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Quantum Mechanical Model of Carrier Transport in SCH-Quantum Well Lasers

H. Tsuchiya, M. Ogawa, and T. Miyoshi
Department of Electrical and Electronics Engineering
Kobe University
Rokko-dai, Nada-ku, Kobe 657, Japan

The quantum mechanical model of carrier transport in SCH-quantum well lasers based on the Wigner function is presented for the first time. In the simulation, the three quantum Liouville equations with respect to the Wigner functions defined for electron, heavy-hole and light-hole simultaneously with the Poisson's equation to consider self-consistency in potential. As a simulation model, InGaAsP/InGaAs SCH-single quantum well lasers are considered. The influence of carrier transport on the gain characteristics of SCH-single quantum well lasers is discussed.

1.INTRODUCTION

Quantum well(QW) lasers are expected to improve the laser characteristics, in particular, threshold current, direct modulation bandwidth and spectral line - width. Since it is now possible to fabricate the QW lasers as designed with the progress of precise crystal growth and ultrafine process, the precise simulation describing the quantum mechanical transport of carriers, instead of the classical hydrodynamic model[1)] and the phenomenological rate equations[2)], has become more important.

The main purpose of this paper is to show that an exact gain model considering carrier transport in the quantum well is indispensable for the precise design of the QW laser. In the conventional theory, to estimate the optical gain of the QW lasers, electrons and holes are assumed to be equally injected to the quantum well layer as well as the bulk double heterojunction(DH) lasers. However, in the actual QW lasers, such an assumption may be doubtful because electrons and holes show their own carrier transport, such as the carrier capture into the quantum well and the carrier escape from the quantum well by thermionic emission and tunneling. To discuss the *real* gain characteristics of the QW lasers considering such a carrier transport phenomena, we will propose the quantum transport model of the QW lasers based on the Wigner function. The Wigner function model, which has been successfully introduced to design quantum electronic and optical devices so far[3-5)], is the fundamental representation of quantum transport incorporating quantum statistical mechanics. In the simulation of the QW lasers, the three Liouville equations with respect to the Wigner functions defined for electron, heavy-hole and light-hole, and the Poisson's equation to consider self-consistency in potential are solved simultaneously.

In this paper, the real gain characteristics considering carrier transport are presented and compared with the results of the conventional gain model. We will also compare the simulation results of our real gain model with the experimental data reported for the multi-quantum well lasers[6)]. As a result, it is shown that the carrier transport plays an important role on the gain characteristics of SCH-QW lasers.

2.QUANTUM TRANSPORT MODEL OF SCH-QUANTUM WELL LASERS

The device schematic model of an $In_{1-x}Ga_xAs_yP_{1-y}$ / $In_{0.53}Ga_{0.47}As$ SCH-QW laser is shown in Fig. 1(a). For the quantum mechanical simulation, only the finite quantum region shown in Fig. 1(b) is analyzed. The bandgap wavelength of the optical confinement layer λ_g is variable. The quantum transport model

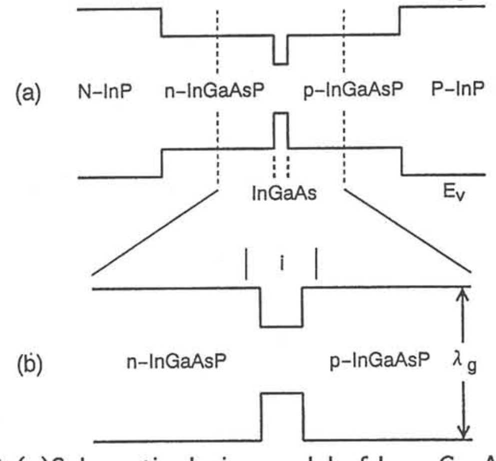

Fig. 1 (a)Schematic device model of $In_{1-x}Ga_xAs_yP_{1-y}$ / $In_{0.53}Ga_{0.47}As$ single quantum well laser with SCH-structure. (b)Model used in the simulation.

of the QW lasers has to describe carrier transport phenomena, such as the carrier diffusion in the optical confinement layers, the carrier capture into the quantum wells, the carrier recombination inside and outside the quantum wells, the carrier escape from the quantum wells, and the tunneling between the quantum wells. In this study, we define three Wigner functions for electron(e), heavy-hole(hh) and light-hole(lh), and discuss the 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[3].

