Comparison of radiative properties of InAs quantum dots and GaInNAs quantum wells emitting around 1.3 µm

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

Comparison of radiative properties of InAs quantum dots and GaInNAs quantum wells emitting around 1.3 μm

A. Markus,[a] A. Fiore, J. D. Ganière, U. Oesterle, J. X. Chen, B. Deveaud, and M. Ilegems

Institute of Quantum Electronics and Photonics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

H. Riechert

Corporate Research, Infineon Technologies, CPR 7, 81730 München, Germany

The emission properties of self-assembled InAs quantum dots (QDs) and lattice-matched GaInNAs quantum wells (QWs) emitting around 1.3 μm were investigated by temperature-dependent and time-resolved photoluminescence (PL). The QDs have much higher PL efficiency at low excitation, but saturate faster as the excitation is increased, due to the lower density of states. Lifetime measurements show that nonradiative recombination plays a more important role in the GaInNAs QW than in QDs. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1447595]

Optical gain materials that enable long wavelength (1.3 and 1.55 μm) amplification and emission on GaAs substrates are attractive for the realization of temperature insensitive lasers and vertical cavity surface emitting lasers. The most promising materials are GaInNAs quantum wells (QWs)[1] and InAs quantum dots (QDs).[2] However, the physics involved into these two approaches is quite different. In the $Ga_{1-x}In_xN_yAs_{1-y}$ system the addition of a small concentration of nitrogen leads to a dramatic redshift of the band gap energy[3–5] and allows one to tune the host material to the desired wavelength. With the appropriate x/y concentrations the quaternary material can be lattice matched to GaAs.[6] On the other hand, in InAs QDs the difference in lattice parameter between GaAs and InAs results in the formation of coherently strained three dimensional InAs islands,[7–11] which partly relaxes the elastic energy and delays the appearence of dislocations. The electronic states in these self-assembled islands then strongly depend on their size[12] and shape and on the strain field around them.[13] To lower the transition energy, the QDs can be embedded in an InGaAs QW, which leads to lower quantum confinement, to reduced strain[14] in the QDs and to an increase in height of the QDs due to spinoidal activated decomposition.[15]

In this letter we investigate the radiative properties of identical structures of both materials under the same experimental conditions. The comparison allows us to present evidence of the role of the density of states and defects, two key parameters of laser performance. Both samples were grown by molecular beam epitaxy and consist of a single active layer: InAs QDs covered by 5 nm of InGaAs, or a 6 nm $Ga_{1-x}In_xN_yAs_{1-y}$ QW ($x=0.36, y=0.015$), both embedded in a 200 nm GaAs matrix. The areal dot density of the QD sample is 3×10^{10} cm^{-2}, derived from transmission electron microscopy (TEM) measurements. Both samples have thin AlAs barriers on both sides of the active region. Details of growth are given elsewhere.[16,17]

The effect of temperature T on the continuous wave (cw) photoluminescence (PL) of both samples is shown in Fig. 1. For the PL experiment the samples were excited with a Ti:sapphire laser system tuned to 800 nm. At low excitation density $G=20$ W/cm^2 on the InAs QD sample (see the inset of Fig. 1, solid lines) a peak can be observed at low temperatures with a transition energy of 1.01 eV, which redshifts at room temperature to 0.94 eV ($\lambda=1.31$ μm). The GaInNAs PL (dashed lines) is peaked at 1.04 eV at 4 K and at 0.97 eV ($\lambda=1.27$ μm) at room temperature ($G=110$ W/cm^2). Note that a much stronger PL signal is obtained from the QDs at low excitation density. The two materials exhibit quite different temperature dependences. In the range of 5 K$<T$ <100 K the integrated intensity of the QW decreases dramatically (Fig. 1, dashed lines), whereas the value for the QDs stays more or less constant (solid lines). Due to higher carrier localization inside the QDs, nonradiative recombination becomes important only above 100 K.

