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Quantum cascade laser modeling in the terahertz range and investi-gating the effect of temperature on its characteristics

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Abstract:

Quantum cascade lasers (QCLs) represent a highly innovative design in quantum engineering and demonstrate how artificial materials with tailored properties can be realized through quantum design. Their inherent quantum nature conceptually affects their core concepts. QCLs exhibit intrinsic linewidths that approach the quantum limit and are locked into their own states. Minimized metrology is also effective within boundary frequency domains. In this paper, the effect of temperature on the characteristics of GaN/AlGaN and GaAs/AlGaAs quantum cascade lasers in the terahertz range is done based on rate equations. The temperature dependence of the phonon sputtering rate, changes in line width, and lifetime of thermionic emission have been investigated, and the effect of temperature on the photon lifetime in two materials, GaAs and GaN, has also been investigated and compared, and the effect of temperature on the output photon density, power and gain. The unsaturated mode and its dependence on temperature show that GaN material can work at high temperatures.

Keywords: Quantum cascade laser; Laser rate equation; Laser temperature effect; Photon lifetime

Introduction

After the invention of QCL terahertz [1] several issues were determined as the main challenges in solving this type of terahertz sources. The inversion population at low transmission energies associated with terahertz frequencies and low-loss design for proper optical mode confinement have been the main challenges. In a Terahertz QCL, since the intersubband transition energy is lower than the LO phonon energy, therefore, the emission probability of polarized optical phonons is significantly reduced, which increases the lifetime of the upper laser. These conditions are suitable for efficient population inversion, however, other non-radiative mechanisms such as electron-electron scattering, electron-impurity scattering, or electron-acoustic phonon scattering limit the slow performance. It is also possible to suppress the red-polarized optical phonon emission by slowing down the terahertz operation and quantum cascade laser, while this is not easily applicable in electron-electron scattering. Because this process depends on things like doping sheet density and multiple.

Quantum technology (QT) platforms capable of exploiting non-classical states of light or atoms are ultimately designed to target applications in various strategic fields; simulation and calculations, communications, measurement, and metrology. QT's small, compact, and integrated geometries successfully operate in the visible and near-infrared electromagnetic fields. However, the migration of QT to the terahertz (THz) frequency domain is fraught with substantial obstacles, because the production, manipulation, and detection of small packets of light are generally technically challenging when the energies of the photons involved are very small (< 10 MeV) [2].

Quantum cascade lasers have gained more attention due to their better efficiency. One of the quantities that cause unwanted effects in such lasers is the effect of spontaneous emission, which causes changes in response time, output photon density, and out-put power. According to the type of formation of AlGaAs/GaAs material and the study of theoretical and laboratory results [3] as well as the numerical results obtained from [4] that show the effect of dynamic parameters on the performance of quantum cascade lasers. These studies have made a step to improve the laser performance, reduce the threshold current, and increase the output power. High peak and room power performance in the far infrared region is reported for two-channel quantum cascade lasers (QCLs) that are seamlessly integrated on a single silicon substrate. A 55-step laser structure with AlInAs/InGaAs core and InP cladding was grown by molecular beam epitaxy directly on an 8-inch [5].

Rate equations

The rate equations used in this model include the number of electrons in the fourth layer N_4, for the third layer N_3 and for the second layer N_2, and the number of photons in the cavity $N_{ph1,2}$, and the corresponding rate equations (1-4) are written as follows:

$$
\begin{aligned}
\frac{dN_4}{dt} &= \eta_1\frac{NI}{e} - \frac{N_4}{\tau_{4T}} - \Gamma\frac{\acute{c}\sigma_{43T}}{V}(N_4-N_3)N_{ph1}\\
\frac{dN_3}{dt} &= (1-\eta_1)\frac{NI}{e} + \frac{N_4}{\tau_{4T}} - \frac{N_3}{\tau_{3T}} + \Gamma\frac{\acute{c}\sigma_{43T}}{V}(N_4-N_3)N_{ph1}\\
\frac{dN_2}{dt} &= \eta_2\frac{NI}{e} - \frac{N_2}{\tau_{2T}} - \Gamma\frac{\acute{c}\sigma_{21T}}{V}(N_2-N_1)N_{ph2}\\
\frac{dN_1}{dt} &= (1-\eta_2)\frac{NI}{e} + \frac{N_2}{\tau_{2T}} - \frac{N_1}{\tau_{1T}} + \Gamma\frac{\acute{c}\sigma_{21T}}{V}(N_2-N_1)N_{ph2}\\
\frac{dN_{ph1}}{dt} &= N\Gamma\frac{\acute{c}\sigma_{43}}{V}(N_4-N_3)N_{ph1} - \frac{N_{ph1}}{\tau_{ph1}} + N\beta\frac{N_4}{\tau_{sp1}}\\
\frac{dN_{ph2}}{dt} &= N\Gamma\frac{\acute{c}\sigma_{21}}{V}(N_2-N_1)N_{ph2} - \frac{N_{ph2}}{\tau_{ph2}} + N\beta\frac{N_2}{\tau_{sp2}}
\end{aligned} \tag{1}
$$

