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 2.1×10^{-15} to 1.5×10^{-13} cm^2), but the most significant consequence is an order of magnitude increase in gain compression (from 2.5×10^{-17} to 1.8×10^{-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[1–4] related to dynamics, spectral, and noise properties exist for quantum-wire and quantum-box lasers. In particular, increase in differential gain and consequent expectations of low threshold current and high bandwidths[4] have caused interest. Verified expectations include emission from multiple subbands due to reduction in density of states,[5] large time constants associated with capture processes,[6] and ultralow threshold currents.[7] This letter reports experimental measurement of additional attributes of self-confined quantum wire lasers that have been fabricated in V grooves by molecular beam epitaxy.[7] By comparing these properties with those of ridge lasers that have been fabricated from wafers grown simultaneously, we make observations on the variations in characteristics that can be directly attributed to effects of multiconfinement.

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 Γ, which is estimated to be ≈0.106 for ridge lasers and ≈0.016 for the quantum-wire lasers based on transmission-electron micrographs of grown structures. The use of strained wells in these structures substantially enhances the differential gain because of distortion in the band structure. Strong electronic confinement, high lifetimes in the grown region, and suppression of surface recombination in the as-grown structure, allow low threshold currents to be achieved.

The fabricated quantum-wire lasers show two distinct behaviors depending on growth. In their modulation response, lower efficiency lasers reported earlier[7] show a low frequency rolloff, while higher efficiency lasers that show threshold currents of $\geqslant188$ μA, differential output of ≈0.5 μW/μA, and continuous peak power of ≈50 μW, 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 ≈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.*[9] which allows removal of

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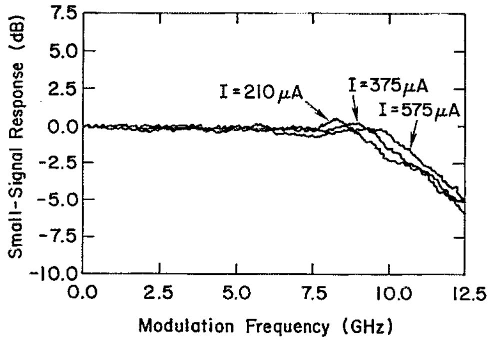

FIG. 1. Small-signal modulation response of a high efficiency quantum-wire laser which exhibits small low frequency rolloff. The laser cavity length is 1 mm.

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 (γ), extended from quantum-well to quantum-wire structures as a simple scaling of the width, is

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

Here, τ is the differential lifetime at threshold, f_r is the relaxation oscillation frequency, τ_p is the photon lifetime of a cold cavity, ϵ is the gain-compression coefficient, and dg/dn is the differential gain. The predictions of larger f_r, given by

$$f_r=\frac{1}{2\pi}\sqrt{\frac{v_{\rm gr}\Gamma dg/dn}{\tau_p}\frac{S_0}{1+\epsilon S_0}}, \tag{2}$$

where Γ is the optical confinement factor, $v_{\rm gr}$ 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

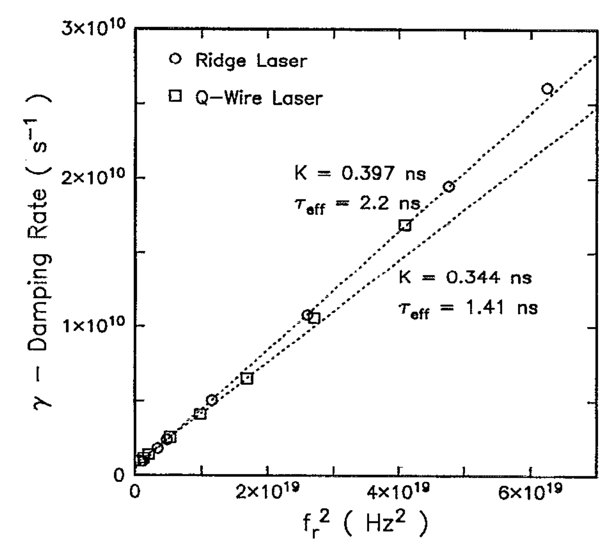

FIG. 2. Damping rate as a function of frequency for ridge and quantum-wire laser.

