Numerical design and frequency response of MQW transistor lasers based entirely on group IV alloys

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Abstract
A theoretical model is developed for $n-p-n$ mid-infrared transistor lasers (TLs) with a strain-balanced Ge$_{0.85}$Sn$_{0.15}$ multiple quantum well (MQW) structure in their base. The variation of the optical confinement factor, the modal gain, and the threshold current density is rigorously investigated for different numbers ($N$) of QWs in the MQW structure. The results show that overall the optical confinement factor and the modal gain increase with $N$. The frequency response of the MQWTTL in the common-base (CB) configuration is estimated from the small-signal relationship between the photon density and the emitter current density by solving the laser rate equation and the continuity equation, considering the virtual states as a conversion mechanism. Increasing $N$ causes the modulation bandwidth first to increase then to decrease with $N$. This reveals a shift in the nature of the device for higher values of $N$. The results also suggest that judicious selection of $N$ will enable the proposed device to become a viable monolithic light source.

Keywords Transistor laser · GeSn alloy · Modulation bandwidth · Multiple QW

1 Introduction
During the past few years, research on electronic–photonic integrated circuits (EPICs) has increased tremendously due to their potential features such as low cost, high-speed data processing, etc. [1, 2]. Many works describing attempts to implement important components for EPIC such as detectors and interconnects have thus been reported [3–5]. However, the quest for an all-group IV optical source to form the main backbone of EPICs has not yet been successful. One can state that this represents the final milestone on the path to the realization and fabrication of EPICs [2].

This issue has been addressed through the development of monolithic optical sources by various researchers recently. Some of the notable attempts in this regard include silicon Raman lasers and Ge lasers [6–8]. However, they have not become very popular as capable alternatives to light sources based on group III–V materials. Fortunately, the emergence of group IV photonics (GFP) as a viable platform for EPIC has opened the door to the realization of integrated light sources [9].

Group IV alloys such as Si-Ge-Sn and Ge-Sn are emerging as major players in GFP [10]. Their most significant property that has attracted attention from researchers is the ability to form a direct bandgap in GeSn and SiGeSn by using an appropriate Sn content [11]. Moreover, the spectral response of these alloys can be extended to the near- and mid-infrared (IR) regions, which makes them potential candidates for use as active materials in mid-IR photonic devices, especially monolithic light sources.

Concurrently, heterojunction bipolar light-emitting transistors (HBLET) have emerged, integrating the functionality of both a transistor and laser to realize an efficient light source [12]. Owing to its ability to produce outputs in both the electrical and optical domain as well as a high modulation bandwidth, the transistor laser (TL) is considered to be a critical component for use in telecommunications and other applications. TLs based on group III–V alloys have already earned an reputation as excellent light sources and have been

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explored by the researchers [13–16]. Furthermore, the success of III–V TLs has motivated researchers to investigate and design group IV counterparts for potential use as EPIC-compatible light sources.

Against this background, theoretical work describing the realization of models for single-QW transistor lasers (SQWTLs) based on group IV alloys for operation in the mid-IR has already been reported by the authors [17]. Calculations of the material gain as well as other performance parameters such as the modal gain, optical confinement factor, photon density, current gain, etc. for SQWTLs have also been reported [17, 18]. Unfortunately, the low value of the optical confinement factor hampers the performance of such SQWTLs [18]. To address this issue, some researchers have introduced a multiple quantum well (MQW) structure and evaluated performance parameters such as the threshold current density, current gain, and output photon density for SiGeSn/GeSn MQWTLs [19–22]. Predictions of the frequency response of MQWTLs is crucial to gauge their modulation bandwidth. Frequency-domain analysis has already been reported for MQWTLs and SQWTLs based on group III–V materials [23]. However, to the best of the authors’ knowledge, a detailed transient analysis for MQWTLs based on group IV alloys has not been presented in literature yet. In this regard, it is expected that optimization of the number of quantum wells will enable a suitable modulation bandwidth to be obtained.

