Influence of base-region thickness on the performance of Pnp transistor-VCSEL

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Abstract: We have recently reported a 980nm GaAs-based three terminal Pnp transistor-vertical-cavity surface-emitting laser (TVCSEL) operating at room temperature with optical power up to 1.8mW. However, the current gain \( \beta = \frac{\Delta I_c}{\Delta I_b} \) was near zero just before lasing and became negative after the lasing threshold. The main cause of the negative current gain was found to be a gradual and position-dependent forward-biasing (saturation) of the base-collector junction with increasing bias even before lasing threshold. In this article, detailed multi-physics device simulations are performed to better understand the device physics, and find ways to avoid the premature saturation of the base-collector junction. We have optimized the thickness of the base region as well as its doping concentration and the location of the quantum wells to ensure that the T-VCSEL is in the active mode throughout its range of operation. That is, the emitter-base junction is forward biased and base-collector junction is reversed biased for sweeping the excess charges out of the base region.

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OCIS codes: (250.0250) Optoelectronics; (250.7260) Vertical cavity surface emitting laser.

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A review article describing the progress in TL has recently been published [4]. Unlike the most important papers published in Applied Physics Letters throughout its entire history [3], describing the first room-temperature operation of a TL [2] was recognized as one of the five demonstration in 2005, has received significant interest. For instance, in 2006 the pioneering paper T

1. Introduction and background

The transistor laser (TL) [1] is a new breed of semiconductor laser that since its first demonstration in 2005, has received significant interest. For instance, in 2006 the pioneering paper describing the first room-temperature operation of a TL [2] was recognized as one of the five most important papers published in Applied Physics Letters throughout its entire history [3]. A review article describing the progress in TL has recently been published [4]. Unlike the
monolithic integration of a transistor and a laser diode on the same chip where the transistor performs as the driver of the laser [5], the TL relies on the fusion of the two components into a single device where the base recombination is used to provide stimulated emission. In contrast to earlier works on devices that could function either as a transistor or as a laser depending on the biasing conditions [6], the TL has two independent input signals and can simultaneously output an electrical and an optical signal. Due to an altered carrier dynamics in the base/cavity region and the three-terminal configuration, the TL has a number of attractive properties and potential advantages compared to conventional diode lasers, many of which have already been demonstrated and that can be briefly summarized as follows:

- An ultrafast radiative recombination lifetime allowing for resonance-free frequency response (and thereby suppression of relaxation oscillations and reduced turn-on delay) [7]; enhancement of the modulation bandwidth [8–12]; and reduction of the relative intensity noise (RIN) close to the shot-noise limit [13].

- Collector current-feedback allowing for the elimination of the monitor photodiode and for simplified power stabilization circuitry [14]; enhanced modulation bandwidth [15]; and a reduction in the 3rd order intermodulation distortion (IMD) [16]. The improved linearity may also allow multi-level modulation formats for digital applications [17].

- Transistor-based design techniques and modes of operation allowing for voltage-driven operation (leading to simplified or even eliminated driver electronics) [18]; common-emitter or common-base configurations to engineer the frequency response and overall gain [19]; and increased-flexibility matching network designs or ultra-compact negative-resistance oscillators, mixers, etc., for analog applications [20].