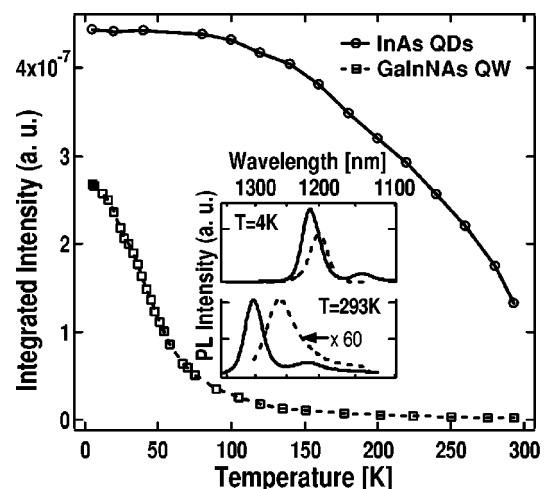In order to investigate the role of the different density of

FIG. 1. Temperature dependence of the PL integrated intensity of the GaInNAs QW (dashed line) and the InAs QDs (solid line). The inset shows PL spectra from both samples at $T=4$ K and at room temperature.
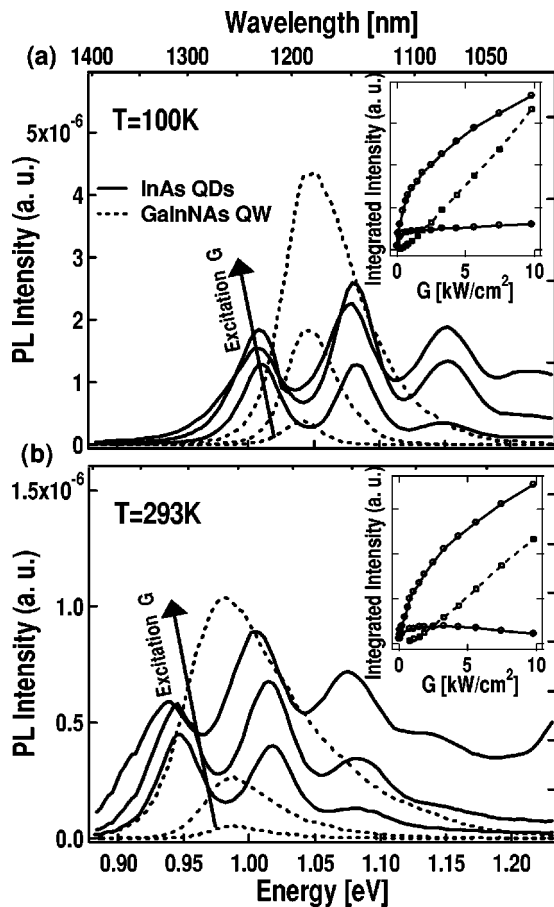
[a]Electronic mail: alexander.markus@epfl.ch

FIG. 2. PL from the GaInNAs QW (dashed line) and the InAs QDs (solid line) at three different excitation densities $G = 200$, 1500 and 9800 W/cm^2 (a) at $T = 100$ K and (b) at room temperature. The insets show the integrated intensity of the GaInNAs QW peak (dashed line), of the total InAs QDs spectra (upper solid line) and of the InAs QDs ground state peak (lower solid line) as a function of the excitation density.
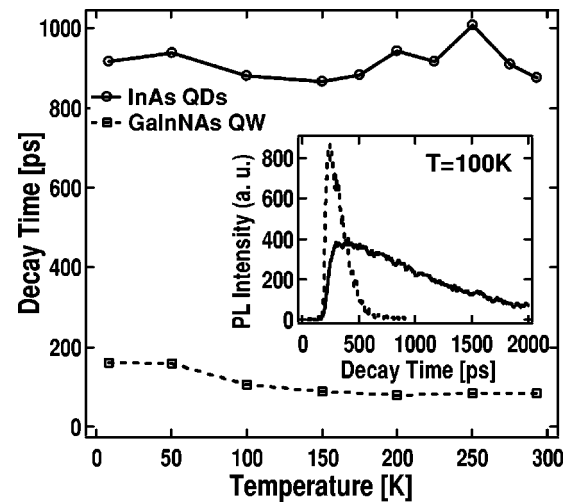

FIG. 3. Temperature dependence of the lifetimes of the GaInNAs QW (dashed line) and the InAs QDs (solid line). The inset shows the decay curve of both samples at $T = 100$ K.

