Extended Abstracts of the 20th (1988 International) Conference on Solid State Devices and Materials, Tokyo, 1988, pp. 339-342

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High Speed Modulation Capability and Low Threshold Current Density in Strained Quantum Well Laser Structures

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Extremely-high speed capability of a strained quantum well (QW) is shown for the first time. A relaxation oscillation frequency f_r, which gives a measure of the upper modulation frequency limit, was found to be increased by 3 times in a 50Å $In_{0.9}Ga_{0.1}As/In_{0.52}Al_{0.48}As$ QW structure compared with that in a 50Å $GaAs/Al_{0.4}Ga_{0.6}As$ QW structure for the undoped case. One of the main factors for this improved frequency band width is attributed to the reduced subband nonparabolicity as well as the reduced valence band density of state in the strained QW structure. The corresponding lasing threshold current is one-order of magnitude smaller than that of the GaAs/AlGaAs QW structure. With a p-doping in the QW the f_r value increases, and the 3-dB cutoff frequency of about 90 GHz will be expected with an acceptor concentration of 5×10^{18} cm^{-3} in the $In_{0.9}Ga_{0.1}As/In_{0.52}Al_{0.48}As$ QW.

Increase in high-frequency modulation band width of semiconductor lasers is one of the main research target for high bit-rate optical-fiber communications and for high speed opto-electronic integrations. The direct modulation bandwidth of a semiconductor laser is given by the relaxation oscillation corner frequency f_r which is of the form[1)]:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{c\,G}{n_r}\frac{S_0}{\tau_p}}\,, \tag{1}$$

where S_0 is the stationary photon density in the cavity, G is the differential gain (i. e., $G=\partial g/\partial n$ where g is the optical gain and n is the carrier concentration), τ_p is the photon lifetime, n_r is the refractive index of the laser medium, and c is the light velocity. There have been various trials to increase the f_r value such as quantum well (QW) structures[2)], low temperature operations[1)], short cavity lasers[1)], and p-type doping in QW's.[3)]

From a viewpoint of the material, the progress of the epitaxial growth technique made it possible to employ a strained QW structure as an active layer of a semiconductor laser. A continuous wave room temperature operation was reported in a strained $In_{0.37}Ga_{0.63}As/Al_yGa_{1-y}As$ QW laser with the low lasing threshold current density (J_{th}) of ~150A/cm^2.[4)] The reduction of J_{th} was proposed theoretically in strained QW structures.[5,6)] This was based on the reduction of the valence band effective mass by the biaxial compression in the plane of the QW. But it was corrected later[7)] that the effective mass at the zone center is independent of the strain.

The purpose of this paper is to show for the first time the extreme high-speed capability of strained QW structures in addition to the low threshold current property from the theoretical comparisons between the strained and unstrained QW laser structures. It will be shown later that the reduction of the valence-band effective mass comes from the lifting of the band degeneracy in the QW structure and that the main factor which gives the above different laser properties is the nonparabolicity in the valence-band subband structures due to the band mixing and the related increase of the valence-band density of state (DOS). Further expansion of the modulation bandwidth with the p-type doping in the strained QW is also discussed.

The differential gain value G will be critically dependent on the DOS and therefore the band-mixing effect[8)] in the valence band, which was neglected in the former works,[5,6)] was taken into account. The details of the analysis is reported elsewhere.[8,9)] In the calculations, (001) oriented QW was assumed and the subband structures were evaluated along the principal symmetry axes of [100] and [110]. Figure 1(a) shows the valence-band for an unstrained 50Å GaAs/$Al_{0.4}Ga_{0.6}As$ QW. The band offset of the valence band ΔE_v was taken to be 40% of the energy gap difference ΔE_g. The Luttinger mass parameters used for the calculations are γ_1=6.85, γ_2=2.10, and γ_3=2.90 for GaAs.[10)]

Similar calculations were performed on strained QW's. Figure 1(b) is one of the example where 37% of In incorporation is assumed in the QW structure shown in Fig. 1(a). The 2.6% biaxial compression in the $In_{0.37}Ga_{0.63}As$ results in a 1052-meV conduction to HH bulk band gap and a 1205-meV conduction to light-hole (LH) bulk band gap using the deformation potentials given in Ref. 11. Considering the inaccurate knowledge of the band offset especially in this strained system, a range of ΔE_{HH} from 40 to 60% of ΔE_g was assumed for the calculation, but the results are relatively insensitive to the assumed ΔE_v value in this range. The Luttinger mass parameters used for InAs are γ_1=19.67, γ_2=8.37, and γ_3=9.29[12)] and InGaAs parameters were interpolated with the GaAs and InAs parameters.

