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Capture and confinement of light and carriers in graded-index quantum well laser structures

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Abstract

We investigated graded-index separate-confinement heterostructure lasers and compared their performance with a conventional quantum well laser by using Raman and time-resolved photoluminescence spectroscopy. We found that grading the index of the $Ga_{1-x}Al_xAs/GaAs$ waveguide and increasing the Al content improves considerably both, the light and carrier trapping and reduces carrier escape from the active region. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Quantum well lasers; Carrier capture; Time-resolved spectroscopy

Carrier-capture, Carrier-escape and light mode guiding, are responsible for the modulation response of laser devices in optoelectronic applications. Graded-index separate-confinement heterostructure (GRINSCH) optical cavities simultaneously guide the emitted light along the active region and facilitate carrier relaxation towards it. The carrier capture by the quantum wells, which is very important for the modulation response [1] and the quantum efficiency [2] of the lasers, can be tailored by a proper design of the barriers surrounding the wells [3].

Three laser structures each containing a 9 nm single InGaAs quantum well (SQW) as active layer but different barrier designs, which serve for carrier confinement and light guiding, were studied. While in laser #1 the SQW was embedded in a simple GaAs waveguide, lasers #2 and #3 had a graded waveguide, which was obtained incorporating short period superlattices (SPSLs) made of $Al_xGa_{1-x}As$ layers with the Al content increasing from the centre towards the cladding layer. In laser #3 the Al content was basically twice that of laser #2, yielding a higher confinement potential (for sample details see Ref. [4]). Time-resolved photoluminescence (trPL) measurements were done with the up-conversion technique providing a time resolution of 2 ps. Raman spectra were collected in the back-scattering geometry at different incidence angles, from 0° to 60° to the sample normal, and different polarisation conditions.

The carrier capture time obtained from the rise of the trPL emission was measured as a function of excitation energy (Fig. 1). This allowed selective carrier injection into specific layers of the structure, due to the different band gap of the different layers. Above a certain energy, where the injection changes from the InGaAs layer into the waveguide region, both lasers, #1 and #2, have considerably increased capture times reflecting the influence of the barrier structures in the

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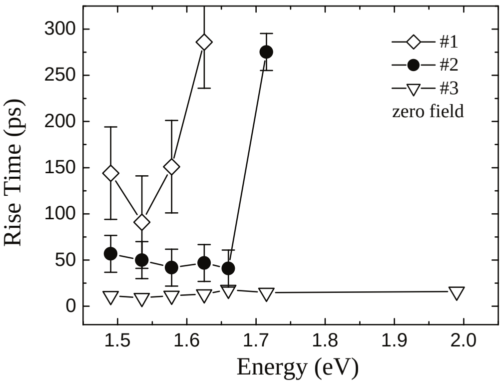

Fig. 1. (a) Carrier capture times as a function of injection energy at zero electric field. The lowest energy corresponds to the direct injection into the InGaAs SQW.

capture process. Only laser #3 maintains a fast capture even at high injection energies, which approximately correspond to the case of electrical injection.

The carrier escape from the SQW was probed by applying an electric field to the p–i–n structures perpendicularly to the SQW plane. The electric field-induced tunnelling gives direct insight into the laser structures capability of carrier confinement to the active layer: the rise- and decay-time of the photoluminescence (PL) are strongly reduced when tunnelling occurs. Fig. 2 shows the change of PL rise- and decay-time, and the time integrated PL intensity as a function of electric field for an injection energy of 1.65 eV. At this energy, the injection occurs in the waveguide layers in all three lasers. As the field is increased (bias decreased in the p–i–n structures from flat-band conditions towards negative voltages) in lasers #1 and #2 (Fig. 2a–d), the tunnelling of the carriers out of the QWs leads to reduced rise- and decay-times and to a concomitant decrease of the PL emission intensity due to the reduction of the overall carrier density in the SQWs. Only in laser #3 (Fig. 2e and f) the rise- and decay-time increase due to the field indicating reduced tunnelling. However, in structure #3 the improved carrier confinement of the barriers leads to an increase of the decay time with increasing field, due to the reduction of the electron–hole overlap [5].

