Vol. **112** (2007) *ACTA PHYSICA POLONICA A* No. 2

Proceedings of the XXXVI International School of Semiconducting Compounds, Jaszowiec 2007

Control of Photon Polarization in GaAs/AlAs Single Quantum Dot Emission

J. Suffczyński[a], A. Trajnerowicz[a], T. Kazimierczuk[a], B. Piętka[a,b], K. Kowalik[a], P. Kossacki[a], A. Golnik[a], M. Nawrocki[a], J.A. Gaj[a], A. Wysmołek[a], R. Stępniewski[a], M. Potemski[b] and V. Thierry-Mieg[c]

[a]Institute of Experimental Physics, Warsaw University
Hoża 69, 00-681 Warsaw, Poland
[b]Grenoble High Magnetic Field Laboratory, CNRS, Grenoble, France
[c]Laboratoire de Photonique et de Nanostructures, Marcoussis, France

We study polarization resolved correlation between photons emitted in cascaded biexciton–exciton recombination from a single quantum dot formed in type II GaAs/AlAs bilayer. Magnetic field induced transition from anisotropy controlled to the Zeeman controlled emission was demonstrated by a circular polarization correlation between the emitted photons. A simple model describing the effect allowed us to determine the anisotropic exchange splitting of the excitonic state. This method of the anisotropic exchange splitting determination can be useful in the case when other methods are not sensitive enough.

PACS numbers: 78.55.Cr, 78.66.Fd, 78.67.Hc, 78.47.+p

1. Introduction

Most of the secure quantum communication protocols proposed so far [1] exploit linearly and circularly polarized individual photons as carriers of encoded information. This creates a demand for generation of single photons with a desired polarization. Cascaded recombination of biexciton and exciton confined in an anisotropic quantum dot (QD) results in emission of two photons correlated in a linear polarization basis. A possibility of control of polarization basis, in which photon pair is emitted, would be of value for practical implementation of QDs as building blocks of the quantum communication devices.

In this work, we show that switching between linear and circular polarization basis of correlation in biexciton–exciton cascaded emission from single GaAs/AlAs quantum dot is feasible with the use of external magnetic field. We study magnetic field induced transition between anisotropy controlled and the Zeeman controlled emission from individual quantum dot. We demonstrate the utility of these studies, involving polarized photon correlation measurements, for determination of the anisotropic exchange splitting (AES) of excitonic states in quantum dots.

2. Sample and experimental setup

The investigated QDs are formed in type II GaAs/AlAs bilayer. Due to the deep confining potential, QDs exhibit a multiple zero-dimensional shell structure, with inter-shell energy separation of the order of 10 meV [2].

The sample was mounted directly on a microscope objective [3] and placed inside a pumped helium cryostat at 1.8 K. A continuous wave tunable Ti:Al_2O_3 laser provided excitation below the energy gap of the barrier material (at 718 nm), assuring quasi-resonant excitation conditions. The typical power of excitation beam was 100 μW over the 1 μm diameter spot. Photoluminescence was excited and collected through the same microscope objective. Single photon correlation measurements were performed in a Hanbury-Brown and Twiss setup. The signal after polarization and spectral filtering were detected by two avalanche photodiodes. The detailed description of the experimental setup can be found in Ref. [4].

3. Experimental results

The QD selected for this study was characterized by measurements of photoluminescence (PL) in magnetic field (Fig. 1). The excitonic Zeeman splitting

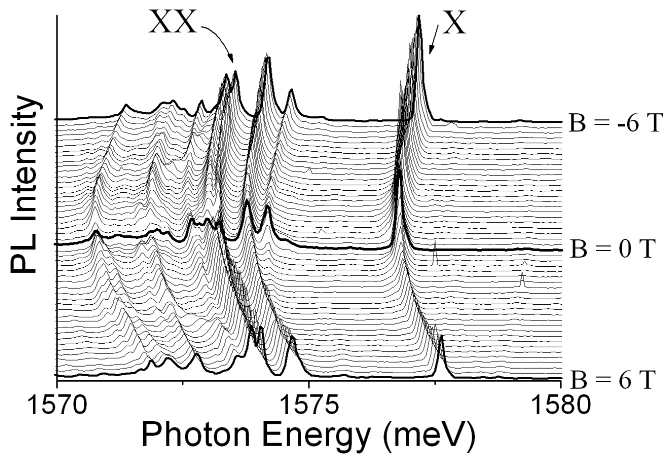

Fig. 1. Photoluminescence spectra of the lowest shell of the selected quantum dot in magnetic field from 0 to 6 T. Detection in two circular polarizations encoded in the sign of magnetic field. Transitions of exciton (X) and biexciton (XX) indicated.

was determined as a function of the magnetic field, attaining 0.4 meV at $B = 6$ T. The excitonic g factor was determined as $g = 1.15$.

