GaAs based Vertical-Cavity Surface-Emitting Transistor-Lasers

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Abstract

The ever-increasing demand for broadband capacity of the global optical communication networks puts enormous requirements on the semiconductor laser used in the optical transmitter. Industrial standard bodies for optical communication project requirements of single-channel data rates as high as 100 Gbit/s around year 2020. This is a significant step with respect to today’s technology which is only at the verge of introducing 25 Gbit/s emitters. The preferred light source for these applications is the vertical-cavity surface-emitting laser (VCSEL) which can offer cost- and power-efficient directly modulated operation. However, it has proven extremely difficult to push the modulation bandwidth of VCSELs beyond 30 GHz and radically new device concepts are demanded to meet the upcoming needs. One such new device paradigm consists of the transistor laser which is the fusion of a semiconductor laser and a high-speed heterojunction bipolar transistor (HBT) into a single device, with potential significant advantages in modulation bandwidth, noise properties and novel functionality by virtue of the three-terminal configuration. The present thesis deals with the design, fabrication and analysis of vertical-cavity surface-emitting transistor-lasers (T-VCSELs), a device previously not realized or investigated in great detail.

GaAs-based T-VCSELs are investigated both theoretically and experimentally. A three-dimensional model is set up with a commercial software package and used for performance predictions and analysis as well as design and optimization purposes. It is concluded that a T-VCSEL biased in the common-base configuration may have a bandwidth surpassing those of conventional diode-type VCSELs or a T-VCSEL itself in the common-emitter configuration. Fabricated T-VCSELs make use of an epitaxial regrowth design to homogeneously integrate an AlGaAs/GaAs HBT and an InGaAs/GaAs VCSEL. An intracavity contacting scheme involving all three terminals, undoped distributed Bragg reflectors and modulation doping are used to ensure a low-loss laser structure. The first generation of devices showed sub-mA range base threshold current in combination with a high output power close to 2 mW but did not fulfill the requirements for a fully operational transistor laser since the transistor went into saturation before the onset of lasing ($I_{Bsat} < I_{Bth}$). From numerical simulations this premature saturation was demonstrated being due to a lateral potential variation within the device and large voltage drops along the base and collector regions. As a remedy to this problem the base region was redesigned for a reduced resistance and transistor current gain, and the saturation current could thereby be extended well beyond threshold. These devices showed excellent transistor-laser characteristics with clear gain-compression at threshold, mA-range base threshold current, mW-range output power, high-temperature operation to at least 60°C, low collector-emitter offset voltage and record-low power dissipation during lasing. Furthermore, the collector-current breakdown characteristics was investigated in some detail and it is concluded that this, in contrast to previous models, presumably not is due to an intracavity photon reabsorption process but rather to a quantum-well band-filling effect.
List of appended papers

Paper A: Design and modeling of a transistor vertical-cavity surface-emitting laser

Paper B: Room-temperature operation of a transistor vertical-cavity surface-emitting laser

Paper C: Minority current distribution in InGaAs/GaAs transistor-vertical-cavity surface-emitting laser

Paper D: Performance optimization of GaAs-based pnp-type vertical-cavity surface-emitting transistor-lasers

Paper E: Influence of base-region thickness on the performance of pnp transistor-VCSEL

Paper F: 1.3-µm buried tunnel junction InGaAs/GaAs VCSELs
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Paper G: AlGaAs/GaAs/InGaAs pnp-type vertical-cavity surface-emitting transistor-lasers
Publications resulting from the work but not included in this thesis

1. Single-mode InGaAs/GaAs 1.3-µm VCSELs based on a Shallow Intracavity Patterning

2. Self-Consistent Modeling of a Transistor Vertical-Cavity Surface-Emitting Laser

3. Large-area single-mode 1.3-µm InGaAs/GaAs VCSELs based on a shallow intracavity patterning

4. Epitaxially regrown VCSELs and transistor VCSELs

5. Development of epitaxially regrown InGaAs/GaAs 980nm vertical transistor lasers

6. Current distribution in InGaAs/GaAs transistor vertical-cavity surface-emitting lasers

7. Transistor vertical-cavity surface-emitting lasers,

8. Toward ultra-high-bandwidth vertical-cavity surface-emitting lasers
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1. Introduction

1.1 High-speed VCSELs

Ever since Prof. Kenichi Iga and his team at Tokyo Institute of Technology proposed and demonstrated the first vertical-cavity surface-emitting laser (VCSEL) during the 1970s [1], the development of these devices has made a remarkable progress and nowadays VCSELs represent a mature device technology with numerous applications in various fields such as optical communication, sensing, reprographics, computer mice, etc. [2]. Owing to the short optical cavity and small gain volume, VCSELs have merits such as low threshold current, longitudinal single-mode emission and high power efficiency. They also correspond to a cost-efficient technology compared to conventional edge-emitting semiconductor lasers since they allow on-wafer fabrication and testing including two-dimensional array fabrication.

In the standard silica fiber-based networking applications, high-speed VCSELs based on different material systems covering the wavelength range from 850-nm to 1550-nm are commercially available and attracting enormous research efforts. The traditional main application areas of high-speed VCSELs are at all levels in optical communication networks. 850-nm VCSEL has the longest research history and was first commercialized [3] driven by applications such as Ethernet, InfiniBand and Fiber Channel. On the other hand, from metro and access networks, long-wavelength VCSELs operating at 1300-nm and 1550-nm are developed due to the low absorption loss and dispersion distortion in optic fibers. In comparison to short wavelength VCSELs, the progress of high-speed long-wavelength VCSELs was slow due to inherent material issues of the InP-based system. These challenges include intrinsic poor thermal conductivity as well as difficulties in finding good DBR candidates with appropriate refractive indices difference.

In addition, VCSEL has been qualified as the optical interconnect in data centers (Storage Area Networks, SAN), high performance computing (HPC) systems as well as consumer electronics (USB, PCI Express, HDMI, etc.) to replace galvanic interconnects in datacom-applications. VCSEL-based high-speed optical interconnects are widely used as a new market in recent years and propel the development and manufacturing in turn. Furthermore, the dense deployments of high-speed interconnect networks results in tremendous power consumption together with heat dissipation issue. New data centers have been located in cool climate areas with easy access to power plants and rivers or lakes for cooling water, within which the data transfer consumes most part of the energy. As a result, energy efficiency of the high-speed VCSELs as the power per transmitted bit becomes the most salient figure of merit for this application. Besides, as the migration steps towards lower level, operation at elevated temperatures pronounces its importance since it can easily reach over 80°C inside a computer system. As a result, VCSELs are particularly well matched candidates as optical interconnects owing to the high-speed and thermal stability performance, especially the power efficiency. For this application, GaAs-based 850-nm and 980-nm VCSELs are able to accommodate these critical requirements [2].

The highest modulation bandwidth demonstrated so far for a 850-nmVCSEL is 28 GHz [4]. This is also the current record for any wavelength-VCSEL. These VCSELs have been used to realize error free (BER<10^-12) data transmission up to 57 Gbit/s [4]. For 980-nm VCSELs, a maximum data rate of 49 Gbit/s was presented but at a low temperature of -14°C [5]. By employing a buried tunnel-junction (BTJ) and multiple strained QWs into a short cavity, data rate of 30 Gbit/s up to 10 kilometers single-mode fiber has been reported for 1300-nm VCSEL [6] and 40 Gbit/s in a back-to-back configuration for 1550-nm VCSEL [7]. Using electronic equalization, 64 Gbit/s data transmission was demonstrated over 57-m multimode fiber using a 26 GHz 850-nm VCSEL [8]. From the industrial perspective, vendors are capable of offering products covering different emission wavelengths with 25 Gb/s capability, including IBM/Finisar [9], TE Connectivity [10], VI Systems [11], Avago [12], Philips [13], Sumitomo [14], Furukawa [15], and Vertilas [16].
Transistor

Evolving from previous 10Gbit/s standards, the next generation solutions require single-channel rates of up to 25 Gbit/s [17]. It is suggested that by the year 2020, single-channel data rate as high as 100 Gbit/s will be required. Apparently today's VCSEL technology will have great difficulties to meet these demands, which create a quest for totally new device concepts. There have been some suggestions in the literature regarding improved-bandwidth VCSELS, including external modulation [18], self-injection-locked lasers [19], transverse-mode coupled-cavity VCSELS [20], minimized modal volume using high-index-contrast grating mirrors [21], and/or new modulation formats [22]. During recent years it has also been suggested that transistor-VCSELS (T-VCSELS) may be an option to realize significantly increased bandwidth. The experimental realization of such devices is the topic of the present thesis.

1.2 Transistor lasers: new optoelectronic three-port devices

The inventions of two semiconductor devices have revolutionized society, namely the transistor and the laser which have been instrumental in the development of microelectronics and photonics, respectively, both of which are cornerstones for continuous improvements in ICT systems. The transistor-laser (T-laser) as proposed by Feng and Holonyak in 2004 [23] represents the fusion of these two components into a single device with refined properties, including the potential for a greatly extended modulation bandwidth [24]. The first experimental demonstration of a T-laser was reported in 2005 [25], in which a QW active region was integrated into the base of a heterojunction bipolar transistor (HBT) so that a T-laser was realized. This achievement was highlighted by the American Institute of Physics as being one of the five most important papers published in the journal Applied Physics Letters throughout its entire history [26]. Ever since this proof-of-concept demonstration, T-laser research attracted more attention and more devices have been fabricated by different groups. The short-wavelength AlGaAs/InGaAs/GaAs T-lasers with emission around 1-µm [27], experimental T-lasers based on InP substrates including 1.3-µm emission with AlGaInAs multiple QWs [28] and 1.5-µm emission with InGaAsP multiple QWs [29, 30] have been demonstrated.

Unlike an individual transistor or a laser, T-laser has two independent input signals and can simultaneously output an electrical and an optical signal. The three-terminal configuration along with the active layers alter carrier dynamics in the base/cavity region and result in a number of attractive properties compared to conventional diode lasers. First, the transistor-based operation allows for a fast recombination lifetime, facilitating an enhanced modulation bandwidth [31, 32, 33, 34] with a suppression of relaxation oscillation. In addition, it enables a reduced turn-on delay [35] as well as the relative intensity noise (RIN) [36]. Second, the electrical output from the collector can be used as a feedback signal to reduce the high order intermodulation distortion (IMD) [37] and allow for an all-electrical laser power stabilization circuitry [38] without any monitor photodiode. Moreover, the T-laser is applicable to voltage-driven operation under various configurations such as common-emitter and common-base [39], which leads to a versatile optoelectronic device with simplified driver electronics [40, 41] and increased-flexibility matching network designs or ultra-compact negative-resistance oscillators, mixers, etc., for analog applications [42].

The basic operation principle of a T-laser is illustrated in Fig. 1. In this case, it is based on an npn HBT structure working at normal mode (also called active mode), i.e., the emitter and base junction is forward-biased and the base-collector junction is reverse-biased. An active region consisting of a multiple QWs (MQW) package is incorporated in the base region. Minority carriers of electrons are injected from the emitter into the base, a part of the carriers is consumed by the MQW, and the remaining are swept out of the base to the collector. In a conventional HBT structure, the recombination mechanism which contributes to the base current ($I_b$) involves bulk recombination, base-emitter space-charge recombination as well as back injection of holes from base to emitter [43]. In the case of a T-laser, owing to the presence of QWs in the base, injected electrons get additional chances to be captured by the QWs and recombine with holes, spontaneous and stimulated emission is thereby generated. The majority carrier supply from base contact leads to the dominant component of
$I_b$, bulk recombination, while other contributions become negligible. In other words, recombination center of QWs serves as the “optical collector” of injected carriers. Together with the collector current ($I_C$), both an electrical output and an optical output signals are generated simultaneously.

![Diagram of current components in an npn T-VCSEL](image)

Figure 1.1: Illustration of the current components in an npn T-VCSEL biased in the common-emitter configuration. The electron and hole currents are indicated by the red and blue arrows, respectively. The major current components are: 1) Electron-injection over the forward-biased base-emitter junction ($I_e$); 2) Base recombination current ($I_{br}$); 3) Part of the emitter current that is swept into the collector ($I_{Ce}$); 4) Majority-carrier contributions due to tunneling over the base-collector junction; and 5) Minority carrier contributions due to electron and hole injection over the base-collector junction (only effective in the saturation regime).

