

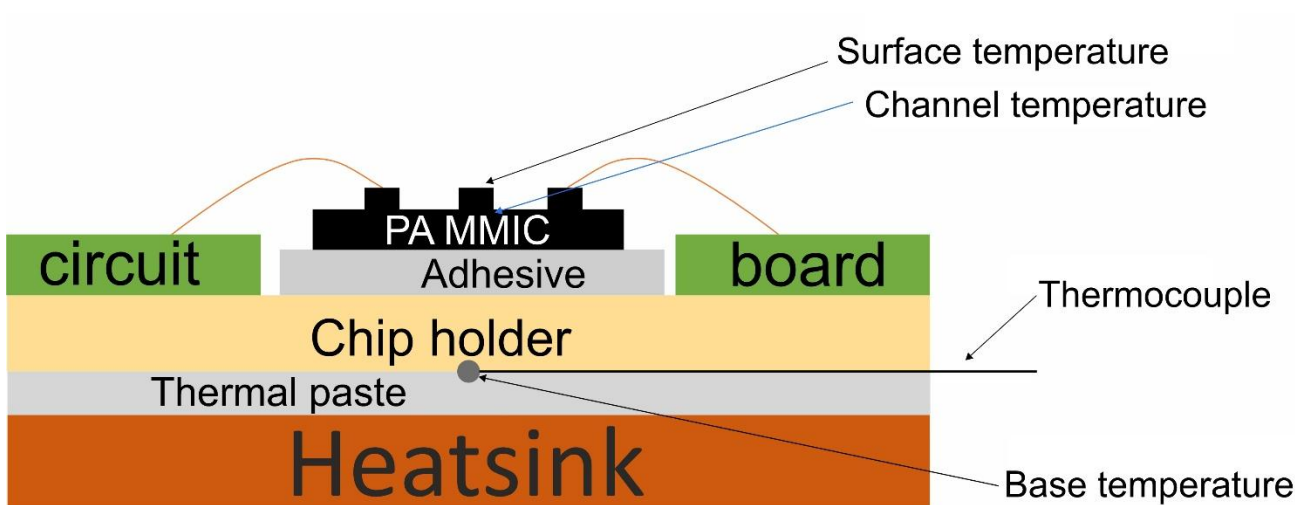
Abstract

GaN solid state power amplifiers are important components for wireless power transfer in mobile communication base transceiver stations, radar systems, wireless charging devices and other applications. The increase in power density in electronic devices has led to a large rise in heat flux, thereby requiring effective thermal management of them. To provide the GaN HEMT channel temperature below 225°C, it is important to realize an appropriate thermal analysis and management strategy.

The paper presents the results of Infrared (IR) thermography characterization of GaN HEMT microwave power amplifiers dies and using them for HEMT thermal modes and thermal parameters definition.

