AIP Applied Physics Letters

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Citation: Applied Physics Letters **85**, 1904 (2004); doi: 10.1063/1.1794379
View online: http://dx.doi.org/10.1063/1.1794379
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/85/11?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 11 13 SEPTEMBER 2004

Optical properties of InP/GaInP quantum-dot laser structures

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(Received 30 April 2004; accepted 19 July 2004)

We have grown InP quantum dots with different rates and on substrates with different orientations. The growth conditions have a major influence on the form of the gain spectrum. Using a high growth rate on a 10° off (100) substrate we obtain a broad gain spectrum due to contributions from a bimodal dot size distribution whereas a sample containing mostly small dots, produced using (211)B substrates, has a narrower gain spectrum centered at a shorter wavelength of ~700–710 nm. The modal gain saturates at a magnitude significantly smaller than the modal absorption, nevertheless the measured values of modal gain are sufficient to sustain laser action, and structures grown at high growth rate on 10° off (100) substrates are capable of providing laser devices operating in the region of 750 nm. © *2004 American Institute of Physics.*

[DOI: 10.1063/1.1794379]

In recent years, self-assembled quantum dots have attracted much interest for laser applications due, in part, to predictions of improvements in terms of threshold current, a reduced threshold current temperature dependence, and increased differential gain. Real quantum dot lasers are affected by dot size and composition fluctuations and considerable optimization and understanding is necessary to realize enhanced performance. Quantum dot lasers have been explored extensively in the InAs/GaAs system because they emit around the technologically important wavelength 1.3 μm and in this material system, a record low cw threshold current density of 19 A cm^{-2} has been achieved.[1] In addition it has been shown that quantum dot lasers can have broad gain spectra, which are of interest for applications such as continuously tunable sources[2] and extremely short pulse generation.[3]

InP dots in GaInP have also aroused interest,[4–6] motivated by the potential benefits of dots in general and, specifically, by the possibility of extending the upper-wavelength limit of conventional, compressively strained, GaInP quantum wells from 690 nm to the region of 750 nm for growth on GaAs substrates. In this letter we report the results of an investigation of the photoluminescence (PL) and optical gain properties of InP/GaInP quantum dot structures for different growth rates and for growth on vicinal (100) and (211)B GaAs substrates.

InP quantum dots were grown in an AlGaInP matrix lattice matched to GaAs by low pressure metalorganic vapor phase epitaxy (MOVPE) at temperatures between 650 and 690 °C and with a vapor phase group V:III of ≈170. GaAs substrates were used with the growth surface of (211)B, and of (100) the latter misorientated by either 3° towards [110] or 10° towards [111]. For initial PL studies the dot material was formed by depositing between 0.5 and 4 monolayers (ML) at growth rates of 0.4, 1.3, and 2.5 ML per second. InP has a lattice parameter which is 3.7% larger than GaAs and nucleates in the Stranski–Krastanow mode. The full layer structures comprised 300 nm of $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ grown on a GaAs buffer layer followed by three layers of dots, each separated by 5 nm of $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$, covered by a further 300 nm of $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ and finally capped by 25 nm of $Ga_{0.51}In_{0.49}P$. Transmission electron microscopy (TEM) images showed that formation of quantum dots took place for a critical thickness of ≈1.6 ML and above.

Photoluminescence measurements taken at room temperature for 1.6 ML of InP deposited on $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ are shown in Fig. 1 for various substrate orientations: we ascribe minor peaks to emission from AlGaInP and the GaInP cap as indicated, and the major peak to emission from the dots. The peak wavelength of emission from the $Ga_{0.51}In_{0.49}P$ changes from ≈670 nm for the sample grown on (100) substrate orientated 3° towards [110] to ≈650 nm for the samples grown on (211)B substrates or substrates misorientated 10° towards [111], as has been documented for a change from ordered to disordered material.[7] For the sample grown on (100) substrate orientated 3° towards [110] there is also evidence for the ordered phase of $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ at ≈610 nm and a splitting in the emission from the dots in the region 760–780 nm. The presence of such structure in the dot PL could arise from effect of the difference in band gap of ordered or disordered barrier material on the confined energy states in the InP dots.

