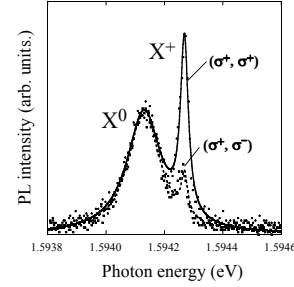


Fig. 2 Polarization-selective photoluminescence spectra of X^+ and X^0 emission lines. High degree of circular polarization of ~ 0.62 was obtained for X^+ at $B = 0$ (T).

from the mesa. Collected luminescence was dispersed by a 0.64-m triple monochromator and introduced to a liquid-nitrogen cooled Si charge-coupled-device detector. The PL polarization was analyzed in a (σ^+, σ^-) basis by a set of quarter-wave plate and a fixed Glan-Thomson linear polarizer in front of the monochromator, where σ^+ (σ^-) denotes the circular polarization with a helicity of $+1$ (-1). The overall system resolution was $4.5 \mu\text{eV}$.

3. Results and discussion

High-resolution PL spectrum from a InAlAs single QD studied in this work is shown in Fig. 1. Four emission lines originating from positively charged exciton (X^+), neutral exciton (X^0), neutral biexciton (XX^0), and negatively charged exciton (X^-) were dominant, which were assigned and confirmed by several independent measurements [13, 14]. Measured second-order photon correlation function $g^{(2)}(\tau)$ unambiguously revealed the single photon emission operation from the single QD in terms of anti-bunching behaviour when the X^+ emission line was introduced into a so-called HBT setup together with either X^0 or X^- emission lines. Expanded spectra at around the X^+ emission analyzed for both the σ^+ and σ^- polarizations at zero magnetic field are shown in Fig. 2. For the X^+ line, distinct difference in intensity between σ^+ and σ^- components was observed. This observation indicates, in spite of non-resonant excitation, effective spin conservation during overall processes included before recombination is achieved. On the other hand, the X^0 line exhibited quite small circular polarization dependence as is expected in an elongated QD where

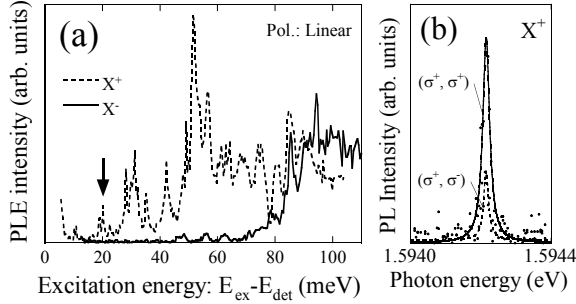


Fig. 3 (a) PLE spectra of X^+ (dashed line) and X^- (solid line) under linear-polarized excitation. X^- shows clear edge structure in energy at around 85 meV, which represents an energy *boundary* discriminating localized and delocalized states (WL edge). (b) X^+ selective formation by exciting localized states in a QD under circular polarized excitation. Excitation energy is 20.3 meV above the detection energy, which is denoted by an arrow in Fig. 3(a).

e - h exchange interaction mixes two exciton eigenstates [7] and then the linearly-polarized photon emission occurs. The resultant DCP from these measurements defined by $(I_{\sigma^+} - I_{\sigma^-}) / (I_{\sigma^+} + I_{\sigma^-})$, where I_{σ^+} (I_{σ^-}) is the radiation intensity for the σ^+ (σ^-) detection, is approximately 0.62 for the X^+ . This is a direct consequence of highly effective mutual polarization transfer between single photon and single electron even under non-resonant excitation at $B = 0$ (T). Figure 3(a) illustrates the results of the photoluminescence-excitation (PLE) measurements detected at both the X^+ and X^- lines. There is striking difference between two charged exciton species, *i.e.*, the X^- line was almost quenched below about 85 meV from the detection energy, while the X^+ survived at lower energy and much richer structures tentatively attributed to phonon resonances and excitation states [15-18] were observed. For delocalized state excitation, since the absorption coefficient is identical for both the neutral and charged trions, carrier capture process will determine the exciton charging states [11,12]. In most of the QDs examined, the X^+ and X^0 were commonly observed, whereas the X^- line was less available. The present InAlAs QDs are naturally p -doped and a residual hole is likely to be present in each QD on average. In this situation, the X^- emission is less probable with the localized state excitation since the electron-hole pair(s) is generated directly inside the

QD. Instead, the X^- emission requires delocalized-state excitation which enables separate carrier capture into the QD. Hence a well-defined threshold energy discriminating localized and delocalized states was clearly found for the X^- at around 85 meV, which corresponds to a wetting layer (WL) edge in the present S-K QDs. As for the X^+ , unlike the X^- , the WL edge does not have critical influence on the formation efficiency. This is because photo-generated electron-hole pair in localized states inside the QD, which is free from carrier capture process, can also form a positive trion with a residual hole in the QD. Thus, charging states of the exciton can be controlled by tuning the excitation energy, and selective formation of the positive trion is possible with high DCP as shown in Fig. 3(b).

