Thermal effects in quantum cascade lasers at $\lambda \sim 4.6 \, \mu m$ under pulsed and continuous-wave modes

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Abstract The thermal effects in InGaAs/InAlAs quantum cascade lasers (QCLs) emitting at $\lambda \sim 4.6 \, \mu m$ under pulsed and continuous-wave (CW) modes using a three-dimensional (3D) heat dissipation model were investigated. Based on the experimentally measured results, the thermal characteristics were theoretically analyzed for various device and heatsinking structures. Also, the heat accumulation effects and dissipation processes were studied in detail under pulsed operation. High cooling efficiencies were achieved by a relatively fast heat diffusion rate from the active core region for the epilayer-down bonded single ridge waveguide buried heterostructure (BH) with a thick electroplated Au around the laser ridge. A further improvement was made by the use of InP embedding layer. In CW mode, the thermal conductance ($G_{th}$) value of 445 W/(K cm$^2$) at 298 K was obtained for the epilayer-down bonded double-channel ridge waveguide QCL with AlN submount, which indicates a reasonable consistency with the available experimental data. By optimizing the device and heatsinking structures, the $G_{th}$ was improved to a high value of 673 W/(K cm$^2$) at 298 K for the epilayer-down bonded single ridge waveguide BH QCL with InP embedding layer on diamond submount in CW mode.

1 Introduction

High-performance short- and mid-infrared quantum cascade lasers (QCLs) are very important for various applications such as trace gas sensing, free space communications, and photoacoustic spectroscopy [1]. For practical applications, the high power and high wall-plug efficiency are absolutely required in both pulsed operation with a high duty cycle and continuous-wave (CW) operation at high operating temperature. Recently, the QCLs with a high wall-plug efficiency, which emitted watt-level output powers mainly at wavelengths around $\lambda \sim 4.6 \, \mu m$, were demonstrated in pulsed and CW operations at room temperature, thanks to a number of significant advances in material growth and fabrication processes [2–5]. Despite important progress in recent years, the device performance is still restricted by strong local heating effect in active core region. Typically, the active core region of QCLs consists of 30–70 cascaded stages of nanometre-sized thin-film multilayers. The QCL is inherently operated under high driving voltage and current, and the large electrical input power induces a strong local heating. To achieve a high device performance, the thermal properties of QCLs should be adequately managed and analyzed.

The QCLs can be thermally characterized from the thermal measurements and simulations in pulsed and CW modes. The transient thermal analysis is very useful to understand the thermal behaviour of QCLs. Although the thermal analysis studies were mainly reported in CW mode [6–10], there has been relatively little work on the thermal analysis in pulsed mode [11, 12]. Moreover, many research studies have been concentrated on the experimental analysis. In order to obtain a deep understanding of efficient heat managements in QCLs, the thermal properties in pulsed and CW modes should be systematically analyzed for various device structures and heatsinking schemes. In this paper, the thermal characteristics of InGaAs/InAlAs QCLs operating at $\lambda \sim 4.6 \, \mu m$ were theoretically investigated in pulsed and CW operations for different device structures and bonding schemes, in comparison with experimentally estimated re-
sults. For various device structures, the thermal properties were calculated by a three-dimensional (3D) thermal analysis, based on the experimentally measured heat source densities.

2 Thermal modelling

Under pulsed and CW operations, the theoretical thermal analysis was carried out for the previously measured device structures of Ref. [2]. Figure 1 shows the schematic diagram of double-channel (DC) ridge waveguide InGaAs/InAlAs QCL structure, operating at $\lambda \sim 4.6 \mu m$, with an epilayer-up bonding scheme. After a 300-nm thick InP buffer layer on n-InP substrate, the 30-period active/injector region (total thickness: $\sim 1.47 \mu m$) as an emitting region was sandwiched between a lower 300-nm and an upper 300-nm thick n-InGaAs layer. The active/injector region was composed of compressive In$_{0.666}$Ga$_{0.334}$As wells and tensile In$_{0.341}$Al$_{0.659}$As barriers. And then, the upper cladding and contact layers consisted of a 2-µm thick n-InP and a 1-µm thick n$^+$-InP, respectively, were followed. For device structure, the wafer samples were processed into the DC ridge waveguide QCLs with an optimized ridge width of 10 µm. A 400-nm thick SiO$_2$ layer was used as an electrical insulator. The top and bottom Ti/Au contact metals were formed, and a 5-µm thick Au layer was employed around the laser ridges. The thinned wafer thickness was $\sim 100 \mu m$. For fabricated QCLs, the devices were cleaved to laser bars with different cavity lengths. The high-reflectivity (HR) coatings on the back facet to reduce the mirror loss of lasers were performed. The QCLs were bonded epilayer-up or -down on a copper heatsink with indium (In) solder. For epilayer-down bondings, the AlN submount was employed between the device and heatsink. The more detailed device structure and experimental methods were also described in Ref. [2].

