phys. stat. sol. (b) **238**, No. 2, 297–300 (2003) / **DOI** 10.1002/pssb.200303047

Quantum dots: a source of multicolor photons with tunable statistics and correlated polarizations

U. Mizrahi[1], **D. V. Regelman**[1], **D. Gershoni***[, 1], **E. Ehrenfreund**[1], and **P. M. Petroff**[2]

[1] Physics Department, Technion-Israel Institute of Technology, Haifa 32000, Israel
[2] Materials Department, University of California, Santa Barbara, CA 93106, USA

Received 30 September 2002, accepted 2 December 2002
Published online 7 July 2003

PACS 42.50.Dv, 78.55.Cr, 78.67.Hc, 85.60.Jb

We report on measurements of temporal and polarization correlations measurements of multi-color photons emitted from cw optically excited single semiconductor quantum dots. We show that there are tunable intensity and polarization correlations among photons emitted at the same, and at different wavelengths due to the recombination of electron–hole pairs from different collective many-carrier quantum states confined in the dots. The observed polarization correlations between the emitted photons are qualitatively explained in terms of long electronic spin memory.

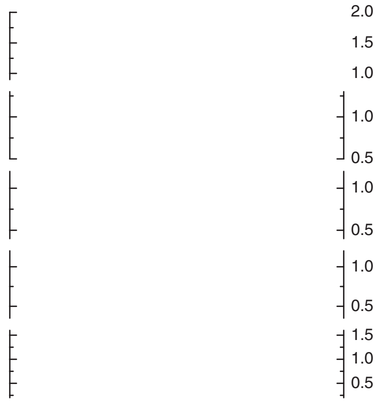
1 Introduction Semiconductor quantum dots (SCQDs) are extensively investigated as a potential, technology compatible quantum light source. We report here on studies of the statistical and polarization properties of the light emitted from optically excited single self assembled SCQDs. We demonstrate some control over the statistics and the polarization correlations of photons emitted from these sources. This control and understanding is crucial for any possible future applications such as cryptography [1], and quantum information processing [2].

2 Experiment and discussion Our semiconductor quantum dot sample was grown by molecular beam epitaxy of a strained epitaxial layer of InAs on (100) oriented GaAs substrate. Small islands of In(Ga)As connected by a very thin wetting layer are thus formed in the Stranski–Krastanov growth mode. We used the partially covered island growth technique [3], in order to better control the vertical dimensions of the QDs. The sample was not rotated during the growth of the strained layer, therefore a gradient in the QDs density was formed. Thus, low-density areas, in which the average distance between neighboring QDs is larger than our optical spatial resolution, could easily be found on the sample surface. We have used a diffraction limited low temperature confocal optical microscope [4] for the photoluminescence (PL) studies of the single SCQDs. In order to measure the temporal correlation between emitted photon pairs we constructed a wavelength selective Hanbury–Brown and Twiss (HBT) arrangement [5].

The PL spectra from a single quantum dot for increasing cw excitation powers are shown in Fig. 1a. The measured spectra strongly depend on the excitation power due to the shell-filling effect (shells are denoted as S, P and D) and the Coulomb interactions among carriers [4]. The radiative recombination of a single pair occupying the dot gives rise to the X^0 line (for simplicity we ignore the fine structure of this line [6], see below). Coulomb exchange interaction gives rise to red shifted PL lines (denoted nX^S) when $n \geq 3$ pairs are present in the SCQD during the recombination.

* Corresponding author: e-mail: dg@physics.technion.ac.il, Phone: +972 4 8293693, Fax: +972 4 823 5107

