Experimental comparison of strained quantum-wire and quantum-well laser characteristics

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Measured gain compression, differential gain, and damping of strained quantum wire lasers are reported and related to attributes specifically traceable to carrier confinement in two dimensions. A comparison is made with the properties of ridge lasers grown simultaneously. Damping and $K$ factors are found to be comparable in the two structures. The differential gain is found to increase by two orders of magnitude (from $2.1 \times 10^{-15}$ to $1.5 \times 10^{-13}$ cm$^2$), but the most significant consequence is an order of magnitude increase in gain compression (from $2.5 \times 10^{-17}$ to $1.8 \times 10^{-16}$ cm$^3$), which limits the bandwidth. Carrier occupation, relaxation, recombination from multiple subbands, intersubband processes, high photon density, and consequent carrier heating and spatial hole burning effects in quantized structures are conjectured to cause some of the observed characteristics.

Reduced dimensionality and incorporation of strain have a strong influence on carrier confinement, capture, emission, relaxation, and recombination in a laser because of their effect on the occupation and interaction properties of carriers occupying the modified energy bands. Quantum-wire structures, with their constrained density of states and active volume, are expected to show large nonlinear effects in electronic and optical processes. Numerous related predictions have been reported and related to attributes specifically traceable to carrier confinement in two dimensions. A consequence is an order of magnitude increase in gain compression (from $2.1 \times 10^{-15}$ to $1.5 \times 10^{-13}$ cm$^2$), but the most significant consequence is an order of magnitude increase in gain compression (from $2.5 \times 10^{-17}$ to $1.8 \times 10^{-16}$ cm$^3$), which limits the bandwidth. Carrier occupation, relaxation, recombination from multiple subbands, intersubband processes, high photon density, and consequent carrier heating and spatial hole burning effects in quantized structures are conjectured to cause some of the observed characteristics.

Briefly, these laser structures consist of three $Ga_{1-x}In_xAs$ quantum wells separated by GaAs barriers and are clad with $Ga_{1-x}Al_xAs$ following a grading region. On off-axis (100) surfaces, grown simultaneously, the GaAs barriers are nominally 40 Å thick in between the wells and 20 Å thick adjacent to the grading region, the quantum wells are 80 Å in thickness with 20% mole fraction of InAs, the graded regions are 1000 Å in thickness, and the cladding layer composition is 75% mole-fraction of AlAs. The growth occurs through a silicon nitride mask in a V groove and leads to a self-isolated growth where the lasing region is entirely surrounded by wider band-gap material; the structures are electrically isolated as grown and have strong bi-directional optical confinement of the quantum wires. The use of strong optical confinement allows for a large optical confinement factor $\Gamma$, which is estimated to be $\sim 0.106$ for ridge lasers and $\sim 0.016$ for the quantum-wire lasers based on transmission-electron micrographs of grown structures.

The fabricated quantum-wire lasers show two distinct behaviors depending on growth. In their modulation response, lower efficiency lasers reported earlier show a low frequency rolloff, while higher efficiency lasers that show threshold currents of $\geq 188 \mu$A, differential output of $\sim 0.5 \mu$W/μA, and continuous peak power of $\sim 50 \mu$W, exhibit negligible rolloff. These higher efficiency lasers are of more interest and are discussed here and compared with ridge lasers. Figure 1 shows the small-signal modulation response of a 1-mm-long laser at different bias currents. A striking feature of this response is a 3 dB bandwidth limited to $\sim 10$ GHz. These laser structures are center-fed with a top metal contact line that is 5 μm in width. Consequently, inductive-resistive-capacitive transmission line effects can be substantial due to the high capacitance of a forward biased diode. We estimate that the electronic phase delay would limit the operation of these structures to 15 GHz. The peaking in response and the limitations of the bandwidths are therefore intrinsic to the structure. This bandwidth is surprisingly small, although it is measured at very low currents. Bandwidths exceeding 30 GHz (Ref. 8) have been demonstrated in multiquantum well strained ridge laser structures. The significantly longer cavity in these devices and its effect on photon lifetime is only partly responsible for this attribute.

To clarify this response, the behavior of damping (Fig. 2) is evaluated using the small-signal response subtraction technique described by Morton et al. which allows removal of
frequency and power insensitive parasitics as sources of errors. The error bars in measurements reported here are estimated to be between 10% and 15%. The expression for the damping factor ($\gamma$), extended from quantum-well to quantum-wire structures as a simple scaling of the width, is

$$\gamma = \frac{1}{\tau_r} + 4 \pi^2 f_r^2 \tau_p \left( 1 + \frac{e}{dg/dn} \right).$$

Here, $\tau_r$ is the differential lifetime at threshold, $f_r$ is the relaxation oscillation frequency, $\tau_p$ is the photon lifetime of a cold cavity, $e$ is the gain-compression coefficient, and $dg/dn$ is the differential gain. The predictions of larger $f_r$, given by

$$f_r = \frac{1}{2 \pi} \sqrt{\frac{\nu_{gr} \Gamma dg/dn}{\tau_p} S_0} \left( 1 + eS_0 \right)^{-1},$$

where $\Gamma$ is the optical confinement factor, $\nu_{gr}$ is the group velocity of photons, and $S_0$ is the steady-state photon density, are predicated on the increase in $dg/dn$, the differential gain, due to quantum confinement effects. The $K$ factor which characterizes the change in damping factor with relaxation frequency is measured to be quite comparable in the ridge and quantum-wire lasers (0.34–0.4 ns) and by itself suggests 3 dB frequencies ($2\sqrt{2\pi/K}$) exceeding 20 GHz in these structures. For the ridge lasers, this is quite consistent with the observed modulation behavior, but is not for the quantum-wire lasers. The $K$ factor is not an adequate measure of the observed frequency-related properties of the structure.

