Simulation of quantum-well slipping effect on optical bandwidth in transistor laser

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Received August 18, 2008

An optical bandwidth analysis of a quantum-well (16 nm) transistor laser with 150-μm cavity length using a charge control model is reported in order to modify the quantum-well location through the base region. At constant bias current, the simulation shows significant enhancement in optical bandwidth due to moving the quantum well in the direction of collector-base junction. No remarkable resonance peak, limiting factor in laser diodes, is observed during this modification in transistor laser structure. The method can be utilized for transistor laser structure design.

OCIS codes: 270.0270, 250.0250, 230.0230.

doi: 10.3788/COL20090705.0435.

Emitter carrier injection and base electron-hole recombination with base carrier transport (emitter to collector) are fundamental to the operation of a transistor. Utilizing electrons and holes, the transistor operates by injecting minority carriers into the base, recombining some of the carriers in this region, and transporting the remainder to the collector[1−3]. The heterojunction bipolar transistor (HBT) has the capability of forming a three-port device, i.e., a transistor laser (TL), in which an optical collector (quantum well, QW) embedded in the base region manipulates base carrier distribution. This makes the TL produce simultaneously two outputs, electrical and optical, which work complementarily[4].

In this letter, we examine the effect of QW position in TL by employing the charge control model[1] to determine the optimized location for QW. The HBT laser (HBTL) structure studied here, described and sketched in detail in Refs. [2] and [5], consists of three regions, two 10^{19}-cm^{-3} doped GaAs regions and one 16-nm undoped InGaAs QW within them. The continuity equations for these three regions are expressed as

$$\partial n/\partial t = D\frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_{\text{bulk}}}, \tag{1}$$

$$\partial n/\partial t = D\frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_{\text{qw}}}, \tag{2}$$

where $n = n(x,t)$ is the base electron distribution, D is the diffusion constant, τ_{bulk} and τ_{qw} are the recombination lifetimes in the GaAs and InGaAs-QW, respectively. Solving these equations, we can shape the distribution of base electrons injected from emitter, as shown in Fig. 1. The position of QW, called W_{EQW} and defined as the distance between its center and the emitter-base interface, is variable during the following analysis. The charge control model for TL[1], as sketched in Fig. 2, simulates the minority carrier profile and consists of superposition of two triangular shape charge populations named as Q_1 and Q_2. In this model, Q_1 and Q_2, which are responsible terms for transporting minority carriers to the QW and electrical collector correspondingly, are in the same order of magnitude and calculated as

$$Q_1 = q\Delta n_1 A W_{\text{EQW}}/2, \tag{3}$$

$$Q_2 = q\Delta n_2 A W_{\text{B}}/2. \tag{4}$$

where q is the electron charge, Δn_1 and Δn_2 are the carrier populations at the emitter-base interface due to Q_1 and Q_2, respectively, A is the device area, and W_{B} is the base width.

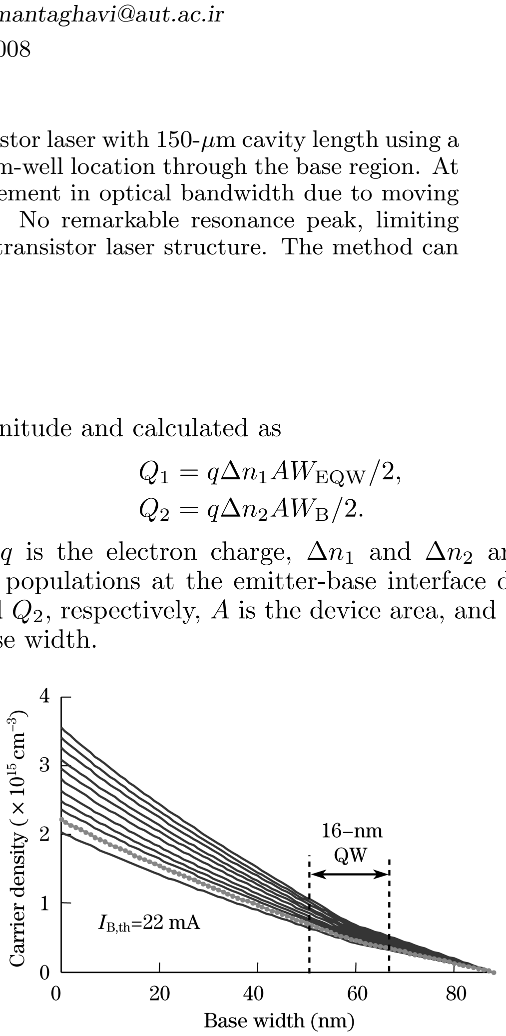

Fig. 1. Calculated minority carrier (electron) distribution corresponding to the current-voltage characteristics of TL[1]. The cavity length is 150 μm, the temperature is 15 °C. $I_{\text{B,th}}$ is the threshold of the base current for laser operation.

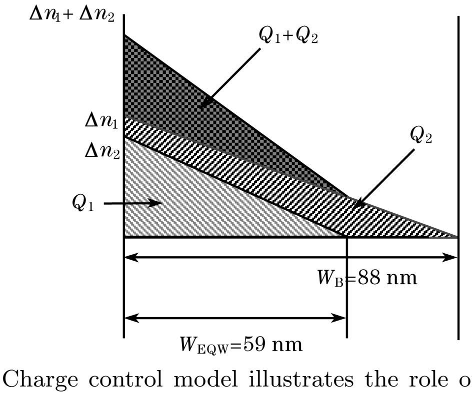

Fig. 2. Charge control model illustrates the role of Q_1 and Q_2 triangles in the entire base carrier distribution.

