Thermal and electronic analysis of GaInAs/AlInAs mid-IR QCLs

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***Abstract*— We report on the measurement of the lattice and electronic temperatures and on the electron lattice coupling in strain-compensated GaInAs/AlInAs quantum cascade lasers operating in the first atmospheric window and grown with interdiffusion at the interfaces. The facet temperature profiles have been measured by means of photoluminescence spectroscopy and used to evaluate the in-plane ($k_{\|}$) and the cross-plane ($k_{\perp}$) thermal conductivities of the active region. An extensive comparison with the $k_{\perp}$ values of QCLs based of different material systems demonstrates the superior thermal performance of the investigated devices. Comparison between the calculated thermal performance of QCLs sharing the same active region structure but different heat-sinking approaches demonstrate the advantages of the planarization of QCLs with high-K dielectric materials in terms of device thermal management**

***Index Terms* —quantum cascade lasers, photoluminescence, thermal properties, electronic properties**

I. INTRODUCTION

Quantum cascade lasers (QCLs) are unipolar semiconductor devices based on the engineering of electronic wavefunctions in multiple quantum well structures. Although high performance and continuous wave (CW) operation at room temperature has been reported for GaInAs/AlInAs-based QCLs in the wavelength range (4.3 μm – 9 μm), [1, 2] the widespread application of these mid-IR sources still demands significant improvement in the thermal management. Understanding the heat dissipation processes and their interplay with the electrical and optical characteristics are key issues for the realization of quantum cascade lasers (QCLs) with improved thermal management. Heat extraction from QCLs is difficult because of two main reasons: i) the high electrical power at the laser threshold; ii) the large device thermal resistance, mainly due to the anisotropic thermal conductivity of the multi-layered active region. Also the assessment of hot electron distributions in QCLs is a basic guide for the design of improved structures aiming at high temperature operation.

To address these topics we developed a band-to-band photoluminescence technique to determine simultaneously the the electronic temperature and the local lattice temperature in operating QCLs. Using the latter data as inputs we validated a two–dimensional anisotropic thermal model and extracted the heat dissipation patterns and the in-plane and the cross-plane active region thermal conductivities [3, 4].

We will present here an analysis of the electronic and thermal properties on strain compensated InGaAs/AlInAs QCLs operating at 4.78 μm, grown by employing InAs and AlAs (0.2 nm) δ-layers grown by molecular beam epitaxy only in the active region of the device with the aim to increase the conduction band discontinuity in the active layers and to include interdiffusion at the interfaces [5].

The first measurement of the electronic and lattice temperature and of the electron-lattice coupling constant in InGaAs-AlInAs based QCLs will be reported. The device thermal resistance will be extracted from the experimental data together with the anisotropic cross-plane component of the active region thermal conductivity.

In the lattice temperature range 60K-150K, we measured $k_{\perp}$ = 2.0 ± 0.1 W/(K×m) [5]. Also from our model we demonstrated that in the temperature range 80K-250K, $k_{\perp}$ monotonically increases with temperature and remains one order of magnitude smaller than the thermal conductivities of bulk constituent materials. A detailed comparison in terms of electron-lattice coupling, $k_{\perp}$ values and thermal boundary resistances between QCLs based on different material systems will be finally reported.

On the basis of the obtained results and using the 2D thermal model as a workbench, we have compared the thermal properties of devices sharing the same core configuration, but different heat sink processing technologies. Our calculations

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demonstrate that the planarization of QCLs with high-K dielectric materials with good thermal conductivity can give a comparable or better thermal performance with respect to buried heterostructures, by means of an easier processing [6].

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