Ultrafast Transistor Laser Containing Graded Index Separate Confinement Heterostructure

Mohammad Hosseini

Abstract**—**Ultrafast transistor laser investigated here has the graded index separate confinement heterostructure (GRIN-SCH) in its base region. Resonance-free optical frequency response with -3 dB bandwidth of more than 26 GHz has been achieved for a single quantum well transistor laser by using graded index layers of $Al_{\xi}Ga_{1-\xi}As$ (ξ: 0.1→0) in the left side of quantum well and $Al_{\xi}Ga_{1-\xi}As$ (ξ: 0.05→0) in the right side of quantum well. All required parameters, including quantum well and base transit time, optical confinement factor and spontaneous recombination lifetime, have been calculated using a self-consistent charge control model.

Keywords**—**Transistor laser, ultrafast, GRIN-SCH, -3db optical bandwidth, $Al_{\xi}Ga_{1-\xi}As$.

I. Introduction

LIGHT-emitting transistor (LET) is a device that combines the functionalities of a laser and a transistor in a single structure. LET was introduced more than a decade ago [1] by extracting radiative recombination in the abase layer of heterojunction bipolar transistor (HBT). Incorporating one (or a few) quantum well(s) in the base region of LET, one can achieve high level of carrier [2]. Continuous wave three-port (one electrical input, one electrical output and one optical output) operation of such a device (called transistor laser (TL)) at room-temperature was first reported in [3].

In order to achieve an optimum performance, the critical parameters that are competing in TL operation must be identified and optimized. If the base width is increased to reduce base resistance (for the same base doping), the current increases, but the base transit time increases too, with subsequent reduction in the frequency (f_T) of operation of the device. On the other hand, a wider base is less susceptible to base neutral region modulation (Early effect), which is advantageous for high current operation [4]. To counterbalance the increment of base transit time, a compositional grading in the base of the TL can be introduced. The grading provides an additional electric field in the base "neutral" region to facilitate carrier transport, and reduce base transit time [5]. When a base quasi electric field is established, the current flow includes a drift component in addition to diffusion component. Consequently, the base transit time decreases [6].

Carrier transit times across the separate confinement heterostructure (SCH) in active region (base) in SQW-TL is demonstrated in Fig. 1. Carrier transport time through the left SCH region is comparatively longer in Heterojunction Bipolar Transistor Laser (HBTL) than the Diode Laser (DL) with the same SCH width because of higher diffusion constant [7]. In order to maximize the modulation bandwidth of quantum well laser, carrier transit time across the SCH should be somehow minimized. One proposed method is based on utilizing graded index (GRIN) structure for the SCH which results in a built-in field and consequently a reduced transit time [8], [9]. Establishing the above-mentioned built-in quasi electric field, the current flow includes a drift component in addition to diffusion component which in turn reduces the transit time [10].

In the present paper, we use a GRIN-SCH structure in SQW-TL. In order to do that, we use $Al_{\xi}Ga_{1-\xi}As$ (ξ: 0.1 → 0) in SCH1 and $Al_{\xi}Ga_{1-\xi}As$ (ξ: 0.05 → 0) in SCH2.

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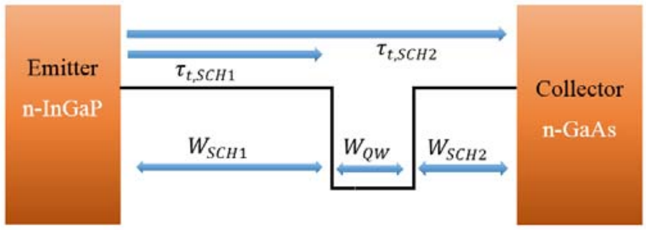
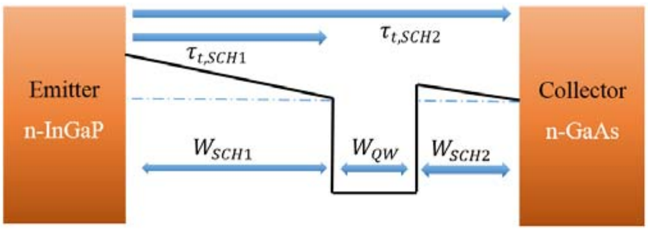


(a) Original structure



(b) Proposed ultrafast GRIN-SCH structure

Fig. 1 Schematic of carrier transport through the SCH in base region

II. Structure and Model

Base region in TL is composed of three series sections, namely SCH1, QW and SCH2. By solving the continuity equations (1), (2) in these regions for original TL (non-graded base), current across the base region can be found [11].

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_{bulk}} \qquad \text{SCH1 and SCH2} \qquad (1)$$

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_{qw}} \qquad \text{QW} \qquad (2)$$

where $n(x,t)$ is the base electron distribution, τ_{bulk} and τ_{qw} are recombination lifetimes in the bulk base and QW, respectively. In charge control model, the current $I = qAD(\partial n/\partial x)$ is assumed to be continuous across the SCH1/QW/SCH2 interfaces.

In GRIN-SCH structure, due to quasi electric field, the base and collector current consist of both diffusion and the drift components [9].