The carrier dynamics of the base region in an npn T-laser is illustrated in Fig. 1.2 (a). Assuming that the device is operating in the normal mode and a single QW is placed in the middle of the base, the excess electron density at the collector side of the base is close to zero due to reverse-biased base-collector junction and the overall electron density profile is a triangular. When the injected electrons diffuse to the QW position, a part of them diffuse across it and reach the collector with a transition lifetime of $\tau_t$, which contributes to the $I_C$. Meanwhile, the rest of electrons undergo the quantum capture process with an effective lifetime of $\tau_{cap}$. Before recombination occurs with a lifetime of $\tau_{rec}$, some captured electrons have the chance to escape from the QW with a lifetime of $\tau_{esc}$ and get swept out of the base. In an ordinary T-laser with a thin base, $\tau_t$ is on the level of few ps, $\tau_{cap}$ and $\tau_{esc}$ are also of ps. In terms of recombination lifetime $\tau_{rec}$, this is characterized by the spontaneous emission below lasing threshold which can be as long as ns. After the stimulated emission becomes dominant, this recombination time decreases and excess electrons get consumed more efficiently as optical output power increases. The unique mechanisms of excess carrier recombination and removal in a T-laser base region give rise to the most important feature that the modulation bandwidth can be extended. In other words, due to the fast removal of electrons from base by the reverse-biased base-collector junction, the effective lifetime of electrons in the base is decreased, which in turn is favorable of a higher modulation speed. In the common-base configuration, the modulated input signal is applied to the emitter terminal and the collector serves as the output terminal, while the base is common for both. The corresponding band diagram of an npn T-VCSEL working in the normal mode is illustrated in Fig. 1.2 (b). Since the modulated carriers in this configuration are electrons, a reduced carrier lifetime based on mechanism described above is valid and therefore the modulation bandwidth enhancement could be realized. When such a device is modulated in a common-emitter configuration (Fig. 1.2 (c)), the base terminal is the input end and the corresponding injected carriers are holes. As a result, the only option for the majority carriers is recombination with electrons captured in the QW conduction...
Given that carrier diffusion and removal process is not applicable in this case, it provides no benefit for high-speed modulation [42]. Another T-laser small-signal modulation configuration is called common-collector. As the name implies, in this configuration, the collector terminal is common and grounded, the input signal is from the base terminal. Because of the same majority carrier injection as in common-emitter configuration, the optical modulation response is expected to be the same as in common-emitter case.

Figure 1.2: (a) Schematic of the carrier distribution profile in the base region in the conduction band. (b) Energy band diagram and carrier dynamics in the common-base modulation configuration. (c) Energy band diagram and carrier dynamics in the common-emitter modulation configuration. From path 1 to 3, injected carriers can be consumed by direct recombination or as a result of QW capture, while path 4 indicates the carrier swept-out process in the common-base configuration (based on [44]).

1.3 T-VCSELs: motivation and review

Inheriting all merits of a T-laser, T-VCSEL would add some typical “VCSEL advantages”, e.g. in terms of low-cost manufacturing, on-wafer testing and large-scale 2D-arrays. A numerical study of a T-VCSEL was made by W. Shi et al at University of British Columbia (UBC) in collaboration with KTH [Paper A]. Both static and dynamic properties were evaluated, illustrating typical behaviors such as differential gain compression at the onset of stimulated emission and voltage-control operation [40].
In addition, an analytical expression of transfer function under small-signal modulation was developed by Faraji et al in UBC which is applicable to both T-lasers and T-VCSELs [31]. Calculations indicated a small-signal modulation enhancement in the common-base configuration as compared to common-emitter configuration. Moreover, the common-base modulation response is not only superior to the common-emitter configuration with respect to maximum bandwidth, but it also follows the intrinsic bandwidth without exceeding the limitation. Given the same input material parameters, results indicated an estimated maximum 3 dB-bandwidth of 48 GHz in the particular common-base configuration.

In 2012, experimental results of GaAs-based 980-nm T-VCSELs were demonstrated for the first time by Wu et al from University of Illinois at Urbana-Champaign [45, 46]. The measured static characteristics do exhibit the predicted phenomena such as low base threshold current compared to T-lasers, current gain compression at the base threshold as well as voltage-control operation. Besides, a photo-assisted tunneling effect at the base-collector junction was proposed under highly reversed-biased condition. However, the continuous-wave (CW) operation was only achieved at -75°C with modest power levels. Later in 2013, the first room-temperature operation of a GaAs-based 980-nm T-VCSEL was reported by KTH, realizing CW emission till at least 50°C with sub-mA base threshold current and mW-range output power [Paper B]. On the other hand, the device exhibited a premature saturation below threshold which results in a partial forward-biased base-collector junction that neutralizes the minority carrier swept-out effect during lasing.

1.4 About this work

This dissertation describes work towards the development of GaAs-based T-VCSELs. A comprehensive 3-D model of T-VCSEL including electrical, optical and thermal effects was established with a commercial software package. The model is calibrated by fitting the simulated performance to static measurements on conventional VCSELs as well as T-VCSELs. In paper A, an npn-type, oxidation-confined T-VCSEL is simulated and basic features of the device such as current gain compression at the onset of base threshold current and voltage control are demonstrated. Furthermore, it is demonstrated that the device operated in the common-base configuration has an extended modulation bandwidth as compared to a conventional diode VCSEL or to a T-VCSEL operated in the common-emitter configuration.

Due to preliminary materials issues related to p-doping close to the QW region, the experimental work focused on 980-nm pnp T-VCSELs, which were designed and fabricated for the first time. The measured device performance in paper B included mW-range output power, sub-mA threshold base current and continuous-wave operation well above room-temperature. However, a premature saturation below threshold was also observed, which is not desirable from application point of view since it effectively obstructs any of the potential T-laser advantages. In paper C, numerical simulations were used to analyze the spatial potential and current distribution in the device. This indicated that the premature saturation is due to a lateral potential variation in the device that results in a gradual turn-on of the base-collector junction so that it locally, in the interior of the device operate in its active mode while it globally operates in the saturation regime as reflected by the measured current-voltage characteristics.

In order to obtain a T-VCSEL that works in the active mode of operation also above lasing threshold, the design was optimized based on the numerical simulations. This evaluation suggested that an increase of the n-type layer thickness underneath the QWs would postpone the saturation and thereby extend the region of active mode of operation [Paper D]. New devices were fabricated according to this design and the corresponding measurements showed good agreement with the simulations. In this way, T-VCSELs in the active mode of operation well beyond threshold were demonstrated with mA level threshold current and mW-range output power up to at least 60°C [Paper E].
Additional design modifications involved buried tunnel-junction (BTJ) current injection, as evaluated on 1.3-μm InGaAs/GaAs VCSELs [Paper F], and an asymmetric current injection scheme for improved lateral feeding from the base and collector contacts. The BTJ-based current injection is expected to lead to more efficient carrier injection with reduces parasitics and optical absorption and it also corresponds to a simplified fabrication procedure. Such devices were fabricated and evaluated in Paper G. However, compared to npn-blocking layer current confinement and symmetric contact configuration they didn’t show any improved performance, calling for additional fine-tuning of these designs. Finally, the mechanism behind the collector current breakdown, in the limit of high base current and/or collector-emitter voltage was discussed with respect to a previously published model based on photon-assisted absorption in the reverse-biased base-collector junction. It is suggested here that this breakdown mechanism is rather due to a band-filling effect in the active layer [Papers F and G].
2. T-VCSEL structure and fabrication

The material growth and most of the device fabrication in this thesis was conducted at the KTH Electrum Laboratory cleanroom facility in Kista [47]. This has included MOVPE growth and regrowth of laser base structures and current confinement layers, stepper lithography, plasma deposition of dielectrics for surface passivation of high-contrast, non-conducting DBRs, evaporation and sputtering metallization, chemical wet etching and reactive ion etching. An electroplating processing step for the final metallization was performed at the MC2 cleanroom facility at Chalmers University of Technology. All devices were fabricated on full two-inch (001) oriented GaAs wafers. The fabrication sequence is borrowed and extended from the one for long-wavelength InGaAs/GaAs VCSELs [48].

2.1 Regrown pn-blocking layer confined T-VCSELs

The schematic layout of a fabricated regrown T-VCSEL structure is shown in Fig. 2.1. First, a basic structure of the device was epitaxially grown on an n-type GaAs substrate, consisting of 36.5 periods of graded $\text{Al}_{0.87}\text{Ga}_{0.13}\text{As}$/GaAs bottom DBR, the entire p-type collector and n-type base region, as well as part of the p-type emitter region. Modulation doping schemes were implemented both in the collector and emitter regions so that the high doped p-type layers were overlapping with the nodes of the standing-wave pattern. In the base region, triple intrinsic $\text{In}_{0.17}\text{Ga}_{0.83}\text{As}$ QWs of 7-nm thickness were sandwiched between two n-type GaAs layers. One of the most critical steps throughout a pnp T-VCSEL process is mesa etching of the base contact position. In the case of a GaAs-based npn T-VCSEL, a InGaP layer is usually employed as the emitter material [45], which works as an etching stop layer as well [49]. However, it doesn’t apply to the emitter material in a pnp T-VCSEL, which is AlGaAs in our cases. Due to epitaxy uniformity and etching precision, the n-type layer on top of the QWs has a thickness of 240-nm in order to make working base contacts on large scale of the wafer.

![Cross-sectional schematic of a fabricated pnp T-VCSEL with regrown confinement scheme.](image.png)

After the initial growth, a reflectance measurement was done using a normal incident white light source. The transfer matrix method was used to calculate the reflectance spectrum from the corresponding layer stack. A good match between the measured and calculated results is demonstrated in Fig. 2.2 by slight tuning of the layer thicknesses. The extracted growth rate is then applied in the further regrowth steps to compensate possible deviations from the nominal thicknesses in the initial layers.
Figure 2.2: A reflectance spectrum from the initial growth, including the bottom DBR and most part of the cavity. The fitting parameters are used to adjust or compensate the growth rate of the materials.

Subsequent processing steps are schematically demonstrated in Fig. 2.3. Starting from a square mesa etch with about 200-nm depth to define active regions as indicated in the second graph. The mask shown in Fig. 2.4 includes five different aperture sizes of 2, 4, 6, 8 and 10-µm, defining the side length of the square-shaped active layer region. The sidewalls of mesas are along the crystallographic $<100>$-type directions and a SiO$_2$ mask is used to cover the mesa during the first regrowth step. The first epitaxial regrowth step is performed with an n-type layer that is thinner than the mesa height, corresponding to Fig. 2.3 (c). After oxide mask removal, a squared mesa with approximately 80-nm height is formed, which defines the electrical and optical confinement simultaneously. This is directly followed by the second regrowth step to complete the cavity above the active region. In subsequent processing steps, dry etching followed by wet etching is used to define the emitter and base mesas respectively. These mesa definitions also determine the positions of the base and collector contacts. The etch depths are here well controlled by layer thickness determinations from reflectance spectrum measurement. Contacts are patterned and deposited by evaporation and lift-off processes. Pd/Ge/Ti/Au n-type contact is formed on top of the base region, outside the emitter mesa. Pd/Ti/Zn/Au p-type contacts for emitter and collector are made on top of the entire cavity and the modulation doped sub-collector layers respectively.
A test dielectric top DBR consisting of four periods of α-Si/SiO₂ bi-layers is deposited on a GaAs substrate by PECVD and measured for reflectivity at the design wavelength of the T-VCSEL, which in this case is 980-nm. The so-called Z-method is used for an easy and accurate reflectivity measurement [50]. The scattered intensity from every second reflection is measured and plotted against the numbers of bounces. An analytic expression is then used to extract the reflectance with high accuracy. The calibrated top dielectric DBR is then deposited. Via holes are etched to the emitter, base and collector contacts and a seed layer of gold is sputtered in the via holes as well as on top of the dielectric DBR. Probe pads are patterned and electroplated. The last step is to remove the seed layer of gold from the
top mirror by a wet etching process. A microscope image of a fabricated 10-µm aperture T-VCSEL is shown in Fig. 2.4.

In addition to the symmetric mesa definitions, another approached implemented in this thesis as part of the second generation layout design was the asymmetric mesa definition [51], as shown in Fig. 2.5. In order to shorten the lateral distance for current transport to the active region and thereby to reduce the corresponding voltage drop, part of the emitter and base mesas including the intracavity contacts are removed and replaced by collector contact. As a result, the shortest distance between collector contact and the center of device in the case of a 10-µm aperture decreases from 28 µm to 11 µm.