In the above equations, η_1, I, $\Gamma v \tau_p$ are the injection efficiency of input current into the active region, input current density in kA/cm^2, confinement factor, and photon lifetime respectively, τ_i are carrier scattering times $\acute{c} = c/n_{eff}$ is the velocity of light in the medium, where n_{eff} is the effective refractive index of the cavity and c represents the light speed in a vacuum;

β is spontaneous emission factor Γ and σ_{32} are the mode confinement and the spontaneous emission factor, respectively.

$$
\sigma_{32}(T) = \frac{4\pi e^2 z_{32}^2}{\eta_{eff}\varepsilon_0\lambda(2\gamma_{32})} \tag{2}
$$

In the above equation, ez_{32} denotes the dipole matrix element; λ is the emission wavelength, ε_0 represents the permittivity of the vacuum coefficient, and $2\gamma_{32}$ is the full width at the half maximum.

The photon lifetime τ_p in the cavity equals, $1/\tau_p = \acute{c}(\alpha_w + \alpha_m)$ where α_w denotes the wave-guide losses in the cavity, and α_m is the losses mirror.

Fig. 1 shows the number of photons for emission wavelengths $\lambda_1 = 33$ µm and $\lambda_2 = 52$ µm.

0.1 Output power

The temperature-dependent power equation from Eq. (3), which is the relationship between the output power and the number of photons, is as follows [6]:

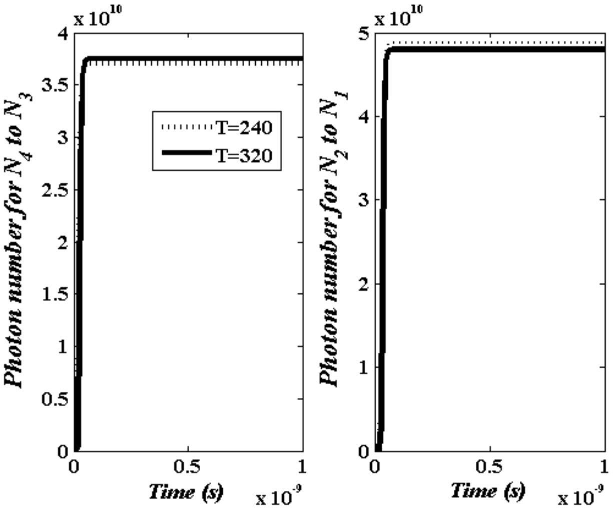

Figure 1. Density of photons.

$$
P_{out1}(T) = \eta_0\frac{\hbar\omega N_{ph1}}{\tau_{ph1}} \tag{3}
$$

η_0 (coupling coefficient) is output power and $\hbar\omega$ is the emitted photon energy, and η_0 is the output power coupling coefficient which can be obtained from the following equation which are calculated from equation (4).

$$
\eta_0 = \frac{1}{2}\frac{\alpha_m}{\alpha_w + \alpha_m} \tag{4}
$$

Discussion and numerical results

In this model, we have studied the temperature dependence of the gain of the un-saturated mode, the lifetime of the carriers, and the output power that came from the source [7]. The values of the parameters used in the simulation are taken from [7–10].

