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Optimal quantum well width and the effect of quantum well position on the performance of transistor lasers

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Transistor laser (TL) model based on InGaP/GaAs/InGaAs/GaAs is analyzed and presented. It is realized that quantum well (QW) with width of 10 nm may be formed for low base threshold current density J_{th}. The emission wavelength is found to be 1.05 μm, and the indium (In) composition is 0.25 for optimal QW width. It is identified that J_{th} decreases with the movement of QW towards the base-emitter (B-E) interface. Small signal optical response is calculated, and the effect of QW position is studied. The bandwidth is enhanced due to the movement of the QW towards the emitter base junction.

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Transistor has contributed to the development of the electronic integrated circuits industry, but researchers have always been looking for a device which can simultaneously handle electrical and optical outputs. Transistor laser (TL) is a unique three-terminal optoelectronic component, which can generate both electrical and optical signals at the same time at possibly 100 Gbit/s with potential for combining electrical and optical integration[1-6]. Theoretical modeling and analysis of the TL characteristics have been done[7-11] with 10 nm-wide QW. In those works of TL, no analysis was made for such a selection of QW width. In this paper, the QW well width is optimized for low threshold current density, and the effects of optimal position of QW in the base region on threshold current density and optical response of InGaP/GaAs/InGaAs(QW)/GaAs heterojunction bipolar transistor laser (HBTL) are studied.

The schematic diagram of the TL structure is shown in Fig.1. The TL structure and the fabrication technique have been previously described in details [1, 12]. The results of the current work are presented. For our analysis, we assume the width of the base region is 100 nm[7].

Differential gain Ω is calculated with following equation[13]

$$\Omega = v_{\mathrm{g}}\frac{\partial g}{\partial n} = \frac{v\alpha}{\Gamma n_{\mathrm{tr}}} \quad , \tag{1}$$

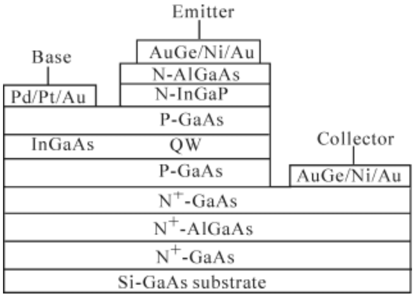

Fig.1 Schematic diagram of transistor laser model

where Γ is the optical confinement factor, $\partial g/\partial n$ is the differential gain factor, α is photon absorption coefficient in the active region, and v_{g} is the group velocity. We assume that optical confinement factor is given by[14]

$$\Gamma = N\phi w_{\mathrm{qw}} \quad , \tag{2}$$

where N is the number of QWs, and ϕ is the optical confinement per unit width of the QW. The typical value for ϕ of 2×10^{-3} nm^{-1}[14] is used. Using above equations and from Ref.[7], the threshold current density J_{th} can be obtained as

$$J_{\mathrm{th}} = \frac{q\left(1+\dfrac{N\phi w_{\mathrm{qw}}n_{\mathrm{nom}}}{v_{\mathrm{g}}\alpha\tau_{\mathrm{p}}}\right)}{\tau_{\mathrm{qw}}}\left(1+\frac{\tau_{\mathrm{cap}}}{v\tau_{\mathrm{rbo}}}\right) \quad , \tag{3}$$

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$$v=\left(\frac{w_{\mathrm{qw}}}{w_{\mathrm{b}}}\right)\left(1-\frac{x_{\mathrm{qw}}}{w_{\mathrm{b}}}\right) \quad , \qquad (4)$$

where w_{qw} and w_{b} are widths of QW and base, respectively. x_{qw} is the QW position in the base region from the base-emitter (B-E) interface. v is the fraction of the base charge captured in the QW.

Fig.2 shows the variation of threshold current density as a function of QW width for $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$. It can be seen that J_{th} has its minimum at w_{qw}=10 nm, then it increases monotonically as w_{qw} increases, so optimal width is 10 nm. This result is comparable to the experimental findings of Zou et al[15]. From the work of Matthews et al[16], the optimal width is 10 nm when indium composition is x=0.25. For this composition, the transition wavelength is 1.05 μm from an n=1 electron state to an n=1 heavy hole state[17]. Tab.1 gives the values of the parameters used in the current simulation.

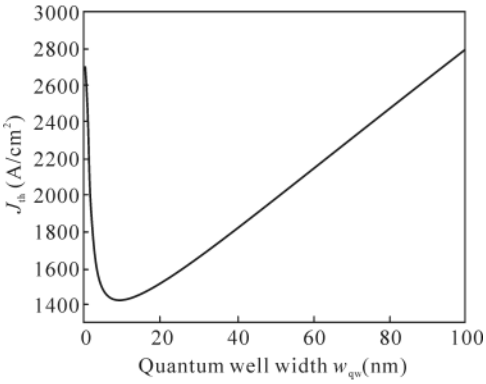

Fig.2 Calculated threshold current density as a function of QW width

Tab.1 Parameters used in the simulation

Parameter	Value	Unit
v_{g}[18]	7.14×10^9	cm/s
α[18]	5	cm^{-1}
τ_{rbo}[7]	134	ps
τ_{cap}	1	ps
τ_{p}	3.6	ps
τ_{qw}	150	ps
n_{tr}	10^{12}	

The effect of QW position on the threshold current is shown in Fig.3.