A GeSn/SiGeSn-based MQWTL with proper design considerations is thus proposed herein, followed by its small-signal analysis by solving the laser rate equation and the continuity equation, considering the virtual states as a conversion mechanism [24]. The remainder of this manuscript is organized as follows: Section 2 describes the proposed model for the group IV-based MQWTL along with appropriate justifications. This section also provides a brief summary of some preliminary study of the MQWTL and corresponding results that serve as a preface for the next section. Section 3 focuses on a detailed small-signal analysis of the SiGeSn/GeSn MQWTL, supported by mathematical modeling. The results obtained using the methodology described in Sect. 3 are then presented and discussed thoroughly in Sect. 4. Finally, some salient conclusions of the present work are drawn in Sect. 5.

### 2 A description of the model and the preliminary study

The schematic structure of the proposed group IV-based MQWTL is shown in Fig. 1 [25], using $n$-type Ge, $p$-type Si$_{x}$Ge$_{y}$Sn$_{z}$ ($x = 0.12$, $y = 0.73$, $z = 0.15$), and $n$-type Si$_{x}$Ge$_{y}$Sn$_{z}$ ($x = 0.11$, $y = 0.73$, $z = 0.16$) as the emitter, base, and collector of the device, respectively. The thicknesses in the TL structure are 200 nm for the Si substrate, 50 nm for the GeSn buffer, 150 nm for the $n$-SiGeSn collector, and 150 nm for the $n$-Ge emitter. Note that the mentioned Si, Ge, and Sn contents in the base and collector are chosen to achieve desirable optical confinement [17]. Multiple ($N$) intrinsic active Ge$_{y}$Sn$_{z}$ ($y = 0.85$, $z = 0.15$) quantum well layers are inserted into the base with regular spacing to form the quantum well structure with alternating barrier and well regions.
To minimize the strain, the quantum well structure is tailored to form a strain-balanced structure [26]. The compressive strain in each GeSn well is counterbalanced by the same amount of tensile strain in each SiGeSn barrier. As a result, the overall multiple quantum well structure is strain balanced with respect to the relaxed GeSn buffer layer. Quantum well regions with 15% Sn content are considered to achieve a direct-bandgap material. Significant carrier and optical confinement are attained, and lasing action occurs in this region. The collector layer sandwiched between the base and buffer layer is lattice matched with the buffer layer. The Z-direction is considered to be the growth axis. A single bound state in each quantum well is ensured by selecting the dimension of the well and barrier as 10 nm. This also facilitates the achievement of the strain-balanced condition of the whole structure.

Model solid theory is used to calculate the band structure of the Γ and L valley of the conduction band as well as the heavy-hole valence band (HH) and light-hole valence band (LH) in the well and barrier [27]. The calculated band structure is used to determine the quantized energy and corresponding wavefunction of the Γ conduction band and HH valence band. The transverse electric (TE)-polarized material gain is also estimated at the band edges in the well and barrier [27].

The optical confinement factor and free-carrier absorption for the different layers is also estimated. The optical confinement factor per well decreases with increasing number of wells in the base. The optical confinement factor and free-carrier absorption for the different layers varies with the number of QWs, the TL structure is simulated for a different number of QWs, the TL structure is simulated for a different number of QWs. The estimated values of the optical confinement factor per well (2.37% for N = 3, 2.29% for N = 5, 2.21% for N = 7, and 2.07% for N = 9) decreases with increasing N. Therefore, in this work, the maximum value of N is considered to be 9.

The optical confinement factor and free-carrier absorption loss in the emitter, base, and collector contact layer and well are evaluated and presented in Table 1 for the different values of N. The mirror loss is calculated by considering the cavity length of the waveguide to be 500 μm with reflectivities R_1 and R_2 of 1 and 0.7, respectively, for each facet, remaining fixed regardless of the value of N. The total loss, including the mirror loss and free-carrier absorption loss, is obtained as 57.67 cm⁻¹, 51.94 cm⁻¹, 46.98 cm⁻¹, and 42.10 cm⁻¹ for N = 3, 5, 7, and 9, respectively [18].

