High temperature operation of 760 nm vertical-cavity surface-emitting lasers investigated using photomodulated reflectance wafer measurements and temperature-dependent device studies

S.A. Cripps, T.J.C. Hosea, S.J. Sweeney, D. Lock, T. Leinonen, J. Lyytikäinen and M. Dumitrescu

Abstract: The wafer of a 760 nm vertical-cavity surface-emitting laser (VCSEL), designed for oxygen sensing up to high temperatures, is investigated using photomodulated reflectance (PR). By varying the angle of incidence, the VCSEL cavity mode (CM) wavelength is tuned through the positions of two excitonic quantum well (QW) transitions. The PR is also measured over a large temperature range to determine when the QW ground-state transition is tuned with the CM. When tuned, the QW/CM PR lineshape becomes anti-symmetric, as predicted by theory. This occurs at 388 K, where the CM and QW wavelengths coincide at 760.7 nm. It is also observed that when tuned, the CM width measured in the reflectance spectrum is maximised. Temperature dependent device studies are also conducted on a 760 nm edge-emitting laser containing a similar active region as the VCSEL. It is found that up to 250 K the device behaves ideally, with the threshold current being entirely due to radiative recombination. However, as the temperature increases, electron leakage into the indirect X-minima of the barrier and cladding layers becomes increasingly significant. At 300 K, approximately 25% of the threshold current is found to be attributed to electron leakage and this increases to 85% at 388 K. The activation energy for this leakage process is determined to be 255 ± 5 meV, indicating that electron escape from the QWs into the X-minima of the barrier and/or cladding layers is chiefly responsible for the device's poor thermal stability. These results suggest that VCSELs containing this active region are likely to suffer significantly from carrier leakage effects.

1 Introduction

Vertical-cavity surface-emitting lasers (VCSELs) offer several favourable characteristics over conventional edge-emitting devices, such as very low threshold currents, low beam divergence, a circular beam profile and single-mode operation. The ability to test on-wafer also leads to significant cost savings compared to edge-emitting lasers (EELs). 760 nm is a strongly absorbing wavelength for gaseous oxygen and there is now considerable effort in developing VCSELs to operate in this region so they can be used in oxygen sensors. Indeed such devices are starting to become commercially available. Oxygen sensors are particularly important in the areas of analytical chemistry, biotechnology, environmental monitoring and industrial engineering [1]. Two of the main advantages of using VCSELs for oxygen sensing are the narrow linewidths achievable and the low costs involved. It is also possible to exploit the effects of current tuning and self-heating in order to scan narrow wavelength bands around 760 nm, and by

applying modulated drive currents, wavelength modulation spectroscopy can be performed [2]. This makes VCSELs well suited for use in spectroscopic studies of trace gases.

An operational VCSEL must ideally be 'tuned' under the conditions in which it is designed to function. When tuned, the quantum well (QW) gain peak overlaps the position of the dip in the VCSEL reflectance spectrum caused by the Fabry-Pérot cavity mode (CM). This ensures that the maximum material gain occurs at the CM wavelength, thereby minimising the threshold carrier density and hence, the threshold current. Photomodulated reflectance (PR) is now recognised as a key non-destructive tool for monitoring the extent of tuning between the QW and CM features [3]. By measuring the reflectance R of a VCSEL and simultaneously modulating its internal electric field with a chopped laser, a modulated reflectance component ΔR can also be detected. This ΔR component generally contains clear derivative-like lineshapes at the positions of the CM and the QW. The PR signal is defined as $\Delta R/R$. Here, we examine the use of PR on a 760 nm VCSEL wafer with the main purpose of finding the temperature and wavelength at which a processed device would be tuned. We also perform device measurements for an EEL, which contains a similar active region as the VCSEL wafer, in order to determine the relative importance of carrier leakage and radiative recombination in lasers based upon this active region.