The transistor vertical-cavity surface-emitting laser (T-VCSEL) combines the functionality and performance advantages of transistor lasers with the inherent advantages of VCSELs such as cost- and power-efficiency, option for two-dimensional arrays, circular beam profile, etc. Hence, it provides the potential for low-cost, low-power consumption digital and analog applications with improved performance, simplified monitor and driver designs, as well as options for transistor-based circuit design techniques. Especially the great potential for high-frequency operation is attracting much interest. Given the ever-increasing demand for broadband capacity of the global optical communication networks at all levels, this is bound to find important applications. Presently, standards for single channel data rates as high as 100 Gbit/s are considered for access networks (100 GbE), and even beyond. So for local area networks and interconnects where parallel solutions are expected to provide Tbit/s capacity. This is a significant step with respect to today's technology, and such requirements on extreme bandwidths constitute a considerable challenge for the semiconductor laser used in the optical transmitter. Optical communication also plays a role in the wireless industry to provide high-capacity data links between distant wireless transmitters that are used to distribute the data locally. Here, microwave signals are distributed optically via Radio-over-Fiber (RoF). One promising approach is the 60 GHz radio waveband which enables 1-10 Gbit/s Ethernet [21]. However, the wireless transmission distance in this band is only 10-100 m, creating a need for large amounts of low-cost transmitters with harsh requirements on modulation bandwidth, linearity and noise. Whereas VCSELs with 3dB-bandwidth of 28 GHz [22] and VCSEL-based optical links with modulation speeds up to 55 Gbit/s have been demonstrated [23], this is approaching fundamental limits. To reach such high and even higher modulation rates over an extended temperature range with sufficient output power, radically new design concepts are required, thus opening up a potentially enabling role for T-VCSELs.
Shi et al. made a numerical study of a T-VCSEL where they assessed both the static and dynamic properties [24]. In particular they showed that the small and large-signal bandwidth can be much larger when the T-VCSEL is operated in the common-base configuration as compared to the common-emitter configuration or a conventional diode laser [24]. Wu, Feng and Holonyak reported the first experimental realization of T-VCSELs in two papers published in the summer of 2012 [25, 26]. Studying the static performance of these lasers, they showed features such as gain-compression due to the onset of stimulated emission [25] (a typical signature of TL action) and voltage-controlled operation [26]. However, these T-VCSELs had an insufficient current confinement and inappropriate gain-cavity tuning and could only be operated continuous wave (CW) at low temperature (-75 °C) with µW level output power.

The first room-temperature operation of a Pnp T-VCSEL was reported by the authors at the end of 2012, showing static performances quite comparable to what can be obtained from conventional VCSELs, including mW-range output power, sub-mA base threshold current and CW operation at least up to 50 °C [27]. Excellent agreement was also obtained using numerical modeling yielding the detailed potential and current distribution within the device [28]. However, the device showed premature saturation of the base-collector junction which locally goes into a forward-biased condition even before lasing threshold, causing current gain \( \beta \) to become zero before lasing and negative after lasing. Obviously, this is not desirable from the transistor action point-of-view where we would like that in the normal operation regime of the TVCSEL, the base-collector junction is kept reversed biased to efficiently sweep the excess carriers out of the base, making it possible to obtain all the benefits of the transistor-laser mode of operation of the TVCSEL.

The previously published simulation results are mostly based on one-dimensional rate-equations models which can not capture the complicated three-dimensional device physics and thermal effects. Some published articles present multiphysics device simulation of Npn TVCSEL but excluding the thermal effects [18,24]. In the present article, detailed multi-physics numerical simulations including the thermal effects are performed to better understand the device physics of Pnp TVCSEL, and find ways to avoid the premature saturation of the base-collector junction. In section 2, a summary is given about our previously fabricated TVCSEL device and its measured performance compared with the simulation results. In section 3, The Base-region is changed by inserting a 100nm n-doped layer below the QWs and 200nm n-doped layer below the QWs subsequently, to shift the QWs towards the emitter, and its effect on the device performance are simulated. We discuss the simulation results, especially the premature saturation of the base-collector junction in section and conclude the article in section 4.

2. Fabricated TVCSEL device

The present analysis refers to our previously presented 980-nm Pnp-type T-VCSELs of which the fabrication details and performance characteristics have been published elsewhere [27, 28]. These devices showed encouraging performance in terms of threshold current, output power and high-temperature operation and also could demonstrate three-terminal operation. However, the TVCSEL was in saturation mode of operation in the interior of the device and active mode in the periphery of the device [28]. The global characteristics as measured on the emitter, base and collector contacts showed that the differential current gain \( \beta = \Delta I_c / \Delta I_b \) went to zero above the threshold base current and that the collector current decreased for even higher base currents. This indicates that the transistor is in saturation. Moreover, the base-collector junction, which is designed to be reverse-biased to sweep out excess minority carriers (holes) from the base region, has in fact partly become forward biased. A Pnp configuration, rather than Npn TVCSEL was studied simply because of material issues (doping-induced loss in the p-doped base/MQW region in an Npn device). We also grew Npn structures but the photoluminescence from the
QWs was much lower as compared to a Pnp structure.

