Temperature increase within quantum-cascade lasers originating from their incomplete soldering

Robert P. Sarzała,* Michał Wasiak, and Włodzimierz Nakwaski

Photonics Group, Institute of Physics, Technical University of Lodz, ul. Wolczanska 219, 90-924 Lodz,

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Abstract—Thermal and electrical properties of the semiconductor quantum-cascade laser are investigated with the aid of an finite-element numerical model. Optimal parameters of the solder and contact layers have been determined. A dramatic impact on the heat-flux generation and spreading within the volume of the laser with an incomplete soldering of the bottom surface of the laser chip has been expected. Therefore in this case, temperature increases at the front mirror are much higher than those in places far from the area of incomplete chip soldering. Moreover, measurements of temperature increases in the mirror plane are not giving adequate information about temperature distributions within an ample internal laser part.

As previously, practically with all new semiconductor devices, during their infant period, currently quantum-cascade semiconductor lasers (QCLs) suffer from acute thermal problems [1-2]. Those problems originate from both an extremely high heat-flux generation within QCL volumes and a very insufficient heat extraction from these volumes. The first is associated with their relatively high threshold currents and threshold voltages necessary to achieve laser action. The second is a result of low effective values of thermal conductivities caused by phonon scatterings and reflections from numerous boundaries between layers within the QCL structure and reducing efficiency of a heat-flux flow towards the laser heat sink. Besides, also various methods of laser bonding seem to have an essential impact on QCL thermal behaviour. In particular, a possible incomplete soldering of the laser chip is expected to lead to a considerable additional temperature increase at the output mirror.

In the present paper, the results of the finite-element-method (FEM) three-dimensional simulation of current spreading, heat generation and heat-flux spreading within volumes of QCL lasers are presented. Special attention is devoted to the effect of incomplete QCL chip soldering.

The AlGaAs/GaAs laser manufactured in the Institute of Electron Technology in Warsaw and emitting the infrared 9-μm radiation (Fig. 1) is used as a typical QCL structure [3]. Typically, the laser ($0.5\times1.0 mm^2$) was usually bonded by the indium solder to the diamond heat spreader attached to the copper heat-sink. The confinement of the current flow towards the active region has been achieved with the aid of both high resistivity Si_3N_4 layer and two semi-cylindrical channels of 8-μm radii etched in parallel to the laser axis in lateral QCL areas and filled with air. In all the calculations, the laser was assumed to be biased by a voltage of 3V. It is not a laser threshold voltage. Our model is only presenting a relative impact on temperature increases within the QCL volume of changes of various construction parameters to test which of them are the most important ones.

The main results of our electrical-thermal 3D simulation are as follows. The laser thermal resistance was estimated between 8 and 10K/W. The optimal diamond heat-spreader thickness is 0.3mm.

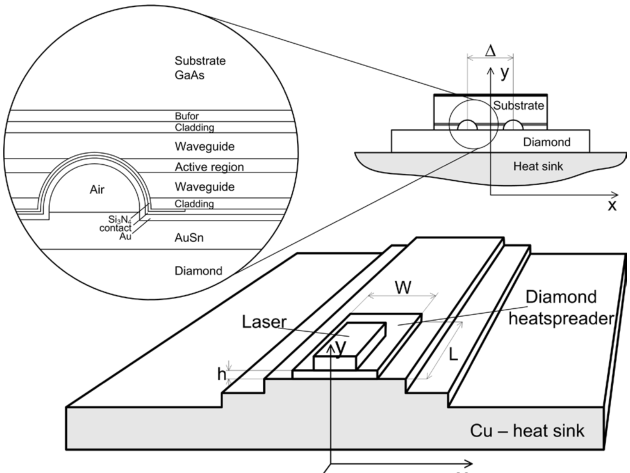

Fig. 1. Structure of the quantum-cascade laser with a diamond heatspreader.

An impact on the QCL thermal behaviour of the heat-spreader length is much less than that of its width. Surprisingly, a replacement of the available imperfect diamond heat spreader with the standard 3-μm indium solder is not followed by essential deterioration of thermal QCL properties. As expected, both the AuSn and indium solders should be as thin as possible. Temperature increases within the laser structure are considerably raised

* E-mail: rpsarzal@p.lodz.pl

with an increase in the distance between the etched channels. Their filling with Au results in about 10-K reduction of active-region temperature.

