The impact of hot-phonons on the performance of 1.3μm dilute nitride edge-emitting quantum well lasers

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Abstract. A robust opto-electronic device simulation tool is extended to model the phonon bottleneck in edge-emitting 1.3μm InGaAsN double quantum well (QW) laser diodes. Both the steady state operation and the transient response of the phonon bottleneck are examined as a function of injection current and heatsink temperature. It is found that the hot phonon population can raise the electron and hole temperatures in the QW active region by up to 7K above the equilibrium lattice temperature at moderate injection currents. At high injection currents, it is found that the phonon bottleneck can significantly decrease the optical power.

1. Introduction
In recent years, the InGaAsN/GaAs material system has shown great promise as a low cost directly modulated source for access network applications. The introduction of small quantities of nitrogen into the quantum well (QW) offers the ability to generate 1.3μm light emission on a low cost GaAs substrate. The high conduction band offset results in devices that exhibit good thermal stability, thereby eliminating the need for active cooling and thus reducing the total unit cost. Devices capable of 10 Gb/s operation at heatsink temperatures of up to 110 °C have been demonstrated [1]. Whilst large improvements in device reliability have been made, uncooled operation is inextricably linked to higher operating temperature and shorter device lifetime. An important aspect of improving device reliability is to minimise heat generation. One way to understand and minimise the physical heating mechanisms is through the use of accurate and predictive simulation tools. In this work, we extend a state-of-the-art electro-optical-thermal device simulator to include the impact of non-equilibrium LO-phonons generated via carrier relaxation in the QW. The strong LO-phonon/carrier interaction coupled with the finite LO-phonon decay time, results in a hot-phonon population being formed around the QW. This in turn elevates the QW carrier temperature far above that of the lattice. The impact of the hot phonon population on the transient response and the light-current (L-I) characteristics of the device is studied and found to be particularly important in dilute nitride devices due to the large conduction band offset caused by the interaction of the conduction band wave function with the nitrogen level.

2. Model
Our 2D electro-optical-thermal simulation tool self-consistently solves the carrier continuity, current continuity, Poisson, quantum well capture/escape and photon rate equations spatially in 2D as well as in the time domain. The QW valance band structure is calculated using a 4x4 band k.p model and the
The range of interacting k_{xy} vectors is given by
\[ q_{xy}(\text{min} / \text{max}) \] [4] and the range of the LO k_{z} vectors with which the 2D carriers can interact is given by \( q_{z} / 2 = 2\pi / L_{w} \), where \( L_{w} \) is the QW width [5].

The non-parabolic band structure is used to calculate the carrier densities, gain and spontaneous emission rates as a function of the quasi-Fermi level position, electron temperature and hole temperature [2]. The bulk thermal model solves the lattice heat equation (1), with a first order correction for the impact of thermal boundary resistance. Joule heating, Auger recombination, Peltier cooling, free carrier absorption and defect recombination mechanisms are included as bulk heat (\( H_{bulk} \)) sources. A four-temperature energy balance model has been introduced for each QW, which consists of energy balance equations for the electron (2), hole (3) and LO-phonon (4) energies. These equations are solved self-consistently with the other device equations to obtain the non-equilibrium LO phonon (T_{LO}), electron (T_{e}), hole (T_{h}) and lattice (T_{L}) temperatures. The 2D carriers in the QW are heated by carrier relaxation from the bulk states to the lasing states (H_{CAP}), free carrier absorption (H_{FCA}) and lateral joule heating (H_{J}). The QW carriers lose energy through the emission of photons via stimulated (R_{Stim}), spontaneous (R_{Spon}) recombination and via emission of acoustic phonon (\( \tau_{AC-eh} = 1 \text{ ns} \)) and LO-phonons (\( \tau_{LO-e} = 27 \text{ ps} \), \( \tau_{LO-h} = 0.07 \text{ ps} \)). The non-equilibrium LO-phonons have a finite life time (\( \tau_{LO-a} \)) and decay into acoustic phonons. The scattering time \( \tau_{LO-a} \) is calculated as a function of lattice temperature using equation (5) with \( v_{LO}^{0} = 8 \text{ ps} \) [3]. The energy pathways of the model are shown in figure 1. The QW carrier energy densities (U_{e/h}), average lasing energy (\( E_{\text{stim}} \)) and average spontaneous emission energy (\( E_{\text{spon}} \)) required for this model are calculated from the non-parabolic band structure (6-7), where \( N \) is the number of subbands.

