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Influence of Bipolar Quantum Transport on Gain Characteristics of Strained-MQW Lasers

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The influence of bipolar quantum transport on the gain characteristics of strained quantum well lasers are studied based on the Wigner distribution function, which describes the statistical distribution of carriers in nonequilibrium state. In the simulation of QW lasers, the three Liouville equations with respect to the Wigner functions for electron, heavy-hole and light-hole, and the Poisson's equation to consider self-consistency in potential are solved simultaneously. The simulation results are compared with the experimental data.

1. INTRODUCTION

Although quantum well(QW) lasers are expected to improve the laser characteristics owing mainly to the step-like density of states in a QW structure, it has been recognized that there still remain some serious problems peculiar to QW lasers. They are the carrier leakage from QW layers(carrier overflow), the nonuniform carrier distribution in multi-quantum-well(MQW) active layers, in particular, the hole localization into p-side wells and the tunneling between the quantum wells. Since all of them are related to carrier transport effects, a design tool of QW lasers incorporating the quantum transport is strongly anticipated. Recently, we have proposed a bipolar quantum transport model of QW lasers based on the Wigner function[1], which describes the statistical distribution of carriers in nonequilibrium state. From the simulation of the carrier injection into a single QW and a double QW lasers, an unequal injection of electron and hole into QW active layer and a bottle neck phenomenon of heavy-hole injection into the p-side wells were demonstrated.

In this paper, we will further discuss the gain characteristics of strained-MQW lasers based on the Wigner distribution function to study the influence of carrier quantum transport on the optical properties of QW lasers. In the simulation of QW lasers, the three Liouville equations with respect to the Wigner functions for electron, heavy-hole and light-hole, and the Poisson's equation to consider self-consistency in potential are solved simultaneously. First, the nonuniform carrier injection into a strained-MQW active layer is discussed. Next, by using the calculated Wigner functions, the optical gain spectra of the strained-MQW laser are evaluated to compare with the experimental data. As a result, it is shown that the nonequilibrium properties of carriers significantly affect on the gain characteristics of QW lasers.

2. WIGNER FUNCTION MODEL FOR STRAINED-MQW LASERS

The schematic band diagram of an InGaAsP/InP strained-MQW laser used in this study is shown in Fig. 1, which consists of five InGaAsP well layers($\sim$ 1% compressively strained) and latticed-matched InGaAsP barrier layers(λ_g = 1.10μm). The widths of the wells and the barriers are 8nm and 10nm, respectively. In this paper, we define three Wigner functions for electron(n), heavy-hole(hh) and light-hole(lh), and discuss the bipolar quantum transport of carriers neglecting the recombination processes. This is to model the gain characteristics of QW lasers before lasing. Then, the quantum transport of each carrier is described by the following Liouville equation for the Wigner function considering the spatial variation of its effective mass[1,2].

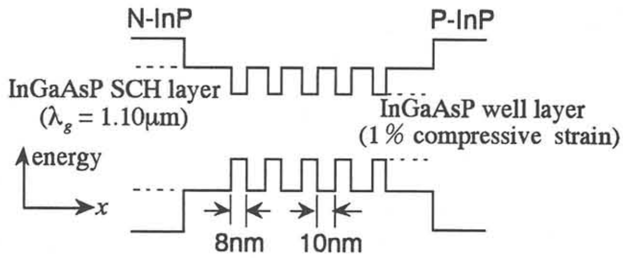

Fig. 1. Schematic band diagram of InGaAsP/InP strained-multi quantum well laser.

