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Effect of Spin-Orbit Split-Off Bands on Linear Gain and Threshold Current Density of GaInP/AlGaInP Strained Quantum Well Lasers

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Effect of spin-orbit split-off bands of GaInP/AlGaInP strained quantum well lasers has been theoretically investigated, using 6 × 6 Luttinger-Kohn Hamiltonian. This analysis shows that laser performance of quantum well structures with a small amount of strain is considerably degraded by spin-orbit split-off bands, while the strain reduces the influence of spin-orbit split-off bands.

1. Introduction

Since the suggestion that compressive strain could reduce the threshold current of quantum well lasers[1)], there has been great interest in the study of strained material system such as InGaAs/GaAs, InGaAsP/InP, and GaInP/AlGaInP. Recently, low threshold, high power, and high temperature operation of GaInP/AlGaInP visible lasers were demonstrated[2-4)] using both compressive and tensile-strained quantum well structures. The strained quantum well is one of the most important elements for high performance lasers, so understanding their theoretical property is critical to maximize the device performance.

In conventinal analysis of strained quantum well lasers, only the mixing between |3/2,±3/2> (heavy hole) and |3/2,±1/2> (light hole) states are taken into account using the 4 × 4 Luttinger-Kohn Hamiltonian[5)]. Although the six-fold degeneracy including |1/2,±1/2> (spin-orbit split-off band) states exists at the top of valence band, the mixing effect of |1/2,±1/2> states is negligible in many III-V semiconductors, because the spin splitting energy, which is the energy difference between |1/2,±1/2> state bands and the others at $k_{\parallel}=0$, is much larger than the energy range of existing holes. Typical III-V semiconductor, GaAs has the spin splitting energy of 0.34eV, which is thought to be large enough to neglect the coupling with the spin-orbit split-off band.

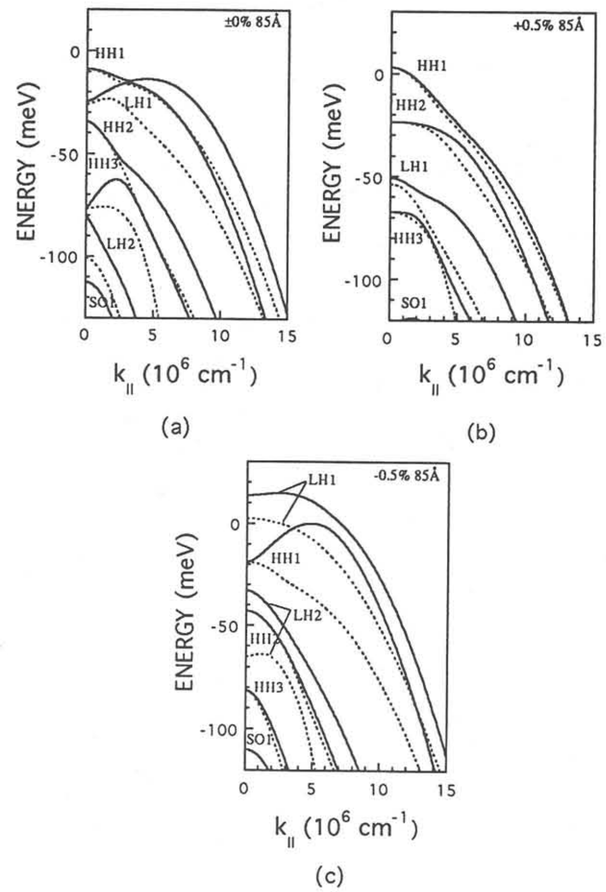

Fig. 1 Valence subband structures of strained quantum wells of (a) $\varepsilon_{\parallel}=\pm0\%$ (unstrained), (b) $\varepsilon_{\parallel}=+0.5\%$ (compressive), and (c) $\varepsilon_{\parallel}=-0.5\%$ (tensile) with the well width of 85Å. Solid and dashed lines show the results from 6×6 and 4×4 Hamiltonian calculations, respectively.

In the GaInP/AlGaInP system, however, the spin-orbit split-off band influences the other band structures, because the spin split-off energy in the quantum well is only about 0.1eV, which is much smaller than that of other laser materials. In this paper, we theoretically investigate the effect of the spin-orbit split-off band of GaInP/AlGaInP strained quantum well lasers using 6× 6 Luttinger-Kohn Hamiltonian.

2. Results and discussion

In the calculation, we use a single quantum well model assuming a constant well width of 85 Å with various strain. Barrier layers of $(Al_{0.5}Ga_{0.5})_{0.51}In_{0.49}P$ are used. Since we assume $Ga_xIn_{1-x}P$ ternary alloy for the well material, the band-gap energy is dependent on the strain. Here, we use ±0% (x=0.51), +0.5% (x=0.44), and -0.5 % (x=0.58) strained quantum well structures, and their equivalent band-gaps are estimated to be 1.936, 1.860, and 1.980 eV, respectively. All of the physical parameters were shown in a previous letter[6].

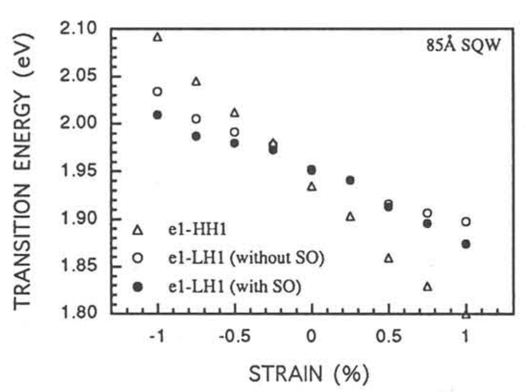

Fig. 2 Strain dependence of transition energies of GaInP/AlGaInP strained quantum well.