Transit time across emitter to quantum well ($\tau_{t,1}$) and emitter to collector $\left(\tau_{t,2}\right)$ can be expressed as:

$$\tau_{t,1} = Q_1/I_B = \left(qA\int_0^{W_{eqw}} n_{eqw}(x)dx\right)/I_B \tag{3}$$

$$\tau_{t,2} = Q_2/I_C = \left(qA\int_0^{W_{ec}} n_{ec}dx\right)/I_C \tag{4}$$

where Q_1 and Q_2 are the base charges, corresponding to n_{eqw} and n_{ec} respectively.

Analytical calculation of optical confinement factor (OCF) for TL has been done by [7]. Effective refractive index of waveguide can be defined as:

$$n_{eff} = \frac{[(W_{SCH1}\times n_{SCH1}^{avg})+(W_{QW}\times n_{QW})+(W_{SCH2}\times n_{SCH2}^{avg})]}{W_B} \tag{5}$$

So, we can calculate OCF (Γ) for different confinement structures. Fig. 2 shows OCF for original and GRIN-SCH structures.

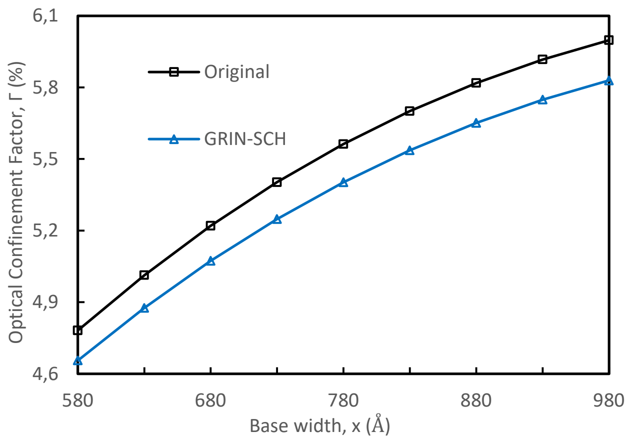


Fig. 2 OCF, Γ for original and GRIN-SCH structures (QW width = 16 nm is constant an SCH width is variable)

III. Results and Discussion

We have calculated physical parameters including electron mobility, diffusion constant, and OCF for GRIN-SCH TL in [9].

Simulation results for transit times in different structures as well as the dependency of transit time on aluminum mole fraction in the GRIN $Al_{\xi}Ga_{1-\xi}As$ layers are shown in Fig. 3. One can drastically reduce transit time by grading the SCH1 as it is wider than SCH2. The effect of SCH1 can be observed again through Fig. 3 (b) compared to Fig. 3 (a). As a conclusion, both the SCH regions` width and the QW (or QWs) location are among critical factors when designing a TL since in the HBTL only one of the carriers are transporting. The other carrier is almost available in TL. This is in contrast to the case of a conventional DL in which both carriers (apparently with different velocities) are transporting through the SCH regions, resulting in a more non-uniform carrier distribution. Our simulation results show this advantage of the TL compared to DL.

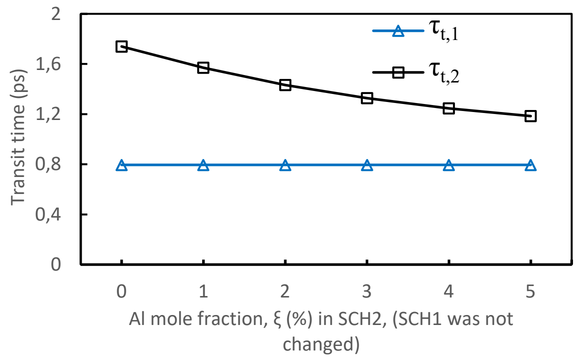


Fig. 3 (a) Dependency of transit times to Al mole fraction in SCH2 when SCH1 was not changed

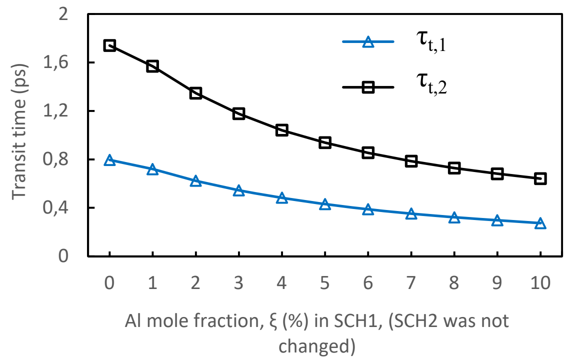


Fig. 3 (b) Dependency of transit times to Al mole fractions in SCH1 when SCH2 was not changed

Analytical equation to describe optical response has been obtained from small signal linear optical response [12], [13].

$$H(\omega) = \frac{A_0}{1-\omega^2/\omega_n^2 + j2(\omega/\omega_n)\zeta} \tag{6}$$

where $\zeta = 1/\left(2\omega_n\tau_{B,spon}\right) + \tau_{ph}\,\omega_n/2$, $\omega_n^2 = \left(\eta/\tau_{ph}\tau_{B,spon}\right)(I_B/I_{TH} - 1), A_0$ is a normalization factor, resonance frequency is $f_R = \omega_n/2\pi(1-2\zeta^2)^{1/2}$, η is a fitting parameter that has previously been calculated Magnitude of the resonance peak is $|H(\omega_R)|^2 = A_0^2/[4(1-\zeta^2)\zeta^2]$.