It is well known that soldering of the laser chip with copper heat-sink or diamond heat-spreader should be carried out very carefully not to create with the solder an electrical short-circuit of the device. That is why less than a necessary amount of solder is often used and then it may cover only a part of the bottom surface of the chip (Fig. 2). Therefore it looks like the laser is shifted a little to leave some part of its front fragment (and also its lateral fragments) without a contact with the solder. Then heat flux extraction from the QCL is strongly violated and its effectiveness is considerably reduced.

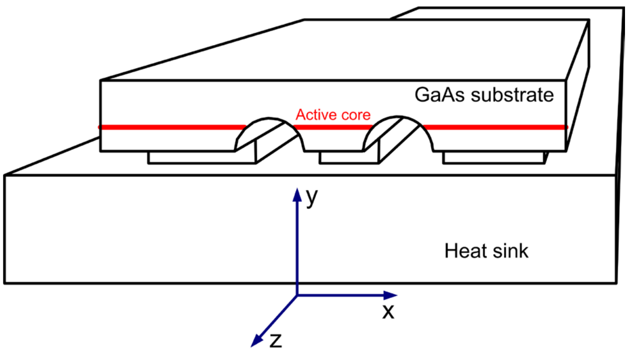

Fig. 2. Incomplete soldering of the bottom surface of the QCL laser.

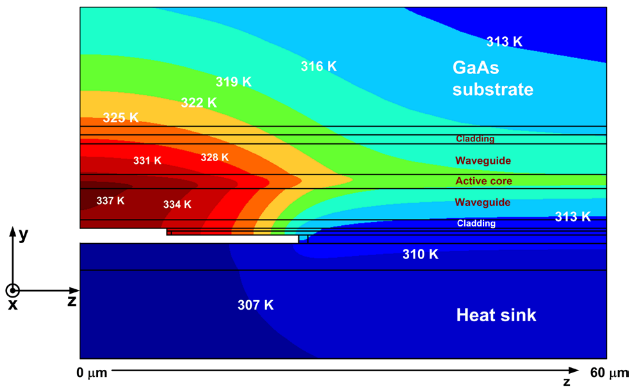

Fig. 3. Isotherm plots in the axial 0yz plane of the QCL laser and its incomplete soldering.

As an example of this behaviour, isotherms determined for the axial 0yz plane of the QCL laser chip (but this time without a diamond heatspreader) with its solder shifted back by 25µm are plotted in Fig. 3. As expected, the heat flux from the front QCL part is initially flowing towards the central laser part and then, after reaching the properly soldered laser region, it is suddenly turning down towards the heat sink. Therefore temperature increases within the front laser part are considerably higher than those in the remaining laser volume.

