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Walker, C.L., Sandall, I.C., Smowton, P.M. et al. (4 more authors) (2005) The role of high growth temperature GaAs spacer layers in 1.3-/spl mu/m In(Ga)As quantum-dot lasers. IEEE Photonics Technology Letters, 17 (10). pp. 2011-2013. ISSN 1041-1135

https://doi.org/10.1109/LPT.2005.854393

The Role of High Growth Temperature GaAs Spacer Layers in 1.3-μm In(Ga)As Quantum-Dot Lasers

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***Abstract*—We investigate the mechanisms by which high growth temperature spacer layers (HGTSLs) reduce the threshold current of 1.3-μm emitting multilayer quantum-dot lasers. Measured optical loss and gain spectra are used to characterize samples that are nominally identical except for the HGTSL. We find that the use of the HGTSL leads to the internal optical mode loss being reduced from 15 $\pm$ 2 to 3.5 $\pm$ 2 cm^{-1}, better defined absorption features, and more absorption at the ground state resulting from reduced inhomogenous broadening and a greater dot density. These characteristics, together with a reduced defect density, lead to greater modal gain at a given current density.**

***Index Terms*—Optical gain, optical loss, quantum dots (QDs), semiconductor lasers.**

SEMICONDUCTOR lasers using quantum-dot (QD) active regions offer many performance advantages compared to quantum-well devices [1]. Self-assembled In(Ga)As QD lasers on GaAs substrates are of particular importance as they have great potential for optical fiber communications in the wavelength range 1.3–1.6 μm using GaAs-based technology. However, QD active regions have a relatively low available modal gain, typically for 1.3-μm emitting devices of the order of 2–9 cm^{-1} per layer [1], [2]. Multiple QD layers are necessary to achieve sufficient modal gain for ground state lasing for a number of applications. However, stacking multiple QD layers modifies the growth of subsequent layers, which in the extreme results in defect formation as a consequence of the increasing amount of strained material deposited. Solutions include strain compensation [3], [4], removal of the largest dots by selective evaporation [5], and the use of high growth temperature spacer layers (HGTSLs) between QD sheets, which have recently been demonstrated to greatly enhance device characteristics in multilayer 1.3-μm In(Ga)As QD lasers [6], [7]. This letter describes the measurement of gain and loss of five-layer QD laser material with and without HGTSLs to reveal the mechanisms responsible for this improvement.

The InAs–$In_{0.15}Ga_{0.85}As$ dot-in-a-well (DWELL) devices were grown by solid source molecular beam epitaxy on 3$''$ n$^+$ (100) GaAs substrates; full details of device growth are covered elsewhere [6]. Five-layer DWELL devices were grown with and without HGTSLs; the only difference between each design was the growth temperature of the spacer layer. The DWELL consists of 3.0 monolayers of InAs grown on 2 nm of $In_{0.15}Ga_{0.85}As$ and capped by 6 nm of $In_{0.15}Ga_{0.85}As$. The DWELL layers are separated by 50-nm GaAs spacer layers. For the devices without HGTSLs, the growth temperature of the GaAs spacers was 510 °C, the same temperature used for growth of the InAs QDs and InGaAs quantum well. For the HGTSL devices, the spacer has an initial 15 nm of GaAs grown at 510 °C followed by a 35-nm HGTSL grown at 580 °C, with the temperature reduced back to 510 °C for the growth of the next DWELL. No additional special efforts were made to smooth the surface after the first QD layer growth. Both structures are incorporated within a GaAs–$Al_{0.40}Ga_{0.60}As$ waveguide structure.

Previous characterization of these samples has revealed an extremely low continuous-wave threshold current density for a five-layer sample of 39 Acm^{-2} emitting at 1.307 μm [6], [7]. Using transmission electron microscopy, it was shown that the samples containing HGTSLs had a dislocation density reduced from $\sim 10^9$ to below 10^6 cm^{-2}[6], [7]. Atomic force microscopy (AFM) measurements of the surface above a layer of QDs for non-HGTSL material revealed subnanometer surface roughness on a length scale $\leq$50 nm, thought to be caused by low surface mobility of the Ga atoms grown at 510 °C. Incorporation of the HGTSL removes this surface roughness, demonstrating that increasing the growth temperature of the GaAs spacer layer was sufficient to smooth the surface, a result of the increased Ga atom mobility. The reduced dislocation density achieved using the smoother HGTSL growth should lead to reduced nonradiative recombination. However, in this letter, we will show that the differences in performance are not just due to reduced nonradiative recombination. This is important because the additional mechanisms may affect all QD lasers where the growth surface is not fully planarised and may be present even though the gross effects due to defect formation are remedied by some other approach.