For the calculation of the valence-band DOS, the rotational symmetry around the [001] axis was assumed where the subband dispersions are represented by the above two cases. Figure 2(a) shows the valence-band DOS for an unstrained 50Å GaAs QW calculated with the [110] dispersion shown in Fig. 1(a). The step-like QW DOS calculated with the bulk effective mass in the [110] direction is also shown in Fig. 2(a) as a reference. The first peak near the valence band edge is attributed to the nonparabolicity of the lowest subband structure (designated as HH1) and the other two peaks are the contributions from that in the second subband (designated as HH2). The effective mass of each subband near the zone center is derived analytically following the procedure similar to Ref. 13 but by including the crystal anisotropy as follows:

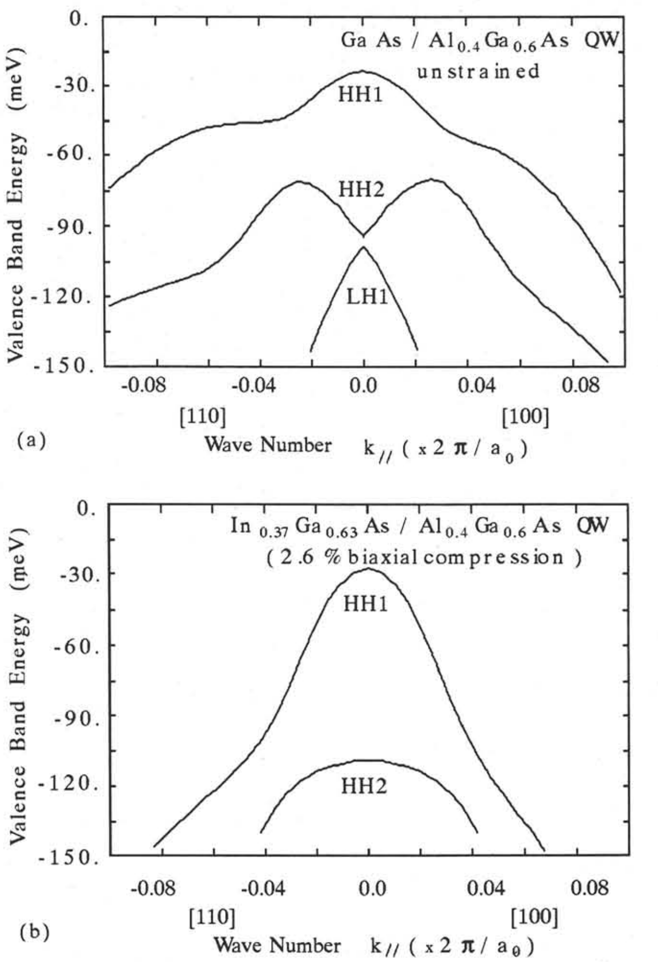
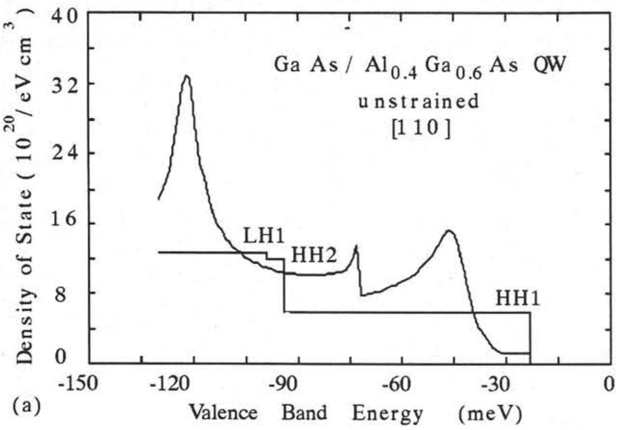


Fig. 1 (a) Valence-band subband structure for an unstrained 50Å GaAs/$Al_{0.4}Ga_{0.6}As$ QW. (b) Valence-band subband structure for an strained 50Å $In_{0.37}Ga_{0.63}As/Al_{0.4}Ga_{0.6}As$ QW with 2.6% biaxial compression.

$$\frac{m^*}{m_0} = \left[\gamma_1 + \gamma_2 - \frac{3\gamma_3^2}{\gamma_2} + 3(\gamma_1 - 2\gamma_2)\left(\frac{\gamma_3}{\gamma_2}\right)^2 \frac{(-1)^{n_-+1} + \cos(k_+L)}{(k_+L)\sin(k_+L)} \right]^{-1} \tag{2}$$

where $k_+L = [(\gamma_1 - 2\gamma_2)/(\gamma_1 + 2\gamma_2)]^{1/2}(n_-\pi)$ and n_- =1 for the HH1 subband. It is noted that the effective mass given in Eq. (2) is isotropic in the QW (001) plane. Evaluation of Eq. (2) and the bulk heavy-hole (HH) mass for the structure assumed in Fig. 2(a) indicates that the effective mass value of the HH1 subband at the zone center is reduced to 1/5 of the bulk value. The corresponding reduction of the DOS at the band edge relative to the step-like DOS is clearly seen in Fig. 2(a) even in this unstrained case. But the peaks in the DOS due to the subband nonparabolicity degrade the differential gain G as discussed later.