2.1. Device geometry

A schematic cross-section of the device, which is based on previous development of high-efficiency GaAs-based VCSEL structures for the 1.3-\(\mu\)m regime [29–31], is shown in Fig. 1. The cavity is constituted by a GaAs-AlGaAs bottom DBR and a dielectric Si-SiO\(_2\) top DBR. Within this layer the transistor is formed by a Pnp GaAs structure with a p-doped AlGaAs barrier at the emitter base interface. The base region hosts the optically active structure formed by three InGaAs quantum wells and a 10nm thick n-doped layer below the quantum wells. Details on the device fabrication steps are given in articles [27,28]. Modulation doping matched with the standing wave intensity profile of the optical field was used in the thick p-doped layers in the emitter and the collector to minimize free-carrier optical losses.

Fig. 1. Schematic cross-section of the TVCSEL.

2.2. Simulation model

To investigate the physical performance of the T-VCSEL we use an advanced multiphysics numerical simulation software PIC3D [32]. PIC3D is based on the finite-element-method and numerically solves the electrical, optical, thermal, QW gain and laser rate-equation models self-consistently. The carrier transport is based on the classic drift-diffusion model [32], with the thermionic-emission model [32] used at the heterojunctions. Lateral optical modes are calculated by the effective-index method [32] assuming a cylindrical geometry. In the strained quantum wells the conduction band is assumed to be parabolic and the valence bands are calculated by the 4x4 \(k\cdot\mathbf{p}\) method to account for valence-band mixing [32]. A Lorentz broadening function with a scattering time of 125 fs is assumed in the quantum well gain calculation. Band gap renormalization is considered as a function of the local carrier density of electrons (\(n\)) and holes (\(p\)). The optical loss due to the free-carriers is calculated by: \(Loss = k_p p + k_n n\). The fixed background optical loss in the cavity is assumed to be 100 /m, and gain saturation is also taken into account. The spontaneous radiative recombination rate is calculated self-consistently from the gain calculation. The Auger recombination is calculated by \(R_{\text{Auger}} = C_p p(n p - n_i^2)\). The thermal conductivity of the AlGaAs/GaAs DBRs is reduced by a factor 0.5 for the lateral di-
reconction and 0.4 for the vertical direction to take into the account the effect of phonon scattering at the DBR interfaces. Thermal effects are included self-consistently by assuming a thermal conductance of the top metal contacts and a constant temperature at the substrate bottom surface. A model including both temperature dependence and doping dependence is used for the electron and the hole mobility in the bulk layers. Incomplete ionization model of the dopants is assumed in the n- and p-doped layers. The fabricated device has a square aperture with side length 10 µm. However to simplify the simulation we assume a cylindrical geometry with the same aperture area defined by a current injection radius of 5.6 µm. A multimode optical model is used with two transverse modes due to the big aperture of the TVCSEL device causing it to lase in multiple transverse modes. A complete list of the used parameters is given in table 1.

The simulation are performed for the common-emitter configuration where the emitter contact is always grounded and the potential of the collector contact is made negative. However for plotting purposes, the collector-emitter voltage is always grounded and the potential of the collector contact is made negative. However for plotting purposes in this article, the collector-emitter voltage $V_{CE}$ is shown as positive for ease of understanding. Similarly, the base voltage is negative with respect to the emitter to forward bias the base-emitter junction, but for plotting purposes, we show $V_{BE}$ as positive. The sign convention we use for plotting the current is that a positive current is flowing into the emitter $I_E$, out of the base $I_b$ and out of the collector $I_c$.