2 Experimental details and results

The VCSEL wafer investigated in this study is an entirely AlGaAs-based structure containing three nominally 8 nm $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ QWs centred within a Fabry-Pérot cavity of optical thickness λ , where λ is designed to be 760 nm at a high

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S.A. Cripps, T.J.C. Hosea, S.J. Sweeney and D. Lock are with the Advanced Technology Institute, University of Surrey, Guildford, Surrey, GU2 7XH, UK

T. Leinonen, J. Lyytikäinen and M. Dumitrescu are with the Optoelectronics Research Centre, Tampere University of Technology, Tampere, Finland

E-mail: j.hosea@surrey.ac.uk

operating device temperature of $\sim 100^\circ\text{C}$. The top distributed Bragg reflector (DBR) mirror contains 36 periods and this is covered by a 52 nm protective GaAs cap layer to stop oxidation of the top DBR layers. The bottom DBR contains 47 periods mounted on a GaAs substrate. The DBR pairs are formed from nominally $\text{Al}_{0.39}\text{Ga}_{0.61}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ and both mirrors contain $\text{Al}_{0.67}\text{Ga}_{0.33}\text{As}$ barrier reduction layers to reduce the electrical resistance of the device. To our knowledge, there have been no previous PR studies published for such VCSELs designed to operate at 760 nm. The VCSEL PR measurements were undertaken using the specialised techniques developed at Surrey, a full account of which can be found elsewhere [3]. Here, the reflectance of the VCSEL was modulated using a mechanically chopped $\sim 2\text{ mW}$, 633 nm HeNe laser.

2.1 Normal incidence reflectivity

Figure 1 shows the normalised reflectance spectrum of the VCSEL wafer taken at normal incidence and room temperature. The stop band can be seen to extend from $\sim 734\text{ nm}$ to $\sim 778\text{ nm}$, and the sharp dip caused by the CM is clearly visible at 755.8 nm, near the centre of the stop band. The cavity of this sample is of a very high finesse; the measured full width at half maximum (FWHM) (meaning the width of the dip at half the maximum depth of the CM feature) is 0.3 nm (0.15 nm when the effect of instrumental resolution is accounted for). The effect of this high finesse on the PR studies will be discussed later. As can be seen, the reflectance spectrum has an unusual stop band profile; rather than the typical flat top there is a pronounced wide dip. Reflectance simulations using the transfer matrix method [4] show that this wide dip is caused solely by the presence of the aforementioned 52 nm absorbing GaAs protective cap layer. Somewhat unfortunately, the optical thickness of this cap is approximately $\lambda/4$. Without this cap, or with its absorption coefficient set to zero, the stop band has the usual flat top. Alternatively, if the thickness of the absorbing cap is doubled, say, in the simulations, the wide dip vanishes. This protective cap was intended to be removed in the final fabricated VCSELs in order to maximise device performance. In order to reduce the risk of sample deterioration during the high-temperature PR studies (see later), the cap was left intact.

2.2 Room temperature PR studies as a function of angle of incidence

Previous PR studies on VCSELs [5] have shown that if the normal-incidence wavelength of the CM, λ_{CM} , is higher

Fig. 1 Normalised room temperature, normal incidence reflectance spectrum of the 760 nm VCSEL wafer

than that of the QW ground-state transition, λ_{QW} , they may be tuned into resonance by increasing the angle of incidence away from normal. The CM can be blue shifted to lower wavelengths by increasing the angle of incidence, as described by

$$\lambda_{\text{CM}}(\theta) = \lambda_{\text{CM}}(0^\circ) \sqrt{1 - \frac{\sin^2(\theta)}{n^2}} \quad (1)$$

where n is the refractive index of the ‘effective’ cavity [3] and θ the angle of incidence. $\lambda_{\text{CM}}(0^\circ)$ is the CM wavelength at normal incidence, given by $2nd/m$, where d is the effective length of the cavity and m the mode order, which is two for the present cavity of optical thickness λ . For this series of measurements, the VCSEL wafer was mounted on a turntable so that the reflectance and the PR could be recorded for a range of different incidence angles ($22.5^\circ - 80.0^\circ$). The instrumental resolution (FWHM) was set at 1.74 nm for this set of initial investigations. By measuring the reflectance spectrum as a function of angle of incidence, the refractive index n and thickness d of the ‘effective’ cavity can be deduced by fitting (1) to the measured variation of $\lambda_{\text{CM}}(\theta)$ [3]. This was done here and a good fit was obtained (results not shown), giving $n = 3.405 \pm 0.002$ and $d = 222.0 \pm 0.2\text{ nm}$. This value of n agrees well with the actual refractive index of the main AlGaAs cavity material (3.400). The deduced d is, however, slightly larger than the nominal cavity thickness (216 nm). This is consistent with the fact that the cavity mode standing wave penetrates slightly into the DBR layers, thereby increasing the width of the ‘effective cavity’.

