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Gain saturation in InP/GaInP quantum-dot lasers

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We have measured the gain-current and gain-quasi–Fermi level separation characteristics for InP/AlGaInP quantum-dot-laser structures. Saturation of the gain-current characteristics is apparent even though photoluminescence excitation spectroscopy measurements indicate that the 2D states are energetically distant from the dot states. The gain is reduced from the maximum value by the distribution of carriers in the excited dot states, the states in smaller dots and the 2D states. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1844600]

In this letter we examine the saturation of the gain-current characteristics of laser structures emitting around 750 nm and fabricated from material containing InP dots grown on $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ lattice matched to GaAs. We have previously reported that the gain, although sufficient for a working laser, is limited in this material system[1] and investigate the origin of this effect. It has recently been suggested that for InGaAs dots the gain might be low because of incomplete population inversion of the available states due to the presence of excited dot states[2] or the wetting layer.[3] We find that for the InP dots grown on $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ the wetting layer is difficult to detect being either absent or distanced in energy from the dots. This provides an opportunity to investigate the gain saturation process in this system where the wetting layer is absent to examine the conclusions of Ref. 3. We find that gain-current saturation behavior in the InP dot devices resembles that observed in the III-arsenide materials, with full population inversion prevented by a combination of the higher energy dot and two-dimensional (2D) states.

Laser heterostructures were grown by low pressure metalorganic vapor phase epitaxy (MOVPE) on 10° off (100) towards [111] GaAs substrates. The active dot material (grown at 650 °C and with a group V:III ratio of ≈170) was formed by depositing 6 Å of InP at 2.5 ML/s on $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ and then covering with 80 Å of GaInP. This pattern is repeated five times, separated by 80 Å thick $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ barriers. An atomic force microscopy (AFM) image of a single dot layer sample grown without a capping layer is shown in Fig. 1. In this material system dots form with a bimodal size distribution with the proportion of dots of the two different sizes depending on the growth conditions, including growth temperature, growth rate, and substrate orientation,[1,4] and these two size distributions are apparent in the AFM image in Fig. 1.

Standard photoluminescence measurements indicate emission from both large and small dots[1] but to examine the structure in more detail we use photoluminescence excitation (PLE) measurements taken at 10 K. In the PLE spectrum in Fig. 2, where detection is at 1.660 eV, corresponding to part of the inhomogeneously broadened ground state of the large dots, the signal from the small dots is absent. This occurs because at low temperatures carriers are no longer able to thermalize between dots of different sizes. This allows us to see that the spectrum drops close to zero between the signal corresponding to the 8 nm wide $Ga_{0.51}In_{0.49}P$ quantum well at 2.000 eV and the dot signal at lower energy. We believe that the remaining nonzero signal is due to low levels of elastically scattered light. This drop in signal and the lack of an obvious feature in this energy range suggests that there are no continuum states, characteristic of a two-dimensional system, in this energy range. A wetting layer, at energies lower than the $Ga_{0.51}In_{0.49}P$ quantum well absorption edge observed at 2.000 eV, would be expected to produce a continuum signal complete with excitonic features and so we conclude that the InP dots are either forming by the Volmer-Weber process or the wetting layer is interdiffused with the subsequently grown layers of GaInP or the AlGaInP pregrown layer[5] and hence shifted to higher energy. The apparent absence of a wetting layer in this material system has been previously reported.[6]

The net optical modal gain and net modal absorption spectra of the samples were measured using the single-pass amplified spontaneous emission from a segmented oxide-stripe device.[7] Net modal gain and absorption spectra taken at 300 K are shown in Fig. 3 with a detail of the absorption data shown below the main figure. Positive gain of about

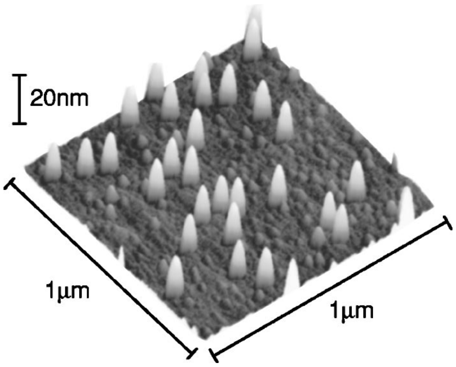

FIG. 1. Atomic force microscopy image of a single layer of uncapped InP dots grown on $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$. A bimodal distribution of dot sizes is apparent.

