Modulation characteristics of short cavity strained-layer lasers

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ABSTRACT

The low frequency response and damping behavior of four quantum well (4QW) graded-index separate confinement heterostructure (GRINSCH) and SCH strained-layer lasers are compared. The SCH laser is shown to be better in both respects due to a shorter carrier capture time into the quantum wells. A record 3-dB bandwidth of 28 GHz is reported for a 150 μm cavity length 4QW strained-layer SCH laser. The change in the differential gain, non-linear gain coefficient, and damping rate are studied as a function of the quantum well thickness and barrier height. It is found that decreasing the well thickness does not change the non-linear gain coefficient nor the differential gain appreciably in relatively deep wells. Shallower quantum wells, however, are observed to have lower differential gain and a higher damping rate.

1. INTRODUCTION

Both theoretical calculations and experimental data have shown that the increased differential gain in strained-layer $In_xGa_{1-x}As$ quantum well (QW) lasers makes them faster than GaAs QW lasers[1,2]. A five quantum well structure containing 50 Å $In_{0.3}Ga_{0.7}As$ layers with GaAs barriers has demonstrated an extremely high differential gain of 2.1×10^{-15} cm^2 in a 200 μm cavity length laser[3]. This factor of seven improvement in differential gain over that of bulk, p-type doped InGaAsP lasers[4] clearly shows the potential of strained-layer quantum well (SLQW) lasers for very high modulation bandwidths. Thus, the development of SLQW lasers with 3-dB bandwidths from 16.5-28 GHz has been rapid[5,6,7,8,9]. To date, GaAs-based strained layer devices have an edge in reported 3-dB bandwidths over InP-based devices, but lasers from both material systems have demonstrated very low K-factors from 0.8-0.22 ns[6,7,8,9,10]. These numbers indicate that **intrinsic** maximum 3-dB bandwidths from 40-110 GHz.

Damping in QW lasers must be considered to ensure that the improvement in RF bandwidth from the increased differential gain in SLQW structures is not nullified by a very high non-linear gain coefficient, ε. Published values of ε in QW lasers have varied widely. Some reported ε's are as low as those of bulk lasers (about 1×10^{-17} cm^3)[9,11] while other numbers are anomalously high (about $5.7\text{-}7.55 \times 10^{-17}$ cm^3)[12,13,14,15]. Although the exact cause of these differences is not clear, several structure dependent theories have been proposed to explain the wide variation in ε. These models, which include carrier heating[16], spectral hole burning[17], and carrier transport effects[12,18,19], indicate that gain saturation in QW lasers may depend heavily on quantum well depth and thickness, barrier thickness, and well number.

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It has been known for almost ten years now that short cavity length lasers exhibit higher frequency response by virtue of a smaller photon cavity lifetime[20]. Recently, however, it has been theorized and experimentally verified that the carrier capture time into the quantum well can also greatly influence the maximum bandwidth of a QW laser[9,21]. The finite capture time produces a low pass filter effect that can significantly degrade the modulation response. Thus, optimization of high-speed QW lasers should involve minimizing this carrier capture time. In this work, the differential gain, non-linear gain coefficient, and low frequency response in short cavity length graded-index separate confinement heterostructure (GRINSCH) and SCH MQW strained-layer $In_xGa_{1-x}As/GaAs$ ridge waveguide lasers are analyzed. The primary focus will be to compare lasers with different optical waveguide structures and different quantum well thicknesses.

2. MATERIALS AND FABRICATION

A GRINSCH layer with a four QW (4QW) active region was grown by MBE on a semi-insulating GaAs substrate. The following is a brief description of the layer structure: 1) a 1 μm GaAs n^+ buffer, a 0.15 μm n-type region graded to $Al_{0.7}Ga_{0.3}As$, and 0.45 μm n-$Al_{0.7}Ga_{0.3}As$ lower cladding region, 2) a GRINSCH active region consisting of an undoped 0.25 μm $Al_xGa_{1-x}As$ layer graded from $x = 0.7$ to $x = 0.3$, four undoped 50 Å $In_{0.3}Ga_{0.7}As$ quantum wells with undoped 250 Å GaAs barrier layers, and an undoped 0.25 μm $Al_xGa_{1-x}As$ layer graded from $x = 0.3$ to $x = 0.7$, 3) a 0.45 μm p-$Al_{0.7}Ga_{0.3}As$ upper cladding region, a 0.15 μm p-type layer graded to GaAs, and a 0.1 μm p^+ GaAs cap. A 4QW SCH structure with the same active region as the 4QW GRINSCH material was grown for comparison. The SCH layer consists of a 0.2 μm wide optical confinement region with 0.81 μm p^+ and n^+ $Al_{0.7}Ga_{0.3}As$ cladding regions both doped at 2×10^{18} cm^{-3}. The quantum well gain region of four 50 Å $In_{0.3}Ga_{0.7}As$ layers bounded by 250 Å GaAs barriers is centered within the optical confinement area.