Figure 2 shows example room temperature PR spectra for the VCSEL wafer as a function of incidence angle. A static feature can be identified near 740 nm, and a much weaker one near 731 nm. These features are magnified in the spectrum at 25° so they can be compared to the strong CM feature. The CM wavelength (determined from the simultaneous

Fig. 2 Example room temperature PR measurements of the 760 nm VCSEL wafer sample as a function of angle of incidence (successive spectra are offset by 2.5×10^{-3} for clarity)

reflectance measurements, which are not shown) blue shifts with increasing angle, as predicted. The positions of the three features are indicated by dashed lines. The static features are identified as QW excitonic transitions, as confirmed by theoretical calculations using the VCSEL material parameters. The static feature near 740 nm is due to the ground-state electron to heavy-hole transition (e_1hh_1) and the 731 nm feature arises from the ground-state electron to light-hole transition (e_1lh_1). The actual QW e_1hh_1 and e_1lh_1 wavelengths were determined by performing Kramers-Kronig (KK) transforms on the PR spectra to yield the PR modulus spectra. This process removes the phase detail from the derivative-like lineshapes and results in simple peaks at the transition wavelengths [6], giving 740.0 ± 0.5 nm and 731 ± 2 nm for the two present QW transitions. Determining the exact position of the feature at 731 nm proved difficult because of the weak signal, which explains the increased uncertainty compared to the feature at 740 nm. It is clear from Fig. 2 that the PR lineshape varies greatly as a function of incidence angle. At 25° the CM feature is clearly visible but as the CM and QW features begin to interact the lineshapes become more complex. At 55° , for example, the lineshape is very detailed and shows a clear interaction between the CM and the two QW features. The most important point to note is that at an incidence angle of 45° the intricate coupled QW/CM PR lineshape assumes a simpler, anti-symmetric profile. It has been shown previously that, when the CM broadening is significantly less than that of the QW feature in PR, an anti-symmetric lineshape occurs when the VCSEL is tuned such that $\lambda_{QW} = \lambda_{CM}$ [5]. This occurs in Fig. 2 for the e_1hh_1 QW transition at 45° . It can also be seen that at an angle of incidence of 60° the CM and e_1lh_1 QW become nearly tuned, and again there is an approximately anti-symmetric lineshape near this lower-wavelength feature. It may also be noted that there is an interesting dissimilarity between the two anti-symmetric lineshapes formed at 45° and 60° : when the CM is tuned with the e_1hh_1 QW transition, the anti-symmetric lineshape has two extra weaker lobes to either side. However, these do not occur when the CM is tuned with the e_1lh_1 QW transition. This observation will be discussed again later.

2.3 Temperature dependence of the normal-incidence PR

Varying the angle of incidence in PR as a means of determining the VCSEL QW transition wavelengths is a powerful technique, but to understand more about the ideal operating conditions of a device it is useful to examine the temperature variation. The present wafer was designed to produce VCSELs which operate up to high temperatures and at a wavelength of 760 nm. Clearly, to achieve this, a good knowledge of how the CM and QW wavelengths vary with temperature is needed. This set of PR measurements was performed at normal incidence, with the wafer sample mounted in air on a simple heater. To ensure that the sample was not damaged it was not heated above 470 K.

Figure 3 shows example PR spectra for a selection of the different temperatures studied. As mentioned earlier, the cavity has a very high finesse, which is of particular significance in PR studies. The sharp CM feature produces a strong PR signal of width considerably less than that of the corresponding QW PR feature. This results in some very intricate VCSEL PR spectra, especially when the CM and QW PR features are near to each other. Thus, in order to resolve such detail, especially near the resonance condition, the instrumental resolution (FWHM) was tightened to 0.26 nm for this set of measurements. As a

Fig. 3 Example normal incidence PR measurements of the 760 nm VCSEL wafer as a function of temperature (a 3×10^{-2} offset has been employed to successive spectra for clarity)

consequence, the R and ΔR signal strengths are greatly reduced and the weak e_1lh_1 QW transition is no longer discernible in the PR. However, the true extent of the relative broadening of the CM and QW features is revealed. This can be seen by examination of the spectrum at 303 K for instance, where the CM PR feature is approximately five times sharper than that of the ground-state QW transition. In the earlier room temperature studies with poorer instrumental resolution the same QW feature appeared approximately twice as wide as the CM feature (see Fig. 2). Figure 3 shows that both the CM and QW wavelengths red shift with increasing temperature. The increase of the CM wavelength is due primarily to the increase in the refractive index of the cavity as the VCSEL is heated, which has a more significant effect than the thermal expansion of the cavity [7]. Heating also reduces the QW band gap energy. It is clear from Fig. 3 that the two features move at unequal rates, with measured coefficients of $(\Delta\lambda/\Delta T)_{CM} = 0.05$ nm/K and $(\Delta\lambda/\Delta T)_{QW} = 0.23$ nm/K (see later), values which are comparable to those measured for similar AlGaAs resonant-cavity light-emitting diode (RCLED) structures [8]. Clearly, the CM position is far less sensitive to temperature variation than that of the QW, which is a key reason for choosing VCSELs over EELs in environments where the temperature can vary appreciably: a VCSEL operational wavelength is defined by the CM and not the QW.