![Figure 2.5 Cross-sectional schematic of a T-VCSEL with asymmetric mesa design.](image)

**2.2 Tunnel-junction confined T-VCSELs**

In the case of a highly doped pn junction, the thin depletion region gives rise to a sufficiently narrow barrier that electrons are able to tunnel directly between energetically aligned valence band states on the p-side to conduction band states on the n-side. A typical $I$-$V$ curve of such a tunnel diode is displayed in Fig. 2.6. In the forward bias direction, the tunnel diode has a region of negative differential resistance (between point B and C) due to the finite bias region of overlapped conduction and valance-band states, which are widely used in microwave applications. As for the reverse biased condition, the Fermi level of conduction band in n-type region is lower than the Fermi level of valence band in p-type region. As a result, the filled states on the p-type side align with empty states on the n-type side, which directly gives rise to a tunneling current of electrons from p-type region to n-type region. Further increase of the reverse bias voltage simply increases the tunneling current, corresponding to a low series resistance. By employing a reverse-biased tunnel junction as the current confinement scheme in a pnp T-VCSEL, the fabrication is simplified by reducing the regrowth steps from two to one. Furthermore, the partial replacement of the emitter region from p-type to n-type is favorable for optical and thermal characteristics due to lower free carrier absorption and higher mobility. In addition, the tunnel junction induced low series resistance as well as junction capacitance results in a lower electric parasitics.
T-VCSELs with buried reverse biased tunnel-junction were fabricated by a single regrowth epitaxy step. A schematic of the device is shown in Fig. 2.7. The device has a similar base structure as the previous described T-VCSEL except for the confinement structure. In this case, a tunnel junction formed by a 10-nm p-type (C: $2 \times 10^{20}$ cm$^{-3}$) GaAs layer and a 20-nm n-type (Si: $1 \times 10^{19}$ cm$^{-3}$) In$_{0.1}$Ga$_{0.9}$As layer was grown on top the p-type emitter region. The initial growth was ended with another 50-nm n-type (Si: $2 \times 10^{18}$ cm$^{-3}$) thin layer on top of the highly doped InGaAs layer. Afterwards, a wet etching process was performed to define squared mesa for the electrical and optical confinement by the same recipe as in the case of a regrown confined T-VCSEL. Following the removal of SiO$_2$ mask layer on top of the active region, a straightforward single-regrowth step was required for the rest of the n-type cavity with a uniform doping (Si: $2 \times 10^{18}$ cm$^{-3}$). The device fabrication process follows essentially the same procedures as for the case of a pn-blocking layer injection device. The only difference is the n-type emitter contact in a tunnel-junction T-VCSEL that replaces p-type ones in the previous design.
Figure 2.7: Cross-sectional schematic of a reverse biased tunnel-junction T-VCSEL.
3. T-VCSEL modeling

Numerical modeling and parameter fitting are of major significance in the development and optimization of semiconductor devices. An important aspect of this work is an iterative comparison between simulated and measured device characteristics for a gradually refined model and improved agreement. This can then be used for performance analysis and device optimization as well as ultimate performance predictions. In the present, work we made used of a comprehensive commercial simulator PICS3D (Photonic Integrated Circuit Simulator in 3D) [52] that is capable of a full three-dimensional, self-consistent analysis of the light-current-voltage (L-I-V) characteristics, including optical mode distribution and thermal effects for the performance analysis and optimization of fabricated devices but also for general performance predictions. The general features of T-VCSEL operation as well as the conditions for improved modulation bandwidth for oxidation-confined T-VCSELs were examined [Paper A], but the model was also used to understand the limitations and optimization of the here fabricated epitaxially regrown T-VCSELs, specifically the design of the base region for an extended current-voltage range of T-VCSEL operation [Paper E].

3.1 General introduction

Three-dimensional mesh generation is very complex, and it consists of a number of 2D meshes generated by parallel cross sections varying slowly in the third direction. For example, a ridge waveguide laser would use the waveguide cross-section as the x, y direction and the z axis would be the longitudinal propagation axis. In the case of our T-VCSELs with square geometry and intra-cavity contacts, it requires multiple such segments in a stack to fully describe a 3D structure and therefor results in a large amount of total mesh points and computation time. By making use of the rotational symmetry, we can reduce the three-dimensional coordinate system to a two-dimensional one in order to save model building and computation time. Given the same volume of the active region, test VCSEL structures with square and cylindrical mesas were evaluated respectively in Fig. 3.1. The results showed a slight increase of the slope efficiency and an identical electrical characteristic when the simplified approach was used. The slope variation might be due to mode difference by solving Helmholtz equations in Cartesian or cylindrical coordinate systems [53].

By default PICS3D uses drift-diffusion theory to describe carrier transport in the bulk layers, together with a thermionic emission model as the boundary condition for heterojunctions [54, 55, 56]. A quantum well is treated as having two back-to-back heterojunctions and transport is mesh-point sequential: carriers from the left barrier must first drop into the well before they jump to the right
barrier [57]. The current density including drift and diffusion components also takes thermal effects into account by an extra term describing the effect of temperature gradient on current distribution. The dependence of electric resistivity on carrier mobility is provided by the Hall measurement ally useful when an density. As the computation of subbands using on. The free quantum model was applied which assumes a single, symmetric, flat well reduces the bandgap and independent which has major influences on emission wavelength, DBR reflectivity as well as slope efficiency. The refractive index of each layer is updated according to local mesh temperature at each bias during a continuous-wave simulation. The optical loss $\alpha_f$ is governed by free-carrier absorption and Auger recombination. The free-carrier absorption is also referred as intraband absorption and is calculated by a linear combination of the contributions from electron and hole concentrations $\alpha_f = k_n n + k_p p$, $k_n$ and $k_p$ are absorption coefficients for electrons and holes respectively. The Auger recombination effect is simplified as $R_{aug} = C_p n^\frac{3}{2}$ with major contributions from valence band Auger recombination, $C_p$ is Auger recombination coefficient for holes. Another uniform background optical loss is also taken into account for non-active materials as a fitting parameter to compensate the uncertain loss mechanisms.

Accurate thermal simulation results in correct temperature–dependent material parameters among which the most important ones are carrier mobility, bandgap energy, various recombination coefficients and refractive index. All of these temperature–dependent parameters are evaluated and updated with local mesh temperatures at each bias point. The heat source can be separated into contributions from Joule heat, generation/recombination heat and Thomson/Peltier heat. Heat flux is governed by material thermal conductivity defined as function of both material composition and local temperature.

The calculation of the quantum wells gain-current relationship requires among the most sophisticated models in the simulation and there are different levels of approximations to include in the calculations. In this work, the default quantum model was applied which assumes a single, symmetric, flat-band and step-wise potential profile. Quantum wells in a MQW region are assumed to be isolated from each other and wave functions do not overlap. The quantum well levels are calculated at every bias point during an actual simulation because the bandgap of the active region is a function of carrier density. As the bias increases, the higher carrier density in the quantum well reduces the bandgap and changes the quantum well depth. A full computation of subbands using $k.p$ theory is performed taking the strain induced non-parabolic valence band splitting and mixing into account. Carrier densities and interband optical transitions are obtained using numerical integral over the non-parabolic subbands, resulting in longer computation time.

### 3.2 Npn oxidation-confined T-VCSEL model

The T-VCSEL simulations in this thesis were originated from the model established by W.Shi et al. at the University of British Columbia in collaboration with KTH [Paper A]. It revealed the unique features of a T-VCSEL which were qualitatively reflected in the performance of the fabricated devices described in Papers D, F and G.

To calibrate the model, comparisons were made with PL measurements on a reference structure containing the MQW active layer as well as complete $L-I-V$ characterization of a diode VCSEL with a similar overall layer design as the T-VCSEL to be modelled. The effective bandgap for optical gain
calculations is reduced because of exchange effects [60]. Such a bandgap shrinkage is given by
$$\Delta E_g = 3 \times 10^{-10} \text{eV/m} \cdot \left( \frac{n}{2} + \frac{p}{2} \right)^{1/3}.$$ Since this term increases with carrier concentration, it causes a “red shift” tendency in the optical gain spectrum as the carrier concentration is increased. The peak optical gain also has a “blue shift” tendency due to the band filling effect (i.e., the Fermi level separation becomes larger as more subbands are filled). The blue shift effect is usually stronger than the red shift effect due to bandgap shrinkage. Broadening of intra-band scattering significantly reduces the local gain function and must be considered. The software has used the same broadening line shape functions which is the Lorentzian shape function for the spontaneous emission spectrum as for the gain function. This allowed us to compare experimental data with the broadened spontaneous spectrum calculation. Besides, the Coulomb interaction between electrons and holes confined in an active region was in particularly considered [61]. The role of Coulomb interaction can be explained in a way that while Coulomb force attracts electrons and holes at a closer distance, electron-hole radiative recombination rate increases, which manifests in enhancement in intensity of spontaneous emission as well as in gain magnitude. In addition Coulomb interaction modifies spontaneous emission and gain spectra of laser diodes by shifting the gain peak towards lower energies. By tuning the scattering time of 85 fs in Lorentzian broadening, calculated spontaneous emission showed a good agreement with the measured PL result (shown in Fig. 3.2).

Figure 3.2 Calculated and measured PL results, with and without Coulomb enhancement effect (Paper A).

A further VCSEL sample was fabricated employing the same QWs structure as the active layers. With the fixed parameters of the QWs, standard \( L-I-V \) curve were used for the extrapolation of remaining electrical and optical key parameters. The optical output power as a function of current injection gave rise to free-carrier absorption coefficients of \( k_n = 3 \times 10^{-18} \text{cm}^2 \) for electrons and \( k_p = 6 \times 10^{-18} \text{cm}^2 \) for holes. The Auger coefficient \( C_p \) was assumed to be \( 6.5 \times 10^{-30} \text{cm}^6 \cdot \text{s}^{-1} \). For the AlGaAs/GaAs DBRs, the thermal conductivity was modified by a factor of 0.4 in vertical direction to compensate frequent phonon scattering at multi-interfaces and a factor of 0.5 in lateral direction to take alloy scattering of phonons into consideration. In addition, the carrier mobility was reduced to 75% in the DBRs to compensate phonon scattering effect. All the above parameters contributed to a good fitting result as demonstrated in Fig. 3.3. Moreover, it offered reasonable initial guesses for the pnp regrown-confined T-VCSEL models.
Another important mechanism during the carrier transport process in a T-VCSEL is the QW capture and escape effects, which competes with the carrier diffusion to the collector. In order to describe such a phenomenon, a quantum capture/escape model was implemented along with a capture lifetime $\tau_{\text{cap}}=1\ \text{ps}$ and an escape lifetime $\tau_{\text{esc}}=20\ \text{ps}$. An npn oxidation-confined 980-nm T-VCSEL model was built upon the parameters and effects described above. The simplified schematic is shown in Fig. 3.4. Both of the DBRs were made of AlAs/GaAs layer stacks and doped for electrical conduction. A single InGaAs/GaAs QW structure was embedded between two highly p-doped thin layers. An n-type InGaP layer served as both the emitter layer and etching stop layer. In this design, the oxidation confinement scheme was implemented with an aperture of 6-μm. For the sake of simplicity and easy convergence, the model didn’t include impact ionization and Zener tunneling effects as well as the thermal effects.

The numerical calculation demonstrated the static characteristics of a T-VCSEL which inherited merits of both the VCSELs and the T-lasers. More importantly, the material parameters extracted from the numerical simulations were used for an analytical analysis of the dynamic performance.
3.3 Pnp regrown-confined T-VCSEL model

The epitaxially regrown-confined pnp-T-VCSEL model was implemented in PICS3D to simulate the room-temperature performance. The input files are essentially similar to those described in the previous section with some exceptions related to the carrier confinement configuration (listed in Appendix III). Special attention should be paid to the pn-blocking layer since it easily results in convergence difficulties due to the fact that the simulator uses either quasi-Fermi levels or carrier concentrations as the variables to solve equations corresponding to the amount of current flow which exhibits a lot difference from the blocking layer and the adjacent regions. Therefore, a trick was applied to ensure the convergence by ramping up the doping density in the blocking layer from an artificially reduced density to the real level. The calculated results show a good match with the measured ones from the first fabricated T-VCSELS, as shown in Fig. 3.5.

![Image](image.png)

Figure 3.5: Calculated (dash lines) vs measured (solid lines) performances of a T-VCSEL with 10-µm aperture. The inset shows the same experimental results below $I_B=1$ mA (Paper C).

Although there is a qualitative match between the simulated and measured optical output power, the absolute value of the measured one is a factor of three lower, as shown in Fig. 3.6. This discrepancy may be due to several different effects and shortcomings of the numerical model or combinations thereof, including overestimated material gain, overestimated modal gain (not taking account of spatial gain-mode mismatch due to uncertainties in epitaxial layer thicknesses, underestimated lateral carrier diffusion in the QWs, mismatch between carrier resonance and gain peak, or the usage of a circular rather than quadratic active region area), overestimated mirror loss (uncertainties in dielectric DBR layer thicknesses or refractive indices), underestimated internal losses (due to deviations from nominal doping levels, mismatch between modulation-doped layers and optical standing wave, or insufficient transverse optical confinement) or simply that divergent optical modes are not captured in the experiment which relies on a large-area detector positioned at some distance from the chip instead of using an integrating sphere positioned in closest proximity to the chip. Extensive calibrations between the model and similarly designed diode-VCSELS and T-VCSELS may resolve this issue. It should be noted that the agreement between the simulated and measured curves here is significantly better than what was obtained in Paper E. This is achieved by tuning $k_n$, $k_p$ and $C_p$ to generate the lowest $P_{out}$ with the same $I_{th}$ as measured, while a set of different values of those coefficients were used in Paper E.
Figure 3.6: Calculated versus measured lasing power of a T-VCSEL with 10-µm aperture.

As is clear from the inset of Fig. 3.5, transistor saturation occurs before the lasing threshold when increasing $I_B$. This is undesirable and requires optimization of the device structure. From an analysis of the inner carrier flow and potential distribution (further discussed in the next chapter) different alterations of the device structure were made and examined by simulations. An effective strategy was here found to be an extension of the n-doped layer underneath the QWs, as indicated in Fig. 3.7. Three structures were investigated, with this layer being 10, 100 and 200-nm, and the first structure serving as a reference corresponding to the first-generation devices. To maintain the emission wavelength at 980-nm a corresponding reduction in thickness had to be made to the collector region.

