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# Thermal resistance of LEDs based on a narrow-gap InAsSb solid solution

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This paper examines the thermal resistance of the mid-infrared „flip-chip“LEDs based on the $p$-InAsSbP/$n$-InAsSb heterostructure. It was shown that the measurement of thermal resistance via a thermal control unit (forward p-n junction voltage) for LEDs based on narrow-gap semiconductors must be carried out at low temperature when thermal control unit is constant.

**Keywords:** mid-IR range, IR LED, thermal resistance, thermal control unit.

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Light-emitting diodes (LED) of the mid-infrared (IR) radiation range ($3-6\,\mu$m) have found application in a number of optical sensors, for example, for analyzing the composition of gas mixtures [1,2]. The internal quantum yield of such LED usually does not exceed 10% [3], which, under conditions of high pumping currents, allows to neglect „optical cooling“ and assume that all the supplied electrical energy is converted into heat. For multi-element structures, for example, such as monolithic LED matrices or micro-optocouplers, the flow of direct current in one of their elements causes an increase in temperature in the element adjacent to it and, accordingly, a decrease in its operating efficiency [4,5]. Therefore, when developing an emitting LED crystal, controlling the thermal resistance of the $p-n$ junction/heat sink is an urgent task for both single and multi-element devices.

In this work, using a method based on measuring transient temperature-sensitive characteristics, the thermal resistance of the emitting crystal of a flip-chip design based on the $p$-InAsSbP/$n$-InAsSb heterostructure is experimentally studied.

## Object under study

The LED emitting crystal ($\lambda = 4.7\,\mu$m) in the form of a diode troika was fabricated based on the $p$-InAsSbP/$n$-InAs$_{0.9}$Sb$_{0.1}$ heterostructure grown on an undoped $n$-InAs substrate, and was similar to that described earlier in [6]. The crystal of $0.4-0.55$mm size contained three round mesas with a diameter $\text{Ø}_{\text{mesa}} = 190\,\mu$m and a height $20\,\mu$m with metal anodes ($\text{Ø}_{\text{A}} = 170\,\mu$m) on their tops and metal horseshoe-shaped cathodes placed on the side of the mesas on an InAs substrate. Using the „flip-chip“ method, the emitting crystal was mounted on a heat-conducting AlN circuit board. The arrangement of layers, the general design of the emitting crystal and the mounting diagram on the switching carrier board mounted in the case and on the heat sink are shown in Fig. 1.

The well-known advantages of the given „flip“-chip LED design from an optical point of view are the absence of shading contacts, and from a thermal point of view the location of the $p-n$ junction and contact pads in close proximity to the heat-sinking switching circuit board (device base), made of ceramic (AlN) with high thermal conductivity. The thermal resistance of individual elements of the sample was determined by thermoelectric analogy [7]. A schematic representation of the heat transfer path when one of the three elements of the sample is connected (the right mesa in Fig. 1) in the form of a chain of series resistances from the $p-n$ junction to the heat sink is shown in Fig. 1.

The method for examination of thermal resistance $R_{\text{th}}$ was based on the determination of transient temperature-dependent characteristics (forward $p-n$ junction voltage in response to an abrupt impact of a heating current pulse) with a Thermal Transient Tester T3Ster device [8], which performs measurements in accordance with the JEDEC-JESD 51-14 international standard. In our case, the direct

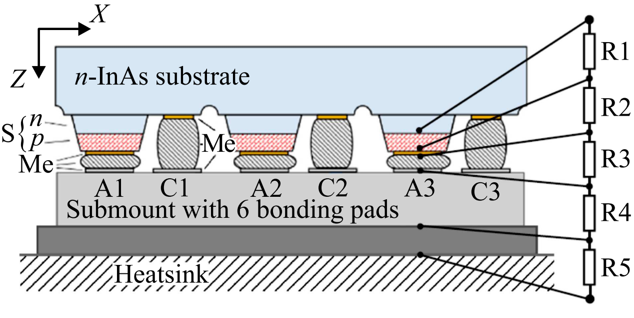

**Figure 1.** Diagram of the longitudinal section of a diode troika mounted on a circuit board, and a diagram of the thermal circuit, where HS — heterostructure, Me — metals (contacts and solder), A$_i$ — anodes, C$_i$ — cathodes, $R_i$ — thermal resistance of layers.

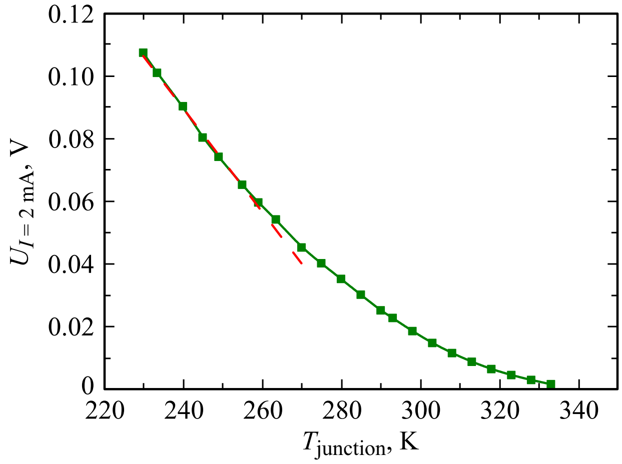

**Figure 2.** Dependence of the forward voltage on the LED on the temperature of the $p-n$ junction at $I = 2$ mA. There is linear part of the dependence in the range 230−265 K.

voltage on the LED was used as a temperature-sensitive parameter at the transmittance of a small measuring current through it, the magnitude of which excluded self-heating. The value of the measuring current was chosen to be 2 mA, the heating current pulse, in turn, was — 100 mA.