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\begin{aligned}
\frac{\partial f_i}{\partial t} &= \hbar\int_{-\infty}^{\infty}\frac{dk'_x}{8\pi}M_i^1(x,k_x-k'_x)\frac{\partial f_i}{\partial x} \\
&-\hbar\int_{-\infty}^{\infty}\frac{dk'_x}{4\pi}k'_xM_i^2(x,k_x-k'_x)f_i(x,k'_x) \\
&+\hbar\int_{-\infty}^{\infty}\frac{dk'_x}{16\pi}M_i^3(x,k_x-k'_x)\left[\frac{\partial^2 f_i}{\partial x^2}-4k'^2_x f_i(x,k'_x)\right] \\
&-\hbar\int_{-\infty}^{\infty}\frac{dk'_x}{4\pi}k'_xM_i^4(x,k_x-k'_x)\frac{\partial f_i(x,k'_x)}{\partial x} \\
&-\frac{1}{\hbar}\int_{-\infty}^{\infty}\frac{dk'_x}{2\pi}V_i(x,k_x-k'_x)f_i(x,k'_x) \\
&+\int_{-\infty}^{\infty}dk'_x[W(k'_x,k_x)f_i(x,k'_x)-W(k_x,k'_x)f_i(x,k_x)] \quad (1)
\end{aligned}
$$

$$(i = e, hh, lh)$$

where M_i^1, M_i^2, M_i^3, and M_i^4 are the terms representing the spatially varying effective masses, and V_i is the potential term. In the classical limit, the equation (1) reduces to the Boltzmann transport equation including new force term due to the variable effective mass. In the Liouville equation (1), scattering effects are phenomenologically included in the right-handside of the equation. $W(k'_x, k_x)$ is the transition probability from the state k'_x to the state k_x. In this paper, LO phonon scattering processes are considered based on Fermi's golden rule.

The above Liouville equation (1) is solved simultaneously with the Poisson's equation to include the self-consistency in potential. As the boundary conditions for the Wigner functions, the electrons are assumed to be injected only from n-InGaAsP and the heavy-hole and the light-hole only from p-InGaAsP. The discretization of the equations by the finite-difference method was discussed in detail in ref. 2. The effective masses of heavy-hole and light-hole in strained QW layers are determined by the dispersion relations derived from the Luttinger-Kohn hamiltonian.

3. CARRIER INJECTION INTO STRAINED-MQW LASERS

First, to study the nonuniform carrier injection into the strained-MQW active layers, the electron and the hole density distributions are simulated. Fig. 2 shows the carrier density distributions and the band energy variations computed for the bias voltage of 1.24V, where the quantum well regions are designated by the shaded patterns. Nonuniform carrier injection into QW active layers is clearly seen in Fig. 2(a). In particular, electrons(n) and heavy-holes(p_{hh}) are found to be accumulated the most in the well layer nearest n- and p-region, respectively, as expected. However, looking at the three QW layers located at the middle of active region, the electron density increases and the heavy-hole density decreases with distance. This is because the potential energy decreases with distance as shown in Fig. 2(b) due to the space charge effect, which is caused by the unequal injection of electron and hole into QW active layers.

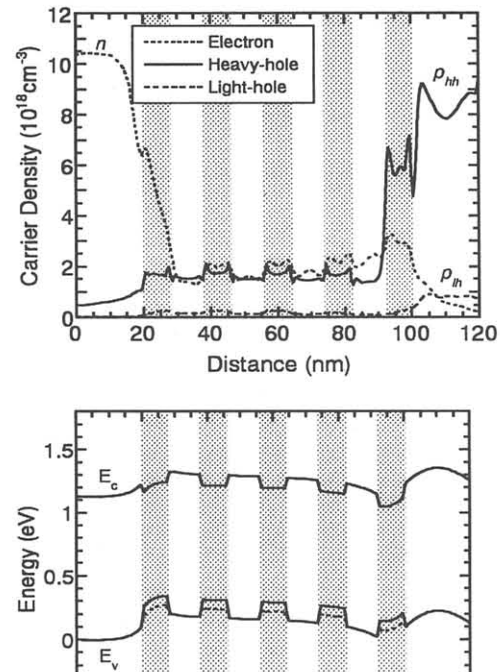

Fig. 2. Computed carrier density and potential energy distributions for bias voltage of 1.24V. The shaded patterns indicate the quantum well region.