The dash lines in Fig. 3.8 shows simulations of the collector current as function of the base current for a constant collector-emitter voltage. A clear effect from the extended base region is seen. This was also implemented in fabricated devices with the corresponding measurements shown as the solid lines in Fig. 3.8. More details of this analysis and development are described in the next chapter. The slight difference in the simulated curves between Fig. 3.8 and Fig. 3.5 is due to different simulation input parameters and models involved as well as an updated software package. In addition, an increased current gain is obtained from the measurements of the 10-nm sample in the second generation as compared to the first generation devices (Fig. 3.5) despite the same nominal layer configuration and processing procedures. This might be attributed to small deviations in the layer thicknesses, doping
concentrations and/or device topography. In addition, these devices were fabricated using different mask sets corresponding to different layouts of the probe metal that also corresponds to larger contact areas and thereby reduced contact resistances in the newer generation devices in Fig. 3.8. The details regarding input parameters and calculated results of each design are given in Paper D.

Figure 3.8: Calculated (dash lines) and measured (solid lines) of the $I_B$ vs $I_C$ curves in different designs at a constant $V_{CE}$=3 V. The layer configuration in each design is the same except the thickness of n-doped layer underneath the QWs in the base region, with 10-nm, 100-nm and 200-nm respectively.
4. T-VCSEL material and device characterization

The first T-VCSEL design and simulation was based on an npn HBT structure, because of the high electron mobility which was beneficial for modulation respond and the emitter material of InGaP which facilities an easy etching process [62, 63]. However, due to practical issue of the active layer quality in such an npn structure, we turned to the fabrication of a pnp 980-nm T-VCSEL instead. In this chapter, the PL study of the QW properties in different base region was demonstrated. Moreover, measurement results from generations of pnp T-VCSELs are presented and analyzed. Improved performance was obtained attributed to numerical optimization.

4.1 Active layer integrity

Different from a conventional diode laser but similar to a HBT, the T-laser requires a high doping concentration in the base very close to the active region since it is the base recombination and its relation to the QW recombination that provide the basis for the operational characteristics. However, a high doping concentration in the cavity or close to the QWs is also known to induce losses due to free-carrier absorption or enhanced non-radiative carrier recombination, and dopant diffusion or segregation during growth of the active region may induce QW degradation [29, 64]. It is therefore of importance to detect any degradation in the luminescence efficiency related to the doping and to optimize the growth with this in mind. Prior to the growth of the T-VCSEL structures we therefore carried out a systematic study to investigate the dependency of QW luminescence as function of p- and n-type doping using Zn or C, or Si as dopants, respectively. Several samples employing triple QWs in the middle of the layer structures were prepared, as shown in Fig. 4.1. The structure in Fig. 4.1(a) was a reference sample, in which the QWs were embedded in intrinsic GaAs layers. Focusing on the Zn/C-doped (8×10¹⁸cm⁻³) p-type samples, different alternative structures were designed as shown from Fig. 4.2 (b) to (f), including changing the growth temperature, doping level and locations, and post annealing of doped layer, in which the QWs were located at the same position with the same growth condition.
Figure 4.1: Layer structures of the PL samples as well as the layer thickness and growth temperatures. (a) Reference sample with intrinsic GaAs. (b) – (f) Test sample with Zn doped layers on top and/or underneath the active layers.

PL measurement results based on these samples were demonstrated in Fig. 4.2. A significant decrease of the signal was observed comparing the Zn-doped sample to the reference. The result repeated itself by growing the same structure once again. Afterwards, another two dopant candidates which were carbon and silicon was tested based on the identical layer structure as shown in Fig. 4.1 (b). The C-doped p-type resulted in a similar degenerated signal while the Si-doped n-type sample retained the QW integrity by generating the same PL intensity as the reference.
Despite no solid conclusions could be drawn on any dependencies, there were some indications of distance and/or doping concentration dependency, suggesting a deteriorated PL signal as the p-type doping level increases and/or the layer position closer to the QWs. On the other hand, no extended defects were observed by PL microscopy or cathode luminescence in any of the sample mentioned above.

Since dopant diffusion was identified as the potential mechanism that gave rise to the QW degradation, secondary ion mass spectrometry (SIMS) measurements were performed on the Zn-doped and C-doped samples respectively. The corresponding results are illustrated in Fig. 4.3. The QWs are marked by the indium concentration while the 40-nm p-type layers on top of the QWs are on the left side and the 10-nm p-type layers underneath the QWs are on the right side. In the case of C-doped sample, it is evident that there is no carbon diffusion into the QW layers. On the other hand, segregation of zinc appears to be present in the bottom QW layer at the InGaAs/GaAs interfaces, enhancing the zinc concentration in the InGaAs QW by about a factor of five in comparison to the neighboring GaAs regions. Despite that such a phenomenon is not observed at the left flank of the 40-nm Zn-doped layer, the other QWs are free from the diffused zinc dopants.
Figure 4.3: Depth and concentration profile of Zn and C with In, Ga, and Al marker in the Zn-doped (top) and C-doped (bottom) samples with the same epitaxy structure.

The above results indicate that further experiments and growth optimizations are required to ensure high-quality QWs and efficient luminescence from an npn-type T-laser structure. While similar problems with InP-based T-lasers have been reported in the past and also are likely reasons for the rather modest threshold and power levels achieved from GaAs-based T-VCSELs [65], we have understood from other contacts that it is indeed possible to optimize the growth for preserved QW efficiency in the vicinity of both high p- and n-doping [66]. Anyway, partly because of these findings we decided to concentrate our efforts to pnp-type T-VCSELs, the other reason being that this would allow us to use a buried tunnel-junction injection scheme in combination with an n-type emitter region.

4.2 Results of regrown-confined T-VCSELs

The first fabricated T-VCSELs were of the pn-blocking layer-type described in Sec. 2.1. This was a natural extension of our previous work on similar-type diode-VCSELs which had already demonstrated good performance [48]. The first batch of these devices showed good performance in terms of threshold, output power, voltage control and high-temperature operation as described in Papers B and C. However, as discussed in the context of Fig. 3.5, they also showed a premature saturation, i.e. the transistor went into saturation before lasing threshold when increasing the base current. The reason for this was discussed extensively in Papers C, D and E as being due to a spatial potential distribution within the device and in particular to lateral voltage drops in the base and collector. As a result, the potential over the base-collector junction will be position-dependent and the state of the transistor will vary along this junction [Paper D, 40]. This is obviously an undesirable situation since the functionality of the T-laser relies on the transistor being in its active range of
operation and that the measured collector current resembles the optical output power for feedback operation or power monitoring.

The second generation of these devices therefore had an altered base-emitter region for reduced electrical gain, leading to a reduced collector current and thereby a reduced potential drop in the collector. Typical $L-I-V$ characteristics of such a second-generation device are presented in Fig. 4.4. The different features of these curves are discussed in detail in Papers D and G. Here we only point out the typical T-laser characteristics that can be observed:

- At threshold around 2 mA, there is clear gain saturation due to the onset of stimulated emission and a corresponding reduction in recombination lifetime. This leads to a flattening of $I_C$ as a direct consequence of the reduced differential gain ($=dI_C/dI_B$) but also to a flattening of $V_{BE}$ since the increase in $I_B$ beyond this point will be supported by an increased recombination current.
- For sufficiently high $V_{CE}$ and/or $I_B$, there is a sharp breakdown-character increase in the collector current. A similar breakdown was observed for npn-type oxidation-confined T-VCSELs by Wu et al. who attributed it to a Franz-Keldysh-type band-to-band absorption in the base-collector junction [46]. This is discussed in Papers D and G where it is argued that, primarily based on the temperature dependency of $L-I-V$ characteristics, it is rather due to a band-filling effect and saturation of the QWs.
- The complete quenching of the optical output power after “roll-over” has a signature in the collector current, presumably reflecting a photon-assisted carrier transport. However it is also noted that this quenching occurs at the same base-emitter voltage (approximately 3.5 V) independent of $V_{CE}$ or device size. This is discussed in Papers D and G where it is argued that it reflects a potential and current redistribution in the base region with increasing $V_{BE}$ that eventually leads to an insufficient supply of electrons to the QWs to maintain threshold carrier density.
- For increasing $I_B$, $I_C$ is rapidly decreasing until it eventually becomes negative (not shown in Fig. 4.4), reflecting that the base-collector junction is fully forward-biased and the device work as a double-injection diode.

Figure 4.4: $L-I-V$ curves of a 10-µm aperture device in the 200-nm sample at different biasing $V_{CE}$ under the common-emitter configuration (Paper G).
Typical electrical and optical common-emitter collector diagrams are shown in Fig. 4.5. The dash lines indicate a lower base potential than the collector \( (V_{BC} < 0) \) measured at the terminals based on the \( V_{BE} \)-vs-\( V_{CE} \) results which is not presented here but follows the same trend as the \( I_C \)-vs-\( V_{CE} \) diagram since \( V_{BE} \) depends on \( I_E = I_C + I_B \) and \( I_B \) is kept constant. The solid lines correspond to the situation when the measured base terminal potential is higher than the collector terminal \( (V_{BC} > 0) \). Meanwhile, black color indicates that only spontaneous emission is observed and red color suggests the stimulated emission. The \( V_{CE} \) offset voltage increases with a higher \( I_B \) and the \( V_{CE} \) biasing at \( V_{BC} = 0 \) is located in the active region of the collector diagram given a certain \( I_B \) indicated as the transition point from dash line to solid line, both of which is attributed to voltage drops induced by layer resistances. The gain compression at threshold is clearly observed as a denser distribution of lines in the \( I_C \)-vs-\( V_{CE} \) diagram for a constant increment in \( I_E \). The breakdown in \( I_C \), matching the quenching of \( P_{out} \), is observed to occur at decreasing \( V_{CE} \) for increasing \( I_B \), consistent with the observations in Fig. 4.4. From a closer inspection (Paper D) it is possible to see a reduction in threshold current in the limit of high \( V_{CE} \) (around 4.5 V) due to direct tunneling of electrons from the collector to the base. An interesting observation is also that large part of the light emission can be obtained in the transistor saturation regime \( (V_{BC} < 0) \).

![Collector diagram and voltage-controlled lasing of a 10-µm aperture device in the 200-nm sample at room-temperature in the common-emitter configuration (Paper G).](image)

The measured results of a 10-µm aperture with asymmetric mesa and 200-nm base doping layer in comparison to the symmetric mesa design are demonstrated in Fig. 4.6. Despite a similar \( I_{Bth} \) and current gain, \( V_{BE} \) increases much faster in the case of the asymmetric mesa, indicating a higher effective cavity resistance as a result of a non-uniform current injection. Besides, the optical output power is only 60% as compared to the symmetric mesa design for the same aperture size. This suggests a carrier-gain mismatch induced by the non-uniform injection profile.
Figure 4.6 Measurement results of $V_{BE}$ (top) and $I_C$ (bottom) as function of $I_B$ of a 10-µm aperture T-VCSEL with asymmetric and symmetric mesa designs.

4.3 Results of tunnel-junction confined T-VCSELs

Buried tunnel-junction (BTJ) devices were first evaluated in conventional diode-VCSELs and despite the non-optimized tunnel junction a clear reduction of the parasitic contributions were obtained [Paper F]. For the T-VCSELs, both of GaAs (p-type)/InGaAs (n-type) and InGaAs (p-type)/InGaAs (n-type) were implemented, where the latter type would be expected to show an even reduced voltage drop and series resistance. Figure 4.7 shows measured $L$-$I$-$V$ characteristics from a 10-µm aperture BTJ-T-VCSEL with standard symmetric mesa design. Compared to the results of a similar device with pn-blocking layer confinement scheme, a much lower current gain and $P_{out}$ along with a higher $V_{BE}$ are obtained from the BTJ-T-VCSEL, which at first sight appears counter-intuitive. The measured results indicate that the tunnel-junction provides higher resistance than expected thereby yielding a higher $V_{BE}$.
Figure 4.7 L-I-V characteristics of a 10-µm aperture T-VCSEL with symmetric mesa and InGaAs/InGaAs buried tunnel-junction designs.
5. Summary and outlook

5.1 Conclusions

In this thesis, a new optoelectronics device, the T-VCSEL, has been examined both theoretically and experimentally. Comprehensive three-dimensional numerical simulations taking account of electrical, optical and thermal properties has been used for device design, optimization and performance predictions, and several generations of prototypical GaAs-based T-VCSELs have been fabricated and analyzed. The work and results can be summarized as follows:

- A T-VCSEL biased in the common-base configuration may have a modulation bandwidth surpassing those of conventional diode-VCSELs or T-VCSELs biased in the common-emitter configuration.
- Several generations of GaAs-based T-VCSELs were designed, fabricated and analyzed. The design makes use of an epitaxial regrowth process including triple-intracavity contacting, undoped DBRs and modulation doping for minimized optical loss. This resulted in the first demonstration of T-VCSELs operating continuous-wave at room-temperature and beyond with static performance figures resembling those of conventional diode VCSELs in terms of threshold current, output power, power efficiency and high-temperature operation.
- The collector current breakdown mechanism, in previous works identified as a Franz-Keldysh-photon reabsorption process [46], was analyzed in some detail and it was concluded that the governing mechanism behind this breakdown rather is related to a band-filling effect.
- Different design variations for an efficient current injection based on epitaxially regrown pn-blocking layers, a BTJ and/or an asymmetric device layout for improved lateral feeding were investigated. The BTJ concept corresponds to a simplified processing sequence and reduced parasitics and should be of interest for further optimizations, whereas the asymmetric current injection resulted in reduced power, increased threshold and reduced operation range. This may very well have the potential for improvement using better optimized contact layout and/or layer structure.