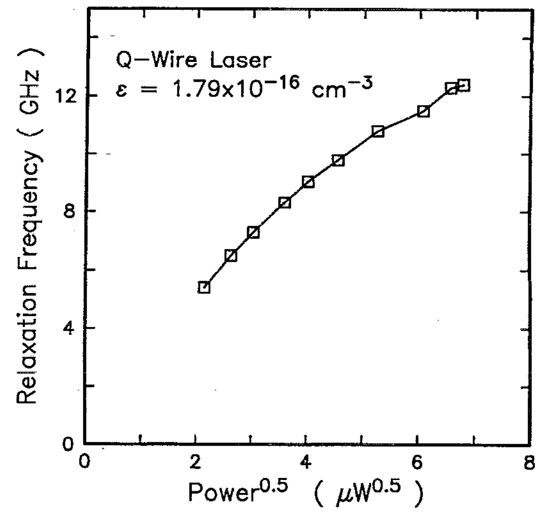

FIG. 3. Power dependence of quantum-wire relaxation frequency.

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 ϵ, to obtain an alternative confirmation. These are found to be within the same error margin as the experimental data, and we estimate 1.79×10^{-16} 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 I. Summary of experimentally derived laser parameters.

	Quantum wire	Ridge
η_i	0.834	0.863
α_i (cm^{-1})	4.21	4.40
T_0 (K)	263	206
$\tau_{\rm ph}$ (ps)	8.55	8.44
$\tau_{\rm nrad}$ (ns)	2.14	2.89
B (cm^3/s)	0.11×10^{-10}	0.21×10^{-10}
Γ	0.0157	0.106
K (ns)	0.344	0.397
dg/dn (cm^2)	1.5×10^{-13}	2.1×10^{-15}
ϵ (cm^3)	1.79×10^{-16}	2.54×10^{-17}

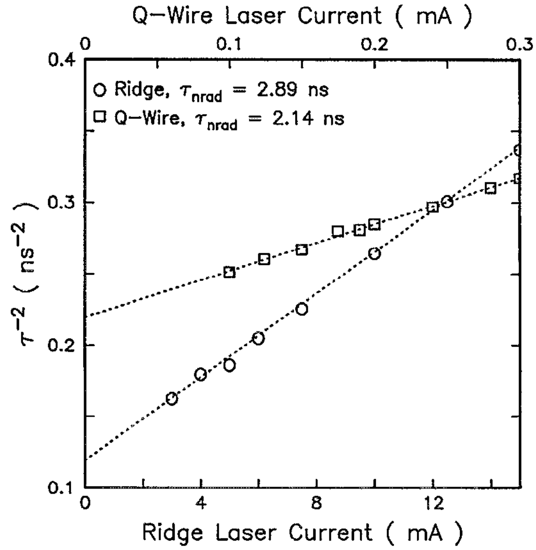

FIG. 4. Inverse square of time constant at a function of laser current for ridge and quantum-wire laser.

lifetime in the cavity is quite comparable for the ridge and the quantum-wire laser. This was derived using network parameter measurements of the devices treated as diodes; the lifetime can be estimated from the relationship for the intrinsic impedance, Z, given by

$$Z=R_s+\frac{R_p}{1+\omega\tau^2}-j\,\frac{R_p\omega\tau}{1+\omega^2\tau^2}, \tag{3}$$

where

$$\frac{1}{\tau^2}=\frac{1}{\tau_{\rm nrad}^2}+\frac{4BI}{qV}. \tag{4}$$

Here, R_s the series resistance, R_p the parallel resistance, the imaginary term models the capacitive component in parallel with R_p, $\tau_{\rm nrad}$ the nonradiative lifetime, I the current, and B the bimolecular recombination coefficient. A plot of τ^{-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[10] 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 carrier heating induced by stimulated emission itself,[11] and (d) lattice heating. The maximum power from the quantum-wire lasers is ≈50 μW (≈25 kW/cm^2) 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.

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.*[6] 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. The 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 in these laser structures is quite large; this makes the possibility of spectral hole burning as a dominant cause less likely. The experimental evidence points to heating effects as being substantial in these structures with only a small increase in characteristic temperature from ridge (206 K) to quantum-wire structures (263 K). This may cause the observed behavior, possibly enhanced by the other effects discussed above.

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.

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