Exciton dephasing in single InGaAs quantum dots

Leosson, Kristjan; Østergaard, John Erland; Jensen, Jacob Riis; Hvam, Jørn Marcher

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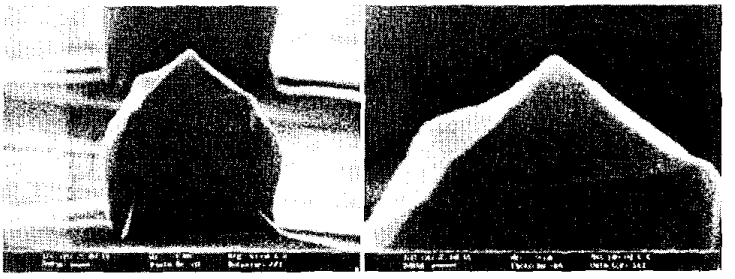
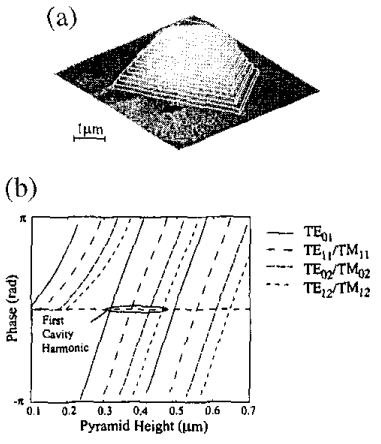


QTuA16 Fig. 1. SEMs of pyramids formed by re-growth on pre-patterned substrates. The top of the mesa structures clearly demonstrates stable {110} facet formation.



QTuA16 Fig. 2. (a) Pyramids are modeled by mode-matching stacked square waveguide sections. The modeling schematic is superimposed on an AFM image of a GaAs pyramid with a 2-μm base. (b) Reflection of modes impinging on the waveguide base is unitary because walls are assumed to be infinitely conducting. Local mode dispersion throughout the pyramid causes modal phase shifts.

1-μm size square mesas, orientated in the <010> direction on a GaAs (001) substrate. The mesas were formed by standard wet etching using H_3PO_4:H_2O_2:H_2O. The patterned samples were subsequently used as substrates for re-growth using MBE to deposit 0.5 μm of GaAs at a rate of 0.25 μm h^{-1} and a substrate temperature of 570°C. This resulted in uniform pyramidal structures with {110} type side-wall facets, as assessed by scanning electron microscopy and atomic force microscopy. Figure 1 shows a scanning electron micrograph (SEM) of a typical pyramidal structure.

Following early work on modelling of microwave devices,[3,4] we have applied the Mode Matching Method (MMM) to calculate the optical characteristics of pyramidal structures. MMM has recently been applied to VCSELs[5,6] of uniform cross section. When applied to pyramidal structures, MMM requires integration of selected thin waveguide sections to form an entire structure. Figure 2(a) demonstrates how slabs of square waveguide are selected. It is important to note that the high dielectric constant of the GaAs inhibits a scalar treatment of the electromagnetic field. Mode solutions of individual waveguide sections are referred to as local modes of a pyramid. The lateral size and material composition of each waveguide section govern the pyramid's local mode structure. A reduction in lateral size decreases the number of local modes.

The local modes are reflected at critical distances from a pyramid's base. We refer to these as *reflectance lengths*. Clearly, the reflectance lengths depend on dielectric contrast because this governs mode dispersion and the width of the pyramid base. Local mode analysis is simplified considerably if the pyramids are clad with metal. The assumption of infinite conductivity ensures that all modes are reflected without loss but with a mode-dependent phase shift. The modal reflection phase of four non-degenerate modes, (TE_{01}, TE_{11}/TM_{11}, TE_{02}/TM_{02} and TE_{12}/TM_{12}) local to the waveguide base, has been calculated using this assumption. Figure 2(b) shows the phase of the reflected modes, measured relative to the pyramid's base, against pyramid height for a wavelength of 1 μm.

The phase dependence of the modal reflection has interesting consequences for the design of microcavities incorporating a pyramidal structure in place of a DBR and light-emitting quantum wells or dots. Longitudinal modes, dispersed by the microcavity, are affected by the pyramid. The longitudinal cavity resonances are split into their constituent transverse modes. The transverse modes can be spectrally filtered providing the transverse splitting is greater than the spectral width of the internal light source. This effect is termed *mode filtration*.

The differences in modal reflectance length, measured along the zero phase line for the first pyramidal harmonic with respect to the fundamental mode, are ≈ 53 nm (TE_{11}/TM_{11}), 96 nm (TE_{02}/TM_{02}) and 125 nm (TE_{12}/TM_{12}). When coupling to a radiation source, spectral splittings are: $\Delta\lambda \approx 15$ nm, 27 nm and 35 nm. These are greater than the typical luminescence line widths of quantum wells. This demonstrates that transverse mode filtration of the longitudinal cavity mode should be possible.