After calculation of the optical confinement factor and modal loss, the modal gain and threshold modal gain can be calculated to predict the threshold carrier density (Nth). The threshold modal gain is considered to be equal to the total loss, including the model loss and mirror loss [17, 18]. The variation of the modal gain as a function of the total injected carrier density is plotted for different values of N in Fig. 3. The modal gain increases with the number of QWs, as the overall optical confinement factor increases. However, this figure also reveals that the rate of increment of the modal gain with N is decreasing because the effective optical confinement factor per well decreases with increasing N, as pointed out above. The effect of N on Nth is seen in Fig. 4, which shows a plot of the threshold carrier density as a function of N. This figure clearly depicts that initially, for smaller values of N, Nth decreases very rapidly, but thereafter almost saturates with increasing N.

3 Small-signal analysis

In the present analysis, the transistor is assumed to be operated in the normal active mode and diffusion to be the dominant carrier transfer mechanism. Figure 5 depicts a representation of the carrier mechanism in the biased transistor along with the energy bands (Γ conduction and HH valence). The locations of the emitter–base (EB) and collector–base (CB) junctions are represented in the figure by \( x = -W_B/2 \), \( x = W_B/2 \), respectively, where \( W_B \) is the width of the base. The location of an arbitrary well \( n \) can be expressed as...
Fig. 2 The distribution of the TE field $E_x$ for the quasi-TE fundamental mode at $\lambda = 2.68$ μm. The peak transverse electrical field is located near the active region, providing a QW optical confinement factor of a 7.07% for $N=3$, b 11.4% for $N=5$, c 15.5% for $N=7$, and d 19.00% for $N=9$

$x_n = -\frac{W_b}{2} + nW_b + (n-1)d + \frac{d}{2}$, \hspace{1cm} (1)

where $d$ and $W_b$ are the width of the well and barrier, respectively. In Fig. 5, due to the forward-biased base–emitter junction, carriers (electrons) are injected from the emitter into the base (barrier) [25]. Some of the unbound injected minority carriers are quantum captured into the bound state in the first QW with a capture probability of $1/\tau_{\text{cap}}$ while the rest diffuse to the next QW. After several captures in different QWs, the carriers reach the collector and are swept out due to the reverse-biased base–collector junction. Some carriers may also escape from the QW with a lifetime of $\tau_{\text{esc}}$.

During such transport of the carriers through the wells and barriers, interwell coupling is not considered in this analysis, hence the effective interwell transport time ($\tau_c$) is ignored. This can be justified as follows: The effect of such interwell coupling on carrier transport depends on the height of the energy barrier and the thickness of the well [28, 29] and can be expressed mathematically by the tunneling time ($\tau_t$). In the proposed MQWTL, the height of the energy barrier is very low (0.0712 eV). Therefore, the escape lifetime dominates the tunneling time, hence $\tau_c$ is not included in the calculation.

Small-signal analysis is an important approach to obtain the frequency response and thereby the modulation bandwidth of the device. The excess minority carrier density in the base can be expressed as

$\delta n = \delta N_0 + \delta n e^{i\omega t}$, \hspace{1cm} (2)

where $\delta N_0$ is the steady-state solution of the diffusion equation. $\delta n$ is the amplitude of the small-signal component and $\omega$ is the angular frequency. In the presence of small-signal sinusoidal modulation, the diffusion equation for the excess minority carriers in the base region can be written as [18]

$j_0\delta n = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau_B}$, \hspace{1cm} (3)

where $D_n$ is the diffusion constant coefficient of electrons in the base and $\tau_B$ is the carrier lifetime in the base region. Equation (3) is solved with the following boundary conditions:

$j_e = qD_n \frac{\partial \delta n}{\partial x}, \hspace{0.5cm} x = -\frac{W_B}{2}$, \hspace{1cm} (4)

$j_e = qD_n \frac{\partial \delta n}{\partial x}, \hspace{0.5cm} x = \frac{W_B}{2}$, \hspace{1cm} (5)