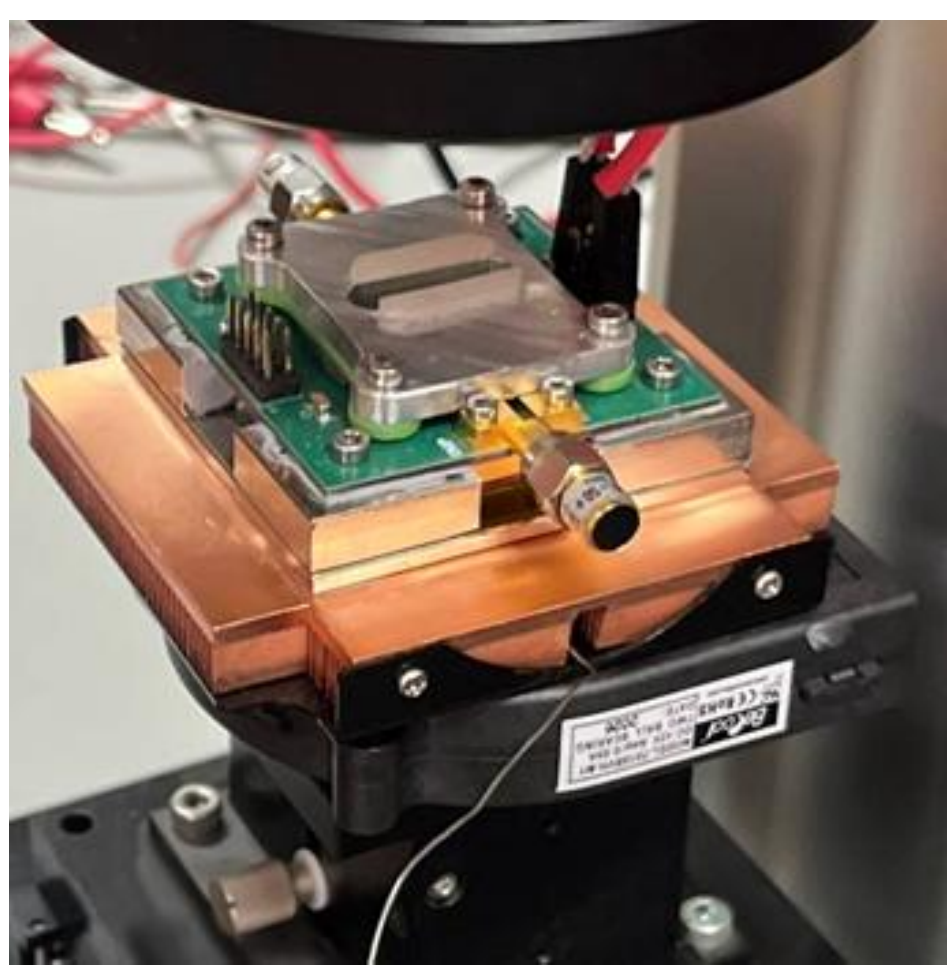
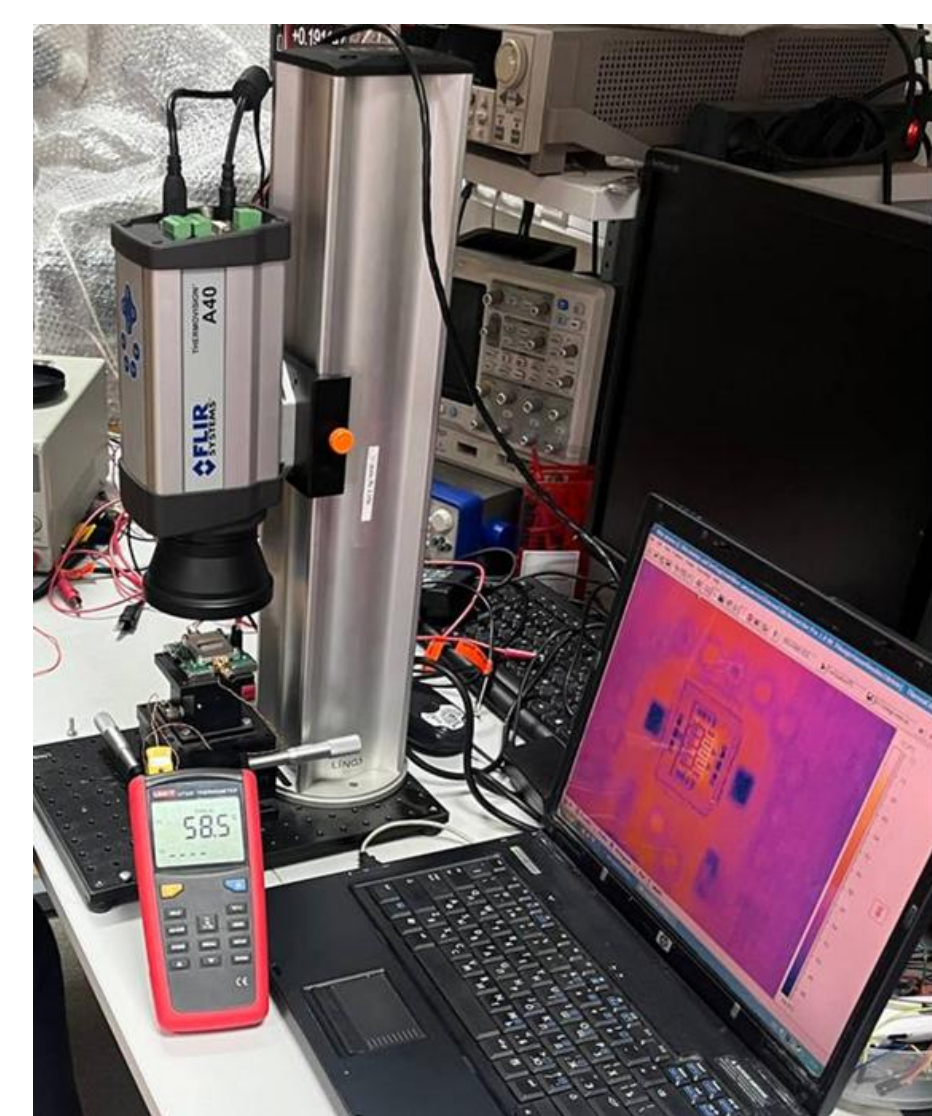
The surface temperature measurements of the GaN HEMT for microwave power amplifier ICs were carried out using the IR Flir A40 camera with 17 um macro lenses, at a constant external temperature (room temperature) and different electrical bias (Vgs), drain currents and powers for the HEMTs. The channel temperature GaN HEMT was determined by electro-thermal modeling in TCAD.