5.2 Suggestions for future work

The T-VCSEL is still in a very early stage of development. While the present study represents the first successful demonstration of the room-temperature operation of such devices, there is a long way to go before it becomes clear whether it can have any impact on applications, e.g., in high-speed data communication as frequently suggested in literature. This will correspond to a cumbersome step-by-step approach to evaluate different design approaches for optimized static performance, dynamic measurement to evaluate intrinsic and extrinsic bandwidth limitations, noise properties linearity, feedback-operation, etc. Equivalent circuit models need to be constructed to evaluate the potential for using it as building blocks in more advanced configurations that for instance taking account of transistor-based design techniques to realize compact circuits for microwave applications. The most immediate concerns will be to evaluate design-improvements for the here presented devices in terms of static and dynamic properties:

- The optimization and implementation of improved BTJ structures. Using the present n⁺p⁺ InGaAs/(In)GaAs as a base line other heterojunctions for more efficient tunneling should be evaluated. This may include higher In-content or increased-doping InGaAs/InGaAs junctions but also more novel varieties such as (In)GaAs(Sb):p⁺⁺/(In)GaAs(N):n⁺⁺ junction for where Sb and N have the effects of pushing up the valence band edge and pushing down the conduction band edge, respectively [67]. However, it is important to note that the tunnel junction needs to be designed in
such a way that band-to-band absorption of the lasing light should be avoided. This approach has so far been more common for long-wavelength VCSELs in the 1100 to 1550-nm regime [7, 16, 68].

- Theoretical and experimental investigations on an altered layer structure and lateral device design to meet the combined requirements on a short-cavity with functional transistor operation.
- Further investigations and optimization of p-doped cavity/active layer regions for preserved luminescence properties so that also npn-type T-VCSELs can be examined.
- Extensive dynamic characterizations to explore the bandwidth limitations and construction of equivalent circuit models.
- Refined theoretical models to enable a more thorough understanding of ultimate performance limitations.
- Identifications and investigations of different applications that may benefit from the T-VCSEL, e.g. taking account of the three-terminal configuration for signal-mixing, collector current-based feedback operation or the potentially extended dynamic properties.
Guide to the papers

Paper A: Design and modeling of a transistor vertical-cavity surface-emitting laser
A numerical model of npn T-VCSEL is established, incorporating various physical models to describe important effects such as Coulomb enhancement, free-carrier absorption, Auger recombination, QW capture/escape process, etc. The material parameters and coefficients are carefully calibrated against the photoluminescence results of InGaAs QWs as well as L-I-V curves of a conventional GaAs-based VCSEL with otherwise similar design as the here considered T-VCSEL. Both the static performance and modulation response are derived based on the simulation, which demonstrate the influence of quantum capture/escape process on electrical and optical properties and the modulation bandwidth enhancement in the common-base configuration.

Author contribution: part of 980-nm VCSEL design and growth, discussions on the analysis and modeling

Paper B: Room-temperature operation of a transistor vertical-cavity surface-emitting laser
A GaAs-based 980-nm pnp T-VCSEL working at room-temperature up to 50°C is demonstrated for the first time. A pn-blocking layer is implemented during two regrowth steps as the electrical and optical confinement scheme. Square active regions and mesas are defined and a Si/SiO₂ dielectric top DBR is deposited. The device is operated in current and voltage controlled modes, with mA-level threshold current and mW-range optical power.

Author contribution: Part of the device design and fabrication, characterization, data analysis

Paper C: Minority current distribution in InGaAs/GaAs transistor-vertical-cavity surface-emitting laser
The static performance of the T-VCSELs demonstrated in Paper A is examined using numerical simulations. It is found that the internal potential and carrier distributions have a large impact on the device performance, e.g. leading to a premature saturation below threshold. As a result, it operates in the active mode in the interior of the device while the measured current-voltage characteristics indicate that it is in saturation.

Author contribution: Device characterization, simulation, data analysis, writing the paper

Paper D: Performance optimization of GaAs-based pnp-type vertical-cavity surface-emitting transistor-lasers
GaAs-based pnp T-VCSELs are fabricated with systematic variation of the base width. It is demonstrated that the active mode of operation can be extended by an increased base width due to the combined effects of reduced base resistance and current gain. This results in transistor-laser like characteristics well beyond lasing threshold, including mA-range threshold current, mW-range output power, record-low power dissipation during lasing and high-temperature lasing up to at least 60°C. The collector current breakdown characteristics as function of base current or emitter-collector voltage is studied in some detail and in contrast to previous studies it is suggested that the breakdown mechanism presumably is trigged by a quantum band-filling effect.

Author contribution: Device design and fabrication, characterization, data analysis, writing the paper
Paper E: Influence of base-region thickness on the performance of pnp transistor-VCSEL

Numerical multi-physics device simulations are performed in order to better understand the device physics of the first generation T-VCSELs (presented in Papers B and C) and as a tool for device optimization. The simulations suggest that the operating range of the T-VCSEL can be enhanced from an extension of the base width, which was later confirmed by measurements on fabricated devices (Paper D). Guidelines are also provided regarding the doping distribution in the base region and the positioning of the quantum wells, and it is suggested that alternative device designs that allow the positioning of the metal contacts closer to the center of the device should be evaluated.

Author contribution: Device fabrication and characterization, part of the simulation optimization

Paper F: 1.3-µm buried tunnel junction InGaAs/GaAs VCSELs

InGaAs/GaAs VCSELs are fabricated using an epitaxial regrowth process. Using highly strained InGaAs/GaAs QWs with emission wavelength beyond 1200-nm in combination with a negative gain-cavity detuning, it is possible to extend the wavelength towards 1300-nm. Pn-blocking layer and buried tunnel-junction confinement are compared and it is concluded that the latter can provide lower series resistance and improved high-speed dynamics through a reduction of the electrical parasitics.

Author contribution: Part of the device design and fabrication, characterization

Paper G: AlGaAs/GaAs/InGaAs pnp-type vertical-cavity surface-emitting transistor-lasers

The fabrication and optimization of pnp-type T-VCSELs are reviewed. Measurements on T-VCSELs with systematic design variations reveal a rich interplay between electrical field, current distribution and optical field that needs to be taken into account in the optimization process. Tunnel-junction current injection and devices with asymmetric contact layout are investigated for the purpose of reducing the extrinsic base, emitter and collector resistances.

Author contribution: Device design and fabrication, characterization, data analysis, writing the paper
References


development at Philips," in SPIE OPTO. International Society for Optics and Photonics, 2013.


British Columbia, 2011.


[66] R. King, Philips Photonics, private communication.


Appendix I: Processing list of T-VCSEL

1. Epitaxy
1.1 Growth according to layer configuration

2. Regrowth
2.1 Deposition of SiO₂ and Si₃N₄
2.1.1 HCl: H₂O=1: 2, 30sec, rinse in DI-H₂O
2.1.2 Deposition of 100-nm SiO₂ in Pekka: 300°C, 90sec
2.1.3 Deposition of 60-nm Si₃N₄ in Pekka: 300°C, 250sec

2.2 Lithography of aperture 1
2.2.1 HMDS, 25min
2.2.2 Spinning: SPR700-1.2, 4000rpm, 30sec
2.2.3 Contact hotplate: 95°C, 60sec
2.2.4 DSW stepper: ex xiangact1\1,2,3,4,5, exposure 0.3sec on patterns and 0.35sec on blank edges
2.2.5 Contact hotplate: 115°C, 60sec
2.2.6 Develop: CD-26, 32sec
2.2.7 Rinse in bubble water, 60sec

2.3 Si₃N₄ etch
2.3.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
2.3.2 Etch in ESA: 15mTorr, 45W, 25sccm CF₄, 7min
2.3.3 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 2min

2.4 Removal of resist
2.4.1 Acetone + propanol + H₂O, 5min + 5min + 5min
2.4.2 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec

2.5 Lithography of aperture 2
2.5.1 HMDS, 25min
2.5.2 Spinning: SPR700-1.2, 4000rpm, 30sec
2.5.3 Contact hotplate: 95°C, 60sec
2.5.4 DSW stepper: map xiangact2\mapreg,1,2,3,4,5, exposure 0.3sec on patterns and 0.35sec on blank edges
2.5.5 Contact hotplate: 115°C, 60sec
2.5.6 Develop: CD-26, 32sec
2.5.7 Rinse in bubble water, 60sec

2.6 Si₃N₄ etch
2.6.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
2.6.2 Etch in ESA: 15mTorr, 45W, 25sccm CF₄, 7min
2.6.3 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 2min

2.7 Removal of resist
2.7.1 Acetone + propanol + H₂O, 5min + 5min + 5min
2.7.2 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec

2.8 SiO₂ etch
2.8.1 BHF: H₂O=1: 25, 2min30sec

2.9 GaAs wet etch (in the case of pn-blocking T-VCSEL)
2.9.1 Si₃N₄ etch in ESA: 150mTorr, 30W, 45sccm CF₄, 5sccm O₂, 3min
2.9.2 HCl: H₂O=1: 2, 2min30sec
2.9.3 GaAs wet etch: H₂O: NH₄OH: H₂O₂=1000: 20: 7

2.9 GaAs wet etch (in the case of tunnel junction T-VCSEL)
2.9.1 HCl: H₂O=1: 2, 2min30sec
2.9.2 GaAs wet etch: H₂O: NH₄OH: H₂O₂=1000: 20: 7

2.10 Regrowth (in the case of pn-blocking T-VCSEL)
2.10.1 Regrowth of blocking layer
2.10.2 SiO₂ etch: BHF, 30sec
2.10.3 2nd regrowth of conducting layer

2.10 Regrowth (in the case of tunnel junction T-VCSEL)
2.10.1 Si₃N₄ and SiO₂ etch: BHF, 30sec
2.10.2 Regrowth of conducting layer

3. Base mesa define
3.1 Deposition of SiO₂
3.1.1 Deposit 200-nm SiO₂ in Pekka: 300°C, 180sec
3.2 Lithography of base mesa
3.2.1 HMDS, 25min
3.2.2 Spinning: SPR700-1.2, 4000rpm, 30sec
3.2.3 Contact hotplate: 95°C, 60sec
3.2.4 DSW stepper: map xiangbpit\mapreg,1,2,3,4,5, exposure 0.3sec on patterns and 0.35sec on blank edges
3.2.5 Contact hotplate: 115°C, 60sec
3.2.6 Develop: CD-26, 32sec
3.2.7 Rinse in bubble water, 60sec
3.3 SiO₂ etch
3.3.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
3.3.2 BHF: H₂O=1: 25, 5min
3.4 GaAs dry etch
3.4.1 RIE in Fabio: 2mTorr, SiCl₄ = 3sccm, Ar = 2sccm, power = 40W
3.5 Remove of resist
3.5.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 2min
3.5.2 Acetone + propanol + H₂O, 5min + 5min + 5min
3.5.3 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
3.6 GaAs wet etch
3.6.1 GaAs wet etch: H₂O: NH₄OH: H₂O₂=1000: 20: 7
3.7 SiO₂ etch
3.7.1 BHF, 30sec

4. Collector mesa define
4.1 Deposition of SiO₂
4.1.1 Deposit 200-nm SiO₂ in Pekka: 300°C, 180sec
4.2 Lithography of collector mesa
4.2.1 HMDS, 25min
4.2.2 Spinning: SPR700-1.2, 4000rpm, 30sec
4.2.3 Contact hotplate: 95°C, 60sec
4.2.4 DSW stepper: map xiangbpit\mappit,1,2,3,4,5, exposure 0.3sec on patterns and 0.35sec on blank edges
4.2.5 Contact hotplate: 115°C, 60sec
4.2.6 Develop: CD-26, 32sec
4.2.7 Rinse in bubble water, 60sec
4.3 SiO₂ etch
4.3.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
4.3.2 BHF: H₂O=1: 25, 5min
4.4 GaAs dry etch
4.4.1 RIE in Fabio: 2mTorr, SiCl₄ = 3sccm, Ar = 2sccm, power = 40W
4.5 Remove of resist
4.5.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 2min
4.5.2 Acetone + propanol + H₂O, 5min + 5min + 5min
4.5.3 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
4.6 GaAs wet etch
4.6.1 GaAs wet etch: H₂O: NH₄OH: H₂O₂=1000: 20: 7
4.7 SiO₂ etch
4.7.1 BHF, 30sec

5. TLM mesa define
5.1 Deposition of SiO₂
5.1.1 Deposit 200-nm SiO₂ in Pekka: 300°C, 180sec
5.2 Lithography of TLM mesa
5.2.1 HMDS, 25min
5.2.2 Spinning: SPR700-1.2, 4000rpm, 30sec
5.2.3 Contact hotplate: 95°C, 60sec
5.2.4 DSW stepper: map xiangtlm\mapreg,1, exposure 0.3sec
5.2.5 Contact hotplate: 115°C, 60sec
5.2.6 Develop: CD-26, 32sec
5.2.7 Rinse in bubble water, 60sec
5.3 SiO₂ etch
5.3.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
5.3.2 BHF: H₂O=1: 25, 5min