We measured polarization resolved cross-correlations between photons related to biexcitonic and excitonic recombination in the magnetic field varied from 0 to 0.5 T and applied in the Faraday configuration. No polarization correlation was observed in circular basis in the absence of magnetic field (not shown). Positive linear polarization correlation of XX–X photon pair was evidenced at $B = 0$ T by the appearance of a bunching peak and an antibunching dip in correlation histograms recorded in the same or orthogonal linear polarizations, respectively (Fig. 2). Such a result is expected [5] for QDs exhibiting in-plane anisotropy, since

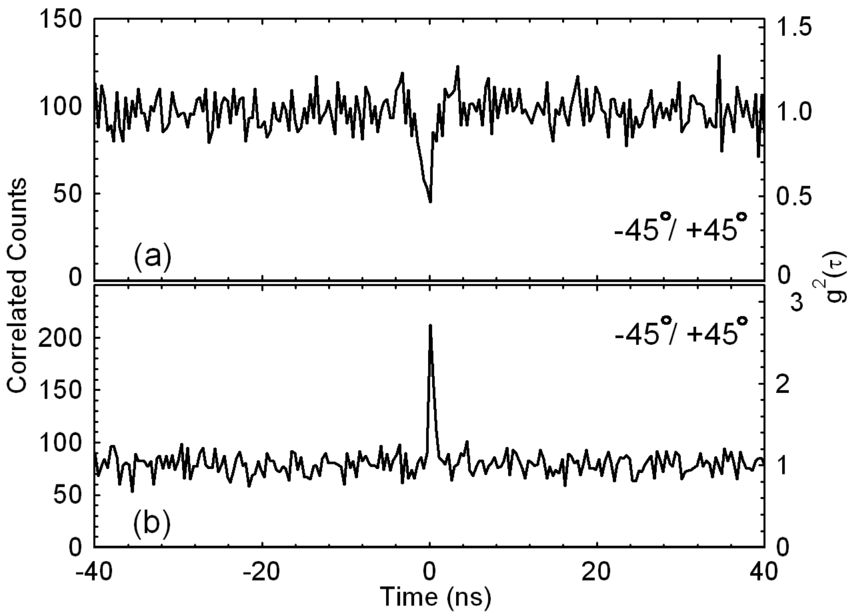

Fig. 2. Biexciton–exciton cross-correlation measured at $B = 0$ T in linear polarization basis corresponding to principal axes of the dot (at 45° to lab axis). Bunching (antibunching) in histogram recorded in parallel (orthogonal) linear polarizations results from anisotropy-controlled emission. Respective single counter rates were: (a) XX — 9500/s, X — 4400/s and (b) XX — 4500/s, X — 3400/s. Acquisition time: (a) 2 h, (b) 4 h.

the intermediate excitonic state of the cascade is split by energy of electron–hole exchange interaction in two components emitting in orthogonal linear polarizations. We quantify the degree of linear polarization correlation by

$$P_{\text{lin}} = \frac{I^{aa} - I^{ab}}{I^{aa} + I^{ab}}, \tag{1}$$

where I^{xy} refers to the intensity of the second order correlation function $g^2(\tau)$ at

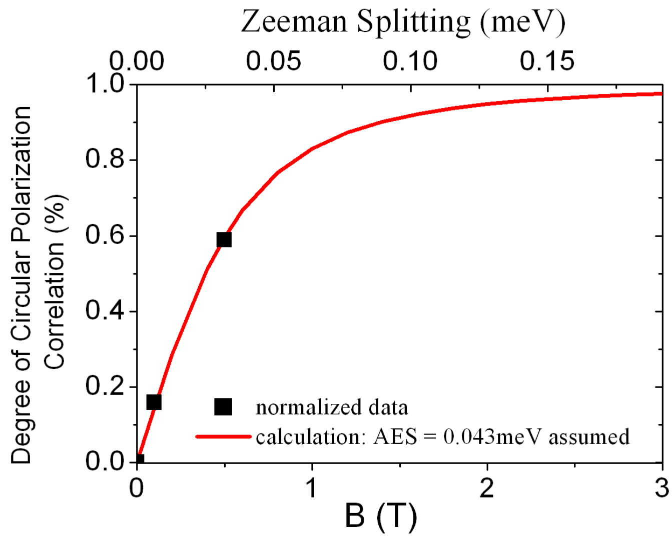

Fig. 3. Degree of circular polarization correlation of the photons from biexciton–exciton cascade determined from the experiment (points) and obtained from the fitting of the model to the data (line).