states in the luminescence of the two materials, we measured PL spectra at high excitation densities [Fig. 2(a) at 100 K and Fig. 2(b) at room temperature]. At 100 K and at $G = 200$ W/cm^2 a small PL signal from GaInNAs [Fig. 2(a), dashed lines] was detectable. At that excitation of the InAs QD sample (solid lines) three peaks are observed that correspond to three energy states. The appearance of excited states in the spectrum is clear evidence of population saturation in the ground state, due to the limited density of states. As the power is increased, the peak height of the QW increases superlinearly with the pump power, whereas the QDs' ground state peak only increases slightly. Furthermore, the peak intensities of the QDs' first and second excited state transitions gain factors of up to 1.9 and 6.7, respectively. Obviously the available QD ground states are already nearly filled and only higher energy states can contribute to a higher PL intensity. That behavior becomes more evident in the inset of Fig. 2(a), which correlates G with the integrated PL intensity. The dashed line refers to the GaInNAs QW, and the lower solid line curve to the QDs' ground state peak only, as deduced from a Gaussian fit, and the upper solid line curve takes into account all available states in the QDs. While the ground state emission is almost completely saturated at $G = 1000$ W/cm^2, the total amount of QD emission shows sublinear growth, indicating that population of the excited states

and the wetting layer leads to increased nonradiative recombination. Note that the full width at half maximum (FWHM) of the GaInNAs PL lines increases with the excitation density (from 50 to 97 meV at room temperature), due to the increasing population of high energy states.

Time-resolved photoluminescence was used to obtain information about the dynamics of interband radiative recombination. The experiment was performed by exciting the sample with a 100 MHz, 8 ps pulsed Ti:sapphire laser with an average excitation density of $G = 370$ W/cm^2, and detecting the PL with a Hamamatsu streak camera with an infrared-enhanced photocathode. The time-dependent trace for both samples at a temperature of 100 K at the PL maximum is shown in the inset of Fig. 3. The decay part of each curve was empirically fitted on a single exponential function in order to extract a decay time constant. The QDs' ground state showed larger deviations from single exponential decay than the QW due to refilling effects from higher energy states. The time constants obtained at different temperatures at the PL maximum are displayed in Fig. 3. For QDs we find a lifetime of about 900 ps, constant over temperature within experimental error. The QW lifetimes decrease with the temperature from 180 to 80 ps, indicating an increase in nonradiative recombination. Unlike the QDs the QW shows a strong energy dependence of the decay time. Figure 4 depicts the variation of the QW decay times detected at different energy positions relative to the respective PL maximum for different temperatures. The decay time strongly varies with the energy, particularly at low T. This is strong evidence of carrier localization. At lower thermal energies carriers are trapped in localized potentials with longer lifetimes. The occurrence of these localized exciton states is likely due to In–N clusters, leading to lower levels (tails) in the density of states of the QW, as already reported.[18–20] When the temperature is increased carriers gain enough thermal energy to populate the free exciton states in the QW with a shorter lifetime. Progressive carrier transfer from localized exciton states to free exciton states leads to less variation of the decay times. However, compared to in the case in Ref. 18, in the sample under investigation the deviation in lifetimes is
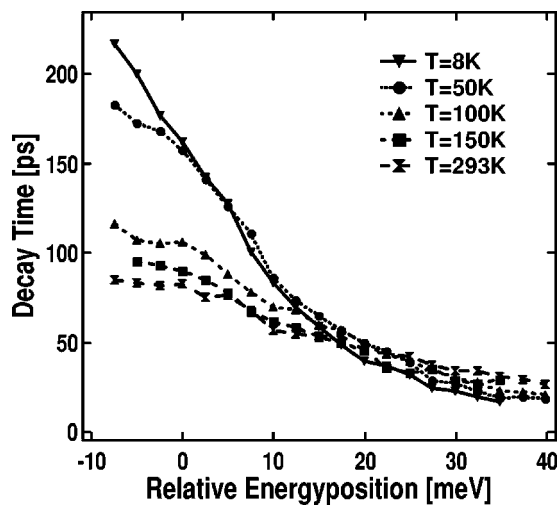
FIG. 4. Energy dependence of the GaInNAs QW decay times at various temperatures. The energy axis indicates the energy position relative to the PL spectral peak at each temperature.

rather small, indicating comparatively good interfaces.

In conclusion, temperature-dependent and time-resolved photoluminescence experiments were employed to compare the radiative properties of self-assembled QDs and lattice-matched GaInNAs QWs. The QDs were shown to be a better material with respect to PL efficiency and radiation lifetime. But the drawback of QDs is the lower density of states, leading to PL saturation even at low excitation densities. In particular, at excitation densities where no PL signal from GaIn-NAs was detectable, the QD ground state transition was found to already be nearly saturated. The lifetime observed in QDs is around 900 ps, for the temperature of helium a factor of 11 higher than in the GaInNAs QW. Also the more rapid decrease of the integrated intensity of the QW at low temperatures shows that nonradiative recombination is more important in the QW. This explains the high threshold current densities of GaInNAs lasers (5.8 kA/cm^2 in 800 μm long laser cavities fabricated from this material). Finally, in the QW indications of carrier localization were found, deduced from the energy dependent lifetimes and temperature-dependent FWHM of the PL line.