5.4 GaAs dry etch
5.4.1 RIE in Fabio: 2mTorr, SiCl₄ = 3sccm, Ar = 2sccm, power = 40W

5.5 Remove of resist
5.5.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 2min
5.5.2 Acetone + propanol + H₂O, 5min + 5min + 5min
5.5.3 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec

5.6 SiO₂ etch
5.6.1 BHF, 30sec

6. N-type contact deposition
6.1 Si₃N₄ deposition
6.1.1 Deposit 135-nm SiO₂ in Pekka: CIP21, 25min
6.2 Lithography of N-metal
6.2.1 HMDS, 25min
6.2.2 Spinning: Si818, 4000rpm, 30sec
6.2.3 Contact hotplate: 115°C, 60sec
6.2.4 DSW stepper: map xiangnmp\mappit,1 (for pn-blocking T-VCSEL) ; mapxiangnmp2\mappit,1 (for tunnel junction T-VCSEL)
6.2.5 Develop: 351: H₂O=1: 5, 50sec
6.2.6 Rinse in bubble water, 60sec

6.3 Si₃N₄ etch
6.3.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
6.3.2 Etch in ESA: 15mTorr, 45W, 25sccm CF₄, 5sccm O₂, 260sec
6.3.3 Etch in ESA: 150mTorr, 25W, 50sccm CF₄, 5sccm O₂, 150sec
6.3.4 Ash in ESA: 150mTorr, 25W, 50sccm O₂, 120sec
6.3.5 HCl: H₂O=1: 2, 30sec, rinse in DI-H₂O

6.4 Evaporation of N-metal
6.4.1 Evaporation in Barbara: Pd (40nm)/Ge (80nm)/Ti (40nm)/Pd (40nm)/Ti (10nm), from bottom to top

6.5 Lift-off of N-metal
6.5.1 Lift-off: acetone+ propanol + DI-H₂O, 5min + 5min + 5min
6.5.2 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec

7. P-type contact deposition
7.1 Lithography of P-metal
7.1.1 HMDS, 25min
7.1.2 Spinning: Si818, 4000rpm, 30sec
7.1.3 Contact hotplate: 115°C, 60sec
7.1.4 DSW stepper: map xiangpmp\mapmet,1 (for pn-blocking T-VCSEL); map xiangpmp2\mapmet,1 (for tunnel junction T-VCSEL)
7.1.5 Develop: 351: H₂O=1: 5, 50sec
7.1.6 Rinse in bubble water, 60sec
7.2 Si₃N₄ etch
7.2.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
7.2.2 Etch in ESA: 15mTorr, 45W, 25sccm CF₄, 5sccm O₂, 260sec
7.2.3 Etch in ESA: 150mTorr, 25W, 50sccm CF₄, 5sccm O₂, 150sec
7.2.4 Ash in ESA: 150mTorr, 25W, 50sccm O₂, 120sec
7.2.5 HCl: H₂O=1: 2, 30sec, rinse in DI-H₂O
7.3 Evaporation of P-metal
7.3.1 Evaporation in Zita and Barbara: Au (5nm)/Zn (30nm)/Au (40nm)/Pd (40nm)/Ti (10nm), from bottom to top
7.4 Lift-off of P-metal
7.4.1 Lift-off: acetone+ propanol + DI-H₂O, 5min + 5min + 5min
7.4.2 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec

8. Mirror hole define
8.1 Lithography of mirror hole
8.1.1 HMDS, 25min
8.1.2 Spinning: Si818, 4000rpm, 30sec
8.1.3 Contact hotplate: 115°C, 60sec
8.1.4 DSW stepper: map xiangmirr\mapmet,1
8.1.5 Develop: 351: H₂O=1: 5, 50sec
8.1.6 Rinse in bubble water, 60sec
8.2 Si₃N₄ etch
8.2.1 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec
8.2.2 Etch in ESA: 15mTorr, 45W, 25sccm CF₄, 5sccm O₂, 260sec
8.2.3 Etch in ESA: 150mTorr, 25W, 50sccm CF₄, 5sccm O₂, 150sec
8.2.4 Ash in ESA: 150mTorr, 25W, 50sccm O₂, 120sec
8.3 Remove of resist
8.3.1 Acetone+ propanol + H₂O, 5min + 5min + 5min
8.3.2 Ash in ESA: 15mTorr, 45W, 25sccm O₂, 30sec

9. Mirror deposition
9.1 Deposit first top mirror layer
9.1.1 Deposit SiO₂ in Pekka: 250°C
9.2 Contacts annealing
9.2.1 Annealing in PEO, 325°C, 30min
9.3 Deposit the rest of mirror
9.3.1 Deposit α-Si in P5000: 250°C (×number of periods)
9.3.2 Deposit SiO₂ in Pekka: 250°C (×number of periods-1)

10. Via hole
10.1 Lithography of via hole
10.1.1 HMDS, 25min
10.1.2 Spinning: Si818, 4000rpm, 30sec
10.1.3 Contact hotplate: 115°C, 60sec
10.1.4 DSW stepper: map xiangvia\mappit,1
10.1.5 Develop: 351: H$_2$O=1: 5, 50sec
10.1.6 Rinse in bubble water, 60sec

10.2 Etch via hole
10.2.1 Ash in ESA: 15mTorr, 45W, 25sccm O$_2$, 30sec
10.2.2 LP α-Si etch in ESA: 25mTorr, 50W, 25sccm CF$_4$, 5sccm O$_2$ (× number of periods)
10.2.3 HP α-Si etch in ESA: 150mTorr, 30W, 50sccm CF$_4$, 5sccm O$_2$ (× number of periods)
10.2.4 SiO$_2$ etch in ESA: 25mTorr, 50W, 25sccm CF$_4$, 5sccm O$_2$ (× number of periods)

10.3 Remove of resist
10.3.1 Ash in ESA: 15mTorr, 45W, 25sccm O$_2$, 2min
10.3.2 Acetone+ propanol + H$_2$O, 5min + 5min + 5min
10.3.3 Ash in ESA: 15mTorr, 45W, 25sccm O$_2$, 30sec

11. Surface metal
11.1 Sputtering of seed layer
11.1.1 Sputter in KDF: TiW, 1.5kW, speed 75, pass 8, 250nm
   Au, 1.5kW, speed 200, pass 8, 100nm
11.2 Backside protection
11.2.1 Deposit 200-nm SiO$_2$ in Pekka: 300°C, 180sec
11.3 Lithography of surface metal
11.3.1 HMDS, 25min
11.3.2 Spinning: S1818, 4000rpm, 30sec
11.3.3 Contact hotplate: 115°C, 60sec
11.3.4 DSW stepper: map xiangsvap\mappit,1
11.3.5 Develop: 351: H$_2$O=1: 5, 50sec
11.3.6 Rinse in bubble water, 60sec
11.4 Plating of surface metal
11.4.1 Ash in ESA: 15mTorr, 45W, 25sccm O$_2$, 30sec
11.4.2 Plating at Chalmers
11.5 Remove of resist
11.5.1 Ash in ESA: 15mTorr, 45W, 25sccm O$_2$, 2min
11.5.2 Acetone+ propanol + H$_2$O, 5min + 5min + 5min
11.5.3 Ash in ESA: 15mTorr, 45W, 25sccm O$_2$, 30sec
11.6 Remove of seed layer
11.6.1 Au etch, KI
11.6.2 TiW etch, H$_2$O$_2$
Appendix II: Process flow of pn-blocking confined T-VCSEL
(Cross-sectional schematics in accordance to process procedures in Appendix I)
Appendix I: Simulation files of pn-blocking confined T-VCSEL

1. Material parameters (Double column format)

$***********************************
$ macro algaas
$ for bulk Al(x)Ga(1-x)As
$ Lattice matched to GaAs
$ [free-style]
$ Temperature dependent version of macro algaas
$ Renamed from algaas.temp
$ Typical use:
$ load_macro name=algaas var1=#x mater=#m &&
$ var_symbol1=x
$ parameter_range x=[0 1]
$ parameter_range temper=[77 600]
$ parameter_range total_doping=[1.e20 1.e26]
$ parameter_range doping_n=[1.e20 1.e26]
$ parameter_range doping_p=[1.e20 1.e26]
$ parameter_range trap_1=[1.e18 1.e24]
$***********************************

begin_macro algaas
material type=semicond band_valleys=(1 1)
&&
el_vel_model=n.gaas hole_vel_model=beta

dielectric_constant variation=function
function(x)
13.1 - 3 * x
dern_function

electron_mass variation=function
function(x)
for 0.<x<0.45
0.067 + 0.083 * x
for 0.45<x<1.
0.85 - 0.14 * x
dern_function

hole_mass variation=function
function(x)
( ( 0.087 + 0.063 * x ) ** (3 / 2)
+ ( 0.62 + 0.14 * x ) ** (3 / 2) ) ** (2 / 3)
end_function

band_gap variation=function
function(x,temper)
for 0.<x<0.45
shift=-5.5e-4 * temper**2
/(temper+225)+9.4285712E-02 ;
1.424 + 1.247 * x +shift
for 0.45<x<1.
shift=-5.5e-4 * temper**2
/(temper+225)+9.4285712E-02 ;
1.9 + 0.125 * x + 0.143 *x * x +shift
end_function

affinity variation=function
function(x,temper)
for 0<x<0.45
offset=0.6;
shift=-5.5e-4 * temper**2
/(temper+225)+9.4285712E-02 ;
4.07 - 0.748 * x-offset*shift
for 0.45<x<1.
offset=0.6;
shift=-5.5e-4 * temper**2
/(temper+225)+9.4285712E-02 ;
3.7964 - 0.14 * x-offset*shift
end_function

electron_mobility variation=function
function(x,temper,total_doping)
for 0<x<0.45
fac=(300/temper)**2.3;
mu_max=1.5 * exp(-18.516 * x ** 2 )*fac;
mu_min=0;
ref_dens=1.69d23;
alpha=0.436;
mu_min+(mu_max-
mu_min)/(1+(total_doping/ref_dens)**alpha)
for 0.45<x<1.
fac=(300/temper)**2.3;
mu_max=0.035*fac;
mu_min=0;
ref_dens=1.69d23;
alpha=0.436;
mu_min+(mu_max-
mu_min)/(1+(total_doping/ref_dens)**alpha)
end_function

hole_mobility variation=function
function(x,temper,total_doping)
dope=1.e22 ;
tfac1=(temper/300)**2.3 ;

fac1=(temper/300)**1.5 ;

mu_max=(0.07- 0.048 * x + 0.02 * x * x)*fac;

mu_min=0;

ref_dens=2.75d23;

alpha=0.395;

mu_min+(mu_max-

mu_min)/(1+(total_doping/ref_dens)**alpha)

end_function

beta_n value=2.

electron_sat_vel variation=function

for 0<x<0.45

fac=(300/temper)**2.3;

0.77e5 * (1 - 0.44 * x )*fac

for 0.45<x<1.

fac=(300/temper)**2.3;

8.e4*fac

end_function

beta_p value=1.

holed_sat_vel variation=function

for 0<x<0.45

fac=(300/temper)**2.3;

0.77e5 * (1 - 0.44 * x )*fac

for 0.45<x<1.

fac=(300/temper)**2.3;

8.e4*fac

end_function

elec_carr_loss variation=function

function(x,temper)

$3.52 - 0.57*x + 3.5e-4*(temper - 300)

$3.52 - 0.57*x + 3.5e-4*(temper - 300)

end_function

beta_n value=2.

hole_sat_vel variation=function

function(temper)

dope=1.e22 ;

tfac1=(temper/300)**2.3 ;

tfac2=(temper/300)**1.5 ;

fac=1/( tfac1 + 1.6e-24*dope*tfac2 );

1.d5*fac

end_function

spec_heat variation=function

function(x)

450*x + 327*(1-x)

end_function

mass_density variation=function

function(x)

3760*x + 5320 *(1-x)

end_function

end_macro algaas

macro for sio2

$ Bulk insulator SiO2

$ [free-style]

$ Typical use:

$ load_macro name=sio2 mater=#m

$ ***********************************

begin_macro sio2

material type=insulator

$ set affinity for the purpose of plotting band diagram

$ ***********************

$ ***********************************
affinity value=4.0
dielectric_constant value=3.9

$real\_index \ value=1.45$
real_index variation=function
function(temper)
1.45 + 1.5e-4*(temper-300)
end_function

$absorption\ value=0.$
thermal_kappa value=1.4 real value = 1.4
spec_heat value=1000

$ mass\ density\ (Kg/m^3)$
mass_density value=2330

$acitve\ layer\ macro:\ In(xw)Ga(1-xw)As/Al(xb)Ga(1-xb)As$
material type=insulator
$ set\ affinity\ for\ the\ purpose\ of\ plotting\ band\ diagram$
affinity value=4.0
dielectric_constant value=13.1
real_index variation=function
function(temper)
3.52 + 1.5e-4*(temper-300)
end_function

absorption value=0.0
thermal_kappa value=55
spec_heat value=327
mass_density value=5320