From Fig.3, we can see that J_{th} decreases with decreasing x_{qw}, i.e., QW moves towards the B-E interface. If we move the QW towards the B-E interface, more charges can be captured, because v increases during this movement. Since more charges are captured to the QW in a given time, threshold current density decreases.

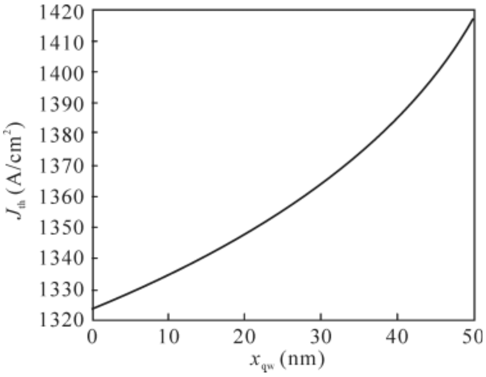

Fig.3 Dependence of threshold current density J_{th} on QW position in the base region of TL

The TL optical response[7] is studied by the following transfer equation as

$$H(\omega)=\frac{\Delta N_{\mathrm{p}}(\omega)}{\Delta J(\omega)}=\left(\frac{1}{1+\mathrm{i}\,\omega\tau_{\mathrm{rb}}}\right)\times\left(\frac{\dfrac{\Omega v N_{\mathrm{p0}}\tau_{\mathrm{rb}}}{\tau_{\mathrm{cap}}\,q}}{\dfrac{\Omega N_{\mathrm{p0}}}{\tau_{\mathrm{p}}}-\omega^2+\mathrm{i}\,\omega\left(\dfrac{1}{\tau_{\mathrm{qw}}}+\Omega N_{\mathrm{p0}}\right)}\right) \quad , \qquad (5)$$

where $N_{\mathrm{p0}}=n_0\dfrac{\tau_{\mathrm{p}}}{\tau_{\mathrm{qw}}}\left(\dfrac{J_0}{J_{\mathrm{th}}}-1\right)$ is the steady state photon density, $n=n_0=n_{\mathrm{tr}}+\dfrac{1}{\Omega\tau_{\mathrm{p}}}$ is the steady-state injected carrier population for $J>J_{\mathrm{th}}$, and $\tau_{\mathrm{rb}}=(1-v/\tau_{\mathrm{rbo}}+v/\tau_{\mathrm{cap}})^{-1}$ is the base charge density.

In the above equations, $\hat{o}_{\mathrm{cap}}$ is electron capture time in QW, $\hat{o}_{\mathrm{rbo}}$ is base charge lifetime, $\hat{o}_{\mathrm{p}}$ is lifetime of photon, $\hat{o}_{\mathrm{qw}}$ is recombination lifetime via spontaneous emission in the QW, and n_{tr} is transparency electron density. In this simulation, it is assumed that QW lies in the middle of the base region, i.e., the distance from the B-E interface to QW is x_{qw}=50 nm. For this value of x_{qw}, the value of the fraction of the base charge captured in the QW region is v=0.05[7].

Fig.4 shows the optical response of TL model for different values of x_{qw}. It can be seen that for -3 dB bandwidth, $f_{3\,\mathrm{dB}}$ is increased with decreasing x_{qw}, i.e., QW moves towards B-E interface. This result may be explained as the movement of QW towards the B-E interface (decreasing x_{qw}) increases v, which decreases the value of effective minority carrier lifetime in the base region[7]. Reduced lifetime results in the fast recombination, which has major impacts for fast modulation of light sources, such as a transistor laser[19].

Theoretical study is performed on InGaP/GaAs/InGaAs (QW)/GaAs TL. QW width is optimized for low threshold

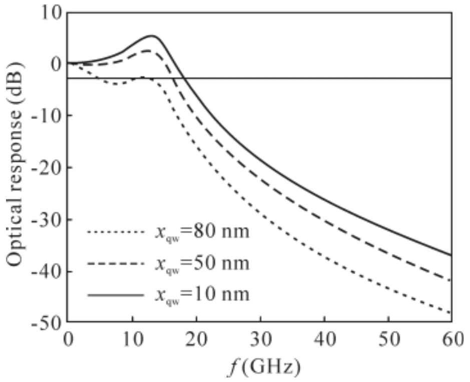

Fig.4 Effect of QW position in the base region on the calculated optical response when Ω =0.5 cm^2/s and n_{tr}=10^{12}

current density. Small signal optical response of the TL model is calculated. Effects of QW position in the base region on calculated optical response are investigated, and it is found that modulation bandwidth is increased when QW moves towards B-E interface.

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