Apart from the carrier confinement, it is also important to avoid photon leakage, and therefore optical mode guiding is essential for optimum device performance.

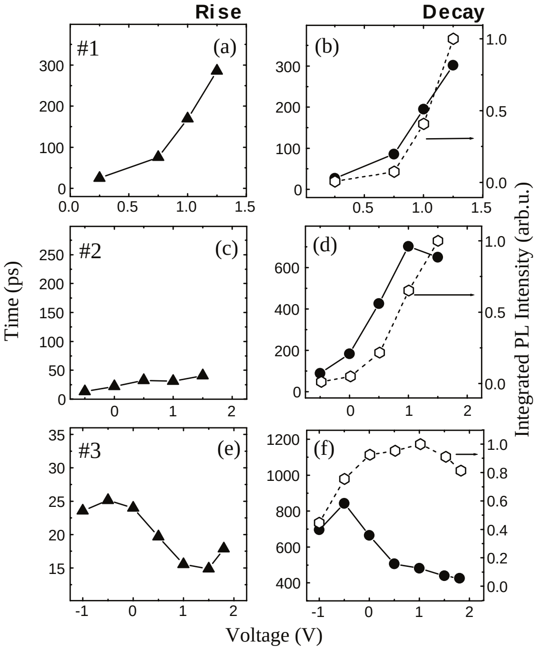

Fig. 2. PL rise- (triangles, left panels) and decay-times (circles, right panels) as a function of applied voltage for structures #1–#3 and an excitation energy of 1.65 eV. The integrated PL intensity is shown by the open diamonds in the right panels.

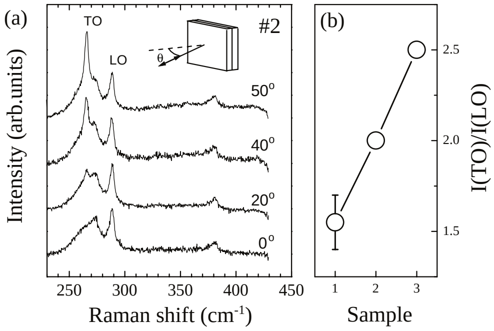

Fig. 3. (a) Raman spectra of laser #2 at different angles of incidence. (b) Ratio between TO and LO intensities at an angle of 45°.

We guided a probe beam through the same structures used in the time-resolved experiments and analysed its Raman spectrum, which gave information on the spatial confinement of the light mode (Fig. 3). The four peaks seen in Fig. 3a correspond to the GaAs- and AlAs-like modes at around 280 and 380 cm^{-1}

of the barrier layers, respectively, and the TO and LO modes at 260 and 290 cm^{-1} to the zone-centre phonons of the SQW, respectively. At normal incidence, where the light polarisation is parallel to the SQW plane, the TO mode is forbidden. However, increasing the angle of incidence, the light beam becomes efficiently guided through the SQW and the TO-peak intensity increases for p-polarised light. The LO-mode of the SQW is practically angle independent and therefore, the ratio between the TO and LO intensities serves as a measure of light guiding efficiency in the SQW. This ratio is shown in Fig. 3b for the three laser structures; its increase from structure #1 to #3 clearly demonstrates the enhancement in guiding efficiency of structure #3.

The GRINSCH laser structures (#2 and #3) showed superior carrier (Figs. 1 and 2) and light trapping properties (Fig. 3b) as compared to lasers with simple GaAlAs barriers (#1). The PL rise in #3 is an order of magnitude shorter than in #1 and unaffected by the excitation energy. Lasers #1 and #2, however, show a markedly increase in rise-time when the carriers are injected into the waveguide rather than into the active layer (Fig. 1a). Confinement of the lasing light mode is improved in #2 and increased by almost a factor 2 in #3 compared to #1 as observed in the angle-dependent Raman spectra (Fig. 3a). Carriers in lasers #1 and #2 exerted to an electric field showed high tunnelling rates which decrease the rise- and decay-times (Fig. 2). Strongly reduced carrier escape from the #3 GRINSCH laser was indicated by the increase of PL decay time on increasing electric field (Fig. 2f), thus confirming that the SPSL with higher Al content improved carrier confinement.

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