Numerical analysis of quantum well with strained thin layers for polarization insensitive optical amplifiers

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Semiconductor optical amplifiers(SOA) have been widely studied because of their flexibility compared to the fiber amplifiers. But the most applications based on the quantum well(QW) SOA suffer from their anisotropic optical gain characteristics, which are caused by the mass dependent behavior of the light holes(LH) and the heavy holes(HH). So far, the tensile strained QW structures have been widely used to enhance the TM mode gain. But the allowed strain and the thickness are limited by the critical thickness and further more, the tensile strain with lattice mismatch around 1 %, where the LH band and the HH band are crossing, make the effective mass so heavier that the device can not operate at low threshold current[1]. Therefore, it is difficult to achieve the peak wavelength of 1.55 μm with conventional tensile strained QW. To avoid the critical thickness problems, we applied the wave function perturbation method to a lattice matched InGaAs/InGaAsP/InP QW via introducing thin and high tensile strained layers in the QW as shown in figure 1[2]. These layers were placed to perturb the wave functions with the idea that the LH feel the tensile strained layers much less than the HH do. These phenomena reflected directly in figure 2 as energy dispersion relations of QW with and without the layers. We presented the first two subbands of valence bands for convenience. The dotted line represents the QW without the layers and the solid line is for the QW with the three layers. Although the bands are coupled between LH and HH, we called them as LH1 and HH1 according to the nature of the bands at k_t=0 where LH and HH are decoupled. The first subband of QW without the layers is HH band while that of the QW with the three layers is LH band. In figure 3, we depicted E-k diagram of the QW with the three layers increasing the multiplier N in the figure 1. As the two layers approach to the center, the LH1 is shifted with only small ranges whereas the HH1 moves relatively large degree since the layer located near the center of the well perturb the even solution of HH1 in a larger degree than the odd solution of LH1. We must note that the positions of the layers do not change the effective mass of each subband but shifts the energy levels of the subbands. The gain characteristics of corresponding to the E-k diagram in the figure 3 are presented in figure 4. The upper three graphs are TM mode gain and the others are TE mode gain. The gain curves were temporarily increased with moving the layers in the two sides toward the center of the well. But this trend was vanished as we kept moving the layers to the center of the well. This method enables us to avoid the LH and the HH crossing even at lower tensile strain as shown in the figure 3. And the 3 dB gain bandwidths are much enhanced from 62.8 nm of a lattice matched 100 Å thick QW to 102.4 nm of QW with the layers as shown in the figure 4. For these analyses, we used the 4×4 Luttinger-Kohn Hamiltonian based on $k{\cdot}p$ method. The effective mass equations were solved with finite element method(FEM). We used the potential as continuous variable to avoid erroneous results. Otherwise, some numerical errors may occur during calculation of the first subband of valence band.

Reference

[1] Peter J. Thijis, Luuk F. Tiemeijer, J. J. M. Binsma, and Teus van Dongen, *IEEE QE*30, pp. 477-499, 1994.
[2] M. Hovinen, B. Gopalan, F. G. Johnson, and M. Dagenais, in *Proc. IEEE Lasers and Electro-Optics Soc. Annu. Meet.*, Boston, MA, Nov. 1996.

InGaAsP (1.3 μm)	Barrier
$In_{0.53}Ga_{0.47}As$	N × 3.5 Å
$In_{0.2}Ga_{0.8}As$	10 Å
$In_{0.53}Ga_{0.47}As$	35 Å - N × 3.5 Å
$In_{0.2}Ga_{0.8}As$	10 Å
$In_{0.53}Ga_{0.47}As$	35 Å - N × 3.5 Å
$In_{0.2}Ga_{0.8}As$	10 Å
$In_{0.53}Ga_{0.47}As$	N × 3.5 Å
InGaAsP (1.3 μm)	Barrier

Fig. 1. QW with three tensile strained layers embedded in the lattice matched InGaAs/InGaAsP/InP QW. The spacing of each layer was chosen to perturb the wave functions. The tensile strain applied to the thin layers is -2.35 %.

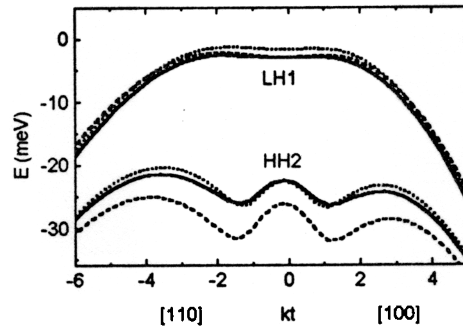

Fig. 3. The numerical simulation results of the first two valence bands of the structure in the figure 1.
——— : N = 5 ; ··········· : N = 6 ; - - - - - : N = 7

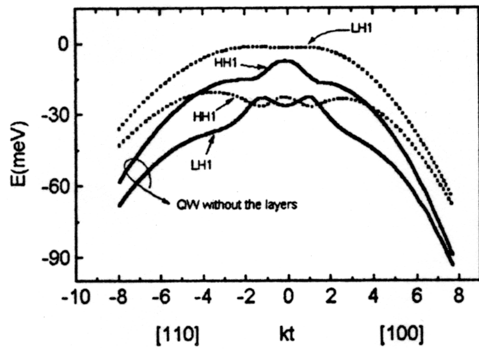

Fig. 2. The band diagram of the first two subbands of QW with and without the tensile strained thin layers. The solid lines are for the QW without the layers and the dotted lines are for the QW with the layers

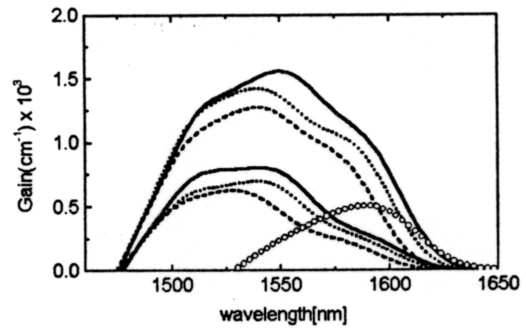

Fig. 4. The transverse electric(TE) and the transverse magnetic(TM) mode gain of the structure in the figure 1. The upper three graphs are TM mode and the other three are TE mode gain. The circled line is TE mode gain of lattice matched QW with Lz = 100 Å.
——— : N = 5 ; ··········· : N = 6 ; - - - - - : N = 7