For the study that analyzes changes in high-speed laser parameters with quantum well thickness, three 3QW SCH laser structures were grown. The layers share the same SCH layout as in the 4QW SCH laser but differ in quantum well design. The first one has 70 Å $In_{0.2}Ga_{0.8}As$ wells with $Al_{0.15}Ga_{0.85}As$ barriers, the second has 50 Å $In_{0.3}Ga_{0.7}As$ wells with GaAs barriers, and the third has 35 Å $In_{0.4}Ga_{0.6}As$ wells with GaAs barriers. As in the GRINSCH laser, all of the SCH layers have a 1.0 μm n^+ GaAs buffer and a 0.12 μm p^+ GaAs cap for the n and p-type ohmic contact layers, respectively, and highly-doped graded 0.15 μm $Al_xGa_{1-x}As$ layers (x varies from 0 to 0.7) between both the cap layer/p-cladding and buffer/n-cladding regions.

With these materials, ridge waveguide lasers were made using a chemically-assisted ion beam etching (CAIBE) technique to form both the ridge and mirrors of the lasers. The CAIBE method that has been developed is thermally assisted and has demonstrated a highly reproducible etch rate[22]. The ridge is etched to the top of the graded-index region, and the mirrors are etched in a subsequent step to the top of the n-type buffer layer. Ni/AuGe/Ag/Au and Ti/Pd/Au metallizations are used for the n-type and p-type ohmic contacts, respectively. The p-type contact covers only the ridge itself. Although this narrow metallization limits the spreading of heat away from the laser, the parasitic capacitance is minimized in this device configuration. All exposures are defined by electron beam lithography to improve fabrication tolerances and to improve the turn-around time of pattern alterations. The device layout is compatible with coplanar waveguide probing, which enables rapid testing of many devices while removing the parasitic capacitance and inductance associated with chip packaging[2]. With coplanar probing, metal stripes as narrow as 3 µm can be contacted. The dimensions for the devices used in the study are 50, 100, 150 x 3 μm^2.

3. RESULTS AND DISCUSSION

The lasers were mounted p-side up on copper heat sinks, and the microwave modulation response was measured from 0.045 to 26.5 GHz with an HP 8510B network analyzer and a New Focus model 1012 long wavelength photodetector. Although heating caused by a thick substrate (≈ 100 µm) limited the bandwidth of the 100 µm 4QW GRINSCH lasers to about 15 GHz, the low frequency rolloff present in these devices was another major problem. In contrast, the low frequency response of the 4QW SCH lasers was considerably better. In Fig. 1, the modulation response of a 100 x 3 µm 4QW SCH device is compared to that of a 100 x 3 µm 4QW GRINSCH laser. It is believed that the low frequency roll-off present in both devices is caused by the finite carrier capture time into the quantum wells and is characterized by a low pass filter of the form $1/(1 + \omega^2\tau_{cap}^2)$[18,21]. After examining Fig. 1 closely, it is clear that the SCH laser has better low frequency behavior than the GRINSCH laser. Capture times of 18 ps and 72 ps are calculated for the SCH and GRINSCH devices, respectively. This substantial difference in capture times can be explained by the possibility that electrons accelerated by the built-in electric field in the GRINSCH structure traverse the quantum well region without losing much energy and are trapped by the wells only after being redirected by the electric field on the opposite side the GRINSCH structure. In the SCH laser, electrons injected into the quantum well region can never overshoot this area because of the high energy barrier on the opposite side of the SCH. Thus, the SCH traps the electrons more quickly than the GRINSCH and has a faster capture time. This process is shown schematically in Fig. 2.