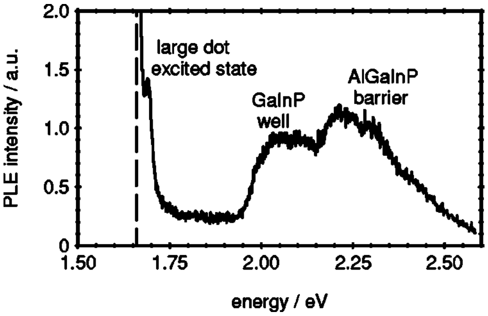

FIG. 2. Photoluminescence excitation spectra taken at a temperature of 10 K where the detection energy is 1.660 eV.

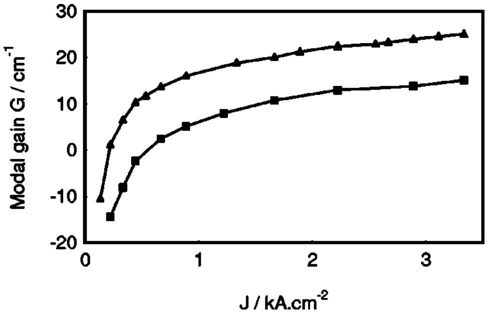

FIG. 4. TE modal gain at a fixed transition energy as a function of current density at 300 K (squares) and 210 K (triangles).

12 cm^{-1} is achieved in the region of 1.635 eV while the measured absorption at this energy is ~100 cm^{-1}. The results show that large optical absorption can be obtained from the dots and that the measured peak modal gain is significantly less than the modal absorption measured at the same energy. This behavior is similar to that observed for InGaAs dots.[3] Gain at an energy of 1.635 eV at 300 K corresponding to the large dot ground states is plotted on Fig. 4 as a function of current density. These data exhibit severe saturation of the gain at a value far below the 100 cm^{-1}, which is the value of absorption derived from the absorption spectrum at this energy. To understand the cause of the low value of saturated modal gain at room temperature we have also plotted the modal gain corresponding to a fixed set of dot states[3] at a lower temperature of 210 K in Fig. 4. The energy is adjusted as the temperature is reduced to compensate for the shift of the measured absorption edge so that the gain is being measured for the same set of dot states. The maximum value of the saturated modal gain increases as the temperature is reduced to 210 K as has also been observed in the InGaAs system.[3] Previously, in the InGaAs dot system, the low value of saturated modal gain was ascribed to incomplete population of the available dot states due to the presence of a large reservoir of states in the wetting layer.[3] The low energy dot states cannot be fully populated because the large reservoir of states in the wetting layer prevent an appreciable movement of the quasi-Fermi levels even with increased drive current. We concentrate on this effect, determining its magnitude and likely origin. To avoid uncertainties to do with nonradiative processes that can be different in different samples we focus on the gain versus quasi-Fermi level separation characteristic to determine the intrinsic performance of the dot active region. We note that extrinsic nonradiative processes such as thermally activated leakage[8] will simply exacerbate any gain—current saturation effects due to the intrinsic processes.

In Fig. 5 we have plotted the modal gain versus quasi-Fermi level separation, as derived from the transparency point on the measured gain spectra. The gain (at 1.635 eV) versus quasi-Fermi level separation is significantly below the value that would be obtained if the states were fully inverted (100 cm^{-1}) but continues to tend towards this value with increasing quasi-Fermi level separation. Therefore, we believe that it is the saturation of the quasi-Fermi level separation with increasing current density that is causing the saturation of the gain with increasing current density as was previously postulated for the InGaAs dot-wetting layer system.[3]

Here the wetting layer is either absent or removed in energy from the dot states. For the InGaAs dot—wetting layer system the transition energy separation between the wetting layer and the dot states investigated was 108 meV (Ref. 3) whereas here the energy separation of the transitions (total electron and hole offsets) between the PLE signal assigned to the GaInP quantum well (which may contain any residual wetting layer) and dot states is 275 meV.