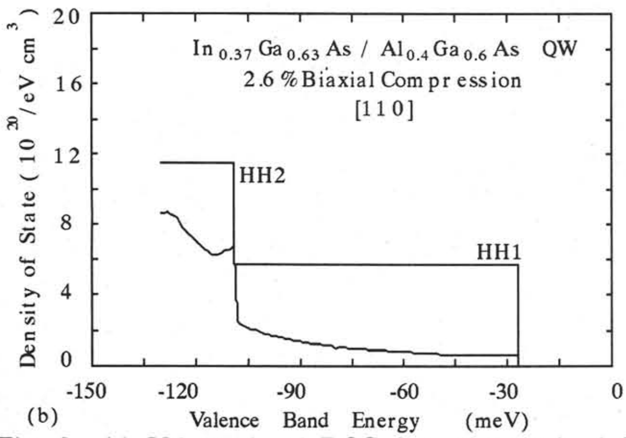


Fig. 2 (a) Valence-band DOS for an unstrained 50Å $GaAs/Al_{0.4}Ga_{0.6}As$ QW. The rotational symmetry around the [001] axis was assumed where the subband dispersions are represented by the [110] dispersion. The step-like DOS was calculated using the bulk effective mass as a reference. (b) Valence-band DOS for an strained 50Å $In_{0.37}Ga_{0.63}As/Al_{0.4}Ga_{0.6}As$ QW. The step-like DOS was calculated using the unstrained bulk effective mass as a reference.

Similar calculations were performed on the DOS of the 50Å strained $In_{0.37}Ga_{0.63}As$ QW. The step-like DOS was calculated as a reference using the effective HH mass value for the unstrained bulk $In_{0.37}Ga_{0.63}As$. It is clearly seen in Fig. 2(b) that the extra peaks do not appear in the DOS due to the reduced subband nonparabolicity, since the HH-LH mixing are reduced by the lowering of the LH band with the biaxial compression.

The laser properties were calculated for several material combinations of interest, i.e., two unstrained QW's of $GaAs/Al_{0.4}Ga_{0.6}As$ on GaAs and $In_{0.53}Ga_{0.47}As/InP$ on InP, and two biaxially compressed QW's of $In_{0.37}Ga_{0.63}As/Al_{0.4}Ga_{0.6}As$ on GaAs and $In_{0.9}Ga_{0.1}As/In_{0.52}Al_{0.48}As$ on InP. The QW width of 50Å was assumed in all cases. The band offset for $In_{0.53}Ga_{0.47}As//InP$ was calculated with the Harrison model and ΔE_c=340 meV and ΔE_v=260 meV were used. The 2.6% biaxial compression in the $In_{0.9}Ga_{0.1}As$ QW results in a 484-meV conduction to HH bulk band gap and a 618-meV conduction to LH bulk band gap. The calculated properties were also insensitive to the assumed band offset in this system.

The procedures for calculating the laser properties are conventional and the main parameters necessary for the calculations are described in the following. When the cavity length L=300 μm, the mirror reflectivity R=0.35, and the effective absorption loss of the guided mode α_{eff} =15 cm^{-1} are assumed, the mode gain Γg=50 cm^{-1} is obtained. In a GaAs/AlGaAs system, the optical confinement factor Γ=0.05 is possible with a graded-index separate confinement heterostructure where twin 50Å QW's are assumed. This gives the threshold optical gain of 1000 cm^{-1}. The same gain value was assumed for all the systems to be discussed in the following. The photon lifetime of 2 ps and TE-polarization were assumed for the calculation.

The calculated relaxation oscillation frequency f_r versus the p-type doping level is shown in Fig. 3 for the

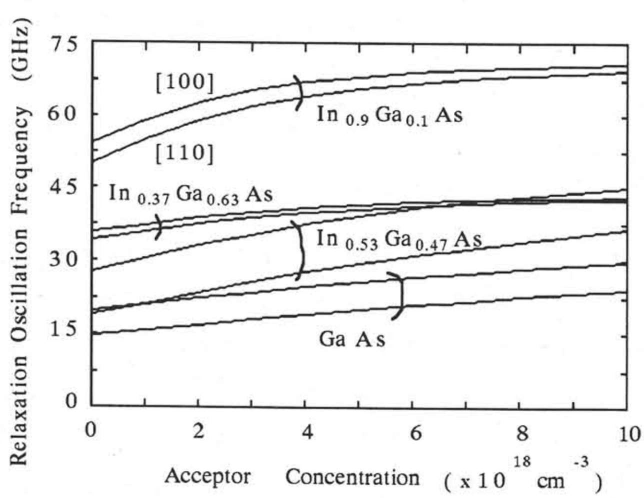


Fig. 3 Relaxation oscillation frequency vs. acceptor concentration in the well was calculated for two unstrained QW's of $GaAs/Al_{0.4}Ga_{0.6}As$ and $In_{0.53}Ga_{0.47}As/InP$, and for two biaxially compressed QW's of $In_{0.37}Ga_{0.63}As$ / $Al_{0.4}Ga_{0.6}As$ and $In_{0.9}Ga_{0.1}As$ / $In_{0.52}Al_{0.48}As$. In each material system, the upper and lower curves were calculated with the [100] and [110] dispersions for the valence subbands, respectively.