Figure 1 shows the valence subband structures of 85Å strained quantum wells. In the figures, HH, LH, and SO represent the heavy hole, light hole, and spin splitting hole subbands at $k_\parallel$=0, respectively. Compared to the results of a conventional 4×4 Hamiltonian calculation, the results of the 6×6 Hamiltonian calculation have stronger non-parabolicity, which is due to the mixing effect of the spin-orbit split-off bands. Under no strain in the 6 × 6 Hamiltonian calculation, HH1 and LH1 subbands have a strong non-parabolicity near the band-edge. The non-parabolicity is much larger than that in 4 × 4 Hamiltonian calculation because of the effect of spin-orbit split-off subbands. When the compressive strain of 0.5 % is induced, the energy difference between HH1 and LH1 becomes large, and the curvature near the band-edge becomes small. The subband structure difference between 6 × 6 and 4 × 4 Hamiltonian calculation is not so large in the compressive-strained quantum well. The tensile-strained quantum well has the LH subband at the band-edge, and a larger curvature at the band-edge is observed. Since the light hole subband is coupled with the spin-orbit split-off bands even at $k_\parallel$=0, the LH energy at $k_\parallel$=0 obtained in 6 × 6 Hamiltonian calculation is higher than that of 4 × 4 Hamiltonian calculation.

The mixing between LH and SO subbands at $k_\parallel$=0 changes the energy of electron-light hole transition. We calculated the energies of electron-heavy hole and electron-light hole transitions, as shown in Fig. 2. In the greater strain regions, the difference between the result with SO subbands and that without SO subbands in the electron-light hole transition is large. It indicates that SO subbands also influence the lasing wavelength of the tensile-strained quantum well lasers.

Figure 3 shows the maximum gain as a function of radiative recombination current of quantum well structures with the various strain. Particularly in the unstrained quantum well, the gain property is degraded when the SO subband effect is included. On the other hand, an improvement of the slope in this property is observed in the tensile-strained quantum well, which is due to the increased hole density of states at the valence band-edge.

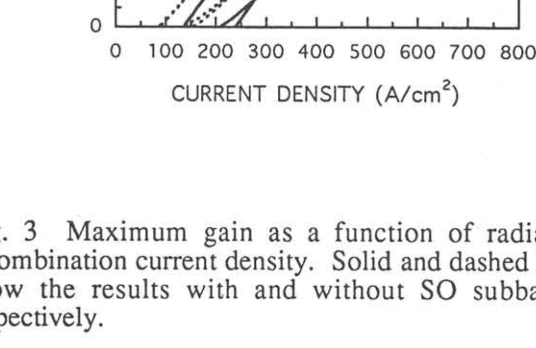

Fig. 3 Maximum gain as a function of radiative recombination current density. Solid and dashed lines show the results with and without SO subbands, respectively.

When the threshold gain is assumed to be 500 cm^{-1}, the threshold current densities of the strained quantum well lasers are estimated, which are shown in Fig. 4. In both the 6×6 and 4×4 Hamiltonian calculations, we can see the threshold current reduction by the strain. However, for a small amount of strain, the difference of the two calculation results is very large. When HH subband is at the band-edge, the strong mixing between LH and SO subbands reduces the hole occupation at the band-edge, which causes gain degradation and threshold current increase. Since the quantum wells with a small amount of strain have larger density of states near the valence band-edge, the hole occupation reduction at the band-edge is remarkable, and as a result, the linear gain is greatly degraded. On the contrary, when the LH subband is at the band-edge, it has a large density of states at the band-edge by the mixing with SO subband, and it makes the differential gain large. Therefore, the tensile strain also can reduce the threshold current density in actual devices, as reported previously[2]. While these results are thought to be varied with the threshold gain, band offset, well width, etc., the effect of spin-orbit split-off bands can not be neglected in any case.

3. Conclusion

In summary, we have theoretically analyzed the effect of the spin-orbit split-off bands on GaInP/AlGaInP strained quantum well lasers. Because of the small spin splitting energy of GaInP, we have found that spin-orbit split-off bands strongly coupled with heavy and light hole subbands, and linear gain properties greatly differs from those without the effect of spin-orbit split-off bands. The unstrained quantum well structure is most influenced by the spin-orbit split-off bands, and laser characteristics such as the differential gain and threshold current are degraded. The characteristics of compressive-strained quantum well changes only slightly with taking into account the spin-orbit split-off bands, and it has the lowest threshold current. In the tensile-strained quantum well structure, the spin-orbit split-off bands improves the differential gain because of the large density of states at the valence band-edge. To take into account the effect of the spin-orbit split-off bands is obviously important for the design of GaInP/AlGaInP strained quantum well lasers.

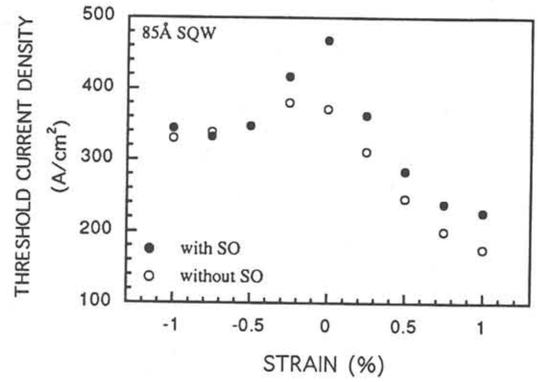

Fig. 4 Strain dependence of threshold current density of GaInP/AlGaInP strained quantum well lasers with assuming the threshold gain of 500 cm^{-1}.

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