

TIME-RESOLVED PHOTOLUMINESCENCE STUDIES OF SINGLE SELF-ASSEMBLED CHARGE-TUNABLE QUANTUM RING STRUCTURES

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Key words to describe the work: Quantum-dot, quantum-ring, photoluminescence, time-resolved photoluminescence, exciton, bi-exciton, lifetime

Key Results: A full study of the lifetimes of the different states of a chargeable quantum ring structure has been carried out.

How does the work advance the state-of-the-art?: An understanding of charged carrier dynamics in quantum dots and ring is of importance in furthering such fields as spintronics and quantum computing.

Motivation (problems addressed): Studies of chargeable quantum dots have revealed various features from the charged exciton's in the system. Lifetime studies provide further insight into the carrier dynamics of these features.

Introduction

Quantum dots and rings are nanometer-sized bundles of semiconductor material that confine electrons in all 3 spatial dimensions. This results in the generation of atomic-like, discrete energy levels in the structures. However, unlike atoms, quantum dots and rings can be easily manipulated and their shape, size and composition altered during growth. The ability to alter their properties in such a way is opening up a large array of possibilities in spintronics and quantum information processing.⁽¹⁾ Charge-tunable quantum rings make use of the Coulomb blockade to allow single electrons to be injected into the rings in a controlled manner. The result is that by combing biasing and photo-excitation we can produce charged excitons with known excess charge.⁽²⁾

This work reports time-resolved photoluminescence (TRPL) studies of charged exciton states in such a structure.

Sample Growth and Preparation

The sample studied here consists of a low density, (10^9 dots per cm^2) fully formed InAs/GaAs quantum rings imbedded in a charge-tuneable structure and grown by molecular beam epitaxy (MBE) techniques.

Self-assembled dots are grown by the Stranski-Krastanov (SK) method. Here strain effects between a lattice mismatched mono-layer and substrate layer (i.e. InAs on GaAs or GaSb on GaAs) result in small island of the monolayer material randomly forming at about 1.5 layers thickness to relieve the strain.

These islands, the dots, are inhomogeneous varying in size and shape by $\sim 10\%$ across the sample.

By introducing a pause in the SK growth of InAs/GaAs quantum dots indium diffusion results in an alteration of composition from dot-like to ring-like.⁽³⁾

The inclusion of a heavily doped n^+ layer underneath a tunnel barrier of GaAs situated just below the rings provides a back contact for the charge tunable system. A 7nm thick NiCr gate is then evaporated onto the sample surface to complete the chargeable structure and to allow for optical penetration.

Experimental Set-Up

A diffraction limited low temperature (4K) confocal microscope arrangement is used, in addition to a low-density ring sample, to study single quantum-rings.⁽²⁾ The microscope provides a spatial resolution of about 820 nm at a wavelength of 950 nm - the luminescence wavelength of the rings. This results in tens of rings being in the focus. As each ring has different physical properties there is an inhomogeneous spectral linewidth broadening of ~ 20 meV. A spectrometer is therefore used to spectrally select a region of interest that contains typically less than ten dots. Each ring also charges at different voltages and this property is used to select just one ring from the ones surrounding it.

Excitation is by an 826nm pulsed laser diode operating at 10 MHz. Luminescence is collected through a single mode fibre connected to a spectrometer with a cooled silicon CCD camera at one output. We can study the spectra using the

CCD/spectrometer system and generate a PL intensity plot over the voltage range as seen in figure 1. Each horizontal line in the plot shows PL from a different initial exciton state. The labels correspond to the neutral exciton, X^0 , bi-exciton, $2X^0$, singly charged exciton, X^{1-} , and the two states of the doubly charged exciton, the triplet state, $X^{2-} T$, and the singlet state, $X^{2-} S$.

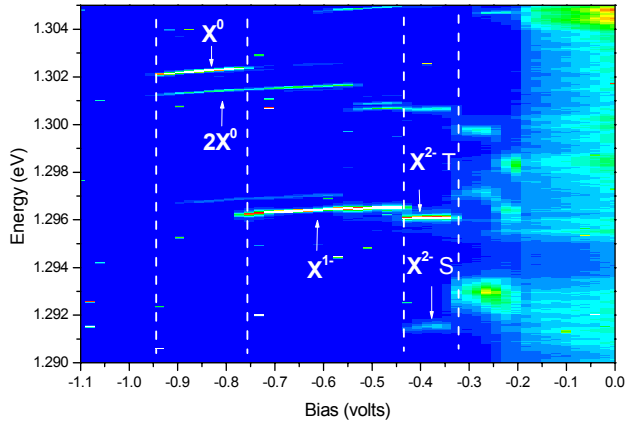


Figure 1: Contour plot of PL energy Vs Bias showing the charged exciton states as they turn on and off with applied voltage. Blue, green and yellow correspond to low, medium and high intensities. All the charged states of interest are noted, the neutral exciton (X), the singly charged exciton (X^1), the two states of the doubly charged exciton (X^{2-} Singlet – Dim and X^{2-} Triplet – Bright.) and the bi-exciton ($2X^0$).

TRPL measurements are carried out by time-correlated single photon counting with a single-photon avalanche photodiode (SPAD) at the second output of the spectrometer. By reconvoluting the instrumental response (full-width at half-max of 0.5ns) with the data lifetimes down to 0.1 ns can be fitted with reasonable accuracy.

The SPAD collects from a region corresponding to a 0.4 nm range from the spectrum, enough to look at just one of the exciton lines without any other close states interfering. We can therefore measure the lifetime at any voltage and for any state.

Results

The recombination lifetime was measured for the X^0 , X^{1-} , X^{2-} (Triplet and Singlet) and $2X^0$ state. A lifetime of 0.8 ± 0.1 ns was found for the X^0 state. The bi-exciton, $2X^0$, has a lifetime of $0.38 \text{ ns} \pm 0.1 \text{ ns}$ (figure 2). This shows strong evidence of the importance of selection rules in recombination when compared to the X^0 result. The other states all showed a similar lifetime of 1.0 ± 0.1 ns (figure 2).

It is believed this is slightly longer than the neutral exciton due to the difference in electron-hole wavefunction overlap of the charged states compared to the neutral exciton.

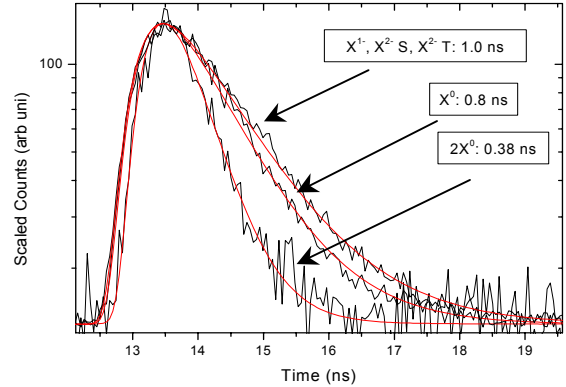


Figure 2: The raw TRPL data and reconvolution fits comparing all exciton states.

Conclusions

A single dot confocal microscope system has been extended to allow for TRPL measurements to be carried out on all charged exciton states in a single quantum ring. The results show that it is possible to study all of the charged states in a ring. This has opened up the possibility of much further work in the field and continuing measurements to help improve the understanding of quantum nanostructures.

References

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