1671-7694/2009/050435-02

Under a constant base-emitter junction voltage V_{BE}, Δn_1 and Δn_2 are not variable, i.e., two triangles are "tied" at the emitter side of the base. So Q_2 should be invariant with any changes in QW position W_{EQW}, while Q_1, representative for the recombination in QW, varies. The area under the Q_1 triangle is a product of Δn_1 and W_{EQW} which can be modified. For instance, with W_{EQW}=15 nm, the carrier density tilting happens "sooner", when traveling from the emitter toward the collector through the base. Thus the carrier profile and the charge control model are reformed, as shown in Figs. 3 and 4, respectively.

Q_1 and Q_2 are then combined to form the overall effective base recombination lifetime τ_{B} of the entire base population, which is expressed as $1/\tau_{\mathrm{B}} = 1/\tau_{\mathrm{bulk}} + Q_1/(Q_1+Q_2)\tau_{\mathrm{t},1}$, τ_{bulk} is about 193 ps and the transient time $\tau_{\mathrm{t},1}$ from emitter to QW is about 0.667 ps. Displacement of the QW position toward the emitter can cause two distinguished effects. The first one is that τ_{B} decreases due to reduction of Q_1 while Q_2 is constant. Secondly, according to the diffusion current equation for the emitter current I_{E}, $I_{\mathrm{E}} = qAD(\partial n/\partial x)$, it would increase significantly as a result of the steeper charge density profile at the base emitter interface. These conditions, together with the constant collector current I_{C}, make the base current rise abruptly beyond the constant threshold current (22 mA)[6]. Plotting the new values of τ_{B} for different base currents (not shown here), we can estimate an amount of ~0.5 ps for the base recombination lifetime in the spontaneous emission region ($I_{\mathrm{B}} \leq I_{\mathrm{B,th}}$), called $\tau_{\mathrm{B,spon}}$, which is ~2.5 ps for the QW located at 59 nm.

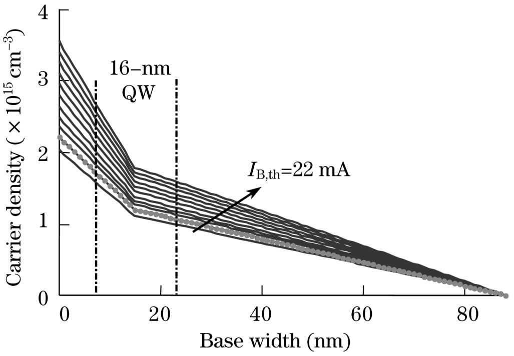

Fig. 3. Modified carrier density profile derived by manipulating charge control model for QW located near the emitter base interface.

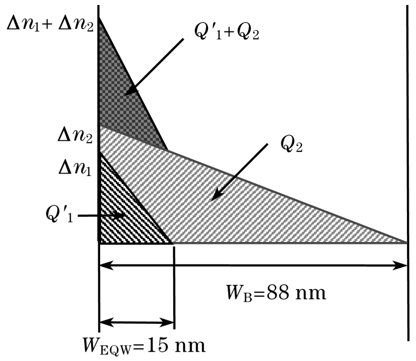

Fig. 4. Modified charge control model for W_{EQW}=15 nm. Q_2 constant while Q_1 decreases to Q_1'.

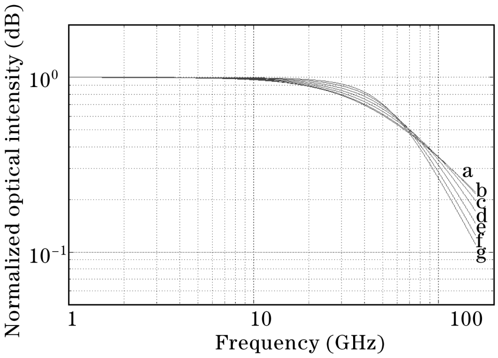

Fig. 5. Optical frequency response for W_{EQW}: (a) 15, (b) 19, (c) 29, (d) 39, (e) 49, (f) 59, and (g) 69 nm.

The optical frequency response for the TL is formulated as[1,2−7]

$$\frac{\Delta P_{\mathrm{m}}(\omega)}{\Delta I_{\mathrm{B}}(\omega)} = \frac{\tau_{\mathrm{p}}\Gamma_b/(qAW_{\mathrm{B}})}{[1-(\omega/\omega_{\mathrm{n}})^2]+j2(\omega/\omega_{\mathrm{n}})\xi}, \tag{5}$$

where $\Delta P_{\mathrm{m}}(\omega)$ is the modulated photon density, $\Delta I_{\mathrm{B}}(\omega)$ is the modulated base current, τ_{p} is the photon lifetime, Γ_b is the optical confinement factor of the waveguide, and natural frequency ω_{n} and damping ratio ξ are

$$\begin{aligned} &\omega_{\mathrm{n}}^2 \approx (1/\tau_{\mathrm{p}}\tau_{\mathrm{B,spon}})(I_{\mathrm{B}}/I_{\mathrm{B,th}}-1), \\ &\xi = (2\omega_{\mathrm{n}}\tau_{\mathrm{B,spon}})^{-1} + 0.5(\omega_{\mathrm{n}}\tau_{\mathrm{p}}). \end{aligned} \tag{6}$$

The frequency response depends on the QW position, as Fig. 5 demonstrates.

In this letter, the charge control model is employed to analyze the dependence of TL optical characteristics on the QW position. Locating the QW closer to the emitter-base interface while keeping V_{BE} constant will result in a reduction in bandwidth. We illustrate that the displacement of QW by 40 nm toward the collector, from its original place at W_{EQW}=59 nm, enhances the optical bandwidth for near 12 GHz. The investigated transistor laser has an electrical bandwidth of ≥100 GHz. Thus it could be "tailored", utilizing the modification reported here, to make optical and electrical cut-offs almost equal.

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