Investigation of 1.3- μm GaInNAs Vertical-Cavity Surface-Emitting Lasers (VCSELs) Using Temperature, High-Pressure, and Modeling Techniques

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Abstract—We have investigated the temperature and pressure dependence of the threshold current (I_{th}) of 1.3 μm emitting GaInNAs vertical-cavity surface-emitting lasers (VCSELs) and the equivalent edge-emitting laser (EEL) devices employing the same active region. Our measurements show that the VCSEL devices have the peak of the gain spectrum on the high-energy side of the cavity mode energy and hence operate over a wide temperature range. They show particularly promising I_{th} temperature insensitivity in the 250–350 K range. We have then used a theoretical model based on a 10-band $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian and experimentally determined recombination coefficients from EELs to calculate the pressure and temperature dependency of I_{th} . The results show good agreement between the model and the experimental data, supporting both the validity of the model and the recombination rate parameters. We also show that for both device types, the super-exponential temperature dependency of I_{th} at 350 K and above is due largely to Auger recombination.

Index Terms—Auger, GaInNAs, model, pressure, temperature, vertical-cavity surface-emitting laser (VCSEL).

I. INTRODUCTION

THERE has been a widespread commercial interest in developing vertical-cavity surface-emitting laser (VCSEL) devices emitting near 1.3 μm for optical fiber communication systems. The advantages of such devices over the incumbent edge-emitting laser (EEL) devices include lower threshold currents, a circular beam output that is ideal for fiber coupling, and the low manufacturing cost of producing two-dimensional device arrays. Until recently however, viable 1.3- μm emitting VCSELs have been hampered by two key problems. First, the material systems available at this wavelength are limited due to the lack of suitable epitaxial layers with high enough refractive index contrast to form the distributive Bragg reflectors (DBRs). For example, the widely used EEL system of InGaAsP–InP shows limited performance in VCSELs [1] due to

both low refractive index contrast and high thermal resistance in the DBRs. Other approaches, such as fusing the InGaAsP active region to the AlGaAs–GaAs DBRs [2] lead to high electrical resistance at the p-junction. Second, low-cost applications require stable uncooled operation over a wide range of temperature. This presents a specific difficulty for VCSELs as the lasing energy of the cavity mode has a different temperature dependence to that of the peak of the optical gain spectrum. Strategies to minimize this, employed at other wavelengths, involve broadening the gain spectrum by the use of several different multi-quantum wells [3], [4] or using the contributions of higher subbands [5]. However, this has the effect of reducing device efficiency by requiring nonlasing states to be pumped.

Recent reports of material systems, which can be lattice matched to GaAs substrates and have been demonstrated in operational VCSELs are InGaAs quantum dots [6] and GaAsSb–GaAs quantum wells [7]. However, the most encouraging performances so far have been shown by using the material GaInNAs where appropriate mixtures of N and In in GaInNAs can be grown pseudomorphically on GaAs, for low N concentration [8]–[11]. Monolithically grown GaInNAs VCSELs have already been demonstrated, producing 1.43 mW (at 1.26 μm) [12] and 500 μW (at 1.28 μm) under continuous-wave (CW) operation at room temperature [13]. There is also experimental evidence that GaInNAs has an intrinsically broad gain spectrum due to different bandgaps arising from statistical fluctuations in N density and alternative stable lattice N sites [14] (originating from different ratios of Ga and In as nearest neighbors) enabling a wide temperature operating range for VCSELs.

In this paper, we report the measured temperature and pressure dependence of the threshold current of 1.3- μm emitting GaInNAs VCSELs and also the equivalent EELs employing nominally identical active regions. We have then used the experimentally determined temperature variation of the main recombination processes measured in the EELs and a theoretical model to calculate the expected temperature and pressure dependence of the VCSEL threshold current. The model is based on a realistic 10-band $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian developed by Tomić and O'Reilly [15]. The results show a good agreement between the model and the experimental data and support the validity of the recombination rate parameters and the model. It also confirms that the

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Fig. 1. Schematic illustration of the intracavity-contacted configuration of the GaInNAs VCSEL.

VCSELs operate over a wide temperature range making them promising devices for communication applications.

II. THE STRUCTURES

The GaInNAs VCSEL structure, which was grown and fabricated by Infineon Technologies is shown in Fig. 1. It is of the intracavity-contacted configuration and the epitaxial structure was grown by solid source molecular beam epitaxy (MBE) using an RF-coupled plasma source to produce reactive monatomic nitrogen from nitrogen gas. The active region consists of two GaInNAs quantum wells (QWs) containing $\sim 2\%$ nitrogen sandwiched between 28 top and 34 bottom pairs of undoped $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As/GaAs}$ DBRs. An oxidisable layer of AlAs adjacent to the cavity was used to form a current aperture of approximately $9\text{-}\mu\text{m}$ diameter. A more detailed description can be found in [13], together with further information on growth issues.

