Optimization of highly strained InGaAs quantum wells for 1.3−µm vertical−cavity lasers

P. Sundgren [1], J. Berggren [1], M. Hammar [1]

1) Department of Microelectronics and Information Technology, Royal Institute of Technology (KTH), Electrum 229, S−16440 Kista, Sweden

Abstract

We report on the optimization process of highly strained InGaAs quantum wells (QWs) grown by metalorganic vapor−phase epitaxy. Low growth temperature (520°C) in combination with low growth rate (0.12 nm/s) is found to be beneficial for the QW quality. Photoluminescence blueshift and improved wavelength uniformity are observed when annealing QWs with photoluminescence wavelengths near or above 1.2 µm. Such QWs have been implemented in high−performance vertical−cavity surface−emitting lasers with room−temperature emission wavelength up to 1.30 µm.

Introduction

The interest in 1.3−µm active material on GaAs during recent years is first−hand motivated by its potential role in realizing 1.3−µm vertical−cavity surface−emitting lasers (VCSELs), but also for edge−emitting lasers with improved temperature stability as compared to InP−based ones. Both VCSELs and edge−emitting lasers at 1.3 µm have been demonstrated with GaInNAs quantum wells (QWs), but there are still concerns regarding reliability and growth control in this material system [1]. A simpler material system and an alternative to GaInNAs, is highly strained InGaAs QWs. To date, InGaAs QWs with photoluminescence at 1.30 µm has not been achieved. However, using large gain−cavity detuning and InGaAs QWs with photoluminescence (PL) at 1190 nm, we have demonstrated very promising VCSELs with emission wavelengths up to 1.26 µm [2]. While this wavelength in principal is sufficient to meet important datacommunication standards, such as 10 Gb/s Ethernet [3], improved device performance and/or extended emission wavelength would benefit from QWs with gain maximum at longer wavelength.

Schlenker et al. found that the degradation of low−temperature grown highly strained InGaAs QWs is due to growth−mode transition from two− to three−dimensional growth, which can be postponed with high growth rate, high V/III ratio and low growth temperature [4]. On the other hand, V/III ratios as low as 5 have been used in one of the best reports on InGaAs−QW edge−emitting lasers above 1.2−µm emission wavelength [5]. Other results on InGaAs QWs include edge−emitting laser emission up to 1230 nm and PL up to 1270 nm but the issue of nununiformity, important in large−scale production, is generally not discussed [6, 7, 8].

In this work, we investigate how the properties of highly strained InGaAs QWs depend on different growth parameters and thermal annealing. A high quality of the QWs is demonstrated by implementation in high−performance VCSELs with emission wavelengths up to 1.30 µm. [9]

Growth optimization

The samples were grown by metal−organic vapor−phase epitaxy (MOVPE) in an Aixtron 200/4 reactor, using TEGa, TMIn, TBAs and AsH_3 as precursors for the InGaAs QWs. Except where mentioned, the QW growth rate was 0.12 nm/s and both As sources were used simultaneously with AsH_3/III = 298 and TBAs/III = 136. The samples were normally annealed at 690°C for 10 minutes. The growth temperatures were calibrated using an Al/Si eutectic. The QW width and strain were obtained from simulating and fitting high−resolution x−ray diffraction

(HRXRD) rocking curves. Measured and simulated HRXRD spectra of a 6.5−nm $In_{0.426}GaAs$ DQW, as for instance used in the VCSELs discussed below, are shown in Figure 1.

Thin (4 nm) double QWs (DQWs) have been grown under different conditions. The strain is plotted as function of the nominal In/III ratio in figure 2. Even for these thin QWs it seems difficult to reach above a strain corresponding to 42.5% In, i.e. the same strain as in the 6.5−nm thick DQW used in the presented VCSELs below. In other words, decreasing the thickness of the QWs does not necessarily imply that the strain can be increased even though the integrated strain is lower.

In figure 3 the PL−peak intensities of InGaAs SQWs are plotted as functions of the growth temperature. The intensity is more or less constant from 510°C to 530°C but it drops rapidly at higher growth temperatures. At 540°C, the intensity is not uniform and the point in figure 3 corresponds to the average value.