We have demonstrated a method for the fabrication of sub-micron scale optical structures, which could be used to form a novel type of optical micro-cavity. The phase of light reflected from a pyramidal structure is mode dependent. Modes are reflected at characteristic reflectance lengths within a pyramid. Light emitted from within a microcavity formed using one pyramidal reflector and one Bragg mirror can only couple into the resonant modes of the cavity. The phase-dependent reflection property suggests that there could be just one transverse mode for the light to couple into thus providing full three-dimensional confinement of photonic states.

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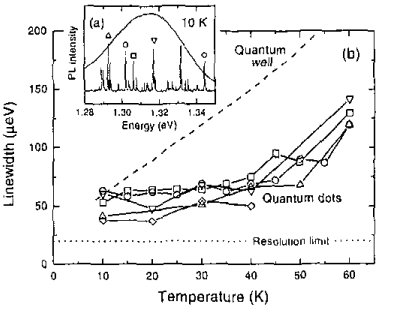
QTuA17

Exciton dephasing in single InGaAs quantum dots

K. Leosson, J. Erland, J.R. Jensen, J.M. Hvam, *Research Center COM, Technical Univ. of Denmark, DTU Building 349, DK-2800 Lyngby, Denmark; E-mail: kl@com.dtu.dk*

The homogeneous linewidth of excitonic transitions is a parameter of fundamental physical importance. In self-assembled quantum dot systems, a strong inhomogeneous broadening due to dot size fluctuations masks the homogeneous linewidth associated with transitions between individual states. The homogeneous and inhomogeneous broadening of InGaAs quantum dot luminescence is of central importance for the potential application of this material system in optoelectronic devices.[1] Recent measurements of MOCVD-grown InAs/InGaAs quantum dots indicate a large homo-



QTuA17 Fig. 1. (a) Macroscopic and microscopic photoluminescence spectra of InGaAs quantum dots. (b) Homogeneous linewidth (FWHM) of luminescence lines marked with corresponding symbols in the inset. The dashed line represents the homogeneous linewidth measured in narrow InGaAs quantum wells.

geneous broadening at room temperature due to fast dephasing.[2] In the present work, we investigate the low-temperature homogeneous linewidth of individual PL lines from MBE-grown $In_{0.5}Ga_{0.5}As$/GaAs quantum dots.

Figure 1(a) shows the 10-K photoluminescence spectrum of an ensemble of $In_{0.5}Ga_{0.5}As$/GaAs quantum dots (broad peak) excited with a He-Ne laser focused to a 50-μm spot size. In order to resolve individual PL lines, we used a microscope objective located inside the cryostat to excite and detect the luminescence from a 0.5-μm area. The PL was dispersed in a 2-m Littrow spectrometer and detected with a cooled CCD array. The spectral resolution of the detection system was 20 μeV. At 10 K, a distribution of linewidths was found, ranging from 20 to 200 μeV and peaking at 40–50 μeV. The radiative lifetime of InAs/GaAs quantum dot ground state is of the order of a nanosecond,[3] corresponding to only a few μeV of lifetime broadening. We therefore attribute the measured linewidth to a short dephasing time, typically around 30 ps.

A further reduction of the number of dots within our detection area was obtained by defining mesas with electron-beam lithography and wet etching. A sharp-line luminescence spectrum from a 200-nm diameter mesa is shown in Fig. 1(a). Here, the sample was excited with 50 μW of cw light from a Ti:Sapphire laser below the bandgap of the GaAs barrier material. We selected several PL lines at different energies with widths close to the peak of the linewidth distribution. The intensity of the selected lines is proportional to the excitation power up to about 0.5 mW, where it saturates. The linewidth depends only weakly on excitation intensity, increasing 20% per decade.

The temperature dependence of the linewidth is shown in Fig. 1(b). A linear increase of about 0.5 μeV/K is observed at low temperatures. This is significantly lower than the approximately 2-μeV/K thermal broadening observed in narrow InGaAs quantum wells,[4] indicated by the dashed line in the figure. We attribute this decrease to reduced acoustic phonon coupling due to the discrete level structure of the dots. Above 50 K, the homogeneous linewidth increases rapidly. Similar behavior has been observed for quantum well excitons localized by width fluctuations[5] but in this case the onset of thermal activation is close to 20 K, reflecting the smaller level spacing in this system.