Fig. 4 shows the intrinsic optical frequency response of different confinement structures. As can be seen, no resonance peak is observed in GRIN-SCH structure which could be another potential advantage of this device. The resonance peak is mainly a limiting factor for optical transmitters based on direct modulation of DLs. It is expected that using modified

GRIN-SCH TL this issue could be resolved. Higher bandwidth observed for the GRIN-SCH structure is a direct consequence of resonance-free response of the optical frequency response. Superior optical modulation performance (both in terms of higher intrinsic bandwidth and lower resonance peak) are evident in proposed structure. When fully combined with other techniques for increasing the bandwidth including multiple quantum well active region, it is anticipated that the final bandwidth could go beyond 100 GHz.

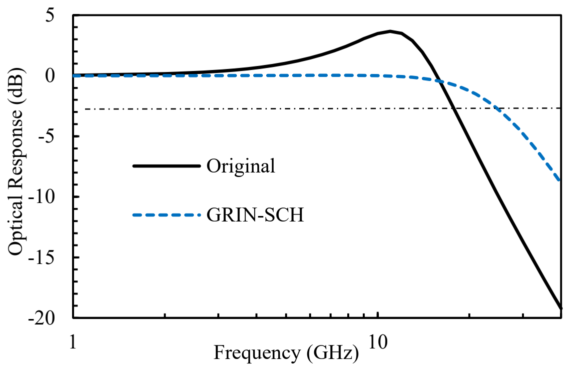


Fig. 4 Optical response of GRIN-SCH structures and conventional GaAs base TL($I_B/I_{th} = 5, N_B = 1 \times 10^{19}$ cm^{-3})

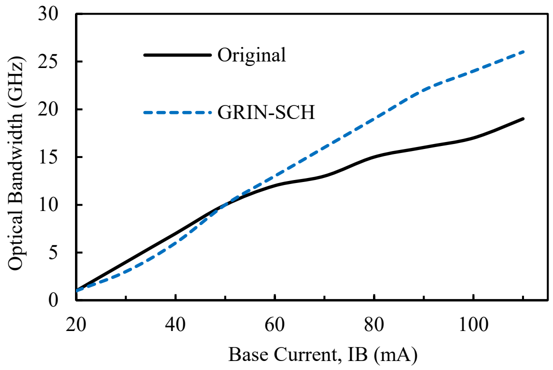


Fig. 5 Base current dependent optical bandwidth of different confinement structures

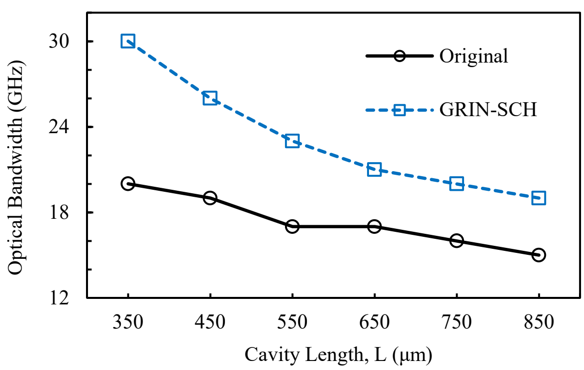


Fig. 6 Cavity length dependent optical bandwidth of different confinement structures; due to smaller photon lifetime in 350 μm cavity length, optical bandwidth increases in this case

Figs. 5 and 6 show the optical bandwidth of confinement structures for different bias levels and cavity lengths. The higher the base current, the more pronounced the effect of graded base. Combined with the effect of graded base, one can conclude that sensitivity to the cavity length variations is more apparent in GRIN-SCH TL compared to its conventional, non-graded version. This could be a disadvantage for our proposed grade base version of TL that should be taken into consideration when fabrication limitations become more important. On the other hand, GRIN-SCH structure shows a 50% improvement in optical bandwidth for a relatively small cavity length of 350 μm.

IV. Conclusion

We studied a GRIN-SCH structure in SQW TL in different confinement structures. Physical parameters including diffusion constant and OCF were calculated for various structural factors. By developing an analytical model, transit time through SCHs, effective base recombination lifetime and charge density profile in the base region were calculated. Then, TL characteristics including differential laser output and optical frequency response were analyzed for the proposed GRIN-SCH structures. Using $Al_{\xi}Ga_{1-\xi}As$ (ξ: 0.1 $\rightarrow$ 0) in the left hand side of QW and $Al_{\xi}Ga_{1-\xi}As$ (ξ: 0.05 $\rightarrow$ 0) in the right hand side of QW, the resonance peak is fully eliminated completely and optical bandwidth increases to 26 GHz compared to 19 GHz in conventional GaAs base TL. We believe this higher optical bandwidth is a direct result of sub-picosecond base recombination lifetime thanks to accelerated carrier transport through the base region.

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