$\delta n(x^-) = \delta n(x^+)$, \hspace{1cm} $n_{\text{V.S}}n$ \hspace{1cm} (6)
Table 1 The calculated optical confinement factor and absorption loss in the emitter, base, and collector contact layers and well for different values of $N$

| $N$  | Base contact layer | Emitter contact layer | Collector contact layer | Well |
|------|--------------------|-----------------------|-------------------------|------|
| 2    | Free carrier absorption (cm$^{-1}$) | 478.973 | 244.115 | 0.2308 | 14.569 |
|      | Optical confinement factor | 0.022 | 0.188 | 0.3966 | 0.0477 |
|      | Absorption loss (cm$^{-1}$) | 10.53 | 45.94 | 0.0915 | 0.695 |
| 3    | Optical confinement factor | 0.021 | 0.176 | 0.386 | 0.070 |
|      | Absorption loss (cm$^{-1}$) | 9.996 | 42.988 | 0.089 | 1.031 |
| 4    | Optical confinement factor | 0.0197 | 0.1649 | 0.3744 | 0.0930 |
|      | Absorption loss (cm$^{-1}$) | 9.478 | 40.258 | 0.0864 | 1.3558 |
| 5    | Optical confinement factor | 0.019 | 0.1543 | 0.362 | 0.115 |
|      | Absorption loss (cm$^{-1}$) | 8.956 | 37.666 | 0.084 | 1.669 |
| 6    | Optical confinement factor | 0.01774 | 0.1437 | 0.3497 | 0.1352 |
|      | Absorption loss (cm$^{-1}$) | 8.5009 | 35.083 | 0.0807 | 1.9706 |
| 7    | Optical confinement factor | 0.017 | 0.135 | 0.337 | 0.155 |
|      | Absorption loss (cm$^{-1}$) | 8.046 | 33.0287 | 0.0778 | 2.26 |
| 8    | Optical confinement factor | 0.01566 | 0.1254 | 0.32133 | 0.1724 |
|      | Absorption loss (cm$^{-1}$) | 7.5047 | 30.6127 | 0.0741 | 2.5123 |
| 9    | Optical confinement factor | 0.015 | 0.117 | 0.308 | 0.19 |
|      | Absorption loss (cm$^{-1}$) | 7.113 | 28.583 | 0.0712 | 2.769 |

Fig. 3 The modal gain as a function of the injected carrier density to obtain the threshold carrier density

Fig. 4 The threshold carrier density as a function of the number of QWs
where \( j_{e} \) and \( j_{c} \) are the emitter and collector current densities at \( x = -W_B/2 \) and \( x = W_B/2 \), respectively. \( W_B \) is the total base width, \( n_{s,n} \) is the virtual state carrier concentration at \( x = x_n \), \( j_{V,S,n} \) is the virtual state current density at \( x = x_n \), and \( J_B \) is the base current density. The conventional laser rate equations in the \( n \)th active region can be written as [18]

\[
j_{V,S,n} = qD_n \frac{\partial \delta(x_n^-)}{\partial x} - qD_n \frac{\partial \delta(x_n^+)}{\partial x},
\]

\[(7)\]

\[j_e = j_c + j_b,
\]

\[(8)\]

where \( j_e \) and \( j_c \) are the emitter and collector current densities at \( x = -W_B/2 \) and \( x = W_B/2 \), respectively. \( W_B \) is the total base width, \( n_{s,n} \) is the virtual state carrier concentration at \( x = x_n \), \( j_{V,S,n} \) is the virtual state current density at \( x = x_n \), and \( J_B \) is the base current density. The conventional laser rate equations in the \( n \)th active region can be written as [18]

\[
\frac{dn_{V,S,n}}{dt} = \frac{j_{V,S,n}}{q_d} - \frac{j_{q,n} - n_{V,S,n}}{\tau_s},
\]

\[(11)\]

\[
\frac{dn_{q,n}}{dt} = \frac{n_{V,S,n}}{\tau_{cap,n}} - \frac{n_{q,n}}{\tau_{esc}},
\]

\[(12)\]

where \( s_n \) is the photon density, \( n_{q,n} \) is the QW carrier density, \( n_{w,n} \) is the transparency carrier density, \( G_0 \) is the differential optical gain, \( R_{sp} \) is the spontaneous emission factor, \( \Gamma_w \) is the optical confinement factor in the well, \( \tau_p \) is the photon lifetime, \( \tau_s \) is the carrier recombination lifetime in the QW, and \( j_{q,n} \) is the current density in the QW energy state for the \( n \)th well. The rate equations relating the bulk minority carrier with the two-dimensional (2D)-QW carriers are

\[
\frac{dS_n}{dt} = \left( \frac{\Gamma_w G_0(n_{q,n} - n_{w,n})}{\tau_s} - \frac{1}{\tau_p} \right) s_n + \frac{\Gamma_w R_{sp}}{\tau_s},
\]

\[(9)\]

\[
\frac{dn_{q,n}}{dt} = \frac{j_{q,n} - n_{q,n}}{\tau_s} - G_0(n_{q,n} - n_{w,n}) s_n,
\]

\[(10)\]