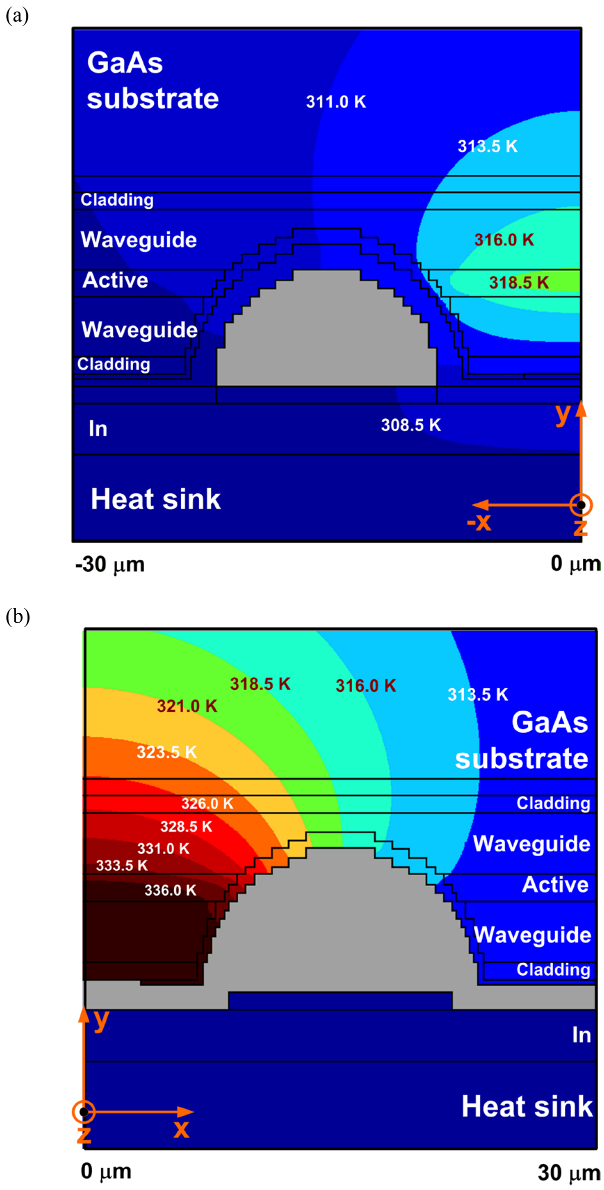

Fig. 4. Isotherm plots in the 0xy plane of the front laser mirror (a) and somewhere in its central part (b).

The same behaviour is also shown in Fig. 4, presenting isotherms in the 0xy plane both on the front (output) laser mirror and somewhere in the central laser part. As expected, from the front part of the active region, because of the bottom air gap, a very intense heat flux flow around the low-thermal-conductivity air channel is clearly seen. At the same time, in the central laser part, much more intense is the heat-flux flow directly to the heat sink. Then because of less effective heat-flux extraction from the front laser part, temperature increases at the front mirror (Fig. 4b) are much higher than those in its central properly soldered part (Fig. 4a). Therefore temperature measurements in the output mirror plane are in this case not giving adequate information about temperature increases within the laser internal part. Our theoretically determined isotherms in the plane of the front laser mirror (Fig. 4b) have been qualitatively confirmed by measurements reported by Pierściński [2].

A high temperature active-region increase is also seen in Fig. 5, presenting a plot of temperature along the 0y axis perpendicular to the layer boundaries both at the facet mirror and within the central laser part. As one can see, the temperature increase at the front mirror is in this case about twice as high as that in places far from the area of incomplete chip soldering. The obvious conclusion is that the above unwanted temperature increase results from incomplete soldering of the laser chip. The heat flux generated within the active region of the front laser part has no efficient way to escape this region, which leads to a dramatic local temperature increase.

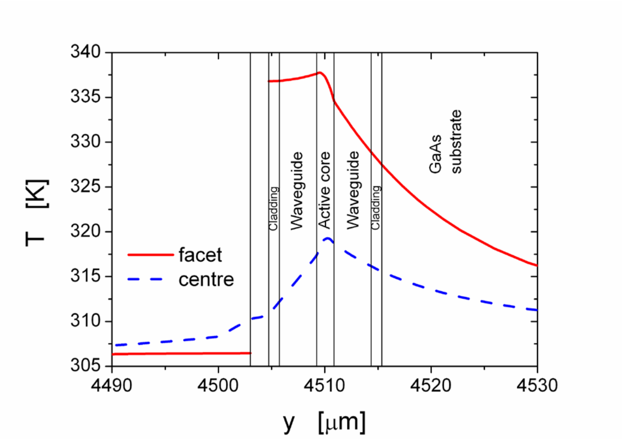

Fig. 5. Temperature along the 0y axis perpendicular to layer boundaries determined for the laser front mirror and somewhere in the laser central part.

As one can see in Fig. 5, in the laser area at the laser facet, the temperature profile from the active region towards the heat-sink is practically parallel to the laser 0y axis, which means that heat flux extraction in this direction is practically negligible. Hence in this region, the heat flux has to travel in the opposite direction towards the substrate and around the air channels (cf. Fig. 4), which leads to considerable temperature increases within this area.

In conclusion, thermal properties of a quantum-cascade laser have been analysed and optimal values of the solder and diamond heat-spreader have been determined. Special attention has been paid to an unwanted impact of possibly incomplete soldering of the bottom surface of the laser chip. Such imperfect soldering has been found to result in dramatic temperature increases at the output laser mirror, incomparable with any other unwanted impact possible within the laser volume. Besides, it should be noted that measurements of temperature distributions in the output mirror plane do not yield, in this case, adequate information about temperature increases within an internal VCSEL part.

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