We can estimate the differential gain in the structures from the low power linear behavior of relaxation frequency ($f_r$) with square root of power per facet. This relationship is shown in Fig. 3 for the quantum-wire laser where a strong saturation with power level is observed—indicative of a strong gain-compression effect. The gain-compression coefficient can be estimated from this nonlinearity. The $K$ factor can also be used to estimate $e$, to obtain an alternative confirmation. These are found to be within the same error margin as the experimental data, and we estimate $1.79 \times 10^{-16} \text{ cm}^{-3}$ as a reliable value for the quantum-wire lasers—a considerably larger number than that for ridge lasers and strongly indicative of the nonlinear saturation effects that occur in reduced density of states systems. A summary of all related parameters for the quantum wire and ridge laser is shown in Table I.

A number of features stand out in the comparison of quantum-wire and quantum-well structures. The effective

<table>
<thead>
<tr>
<th>Table I. Summary of experimentally derived laser parameters.</th>
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<tbody>
<tr>
<td>Quantum wire</td>
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<tr>
<td>$\eta_e$ (cm$^{-1}$)</td>
</tr>
<tr>
<td>$\alpha$ (cm$^{-1}$)</td>
</tr>
<tr>
<td>$T_0$ (K)</td>
</tr>
<tr>
<td>$\tau_p$ (ps)</td>
</tr>
<tr>
<td>$\tau_{md}$ (ns)</td>
</tr>
<tr>
<td>$B$ (cm$/\text{g})$</td>
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<tr>
<td>$\Gamma$</td>
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<tr>
<td>$K$ (ns)</td>
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<tr>
<td>$dg/dn$ (cm$^2$)</td>
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<tr>
<td>$e$ (cm$^3$)</td>
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FIG. 1. Small-signal modulation response of a high efficiency quantum-wire laser which exhibits small low frequency rolloff. The laser cavity length is 1 mm.

FIG. 2. Damping rate as a function of frequency for ridge and quantum-wire laser.

FIG. 3. Power dependence of quantum-wire relaxation frequency.
The most significant difference between the quantum-wire and ridge lasers, is that even though the differential gain is enhanced substantially as expected, the gain-suppression coefficient is also enhanced significantly. This increase in inertial property limits the operational frequency of the quantum-wire laser structures fabricated.

Measurements reported here do not unambiguously point to a single dominant source for the high gain-compression coefficient. The earlier work of Walther et al. does point out the larger capture times in their GaAs quantum-wire structures, but the high-efficiency quantum-wire lasers reported here do not show a low-frequency roll-off. Smaller grading lengths should be expected to improve the capture characteristics near flat-band conditions. A larger gain-compression coefficient then necessitates a small escape time. These characteristics of the quantum-wire lasers are dominated by the lateral confinement of ~350 Å. It is conceivable that the larger well size, and structural inhomogeneities allow this decrease in escape time to occur. The side-mode suppression ratios and efficiency, nonradiative lifetime, 

\[ \frac{1}{\tau^2} = \frac{1}{\tau_{\text{nrad}}} + \frac{4BI}{qV}. \]  

Here, \( \tau_{\text{nrad}} \) is the nonradiative lifetime, \( I \) the current, and \( B \) the bimolecular recombination coefficient. A plot of \( \tau^{-2} \) as a function of drive current is shown in Fig. 4 for the ridge and quantum-wire lasers. The intercept gives comparable nonradiative lifetime for the two lasers of >2 ns.

In comparing the two structures, efficiency, nonradiative lifetime, intrinsic losses, and the low threshold current all support the success in maintaining the optical quality of quantum-wire structure. The differential gain improves by nearly two orders of magnitude, aided by two-dimensional confinement and use of strain. Together with the low optical losses, high confinement factor, due to rapid and high mole-fraction AlAs grading, this allows for a low threshold current to be achieved.

The most significant information in the Table I is the comparable magnitude of damping in the two structures with a significant increase in the gain compression. Two likely causes for this are spectral hole burning and carrier heating—both are accentuated in the presence of strain and multidimensional confinement. Spectral hole burning causes this since differential gain and saturation coefficient are both inversely related to the density of states. Carrier heating may cause this by (a) intraband relaxation time may increase if inhomogeneities in the structure have only a small effect on selection rules, (b) the carrier capture and emission times in the active gain medium are comparable to the stimulated emission time, (c) contribution from carriers induced by stimulated emission itself, and (d) lattice heating. The maximum power from the quantum-wire lasers is ~50 μW (~25 kW/cm²) using an excess current drive of ~100 μA beyond threshold. The maximum power is sensitive to temperature indicating strong lattice heating due to thermal spreading from dissipation in the quantum-wire region.

In conclusion, the most significant difference between the quantum-wire and ridge lasers, is that even though the differential gain is enhanced substantially as expected, the gain-suppression coefficient is also enhanced significantly. This increase in inertial property limits the operational frequency of the quantum-wire laser structures fabricated.

**References**