In addition to the structure due to order/disorder that occur for the samples grown on the different (100) surfaces, there is a much larger difference in the wavelength of the dominant dot emission peak in Fig. 1 between (211)B and (100) substrates. This behavior has been reported before[8,9] and in Ref. 9 a peak separation of 51 nm was attributed to two sets of InP dots of different sizes. We observe a similar peak separation of 50 nm between dots grown on disordered material using (211)B substrates (peak emission at 710 nm) and using (100) substrates misoriented 10° towards [111] (peak emission is at 760 nm). The previous study[9] demonstrated that the proportion of dots of the two different sizes depended on the growth conditions, including growth temperature, growth rate, and the degree to which the substrate

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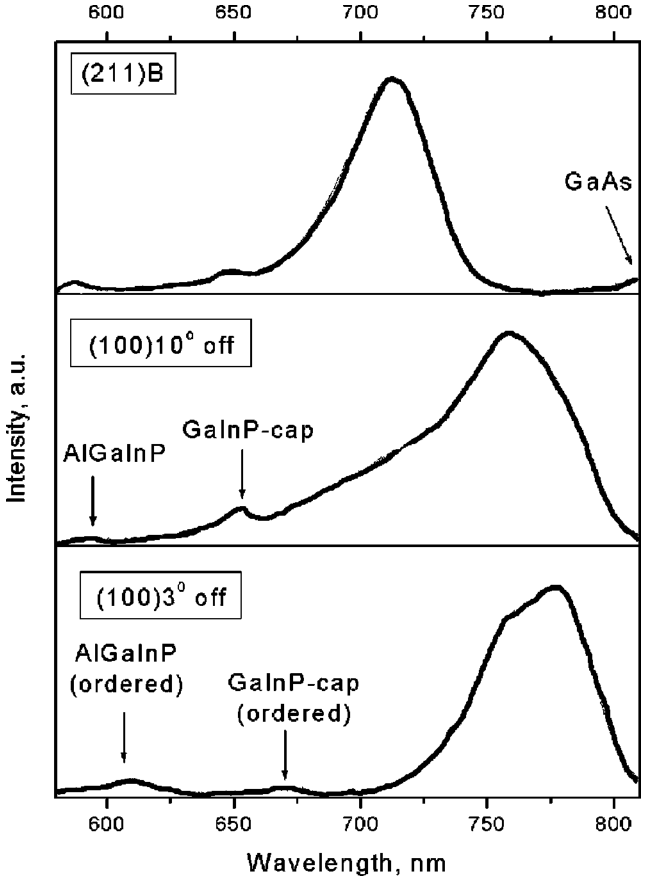

FIG. 1. Room temperature photoluminescence spectra of multilayer InP/AlGaInP structures with a nominal layer thickness of 1.6 ML and grown at 0.4 ML/s on (211)B, 3° off and 10° off (100) towards [111] GaAs substrates.

was misorientated from (100). For different quantities of InP deposited and for different InP deposition rates on the (211)B and the (100) substrates misoriented 10° towards [111], which both give disordered material, we observe consistently two emission peaks centered at about 710 and 760 nm with the relative intensities depending on growth conditions. In previous work[9] long wavelength emission was present for (100) and low off angle substrates with short-wavelength emission dominant for (100) substrates misorientated 10° or 15° towards [111]. Our 10° substrate spectra have emission from both dot sizes and it is necessary to use the (211)B substrates to achieve the shorter wavelength emission associated with dots of smaller size. We believe this is because we have only examined relatively high growth temperatures that are consistent with the relatively straightforward growth of highly *p*-doped laser cladding layers and which were previously shown to favor large dot formation.[9]

Laser heterostructures based on the GaInP/AlGaInP system were grown by MOVPE on substrates misoriented 10° off (100) towards [111] and on (211)B GaAs substrates. The active dot material was formed by depositing 2 ML of InP either at 0.8 monolayers per sec (labeled as low growth rate) or at 2.5 monolayers per sec (shown as high growth rate) on $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ and then covering the dots with 8 nm of $Ga_{0.51}In_{0.49}P$. This pattern was repeated five times, separated by 8 nm $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ barriers. The overall waveguide core width was 275 nm and the cladding layers were 1 μm wide layers of $Al_{0.51}In_{0.49}P$. Photoluminescence spectra exhibit two major peaks centered at about 710 and 760 nm for the 10° off (100) substrate, which is again consistent with a bimodal distribution of dot sizes.