 0370-1972/03/23807-0297 $ 17.50+.50/0


2.0
1.5
1.0
1.0
0.5
1.0
0.5
1.0
0.5
1.5
1.0
0.5

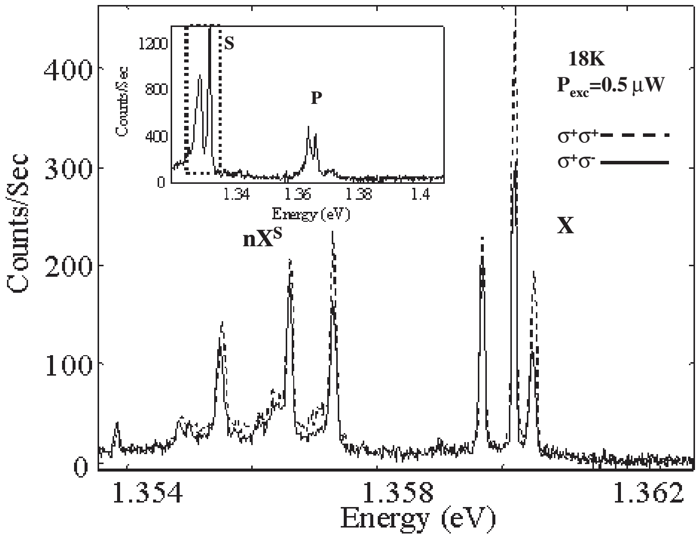


Fig. 3 High resolution photoluminescence spectra of non-resonantly excited single SCQD at co-(dashed line) and cross- (solid line) circular polarizations relative to the circular polarization of the exciting laser. The spectral range shown, which contains the X^0 and nX^S lines, is indicated in the inset by the doted frame.

somewhat noisy, still clearly indicates that when an nX^S photon with a given circular polarization is detected, the X^0 photon that follows will most likely have the same polarization. We found that these correlations, like the intensity correlations, are strongly dependent on the excitation power used (not shown). When we replaced the circular polarizers with linear ones, no detectable difference was observed when the correlation function was measured with or without the polarizers. This is different than the results obtained from measurements of SCQDs in pillar microcavities [8].

We believe that these polarization correlations result from the long electronic spin-flip times. These long times prevent rapid relaxation of electrons from higher energy shells to partially occupied lower ones, due to the exclusion principle. Therefore, it is plausible that the recombination cascade proceeds via excited multi-carriers states, in which the lowest shells are not fully occupied. In these cases it is not difficult to describe events in which the spin states of the recombining nX^S and X^0 electrons are the same. However, at the moment, the nature of the mechanism, which bias against recombination via fully occupied shells, is not entirely clear to us.

An indication for this spin memory effect is evidenced in Fig. 3, where we display high-resolution spectra of the S-shell spectral lines, for co- (dash line) and cross- (solid line) polarizations, relative to the circular polarization of the non-resonant exciting laser beam. In these high-resolution spectra, the fine structure [6] of the X^0 line and that of the nX^S line is clearly resolved. The spectral lines belong to the same dot as evidenced by the photon antibunching in the correlation measurements (see Fig. 1). These novel observations will be discussed elsewhere. It is seen, that indeed, these spectral lines are preferentially co-polarized with the laser, indicating long spin memory relaxation processes. Here, as with the cross-correlation measurements, we could not detect any degree of linear polarization. This is in contradiction with reports from other types of SCQDs [6, 9, 10] but in agreement with reports of measurements performed on similar SCQDs [11].

3 Conclusions We measured the temporal intensity and polarization correlations between pairs of single photons emitted from optically excited single self assembled SCQDs. We have shown that photons from cascading recombination events are preferentially circularly co-polarized. We qualitatively explain our observations in terms of very long spin-flip times.

Acknowledgments Work supported by the Israel Science Foundation and by the US–Israel Binational Science Foundation.

References

[1] C. H. Bennett and G. Brassard, Proc. IEEE Int. Conf. Comput. Syst. Signal Process (1984).
[2] D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).
[3] J. M. Garcia, T. Mankad, P. O. Holtz et al., Appl. Phys. Lett. **72**, 3172 (1998).
[4] E. Dekel, D. Gershoni, E. Ehrenfreund et al., Phys. Rev. Lett. **80**, 4991 (1998).
[5] R. Hanbury-Brown and R. Q. Twiss, Nature **178**, 1447 (1956).
[6] M. Bayer, G. Ortner, O. Stern et al., Phys. Rev. B **65**, 195315 (2002).
[7] D. V. Regelman, U. Mizrahi, D. Gershoni et al., Phys. Rev. Lett. **87**, 257401 (2001).
[8] C. Santori, D. Fattal, M. Pelton, G. S. Solomon, and Y. Yamamoto, Phys. Rev. B **66**, 045308 (2002).
[9] D. Gammon, E. S. Snow, B. V. Shanabrook et al., Phys. Rev. Lett. **76**, 3005 (1996).
[10] V. D. Kulakovskii, G. Bacher, R. Weigand, T. Kümmell et al., Phys. Rev. Lett. **82**, 1780 (1999).
[11] A. Kiraz, S. Fälth, C. Becher, B. Gayral et al., Phys. Rev. B **65**, 161303 (2002).