$compressive\ strain\ is\ negative:
strain_well variation=function
function(xw,temper)
a0ga=5.65325;
a0in=6.0584;
acomp=a0ga+xw*(a0in-a0ga);
(a0ga-acomp)/acomp
end_function

strain_bar value=0.0
band_offset value=0.7

delta_so_well variation=function
function(xw)
0.366-0.0451*xw+0.0691*xw*xw
end_function

delta_so_bar value=0.366

mass_gamma_well variation=function
function(xw)
0.063-0.036*xw
end_function

mass_l_well value=0.56

mass_gamma_bar variation=function
function(xb)
0.067+0.083*xb
end_function

mass_l_bar variation=function
function(xb)
0.56+0.1*xb
end_function

gamma1_well variation=function
function(xw)
g1ga=6.9 ;
g1in=19.7 ;
g1ga+xw*(g1in-g1ga)
end_function

gamma2_well variation=function
function(xw)
g2ga=2.2 ;
g2in=8.4 ;
g2ga+xw*(g2in-g2ga)
end_function

gamma3_well variation=function
function(xw)
g3ga=2.9 ;
g3in=9.3 ;
g3ga+xw*(g3in-g3ga)
end_function

a_well variation=function
function(xw)
dhga=-9.8 ;
dhin=-5.0 ;
dhga+xw*(dhin-dhga)
end_function

b_well variation=function
function(xw)
duga=1.76 ;
duin=1.8 ;
duga+xw*(duin-duga)
end_function

c11_well variation=function
function(xw)
c11ga=11.9 ;
c11in=8.33 ;
c11ga+xw*(c11in-c11ga)
end_function

c12_well variation=function
function(xw)
c12ga=5.38 ;
c12in=4.53 ;
c12ga+xw*(c12in-c12ga)
end_function

gamma1_bar variation=function
function(xb)
g1ga=6.9 ;
g1al=3.45 ;
g1ga*(1.-xb)+g1al*xb
end_function

gamma2_bar variation=function
function(xb)
g2ga=2.2 ;
g2al=0.68 ;
g2ga*(1.-xb)+g2al*xb
end_function

gamma3_bar variation=function
function(xb)
g3ga=2.9 ;
g3al=1.29 ;
g3ga*(1.-xb)+g3al*xb
end_function
$ \text{a_bar variation=function (xb)}$
\begin{align*}
dhga &= -9.8 ; \\
dhal &= -9.8 ; \\
dhga*(1-xb)+dhal*xb \\
\end{align*}
end_function

$ \text{b_bar variation=function (xb)}$
\begin{align*}
duga &= -1.76 ; \\
dual &= -1.76 ; \\
duga*(1-xb)+dual*xb \\
\end{align*}
end_function

$ \text{c11_bar variation=function (xb)}$
\begin{align*}
c11ga &= 11.9 ; \\
c11al &= 12.02 ; \\
c11ga*(1-xb)+c11al*xb \\
\end{align*}
end_function

$ \text{c12_bar variation=function (xb)}$
\begin{align*}
c12ga &= 5.38 ; \\
c12al &= 5.70 ; \\
c12ga*(1-xb)+c12al*xb \\
\end{align*}
end_function

$ \text{kane_para_f_well variation=function (xb)}$
\begin{align*}
inas &= -2.9; \\
gaas &= -1.94; \\
xw*inas+(1-xw)*gaas \\
\end{align*}
end_function

$ \text{kane_para_f_bar variation=function (xb)}$
\begin{align*}
alas &= -0.48; \\
gaas &= -1.94; \\
\end{align*}
end_function

$ \text{lifetime_n value=100.e-9}$

$ \text{lifetime_p value=100.e-9}$

$ \text{lattice_constant value=5.65325}$

$ \text{end_active_layer InGaAs/AlGaAs}$

************************************
$ \text{macro for alas oxide}$
$ \text{Bulk AlAs oxide as an insulator}$
$ \text{[free-style]}$

$ \text{Typical use:}$

$ \text{load_macro name=alas_oxide mater=#m}$

$ \text{begin_macro alas_oxide}$

material type=insulator

$ \text{just a guess for the static dielectric constant}$

$ \text{dielectric_constant value=7.5}$

$ \text{real_index variation=function (temper)}$

$3.52+3.5e-4*(temper-300)$

$ \text{end_function}$

$ \text{absorption value=0.}$

$ \text{set affinity for the purpose of plotting band diagram}$

$ \text{affinity value=4.}$

$ \text{thermal_kappa value=10.}$

$ \text{end_macro alas_oxide}$

2. Layer file

begin_layer

$ \text{rotation angle=0.00}$

$ \text{column column_num=1 w=5.64 mesh_num=8 r=0.9}$
$ \text{column column_num=2 w=1.5 mesh_num=5 r=1.1}$
$ \text{column column_num=3 w=9.5 mesh_num=10 r=1.}$
$ \text{column column_num=4 w=10. mesh_num=10 r=1}$
$ \text{column column_num=5 w=10. mesh_num=10 r=1}$

layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0
layer d=50. n=5 r=1. vcsel_type=sub
vcsel_section vcsel_type=bottomdbr grating_model=2layers active=no &&
layer1=7.e-8 index1=-3.5 layer2=7.95e-8 index2=-3.08 mesh_points=10
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0.6
layer d=5.382 n=10 r=1. vcsel_type=bottomdbr
$
$ vcsel_section vcsel_type=cavity1 grating_model=1layer active=no &&
mesh_points=3
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0.6
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0.6
layer d=0.0503 n=3 r=1. vcsel_type=cavity1
$
$ vcsel_section vcsel_type=cavity2 grating_model=1layer active=no &&
mesh_points=3
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0 grade_to=0.875
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0 grade_to=0.875
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0 grade_to=0.875
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0 grade_to=0.875
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0 grade_to=0.875
layer d=0.02 n=3 r=1. vcsel_type=cavity2
$
$ vcsel_section vcsel_type=cavity3 grating_model=1layer active=no &&
mesh_points=3
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.875
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.875
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.875
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0.875
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0.875
layer d=0.0604 n=3 r=1. vcsel_type=cavity3
$
$ vcsel_section vcsel_type=cavity4 grating_model=1layer active=no &&
mesh_points=3
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0.875 grade_to=0
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0.875 grade_to=0
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0.875 grade_to=0
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0.875 grade_to=0
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0.4375 &&
grade_var=1 grade_from=0.875 grade_to=0
layer d=0.02 n=3 r=1. vcsel_type=cavity4
$\$
vcSEL_section vcsel_type=cavity5 grating_model=1layer active=no &&
\phantom{.}mesh_points=10
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer d=0.048 n=4 r=1. vcsel_type=cavity5
$\$
vcSEL_section vcsel_type=collector1 grating_model=1layer active=no &&
\phantom{.}mesh_points=8
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer d=0.04 n=4 r=1. vcsel_type=collector1
$\$
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.9e+23
layer d=0.1 n=4 r=1. vcsel_type=cavity5
$\$
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 &&
\phantom{.}p_doping=1.92e+24
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0 && p_doping=1.92e+24
layer d=0.04 n=4 r=1. vcsel_type=collector1
$
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0 && p_doping=1.9e+23
layer d=0.1 n=4 r=1. vcsel_type=cavity5
$
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0 && p_doping=1.92e+24
layer d=0.04 n=4 r=1. vcsel_type=collector1
$
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0 && p_doping=1.9e+23
layer d=0.1 n=4 r=1. vcsel_type=cavity5
$
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 && p_doping=1.92e+24
layer_mater macro_name=algaas column_num=5 var_symbol1=x var1=0 && p_doping=1.92e+24
layer d=0.04 n=4 r=1. vcsel_type=collector1
$
p_doping=1.9e+23
layer Mater macro_name=algaas column_num=2 var_symbol1=x var1=0
p_doping=1.9e+23
layer Mater macro_name=algaas column_num=3 var_symbol1=x var1=0
p_doping=1.9e+23
layer Mater macro_name=algaas column_num=4 var_symbol1=x var1=0
p_doping=1.9e+23
layer Mater macro_name=algaas column_num=5 var_symbol1=x var1=0
layer d=0.0957 n=10 r=1. vcsel_type=cavity5
$ vcsel_section vcsel_type=cavity6 grating_model=1layer active=no &&
  mesh_points=4
layer Mater macro_name=algaas column_num=1 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=2 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=3 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=4 var_symbol1=x var1=0
layer Mater macro_name=void column_num=5
layer d=0.04 n=4 r=1. vcsel_type=cavity6
$ vcsel_section vcsel_type=cavity7 grating_model=1layer active=no &&
  mesh_points=6
layer Mater macro_name=algaas column_num=1 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=2 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=3 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=4 var_symbol1=x var1=0
layer Mater macro_name=void column_num=5
layer d=0.01 n=10 r=1. vcsel_type=cavity7
$ vcsel_section vcsel_type=cavity8 grating_model=1layer active=yes &&
  mesh_points=6
layer Mater macro_name=algaas column_num=1 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=2 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=3 var_symbol1=x var1=0
layer Mater macro_name=algaas column_num=4 var_symbol1=x var1=0
layer Mater macro_name=void column_num=5
layer d=0.015 n=4 r=1. vcsel_type=cavity8
$ vcsel_section vcsel_type=qw1 grating_model=1layer active=yes &&
  mesh_points=6
layer Mater macro_name=ingaas column_num=1 var_symbol1=x var1=0.17
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
    avar2=0
layer Mater macro_name=ingaas column_num=2 var_symbol1=x var1=0.17
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
    avar2=0
layer Mater macro_name=ingaas column_num=3 var_symbol1=x var1=0.17
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
    avar2=0
layer_mater macro_name=ingaas column_num=4 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=void column_num=5
layer d=0.007 n=4 r=1. vcsel_type=qw1
$
vcsel_section vcsel_type=barrier1 grating_model=1layer active=yes &&
  mesh_points=6
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0
layer_mater macro_name=void column_num=5
layer d=0.016 n=4 r=1. vcsel_type=barrier1
$
layer_mater macro_name=ingaas column_num=1 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=ingaas column_num=2 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=ingaas column_num=3 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=ingaas column_num=4 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=void column_num=5
layer d=0.007 n=4 r=1. vcsel_type=qw2
$
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0
layer_mater macro_name=void column_num=5
layer d=0.016 n=4 r=1. vcsel_type=barrier2
$
layer_mater macro_name=ingaas column_num=1 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=ingaas column_num=2 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=ingaas column_num=3 var_symbol1=x var1=0.17 &&
  active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb &&
  avar2=0
layer_mater macro_name=ingaas column_num=4 var_symbol1=x var1=0.17 &&
active_macro=InGaAs/AlGaAs avar_symbol1=xw avar1=0.17 avar_symbol2=xb && avar2=0
layer_mater macro_name=void column_num=5
layer d=0.007 n=4 r=1. vcsel_type=qw3
$v$
vcSEL_section vcsel_type=cavity9 grating_model=1layer active=yes &&
   mesh_points=6
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=void column_num=5
layer d=0.015 n=4 r=1. vcsel_type=cavity9
$v$
vcSEL_section vcsel_type=cavity10 grating_model=1layer active=no &&
   mesh_points=12
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=algaas column_num=4 var_symbol1=x var1=0 &&
   n_doping=5.e+24
layer_mater macro_name=void column_num=5
layer d=0.237 n=12 r=1. vcsel_type=cavity10
$v$
vcSEL_section vcsel_type=cavity11 grating_model=1layer active=no &&
   mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.4375 &&
   grade_var=1 grade_from=0 grade_to=0.875 p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.4375 &&
   grade_var=1 grade_from=0 grade_to=0.875 p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.4375 &&
   grade_var=1 grade_from=0 grade_to=0.875 p_doping=1.9e+23
layer_mater macro_name=void column_num=4
layer d=0.01 n=4 r=1. vcsel_type=cavity11
vcSEL_section vcsel_type=cavity12 grating_model=1layer active=no &&
   mesh_points=5
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.875 &&
   p_doping=1.91e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.875 &&
   p_doping=1.91e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.875 &&
   p_doping=1.91e+24
layer_mater macro_name=void column_num=4
layer d=0.01 n=5 r=1. vcsel_type=cavity12
vcSEL_section vcsel_type=cavity13 grating_model=1layer active=no &&
   mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.875 &&
   p_doping=1.91e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.875 && p_doping=1.91e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.875 && p_doping=1.91e+24
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.01 n=4 r=1. vcsel_type=cavity13 vcsel_section vcsel_type=cavity14 grating_model=1 layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0.875 && grade_var=1 grade_from=0.875 grade_to=0 p_doping=1.91e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0.875 && grade_var=1 grade_from=0.875 grade_to=0 p_doping=1.91e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0.875 && grade_var=1 grade_from=0.875 grade_to=0 p_doping=1.91e+24
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.025 n=4 r=1. vcsel_type=cavity15 vcsel_section vcsel_type=cavity16 grating_model=1 layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 insulator_macro=yes var_symbol1=x && var1=0 n_newdoping_index=1 n_doping=2.e+24
layer_mater macro_name=algaas column_num=3 insulator_macro=yes var_symbol1=x && var1=0 n_newdoping_index=1 n_doping=2.e+24
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.0744 n=6 r=1. vcsel_type=cavity29 vcsel_section vcsel_type=cavity17 grating_model=1 layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
  p_doping=1.91e+24
layer_mater macro_name=algaas insulator_macro=yes column_num=2 var_symbol1=x &&
  var1=0 n_newdoping_index=1 n_doping=2.e+24
layer_mater macro_name=algaas column_num=3 insulator_macro=yes var_symbol1=x &&
  var1=0 n_newdoping_index=1 n_doping=2.e+24
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.04 n=4 r=1. vcsel_type=cavity17 vcsel_section vcsel_type=cavity18 grating_model=1layer active=no &&
  mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
  p_doping=1.9e+23
layer_mater macro_name=algaas insulator_macro=yes column_num=2 var_symbol1=x &&
  var1=0 p_doping=1.9e+23
layer_mater macro_name=algaas insulator_macro=yes column_num=3 var_symbol1=x &&
  var1=0 p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
  p_doping=1.9e+23
layer_mater macro_name=void column_num=4
layer d=0.02 n=4 r=1. vcsel_type=cavity18 vcsel_section vcsel_type=cavity28 grating_model=1layer active=no &&
  mesh_points=5
layer_mater macro_name=algaas column_num=1 insulator_macro=yes var_symbol1=x &&
  var1=0 p_doping=1.91e+24
layer_mater macro_name=algaas insulator_macro=yes column_num=2 var_symbol1=x &&
  var1=0 p_doping=1.91e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
  p_doping=1.91e+24
layer_mater macro_name=void column_num=4
layer d=0.08 n=4 r=1. vcsel_type=cavity28 vcsel_section vcsel_type=cavity19 grating_model=1layer active=no &&
  mesh_points=4
layer_mater macro_name=algaas insulator_macro=yes column_num=1 var_symbol1=x &&
  var1=0 p_doping=1.91e+24
layer_mater macro_name=algaas insulator_macro=yes column_num=2 var_symbol1=x &&
  var1=0 p_doping=1.91e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
  p_doping=1.91e+24
layer_mater macro_name=void column_num=4
layer d=0.04 n=4 r=1. vcsel_type=cavity19 vcsel_section vcsel_type=cavity20 grating_model=1layer active=no &&
  mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 &&
  p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 &&
  p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 &&
  p_doping=1.9e+23
layer_mater macro_name=void column_num=4
layer d=0.02 n=4 r=1. vcsel_type=cavity20
vcsel_section vcsel_type=cavity21 grating_model=1layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.08 n=4 r=1. vcsel_type=cavity21
vcsel_section vcsel_type=cavity22 grating_model=1layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.91e+24
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 && p_doping=1.91e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.91e+24
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.04 n=4 r=1. vcsel_type=cavity22
vcsel_section vcsel_type=cavity23 grating_model=1layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=2 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.1 n=4 r=1. vcsel_type=cavity23
vcsel_section vcsel_type=cavity24 grating_model=1layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.91e+24
layer_mater macro_name=algaas insulator_macro=yes column_num=2 var_symbol1=x && var1=0 p_doping=1.91e+24
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.91e+24
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.04 n=4 r=1. vcsel_type=cavity24
vcsel_section vcsel_type=cavity25 grating_model=1layer active=no && mesh_points=4
layer_mater macro_name=algaas column_num=1 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=algaas insulator_macro=yes column_num=2 var_symbol1=x && var1=0 p_doping=1.9e+23
layer_mater macro_name=algaas column_num=3 var_symbol1=x var1=0 && p_doping=1.9e+23
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.1 n=4 r=1. vcsel_type=cavity25
vcsel_section vcsel_type=cavity26 grading_model=1layer active=no &
core_radius=5.64 mesh_points=4
layer_mater macro_name=algaas insulator_macro=yes column_num=1 var_symbol1=x &
var1=0 p_doping=1.91e+24
layer_mater macro_name=sio2 insulator_macro=yes column_num=2
layer_mater macro_name=void column_num=3
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.04 n=4 r=1. vcsel_type=cavity26
vcsel_section vcsel_type=cavity27 grading_model=1layer active=no &
mesh_points=4
layer_mater macro_name=algaas insulator_macro=yes column_num=1 var_symbol1=x &
var1=0 p_doping=1.9e+23
layer_mater macro_name=sio2 insulator_macro=yes column_num=2
layer_mater macro_name=void column_num=3
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.0486 n=4 r=1. vcsel_type=cavity27
vcsel_section vcsel_type=topdbr grading_model=2layers active=no &
layer1=1.69e-7 index1=-1.45 layer2=6.8e-8 index2=-3.6 mesh_points=10
layer_mater macro_name=sio2 insulator_macro=yes column_num=1
layer_mater macro_name=sio2 insulator_macro=yes column_num=2
layer_mater macro_name=void column_num=3
layer_mater macro_name=void column_num=4
layer_mater macro_name=void column_num=5
layer d=0.711 n=10 r=1. vcsel_type=topdbr
top_contact column_num=3 from=1.5 to=7.5 contact_num=3 contact_type=ohmic
top_contact column_num=4 from=2. to=8. contact_num=2 contact_type=ohmic
top_contact column_num=5 from=2. to=8. contact_num=1 contact_type=ohmic
$ end_layer

