Probing the local density of optical states in 2D-photonic crystal membranes

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Abstract: *Time-resolved spectroscopy is performed on ensembles of InAs/GaAs self-assembled quantum dots in photonic crystal membranes. The spatial distribution of the quantum dots in the photonic crystal gives rise to a distribution of the local density of optical states and hence a distribution of radiative decay rates. Accordingly, a non-single-exponential decay curve is expected and measured. However, the multi-level structure of each quantum dot adds to the complexity of the decay curves. Enhancement and inhibition of spontaneous emission are observed and compared to theoretical calculations.*

Introduction

Photonic crystal structures are interesting because of their ability to affect the dynamics of light/matter-interactions. The radiative lifetime of internal light sources can be modified [1], and also the spatial spontaneous emission pattern can be controlled [2]. These effects open up the possibility of constructing more efficient and compact devices such as LEDs [3], and the implementation of quantum information protocols in solid-state systems becomes more attractive [4].

The primary motivation for our research is to improve the basic understanding of the interaction between the quantum dots and the radiation field in the presence of a photonic crystal. In order to study the impact of the photonic structure, we have fabricated a number of photonic crystal membranes while systematically varying the geometry. We optically excite quantum dots within the membranes and detect the time-resolved luminescence decay.

It is a major challenge to deduce the physical understanding from such decay curves, which we observe to be non-single-exponential. This is a signature of the local density of optical states (LDOS), which varies for quantum dots at different positions inside the photonic crystal. Hence, we probe the luminescence decay from an ensemble of quantum dots with varying radiative lifetime, and our experiments present a systematic study of LDOS effects in 2D photonic crystal membranes. Also, the emission pattern is different for different positions inside the photonic crystal, and the fact that our experimental setup selects a certain detection solid angle may play a role in the detailed understanding of the decay curve. Many of these effects have been calculated theoretically in [5] by Koenderink *et al.*, and we will compare our experimental observations with these theoretical results. In addition to the above points, the internal structure of each quantum dot leads to bi-exponential decay curves in absence of the photonic crystal, and the understanding hereof is necessary to obtain the complete picture.

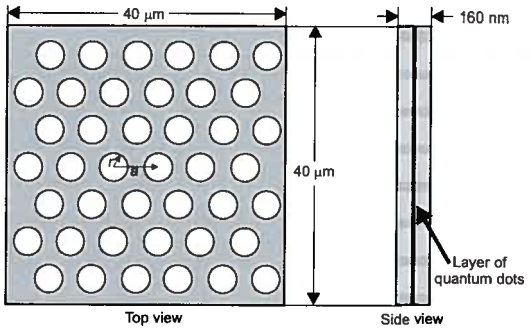

Fig. 1: Schematic view of a membrane (the size of the holes is exaggerated), defining the hole radius, r, and the lattice constant, a. The quantum dots are embedded in a central layer within the 160 nm thick membrane.

Fabrication of quantum dots and photonic crystal membranes

A schematic view of a photonic crystal membrane is shown in Fig. 1. The membranes are made from GaAs, and the dimension of each membrane is $40 \times 40\ \mu m^2$ with thickness 160 nm. Centered within the membrane is a layer of InAs quantum dots grown by molecular beam epitaxy. We observe the fluorescence from the lowest exciton state in the quantum dots, which is polarized in-plane with the membrane. The photonic crystal is made by etching a triangular hole structure with hole radius, r, and hole spacing, a. For all membranes in this experiment we have $r/a = 0.313 \pm 0.006$.

Experimental results

The photonic crystal samples are mounted inside a closed-cycle cryostat operated at $\approx$14 K. The optical setup is shown in Fig. 2. The time-resolved luminescence decay is measured for lattice constants, $a = 180, \ldots, 470$ nm in steps of 10 nm. All of these decay curves are shown together in Fig. 3.

Decay curves measured in absence of the photonic crystal structure are in general bi-exponential (we attribute this effect to the non-radiating dark exciton states, which populate the radiating bright exciton state by a spin flip). The decay curves shown in Fig. 3 are clearly non-single-exponential. This is an effect of probing ensembles of quantum dots with varying LDOS [6]. Separating out the pure LDOS effect from the internal structure of the quantum dots (and possibly

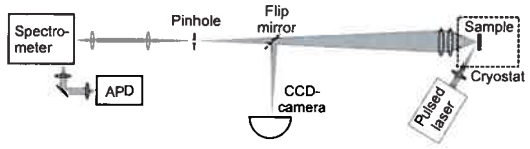

Fig. 2: The experimental setup. A Coherent Mira 900 ti:sapphire femto-second laser, running at wavelength $\lambda_{ex} = 757$ nm, is focused on a single photonic crystal membrane and excites a number of electron-hole pairs in the GaAs layer. These relax into bound exciton states inside the quantum dots, and the luminescence from the radiative recombination of the exciton ground state is detected at $\lambda_{em} = 983$ nm. A pinhole images the fluorescence from a 25 μm diameter circular disk of the central part of the $40 \times 40\,\mu m^2$ membrane onto the spectrometer and further on to an avalanche photo diode (APD). A CCD-camera is used for proper alignment and focusing.