2. Temperature measurements and analysis of the GaN HEMT chips



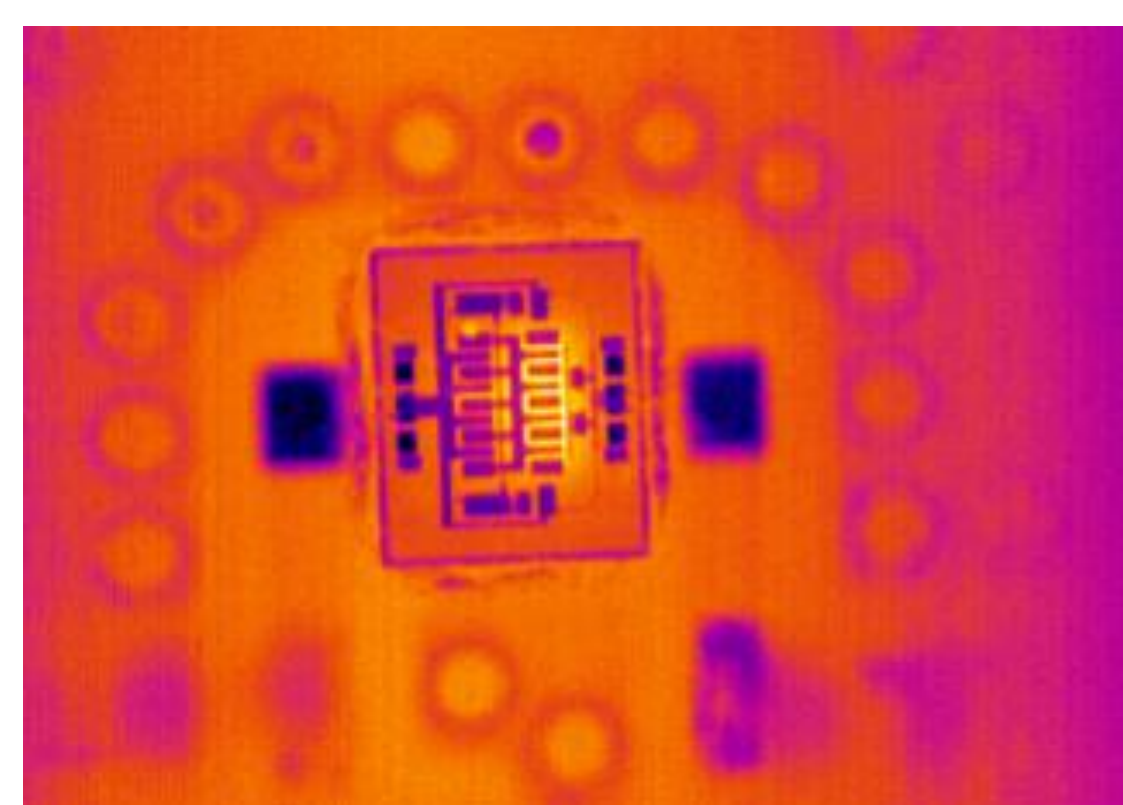
Simplified image of GaN HEMT chip mounted on the heatsink

The FLIR ThermoVision A40 IR camera with a macro lens was used to measure the surface temperature of the GaN HEMT chips.