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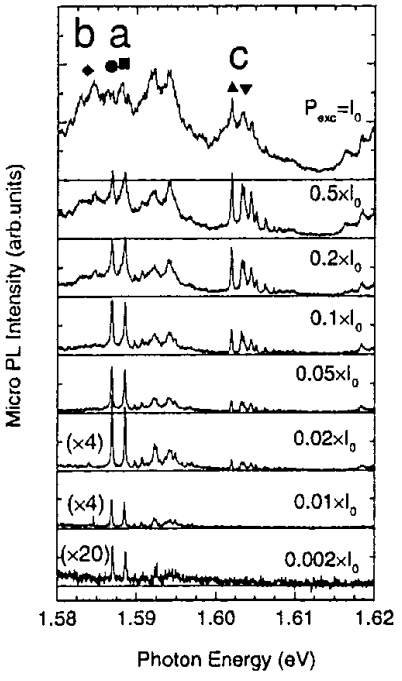
QTuA18

Micro-photoluminescence of single GaAs/A1GaAs quantum dots grown on a (411)A GaAs surface

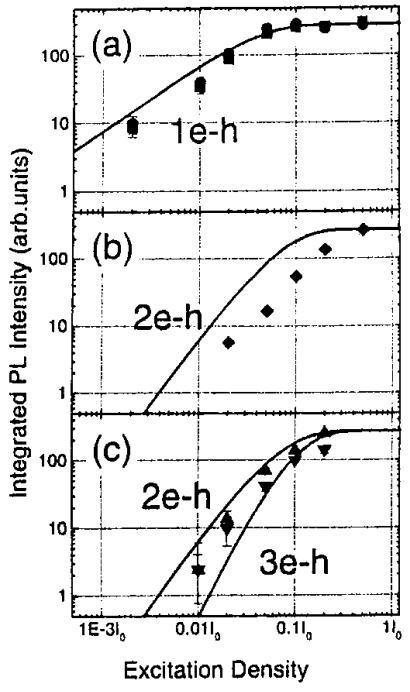
C. Watatani, K. Edamatsu, T. Itoh, H. Hayashi, S. Shimomura, S. Hiyamizu, *Graduate School of Engineering Science, Osaka Univ., Toyonaka 560-8531, Japan; E-mail: eda@mp.es.osaka-u.ac.jp*

Recent development of micro-photoluminescence (μ-PL) spectroscopy has enabled us to observe photoluminescence from a single quantum dot, which has sharp homogeneous linewidth[1] and long coherence time.[2] In this paper, we report on the μ-PL spectra of single GaAs/A1GaAs quantum dots grown on a (411)A surface of a GaAs substrate. We have observed sharp luminescence lines originating not only from the lowest state of the confined exciton, but also from the excited states depending on the excitation power density.

Our QD sample is based on a strain-free GaAs/A1GaAs quantum well grown on a (411)A GaAs surface. Under a certain growth condition with a relatively small As flux, triangular-pyramidal structure was grown on the surface.[3] By growing a quantum well over the pyramid, thicker area of the well is formed on a slope of the pyramid. This area behaves as a QD in which the excitons are confined. The density of the pyramid is as low as 10^7 cm^{-2}, so that we can resolve the luminescence from a single pyramid with a conventional objective lens. The μ-PL measurement was made with the second harmonic light of the CW mode-locked Ti:Sapphire laser (wavelength ~395 nm, pulse width~10 ps, 80 MHz) as the excitation source. By using the picosecond pulses, multiple excitons are easily created in a QD under relatively small mean excitation power. Figure 1 shows the μ-PL spectra for various excitation power densities. At low excitation density, mainly two sharp lines, indicated by (a), are observed. The spectral widths of these lines are ~140 μeV. With increasing excitation density, additional bunches of lines are grown on the lower and higher energy sides, as indicated by (b) and (c), respectively. Figure 2 represents the intensities of lines (a), (b) and (c), depending on the excitation power density. The lines (a) grow linearly with increasing excitation at low density, and saturate at higher density. On the other hand, lines (b) and (c) grow superlinearly up to moderate excitation density. Thus, it is expected that the lines (a) originate from the lowest single exciton state in a QD, and lines (b) and (c) originate from the states including two or three excitons in a QD. Solid curves in Fig. 2 represent the theoretical population probabilities of the QDs that include one, two, and three excitons (e-h pairs), assuming the initial Poisson distribution and succeeding cascade annihilation of the excitons. The model fairly reproduces the experimental result. Considering the energy difference from the lines (a), it is expected that the lines (b) originate from



QTuA18 Fig. 1. Micro photoluminescence spectra of GaAs/A1GaAs quantum dots at 3.3 K excited by a picosecond laser pulses. Excitation power density for I_0 is 28 W/cm^2 = 350 nJ/cm^2 pulse.



QTuA18 Fig. 2. Excitation power density dependence of the luminescence intensities. Graphs (a), (b) and (c) correspond to the lines indicated by the same letters in Fig. 1.