To measure thermal resistance with the T3Ster device, it is required to perform a preliminary calibration and set the temperature coefficient of the forward voltage (TCU) with a measuring current (2 mA), which should be constant. That is, it is assumed that the temperature dependence of voltage is linear. As we have experimentally established, over a wide temperature range the $U_f = f(T)$ dependence is not the same. This is due to the fact that the behavior of $U_f$ is determined by a set of processes in the structure (changes in the band gap, generation of carriers by background radiation, statistics of carriers in the semiconductor). Meanwhile, we can distinguish the temperature range $T_{p-n} = 230-265$ K, in which the dependence $U_f = f(T)$ is close to linear (Fig. 2). The heat sink temperature was set using a closed-cycle cryostat with an optical window „CCS-450 Standard Optical Closed-cycle Refrigerator Systems ". At these temperatures the TCU value is constant and equal to $-1.65$ mV/K. At a specified heat sink temperature $T_{\text{heatsink}} = 250$ K, a spectrum of thermal resistances of the equivalent thermal circuit was obtained and the total thermal resistance was estimated, which amounted to $R_{\text{th}} \approx 250$ K/W.

The T3Ster software provides an opportunity to determine cumulative and differential structure functions [9] that illustrate the thermal impedance: thermal capacity and thermal resistance of elements of a thermal circuit (i.e., individual layers of the LED structure).

Fig. 3 shows an experimental differential structural curve reflecting the thermal resistance of the main links of the LED thermal circuit shown in Fig. 1. Each peak of the differential structure curve corresponds to the interface between the layers of the structure LED. From the analysis of the curve, the following thermal resistance values were obtained: $R_1$ — to $p-n$-junction to the bottom plane of the crystal, $R_2$ — for the contact (anode), $R_3$ — for the mounting layer from the crystal to the circuit board, $R_4$ — for the ceramic (AlN) carrier board, $R_5$ — for a body made of Al.

As follows from Fig. 3, the main contribution to the value of the thermal resistance from the $p-n$ junction to the Al body ($\sim$ 180K/W) is made by the metal-semiconductor contact layer ($R_2 = 45$ K/W) and the solder/metalization layer of the circuit board ($R_3 = 40$ K/W). Based on the value of $R_{\text{th}} \sim 250$ K/W, we can conclude that the overheating of the $p-n$ junction relative to the heat sink at $I = 100$ mA ($U = 0.36$ V) lies within the limits of $\sim 9$ K. At the measurement, the real temperature of the $p-n$junction did not exceed 260 K, therefore, TCU was constant.

## Conclusion

The internal quantum yield of mid-IR LEDs critically depends on temperature, which requires taking into account and controlling self-heating, which is associated with the heat release of the LED and depends on its thermal resistance. The generally accepted method for measuring the thermal resistance of an LED uses a temperature-sensitive parameter — the forward voltage at the $p-n$ junction, namely its temperature coefficient TCU. For visible LED, TCU is constant over a wide range of temperatures, including room temperature and above, and is determined during preliminary calibration. For mid-IR range LED ($\lambda \sim 4.7\,\mu$ m), the TCU value loses its constancy. To ensure the opportunity of determining the thermal resistance of mid-IR LED, we proposed to carry out calibration measurements of TCU and subsequent measurements of $R_{\text{th}}$ at low temperatures. As a result, for the LED based on

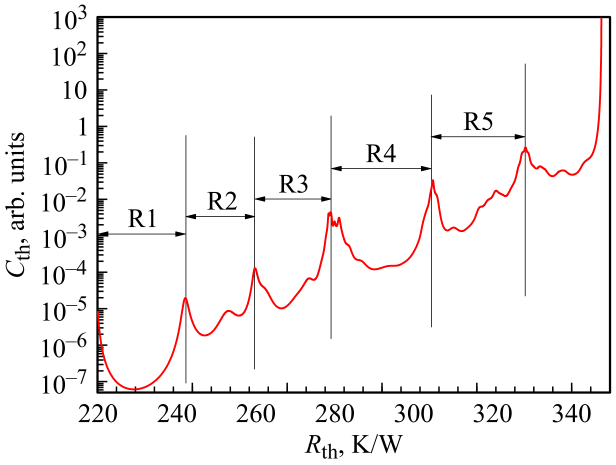

**Figure 3.** Differential structure function obtained using the T3Ster device. The peaks correspond to the elements of the thermal circuit.

$p$-InAsSbP/$n$-InAs$_{0.9}$Sb$_{0.1}$, the values $\mathrm{TCU} = -1.65\,\mathrm{mV/K}$, and $R_{\mathrm{th}} \approx 250\,\mathrm{K/W}$ were obtained, which will be used in the future for the analysis of thermal processes and the development of improved LED mid-IR range.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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