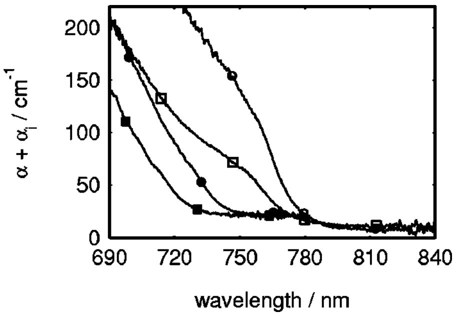

FIG. 2. TE polarized net modal absorption spectra for low −0.8 ML/s (squares) and high—2.5 ML/s (circles) growth rate samples grown on 10° off (100) towards [111] (open symbols) and (211)B (closed symbols) GaAs substrates.

Net modal absorption spectra were measured using a waveguide transmission experiment.[10] Net modal absorption spectra for four samples with high and low growth rates and for growth on 10° off and (211)B GaAs substrates measured at 300 K for light polarized in the plane of the dots layers (TE) are shown in Fig. 2. At long wavelength the net modal absorption tends to the value of the internal optical mode loss, α_i. For growth on 10° off (100) substrates α_i values of 7 and 11 cm^{-1} were obtained for the high and low growth rates, respectively, and a higher internal optical mode loss of 20 cm^{-1} was measured for both (211)B structures.

The absorption spectra are extremely similar to those observed for InGaAs dots emitting in the 1 μm band with large inhomogenous broadening, where the absorption spectrum has an absorption edge at long wavelengths but the individual ground and excited state transitions cannot be clearly defined.[11] As we might expect, the 10° off samples exhibit absorption at longer wavelengths with a feature that corresponds to the larger dots at about 750–760 nm compared to the (211)B samples where there is minimal absorption at wavelengths longer than 740 nm for the high growth rate sample and minimal absorption beyond 730 nm for the low growth rate sample. The measurement clearly shows that a larger optical absorption can be obtained from the higher growth rate quantum dots and even for the low growth rate dots on 10°-off substrates the modal absorption (α_m) is as large as 55 cm^{-1} at wavelengths corresponding to the large dots (internal mode loss α_i of 11 cm^{-1} subtracted from the total measured absorption $\alpha_m + \alpha_i$ of 66 cm^{-1}). The value of modal absorption obtained by subtracting the value of α_i gives the magnitude of the maximum achievable modal gain if the system can be fully inverted. For the 10° off samples this modal absorption is 55 and 123 cm^{-1} for low and high growth rates, respectively, at a wavelength of 750 nm. The (211)B samples have modal absorption of 45 and 110 cm^{-1} for low and high growth rate samples, respectively, at a wavelength of 710 nm.

The optical gain was measured from single-pass amplified spontaneous emission using a segmented-contact oxide-stripe device.[10] TE polarized modal optical gain spectra taken on the high growth rate sample grown on the 10° off (100) substrate as a function of drive current density at 175 and 300 K are shown in Fig. 3. The gain spectra are broad with gain being achieved over a typical spectral width of 90 nm at 300 K. This gain arises from transitions within the

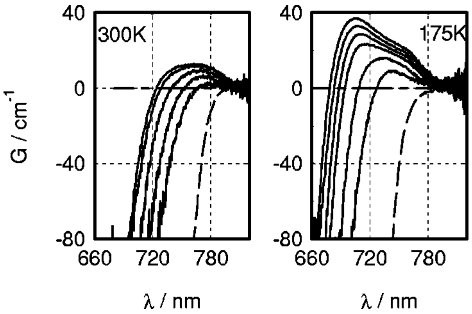

FIG. 3. TE polarized modal gain for injected current densities of 0.4–4 kA/cm^2 measured at temperatures of 175 and 300 K for the high growth rate sample on 10° off (100) substrate.