$$
\begin{aligned}
\frac{\partial f_i}{\partial t} = \hbar \int_{-\infty}^{\infty} \frac{dk'}{8\pi} M_i^1(x, k-k') \frac{\partial f_i}{\partial x} \\
-\hbar \int_{-\infty}^{\infty} \frac{dk'}{4\pi} k' M_i^2(x, k-k') f_i(x, k') \\
+\hbar \int_{-\infty}^{\infty} \frac{dk'}{16\pi} M_i^3(x, k-k') \left[\frac{\partial^2 f_i}{\partial x^2} - 4k'^2 f_i(x, k') \right] \\
-\hbar \int_{-\infty}^{\infty} \frac{dk'}{4\pi} k' M_i^4(x, k-k') \frac{\partial f_i(x, k')}{\partial x} \\
-\frac{1}{\hbar} \int_{-\infty}^{\infty} \frac{dk'}{2\pi} V_i(x, k-k') f_i(x, k') \\
-\frac{1}{\tau_i} \left[f_i(x, k) - f_i^0(x, k) \int dk' f_i(x, k') \right] \qquad (1) \\
(i = e, hh, lh)
\end{aligned}
$$

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. The Liouville equation(1) has the following two features. First, in the classical limit, the equation(1) reduces to the Boltzmann transport equation including new force term due to the variable effective mass. Second, the continuity equation is derived from the equation(1) by integrating with respect to k. In the equation(1), the collision term is phenomenologically added to the right-hand side of the equation. 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. 3.

3.INFLUENCE OF CARRIER TRANSPORT ON GAIN CHARACTERISTICS

First, to study the carrier transport in SCH-single QW lasers, the electron and the hole density distributions are simulated. The width of quantum well is fixed to be 7nm. The carrier relaxation times are given as $\tau_e = 0.37$ps, $\tau_{hh} = 0.07$ps and $\tau_{lh} = 0.42$ps.

Fig. 2 shows the electron and the hole density distributions and the band energy variations calculated for (a)$\lambda_g = 1.3\mu$m and (b)$\lambda_g = 1.15\mu$m SCH-structures, where the heavy-hole (dashed line) and the light-hole(dotted line) distributions are illustrated separately. The quantum well region is between $x =$