The device was designed to emit at $1.3\text{ }\mu\text{m}$ at room temperature with the QW tuned on the high-energy side and designed to have a peak gain at $1.29\text{ }\mu\text{m}$. The EEL was a simple $350\text{-}\mu\text{m}$ -long, $4\text{-}\mu\text{m}$ -wide ridge waveguide laser structure employing a similar active region to the VCSEL but with three QWs and also designed to emit at $1.29\text{ }\mu\text{m}$ at room temperature.

III. PRESSURE MEASUREMENTS

The pressure experiments were carried out with a piston in cylinder system [16] using “Essence F” as the pressure fluid. Light from a mounted device was coupled into an optical fiber threaded through and embedded within the piston using epoxy resin and magnesium oxide. The electrical contacts were sealed into the piston using conical Vespel seals. In all the experiments described, a pulsed current is used (0.5% duty cycle with a $500\text{ }\mu\text{s}$ pulsewidth) to avoid any heating effects. Previous reports of pressure on GaInNAs EELs have shown two particular effects distinct from AlGaInAs and InGaAsP at this wavelength [17]. First, there is a sublinear increase of the lasing energy, due to the interaction of the conduction band edge with the N level (not discernable in this experiment). Second, there is a rise in the threshold current with increasing pressure in contrast to InGaAsP suggesting an unusual increase of Auger recombination

Fig. 2. Schematic illustration of the tuning/detuning effect in VCSELs due to the different pressure dependence of the gain peak and cavity-mode energies. In this instance i) the gain peak is tuned on the low-energy side of the cavity mode at $P = 0$. ii) Increasing pressure brings about ideal gain-cavity alignment and iii) further pressure eventually causes a detuning of the gain peak on the high-energy side of the cavity mode.

with pressure [18]. Pressure applied to the VCSEL will have a similar effect on the active region as in the EEL, but there will be an additional effect of a change in gain-cavity alignment as the cavity resonance and the gain peak energies have different pressure dependences [19], as illustrated in Fig. 2.

The measured lasing energy (E_{lase}) pressure dependences for both the EEL and the VCSEL are shown in Fig. 3. At atmospheric pressure the peak of the gain given by the E_{lase} of the EEL ($\sim 970\text{ meV}$) is on the high energy of the cavity mode ($\sim 949\text{ meV}$). As the pressure is applied, the E_{lase} for the EEL increases at a rate of $dE/dP = 73\text{ meV (GPa)}^{-1}$ compared with $dE/dP = 17\text{ meV (GPa)}^{-1}$ for the VCSEL, leading to a detuning rate with pressure of $dE/dP = 56\text{ meV (GPa)}^{-1}$. Extrapolating these rates backward beyond zero pressure, there is a “virtual” crossover (ideal gain-cavity alignment) at $\sim -0.4\text{ GPa}$. As thermal tuning/detuning occurs in the opposite sense to pressure, this indicates that atmospheric pressure ($\sim 0\text{ GPa}$) gain-cavity alignment is found well above room temperature. The way this detuning affects the I_{th} pressure dependence of the VCSEL can be seen in Fig. 4 together with the equivalent measured data for the EEL. There is a rapid increase in I_{th} for the VCSEL, which can partly be explained by the detuning on the steeper low-energy side of the gain peak [19], which means that the device requires a higher current density to reach threshold. Further to this, however, since monomolecular and Auger recombination are both functions of carrier density [20] and as the threshold carrier density increases with pressure due to an increase in effective mass so the detuning couples to these two loss mechanisms causing the particularly steep increase of I_{th} with pressure seen here. There

Fig. 3. Pressure dependence of both E_{lase} for the VCSEL determined by the cavity-mode pressure dependence and E_{lase} for the EEL, which lases close to the peak-gain energy. As the VCSEL is tuned with the gain-peak on the high-energy side of the cavity mode at room temperature and pressure (RTP), increasing pressure results in a detuning effect shown by diverging E_{lase} for EEL and VCSEL devices.

Fig. 4. Pressure dependence of I_{th} for VCSEL and EEL. For the EEL the small increase in I_{th} with pressure is close to ideal where $I_{\text{th}} = E_g^2$. For the VCSEL, however, the detuning effect with increasing pressure causes a rapid increase in I_{th} as detuning couples to increased Auger and monomolecular recombination.

is also a rise in I_{th} for the EEL above the ideally expected $I_{\text{th}} \propto E_g^2$ [21], which only appears small compared with the VCSEL on the scale of Fig. 4.