4. GAIN CHARACTERISTICS CONSIDERING BIPOLAR QUANTUM TRANSPORT

Next, we study the influence of bipolar quantum transport on the gain characteristics of strained-MQW laser. Since the Wigner function corresponds to nonequilibrium distribution functions of carriers, the optical gain spectra of QW lasers in nonequilibrium state can be evaluated by using the Wigner functions. The calculated Wigner function for electron is shown in Fig. 3. The distribution functions for heavy-hole and light-hole are obtained as well. Several peaks in k_x-space are observed inside the QW layers, which must correspond to the quantized subbands formed in the well. However, the distribution functions are not discrete, but continuous. The above result means that the nonequilibrium distribution functions of carriers are quite different from the Fermi-Dirac functions at thermal equilibrium. Since current injection causes nonequilibrium states of carriers, the Fermi-Dirac functions are not applicable to the analysis of gain spectra when the injected current is as large as the population inversion is realized in the QW active layers. Thus, we modify the optical gain formula[3] as

$$g(E) = \sum_{v=hh,lh} \frac{E}{cn_r\varepsilon_0\hbar} \int_{-\infty}^{\infty} \frac{L_W}{\pi} dk_x^c \int_{-\infty}^{\infty} \frac{L_W}{\pi} dk_x^v \int_0^{\infty} dk_t \frac{k_t}{\pi L_W} \times \frac{|R_{cv}|^2 [F_c(x,k_x^c,k_t) + F_v(x,k_x^v,k_t) - 1] \left(\frac{\hbar}{\tau_{in}}\right)}{[E - E_{cv}(k_x^c,k_x^v,k_t)]^2 + \left(\frac{\hbar}{\tau_{in}}\right)^2} \quad (2)$$

where the subscripts x and t denote the directions perpendicular and parallel to the well layer, respectively, and v indicates either heavy-hole(hh) or light-hole(lh). The same shall apply hereafter. L_W is the width of the quantum well. τ_{in} is the relaxation time of the dipole moment and taken as 0.11ps for 1.3μm InGaAsP lasers[4]. Here, note that F_c and F_v are the nonequilibrium distribution functions in the conduction and the valence bands, respectively, and defined as

$$F_i(x,\boldsymbol{k}^i) = \frac{1}{1 + \dfrac{\exp\left(\dfrac{\hbar^2 k_t^2}{2m_{it}^*(x)k_BT}\right)}{\exp\left[\dfrac{\pi\hbar^2}{m_{it}^*(x)k_BT} f_i(x,k_x)\right] - 1}} \quad (3)$$

$$(i = e, hh, lh)$$

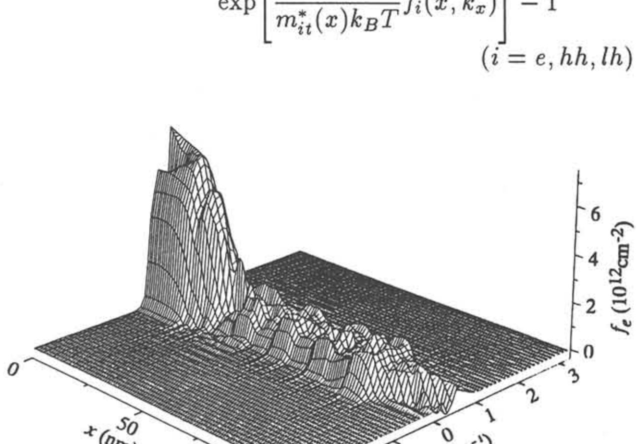

Fig. 3. Wigner distribution function for electron.

where $f_i(x, k_x)$ is the Wigner function calculated in the Liouville equations (1). In the equation (3), the exponential distribution is assumed in the transverse directions. Further, in the equation (2), the summations for the discretized subbands, which is used in the conventional gain formula, are replaced by the integrals with respect to k_x considering the continuous states in the wells. $|R_{cv}|^2$ is the matrix element of the dipole moment, and written as[5)]

$$|R_{chh}|^2 = \begin{cases} \frac{3}{4}\left(1+\cos^2\theta\right)|R|^2 \int dx\, \psi_{c,k_x^c}\psi_{hh,k_x^{hh}} & ,\mathrm{TE} \\ \frac{3}{2}\sin^2\theta\, |R|^2 \int dx\, \psi_{c,k_x^c}\psi_{hh,k_x^{hh}} & ,\mathrm{TM} \end{cases} \quad (4)$$