four material systems. The optical output power P_{out} of 20 mW from a 2 μm wide stripe, i.e., 20 mW/(2μmx0.01μm/0.05) was assumed in the calculation, which is the feasible power level even in the strained QW laser structure.[4] It is noted that lasers which oscillate in the longer wavelength is advantageous to increase the f_r value for a given optical output power since the photon density S_0 in Eq. (1) is related to P_{out} by the equation of $S_0 = P_{out} / (c/n_r) / (hc/\lambda)$, where h is the Planck constant and λ is the oscillation wavelength. The oscillation wavelength assumed for each system is 0.81 μm for GaAs QW, 1.04 μm for $In_{0.37}Ga_{0.63}As$ QW, 1.39 μm for $In_{0.53}Ga_{0.47}As$ QW, and 1.89 μm for $In_{0.9}Ga_{0.1}As$ QW which were calculated from the lowest transition energies for the 50Å QW's. The increase of the f_r value in the strained systems such as $In_{0.37}Ga_{0.63}As$ and $In_{0.9}Ga_{0.1}As$ QW's is clearly seen in Fig. 3. This is because the Fermi level in the valence band of the strained QW easily shifts for a change of the carrier concentration due to the reduced DOS near the band edge as shown in Fig. 2(b) and the resultant increase of the differential gain. The larger improvement in the $In_{0.9}Ga_{0.1}As$ system is attributed to the smaller conduction band effective mass and the longer oscillation wavelength. For the undoped $In_{0.9}Ga_{0.1}As$ QW, the f_r value is about 3 times larger than that of the GaAs QW and it reaches as high as 67 GHz with the acceptor doping level of $5x10^{18}cm^{-3}$. Since the 3-dB cutoff frequency is given by 1.2 f_r -1.5f_r , the 3-dB cutoff frequency near 90 GHz is expected. When the same photon density S_0 is assumed, the unstrained GaAs and $In_{0.53}Ga_{0.47}As$ QW's give almost the similar f_r values. The f_r value in the GaAs system increases with p-doping of $1x10^{19}$ cm^{-3} by 70-80% compared with the undoped case, which is in reasonable agreement with the measurement.[3]

The calculated lasing threshold current density for the $In_{0.9}Ga_{0.1}As/In_{0.52}Al_{0.48}As$ QW is about 43 A/cm^2 and is slightly reduced with the p-doping as shown in Fig. 4, which is about 1/9 of that for the GaAs QW. The assumed twin 50Å QW is not the optimum structure for the reduction of the threshold current and it will be reduced further with an adequate design. The Auger recombination which increases the threshold current in the long wavelength lasers was not included in the present calculation, but it will be effectively reduced in the strained system[6] since the carrier concentration at threshold is $9x10^{17}$ cm^{-3} in the strained $In_{0.9}Ga_{0.1}As$ QW and is reduced to ~1/3 of that in the unstrained $In_{0.53}Ga_{0.47}As$ QW.

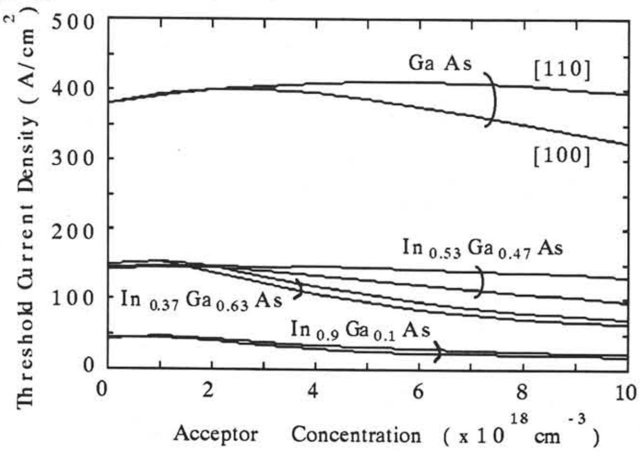


Fig. 4 Threshold current density vs. acceptor concentration in the well which corresponds to Fig. 3. In each material system, the upper and lower curves were calculated with the [100] and [110] dispersions for the valence subbands, respectively.

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