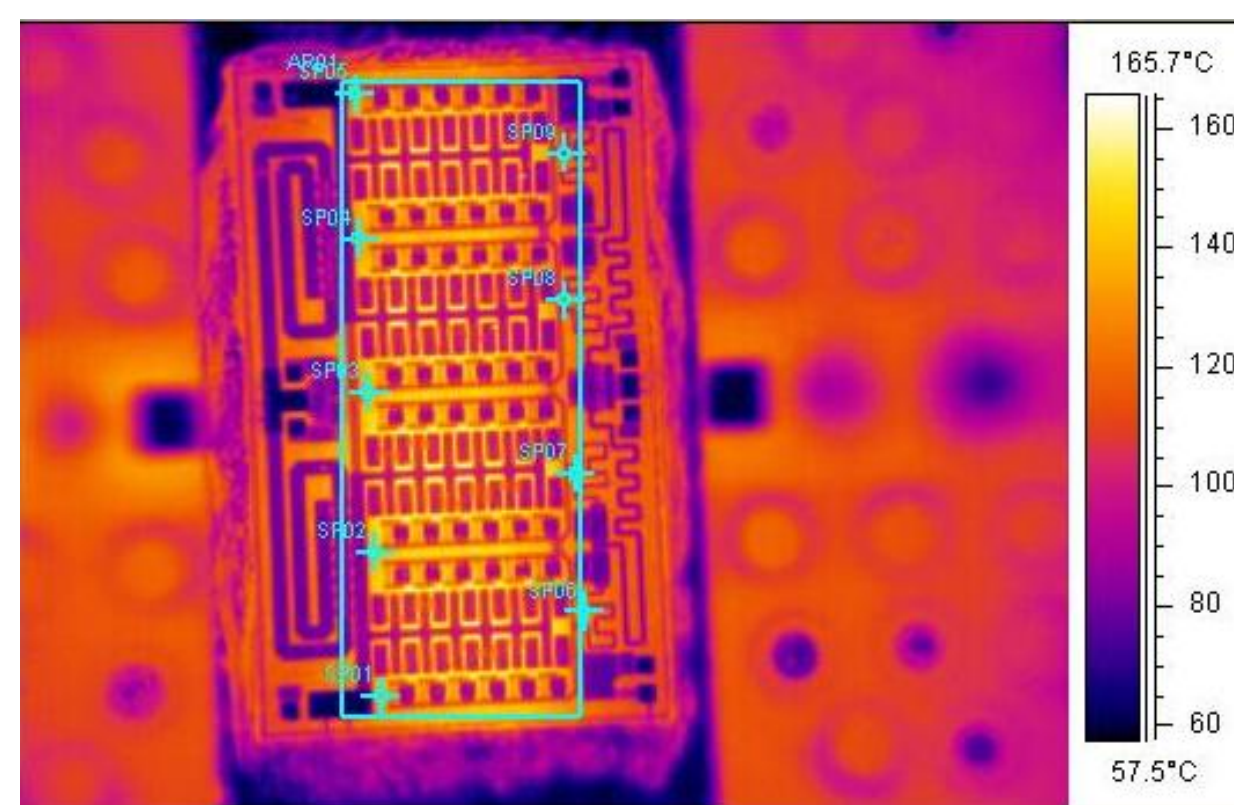
The following electrical modes were set up when measuring the temperature of GaN HEMT chips:

- 1) for the one-stage amplifier the supply voltage was $U = 28$ V, and the maximum current I_n was not more than 0.32 A, and the gain was 25 dBm;
- 2) for the two-stage amplifier the supply voltage was $U = 28$ V, and the maximum current I_n was not more than 1.54 A, and the gain was 27 dBm;
- 3) for the multi-stage amplifier the supply voltage was $U = 28$ V, and the maximum current I_n was not more than 2.20 A, and the gain was 33 dBm.



Chip thermal map at $V_{gs} = -1.39$ V

U_{ds} , V	U_{gs} , V	I_d , mA	t_{base} , °C	Max T_{surf} , °C	P_{diss} , W	R_{th} , °C/W
28	-2.30	76	42	50	2	3.5
	-2.10	134	50	60	4	2.7
	-1.90	190	61	74	5	2.4
	-1.70	246	68	85	7	2.4
	-1.50	290	77	94	8	2.2
	-1.39	318	82	100	9	2.2



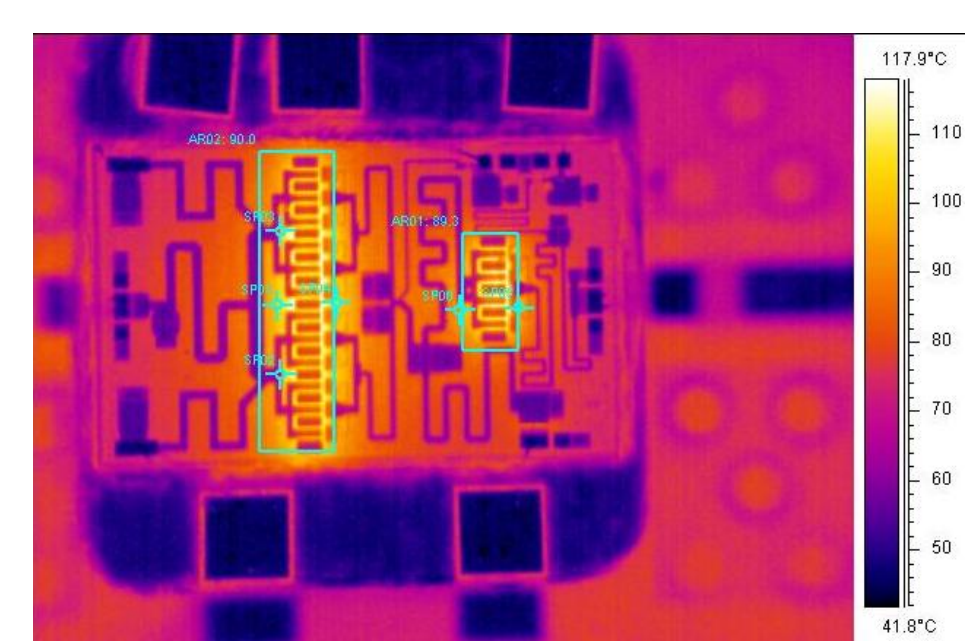
Chip thermal map at $V_{gs} = -5.27$ V

The thermal resistance and maximum temperature values of the one-stage amplifier under different electrical conditions.