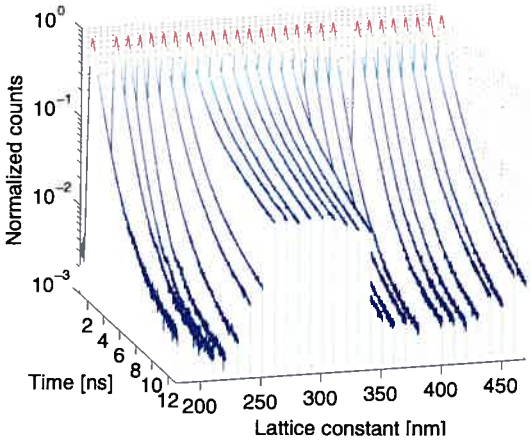

Fig. 3: All measured decay curves with background subtraction and normalized to the same initial value of unity. In the range $a = 270$ nm to 350 nm, the decay clearly extends to longer times compared to the remaining cases.

other effects) is a challenge and a topic of our current research. Hence, we will not attempt to explain the detailed shape of the decay curves here but instead treat a few pronounced features.

For each curve in Fig. 3, we extract the fastest and slowest decay rate by fitting the first and last part, respectively, to a straight line on the log-scale. The results are shown in Fig. 4 and we see a clear feature of the 2D photonic bandgap for lattice constants in the range $0.265 \leq a/\lambda_{em} \leq 0.345$. For the fastest rates, we compare the results to a reference value measured in absence of the photonic crystal (the blue line in Fig. 4). The fast decay rate inside the bandgap is below 70% of the reference value, and outside the gap it may be 30% higher than the reference value. The slowest decay rates (marked with red squares in Fig. 4) also show a pronounced bandgap feature.

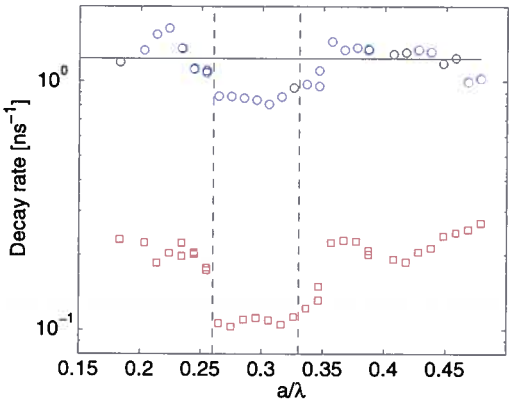

Fig. 4: The fastest (blue circles) and slowest (red squares) decay rates found by fitting the first and last parts of all decay curves shown in Fig. 3. On the horizontal axis is the lattice constant, a, normalized to the emission wavelength, $\lambda_{em} = 983$ nm. The blue line represents the fast decay rate in absence of the photonic crystal structure. The vertical dashed lines mark the bandgap edges predicted in [5].

We may compare these experimental observations with theoretical results derived in [5], where calculations are given for membranes with $r/a = 0.3$ and thickness 250 nm (compared to our values $r/a = 0.313$ and thickness 160 nm).

First of all, the photonic bandgap edges for in-plane polarized emission is calculated in [5] to be positioned at $a/\lambda = 0.26$ and 0.33. These limits are marked in Fig. 4 with vertical dashed lines and are seen to almost coincide with our experimental observations.

We may also compare the enhancement and inhibition of the decay curves. Inside the 2D band gap, the fastest rate is predicted to be less than 50% of the reference value. Outside the gap, the enhancement is predicted to be up to five times faster than the reference value. These predictions are more pronounced than our experimental observations. The reason for this is unknown at the moment, but it seems obvious that if the quality of the photonic crystal is non-perfect, radiation modes will be affected less and the emission properties of the quantum dots should be closer to the case of an isotropic medium. Note that simulated decay curves can be found in [5].

Conclusion

In conclusion, we have studied the effect of a photonic crystal structure on the fluorescence emission from quantum dots in thin membranes. The observed time-resolved luminescence decay curves show clear features of a 2D photonic bandgap, and the results are in general in agreement with predictions by Koenderink *et al.* [5], although the observed effects on the magnitude of the decay rates are less pronounced than expected. However, many quantitative details are still to

be understood and present a challenge for future work.

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References

[1] P. Lodahl *et al.*, Nature, vol. 430, p. 654, 2004.

[2] M. Fujita *et al.*, Science, vol. 308, p. 1296, 2005.

[3] K. J. Vahala, Nature, vol. 424, p. 839, 2003.

[4] C. Simon *et al.*, Phys. Rev. B, vol. 75, art. 081302(R), 2007.

[5] A. F. Koenderink *et al.*, J. Opt. Soc. Am. B, vol. 23, p. 1196, 2006.

[6] I. S. Nikolaev *et al.*, Phys. Rev. B, vol. 75, art. 115302, 2007.