Single photon emission and quantum ring-cavity coupling in InAs/GaAs quantum rings

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Abstract. Different InAs/GaAs quantum rings embedded in a photonic crystal microcavity are studied by quantum correlation measurements. Single photon emission, with $g^{(2)}(0)$ values around 0.3, is demonstrated for a quantum ring not coupled to the microcavity. Characteristic rise-times are found to be longer for excitons than for biexcitons, resulting in the time asymmetry of the exciton–biexciton cross-correlation. No antibunching is observed in another quantum ring weakly coupled to the microcavity.

1. Introduction
The use of semiconductor quantum rings (QRs), instead of quantum dots (QDs), gives more flexibility in the design of single photon emitters, due to their new properties resulting from their ring-like shape [1-3]. Single photon emission is characterized a minimum in the second order correlation function at zero delay time [4]. Photon antibunching under pulsed excitation has already been reported in GaAs/AlGaAs double QRs [5]. Efficient quantum information applications can be achieved by incorporating the nanostructures into solid state nanocavities.

In the present work we report second order time [$g^{(2)}(\tau)$] correlation measurements in InAs/GaAs QRs in a photonic crystal microcavity under continuous non-resonant excitation. Clear photon antibunching and bunching detecting coincidences are shown in auto- and cross-correlation configurations respectively, for exciton (X) and biexciton (XX) emission lines of a single QR not coupled to the cavity mode (CM). The characteristic time (rise time, $t_R$) of $g^{(2)}(\tau)$ of the exciton is significantly larger than the biexciton one, consistent with the asymmetric shape of the XX-X cross-correlation near $\tau=0$. On the other hand, no antibunching is observed for another QR weakly coupled to the CM when they are brought in resonance.

2. Experiment
Self assembled InAs QRs were grown by solid source molecular beam epitaxy [6] inside a 158 nm thick GaAs slab grown on top of a 500 nm thick Al$_{0.75}$Ga$_{0.25}$As sacrificial layer. The QR surface
density is $7.5 \times 10^9$ cm$^{-2}$ and their average height and lateral size are 2 and 50 nm respectively. Cross-sectional STM images reveal that the QR shape is maintained after capping [7]. A photonic crystal (PC) triangular lattice of holes of 140 nm diameter with a lattice constant of 230 nm was patterned by electron beam lithography and dry etching [8]. Air suspended membranes were realized by sacrificial etching of the underlying AlGaAs layer. The optical cavity is formed by a missing hole in the PC and a slight inward shift of its nearest neighbors truncated holes (H1 calzone cavity) [9]. The lowest energy mode of this kind of microcavity splits into two linearly counter-polarized components.

Photoluminescence (PL) spectra of single QRs were taken with a micro-PL setup with a 2 μm spot size using a He-Ne laser and a CCD detector located at one of the exits of a single spectrometer. The intensity correlation measurements were done with a Hanbury-Brown and Twiss interferometer located at the second exit of the spectrometer. Two avalanche photodiodes with 0.5 ns response time and 30% efficiency at the emission wavelength (920 nm) were used for coincidence detection. A Ti:sapphire tunable laser was used for resonant excitation measurements. A continuous He-flow cryostat was used for temperature dependent measurements.

3. Results and discussion

A SEM image of the microcavity is shown in Figure 1(a), where the approximate position of the QR not coupled to the CM is marked by the shaded area. This QR (named QR1) is too far to be coupled to the CM, but as its emission lies spectrally on the photonic bandgap provided by the PC, the emitted light can be more efficiently collected [10]. Due to this effect the PL intensity recorded of QRs inside the PC is enhanced by a factor of 6 with respect to the outer QRs. The PL spectra of QR1 are presented in Figure 1(b) as a function of the excitation intensity. The X, XX and positive trion ($X^+$) are

![Figure 1](image_url)