\[
C_{L} \frac{dT_{L}}{dt} = \nabla k_{L} \nabla T + H_{bulk} + \left( U^{LO}(T_{LO}) - U^{LO}(T_{L}) \right) / \tau_{LO-a} + \left( U^{e}(T_{e}) - U^{e}(T_{L}) \right) / \tau_{AC-e} + \left( U^{h}(T_{h}) - U^{h}(T_{L}) \right) / \tau_{AC-h} + (U^{e}(T_{h}) - U^{e}(T_{L})) / \tau_{LO-e} + (U^{h}(T_{h}) - U^{h}(T_{L})) / \tau_{LO-h}
\]

\[
\frac{dU_{e}}{dt} = H_{cap}^{e} + H_{SRH}^{e} + H_{Auger}^{e} + H_{e}^{e} - \bar{E}_{e}^{\text{stim}} R_{Stim} - \bar{E}_{e}^{\text{spon}} R_{Spon} - \left( U^{e}(T_{e}) - U^{e}(T_{LO}) \right) / \tau_{LO-e} - (U^{e}(T_{h}) - U^{e}(T_{L})) / \tau_{AC-e} + (U^{e}(T_{h}) - U^{e}(T_{L})) / \tau_{e-h} + \left( U^{h}(T_{h}) - U^{h}(T_{L}) \right) / \tau_{e-h}
\]

\[
\frac{dU_{h}}{dt} = H_{cap}^{h} + H_{SRH}^{h} + H_{Auger}^{h} + H_{e}^{h} - \bar{E}_{h}^{\text{stim}} R_{Stim} - \bar{E}_{h}^{\text{spon}} R_{Spon} - \left( U^{h}(T_{h}) - U^{h}(T_{LO}) \right) / \tau_{LO-h} - (U^{h}(T_{h}) - U^{h}(T_{L})) / \tau_{AC-h} - (U^{e}(T_{h}) - U^{e}(T_{L})) / \tau_{e-h} - (U^{h}(T_{h}) - U^{h}(T_{L})) / \tau_{e-h}
\]

\[
\frac{dU^{LO}}{dt} = \left( U^{e}(T_{e}) - U^{e}(T_{LO}) \right) / \tau_{LO-e} + \left( U^{h}(T_{h}) - U^{h}(T_{LO}) \right) / \tau_{LO-h} - (U^{LO}(T_{LO}) - U^{LO}(T_{L})) / \tau_{LO-a}
\]

\[
\tau_{LO-a} = \frac{\tau_{LO}^{0}}{1 + 2[\exp(0.5\hbar \omega_{LO} / k_{B} T_{L}) - 1]} \quad [3]
\]

\[
\bar{E}_{e/h}^{\text{stim}}(h \omega) = \frac{\sum_{N} R^{n}_{stim}(h \omega, E, T_{e}, T_{h}) L(h \omega - E) EdE}{\sum_{N} R^{n}_{stim}(h \omega, E, T_{e}, T_{h}) L(h \omega - E) dE} \quad [7]
\]

\[
\bar{E}_{e/h}^{\text{spon}} = \frac{\sum_{N} R_{Spon}(E, T_{e}, T_{h}) EdE}{\sum_{N} R_{Spon}(E, T_{e}, T_{h}) dE} \quad [8]
\]