The thermal resistance and temperatures at the hottest points for the multi-stage amplifier in the main electrical mode.

U_{ds} , V	U_{gs} , V	I_d , mA	t_{base} , °C	Max T_{surf} , °C	P_{diss} , W	R_{th} , °C/W
28	-5.27	2200	80	SP01 – 135 SP02 – 142 SP03 – 140 SP04 – 135 SP05 – 130 SP06 – 129 SP07 – 130 SP08 – 128 SP09 – 108 $T_{max} = 170$	62	1.5

The thermal resistance and temperatures at the hottest points for the two-stage amplifier in the main electrical mode.



U_{ds} , V	U_{gs} , V	I_d , mA	t_{base} , °C	Max T_{surf} , °C	P_{diss} , W	R_{th} , °C/W
28	-3.25	1537	61	SP01 – 103 SP02 – 86 SP03 – 98 SP04 – 105 SP05 – 96 SP06 – 95 $T_{max} = 110$	43	1.2

The measured thermal resistances: for the one-stage amplifier $R_{th} = 2.2$ °C/W, for the two-stage amplifier $R_{th} = 1.2$ °C/W, and for the multi-stage amplifier $R_{th} = 1.5$ °C/W.

Infrared Thermography Characterization of Thermal Behavior of GaN HEMT Microwave Power Amplifiers Chips

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1. GaN Solid State Power Amplifiers chips under test

GaN HEMT Microwave Power Amplifiers Chips were used to study the thermal fields and thermal modes of GaN transistors. GaN HEMT chip structures included: one-stage, two-stage and multi-stage microwave amplifier circuits with input and output resonance matching circuits, input stabilization circuits (parallel RC circuit), and input and output inductors to provide DC operation of the circuits.

The temperature distribution on the surfaces of GaN HEMT chips were studied under the different electrical conditions using the IR thermal imaging camera.

The measured surface temperature of the GaN HEMT transistor did not provide sufficient information to accurately determine the acceptability of its thermal operation without taking into account the actual temperature of the HEMT channel. Therefore, the IR analysis results were used for TCAD electro-thermal models of GaN HEMTs calibration and for the further TCAD simulations and investigations of HEMT structures thermal modes.

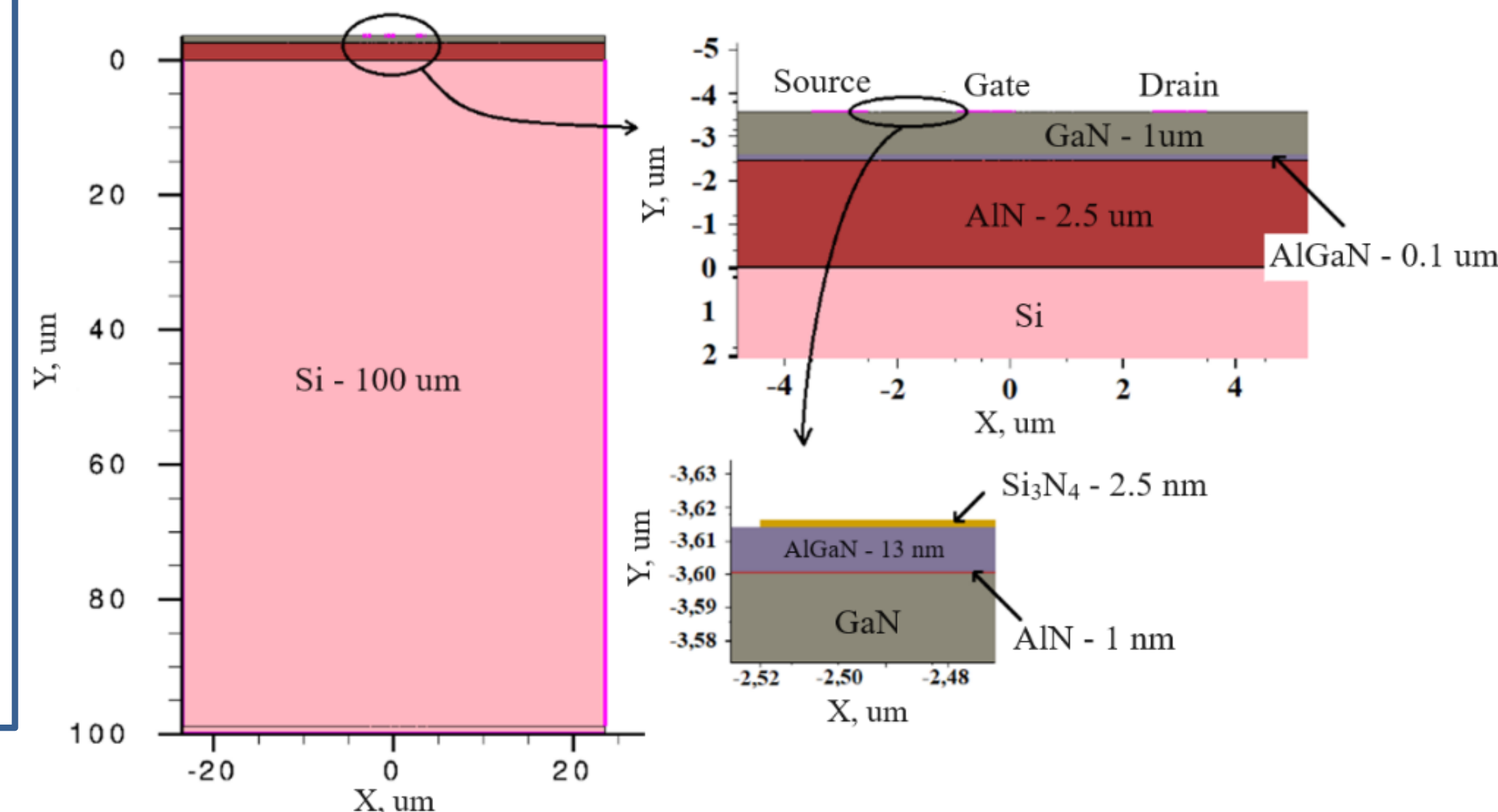
3. TCAD simulation of GaN HEMT chip using the IR analysis results