larger group of dots of the bimodal distribution with perhaps some influence on the short wavelength side of the spectrum from the smaller group of dots being apparent at the highest drive current. In the 175 K gain spectra a second peak is apparent on the short wavelength side at higher injection levels, which we believe is due to the smaller group of dots in the bimodal distribution of dot sizes. Positive gain of about 15 cm^{-1} is achieved in the region of 750 nm at room temperature with higher gains realized at the lower temperature. The highest gain we achieve is significantly below the value of absorption measured at this wavelength for this sample. Similar results have previously been observed for InGaAs quantum dot laser material where this behavior is ascribed to incomplete inversion of all the available dot states.[12] We believe this is also true of the InP dots in the present work.

In Fig. 4 we plot examples of gain spectra at room temperature for the high growth rate on 10° off (100) substrates and for the low growth rates on (211)B substrates. Measurements on the structure grown at a low rate on a 10° off (100) substrate, not shown in Fig. 4, show a reduction in the absorption with increasing drive current density but very little (1–2 cm^{-1}) gain. Data for the high growth rate on (211)B substrate (not shown in Fig. 4) is similar to that of the low growth rate on (211)B (shown in Fig. 4) but with a peak gain at slightly shorter wavelength than the low growth rate data are consistent with the absorption data for these two samples in Fig. 2. The gain spectrum shown for the high growth rate on 10° off (100) substrate sample [the same data as the highest current density spectrum (4 kA cm^{-2}) in Fig. 3] and covers a large wavelength range which probably encompasses emission from both large and small dots. Two gain spectra for the low growth rate sample grown on (211)B are plotted for current densities of 667 and 1000 A cm^{-2}. The peak of the gain from the low injection sample coincides with the short wavelength part of the gain spectrum of the 10° off axis substrate sample further supporting the idea that the room temperature gain curve for the 10° off axis substrate sample is so broad because it includes emission from both dot sizes. The peak of the gain spectrum for the higher current density spectrum measured for this sample is shifted to shorter wavelength and for the same peak gain as was achieved for the 10° off axis substrate sample the gain spectrum is much narrower, presumably because the larger dots are not present in this sample.

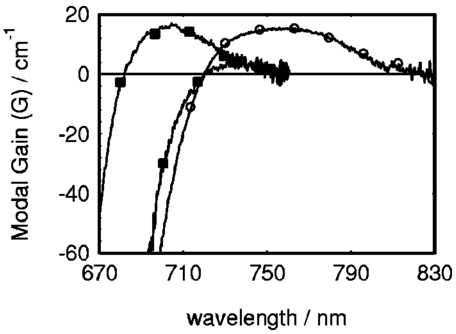

FIG. 4. TE polarized modal gain spectra measured at room temperature for low 0.8 ML/s growth rate on (211)B GaAs substrate (solid squares) and high 2.5 ML/s growth rate samples grown on 10° off (100) towards [111] GaAs substrate (open circles).

In summary we have grown InP quantum dots with different growth rates and on substrates with different orientations. We find that the growth conditions have a major influence on the form of the gain spectrum. Using a high growth rate on a 10° off (100) substrate we obtain a broad gain spectrum, up to 90 nm at 300 K, due to contributions from a bimodal dot size distribution whereas a sample containing mostly small dots, produced using (211)B substrates, has a narrower gain spectrum centred at a shorter wavelength of ~700–710 nm. In common with InAs dots we find that the modal gain saturates at a magnitude significantly smaller than the modal absorption, suggesting that the InP dot system is not fully inverted at high injection. The measured values of modal gain are sufficient to sustain laser action, and structures grown at high growth rate on 10° off (100) substrates are capable of providing laser devices operating in the region of 750 nm.

The authors acknowledge the financial support of the UK EPSRC under Grant No. GR/N21888/01.

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