3. QW gain file (Double column format)

begin_gain
use_macrofile macro1=TVCSEL_Oct2012.mac
plot_data plot_device=postscript
include file=TVCSEL_Oct2012.mater
$independent_mqw
$self_consistent

set_active_reg broadening = lorentzian
tau_scat = 8.50e-014 &&
valence_mixing =yes exch_coef =1.0e-010 &&
gain_coulomb =yes

gain_wavel wavel_range=[ 0.9 1.05] &&
conc_range=[ 0.5000E+24 0.1000E+26] &&
curve_number=30
$ data_point=100
$ data_file=pl.txt
index_wavel wavel_range=[ 0.9 1.05] &&
conc_range=[ 0.5000E+24 0.1000E+26] &&
curve_number=30 init_conc=1.5e24
current_conc conc_range=[ 0.5000E+24 0.1000E+26] &&
data_point=30 &&
use_macro=yes fit_outfile=tmp.data
modify_qw kp_bands=2 mater=6
gain_density wavel_range=(0.977 0.983) &&
4. Solver file (Double column format)

begin

use_macrofile macro1=TVCSEL_Oct2012.mac
load_mesh mesh_inf=TVCSEL_Oct2012.msh

include file=TVCSEL_Oct2012.gain
include file=TVCSEL_Oct2012.doping
output sol_outf=TVCSEL_Oct2012.out

import_kp_data
import_gain_data

$ VCSEL parameters

cylindrical axis=y

vcSEL_model use_eim=yes eim_zero=7.14
add_r_division=5

$q_transport q_elec_trap_tau=25e-12
q_hole_trap_tau=25e-12
&&
$n_side_down=yes q_trap_model=yes

$q_transport q_elec_trap_tau=25e-12
q_hole_trap_tau=25e-12
$n_side_down=yes q_trap_model=yes

auger_n variation=function mater=6
function(temper)
$6.0e-42 + (temper - 300)*0.1e-42
3.5e-42 + (temper - 300)*0.05e-42
end_function

auger_p variation=function mater=6
function(temper)
$80.0e-42 + (temper - 300)*1e-42

parallel_linear_solver solver=MUMPS

contact num=1 type=ohmic thermal_type=3
&&
thermal_cond=0.1

contact num=2 type=ohmic thermal_type=3
&&
thermal_cond=0.1

contact num=3 type=ohmic thermal_type=3
&&
thermal_cond=0.1

thermal_interf thm_num = 1 thm_type = 1
thm_within_x= [0,36] &&
thm_within_y= [0,0] thm_ext_temp=300

heat_flow damping_step = 3.5 max_iter = 200
j_e_model = yes &&
thm_transient = yes
init_wave backg_loss = 300 init_wavel = 9.800000E-001 &&
wavel_range = [9.00000E-001, 1.1000E+000] gain.sat = 1.500e-023

multimode mode_num = 1

$ Set Newton parameters for equilibrium solution
newton_par damping_step = 3 var_tol = 1.e-8 res_tol = 1.e-8 &&
max_iter = 100 opt_iter = 15 stop_iter = 50
print_flag = 3
$
$ Solve equations at equilibrium
equilibrium index_newdoping = 1
newdoping_order = -2

rtgain_phase density = 0.3000E+25
$
$ You may stop here to examine the round trip gain
$stop
$

newton_par damping_step = 1 var_tol = 1.e-4 res_tol = 1.e-4 &&
max_iter = 50 opt_iter = 15 stop_iter = 9
print_flag = 3 change_variable = yes

scan var = voltage_1 value_to = -3 var2 = voltage_2 value_to = -1.2 &&
init_step = 5.000E-002 min_step = 1.00000E-007 &&
max_step = 0.5

newton_par damping_step = 1 var_tol = 1.e-4 res_tol = 1.e-4 &&
max_iter = 50 opt_iter = 15 stop_iter = 9
print_flag = 3 change_variable = yes

scan var = new_doping value_to = 0
print_step = 100 &&
init_step = 0.001 min_step = 1.e-15
max_step = 0.2

scan var = current_2 value_to = 5e-3 print_step = 0.5e-3 &&

init_step = 0.1E-03 min_step = 1.e-8
max_step = 0.002 &&
auto_finish = rtgain auto_until = 0.997
auto_condition = above

newton_par damping_step = 1 var_tol = 1.000000E-004 &&
res_tol = 1.000000E-004 max_iter = 50
opt_iter = 15 &&
stop_iter = 9 print_flag = 3 change_variable = yes

scan var = current_2 value_to = 20.00000E-003 &&
init_step = 0.5e-3 min_step = 1e-4
max_step = 1e-3 &&
min_step = 1e-7 solve_rtg = yes var2 = time
value2_to = 1

$scan var = time var2 = current_2 value_to = 1.e-12 &&
$ value2_to = 3.01000E-003 print_step = 1.e-12 &&
$ init_step = 3.e-13 min_step = 1.e-13
max_step = 1.e-12 &&
$ solve_rtg = yes

$scan var = time var2 = current_2
value_to = 200.e-12
print_step = 2e-12 &&
$ var2 = current_2 function_label2 = my_pulse
max_step = 0.2e-12 solve_rtg = yes
$scan_function label = my_pulse type = pulse
pulse_t1 = 2e-12 pulse_tr = 1e-12 &&
$pulse_dt = 0e-12 pulse_tf = 3e-3 pulse_s1 = 3e-3 pulse_s2 = 3.1e-3

$newton_par damping_step = 1 var_tol = 1.e-4 res_tol = 1.e-4 &&
$max_iter = 50 opt_iter = 15 stop_iter = 9
print_flag = 3 change_variable = yes

$scan var = voltage_2 value_to = -1.2 &&
$ init_step = 0.500E-002 min_step = 1.000000E-007 &&
$max_step = 0.1

$scan var = current_2
value_to = 4.e-3
print_step = 0.5e-3 &&
$init_step = 0.5e-3 min_step = 1.e-8
max_step = 0.002 &&
auto_finish = rtgain auto_until = 0.997
auto_condition = above

newton_par damping_step = 1 var_tol = 1.e-4 res_tol = 1.e-4 &&
max_iter = 50 opt_iter = 15 stop_iter = 9
print_flag = 3 change_variable = yes

$scan var = voltage_2
value_to = -1.2 &&
$ init_step = 0.500E-002 min_step = 1.000000E-007 &&
$max_step = 0.1

$scan var = current_2
value_to = 5e-3
print_step = 0.5e-3 &&
$scan var=new_doping value_to=0
print_step=100 &&
$ init_step=0.001 min_step=1e-15
max_step=0.2
$
$newton_par damping_step=1. var_tol=1e-4
res_tol=1e-4 &&
$ max_iter=50 opt_iter=15 stop_iter=9
print_flag=3 change_variable=yes
$
$scan var=current_2 value_to=4.8e-3
print_step = 2e-3 &&
$ init_step=0.01E-03 min_step=1.e-8
max_step=0.0002 &&
$ auto_finish=rtgain auto_until=0.995
auto_condition=above
$
$
$newton_par damping_step = 1 var_tol = 1.000000e-004 &&
$ res_tol = 1.000000e-004 max_iter = 50
opt_iter = 15 &&
$ stop_iter = 9 print_flag = 3
change_variable =yes
$
$scan var=voltage_1 value_to = -5 var2 =
current_2 value2_to = 4.8e-3 &&
$print_step = 0.2 &&
$ init_step=1E-03 min_step=1.e-4
max_step=0.1 &&
$ auto_finish=rtgain auto_until=0.995
auto_condition=above
$
$scan var=voltage_1 value_to = -5 var2 =
current_2 value2_to = 4.8e-3 &&
$ print_step=0.2 init_step=1e-3
max_step=1e-1 &&
$ min_step=1e-7 solve_rtg=yes var3=time
value3_to=1
$
$
end
$

$ Longitudinal mode session:
begin_zsol
lateral_mode3d mode_num=1 sort_modes=no
longitudinal ref_wavel= 0.9800E-06 &&
left_f_refl= 0.3000E+00 &&
right_f_refl= 0.3000E+00
include file=TVCSEL_Oct2012.vcsel
mode_srch iter_num = 75 wavel_xrange =
[9.30000E-007,9.90000E-007] &&
omega_xrange = 8
end_zsol