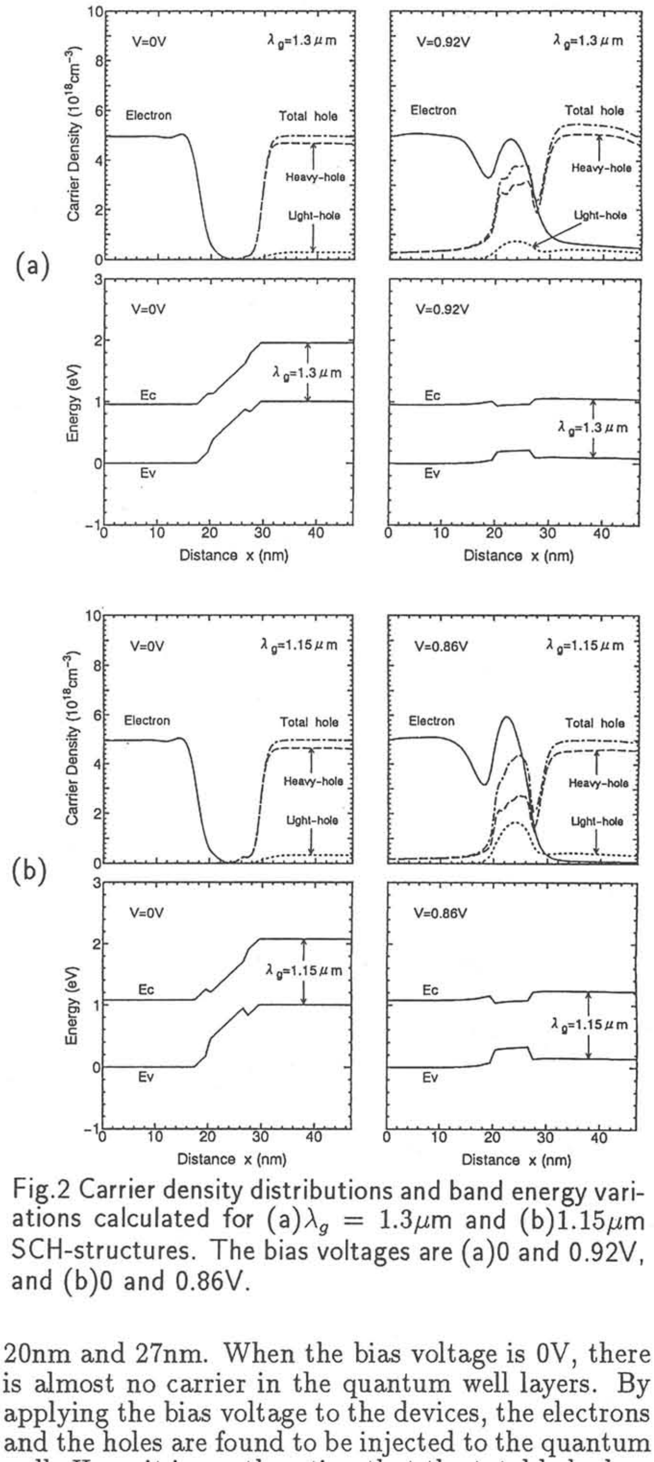

Fig.2 Carrier density distributions and band energy variations calculated for (a)$\lambda_g = 1.3\mu$m and (b)1.15μm SCH-structures. The bias voltages are (a)0 and 0.92V, and (b)0 and 0.86V.

20nm and 27nm. When the bias voltage is 0V, there is almost no carrier in the quantum well layers. By applying the bias voltage to the devices, the electrons and the holes are found to be injected to the quantum well. Here, it is worth noting that the total hole density injected to the quantum well is smaller than the injected electron density in both cases of $\lambda_g = 1.3\mu$m and 1.15μm. In short, the condition that electrons and holes are equally injected to the quantum well is not satisfied when the carrier transport is considered. Further, it is found from Fig. 2 that there is only one peak in the electron and the light-hole distributions inside the quantum well region, while several peaks are observed for the heavy-hole distribution. The number of heavy-hole peaks are three and four in Fig. 2(a) and (b), respectively, which corresponds to the number of the quantized subbands in the well. The larger number of the heavy-hole subbands in 1.15μm of SCH-structure will deteriorate the gain characteristics of the SCH-QW laser as discussed later.

Next, by using the carrier densities injected to the quantum well shown in Fig. 2, the laser gain spectra are studied. Fig. 3(a) and (b) show the gain spectra calculated for (a)$\lambda_g = 1.3\mu$m and (b)$\lambda_g = 1.15\mu$m SCH-structures. The well-known fact that the gain of TE mode is larger than that of TM mode is confirmed even in this quantum transport analysis. Here, it should be noted that the shape of the gain spectra is slightly narrower for $\lambda_g = 1.3\mu$m, which is in agreement with the experimental results reported in the multi-quantum well(MQW) lasers[6]. The maximum gains for TE mode are plotted in Fig. 4 as a function of the injected electron density, where the calculated results of the conventional gain model(N=P) are also indicated for comparison. Since the hole density injected to the quantum well becomes smaller than the injected electron density in our gain model considering carrier transport, the maximum gain reduces compared with the conventional gain model. In addition, our gain model gives larger maximum gains in case of $\lambda_g = 1.3\mu$m, which is contrary to the results of the conventional gain model. This is because the heavy-hole densities captured into the fundamental level decrease in $\lambda_g = 1.15\mu$m due to the existence of the fourth quantized subband of heavy-hole.

Further, from the results of our gain model shown in Fig. 4, the differential gains are calculated to be 2.17×10^{-16}cm^2 and 1.97×10^{-16}cm^2 for $\lambda_g = 1.3\mu$m and 1.15μm SCH -structures, respectively, both of which are larger than 1.33×10^{-16}cm^2 estimated for the $In_{0.53}Ga_{0.47}As$ DH laser. The differential gain for 1.3μm of SCH-structure is evidently larger, which means that the injected holes are efficiently captured into the fundamental level of heavy-hole. The larger differential gain of $\lambda_g = 1.3\mu$m was experimentally reported in the InGaAsP / InGaAs MQW lasers[6]. Although the difference between the differential gains of $\lambda_g = 1.3\mu$m and 1.15μm in ref. 6 is greater than our result, it may be because the single quantum well structure is considered in this study. In the MQW lasers, the difference shown in Fig. 4 must be amplified and additionally, the higher barrier of $\lambda_g = 1.15\mu$m will deteriorate the succeeding smooth carrier injection, in particular, the heavy-hole injection into each quantum well.