Using the calibrated TCAD model, we determined the hottest point of the transistor ($T_{channel}$) and the temperature at the lower boundary of the substrate ($T_{substrate}$). Then, we calculated the thermal resistance between the HEMT chip and the substrate as follows (see the text below):

$$R_{th} = (T_{channel} - T_{substrate}) / P_D,$$

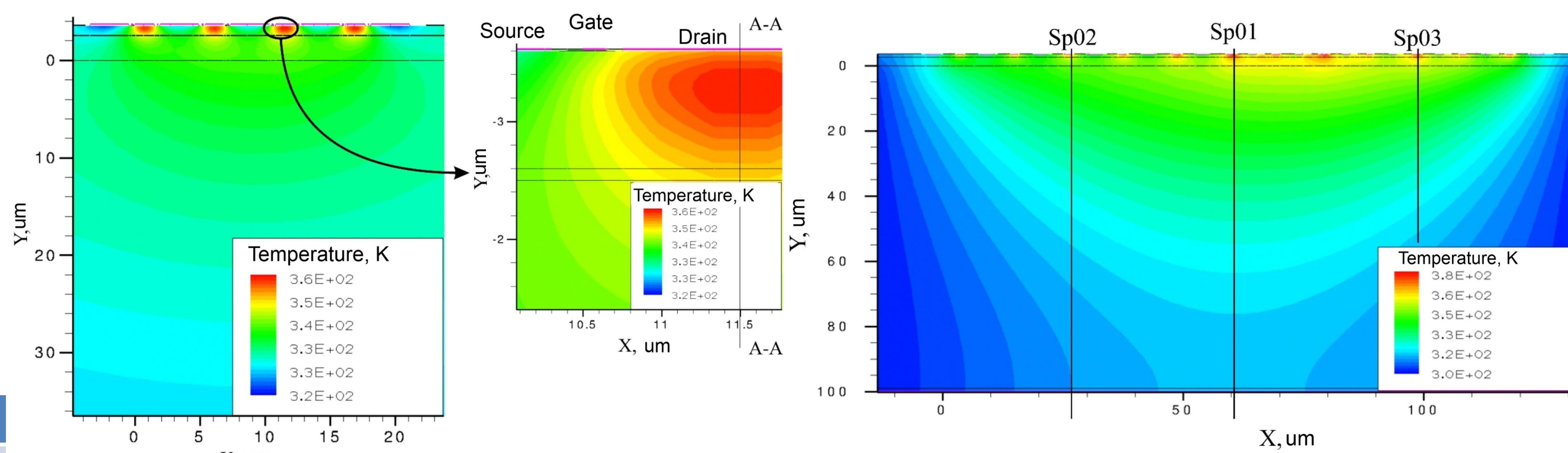
where P_D – HEMT dissipation power.