| Parameter | Value |
|-----------|-------|
| InGaAs/GaAs QW valence band offset | $\Delta E_c = 0.7\Delta E_g$ |
| Auger recombination coefficient | $C_p = 1 \cdot 10^{-42} + (T - 300) \cdot 10^{-45} \text{ m}^6/\text{s}$ |
| Top metal thermal conductance | 0.1 W/K |
| Substrate heat sink temperature | 300K |
| Refractive index $n_{Al_{0.1}Ga_{0.9}As}$ | 3.52-0.57x |
| Refractive index $n_{a-Si}$ | 3.7 |
| Refractive index $n_{SiO_2}$ | 1.45 |
| dn/dT | $1.5 \cdot 10^{-3}(T - 300K)$ |
| Gain saturation constant | $g = 1.5 \cdot 10^{-23} \text{ m}^4$ |
| $In_{0.17}Ga_{0.83}As$ band gap $E_g$ | $1.14 + 4 \cdot 300^2/(300 + 225) - 4 \cdot T^2/(T + 225) \text{ eV}$ |
| Non-radiative carrier lifetime in bulk | 100ns |
| Non-radiative carrier lifetime in QW | 10ns |
| Free carrier absorption p doped region | $k_p = 6.0 \cdot 10^{-22} + (T - 300) \cdot 10^{-24} /\text{m}$ |
| Free carrier absorption n doped region | $k_n = 3.0 \cdot 10^{-22} + (T - 300) \cdot 10^{-24} /\text{m}$ |
| Band gap renormalization factor | $\Delta E_g = 1 \cdot 10^{-10}(0.5(n + p))^{1/3} \text{ eV}$ |

2.3. Simulation results: comparison with experimental results

The simulated material gain of a single quantum well is shown in Fig. 2(a). In the full device simulations, the ratio of hole-density to electron-density (p/n ratio) in the quantum wells is around 0.7. So in the gain calculation, before full simulation, the ratio of p/n = 0.7 is set to get a realistic gain value from the quantum wells. Fig. 2(b) shows the maximum material gain from the quantum wells against the carrier density inside the quantum well. Since the experimental investigated reference TVCSEL has a resonant wavelength between 977-980nm under operating conditions [27], we limit the recorded maximum material gain to the same wavelength range for plotting purpose. We find that the peak material gain increases monotonically and the transparency carrier density is $1.8 \times 10^{18} \text{ cm}^{-3}$. The modal gain of the three quantum wells is shown in Fig. 2(c) recorded during full device simulation including thermal effects. With
increasing base current $I_b$ the modal gain shifts to longer wavelengths due to the increasing temperature inside the device resulting in band gap shrinking.

![Material gain spectrum of a single QW](image1.png)

![Peak material gain of a single QW](image2.png)

![Modal gain spectrum of three QWs](image3.png)

Fig. 2. Material gain spectrum (a); the peak material gain of a single QW (b); Modal gain spectrum of the three QWs at different bias currents during full device simulation (c).

In Fig. 3(a) the simulated optical output power against $I_b$ at different $V_{CE}$ is plotted. The threshold current is around 1mA. At $V_{CE} = 1\text{V}$ and $2\text{V}$ the device shows typical transistor laser behavior as thoroughly discussed in [15, 18, 19, 24]. At higher $V_{CE}$, the device experiences premature drop in the optical output power due to thermal heating. As the temperature in the device increases, the modal gain peak shifts to longer wavelength due to bandgap shrinking (as shown in Fig. 2(c)). The carrier density in the quantum wells also increases to keep the gain equal to the loss in the cavity. In addition, the free carrier losses and Auger recombination losses also increase at elevated temperature and carrier density. The measured optical output power for a 100 $\mu\text{m}^2$ aperture area rectangular TVCSEL is shown in Fig. 3(b). The measured power is much lower as compared to the simulated curves. However general features of the two graphs are comparable. The threshold current values are comparable, and increase in the threshold current at higher $V_{CE}$ behavior is also similar. The premature saturation behavior of the optical power at higher $V_{CE}$ is also similar.

In Figs. 3(c) and 3(d) the simulated and measured base-emitter voltage $V_{BE}$ curves are plotted respectively against the $I_b$ at different $V_{CE}$ values. These two curves match well. At higher $V_{CE}$, the $V_{BE}$ is higher. At a certain $I_b$, $V_{BE}$ starts to flatten due to the fact that base-collector junction becomes partly forward biased and the base voltage is partly clamped [18, 24]. At higher $V_{CE}$ the base-collector junction turns on at a higher $I_b$. 