IV. TEMPERATURE DEPENDENCE MEASUREMENTS

The temperature dependence measurements were carried out using a static exchange gas cryostat allowing the temperature to be varied between 77 and 400 K. The measured E_{lase} temperature dependence for the EEL is shown in Fig. 5 together with calculated E_{lase} for the VCSEL [E_{lase} measured at room

temperature (RT)]. The rate at which the cavity mode changes with temperature is calculated in two ways. First, the ratio of dE_{lase}/dT for EEL and VCSEL ($7.3/1.7 = 4.29$) is assumed to be the same as the ratio dE_{lase}/dP [22]. $dE_{\text{lase}}/dT = -0.34 \text{ meV}\cdot\text{K}^{-1}$ for the EEL and dE_{lase}/dT is calculated for the VCSEL as $0.079 \text{ meV}\cdot\text{K}^{-1}$. Second, E_{lase} is physically determined by the effective cavity length and this changes due to the temperature dependence of the refractive index of the cavity and the material thermal expansion coefficient. The values for GaAs which constitutes a large part of the cavity have been assumed from the bulk values with $dn/dT \sim 3 \times 10^{-4} \text{ K}^{-1}$ [23]

Fig. 5. Temperature dependence of both E_{lase} (calculated) for the VCSEL determined by the cavity-mode temperature dependence and E_{lase} (measured) for the EEL which lases close to the peak-gain energy. As the VCSEL is tuned with the gain peak on the high-energy side of the cavity mode at RTP, increasing temperature results in a tuning effect shown by converging E_{lase} for EEL and VCSEL devices. Ideal gain-cavity alignment is predicted at ~ 350 K.

Fig. 6. Temperature dependence of I_{th} for VCSEL and EEL. At low temperature, there is only a small increase in I_{th} for the EEL due to radiative and monomolecular recombination. However, above 250 K Auger recombination starts to become significant and above RT there is a super-exponential increase in I_{th} . For the VCSEL at low temperatures I_{th} is high as the device is detuned. Increasing temperature improves gain-cavity alignment leading to a minimum I_{th} at ~ 280 K. Further increase shows the temperature dependence of the VCSEL becomes similar to that of the EEL being dominated by Auger even though gain-cavity alignment is improving.

and the linear thermal expansion coefficient $\sim 5.97 \times 10^{-6} \text{K}^{-1}$ [24], resulting in a slightly higher value for the VCSEL of $dE_{\text{lase}}/dT \sim -0.085 \text{ meV}\cdot\text{K}^{-1}$. Using the latter calculated tuning rate and assuming that the EEL approximates to the E_{lase} of the VCSEL active region, we estimate that the VCSEL will attain ideal gain cavity alignment at a temperature of ~ 350 K (shown in Fig. 5).

Fig. 6 shows the temperature dependence of I_{th} for the GaInNAs EEL and VCSEL normalized (at crossover ~ 350 K). For the EEL at low temperatures I_{th} is made up of monomolecular and radiative recombination [20]. From ~ 250 K and above Auger starts to increase leading to a super-exponential increase in I_{th} at 350 K and above. For the VCSEL, I_{th} decreases from ~ 180 K as the gain-cavity alignment of the device improves, reaching a minimum at ~ 280 K. However, at RT and above, the tuning effect becomes less significant as the gain spectrum broadens and Auger recombination starts to dominate. Hence,

Fig. 7. Outline of the model used to calculate the I_{th} pressure and temperature dependence.

Fig. 8. Gain spectra at RT and $P = 0$ where $n_{\text{th}} = 2.718 \times 10^{12} \text{ cm}^{-2}$ and the VCSEL cavity mode energy has been measured to be $E_{\text{lase}} = 0.948 \text{ eV}$. Applied pressure results in rapid detuning of the cavity mode on the steep low energy side of the gain spectrum.

both devices show similar temperature dependences above RT. It should be noted that this VCSEL does show a wide temperature operating range of ~ 200 K and also that I_{th} is comparatively temperature insensitive in the region 250–350 K, which is the likely operating temperature range. This is very promising for using these VCSELs in communication applications.

V. THE MODELED VCSEL I_{th} PRESSURE AND TEMPERATURE DEPENDENCE

The procedural outline used to model the VCSEL I_{th} pressure and temperature dependence is shown in Fig. 7. First, it is necessary to generate gain spectra for varying carrier concentration and this has been done using a 10-band **k.P** Hamiltonian model developed by Tomić and O'Reilly. The model is

Fig. 9. The total current density as a function of carrier concentration also showing the individual contribution of each recombination mechanism at RT and $P = 0$.

discussed in detail in [15] but briefly, the key novelty (in comparison with, e.g., [25]) involves a 10-band $\mathbf{k}\cdot\mathbf{P}$ Hamiltonian to describe the band dispersion where two spin-degenerate nitrogen states have been added to the conventional 8-band $\mathbf{k}\cdot\mathbf{P}$ Hamiltonian. This accounts for the bandgap reduction due to an anti-crossing interaction between the conduction band edge and a higher lying nitrogen resonant band and the modified conduction band dispersion. The parameters used reproduce excellently the ground and excited state transition energies deduced from photomodulated reflectance spectroscopy measurements on GaInNAs–GaAs QW structures [26]. Fig. 8 shows gain spectra generated by the model at room temperature and pressure for GaInNAs (36%-In 2%-N) incorporating 2.1% compressive strain and a Lorentzian broadening parameter of 17.5 meV which has been estimated from spontaneous emission experiments [20].