**Figure 1.** (a) SEM image of the microcavity with the location of QR1 (left panel), QR2 and QR3 (right panel). (b) Power dependent PL spectra (normalized to the X line intensity) of QR1. Spectra were taken at 7 K. (c) Temperature and polarization dependent PL spectra of QR2 and CMs. (d) Energies of QR2 and V-CM emission lines as a function of temperature. (e) Emission intensity of QR2 and QR3 as a function of detunings for V polarization. (f) Polarization diagram of the QR3 emission at two different detunings with respect V-CM, 1.77 meV and 0.57 meV.
identified by their power dependence \( I \propto P^\gamma \). We obtain \( \gamma = 1.02 \) for X, \( \gamma = 1.87 \) for XX and \( \gamma = 1.39 \) for X+. The peak widths of X and XX are rather large (0.7 meV) compared to QD excitons, similarly as reported for GaAs QRs [5]. The origin of this large width is not known, but it is possibly related to spectral broadening. The X and XX line-shapes broaden and slightly red-shift upon decreasing excitation power. At low excitation intensities the spectra is dominated by low energy acoustic phonon sidebands. Increasing the excitation power screens out the piezoelectric coupling of X and XX to acoustic phonons and the zero-phonon line emission prevails in the spectra [11].

Two more QRs (named QR2 and QR3) located near the microcavity have been studied. Their positions with respect to the cavity center have been roughly estimated by scanning the microscope objective in the sample plane to optimize the different PL intensities. We find that QR2 and QR3 are at 0.5±0.15 and 0.9±0.15 μm respectively, away from the CM maxima almost in opposite directions along H direction (see right panel in Figure 1(a)). The individual coupling of these two QRs has been studied by changing the sample temperature and, in the case of QR2, also by controlled Xe thin film deposition. Figure 1(c) shows the PL spectra of QR2 and the cavity modes for different temperatures and both polarizations. QR3 emission occurs at 1.343 eV and is clearly observed only at resonant excitation (not shown). Figure 1(d) shows that no energy anticrossing is observed in QR2 (neither in QR3), indicating weak coupling to the cavity. However, significant intensity increases are observed for both QRs at zero detuning (Figure 1(e)). A second evidence of the QR3 coupling to the V-CM is shown in Figure 1(f). The QR3 emission experiments a rotation in its polarization towards the V-CM polarization direction as its detuning is decreased. The QR2 emission line is fully V-polarized even at large detuning from the V-CM, giving evidence of the remaining mode influence on the off-resonance QR emission [12].

Quantum correlations measurements have been performed on QR1 under continuous excitation. The second order auto-correlation function of the X line for low excitation power is presented in Figure 2(a). By fitting (solid line) the experimental data to the standard expression:

\[
g^{(2)}(\tau) = 1 - \beta \exp\left(-\frac{|\tau|}{\tau_R}\right)
\]

convoluted with the instrumental time response of the detectors and corrected for background, we find \( g^{(2)}(0) = 0.34 \) and \( \tau_R = 1.2 \) ns. The corresponding values for the XX auto-correlation function (not shown) are \( g^{(2)}(0) = 0.27 \) and \( \tau_R = 0.6 \) ns. The \( g^{(2)}(0) \) values below 0.5 are indicative of single photon emission. The XX-X cross-correlation function is shown in Figure 2(b). The typical asymmetric shape is characteristic of the XX-X emission cascade. A simple exponential fit (solid line) has been used to estimate the involved times, instead of solving the complete rate equation system [13]. We found characteristic times of 2.4 and 1.3 ns for the left and right hand side respectively. This time asymmetry

![Figure 2.](image-url) (a) Auto-correlation of the X emission and (b) cross-correlation function between X and XX emissions of QR1.
is the consequence of the different rise times found in the autocorrelation functions of X and XX. For an empty QR, the capture of an electron-hole pair can result in either a bright or a dark X. Instead, the capture of a second e-h pair always results in an optically active XX. As we have in our experiments almost equal X and XX PL intensities, the probability of emitting two consecutive X photons with short time delay is expected to be lower than between XX photons. Quantum-correlation measurements have also been performed in QRs located near the cavity. No antibunching is observed in the second order auto-correlation function of QR2 – V-CM system when they are on resonance. This is probably due to the high (>1) photon number in the cavity, as a consequence of the high power needed to carry out the experiment. Unfortunately, off-resonance measurements are not possible due to the low signal detected of QR2 emission at large detunings.

4. Conclusions
In summary, evidence of single photon emission by InAs QRs inside a PC lattice is given under continuous excitation. Auto- and cross-correlation measurements of the exciton and biexciton transitions indicate characteristic times longer for the X emission than for the XX one for similar emission intensities. Weak-coupling is demonstrated in QRs located near the photonic crystal microcavity by intensity enhancement and polarization properties when the detuning between QR and CM is decrease. No antibunching is observed in a QR coupled to a CM when they are on resonance.

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