#222018 - $15.00 USD

Received 18 Sep 2014; revised 17 Oct 2014; accepted 17 Oct 2014; published 28 Oct 2014

(C) 2014 OSA 3 November 2014 | Vol. 22, No. 22 | DOI:10.1364/OE.22.027398 | OPTICS EXPRESS 27404
In Figs. 3(e) and 3(f) simulated and measured collector current $I_C$ curves are plotted respectively against the base current $I_b$ at different $V_{CE}$ values. These two curves also match at lower $I_b$ values but differ slightly at higher $I_b$. Below the lasing threshold, the $I_C$ increases sharply with the increase of the $I_b$. When the $I_b$ approaches the laser threshold current, the $I_C$ saturates and then start to decrease quickly as $I_b$ increases. This shows that the base-collector junction becomes forward biased slightly below the threshold causing the collector current to flatten and decrease afterwards. The corresponding current gain $\beta = \Delta I_C/\Delta I_b$ plot is shown in Fig. 4(a). Slightly below threshold $\beta$ becomes zero and then negative. This peculiar behavior is not desirable for the transistor action of the TVCSEL. This behavior is further discussed below. In Fig. 4(b), the emitter current $I_E$ is plotted against $I_b$ at different $V_{CE}$ values. These curves show the forward-biased behavior of the base-emitter junction, turning the junction on at low $I_b$ values, and clamping of the $I_E$ as the base-collector junction becomes forward biased at higher $I_b$ values.

In Fig. 4(c) we show the maximum temperature inside the TVCSEL as a function of $I_b$. At higher $V_{CE}$, the device has higher temperature due to the higher emitter and collector currents. This explains the optical power drop and roll off behavior at higher $V_{CE}$. The higher temperature inside the TVCSEL also shifts the lasing wavelength to longer wavelengths as shown in Fig. 4(d) due to the fact that refractive indices of different layers are temperature dependent.

In Figs. 5(a) and 5(b) the simulated and measured optical power results are plotted as a function of $V_{CE}$ at different base currents $I_b$. As $V_{CE}$ rises the optical output power increases first and then saturates. At higher $I_b$ the optical power saturation happens at higher $V_{CE}$. At higher $I_b$ and higher $V_{CE}$ the optical power starts to drop due to thermal rollover. The simulated optical power is much higher than the measured values as pointed out before. However, there is some qualitative resemblance in the two graphs. The initial increase in the optical power and saturation behavior is reproduced in the simulations. There is a minimum $V_{CE}$ needed for lasing called threshold $V_{CE}$. At higher $I_b$ the threshold $V_{CE}$ decreases. The thermal roll-over behavior of the optical power at higher $I_b$ and $V_{CE}$ is also reproduced in the simulated results.

In Figs. 5(c) and 5(d) the simulated and measured collector current $I_c$ is plotted respectively against $V_{CE}$ at different base currents. The experimental and measured values match well in the initial part of the $V_{CE}$. Due to the premature saturation of the base-collector junction even before the threshold base current, the collector current does not increase with the base current, rather it decreases at higher $I_b$. In Fig. 5(e), the emitter current $I_E$ is plotted against $V_{CE}$ at different $I_b$ values. The emitter current plot also shows abnormal operation of the TVCSEL where the emitter current keeps on increasing as the $V_{CE}$ is increased.

In Fig. 6, we plot the band diagrams in the center of the TVCSEL at different bias conditions. At $I_b = 0.275mA$ the emitter-base junction is forward biased and the base-collector junction is reversed biased. This is the normal operation regime of transistor VCSEL where the reverse biased base-collector junction sweeps the excess carriers from the base, thus, reducing the carrier lifetime in the base region. At $I_b = 0.75mA$, the base-collector junction is forward biased in the center of the TVCSEL indicating that the TVCSEL is in saturation mode, and the transistor action is lost.