Figure 4 shows a PL comparison between the InGaAs quantum used in our first generation of 1.3−µm VCSELs [2] and for more recent and improved devices [9]. Also included is the PL of a 1240−nm InGaAs single QW (SQW), which is the longest wavelength we have achieved so far. A clear improvement in maximum PL intensity as well as uniformity is obtained with the optimized growth parameters. The growth rate was decreased from 0.81 to 0.12 nm/s and according to the above experiment the temperature was reduced from 540°C to 520°C. In contrast to what is usually believed, a lower growth rate seems to be beneficial for the QWs, although it should be mentioned that the samples have slightly different strain and QW thickness.

We have also investigated the use if $GaAsP_x$ (x = 0.12 and 0.24) strain compensating barriers and $In_{0.2}GaAs$ intermediate layers. While this presumably is of importance for the realization of multiple−QW structures, it was not found to have a significant positive effect on our single and double InGaAs QWs. Further optimization of the strain compensation and/or intermediate layers may however lead to an improving effect.

Annealing

Several wafers with highly strained InGaAs SQWs and DQWs were grown. The samples were held at 520°C for 6 minutes during the 100−nm GaAs−cap growth. After growth the wafers were cleaved and the different pieces were post−growth annealed for 10 minutes at 630, 690 or 760°C. Figure 5 shows how the room−temperature PL−peak wavelength is shifted with annealing for a SQW. A striking observation in this figure is that there is only a small difference between the samples annealed at 630 and 690°C, while both of them has more than 20 nm blueshift compared to the as−grown sample. The other annealed highly strained QWs exhibited similar blueshifts.

The measured PL wavelength was compared to the wavelength calculated from the QW width and strain. Abrupt interfaces were assumed. The strain in the QW is not significantly reduced for an annealing temperature of 690°C or lower but the estimated thickness is increasing slightly with annealing temperature. Assuming that the strain is proportional to the In content, we have estimated the PL emission wavelength, which is plotted in figure 5. While the annealed samples follows the measured trend, a clear deviation from the measured PL wavelength is observed for the as−grown sample. Hence, the assumption with abrupt interfaces and homogeneous composition is not entirely correct and the blueshift cannot be fully understood by simple out−diffusion of In.

Other issues with these highly strained QWs are non−uniformities in both PL−peak wavelength and intensity. These non−uniformities are only present at very high strains, corresponding to PL wavelengths near or beyond 1200 nm, depending on the growth parameters. During annealing, the PL−peak wavelength becomes much more uniform while the intensity non−uniformity remains.

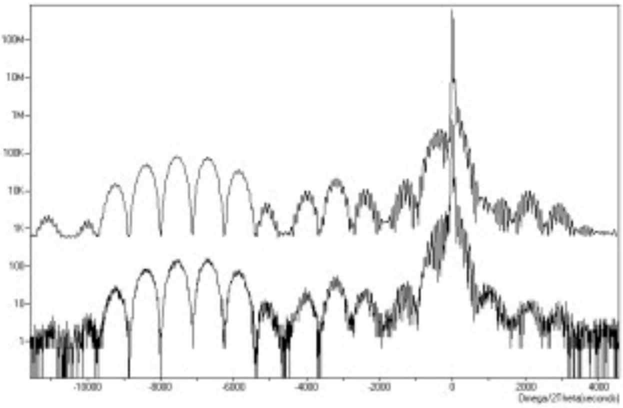

Figure 1. Simulated (upper curve) and measured (lower curve) HRXRD (004) reflection of a 6.5-nm $In_{0.426}GaAs$ DQW.

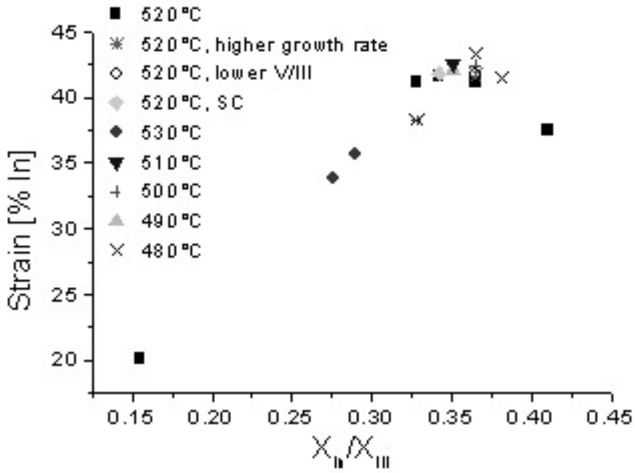

Figure 2. Strain as a function of In/III ratio for different growth conditions.