In QD structures, the optical gain can be limited due to the limited number of states available for inversion and due to the incomplete population of these states. Therefore, both the optical losses, which determine the quantity of gain necessary to reach threshold, and the number and distribution of states available for inversion are critical. Here we evaluate the advantages of the HGTSL structure in these respects using the edge-emitted amplified spontaneous emission segmented contact method [8] for gain and loss measurements. Devices were characterized using

Manuscript received April 28, 2005; revised June 21, 2005. This work was supported by the U.K. Engineering and Physical Sciences Research Council (EPSRC) under Grant GR/S49308/01, and by the European Commission GROWTH Programme NANOMAT Project under Contract G5RD-CT-2001-00545.

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Digital Object Identifier 10.1109/LPT.2005.854393

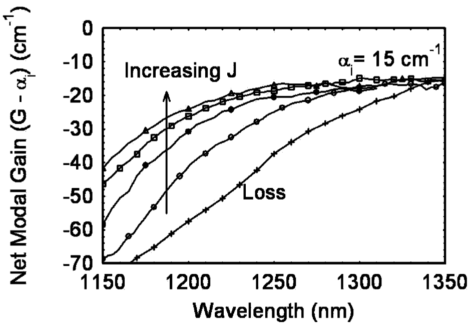

Fig. 1. Measured net modal gain spectra at 300 K for the sample without HGTSLs. The lowest curve is measured using the passive loss experiment, where the section under test is not electrically driven, and the remaining spectra are for drive current densities (J) of 286, 715, 952, and 4280 Acm^{-2}. At long wavelength, the net modal gain tends to the value of internal optical mode loss, α_i, $= 15 \pm 2$ cm^{-1}.

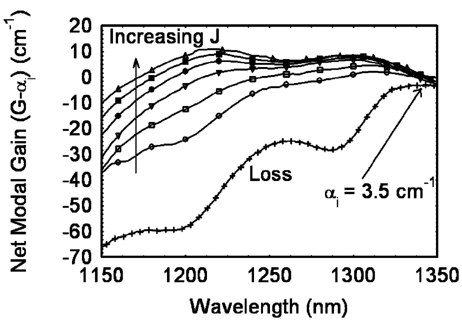

Fig. 2. Measured net modal gain spectra at 300 K for the sample with HGTSLs. The lowest curve is measured using the passive loss experiment, where the section under test is not electrically driven, and the remaining spectra are for drive current densities (J) of 76, 152, 228, 304, 381, and 457 Acm^{-2}. At long wavelength, the net modal gain tends to the value of internal optical mode loss, α_i, $= 3.5 \pm 2$ cm^{-1}.

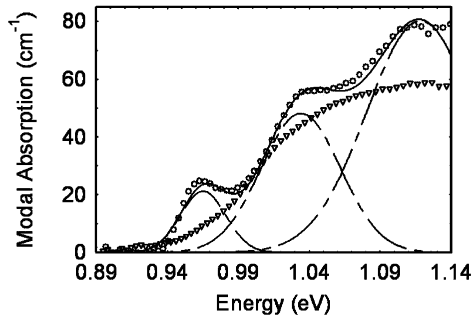

Fig. 3. Measured modal absorption spectrum (plotted as a function of energy) for the HGTSL sample (circles) and the non-HGTSL sample (triangles). The solid line is a fit to the HGTSL data using three Gaussian curves (dashed lines) that represent three inhomogenously broadened QD transitions. The fitting parameters are the area, width, and center energy of the Gaussian distributions.

400-ns pulses at 1 kHz. Fig. 1 shows net modal gain spectra (gain positive and loss negative) at 300 K as a function of applied current density for the device without the HGTSLs. Insufficient modal gain is available for lasing at 300 K with transparency not being achieved even at the highest current density used (4280 Acm^{-2}), which is consistent with the fact that lasing was only achieved in these devices up to 190 K [6]. Fig. 2 shows net modal gain spectra at 300 K for the device with HGTSLs. Two peaks are apparent in the gain spectra corresponding to the dot ground and excited state transitions. As the drive current density is increased, the maximum gain is obtained at wavelengths corresponding to the ground state up to a net modal gain $(G\text{-}\alpha_i)$ of ~8 cm^{-1}. At higher current density, the gain maximum moves to wavelengths corresponding to the excited state transition. Lasers with mirror loss of 8 cm^{-1} (corresponding to a 1500-μm-long device with uncoated facets) or less would lase on the ground state. The differences in the net modal gain spectra are the underlying reason for the better performance of lasers fabricated from the HGTSL material. To understand the origins of the differences in the gain spectra, we focus on the lowest curve in each of Figs. 1 and 2, which are measurements of the negative gain (or optical loss) spectrum, where there is no electrical injection to the section under test [8].