3. Optimization of the base region thickness

It is evident from the previous simulation and measured results that the base-collector junction goes into saturation too early. Our simulations show that during lasing there is significant voltage drop in the thick p-doped emitter layers and p-doped collector layers. At $V_{CE} = 3.0V$ and $I_b = 4mA$ there is approximately 1.0 V drop from the emitter contact to the $Al_{0.875}Ga_{0.125}As$ emitter layer, and 1.6V drop from the collector contact to the center of TVCSEL. Hence the voltage applied at the emitter and collector contacts does not represent the actual potential at
Fig. 3. Simulated (left column) and measured (right column) results of the fabricated TVC-SEL. Simulation and measurements done at fixed heat sink temperature 25°C.
the center of the TVCSEL where lasing is happening. It should be understood that when the base current is high enough the base voltage will be higher and eventually the base-collector junction will become forward biased. In an attempt to postpone the premature saturation of the base-collector junction we decided to increase the p-doped layer thickness below the quantum wells. Simulation results are presented in the next sections for two devices where the original 10nm n-doped layer below the quantum wells is increased to 100nm or 200nm, respectively. The remaining layers are kept the same except for the collector thickness which is reduced. This keeps the cavity thickness constant and the lasing wavelength is the same as before, and most importantly, the standing wave peak coincides with the quantum wells location in the cavity.

3.1. 100nm n-doped layer below the quantum wells

In Fig. 7(a) simulation results are presented for the optical output power against base current at different $V_{CE}$. The threshold current values, maximum output power and the roll-off behavior is similar to the previous device. In Fig. 7(b) we present $V_{BE}$ as a function of $I_b$. These curves look different from the corresponding curves for the previous device in the Fig. 3(c). The base voltage does not increase as sharply as before, and distinct regions in the curves can be identified. First is the initial region where the $V_{BE}$ reaches around 1.2V to turn on the base-emitter junction. Then $V_{BE}$ increases as a normal p-n junction with spontaneous emission. Then as the lasing starts at approximately 1mA, the $V_{BE}$ curves slope gets reduced due to stimulated recombination and corresponding partly clamping of the carrier density in the quantum wells. Finally, the slope of the $V_{BE}$ curves get further reduced when the base-collector junction becomes partly forward biased and further clamps the base voltage.

Fig. 4. Simulation results of the fabricated TVCSEL.
In Fig. 7(c) collector current curves are plotted against base current at different $V_{CE}$. It is evident from these curves that the collector current keeps increasing after the lasing threshold, which is in distinct contrast to the results in the previous section, where the collector current starts to decrease even before lasing. Hence, in the present case, the base-collector junction is still reverse biased after lasing and the TVCSEL operates in the active mode up to a certain base current. At higher $I_b$, the base-collector junction becomes eventually forward biased and the device goes into saturation mode and the $I_c$ starts to decrease. This is also evident from
the Fig. 7(d) where the corresponding current gain $\beta$ curves are plotted. These curves are a bit noisy due to the numerical derivative taken. $\beta$ remains positive after lasing, and even $\beta > 1$ for high $V_{CE}$ after lasing. At high base current when the base-collector junction is forward biased $\beta$ becomes negative and the TVCSEL looses its transistor action. Corresponding band-diagrams in the center of the TVCSEL are shown in Fig. 9 also confirm this behavior. The base-collector junction remains reversed biased up to $I_b = 5\text{mA}$ after lasing, and finally it becomes forward biased.

In Fig. 8(a) optical output power curves are plotted against $V_{CE}$ at different base currents. These curves look very similar to the previous results. In Fig. 8(b) the collector current curves are plotted against $V_{CE}$ at different base currents. There are some differences in this graph as compared to the Fig. 5(c) in the previous section. This is mainly due to the changes in the premature saturation behavior of the device as compared to the previous layer structure. In Fig. 8(c) $I_E$ curves are plotted against $V_{CE}$ at different $I_b$. At low $I_b$ where the device is in the active mode, the emitter current does flatten as $V_{CE}$ is increased. However, at high $I_b$ where the base-collector junction is forward biased, the emitter current keeps on increasing as $V_{CE}$ is increased.

3.2. 200nm n-doped layer below the quantum wells

Simulation results are reproduced for this layer structure, and the results are presented in Figs. 10, 11 and 12. The key difference to be noted is that the collector current keeps on increasing a bit further as compared to the previous two layer structures (Fig. 10(c) vs Fig. 7(c) and Fig.
Fig. 7. Simulation results for the TVCSEL with 100nm n-doped layer below the QWs.

Fig. 8. Simulation results for the TVCSEL with 100nm n-doped layer below the QWs.
Fig. 9. Band diagram for the TVCSEL with 100nm n-doped layer below the QWs.