Maximum 3-dB modulation bandwidths of 15 and 25 GHz were measured on 50 and 100 µm 4QW SCH lasers, respectively. The performance of the 4QW SCH devices was limited by degradation of the very narrow p-contact metallization at the large current densities (> 20 kA/cm^2) required to achieve high optical powers. Thinning the substrate to approximately 40 microns in thickness allowed operation to this high a current density. The best device was a 150 µm cavity length device that had a 3-dB bandwidth of 28 GHz at a bias current of 105 mA, corresponding to an single facet optical power of about 28 mW. The modulation response of this device at various bias currents is shown in Fig. 3. The high-frequency performance of the 150 µm length laser benefits greatly from the improved low frequency behavior. This 4QW SCH device also has significantly lower damping at high powers than 4QW the GRINSCH laser. The non-linear gain coefficient ε of the 150 µm 4QW SCH laser, which is calculated from K-factor data, is 0.68×10^{-17} cm^3, and the differential gain as determined from the slope of the square of the resonance frequency as a function of $(I-I_{th})$ is 1.1×10^{-15} cm^2. These values are slightly higher than those reported previously[9] because the internal quantum efficiency of 65% has been taken into account in this work. As a comparison, the ε for the 100 µm cavity length 4QW GRINSCH laser presented above is 2.4×10^{-17} cm^3 and the differential gain is the same—1.1×10^{-15} cm^2. Spectral hole burning theory cannot account for the large variation in ε between the 4QW GRINSCH and SCH lasers, but well-barrier hole burning (WBHB) theory can qualitatively explain the difference. In the WBHB scenario, the finite carrier capture time introduces an additional term into the damping rate:

$$\gamma = \frac{1}{\sigma\tau_s} + \omega_o^2\tau_p + \frac{1}{\sigma\tau_e}\frac{\omega^2\tau_{cap}^2}{\left(1+\omega^2\tau_{cap}^2\right)} \tag{1}$$

$$\sigma = 1 + \frac{\tau_{cap}/\tau_e}{(1+\omega^2\tau_{cap}^2)} \tag{2}$$

where γ is the damping rate, τ_s is the carrier recombination rate, τ_p is the photon cavity lifetime, τ_{cap} is the carrier capture time into the well, τ_e is the emission time out of the well, and ω_0 is the relaxation oscillation frequency. The additional term is the third one on the RHS of (1). For a large τ_{cap} as in the GRINSCH laser, the damping varies as $\omega_o^2\tau_p + 1/\tau_e$. The emission time is typically on the order of 100 ps[23]. Therefore, $1/\tau_e$ can add significantly to the damping rate. For the SCH laser, however, $\omega^2\tau_{cap}^2 \ll 1$ and assuming that $\tau_s \gg \tau_p$ and that $\omega \approx \omega_0$,

$$\gamma = \omega_0^2\left(\tau_p + \frac{\tau_{cap}^2}{\tau_e + \tau_{cap}}\right) \tag{3}$$

In this regime, the influence of τ_{cap} on the damping rate can be substantially reduced. Any attempt to further simplify (1)–(3) and match experiment and theory, though, must be treated cautiously. The frequency dependence of γ as seen in (1) is quite complicated. It is probably best just to keep in mind the effect τ_{cap} can have on γ and to design the laser accordingly.

When the thickness of a quantum well is reduced, the energy separation between subbands in the well increases. Consequently, the 2D density of states decreases, and the differential gain is expected to rise. On the other hand, spectral hole burning predicts that the non-linear gain coefficient is proportional to $1/L_z$[17]. Thus, this theory states that the damping rate should increase as the quantum well thickness decreases. These competing effects suggest that an optimum quantum well thickness for high-speed operation may exist. The three 3QW layer structures described in the MATERIALS AND FABRICATION section were designed to examine this possible tradeoff. In addition, the wafer with 50 Å $In_{0.3}Ga_{0.7}As$ wells and GaAs barriers was designed to have a lower barrier height than the other two designs. This approach was taken to determine if the quantum well barrier height had any effect on the differential gain or the damping rate. The preceding discussion applies mostly to the valence band in which the band offset between $In_xGa_{1-x}As/GaAs$ and $GaAs/Al_xGa_{1-x}As$ is only about 0.38 ΔE_g.

