Polarization Correlations of Single Photons Emitted by Quantum Dots in Planar Microcavities

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Abstract. We measured the second order correlation function between single photons emitted from optically excited single self-assembled quantum dots embedded in planar microcavities. We clearly distinguish between radiative recombination processes in the presence of a charge in the dot to recombination in its absence. We observed strong correlations of the linear polarization states of photons emitted by the recombining neutral biexcitons and the polarization states of consecutive recombining neutral excitons.

Non-classical light sources are needed for recently proposed optical implementations of quantum cryptography and quantum computation. Single semiconductor quantum dots (QDs) are attractive as non-classical light sources because their properties can be easily engineered, they do not suffer from photo-bleaching effects, and they can be easily integrated into larger structures and devices compatible with modern micro- and nano-electronics [1,2]. Here we report on the use of time-resolved intensity and polarization correlation measurements in order to characterize various lines in the photoluminescence (PL) spectrum of single QDs.

The microcavity QDs were grown by molecular beam epitaxy (MBE) on a (100) oriented GaAs substrate. One strained epitaxial layer of InAs was deposited in the center of a one wavelength cavity formed by two unequal stacks of alternating quarter wavelength layers of AlAs and GaAs. The QDs were formed by the Stranski-Krastanov self-assembly growth mode [1]. Their height was controlled by the partially covered island method [2] and the microcavity was designed to have a relatively low Q factor (~200) and a cavity mode, which matches the PL from the ground level of the QDs. This design provided improved collection efficiency [1] of photons from QDs PL spectral lines which resonate with the microcavity mode.

We use a diffraction limited low temperature confocal optical microscope for the PL studies of the single microcavity QDs (MCQDs) [3]. Temporal correlations of emitted photon pairs are measured using a wavelength and polarization selective Hanbury-Brown-Twiss arrangement [3-5]. The relative polarizations of two consecutively emitted photons, from the same as well as from different spectral PL lines, can thus be accurately determined.

In Fig. 1 we present PL spectra from a single, resonant MCQD for various excitation intensities (a) and for various excitation energies (b). At low excitation intensities and high excitation energy (Fig. 1a) only lines No.1 and No. 2 appear. These lines are due to ground levels electron-hole (e-h) pair recombination in the absence of additional pairs ("single exciton" lines). As the excitation intensity increases, additional group of five lines (the most pronounced ones are lines Nos. 3, 4 and 5) at lower energy emerges. These lines are due to ground e-h pair recombination in the presence of additional "spectator" pairs (bi- or multi-excitons [6]). As we reduce the excitation energy, lines No. 1, 3 and 5 lose strength and eventually vanish. We use this observation to conclude that these lines are due to recombination when the QD is neutral, since no optical discharging [7-9] is possible at low excitation energy. Thus, line No. 1(2) corresponds to the recombination of ground e-h pair in the absence (presence) of charge in the QD - neutral exciton X^0 (- negatively charged exciton X^{-1}). Line No. 3 (4) corresponds to the recombination of ground e-h pair in the presence of another ground e-h pair in the absence (presence) of charge – neutral (charged) biexciton - XX^0 (XX^{-1}).

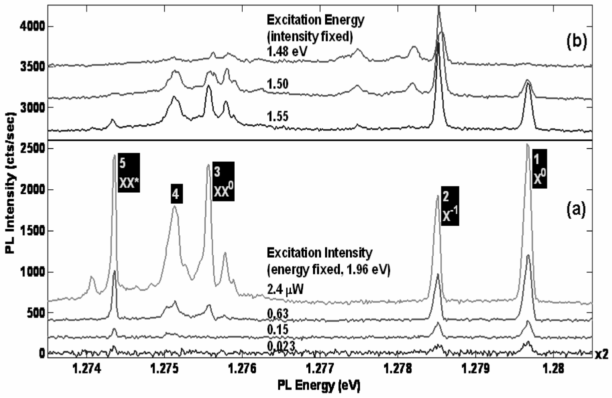

FIGURE 1. PL spectra of a single, resonant MCQD for various excitation intensities (a) and excitation energies (b).

Line No. 5 is probably due to the recombination of a ground e-h pair, in the presence of an excited another e-h pair with the same spin(s), which do not relax to their ground states due to the Pauli exclusion principle.

We further substantiate our interpretation in Fig. 2

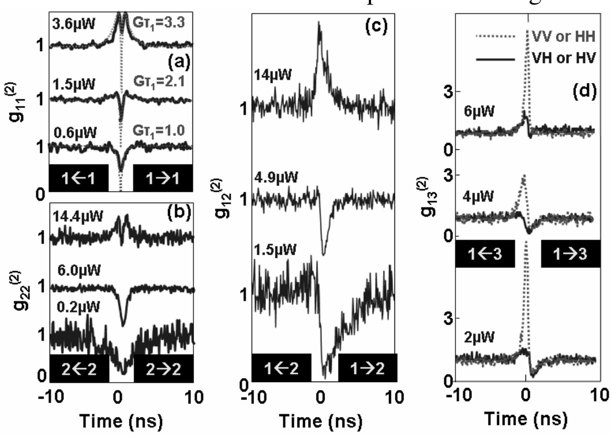

FIGURE 2. Auto-(a,b) and cross-correlation (c,d) measurements of photons from the X^0, X^{-1} and XX^0 lines for various cw excitation intensities. The dashed lines in (a) correspond to the theoretical model of Ref. 2. Dashed (solid) lines in (d) correspond to co- (cross-) linearly polarized light along the H or V directions.

where the intensity and polarization correlations measurements between photons from the first three lines only, are presented. The auto-correlation measurements of the lines X^0 (Fig. 2a), X^{-1} (Fig. 2b) and XX^0 (not shown), clearly demonstrate that each of these lines is a spectral source of single photons [1-5]. The intensity dependence of the second order correlation function is clearly given by our model [3] as shown by the dashed line in Fig. 2(a). The cross-correlation measurements of the X^{-1} and X^0 lines (Fig. 2c) show clear and strong asymmetric anti-bunching behavior around t=0. This clearly demonstrates that these are mutually exclusive states of the MCQD, with vastly different rates of switching between them. Clearly, the transition of the MCQD from a neutral state to a charged state is much slower than the opposite sequence of events. This is because recharging requires tunneling of charges from a nearby trap into the MCQD, while discharging is done by the optical excitation [7-9].

The asymmetry in the cross correlation measurements between the neutral biexciton XX^0 and neutral exciton X^0 photons (2d) clearly reveals the temporal sequence of these events. As expected, while emission of XX^0 photon is likely to be followed by an emission of X^0 photon, the opposite can never happen [3, 4]. Furthermore, the linear polarizations of both photons must be the same, as is clearly demonstrated by the polarization dependency of the cross-correlation measurements. The reason for this behavior is the anisotropic e-h exchange interaction which removes the degeneracy between the two bright exciton states [5, 10, and 11]. As a result, the optical transition between the non degenerate ground biexciton state and that from the exciton state to the non-degenerate empty crystal state must have the same linear polarization [10, 11]. We directly measured the anisotropic exchange energy splitting (not shown) for this MCQD, using high resolution polarized PL spectroscopy, and found it to be ~30 μeV.

Acknowledgments-The work was supported by the Israel Science Foundation, by the US-Israel Binational Science Foundation (BSF) and by the Technion Vice President Fund for the Promotion of Research

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