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Optical Gain and Intervalence Band Absorption in Long-Wavelength Strained Quantum Well Lasers

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The dependence of optical gain and intervalence band absorption (IVBA) on strain is analyzed for 1.5-μm $In_{1-x}Ga_xAs/InP$ strained quantum well lasers, by using a model including the band mixing effect. We theoretically show that ~1% compressive strain is the optimum strain which provides maximum gain. It is also revealed that IVBA, which decreases the quantum efficiency, is reduced to one-tenth of the unstrained value at around +1% compressive strain.

1. INTRODUCTION

The introduction of a compressively or tensile strained quantum well (QW) structure into the active region of semiconductor lasers has brought significant improvements in laser performance, *e.g.*, low threshold currents. These improvements occur because the compressive strain causes low threshold carrier concentration[1] and low internal loss[1-2] and the tensile strain causes high reduced density of states.[3] Recently it was shown experimentally that the threshold current density of 1.5-μm QW lasers depend on the magnitude of strain and that there is an optimum strain at which the threshold current density is minimized.[4] It was also reported that no lasing was obtained around a strain at which valence subbands degenerate. However a relation between the magnitude of the strain and the optical characteristics which determines the lasing performance has not been theoretically shown, though it is important for designing semiconductor lasers.

In this work, we analyze the dependence of optical gain and IVBA on strain for 1.5-μm InGaAs/InP QW lasers. We use a model that includes band mixing between the heavy hole (HH) states and the light hole (LH) states. It is theoretically shown that ~1% compressive strain is the best for 1.5-μm InGaAs/InP QW lasers because of their higher optical gain and lower internal loss.

2. CALCULATION MODEL

We consider a QW structure with an $In_{1-x}Ga_xAs$ well layer grown on a (001) InP substrate. The crystal lattice of the well layer has biaxial compressive strain when x<0.47 and biaxial tensile strain when x>0.47. The in-plane valence band structure is calculated based on the Luttinger-Kohn effective mass theory,[5] which enables us to take into account the effect of interband mixing between the HH states and the LH states. To include strain-dependent band mixing, we use the strain interaction Hamiltonian derived by Pikus and Bir.[6] Thus, bandgap shifts with strain are automatically introduced in the model. The non-parabolicity of the conduction band and the spin-orbit split-off band is considered by using Kane's k•p perturbation method.[7] The material parameters for $In_{1-x}Ga_xAs$ were determined by interpolating those of GaAs, $In_{0.53}Ga_{0.47}As$, and InAs.[8] Luttinger parameters were determined by interpolating the binary parameters of GaAs[9] and InAs.[10]

When we assume the k-selection rule, the optical gain at the photon energy E is given by

$$g(E) = A\sum_i\sum_j\int\left|M_{ij}\right|^2\rho_{red}(\bar{E}) \times [\,f_c(\bar{E}) - f_v(\bar{E})\,]\,\tilde{h}(E,\bar{E})\,d\bar{E}, \quad (1)$$

where A is a coefficient describing the transition probability, i and j are the indices of the conduction subband and the HH and LH subband, ρ_{red} is the reduced density of states, f_c and f_v are the Fermi-Dirac distributions of the conduction band and of the HH and LH band, respectively, and $\tilde{h}(E,\bar{E})$ is the line shape function defined as a Gaussian function. The momentum matrix element M_{ij} including interband mixing between the HH states and the LH states is given by