The results of this study are summarized in Table 1 for 100 x 3 μm^2 lasers. The differential gain was found from the slope of f_0^2 as a function of $(I-I_{th})$ curves according to the equation:

$$\frac{dg}{dn} = \frac{4\pi^2 eWdL}{\eta_i v_g \gamma}\frac{f_0^2}{\left(I - I_{th}\right)}. \tag{4}$$

The K-factor was taken from γ/f_0^2 at very high bias, and ε was calculated from the K-factor according to the following formula:

$$\varepsilon = \frac{dg}{dn}\left(\frac{Kv_g}{4\pi^2} - \frac{1}{\alpha_t}\right) \tag{5}$$

It is clear from the data in Table 1 that as regards the differential gain, there is no benefit in reducing the quantum well thickness from 70 to 35 Å. This result implies that the subband energy spacings in the 70 Å well are large enough so that any additional separation present in the 35 Å well has no appreciable effect. An interesting result is the fact that the 50 Å well with the smaller energy barrier has a much lower differential gain. This outcome suggests that the relatively heavy 3D states above the quantum well in the valence band have a significant and harmful effect on the differential gain if the barrier is 120 meV or less. Table 1 also shows that the non-linear gain coefficient does not change very much as a function of the quantum well thickness. Apparently, spectral hole burning does not describe the damping behavior of these 3QW lasers very well. The K-factor has been included in the table because it is a more direct indicator of the damping rate than ε is. The 35 and 70 Å well lasers, which have the higher barrier, have a noticeably lower K-factor than the 50 Å well laser. This appears consistent with the well-barrier hole burning theory since a deeper quantum well would have a longer emission time and, thus, a smaller K-factor and damping rate as determined by (1).

4. CONCLUSION

The low frequency response and damping behavior of four quantum well (4QW) graded-index separate confinement heterostructure (GRINSCH) and SCH strained-layer lasers have been compared. The SCH laser was shown to have less low frequency rolloff and a lower damping rate. These results have been attributed to the shorter carrier capture time into the quantum wells in the SCH. Due to the improvements in low frequency rolloff and damping, a record 3-dB bandwidth of 28 GHz has been realized in a 150 µm cavity length 4QW strained-layer SCH laser. The change in the differential gain, non-linear gain coefficient, and damping rate has been analyzed as a function of the quantum well thickness and barrier height. It was experimentally found that the non-linear gain coefficient does not change significantly with well thickness, contrary to the predictions of spectral hole burning theory. It was also found that the differential gain does not improve appreciably when the well thickness is decreased. Finally, shallower quantum wells are observed to have lower differential gain and a higher damping rate. The latter being qualitatively consistent with well-barrier hole burning theory.

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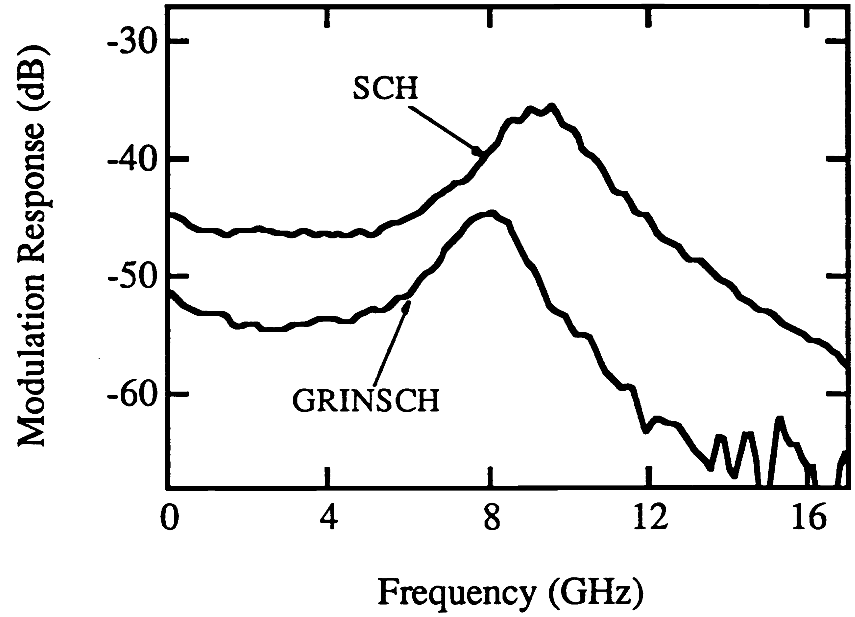

Fig. 1. A comparison of the modulation responses of the 4QW GRINSCH and SCH 100 x 3 μm lasers at current bias of about 21 mA. Below 4 GHz, the GRINSCH laser has noticeably more rolloff than the SCH device.