$\tau = 0$ obtained for the detection of XX and X photon in "x" and "y" polarization, respectively. Degree of linear polarization correlation $P_{\rm lin}$ calculated in that way for the zero field case is $P_{\rm lin} = 0.70$. This value, lower than 1, may originate from exciton relaxation or from uncorrelated background emission. The application of magnetic field introduces the Zeeman type contribution to the X level splitting, reducing thus the influence of the anisotropy. In a sufficiently high magnetic field the Zeeman splitting dominates over the anisotropic one and pure exciton eigenstates of angular momentum $M = \pm 1$ should be observed [6]. The conversion of linearly polarized excitonic states to circularly polarized ones was confirmed experimentally by an increase in the degree of circular polarization correlation with increasing magnetic field (Fig. 3).

4. Model description

We apply a simple model proposed by Besombes et al. [7] to describe the progressive increase in the circular polarization correlation in the XX–X cascade with increasing field. The model expresses the excitonic wave functions as

$$|+\rangle = \cos\theta|+1\rangle + \sin\theta|-1\rangle, \tag{2}$$

$$|-\rangle = \cos\theta|-1\rangle - \sin\theta|+1\rangle, \tag{3}$$

where $\cot(2\theta)$ is equal to the ratio of the Zeeman splitting to the anisotropic exchange splitting and $|+1\rangle$ and $|-1\rangle$ are excitonic wave functions with angular momentum +1 and –1, respectively. Since the factors $\cos\theta$ and $\sin\theta$ determine the contributions of the two excitonic states emitting in orthogonal circular polarizations, degree of circular polarization correlation P_{calc} of photons emitted in XX–X cascade can be calculated in the frame of model as

$$P_{\mathrm{calc}} = \frac{\cos^2\theta - \sin^2\theta}{\cos^2\theta + \sin^2\theta} = \cos 2\theta. \tag{4}$$

The exciton depolarization occurring over exciton lifetime is assumed to be negligible here. Thus the model introduced allows us to calculate P_{calc} as a function of the Zeeman splitting with the AES treated as a fitting parameter.

The experiment provides quantification of degree of circular polarization correlation P_{circ}, which is determined in analogy to P_{lin} defined by formula (1). We assumed that a maximum attainable P_{circ} is equal to the degree of linear polarization correlation in the absence of magnetic field P_{lin} (Fig. 2) and normalized the experimental points by its value. This is equivalent to the assumption that any factors reducing the measured polarization remain unchanged in magnetic field. Figure 3 shows the fit of the model to the normalized experimental points. The AES = 43 μeV obtained from the fit is comparable with AES determined through direct measurement of in-plane anisotropy for other QDs on the same sample. The difference between the value of AES determined basing on P_{circ} calculated following formula (1) with and without subsequent normalization (AES = 30 μeV), serves as a measure of the AES determination accuracy.

5. Conclusions

We observed the transition in magnetic field from linear polarization correlation to circular polarization correlation of photons emitted in the biexciton cascaded decay. By fitting the model to the experimental data, we were able to determine the anisotropic exchange splitting AES value being of the order of tens of μeV. The determination of the AES through photon correlations provides an alternative for direct measurements through polarization resolved microphotoluminescence.

Acknowledgments

This work was partially supported by the Polish Ministry of Science and Higher Education as research grants in years 2006–2009.

References

[1] G. Bennet, C.H. Brassard, in: *Proc. IEEE Int. Conf. on Computers, Systems and Signal Processing, Bangalore (India)*, IEEE, New York 1984, p. 175.

[2] B. Chwalisz-Piętka, A. Wysmołek, R. Stępniewski, M. Potemski, S. Raymond, R. Bożek, V. Thierry-Mieg, *Int. J. Mod. Phys. B* **21**, 1654 (2007).

[3] J. Jasny, J. Sepioł, *Chem. Phys. Lett.* **273**, 439 (1997).

[4] J. Suffczyński, T. Kazimierczuk, M. Goryca, B. Piechal, A. Trajnerowicz, K. Kowalik, P. Kossacki, A. Golnik, K.P. Korona, M. Nawrocki, J.A. Gaj, G. Karczewski, *Phys. Rev. B* **74**, 085319 (2006).

[5] R.M. Stevenson, R.M. Thompson, A.J. Shields, I. Farrer, B.E. Kardynał, D.A. Ritchie, M. Pepper, *Phys. Rev. B* **66**, 081302 (2002).

[6] M. Bayer, G. Ortner, O. Stern, A. Kuther, A.A. Gorbunov, A. Forchel, P. Hawrylak, S. Fafard, K. Hinzer, T.L. Reinecke, S.N. Walck, J.P. Reithmaier, F. Klopf, F. Schäfer, *Phys. Rev. B* **65**, 195315 (2002).

[7] L. Besombes, L. Marsal, K. Kheng, T. Charvolin, Le Si Dang, A. Wasiela, H. Mariette, *J. Cryst. Growth* **214/215**, 742 (2000).