GaN structure implemented in TCAD



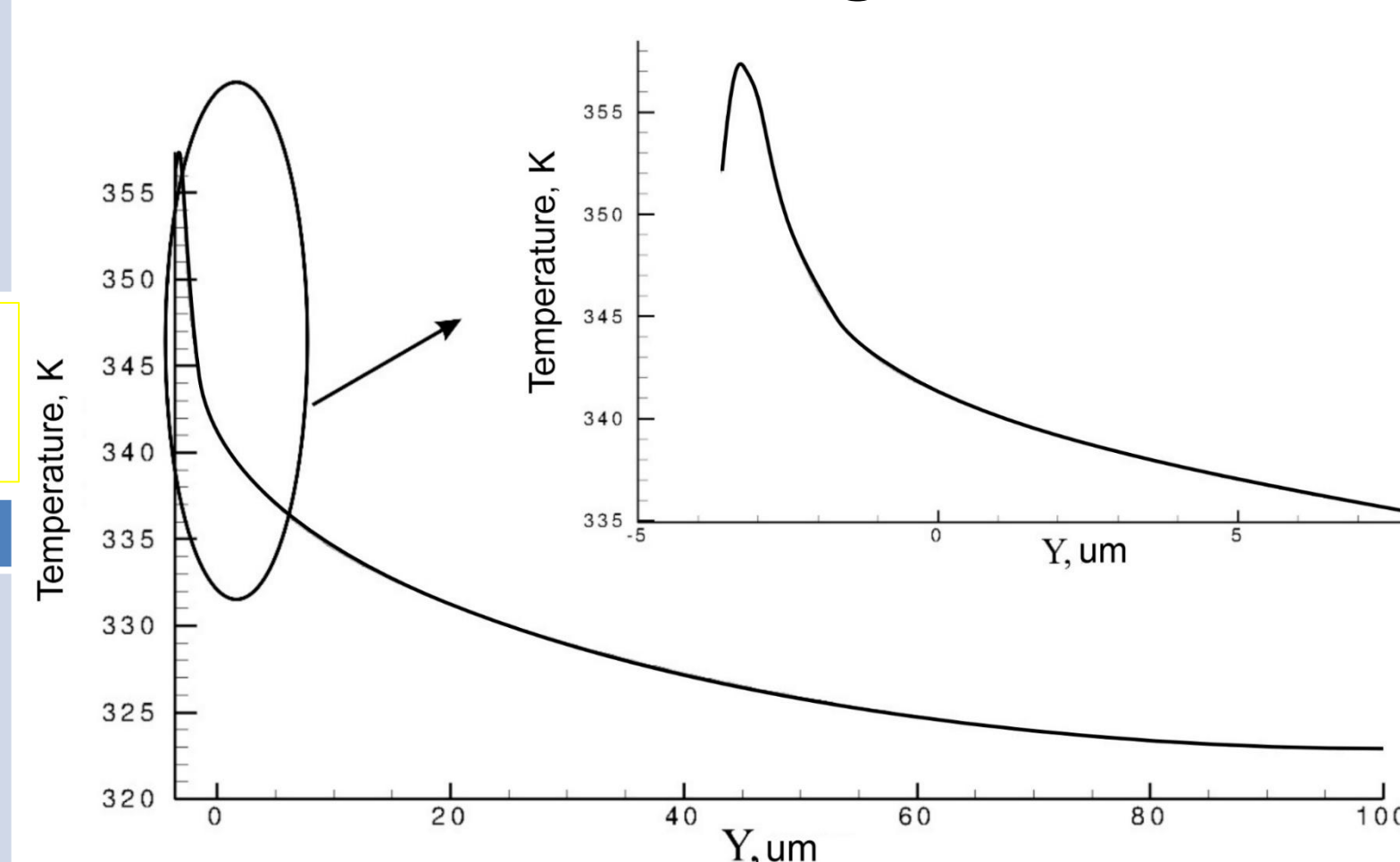
Thermal properties of the chip structure materials used for TCAD simulation:

Material	Si	AlGaIn	AlN	GaN	Au
Thermal conductivity at 25°C, W/m·K	149	0.46–1.15	316	130	318