[1] M. Kondow, K. Uomi, A. Niwa, T. Kitatani, S. Watahiki, and Y. Yazawa, Jpn. J. Appl. Phys., Part 1 **35**, 1273 (1996).

[2] D. L. Huffaker, G. Park, Z. Zhou, O. B. Shchekin, and D. G. Deppe, Appl. Phys. Lett. **73**, 2564 (1998).

[3] W. Shan, W. Walukiewicz, J. W. Ager III, E. E. Haller, J. F. Geisz, D. J. Friedman, J. M. Olson, and S. R. Kurtz, Phys. Rev. Lett. **82**, 1221 (1999).

[4] H. P. Xin and C. W. Tu, Appl. Phys. Lett. **72**, 2442 (1998).

[5] E. D. Jones, N. A. Modine, A. A. Allermann, S. R. Kurtz, A. F. Wright, S. T. Tozer, and X. Wie, Phys. Rev. B **60**, 4430 (1999).

[6] L. Bellaiche, Appl. Phys. Lett. **75**, 2578 (1999).

[7] L. Goldstein, F. Glas, J. Y. Marzin, M. N. Charasse, and G. Le Roux, Appl. Phys. Lett. **47**, 1099 (1985).

[8] D. Leonard, K. Pond, and P. M. Petroff, Phys. Rev. B **50**, 11687 (1994).

[9] M. Grundmann, N. N. Ledentsov, R. Heitz, L. Eckey, J. Christen, J. Boehrer, D. Bimberg, S. S. Ruvimov, P. Werner, U. Richter, J. Heydenreich, V. M. Ustinov, A. Yu. Egorov, A. E. Zhukov, P. S. Kopev, and Zh. I. Alferov, Phys. Status Solidi B **188**, 249 (1995).

[10] S. Farad, R. Leon, D. Leonard, J. L. Merz, and P. M. Petroff, Phys. Rev. B **52**, 5752 (1995).

[11] T. Walther, A. G. Cullis, D. J. Norris, and M. Hopkinson, Phys. Rev. Lett. **86**, 2381 (2001).

[12] K. H. Schmidt, G. Medeiros Ribeiro, J. Garcia, and P. M. Petroff, Appl. Phys. Lett. **70**, 1727 (1997).

[13] A. J. Williamson, L. W. Wang, and A. Zunger, Phys. Rev. B **62**, 12963 (2000).

[14] N.-T. Yeh, T.-E. Nee, J.-I. Chyi, T. M. Hsu, and C. C. Huang, Appl. Phys. Lett. **76**, 1567 (2000).

[15] M. V. Maximov, A. F. Tsatsul'nikov, B. V. Volovik, D. A. Bedarev, A. E. Zhukov, A. R. Kovsh, N. A. Maleev, V. M. Ustinov, P. S. Kop'ev, Zh. I. Alferov, R. Heitz, N. N. Ledentsov, and D. Bimberg, Physica E **7**, 326 (2000).

[16] A. Fiore, U. Oesterle, R. P. Stanley, R. Houdré, F. Lelarge, M. Ilegems, P. Borri, W. Langbein, D. Birkedal, J. M. Hvam, M. Cantoni, and F. Bobard, IEEE J. Quantum Electron. **37**, 1050 (2001).

[17] A. Yu. Egorov, D. Bernklau, D. Livshits, V. Ustinov, Zh. I. Alverov, and H. Riechert, Electron. Lett. **35**, 1643 (1999).

[18] A. Kaschner, T. Lüttgert, H. Born, A. Hoffmann, A. Yu. Egorov, and H. Riechert, Appl. Phys. Lett. **78**, 1391 (2001).

[19] L. Grenouillet, C. Bru-Chevallier, G. Guillot, P. Gilet, P. Duvaut, C. Vannufel, A. Million, and A. Chenevas-Paule, Appl. Phys. Lett. **76**, 2241 (2000).

[20] A. Polimeni, M. Capizzi, M. Geddo, M. Fischer, M. Reinhardt, and A. Forchel, Phys. Rev. B **63**, 195320 (2001).