$$|R_{clh}|^2 = \begin{cases} \frac{1}{4}\left(5-3\cos^2\theta\right)|R|^2 \int dx\, \psi_{c,k_x^c}\psi_{lh,k_x^{lh}} & ,\mathrm{TE} \\ \frac{1}{2}\left(1+3\cos^2\theta\right)|R|^2 \int dx\, \psi_{c,k_x^c}\psi_{lh,k_x^{lh}} & ,\mathrm{TM} \end{cases} \quad (5)$$

$$\cos^2\theta \approx \frac{k_x^{v\,2}}{k_x^{v\,2}+k_t^2} \quad (6)$$

$$|R|^2 = \frac{e^2\hbar^2}{E_{cv}^2}\left(\frac{m_0}{m_c^*}-1\right)\frac{E_g(E_g+\Delta)}{12m_0(E_g+\frac{2}{3}\Delta)} \quad (7)$$

$$E_{cv} = E_g + \frac{\hbar^2 k_x^{c\,2}}{2m_{cx}^*} + \frac{\hbar^2 k_x^{v\,2}}{2m_{vx}^*} + \frac{\hbar^2 k_t^2}{2}\left(\frac{1}{m_{ct}^*}+\frac{1}{m_{vt}^*}\right). \quad (8)$$

The wavefunctions in the equations (4) and (5) are represented by using the Wigner functions as

$$\psi_{i,k_x^i}(x) = \sqrt{\frac{f_i(x,k_x)}{\int_{well} dx\, f_i(x,k_x)}} \quad (i = e, hh, lh) \quad (9)$$

where the wavefunctions are normalized in each well region.

By using the gain model mentioned-above, the optical gain spectra of the strained-MQW laser are evaluated as shown in Fig. 4, where the experimental gain spectra measured by the Hakki and Paoli's method, and the simulation results of conventional gain model are also plotted. It is found that the gain spectra of our model are in good agreement with the experimental gain curves, especially at the longer wavelength. The gain curves in our model decreases gradually as the wavelength becomes longer than the gain peak, while the gain spectra of the conventional model drops abruptly. We consider from the Wigner distribution function shown in Fig. 3 that the carriers with energy smaller than the fundamental subband exist in the nonequilibrium quantum transport that contributes to the gain spectra at the longer wavelength.

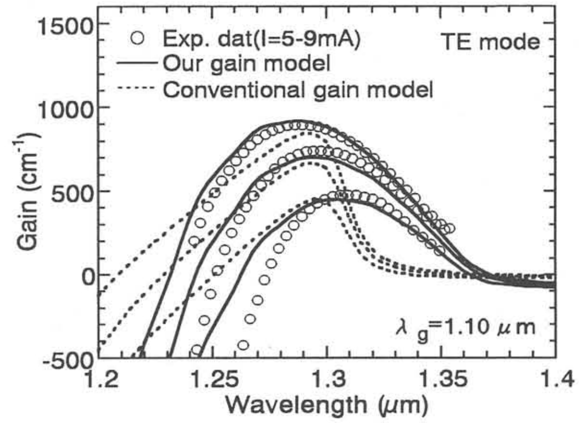

Fig.4. Gain spectra calculated by using Wigner distribution functions. The experimental data and the simulation results of conventional gain model are also indicated.

5. CONCLUSION

The influence of bipolar quantum transport on the gain characteristics of strained-MQW lasers are studied based on the Wigner distribution function. In the simulation of QW lasers, the three Liouville equations with respect to the Wigner functions for electron, heavy-hole and light-hole, and the Poisson's equation to consider self-consistency in potential are solved simultaneously. As a result, the nonuniform carrier injection into the strained-MQW active layer is clearly shown. Further, by using the calculated Wigner functions, which correspond to nonequilibrium distribution functions of carriers, the optical gain spectra of the strained-MQW laser are evaluated to compare with the experimental data. It is found that the gain spectra of our model are in good agreement with the experimental gain curves, which means that the nonequilibrium properties of carriers significantly affect on the gain characteristics of QW lasers. Thus, we believe that the Wigner function model will provide a powerful tool in the precise design of quantum well lasers.

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