Interferometric Temperature Mapping of GaAs-based Quantum Cascade Laser

C. Pflügl, M. Litzenberger, W. Schrenk, D. Pogany, E. Gornik and G. Strasser
Institute of Solid State Electronics, TU Vienna, Austria

Quantum cascade lasers (QCLs) based on intersubband / interminiband transitions in GaAs/AlGaAs are unipolar semiconductor lasers [1], [2]. Compared to InP-based QCLs ([3] and references within), GaAs-based QCLs offer the advantage of higher flexibility in the engineering of the electronic states. In spite of the improvements concerning output power [4], threshold current [5], single mode operation and maximum operating temperature [6] their performance is still limited by strong heating of the active region due to poor heat dissipation. Improving the lasers with respect to better thermal characteristics requires knowledge about the thermal dynamics in the laser under operation.

We want to report on a technique, namely the interferometric thermal laser mapping technique, which we used to investigate GaAs-based QCLs under operation. Comparing the experimental results with a thermal model enables to determine the heat distribution of the working devices and reveals the heat conductivity of the multilayered active region.

An infrared laser probe beam (wavelength of 1.3 µm, well below the GaAs bandgap), is directed to the sample from the device backside, passes through the substrate and laser active area and is back reflected on the surface metallization. The current-induced heating causes a temperature increase in the active region, which induces changes in the semiconductor refractive index. The resulting phase shift, which is detected interferometrically, provides quantitative information on the thermal dynamics [7], [8].

The investigated QCL has an active region consisting of 50 periods of a chirped $Al_{0.45}Ga_{0.55}As$ /GaAs superlattice. This active region is embedded into a double plasmon enhanced waveguide. Ridge waveguides with a width of 10 µm are fabricated by etching 10 µm trenches. The extended TiAu contacts are insulated with SiN. The length of the laser is 1.3 mm.

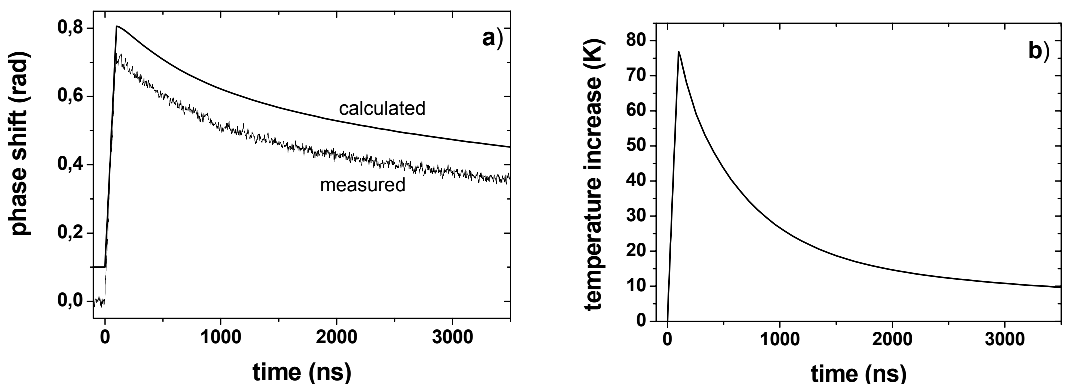

Fig. 1: (a) Calculated and measured phase shift in the middle of the laser ridge. The calculated graph is shifted by 0.1 rad for clarity. (b) From the phase shift extracted temperature increase in the middle of the active region.

We measured the transient phase shift during pulsed mode operation at room temperature, with a typical pulse length for GaAs based QCLs of 100 ns. The time evolution of the phase shift in the middle of the laser ridge (see Fig. 1 (a)) can be used to determine the anisotropic heat conductivity of the multilayered active region, $k_{ar}=(k_{||}, k_{\perp})$, where $k_{||}$ is the in-plane heat conductivity and $k_{\perp}$ the cross-plane component perpendicular to the layers. For all parameter in this model standard literature data are used except the anisotropic heat conductivity of the active region, which was fitted. A best fit was obtained with an anisotropic heat conductivity $k_{||}$ = 0.25 W/Kcm and $k_{\perp} \approx$ 0.015 W/Kcm [9]. After the heating during the pulse (t < 100 ns) the first strong cooling is determined by the in-plane heat conductivity. After the in-plane heat fluxes are mostly saturated the further cooling depends on the low cross-plane heat conductivity. This model also reveals the temperature distribution of the working devices. Figure 1 (b) shows the calculated temperature increase in the middle of the active region. The maximum temperature increase in the active region at the end of the pulse, we found to be 77 K at an applied current of 3.1 A corresponding to a dissipated power in the active region of 63 W (1.24 W/cm^3) during the pulse.

The reduced in-plane heat conductivity compared with the weighted average of its constituents (k = 0.31 W/Kcm [10]) can be explained by partly diffusive scattering of the phonons at the interfaces in the multilayered active region. The cross-plane conductivity was found to be much smaller than the heat conductivity of an $Al_{0.17}Ga_{0.83}As$ alloy (k = 0.18 W/Kcm [10], the average Al-content of the investigated active region is 17 %). In our superlattice structure the width of the single layers is in the range of a few nm and thus is much smaller than the mean free path of thermal phonons in GaAs at 293 K ($\Lambda \approx$ 50 nm [11]). In this case the heat conductivity is no longer determined by the properties of the involved materials but rather it must be considered that the effect of the superlattice is to modify the phonon-dispersion relation [12]. This crucial difference of the two components shows that the best way to improve the lasers with respect to a better thermal behavior is to support the in-plane fluxes. This can be done e.g. by fabricating the lasers as buried heterostructures or thicker gold layers in the trenches.

In conclusion, we have shown that the presented technique is a valuable tool to investigate the thermal dynamics in GaAs-based QCLs. Comparing the experiment with a thermal model enables us to extract the anisotropic heat conductivity of the multilayered active region as well as the temperature distribution in the working devices. The ratio of the two components of the heat conductivity $k_{||}/k_{\perp}$ was found to be in the range of 15-20. The maximum temperature increase in the investigated active region is up to 80 K depending on the applied current.

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