Fig. 5 A representation of the carrier mechanism in the MQWTL

\[
H(j\omega) = \frac{1}{\cosh \left( \frac{s_1 + W_B}{L_0} \right) + \frac{(qD_n \cosh \left( \frac{s_1 + W_B}{L_0} \right))}{H_2(j\omega)}} - \frac{1}{H_3(j\omega)} + \frac{1}{H_3(j\omega)} + \frac{(qD_n \sinh \left( \frac{s_1 + W_B}{L_0} \right))}{H_2(j\omega)}
\]

\[(13)\]
where

\[
H_1(j\omega) = \frac{s}{J_{\text{qw,n}}} = \frac{-\left(\Gamma_w G_0 S_0 / q d\right)}{\omega^2 - j\omega(1/\tau_s - G_0 S_0) - (G_0 S_0 / \tau_p)},
\]

(14)

\[
H_2(j\omega) = \frac{s}{J_{\text{v,n}}} = \frac{1}{\left[\left(1 + (\tau_{\text{cap,n}}/\tau_s) + j\tau_{\text{cap,n}}\omega/H_1(j\omega)\right) + \left[\left(qd(\tau_{\text{cap,n}}/\tau_{\text{esc}})(j\omega + (1/\tau_s))\right)/\left(\Gamma_w G_0 S_0 / j\omega\right)\right]\right]}.
\]

(15)

\[
H_3(j\omega) = \frac{s}{n_{\text{v,n}}} = \frac{1}{\left(\tau_{\text{cap,n}}/\tau_{\text{esc}}\right)(1/(\Gamma_w G_0 S_0 / j\omega)) + (\tau_{\text{esc}}/qd)(1/H_1(j\omega))}.
\]

(16)

Here, \(x_1\) and \(x_2\) are the mid-point of the first and second QW from the emitter junction. The transfer function \(H_1(j\omega)\) is the intrinsic response between the photon and the QW current density, which does not include the carrier capture or escape process. \(H_2(j\omega)\) and \(H_3(j\omega)\) are the transfer functions that relate the photon and virtual state current and carrier concentration density. Actually, these transfer functions include the effect of carrier capture and escape process from the QW to virtual state, and vice versa.

### 4 Results and Discussion

The calculation of the relevant material and device parameters for the MQWTL is very important before estimation of its modulation response. Some material and device parameter values are the same for TLs with both the SQW and MQW configuration. Therefore, in this work, these values are considered to be the same as for the single QWTL as reported elsewhere [18]. However, there are also a few relevant device parameters that vary with the number (\(N\)) of QWs. These parameters are obtained for different values of \(N\) and are presented in Table 2.