The thermal analysis was conducted by a 3D anisotropic heat dissipation model using commercial COMSOL software, based on the finite-element method. Through the thermal simulation, the maximum internal temperature ($T_{max}$), temperature distribution, heat flux, and thermal conductance ($G_{th}$) were obtained in pulsed and CW operations. The transient heat transfer equation is given by [13]

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q,$$ (1)

where $\rho$ is the density, $C_p$ is the specific heat, $t$ is the time, $T$ is the temperature, $Q$ is the heat source density, and $k$ is the thermal conductivity of constituent materials. For steady-state operation (i.e., CW operation), (1) is changed into $Q = -\nabla \cdot (k \nabla T)$. Table 1 shows the material parameters of the DC ridge waveguide InGaAs/InAlAs QCLs operating at $\lambda \sim 4.6 \mu m$. For more reasonable thermal analysis, the temperature-dependent thermal conductivities were used in this simulation. The specific heat was considered as a constant value because it is temperature-independent above room temperature [14]. Also, all the layers except for the active core region were considered to be isotropic materials. In the active core region, we took into account an anisotropic thermal conductivity ($k_\parallel \neq k_\perp$). Due to large number of interfaces in active core region, the in-plane $k_\parallel$ and cross-plane $k_\perp$ values have smaller ones than those of the bulk materials [15, 16]. Thus, the in-plane $k_\parallel$ value was estimated to be 75% of the weighted average value in the active core constituent materials (i.e., $k_\parallel = 0.75 \sum_i d_i/(d_{tot} R_i)$) [6]. The cross-plane $k_\perp$ value was extracted by fitting the simulation results obtained from a 3D anisotropic heat dissipation model, and it was considered to be $k_\perp = \sim 2.3 \pm 0.2 \ W/(m \cdot K)$ at heatsink temperatures of 298–338 K.

3 Results and discussion

Figure 2 shows the heat source density as a function of heatsink temperature in CW mode for HR coated DC QCLs. The heat source was considered to be the electrical power dissipated as heat in the active core region. Since the wallplug efficiency is very low (<1%) below threshold, we assumed that all input power would be dissipated as heat. From experimentally measured current-voltage data, the heat source densities ($Q$) at threshold can be calculated by

$$Q = \frac{I_{th} V_{th}}{U},$$ (2)

where $I_{th}$ is the threshold current, $V_{th}$ is the threshold voltage, and $U$ is the volume of active core region. Generally, the mirror loss of laser is increased as the cavity length becomes shorter. The reduction of cavity length leads to the higher threshold current and thus the $Q$ values are gradually increased. Also, a further increment of $d_{th}$ is caused by the raised heatsink temperature [2]. For epilayer-up bondings, the heat source density was increased for shorter cavity, and it was gradually increased with raising the temperature of heatsink. In the case of 4-mm long cavity, the $Q$ value was approximately $1.28 \times 10^{14} \ W/m^3$ at 298 K in CW mode and increased up to $2.05 \times 10^{14} \ W/m^3$ at 348 K due to the heating effect when the heatsink temperature increases. For the epilayer-up bonded 1.5-mm long QCL, the $Q$ value was further increased to $2.23 \times 10^{14} \ W/m^3$ at 298 K. The epilayer-down bonded QCL exhibited slightly lower $Q$ values compared to those of epilayer-up bonded one. The obtained $Q$ values were $1.27 \times 10^{14} \ W/m^3$ and $1.92 \times 10^{14} \ W/m^3$ at 298 K and 348 K, respectively. Similarly, in pulsed mode, the $Q$ values were estimated for epilayer-up bonded DC QCLs with different cavity lengths. The inset shows the heat source density as a function of cavity length for epilayer-up bonded QCLs in pulsed mode at 298 K.