LINEARLY AND CIRCULARLY POLARIZED PHOTON EMISSION FROM AN INDIVIDUAL SEMICONDUCTOR QUANTUM DOT*

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Anisotropic electron–hole exchange in semiconductor quantum dots is discussed in the context of efforts to obtain generation of entangled photon pairs from a biexciton–exciton cascade in a semiconductor quantum dot. Recent studies of anisotropy in III–V and II–VI quantum dots are described, followed by a discussion of attempts to compensate its influence by application of an electric field. Both macroscopic field generated by a voltage applied to electrodes and microscopic local fluctuation field are considered.

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1. Introduction

Optical properties of semiconductor quantum dots have attracted recently considerable attention, motivated by the development of quantum cryptography and perspectives of creation of quantum computers. Entangled photon pairs are very useful in these fields. Obvious advantages of semiconductor light sources, such as small dimensions, low power consumption, and compatibility with existing electronic systems, stimulate efforts to generate entangled photon pairs by excitonic emission from quantum dots. A biexciton–exciton cascade is the principal scheme considered for generation of polarization-entangled photon pairs [1]. The entanglement can be obtained due to spin degeneracy of the quantum dot exciton state, creating two recombination paths (Fig. 1). The wavefunction of the entangled photon pair can be symbolically written $|\Psi\rangle = (|+,-\rangle + |-,+\rangle)/\sqrt{2}$ or $|\Psi\rangle = (|V,V\rangle + |H,H\rangle)/\sqrt{2}$ in terms of circular $(+,-)$ or linear (V,H)

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polarizations, respectively. The entanglement is usually checked by performing photon correlation measurements. So far, polarization-dependent biexciton–exciton cross-correlation has been detected only for linear polarization measured in suitably selected directions [2]. Tests performed for circular polarization gave negative results, indicating lack of entanglement [3]. The main difficulty lies in the anisotropic electron–hole exchange interaction, which lifts the exciton spin degeneracy, creating two distinguishable recombination paths, accessible in two orthogonal linear polarizations, along the axes of quantum dot anisotropy. The two components of the excitonic state are separated by anisotropic exchange splitting (AES), typically of order of 10^{-4} eV [4]. This paper relates efforts undertaken to overcome this difficulty, by measuring the quantum dot anisotropy and examining the possibility of its compensation by application of an electric field.

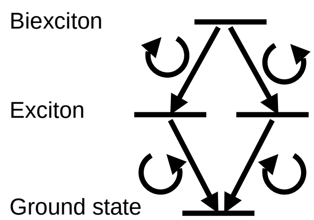

Fig. 1. Biexciton–exciton cascade in a quantum dot. Circular polarizations of the optical transitions are indicated.

2. Growth and characterization of semiconductor quantum dots

Semiconductor quantum dots are typically fabricated using molecular beam epitaxy, in which molecular or atomic beams, sent in high vacuum on a crystalline substrate, create an epitaxial layer with in-plane atomic spacing imposed by the structure of the substrate. A small mismatch between the natural atomic spacing of the layer and that of the substrate can be accommodated by an in-plane strain of the layer. However, in case of a large strain the two-dimensional growth is not possible and the layer material is deposited in the form of small islands, forming a self-assembled quantum dot system. To protect the quantum dots and enable optical experiments, the quantum dot layer is usually covered by a subsequently deposited capping layer. The substrate and cap form barriers confining excitons in the quantum dots. In this work we discuss results obtained on two material systems: III–V InAs/GaAs and II–VI CdTe/ZnTe. Each sample contained a quantum dot layer (InAs or CdTe) embedded between GaAs or ZnTe barriers. In spite of their high density (of order of $10^{10}\,\mathrm{cm}^{-2}$ or more), the quantum dots can be addressed individually in optical experiments. We used a specially designed microscope objective [5], which allowed us to obtain spectra containing narrow lines originating from individual quantum dots. Different types of excitonic transitions can be observed in PL spectra, including neutral excitons and biexcitons. Their identification is based on several different experiments, including excitation power dependence, observation of sudden energy jumps of the spectral lines, and anisotropy measurements [6].

3. Optical in-plane anisotropy of quantum dots

3.1. Anisotropy measurements

Optical in-plane anisotropy of a quantum dot transition can be measured by taking a series of PL spectra at different linear polarizations. The AES can be measured even if it is smaller than the line width. In this case oscillations of the transition energy as a function of the angle of the linear analyzer are observed. Their amplitude determines the anisotropic exchange splitting. Biexciton and exciton transitions exhibit a splitting of the same absolute value but opposite sign. In fact, both splittings measure the same AES of the exciton, which represents in the two cases the final or the initial state respectively. No other excitonic state (biexciton, charged exciton or the ground — empty dot — state) exhibit AES, due to the spin pairing of their carriers.