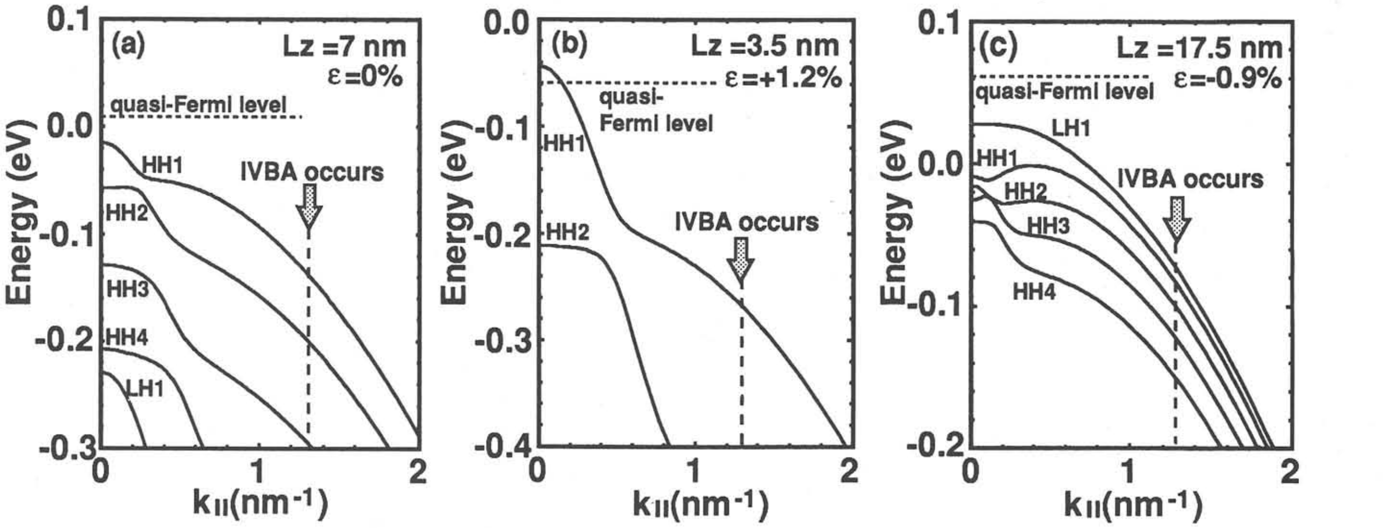

Fig. 1 Calculated in-plane valence band structures. The well widths and strains are (a) Lz=7 nm and ε=0% (gallium composition x=0.47), (b) Lz=3.5 nm and ε=1.2% (x=0.3), and (c) Lz=17.5 nm and ε=-0.9% (x=0.6).

$$\left|M_{ij}^{TE}\right| = \frac{3}{2}\left|M_0\right|^2\left[\,\left|a_{ij}\right| + \frac{1}{3}\left|b_{ij}\right|\,\right], \qquad (2)$$

for TE mode and

$$\left|M_{ij}^{TM}\right| = 2\left|M_0\right|^2\left|b_{ij}\right|^2, \qquad (3)$$

for TM mode. Here a_{ij} and b_{ij} are the respective mixing ratio of the i-th HH (J=3/2) and LH (J=1/2) states in the j-th HH and LH subband. The bulk momentum matrix element M_0 is estimated by the k•p perturbation method. The reduced density of states, the Fermi-Dirac distributions, and the momentum matrix element reflect the strain-included modification of the band structure.

We can also estimate the IVBA coefficient α_{IVBA} in the same way as the optical gain. We consider a transition between the ground-state subbands and use the bulk momentum matrix element. Thus the coefficient α_{IVBA} reflects the modification of the density of states by strain.

3. RESULTS AND DISCUSSION

The calculated in-plane valence band structures of QWs with a strain ε of (a) 0% (lattice matched), (b) +1.2% (compressive), and (c) -0.9% (tensile) are shown in Fig. 1. The well widths in these calculations were adjusted, according to the strain, for an emission wavelength of 1.5 μm. The standard of the energy is put to the top of the well-plane valence band neglecting the quantum confinement effects and the strain potential. The broken lines indicate the quasi-Fermi levels calculated for a hole density of 2×10^{18} cm^{-3} and a temperature of 300 K. For convenience, we name the subbands by the states at the band edge as shown in Fig. 1. Under compressive

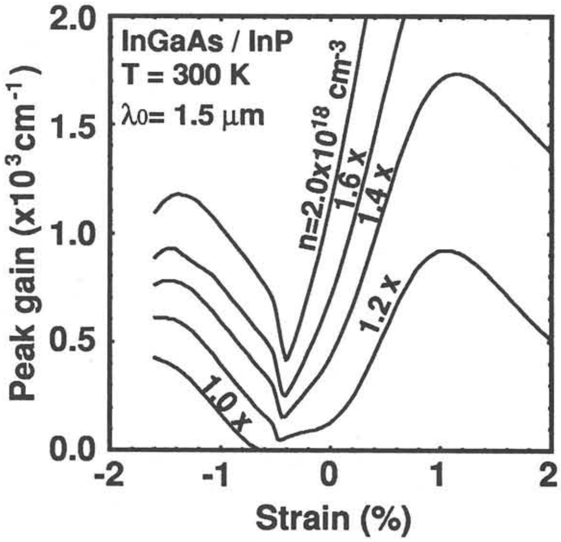

Fig. 2 Calculated dependence of optical gain on strain in 1.5-μm $In_{1-x}Ga_xAs/InP$ strained QW lasers.