In addition to any effect related to a 2D layer complete population of the low energy states can be prevented due to the thermal distribution of holes amongst the many closely spaced dot hole levels and this mechanism was shown to be important for 1.3 μm emitting InGaAs dot structures where the confining potentials are large.[9] Unfortunately, it is very difficult to experimentally disentangle this explanation from

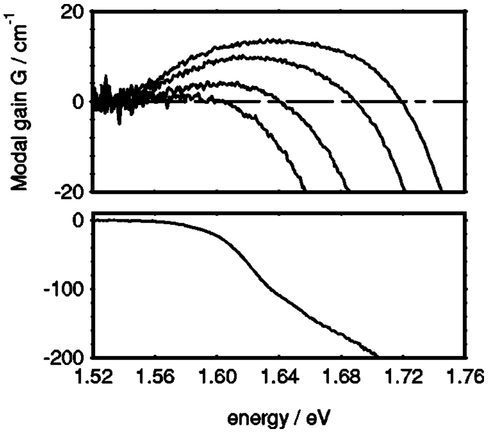

FIG. 3. TE modal gain and modal absorption for measured for injected current densities of 0.3 to 3 kA/cm^{2} at 300 K.

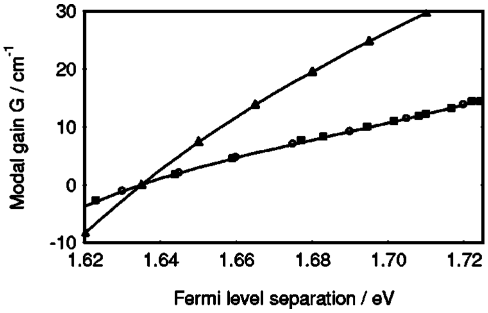

FIG. 5. Experimental (squares) and modeled modal gain vs quasi-Fermi level separation (transparency point) at 300 K showing that the gain does not saturate as a function of quasi-Fermi level separation. The modeled data include the effect of dot states alone (triangles) and dot and 2D states (circles).

that based on the role of the wetting layer or other 2D layer with similar behavior expected in both cases. However, to obtain an estimate of the role of the excited states we have performed a simple calculation where the dot states consist of equally spaced groups of states (modeled as rectangles rather than the Gaussian energy distribution of states to allow an analytical solution) due to the larger dots of the bimodal distribution and a similar representation for the small dots in the bimodal distribution. The separation, position, and number of states used is based on fitting of the absorption spectrum measurements of a sample grown under similar conditions and using a 80:20 conduction:valence band offset ratio. We have assumed a distribution of carriers among the various states according to Fermi-Dirac statistics although we note that recent measurements suggest that this does not have to be the case in dot structures even at room temperature.[10] We calculate the probability of occupation of the electron (f_e) and hole (f_v) dot states corresponding to the transition energy of 1.635 eV, calculate the fraction of the maximum gain that can be achieved $(f_c - f_v)$, and hence calculate the gain achieved using the amplitude of the absorption at 1.635 eV as the value of gain at full inversion. The upper line (triangles) in Fig. 5 is calculated assuming 6 times as many small dots as large dots (derived from fitting the measured absorption spectrum). The gain achieved is substantially below the fully inverted value due to the presence of the excited states but is not as far below as the experimental data. To obtain as small a value of gain at a given quasi-Fermi-level separation from the calculation as obtained in the experiment there would have to be 50 times as many small dots as large dots in the sample, which we believe is unreasonable on the basis of the absorption and AFM measurements. However, the experimental gain versus quasi-Fermi level separation can be reproduced (Fig. 5) by including both the effects of the 2D (GaInP/wetting layer) layers, observed in the PLE data of Fig. 2, and the excited dot states. These results suggest that the higher energy dot states are important in the gain saturation observed in these InP dot samples, as they are in 1.3 μm emitting lasers where the confinement potentials are also large, but that the 2D states must also contribute to the incomplete population of the available states; this is a fundamental problem in quantum dot lasers even if the wetting layer can be removed and suggests tailoring of the dot and 2D energy states is required to minimize the effect. We would like to make the point that the degree to which the 2D states affect the gain saturation is very sensitive to the value of the conduction:valence band offset ratio which is not well known and consequently the good agreement we obtain with the experimental data is meant only to indicate that this mechanism has a role but the exact magnitude of the effect is uncertain and therefore we do not rule out the possibility of additional gain saturation mechanisms.

In summary we have measured the gain-current characteristics for InP/AlGaInP quantum dot laser structures. Saturation of the gain-current characteristic is apparent even though PLE measurements indicate that the 2D states are energetically distant from the dot states. The gain is reduced from the maximum value by the distribution of carriers in the excited dot states, the states in smaller dots and the 2D states.

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