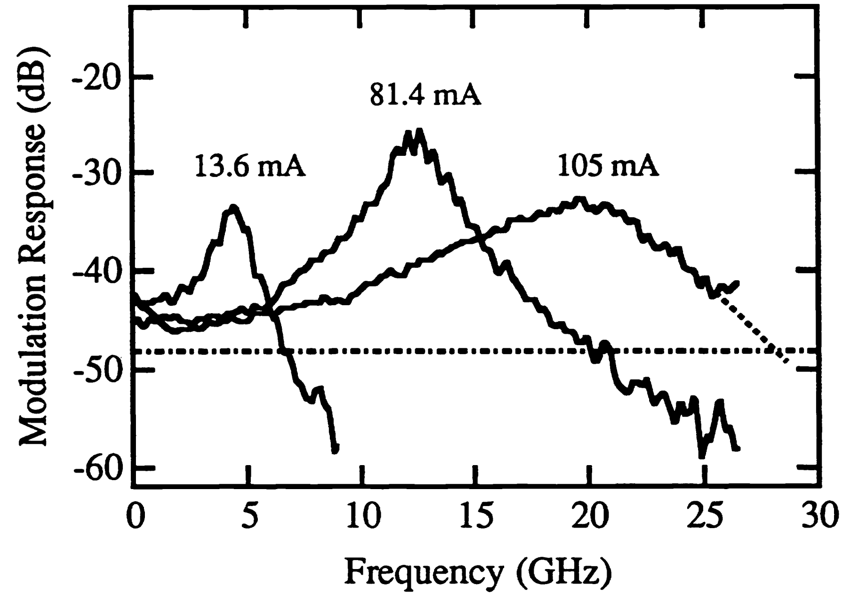

Fig. 2. The CW modulation response of the 150 μm 4QW SCH strained-layer laser at various bias currents. The dot-dashed line is 3-dB below the DC level of the 105 mA curve. The 0-dB bandwidth is 26.5 GHz and the 3-dB bandwidth is found by extrapolation to be 28 GHz.

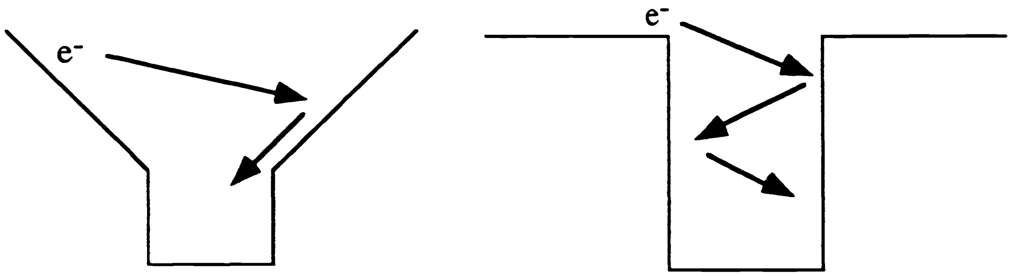

Fig. 3. Schematic diagrams of the possible carrier capture processes in a GRINSCH laser on the left and SCH laser on the right. The overshoot of the quantum well region in the GRINSCH would most likely occur only for electrons.

Table 1. The results of a study which examined the variation of the differential gain and damping in 3QW strained-layer lasers as function of well thickness and quantum well barrier height. The latter is given for the valence band.

L_z (Å)	Barrier Height (meV)	dg/dn (cm^2)	ε (cm^3)	K (ns)
35	156	1.2×10^{-15}	1.7×10^{-17}	0.10
50	118	0.8×10^{-15}	1.6×10^{-17}	0.13
70	150	1.4×10^{-15}	1.9×10^{-17}	0.10