It can be seen from Fig. 3 that the coupled CM/QW PR lineshape becomes anti-symmetric at 388 K. It can be concluded, therefore, that a VCSEL fabricated from the present wafer would be tuned at approximately 115°C (the ideal continuous wave operating temperature would be slightly less than this, due to the effect of current-induced self-heating [9]). Figure 3 also shows that the centre of the anti-symmetric lineshape at 388 K is located at 760.7 nm. Thus, the PR studies confirm that the wafer growth

successfully achieved both the operating wavelength and temperature for this VCSEL.

Now let us turn to the problem of using PR to obtain the full temperature dependence of the wavelengths of the CM and QW ground-state transition. As was mentioned in the room-temperature angle-dependent studies, the CM wavelength can generally be easily determined from a simple reflectivity measurement. We used KK transforms of the PR spectra to determine the QW wavelengths. The KK method is easy, simple and quick, and works well when the CM and QW PR features are separated by more than the sum of their line-widths [6]. It is clearly very useful when the QW features are static: one need only then perform KK transformations at appropriate angles where the QW and CM features are well separated in order to determine the QW transition wavelength at a given temperature. However, in the present temperature-variation studies, the KK method ceases to be so useful since the QW feature is shifting. In the temperature region of most interest, where the VCSEL is nearly tuned, the CM and QW are strongly interacting and are too closely coupled for the KK method to be reliable. To obtain the QW wavelengths here, one could interpolate the KK results from lower and higher temperatures. This interpolation method was used to calculate the value of $(\Delta\lambda/\Delta T)_{\text{QW}}$ quoted earlier and the result can be seen in Fig. 4. Figure 4 summarises Fig. 3 by indicating the position of the CM at all temperatures as measured from the reflectivity spectra and the QW positions obtained from the KK transforms of the PR spectra. The linear interpolation between the measured QW positions indicates that the CM and the QW wavelengths would become equal at 760 ± 1 nm and at a temperature of 385 ± 5 K. While this is in agreement with the result obtained from the anti-symmetric PR spectrum at 388 K in Fig. 3, the uncertainty caused by the interpolation is not ideal. In previous temperature-variation studies of VCSELs [10], this problem was solved by fitting the PR spectra with a coupled CM/QW lineshape model which we developed for VCSELs and RCLDs [3], to obtain the wavelengths of all the PR features. This model assumes simple conventional lineshapes for the CM and QW features but allows for a multiplicative coupling between the features, and has been very successful in reproducing the observed lineshapes, especially when the CM and QW features cross and interact. Here, we attempted to use this same model to fit the measured PR spectra in Figs. 2 and 3. Unfortunately, the model was generally unsatisfactory in reproducing the intricacies of the measured

Fig. 4 Positions of the CM and e_1hh_1 QW transition for the VCSEL wafer as a function of temperature

The arrows indicate the temperature and wavelength at which the two points cross

spectra. We believe this is due to a number of factors. Firstly, the stop band seen in the wafer reflectance measurements has the unusual wide dip caused by the GaAs cap layer (see Fig. 1). On careful inspection of the CM profile in Fig. 1, it is clear that the usual simple dip-like CM profile is modified by the cap layer. Reflectivity simulations also confirm that the simple CM profile is modified by the GaAs cap to take on a more complex shape. Unfortunately, the aforementioned PR lineshape model assumes a simple Lorentzian-like lineshape for the CM PR feature [3] so clearly, any deviation from this will cause difficulty when attempting to use it to fit the PR spectra. A second factor is that our PR lineshape model does not predict the presence of the aforementioned side lobes observed for this VCSEL, e.g. when it is tuned at 45° (see Fig. 2). Clearly, the present VCSEL sample has a more detailed and intricate PR spectrum than can be accounted for by the current simple lineshape model.