Fig. 10. Simulation results for the TVCSEL with 200nm n-doped layer below the QWs.
For example, at $V_{CE} = 4V$, the $I_c$ keeps on increasing up to $I_b = 6mA$, while this value for the device with 100nm below the quantum wells was $I_b = 5mA$. So basically, we have further pushed the base-collector junction saturation point to higher base current at a given $V_{CE}$. Thus with thicker n-doped layer below the quantum wells, the device can work in the active mode up to a higher base current and act as a transistor laser well into the lasing regime.

This may also be observed from a comparison between Figs. 5(c),8(b) and 11(b) showing the $I_c$-vs-$V_{CE}$ curves for different values of $I_b$. These curves represent the typical transistor behavior. That is, in the saturation mode the $I_c$ increases as $V_{CE}$ (or $V_{BE}$) increases, but in the active mode $I_c$ will be relatively independent of $V_{CE}$. For the 10-nm design, the device is in the saturation regime throughout the range of applied $V_{CE}$ and $I_c$ increases monotonously with increasing $V_{CE}$ (Figs. 5(c) and 5(d)). For the 100-nm design, the device is in the active region for the combination sufficiently small $I_b$ and sufficiently large $V_{CE}$ as marked by pronounced "knees" in the $I_c$-vs-$V_{CE}$ curves for $I_b < = 4mA$ in Fig. 8(b); and more so for the 200-nm design ($I_b < = 6mA$; Fig. 11(b)). These "knees" can also be observed from the corresponding $I_c - I_b$ curves (Figs. 3(e), 7(c) and 10(c)) in the three designs.

4. Discussion of results, conclusion and outlook

Using this simulation model, we were able to reproduce the experimentally observed loss of transistor behavior of our experimental reference TVCSEL. Except for the optical output power, we find a good agreement between our simulations and experimental results. The threshold current required for lasing matches well between the simulations and the measurements. While there is a qualitative agreement between measured and simulated optical power in terms of base current and temperature dependency on threshold and roll-over, the measured power is an order of magnitude lower than the predicted value. This may be due to several different effects and shortcomings of the numerical model or combinations thereof, including overestimated material gain (simplified gain model, e.g. not including Coulomb enhancement or many-body effects), 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), over-estimated 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 not are captured in the experiment which relies on a large-area detector positioned at some distance from the chip. Ex- tensive calibrations between the model and similarly designed diode-VCSELs and T-VCSELs may resolve this issue.

By increasing the thickness of the n-doped base layer below the quantum wells, we were able to operate the TVCSEL in its normal active mode after lasing. As discussed in more detail elsewhere [33], an extended base region thickness below QWs changes the potential distribution in the device so that the base-collector junction remains reverse biased as the base current is increased above threshold. However, the thicker the base region the slower the device will be with respect to its modulation bandwidth since the transport of holes in the n-doped base region is mainly diffusion limited [4]. One important feature of the present design is that there is significant voltage drop in the thick p-doped emitter layer and the collector layer. The distance from the collector contact to the center of the TVCSEL is 25 $\mu m$ which is much larger than the usual lasers. If the collector contact can be brought closer to the center of the TVCSEL, for example by asymmetrical contact, then hopefully the excessive voltage drop in the collector layer can be minimized.

The thickness and the placement of the quantum wells in the base region of a PnP TVCSEL is
Fig. 11. Simulation results for the TVCSEL with 200nm n-doped layer below the QWs.

Fig. 12. Band diagram for the TVCSEL with 200nm n-doped layer below the QWs.
crucial to the proper operation of the device. If the quantum wells are too close to the collector side, the base-collector junction becomes forward biased early on and the TVCSEL looses its transistor mode of operation. To operate the TVCSEL in the normal active mode, a certain minimum thickness of the n-doped base layer below the quantum wells is needed. In our design, with 200nm n-doped below the quantum wells, the TVCSEL can operate in the normal active mode up to $I_b = 6mA$ with $\beta > 1$ after lasing. Further work will be done to ascertain the dynamic performance of the TVCSEL and its data transmission capability. Alternate designs such as Npn TVCSEL and Pnp TVCSEL with tunnel junction in the emitter can also be explored.

Acknowledgments

The project is financed by the Swedish Research Council VR grant 2010-4386.