3.2. Influence of macroscopic electric field

In an attempt to compensate the QD anisotropy, the influence of an in-plane electric field on the AES was studied in an InAs/GaAs self-assembled QD system [7]. The field was created by application of a voltage to metallic electrodes deposited on the sample surface. One of the electrodes was annealed to form an ohmic contact, while the other one, not annealed, formed a Schottky diode. The results of the AES measurements as a function of the applied voltage are presented in Fig. 2. On application of 6 V, the AES

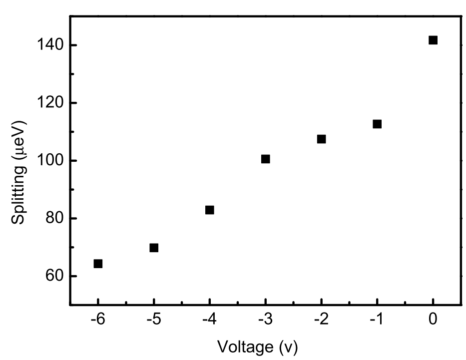

Fig. 2. Anisotropic exchange splitting in an InAs/GaAs quantum dot *versus* voltage applied to electrodes. After [7].

was reduced by more than a factor of 2. The perspective of a complete AES compensation depends on the mechanism of the electric field influence on the excitonic state. If the reduction of the splitting comes from electron–hole separation induced by the field, there is no hope to bring the splitting to zero while keeping a non-vanishing emission probability. The only possibility to meet both requirements is a modification of the quantum dot symmetry by the electric field. The above results did not allow us to distinguish between the two possibilities.

3.3. Local fluctuating electric fields

Further information on the influence of the electric field on the quantum dot excitons was obtained in a study of CdTe/ZnTe self assembled quantum dot system [8]. In this case, instead of depositing electrodes, local fluctuating electric fields were exploited. Individual quantum dot PL lines are known to exhibit sudden jumps of the spectral position, resulting from changes in the charge state of neighbor centers [9], producing the local electric fields. We looked for a correlation between the transition energy and the AES. The results are shown in Fig. 3. A significant correlation can be seen both for excitonic and biexcitonic transitions. The sign of the correlation indicates that the AES increases with increasing electric field. The electron–hole separation in electric field would lead to an opposite sign of the correlation. Therefore, we conclude that the electric field must influence primarily the symmetry of the excitonic wave functions in the quantum dot.

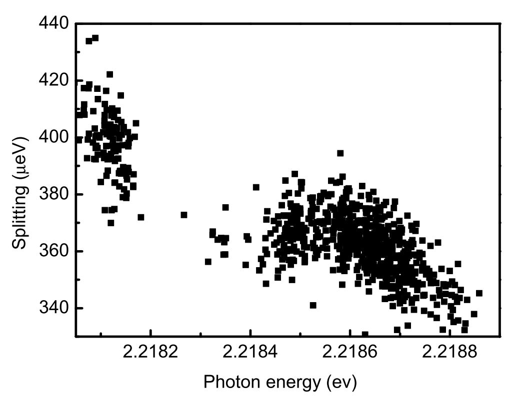

Fig. 3. Correlation between the transition energy (assumed to be a measure of the local electric field) and the AES for the exciton transition in an individual CdTe/ZnTe QD. After [8].

4. Conclusions

We document the influence of the electric field on the anisotropic exchange splitting of excitons in semiconductor quantum dots. In InAs/GaAs QD system, where a macroscopic in-plane electric field was applied, a reduction of the AES by more than a factor of 2 was obtained. In CdTe/ZnTe quantum dot system the correlation between the AES and local microscopic electric field indicates a symmetry modification by the electric field, opening a possibility of complete compensation of the AES and creation of entangled photon pairs in a biexciton–exciton cascade.

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Note added in proof:

First observation of polarization entangled photon pairs from a biexciton–exciton cascade was recently reported by R.M. Stevenson *et al.* (*Nature* **439**, 179 (2006)). In-plane magnetic field was successfully used to reduce the AES splitting.

REFERENCES

[1] O. Benson, C. Santori, M. Pelton, Y. Yamamoto, *Phys. Rev. Lett.* **84**, 2513 (2000).

[2] C. Santori, M. Pelton, G. Solomon, Y. Dale, Y. Yamamoto, *Phys. Rev. Lett.* **86**, 1502 (2002).

[3] R.M. Stevenson, R.M. Thompson, A.J. Shields, I. Farrer, B.E. Kardynal, D.A. Ritchie, M. Pepper, *Phys. Rev.* **B66**, 081302 (2002).

[4] D. Gammon, E.S. Snow, B.V. Shanabrook, D.S. Katzer, D. Park, *Phys. Rev. Lett.* **76**, 3005 (1996).

[5] J. Jasny, J. Sepioł, T. Irngartinger, M. Traber, A. Renn, U.P. Wild, *Rev. Sci. Instrum.* **67**, 1425 (1996).

[6] A. Kudelski, K. Kowalik, A. Golnik, G. Karczewski, J. Kossut, J.A. Gaj, *J. Lumin.* **112**, 127 (2005).

[7] K. Kowalik, O. Krebs, A. Lemaître, S. Laurent, P. Senellart, J.A. Gaj, P. Voisin, *Appl. Phys. Lett.* **86**, 041907 (2005).

[8] K. Kowalik, A. Kudelski, A. Golnik, J. Suffczyński, O. Krebs, P. Voisin, G. Karczewski, J. Kossut, J.A. Gaj, to be published in *Phys. Stat. Sol.*

[9] V. Türk, S. Rodt, O. Stier, R. Heitz, R. Engelhardt, U.W. Pohl, D. Bimberg, R. Steingruber, *Phys. Rev.* **B61**, 9944 (2000).