In Fig. 2, the photon lifetime of two different materials, GaAs and GaN, and their temperature dependence are compared. This result shows the effect of temperature on carrier

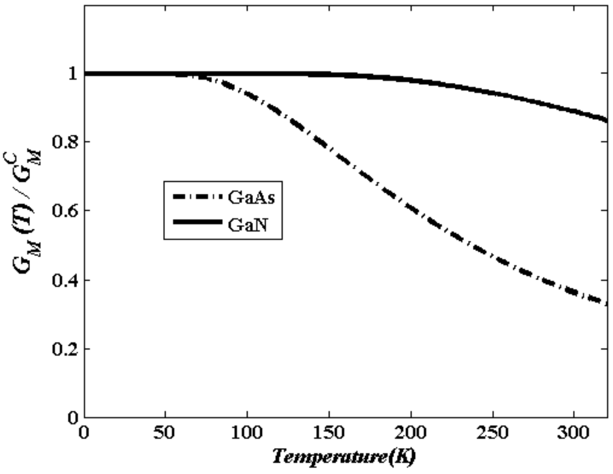

Figure 2. Gain of unsaturated mode for two materials GaAs and GaN and their dependence on temperature.

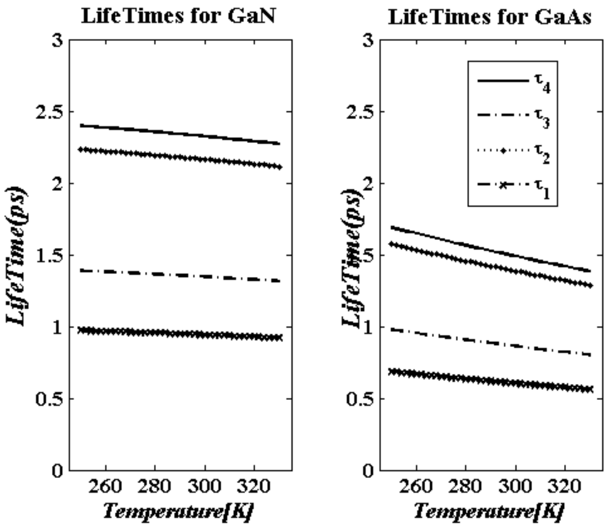

Figure 3. Photon lifetime and its temperature dependence.

lifetime for two materials GaN and GaAs (for different τ). It is clear that first the carrier lifetime decreases with increasing temperature (for both materials) and then the intensity of these changes is less for GaN than for GaAs [1, 8, 11]. Fig. 3 shows the temperature dependence of unsaturated mode gain for two materials GaAs and GaN. This result shows the unsaturated mode gain for GaN and GaAs. The slope of changes shows the temperature stability of GaN compared to GaAs at high temperatures [9, 10].
Fig. 4 shows the effect of temperature on output power in terms of injection current changes. This figure shows the effect of temperature on output power in terms of injection current changes for GaN for emission wavelength $\lambda = 33$ µm. Looking at the figure, it is clear that firstly, the threshold current of GaN is much lower. Secondly, by increasing the injection current (after the threshold current), the dependence of the GaN laser out-put power on temperature changes is much less. Thirdly, the value of the threshold current in GaN shows less dependence on temperature [11, 12].

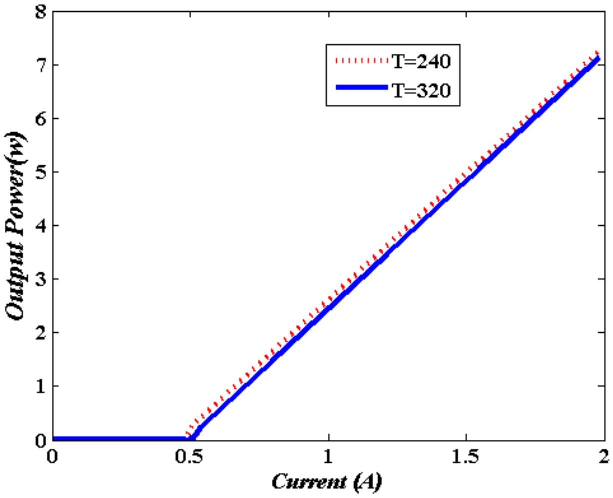

Figure 4. Showing the effect of temperature on output power.