VCSEL results

A 6.5−nm $In_{0.426}GaAs$ DQW grown at 520°C with PL−peak wavelengths up to 1204 nm and a full−width at half maximum below 27 meV was included in monolithically grown VCSELs with n− and p−doped AlGaAs/GaAs DBRs. Selective oxidation of a 40−nm AlAs layer was used for current and mode confinement. Figure 6 shows the single−mode output power around 1.27−µm and forward bias versus the injection current for a device with a 4−µm oxide−aperture diameter. Notably, the maximum output power exceeds 1.0 and 0.6 mW at 10 and 90°C, respectively. From another wafer, VCSELs with even larger detuning had an emission wavelength of 1.30 µm at room temperature. More details will be published elsewhere [9].

Conclusion

Improved quality of highly strained InGaAs QWs was obtained with reduced growth rate and temperature, but the properties of these QWs and the effects of annealing are not fully understood. The excellent performances of the presented lasers show that this concept is a strong candidate for commercial 1.3−µm VCSELs and provides a motivation for further development of InGaAs QWs towards longer emission wavelength.

The European IST: GIFT program and the Swedish Foundation for Strategic Research (SSF) supported this work. Petrus Sundgren acknowledge financial support from Agilent Technologies. Zarlink Semiconductor is acknowledged for the VCSEL processing.

1. M. Hammar, C. Asplund, P. Sundgren, S. Mogg, U Christiansson, T. Aggerstam, V. Oscarsson, C. Runnström, E. Ödling, and J. Malmquist, “1300−nm GaAs−based vertical−cavity lasers”, Proc. SPIE Photonics Fabrication Europe, 28 October − 1 November, 2002 (vol. 4942), Brugge, Belgium

2. C. Asplund, P. Sundgren, S. Mogg, M. Hammar, U. Christiansson, V. Oscarsson, C. Runnström, E. Ödling and J. Malmquist, “1260−nm InGaAs vertical−cavity lasers”, Electron. Lett. **38** (13), 635 (2002)

3. IEEE P802.3ae, “10 Gb/s Ethernet”, IEEE Standards Department, 2002

4. D. Schlenker, T. Miyamoto, Z. B. Chen, M. Kawaguchi, T. Kondo, E. Gouardes, F. Koyama, and K. Iga, “Critical layer thickness of 1.2−µm Highly strained GaInAs/GaAs quantum wells”, J. Cryst Growth **221**, 503 (2000)

5. T. Takeuchi, Y.−L. Chang, A. Tandon, D. Bour, S. Corzine, R. Twist, M. Tan, and H.−C. Luan, “Low threshold 1.2 µm InGaAs quantum well lasers grown under low As/III ratio”, Appl. Phys. Lett. **80** (14), 2445 (2002)

6. F. Bugge, M. Zorn, U. Zeimer, T. Sharma, H. Kissel, R. Hülsewede, G. Erbert, and M. Weyers, ”Highly strained very high−power laser

diodes with InGaAs QWs", J. Cryst Growth **248**, 354 (2003)
7. T. Kondo, M. Arai, A. Onomura, T. Miyamoto, and F. Koyama, "1.23µm long wavelength highly strained GaInAs/GaAs quantum well laser", Proc. IEEE Lasers & Electro−Optics Society Annual Meeting, November 11−14, 2002, Glasgow, UK, p. 618
8. S. Mogg, G. Plaine, C. Asplund, P. Sundgren, K. Baskar, M. Mulot, R. Schatz, and M. Hammar, "High−performance 1.2−µm highly strained InGaAs/GaAs quantum well lasers", Proc. 14th Indium Phoshpide and Related Materials Conference May 12−16, 2002, Stockholm, Sweden p. 107
9. P. Sundgren, R. Marcks von Würtemberg, J. Berggren and M. Hammar, M. Ghisoni, V. Oscarsson, E. Ödling, and J. Malmquist. To be published.

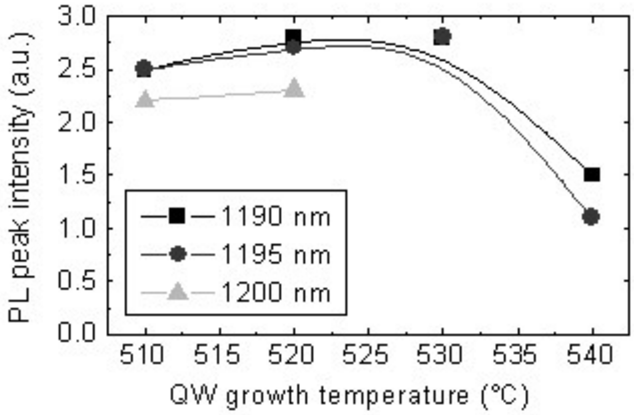

Figure 3. PL-peak intensity for different growth temperatures.