Having obtained all the material and device parameters, the modulation response at \(J_B = 4\) kA/cm\(^2\) is evaluated with the help of Eq. 13. The modulation response is plotted in terms of the variation of the output photon density as a function of the base current density for different values of \(N\) in Fig. 6. The vertical line in this figure represents the values of the output photon density at \(J_B = 4\) kA/cm\(^2\) for different values of \(N\). It can be clearly seen from this figure that the photon density increases with the number of QWs. Figure 7 depicts the small-signal modulation response for the common-base configuration [25]. As \(N\) is increased, the modulation bandwidth is also enhanced initially. Then, after reaching a peak, the modulation bandwidth starts to decline. This trend can be justified as follows: Due to the increase of the optical confinement factor with \(N\), the modal gain also surges. As a result, the threshold base current density \((J_{B\text{th}})\) decreases, thus a higher modulation bandwidth is attained. Subsequently, as the number of wells is increased further, the base width increases and the benefit of the transistor structure diminishes. Therefore, the nature of the device shifts from a transistor laser to a diode laser (DL). From this figure it is also apparent that, for \(N = 3\), the BW is flat, whereas for \(N = 5\) or above, a resonance effect also appears. Thus, for higher values of \(N\), the modulation bandwidth and resonance frequency start to decrease. To provide further understanding of this phenomenon, the 3-dB modulation bandwidth is plotted as a function of the number (\(N\)) of QWs for different values of \(J_B\) in Fig. 8. This figure indicates that the maximum modulation bandwidth of 14.7 GHz is obtained for \(N = 5\) at \(J_B = 4\) kA/cm\(^2\). Moreover, it can also be seen from this figure that the modulation bandwidth increases for higher current densities. However, the maximum modulation bandwidth is obtained at \(N = 5\), reducing thereafter. The choice of \(N\) is thus very important to obtain enhanced performance from the MQWTL. Note here that the present simulation results are obtained with the help of theoretical modeling of the MQWTL. Most of the device parameters for this are extracted from simulation works reported by authors.

In literature, the frequency response of MQWTLs based on group IV materials has hardly been investigated. A higher optical bandwidth is reported for group III–V MQWTLs than their group IV counterparts [14]. For instance, Taghavi

| Parameter                      | \(N = 1\)     | \(N = 3\)     | \(N = 5\)     | \(N = 7\)     | \(N = 9\)     |
|-------------------------------|---------------|---------------|---------------|---------------|---------------|
| Carrier capture lifetime \(\tau_{\text{cap}}\) (ps) | 0.50          | 1.17          | 1.83          | 2.50          | 3.17          |
| Differential optical gain \((G_0)\) (cm\(^2\) s\(^{-1}\)) | 2.71×10\(^{-6}\) | 5.94×10\(^{-6}\) | 6.48×10\(^{-6}\) | 6.50×10\(^{-6}\) | 6.55×10\(^{-6}\) |
| Threshold carrier density \((N_{\text{th}})\) (cm\(^{-3}\)) | 8.83×10\(^{18}\) | 3.21×10\(^{18}\) | 2.75×10\(^{18}\) | 2.58×10\(^{18}\) | 2.50×10\(^{18}\) |
| Transparency carrier density \((N_{\text{tr}})\) (cm\(^{-3}\)) | 2.51×10\(^{18}\) | 2.26×10\(^{18}\) | 2.26×10\(^{18}\) | 2.26×10\(^{18}\) | 2.26×10\(^{18}\) |
| Optical confinement factor \((\Gamma)\) | 0.0245         | 0.07077       | 0.11458       | 0.15513       | 0.1900        |
et al. reported an optical bandwidth on the order of 60 GHz for a group III–V MQWTL including five quantum wells. Moreover, the same group also reported an enhancement of the bandwidth for a group III–V-based MQWTL, beyond 75 GHz under high carrier injection levels [15].

Conclusions

The frequency response of a tin-incorporated group IV alloy-based MQWTL is investigated. A strain-balanced QW structure is considered to make it feasible for fabrication. The modulation bandwidth of the TL with respect to the number of QWs is examined during the analysis. The variation of the optical confinement factor and the modal gain for different numbers \(N\) of QWs is also studied. Overall, the optical confinement factor and modal gain increase with \(N\). However, the optical confinement factor per well and the rate of increment of the modal gain with \(N\) decrease. The frequency response of the MQWTL is evaluated by solving the laser rate equation and the continuity equation, considering the virtual states as a conversion mechanism. The plot of the modulation response reveals a maximum of 14.76 GHz for \(N = 5\). The results indicate that the value of \(N\) must be selected judiciously to achieve a higher modulation bandwidth while optimizing the trade-off between \(N\) and the device mechanism (TL or DL). The proposed TL operates in the mid-infrared region (2–3 μm). The results provide support for the idea that group IV-based MQWTLs have a very bright future as viable sources for mid-infrared photonic integrated circuits (PICs).

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Availability of data and materials It is confirmed that all data and materials as well as software applications or custom code support their published claims.

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