Conclusion

In this model, the effects of temperature on spontaneous emission, output power, unsatu-rated mode gain, and carrier lifetime have been investigated. The simulation results obtained from the rate equations coded in MATLAB software and the temperature dependence of the phonon scattering rate, changes in line width, and a lifetime of thermionic emission were investigated. Also, the effect of temperature on photon lifetime in two materials, GaAs, and GaN has been investigated and compared. In addition, the effect of temperature on output photon density, power, and gain of unsaturated mode and its dependence on temperature show that GaN material can work at high temperatures. As a result, it is suitable to use GaN material instead of GaAs due to its high optical phonon energy, which is more thermally stable.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] E. Lee, K. Moon, I.-M. Lee, H.-S. Kim, D. W. Park, J.-W. Park, D. H. Lee, S.-P. Han, N. Kim, and K. H. Park. "Semiconductor-based terahertz photonics for industrial applications.". *Journal of Lightwave Technology*, 36(2):274–283, 2017.
DOI: https://doi.org/10.1109/JLT.2017.2786260.

[2] M. S. Vitiello and P. De Natale. "automatic detection of schizophrenia by applying deep learning over spectrogram images of eeg signals.

[3] A. V. Babichev, A. S. Kurochkin, E. C. Kolodeznyi, A. V. Filimonov, A. A. Usikova, V. N. Nevedomsky, et al. "Heterostructures of single-wavelength and dual-wavelength quantum-cascade lasers.". *Semiconductors*, 52:745–749, 2023.
DOI: https://doi.org/10.1134/S1063782618060039.

[4] G. Strasser, S. Gianordoli, L. Hvozdara, et al. "Intersubband and interminiband GaAs/AlGaAs quantum cascade lasers.". *Physica E: Low-dimensional Systems and Nanostructures*, 7:1–7, 2000.
DOI: https://doi.org/10.1016/S1386-9477(99)00278-7.

[5] E. Cristobal, M. Fetters, A. W. K. Liu, J. M. Fastenau, et al. "High peak power quantum cascade lasers monolithically integrated onto silicon with high yield and good near-term relia-bility.". *Applied Physics Letters*, 122(14), 2023.
DOI: https://doi.org/10.1063/5.0149072.

[6] A. Hamadou, J.-L. Thobel, and S. Lamari. "Modelling of temperature effects on the characteristics of mid-infrared quantum cascade lasers.". *Optics Communications*, 281(21):5385–5388, 2008.
DOI: https://doi.org/10.1016/j.optcom.2008.07.036.

[7] V. Ortiz, C. Becker, H. Page, and C. Sirtori. "Thermal behavior of GaAs/AlGaAs quan-tum-cascade lasers: effect of the Al con-tent in the barrier layers..". *Journal of Crystal Growth*, 251(1-4):701–706, 2022.
DOI: https://doi.org/10.1016/S0022-0248(02)02507-1.

[8] W. Terashima and H. Hirayama. "Spontaneous emission from GaN/AlGaN terahertz quantum cascade laser grown on GaN substrate.". *Physica Status solidi C*, 8(7-8):2302–2304, 2011.
DOI: https://doi.org/10.1002/pssc.201000878.

[9] D. P. Lozano, S. Couet, C. Petermann, G. Hamoir, J. K. Jochum, T. Picot, E. Menéndez, K. Houben, et al. "Experimental observation of electron-phonon coupling enhancement in Sn nan-owires caused by phonon confinement ef-fects.". *Physical Review B*, 99(6):064512, 2019.
DOI: https://doi.org/10.1103/PhysRevB.99.064512.

[10] G. Sun and R. A. Soref. "Design and simulation of a GaN/AlGaN quantum cascade laser for terahertz emis-sion.". *Microelectronics Journal*, 36(3-6):450–452, 2005.
DOI: https://doi.org/10.1016/j.mejo.2005.02.044.

[11] N. D. Vy and N. D. Hien. "Influence of interface modes compared to confined modes on phonon-assisted cy-clotron resonance effect in quantum wells.". *Superlattices and Microstructures*, 145:106630, 2020.
DOI: https://doi.org/10.1016/j.spmi.2020.106630.

[12] J. Li, T. Wan, and C. Chen. "Two-phonon-resonance terahertz quantum cascade laser based on GaN/AlGaN material system.". *Semiconductor Science and Technology*, 34(7):075018, 2021.
DOI: https://doi.org/10.1088/1361-6641/ab1401.