4. Conclusions

Highly effective mutual transfer of angular momentum between single photon and single electron is demonstrated with a positively charged exciton at zero magnetic field even under non-resonant excitation. Obtained high degree of circular polarization up to 0.6 is a clear indicative of the strongly suppressed spin relaxation before recombination. Exclusive X^+ line emission with high DCP was also demonstrated by selecting excitation energy. These findings are quite encouraging toward the polarization-preserved photon-state converter.

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References

- [1] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, *Rev. Mod. Phys.* **74**, 145 (2002).
- [2] C. H. Bennett and G. Brassard, *Proc. of IEEE Int. Conf. on Comp. Sys. and Signal Proc.*, Bangalore, India 175 (1984).
- [3] C. Santori, D. Fattal, M. Pelton, G. S. Solomon, and Y. Yamamoto, *Phys. Rev. B* **66**, 045308 (2002).
- [4] R. J. Young, R. M. Stevenson, A. J. Shields, P. Atkinson, K. Cooper, D. A. Ritchie, K. M. Groom, A. I. Tartakovskii, and M. S. Skolnick, *Phys. Rev. B* **72**,

- 113305 (2005).
- [5] R. Seguin, A. Schliwa, T. D. Germann, S. Rodt, K. Pötschke, A. Strittmatter, U. W. Pohl, D. Bimberg, M. Winkelkemper, T. Hammerschmidt, and P. Kratzer, *Appl. Phys. Lett.* **89**, 263109 (2006).
 - [6] E. Tsitsishvili, R. V. Baltz, and H. Kalt, *Phys. Rev. B* **67**, 205330 (2003).
 - [7] M. Bayer, G. Ortner, O. Stern, A. Kuther, A. A. Gorbunov, and A. Forchel, P. Hawrylak, S. Fafard, and K. Hinzer, T. L. Reinecke and S. N. Walck, J. P. Reithmaier, F. Klopff, and F. Schäfer, *Phys. Rev. B* **65**, 195315 (2002).
 - [8] I. A. Akimov, A. Hundt, T. Flissikowski, and F. Henneberger, *Appl. Phys. Lett.*, **81**, 4730 (2002).
 - [9] M. E. Ware, A. S. Bracker, E. Stinaff, D. Gammon, D. Gershoni and V. L. Korenev, *Physica E* **26**, 55 (2005).
 - [10] T. Flissikowski, I. A. Akimov, A. Hundt, and F. Henneberger, *Phys. Rev. B* **68**, 161309(R) (2003).
 - [11] J. J. Finley, A. D. Ashmore, A. Lemaître, D. J. Mowbray, M. S. Skolnick, I. E. Itskevich, P. A. Maksym, M. Hopkinson, and T. F. Krauss, *Phys. Rev. B* **63**, 073307 (2001).
 - [12] C. Santori, D. Fattal, J. Vučković, G. S. Solomon, E. Waks, and Y. Yamamoto, *Phys. Rev. B* **69**, 205324 (2004).
 - [13] H. Kumano, S. Kimura, M. Endo, H. Sasakura, S. Adachi, S. Muto, and I. Suemune, *J. Nanoelectron. Optoelectron.* **1**, 39 (2006).
 - [14] H. Kumano, S. Kimura, M. Endo, I. Suemune, H. Sasakura, S. Adachi, S. Muto, H. Z. Song, S. Hirose, and T. Usuki, *Physica E* **32**, 144 (2006).
 - [15] A. G. Milekhin, A. I. Toropov, A. K. Bakarov, M. Yu. Ladanov, G. Zanelatto, J. C. Galzerani, S. Schulze and D. R. T. Zahn, *Appl. Surf. Sci.* **234**, 45 (2004).
 - [16] A. Lemaître, A. D. Ashmore, J. J. Finley, D. J. Mowbray, and M. S. Skolnick, M. Hopkinson, T. F. Krauss, *Phys. Rev. Lett.* **63**, 161309(R) (2001).
 - [17] I. A. Akimov, T. Flissikowski, A. Hundt, and F. Henneberger, *phys. stat. sol. (a)* **201**, 412 (2004).
 - [18] S. Laurent, B. Eble, O. Krebs, A. Lemaître, B. Urbaszek, X. Marie, T. Amand,² and P. Voisin, *Phys. Rev. Lett.* **94**, 147401 (2005).