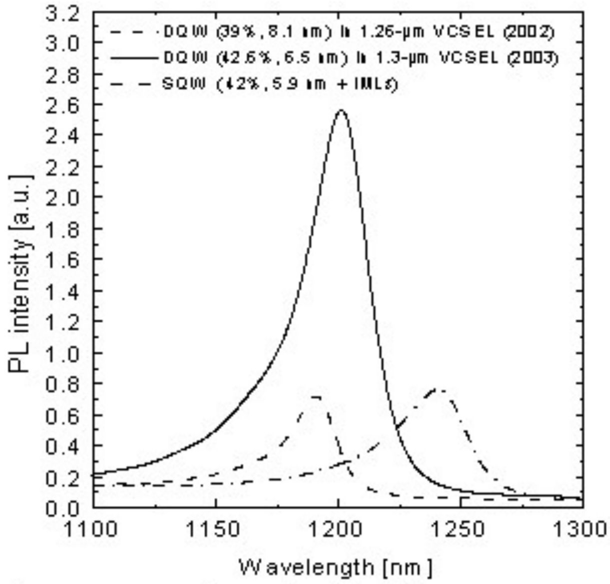

Figure 4. Comparison of PL for different InGaAs QWs. Two of the QWs are used in VCSELs.

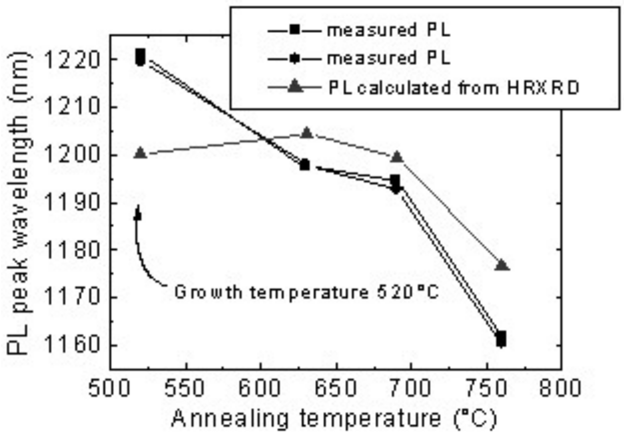

Figure 5. PL-peak wavelength dependence on annealing temperature. The annealing time was 10 minutes except for the as-grown samples, which were kept at 520°C for 6 minutes during the GaAs-cap growth.

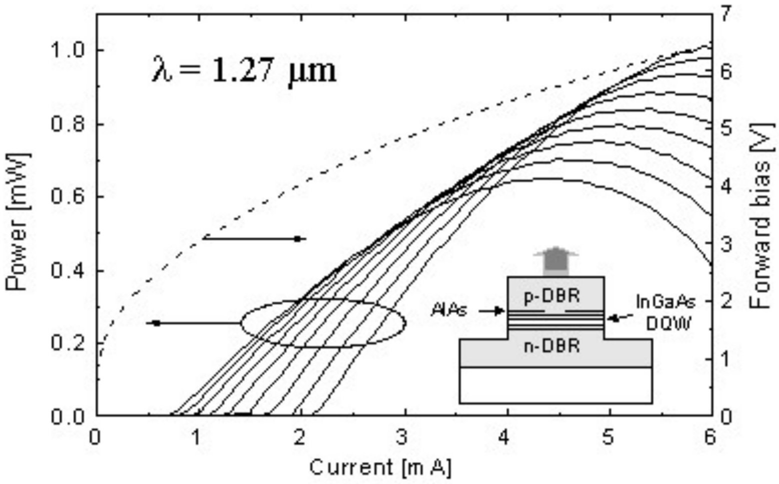

Figure 6. Single-mode light output power and voltage versus injection current in the 10-90°C temperature range for a 1.27-µm VCSEL. The side-mode suppression ratio is larger than 30 dB over the entire operating range in drive current and stage temperature. Due to the negative gain-cavity offset the threshold current is continuously decreasing with temperature. [9]