Fig. 8 also shows the cavity mode energy $E_{\text{lase}} = 0.948$ eV measured at room temperature and pressure together with the experimentally determined E_{lase} pressure dependence. In order to estimate the threshold gain of the VCSEL, the initial threshold current density and subsequently also the threshold carrier sheet density (n_{th}), at $P = 0$ and room temperature is estimated by dividing the threshold current by the aperture area, where the aperture diameter is ~ 10 μm (including 1 μm added to the aperture edge to account for current spreading [27]). The threshold current is then converted to a threshold carrier sheet density using the equation

$$I = eV(An + Bn^2 + Cn^3) \quad (1)$$

where V is the pumped volume of the active region and e is the electronic charge. A is the monomolecular recombination coefficient (recombination through defect centres), B is the bimolecular direct radiative recombination coefficient, and C the Auger three-carrier recombination coefficient. Leakage has been ignored due to the large GaInNAs–GaAs QW to GaAs

Fig. 10. Comparison of measured and calculated I_{th} pressure dependence.

barrier band offset (~ 200 meV [26]): it should be noted that the existence of carrier leakage processes in GaInNAs–GaAs QWs could potentially lead to an overestimation of the Auger recombination rate but based upon calculations in [28] leakage does appear to be negligible up to 400 K. The RT values used here are $A = 1 \times 10^8$ s $^{-1}$, $B = 1 \times 10^{-10}$ cm 3 s $^{-1}$, and $C = 4 \times 10^{-29}$ cm 6 s $^{-1}$ taken from temperature-dependent spontaneous emission measurements on similar 1.29- μm emitting EEL devices made by Fehse *et al.* [20]. The total current density is then plotted as a function of carrier concentration using (1). Fig. 9 shows this for $T = 300$ K. The threshold gain has then been fixed on the gain spectrum at the intersection of the E_{lase} and the threshold carrier density (n_{th}) at $g_{\text{th}} = 825$ cm $^{-1}$.

In order to model the I_{th} pressure dependence we have assumed that over the pressure range considered (0.3 GPa) both the gain spectrum and the recombination coefficients remain constant. Fig. 10 shows an excellent fit of the modeled pressure dependence of I_{th} with the measured data from Fig. 4.

Fig. 11. Comparison of measured and calculated I_{th} temperature dependence.

A similar procedure is carried out for the modeled I_{th} temperature except that the gain spectra are generated for each temperature and the calculated cavity mode lasing energy temperature dependence of $dE_{lase}/dT = -0.085 \text{ meV} \cdot \text{K}^{-1}$ is used. The n_{th} values are calculated as before but employing the temperature-dependent recombination coefficients values from [20] in (1). We have assumed that the threshold gain is constant over the temperature range. Fig. 11 shows a good fit of the calculated data to the measured I_{th} temperature dependence. The small divergence at low temperature between the modeled and measured data may be explained by the fact that the gain model does not include many body effects (in contrast to [29]). At high carrier densities, the charges screen the atomic attractive force leading to an increase in the nearest neighbor electron overlap. This has the overall effect of “bandgap shrinkage,” which reduces the effective gain peak dE_{lase}/dT rate with increasing current density and decreases detuning leading to a slightly higher calculated I_{th} [30].

VI. CONCLUSION

We have measured the temperature and pressure dependence of the threshold current of 1.3- μm emitting GaInNAs VCSELs and of EELs employing the same active regions. We have then used a theoretical model based on a realistic 10-band $\mathbf{k}\cdot\mathbf{P}$ Hamiltonian and the experimentally determined recombination coefficients from EELs to calculate the VCSEL threshold current pressure and temperature dependence. The results show a good agreement between the model and the experimental data and support the validity of both the recombination rate parameters and the model. It also shows that the VCSELs operate over a wide temperature range making them promising devices for communication applications.

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Dr. Adams was awarded the Duddell Medal and Prize by the Institute of Physics, U.K., in 1995 for his work on strained-layer lasers. He is a Fellow of the Institute of Physics, London, U.K., and the Institute of Electrical Engineers, U.K. In 1996, he was Elected Fellow of the Royal Society.

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G. Steinle, photograph and biography not available at the time of publication.

H. Reichert, photograph and biography not available at the time of publication.