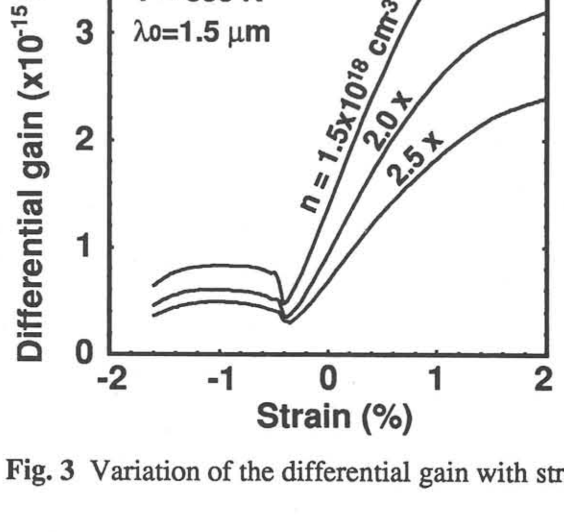

Fig. 3 Variation of the differential gain with strain.

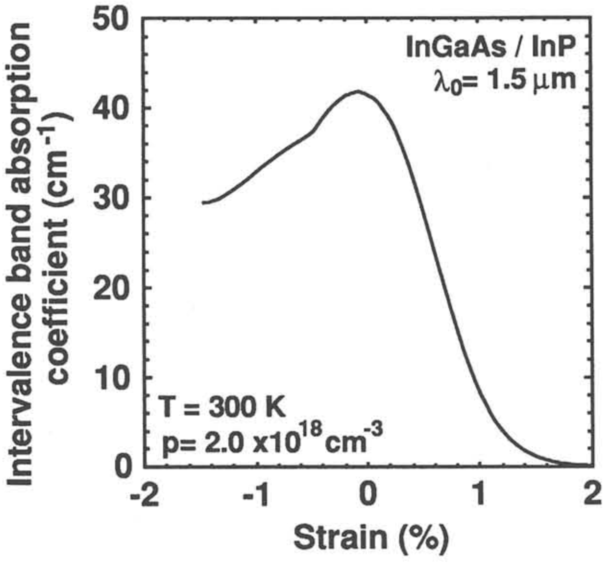

Fig. 4 Calculated dependence of intervalence band absorption coefficients on strain in 1.5-µm In1-xGaxAs/InP strained QW lasers.

strain (Fig. 1 (b)), the non-parabolicity of the HH band decreases, which is expected to provide higher optical gain and lower IVBA. We used these band structures to calculate the optical gain and IVBA of 1.5-µm strained QW lasers.

Figure 2 shows the calculated dependence of optical gain on strain at 300 K. The values shown in Fig. 2 are the peak gain of TE mode when ε>-0.4% and TM mode when ε<-0.4%. The calculated dependence is similar to the dependence of threshold current density reported by Thijs.[3] The optical gain decreases abruptly around a strain of -0.4%. This is because the momentum matrix element decreases as a result of the competition between TE and TM modes resulting from the degeneration of the top of the HH1 and LH1 subbands. Under compressive strain, the gain has a maximum value at ε=1.0%, above which the gain decreases due to the small well width (Lz<4 nm) which results in a large density of states. As with the optical gain, the differential gain has a minimum at ε=-0.4%, as is shown in Fig. 3. Unlike the optical gain, however, the differential gain increases with increasing strain. These results show that the optimum strain is determined by two competitive elements: modification of the band structure by strain which causes larger differential gain and a well width. These are the elements that determine the density of states.

Next we show the dependence of the IVBA coefficients on strain when assuming that the hole density is 2×10^{18} cm^{-3} and the temperature is 300 K (Fig. 4). The absorption coefficients α_{IVBA} are smaller for strained QW lasers than for a bulk laser (~110 cm^{-1}). This is due to the reduction of the reduced density of states resulting from the modification of the band structure. Moreover the coefficient α_{IVBA} decreases dramatically as the compressive strain increases. Around ε=+1%, at which the gain is maximized, the coefficient α_{IVBA} is lowered to one-tenth of the unstrained one. This is due to the reduction of the hole distribution at the energy where IVBA transition occurs (see Fig. 1). On the other hand, there is less change in the absorption coefficient under tensile strain. These results show that the low IVBA of QWs with compressive strain make it easy to obtain lasers with higher quantum efficiency.

4. SUMMARY

The dependence of optical gain and IVBA on strain which is important for designing semiconductor lasers was analyzed by using the effective mass theory including the band mixing effect. As a result, it was revealed that ~1% compressive strain is optimum for 1.5-µm InGaAs/InP QW lasers because of their higher optical gain and lower internal loss.

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