Some modifications to the current PR model are required in order to apply it to a wider range of VCSEL structures. In the present case, however, we are able to apply the alternative symmetry analysis, as mentioned earlier, since this technique assumes nothing about the detailed functional forms of the CM and QW features in the PR, only that the CM is sharper than the QW feature. Since this is the case for the present VCSEL, we are able to conclude with confidence that the PR lineshape will become anti-symmetric when it is tuned. In order to quantify the degree of anti-symmetry of the PR spectra near resonance in Fig. 3, we fitted the spectra with a simple phenomenological single lineshape model. The exact form for such an empirical model is unimportant; all that is required is that it is able to parameterise the observed symmetry. Here, we actually used a conventional third-derivative functional form whose phase parameter describes the degree of anti-symmetry [11]. The fitted phase parameters indicate that the lineshape becomes perfectly anti-symmetric at a temperature of 387 ± 1 K. Since the QW and CM wavelengths are equal at this temperature, and the CM wavelength was determined by separate reflectance measurements, we can infer that the QW wavelength at this temperature is 760.7 ± 0.1 nm. This result agrees reasonably well with the crossing point obtained by interpolation on Fig. 4.

It is worthwhile mentioning an ancillary effect of the crossing of the CM and QW features observed here. Figure 5 shows the FWHM of the CM feature measured from the reflectivity spectra, as functions of incidence angle (at room temperature) and temperature (at normal incidence). The typical error associated with each measurement is indicated on the last data point. For both these sets of measurements the instrumental resolution was tightened to 0.26 nm. It is clear that the FWHM becomes a maximum at an angle of incidence of 45° and at a temperature of 388 K. These are the two conditions at which the coupled QW/CM PR lineshapes became anti-symmetric, i.e. at which the CM and QW are in resonance. It may also be seen from Fig. 5a that the FWHM goes through another, smaller maximum near 60° , the angle where the room-temperature CM wavelength and e_1lh_1 QW transition are nearly in coincidence (see Fig. 2). Thus, the indications are that the FWHM of the CM feature measured from the standard reflectance spectra becomes maximised when it is in coincidence with a QW transition. This cavity broadening effect can be understood in terms of the cavity absorption spectrum which will have maxima at the QW excitonic transition energies. When such features are in coincidence with the CM wavelength, the cavity is most strongly absorbing, and this will broaden the CM feature seen in the reflectance spectrum. This phenomenon has been

Fig. 5 FWHM of the CM feature observed in the reflectance spectra as a function of (a) angle of incidence and (b) temperature. The solid curves are guides for the eye

observed previously for a similar VCSEL [12] and has also been exploited by another group as a method for measuring the absorption of quantum dot superlattices placed within high-finesse microcavities. [13] The effect may well prove useful as a corroborative measurement to PR for monitoring when the CM is in tune with a QW transition.

2.4 Device studies of a 760 nm edge-emitting laser diode

The above PR studies identified that an operational VCSEL fabricated from the wafer studied here would be tuned at a device temperature of 388 K. To get a better understanding of how such a device would perform it is necessary to undertake device studies. In particular, since we are interested in the temperature dependence of the devices it is important to understand the intrinsic carrier recombination properties of the active region and their dependence on temperature. In a VCSEL, the temperature sensitivity is determined by both the structure of the active region and the effects of de-tuning between the peak gain and CM. Therefore, in order to consider the active region in isolation, we undertook studies on EELs containing very similar active regions. The only difference between the EEL and VCSEL structures is a lower nominal aluminium content of 13.5% in the QWs for the EEL samples compared with 15%

Fig. 6 Temperature variation of (a) threshold current density and (b) characteristic temperature T_0 for the 760 nm EEL

The solid curve represents a fit to these data, extrapolated up to 400 K

for the VCSELs. As we shall discuss later, this small difference in the aluminium content of the QW has relatively little influence on the dominant carrier recombination process in the devices. These EEL results provide important information for the optimisation of the VCSEL structures.