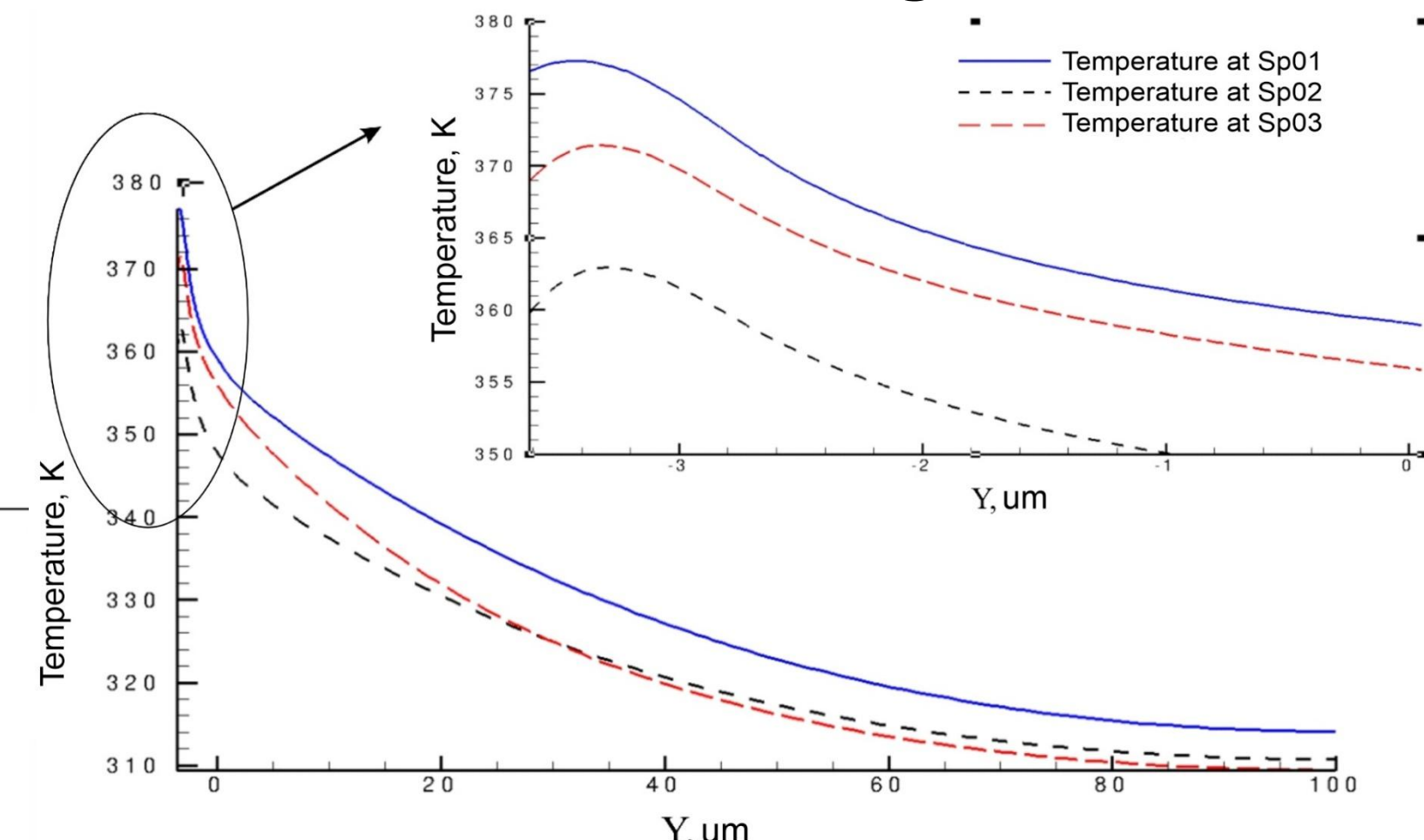


TCAD simulation results:

one-stage



two-stage



The TCAD simulated the channel temperature values of the two-stage amplifier:

- at surface Sp01 was 105°C (the measured surface temperature of the SP01 was 103°C);
- at surface Sp02 was 90°C (the measured surface temperature of the SP02 was 86°C);
- at surface Sp03 was 99°C (the measured temperature of the SP03 was 98°C).

Thus, the TCAD simulated chip-substrate thermal resistance was 1.28 K/W, which was consistent with the evaluation results of the IR measurements.

Conclusions:

The following test variants of the solid-state power GaN HEMT amplifiers chips were analyzed: one-stage amplifier chip ($P_{diss} = 9$ W), two-stages amplifier chips with the different circuit configurations ($P_{diss} = 43$ W and 62 W). The gate-source length of the HEMT were 4 um and the distances between gates were 70 um for all chips.

The IR measured maximum surface temperature of GaN HEMT and the thermal resistance of surface to thermal conducting bases were:

- one-stage amplifier IC chip $T_{max} = 100$ °C ($P_{diss} = 9$ W), $R_{th} = 2.2$ °C/W;
- two-stages amplifier IC chips $T_{max} = 110$ °C, ($P_{diss} = 43$ W), $R_{th} = 1.2$ °C/W;
- multi-stages amplifier IC chips $T_{max} = 170$ °C, ($P_{diss} = 62$ W), $R_{th} = 1.5$ °C/W.

The surface temperature value $T_{max} = 170$ °C was acceptable for this type of transistors (the channel temperatures was less than 225°C). However, it is worth noting that the key aspect for evaluating its reliability was the temperature of the transistor channel. Therefore, the IR analysis results were used for TCAD electro-thermal models of GaN HEMTs calibration for further thermal simulations and for calculation of the GaN IC chips thermal resistances (for circuit analysis). The obtained results of IR analysis and TCAD electro-thermal simulation confirmed the acceptability of the thermal modes of GaN HEMT amplifiers chips from the reliability point of view.