\[
U^{LO}(T) = \frac{\hbar \omega_{LO}}{2\pi} \int_{q_{xy}}^{q_{xy,max}} k_{xy} N(T) dq_{xy} \int_{-\delta_{y}/2}^{\delta_{y}/2} dq_{y} \quad [9]
\]

\[
N(T) = \frac{1}{e^{\hbar \omega_{LO}/kT} - 1} \quad [10]
\]
The energy density of the non-equilibrium phonon population is given by (9), where \( N(T) \) (10) is the occupational probability and \( \omega_{\text{LO}} \) is the LO phonon energy of 35 meV. Carrier-carrier scattering between the electron and hole populations is treated using the relaxation approximation with the scattering constant \( \tau_{\text{e-h}} = 5 \text{ ps} \). Electron/hole energy densities are calculated from the non-parabolic band structure and tabulated prior to simulation. This gives our approach the benefits of the accuracy provided by \( k.p \) band calculations and of the computational speed of a rate equation model.

3. Device

The device studied in this work is a double QW edge emitting dilute nitride laser diode, the layer structure of which is given in figure 2. (Only half of the device is shown and simulated because of its symmetrical nature.) The device is optimised for 10 Gb/s operation within the second telecommunications window at 1.3 \( \mu \text{m} \). The device is 300 \( \mu \text{m} \) long, with uncoated facets and a ridge waveguide (RW) width of 3.2 \( \mu \text{m} \). More details about these devices can be found elsewhere [1].

4. Results

A thermal profile, corresponding to a front facet power of 12 mW, including electron, hole, non-equilibrium LO phonon and lattice temperatures is plotted in figure 4. The full 2D lattice temperature profile obtained from this simulation is shown in figure 3.

Under the ridge, the phonon bottleneck can be seen to elevate the carrier temperature by around 7 K. This large bottleneck corresponds to high carrier injection rates. Further away from the ridge, where the injection current is less, the populations are in equilibrium. A set of L-I curves for different phonon lifetimes \( (\tau_{\text{LO-a}}) \) is shown in figure 5. At high injection currents, the phonon bottleneck raises the
carrier temperature by >15 K and causes a reduction of up to 1 mW in optical power. At lower injection currents, a small impact on the L-I curve is observed.

High carrier temperatures reduce the gain due to the spreading of the Fermi-Dirac distribution. Therefore, to achieve the same optical output power, a higher carrier density and increased injection current are required. When pumping the device harder, the bottleneck becomes more severe. This behaviour can be seen in figure 6, which plots the temperature increase due to the phonon bottleneck as a function of optical output power as for different external heatsink temperatures. A super-linear increase in the temperature caused by the more constricted phonon bottleneck can be seen at heatsink temperatures above 360 K. At lower heatsink temperatures (300-360 K), this behaviour is not observed because the LO-phonon decay time reduction as a function of temperature (through equation 5). Experimentally, the device shows a decrease in performance for heatsink temperatures above 360 K, which could be partially due to the narrower LO-phonon bottleneck.

A 1D time domain simulation at a bit rate of 10 Gb/s is shown in figure 7. The impact of including the non-equilibrium LO-phonons is to reduce the peak optical power due to the elevated carrier temperature and also to delay the peak of the optical pulse. The non-equilibrium LO-phonon population increases its temperature by 3 K within the width of the modulating pulse.

5. Conclusion

The impact of hot phonons on an edge-emitting dilute nitride laser has been investigated. The bottleneck is most significant under the ridge where the injection current is largest. At heatsink temperatures above 360 K, the impact of the phonon bottleneck increases steadily. At high injection currents, the phonon bottleneck is found to increase the carrier temperatures by up to 10 K, with a corresponding decrease in optical power of up to 1 mW. Modulation of the LO-phonon population is observed under high speed modulation. The impact of hot phonons in dilute nitride devices is particularly large due to the large conduction band offset cause by the interaction of the conduction band wave function with the nitrogen level. In order to accurately model the modulation response and thermal rollover in dilute nitride devices, it is essential to include hot phonon effects in device models.

References

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