Novel Heat Removal Waveguide Structure for High Performance Quantum Cascade Lasers

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Abstract: We study the heat removal capability of different core structures in quantum cascade lasers. We find that due to non-isotropic conductivity, core structures with higher depth dissipate heat faster than the conventional higher-width structures.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (140.6810) Thermal effects

1. Introduction

Intense heat is generated within the core of a quantum cascade laser (QCL) due to the high threshold current required for lasing. Specially, for continuous-wave (CW) and high duty-cycle operation, the device active region can be at a considerably higher temperature than the heat sink. Internal heating has a significant effect on device performance independent of the material system used and the wavelength range covered [1]. At higher temperature, more carriers in the device are thermally activated into higher energy, continuum-like states and also back into the lower laser level, resulting a reduction of the population inversion between the lasing levels that adversely affects the gain and the wall-plug efficiency. The wall-plug efficiency depends inversely on ΔT, the temperature difference between the heat sink and the core [2]. More than a decade after first being demonstrated [3], the wall-plug efficiency of QCLs is not in the range required for many applications. Therefore, the goal of this work is to find a core structure that can manage heat more efficiently.

Low thermal conductivity of the materials used in the core of the QCLs, usually InAlAs/InGaAs, makes it difficult to remove heat at a rapid rate. Moreover, the thermal conductivity of the multilayered quantum heterostructure core is anisotropic and both the in-plane ($\kappa_{\|}$) and cross-plane ($\kappa_{\perp}$) conductivity are much lower than the bulk values of the constituent materials [4]. Additionally, $\kappa_{\perp}$ is significantly lower than $\kappa_{\|}$. Therefore, heat dissipation is much slower in the direction of the growth axis than in the lateral direction. As QCLs generally consist of 30 ~ 35 periods, the depth of the core is about 3 μm ~ 4 μm. To confine the emitting optical mode in the mid-infrared range, the width has to be higher ($\geq$7 μm), so that the width is greater than the total height of all the heterostructure layers. Since $\kappa_{\perp}<\kappa_{\|}$, this type of core structure cannot remove heat efficiently. On the other hand, if we increase the number of periods to ~100, the core structure is about ~7 μm and we etch the core to a 3 μm width, the total height becomes greater than the width. Since $\kappa_{\|}$ is much higher, this type of structure can remove the heat very efficiently.

2. Thermal Modeling

The steady-state thermal model is based on the heat diffusion equation in two dimensions [1]

$$-\nabla\cdot\left[\kappa(x,y,T)\nabla T(x,y)\right]=Q(x,y) \tag{1}$$

where T is the temperature (K), κ is the thermal conductivity (W/m-K), and Q is the power density of the heat source (W/m^2). As κ depends on temperature, calculation of T requires an iterative approach. We solve equation (1) using the finite element method.

We use the thermal conductivities reported in [4]. Since $\kappa_{\|}$ and $\kappa_{\perp}$ have only been reported up to 400 K, we use extrapolated values beyond 400 K. The conductivity $\kappa_{\|}$ is estimated by taking 75% of the weighted conductivity average of bulk InAlAs/InGaAs. The ratio $\kappa_{\|}/\kappa_{\perp}$ is not known exactly at high temperature. We estimate $\kappa_{\|}/\kappa_{\perp}$ = 5 for $T \geq$ 300 K.

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3. Simulation Results

We determine the internal heating for InAlAs/InGaAs QCLs with different core structures. We are modeling a QCL that is grown lattice-matched to the InP substrate. The InP is regrown above the core to increase the heat removal from around the core due to the high thermal conductivity of InP compared to that of ternary $Ga_xIn_{1-x}As$ [5,6]. The cavity length of the laser is 3 mm, and it is designed to emit a wavelength of 8 μm. Thick gold layer is electroplated on the top and the laser is mounted on the heat sink with the epi-layer down. So, we assume that heat is dissipated only through the gold layer. The heat sink is at room temperature. The laser operates CW and dissipates 10 W of power.

We calculate the steady-state temperature build-up and heat flux for QCLs with different core structures and the results are given in Figs. 1 and 2. Fig. 1 illustrates the thermal operation of QCLs using conventional (7 μm × 3 μm) and proposed (3 μm × 7 μm) core structures. We see a maximum of ~251 K rise over the sink temperature in conventional core structures. By contrast, we find ΔT is only ~95K in the proposed core structure. The increase in the number of layers contributes to this efficient heat removal. Thermal performance can further be managed by growing InP layers in the core region (proposed by Professor Gmachl's group in Princeton University for conventional core structures). These InP layers can help in heat removal and thus act as heat pipes. We simulate the effects of InP heat pipes in the core structures discussed above. InP heat pipes can not be too thick; otherwise, the optical mode confinement deteriorates. We assume heat pipes that are 0.1 μm thick, and so do not affect the optical mode confinement significantly. The steady-state peak temperature build-up in the two types of core structures without and with heat pipes are summarized in Fig. 2. Temperature rise is greatly reduced with the use of InP heat pipes in conventional core structures. We see that peak temperature drops from 551 K to 418 K when four heat pipes are used. However, by using a higher depth core structure, the temperature can be reduced even further, to 395 K.

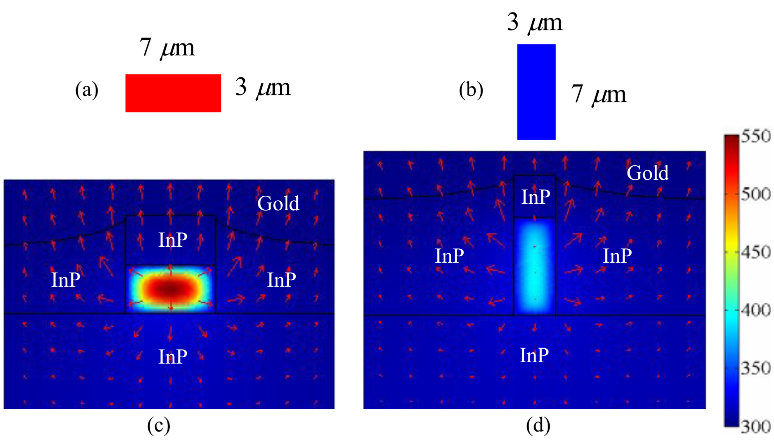

Fig. 1. Core structures (a) Conventional (b) Proposed, Thermal profiles - surface: Temperature (K) and arrow: Heat flux (W/m^2) in QCLs with (c) conventional (d) proposed core structure.

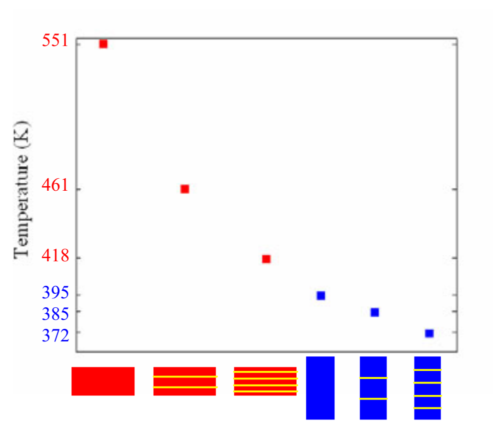

Fig. 2. Maximum temperature rise in different core structures.

4. Conclusion

We report that a dramatic reduction in the maximum temperature rise can be achieved in QCLs by changing the core structure. Higher depth (7 μm) core with a reduced width dissipates heat much faster than does a conventional lower depth (3 μm) core structure with a large width since $\kappa_{\parallel}/\kappa_{\perp}>>1$. Additionally, InP layers can help in extracting heat from the core.

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