The EEL investigated here is a broad-area device with a stripe width of 40 μ m and a length of 1000 μ m. We measured both the stimulated facet emission and the windowed spontaneous emission from the device as a function of applied current over a wide range of temperatures (80 K to 350 K). The devices were measured in pulsed mode (500 ns pulse width at 10 kHz repetition) in order to avoid current heating effects. The full experimental procedure is detailed elsewhere [14]. Figure 6a displays the measured threshold current density, J_{th} (closed circles) as a function of temperature. From this plot we observe two clear operating regimes. At low temperatures (below ~ 250 K), J_{th} increases linearly with temperature. This is consistent with J_{th} being dominated by the radiative current density (J_{rad}) since one would ideally expect that $J_{rad} \propto T$ for a QW laser [15]. Above 250 K, J_{th} increases swiftly and super-linearly. This has previously been observed in 667 nm lasers [16] and may be understood in terms of thermally-activated electron leakage into indirect X-minima. Assuming simple Boltzmann statistics, the thermally activated leakage can be modelled by assuming a diffusive process so that J_{leak} can be expressed as

Fig. 7 Natural log plot of leakage current from 240 K to 350 K as a function of inverse temperature

The activation energy of the leakage process is determined to be 255 ± 5 meV from the linear fit (solid line)

$$J_{leak} = J_0 \exp\left(-\frac{E_a}{k_B T}\right) \quad (2)$$

where J_0 is a constant, k_B is the Boltzmann constant and E_a is the activation energy of the leakage process. If we assume that J_{rad} continues to increase at the same rate, by extrapolating J_{rad} to high temperature (dashed line in Fig. 6a) we may determine J_{leak} (dotted line in Fig. 6a) from $J_{leak} = J_{th} - J_{rad}$. In Fig. 7 we plot $\ln J_{leak}$ versus $1/T$ from which we extract the activation energy of the leakage process, $E_a = 255 \pm 5$ meV. This is consistent with the calculated separation between the QW electron ground state and the X-minima in the AlGaAs barrier/waveguide layers of 260 meV. We note that the separation between the QW electron ground state and cladding X-minima is similar at 240 meV, so leakage into the cladding layers may also contribute to the leakage current. A full drift-diffusion calculation would provide further insight into the relative importance of these carrier leakage paths in these structures, but this is beyond the scope of this paper. However, our results would suggest that diffusion-driven thermally-activated leakage into the barrier/waveguide X-minima is of most significance and is responsible for the poor thermal properties.

In Fig. 6a, the calculated variation of J_{leak} is extrapolated up to 400 K in order to incorporate the temperature range of interest as determined by our PR studies. The fit of J_{th} (solid line) is also extended to 400 K and it represents the sum of the fitted leakage and radiative current components. At room temperature we find that approximately 25% of J_{th} is due to the carrier leakage process, but at 388 K (the temperature at which our PR studies indicate the VCSEL wafer is tuned) we find that 85% of J_{th} is attributed to the leakage current. Figure 6b shows the corresponding variations of the characteristic temperature T_0 , for each of the current paths where $T_0(J_x) = J_x(dJ_x/dT)^{-1}$ and J_x corresponds to each respective current path. From this it is clear that leakage dominates the T_0 for these devices and is responsible for the low T_0 value of ~ 70 K at room temperature.

Whilst it is clear that electron leakage has a major impact on the total threshold current of the EELs, one would expect this to be exacerbated in the VCSELs where high leakage currents cause an increase in free-carrier absorption in the DBRs, which tends to reduce their reflectivity. Due to their

small size, VCSELs also tend to suffer from self-heating effects which will tend to enhance the effect of carrier leakage. This work clearly demonstrates the need to develop new active regions which can help to minimise electron leakage. This is the subject of ongoing work.

3 Conclusions

The non-destructive PR studies of the 760 nm VCSEL wafer have enabled us to find the wavelengths of two QW excitonic transitions and our temperature dependent measurements indicate that the QW ground-state transition would be tuned with the CM at 388 K at a wavelength of 761 nm. The PR lineshape of the coupled QW/CM feature became anti-symmetric when the VCSEL wafer was tuned, as predicted by the theory. However, the intricate detail revealed in these PR spectra imply that our current theory of VCSEL PR lineshapes requires some modification. The enhanced CM broadening observed in the reflectance measurements for this sample, if generally applicable, could provide a useful alternative technique for finding the conditions where VCSELs and RCLEDs are tuned. It is expected, however, that this effect may be most pronounced in VCSELs with very high finesse cavities, such as the present sample.

The 760 nm EEL device studies have shown that thermally-activated electron leakage from the QW into the X-minima of the barrier and/or cladding layers dominates the thermal performance of the devices, accounting for 25% J_{th} at room temperature, rising to 85% J_{th} at 388 K, the operating temperature. These results suggest that improved active region design which minimises this leakage current will significantly improve the performance of EELs and VCSELs based upon this material.

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