4.CONCLUSION

The quantum mechanical model of carrier transport in SCH-quantum well lasers based on the Wigner function has been presented for the first time. Under the condition below the laser threshold, we have been successful in solving the three Liouville equations with respect to the Wigner functions defined for electron, heavy-hole and light-hole, and the Poisson's equation simultaneously. From the carrier density distributions simulated by the Wigner function model, it is shown that electrons and holes are not equally injected to the quantum well active layer, which means that the assumption used in the conventional gain model is not valid for the quantum well lasers. Further, the influence of carrier transport on the gain spectrum and the differential gain of SCH-single QW lasers are studied. Since the simulation results are in good agreement with the experimental data reported for the multi-quantum well lasers, we believe that the Wigner function model will provide a powerful tool in the precise design of quantum well lasers.

In this paper, we discussed only the static quantum transport of carriers below the laser threshold. To discuss the dynamic characteristics of quantum well lasers, we will have to introduce the terms describing the interactions between electrons and photons into the Liouville equations of the Wigner functions.

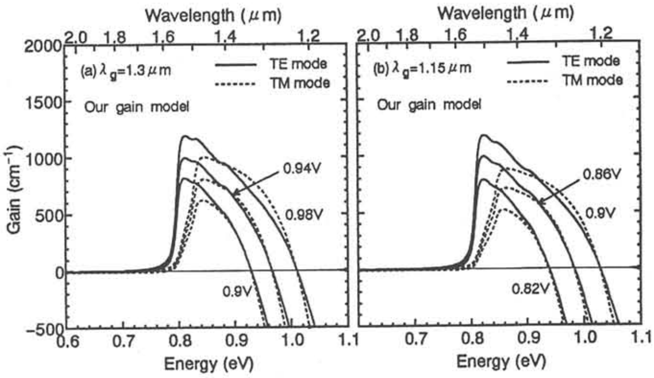

Fig.3 Gain spectra calculated for (a)$\lambda_g = 1.3\mu$m and (b)1.15μm SCH-structures. The bias voltages are (a) 0.9, 0.94 and 0.98V, and (b) 0.82, 0.86 and 0.9V.

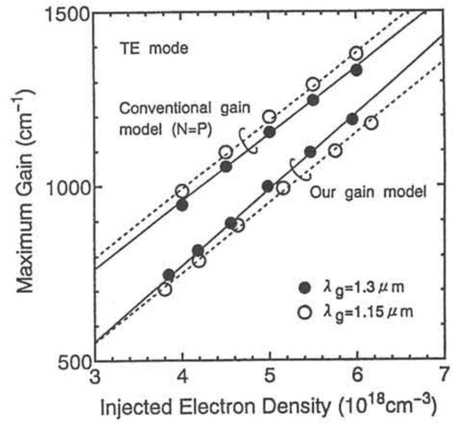

Fig.4 Maximum gains for TE mode as a function of injected electron density for $\lambda_g = 1.3\mu$m and 1.15μm. The solid and the dotted lines represent a weighted least square fit to the maximum gain data.

REFERENCES

1)H. Hirayama et al., IEEE J. Quantum Electron., **QE-28**(1992) 68.

2)R. Nagarajan et al., IEEE Photonics Technol. Lett., **3**(1992) 121.

3)H. Tsuchiya et al., IEEE Trans. on Electron Devices, **ED-38**(1991) 1246.

4)H. Tsuchiya et al., IEEE Trans. on Electron Devices, **ED-39**(1992) 2465.

5)T. Miyoshi et al., IEEE J. Quantum Electron., **QE-28**(1992) 25.

6)H. Watanabe et al., in *Nat. Conven. Rec. IEICE Japan*, Mar. 1990, (in Japanese), C-147, p. 4-202.