Comparison of the loss data (no electrical injection) for both structures, which at long wavelengths tends to the value of α_i, demonstrates that α_i is reduced from 15 ± 2 cm^{-1} to 3.5 ± 2 cm^{-1} for the HGTSL device. This difference is presumably due to a combination of additional surface roughness and the presence of defects in the sample without the HGTSL. Although any additional α_i in other non-HGTSL samples may be less pronounced, even differences of only 1–2 cm^{-1}, which are probably not resolvable by any existing technique of measuring α_i, are important in dot structures where the available gain is limited.

In addition, the loss spectra, which at shorter wavelengths reflect the absorption of the dots, also have a different shape indicating a significant change in QD formation. To allow a more detailed comparison of the absorption, the lowest curves in Figs. 1 and 2 are replotted in Fig. 3 in terms of loss (negative gain) with the values of α_i subtracted from the data. In these absorption spectra (which are also plotted over a wider range), peaks for the QD ground state and next two higher energy states are apparent for the HGTSL device, whereas the spectrum for the device without HGTSLs lacks clear features. This is consistent, as we shall show below, with more uniform dot formation (reduced inhomogenous broadening) being achieved with the HGTSL.

To confirm that the differences in the absorption spectra can be explained by differences in the inhomogenous broadening, we fit the spectra with Gaussians with each Gaussian representing an inhomogenously broadened transition in the QDs. In Fig. 3, we show the results of fitting the experimental HGTSL absorption data with these Gaussian curves. The best fit is obtained with Gaussians centered at 0.965, 1.033, and 1.117 eV and with inhomogenous broadening characterized with values for sigma of 16, 28, and 38 meV. In Fig. 4, we show the results of fitting the experimental non-HGTSL absorption data (the loss data with the internal optical mode loss subtracted) with Gaussian curves centered at the same energies as for the HGTSL sample. The inhomogenous broadening and the total area under all the Gaussian curves are treated as fit parameters. The best fit to the data is obtained with values for sigma of 30, 35, and 55 meV and with the total quantity of absorption (area under all the Gaussian curves) reduced by a factor of 1.6 as compared to the HGTSL case. The simplest explanation for the total quantity of absorption being reduced is that the total number of

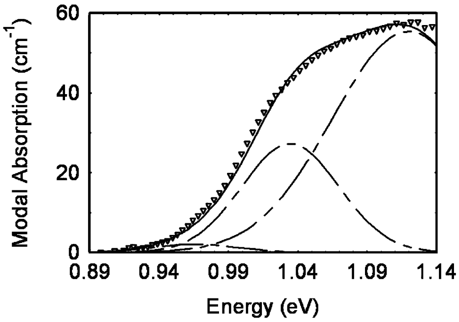

Fig. 4. Measured modal absorption spectrum for the sample without HGTSLs (triangles). The solid line is a fit to the data using three Gaussian curves (dashed lines) that represent three inhomogenously broadened QD transitions.

dots within the non-HGTSL sample is reduced by a factor of 1.6, for which there is some supporting evidence from AFM measurements. Although results inferred from AFM measurements on uncapped structures should be treated with caution because of changes that can occur during cool down, fewer dots have been observed for the non-HGTSL structure [7].

Overall, the absorption measurements reveal an increased dot density and a reduced inhomogenous broadening in the samples with the HGTSL. In addition, the sample with the HGTSL has a lower internal optical mode loss. These three effects lead to an increased net modal gain for a given injection level and together with a reduced defect density, which leads to less nonradiative recombination, explain the results in Figs. 1 and 2 where more gain is observed at any given drive current density for the HGTSL structure.

In summary, we have demonstrated that 1.3-μm In(Ga)As QD laser material incorporating HGTSLs has a low internal optical loss, with α_i reduced from 15 $\pm$ 2 cm^{-1} to 3.5 $\pm$ 2 cm^{-1}. The absorption spectrum for devices with HGTSL exhibits less inhomogenous broadening and we suggest that the quantity of dots present in the sample without HGTSL is reduced, based on the reduction by a factor of 1.6 in the magnitude of the absorption. These mechanisms, and the reduced defect density that has previously been observed in HGTSL samples, lead to a larger gain at a given current density for lasers fabricated from the HGTSL material. In future work, the inclusion of HGTSL should allow the inclusion of more DWELL layers to increase the available modal gain, without the negative effects of defect formation, increased α_i, a reduced dot density, and increased inhomogenous broadening. The measurements also suggest that, even when other approaches are used to reduce the defect density, care should be taken to planarise the surface before the growth of dots.

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