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Methods and features of measuring the thermal resistance of integrated microwave amplifiers on heterojunction bipolar transistors

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Abstract: **The method of measuring the thermal resistance (TR) of semiconductor devices (SD) according to OST 11 0944-96 and the original modulation method implemented in the hardware and software package developed by the authors are described. In both methods, the SD is heated by pulsed power, and the temperature of its active region (transition) is determined by a change in the temperature–sensitive parameter (TSP) - the voltage at the SD at a low current passed through the SD in the pauses between the pulses of the heating current. The measurement error of the vehicle by the standard method strongly depends on the choice of the duration of the heating current pulses and the delay time when measuring the voltage at the SD after switching off the heating current. In the modulation method, the duration of the heating current pulses is changed according to the harmonic law, and according to the results of measuring the voltage at the SD during the passage of the heating and measuring current, the modulus of the thermal impedance of the SD is determined as the ratio of the first harmonic of the transition temperature to the first harmonic of the heating power. According to the frequency dependence of the thermal impedance module, the components of the vehicle of the object are determined, while the requirements for maintaining the temperature of the device body are significantly reduced and, as a result, the measurement error of the vehicle is reduced. The results of comparative measurements of the TR of integrated microwave amplifiers (amplifying cascades) on InGaP/GaP HBT by the standard and modulation method at different values of the amplitude of the heating current are presented. It is shown that the results of measuring the TR of integrated microwave amplifiers by both methods are in good agreement with each other. It is established that with an increase in the amplitude of the heating current, the TR junction-case of integrated microwave amplifiers decreases, which is due to the alignment of current distribution in the structure of the GBT during heating.**

Keywords: **integrated microwave power amplifiers, heterobipolar transistors, thermal parameters, measurement, modulation method**

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CONTENTS

1. INTRODUCTION

Microwave power amplifiers based on heterojunction bipolar transistors (HBT) are widely used in various radioelectronic systems operating in the *S*- and *L*-bands [1,2]. One of the key problems for this devices class is heat removal from dies, since the microwave power amplifiers efficiency is much less than unity [1,2]. At the same time, the real thermal parameters of the microwave power amplifier modules can differ significantly from the calculated ones, therefore, it is necessary to control their thermal parameters both at manufacturing enterprises and at the input control of electronic equipment manufacturers using such devices.

To control the microwave power amplifiers thermal parameters, the methods of IR thermometry [3,4], Raman thermometry [5], or photoconductivity spectroscopy [6] are used. These methods are not very accurate, and obviously unsuitable for fully finished products in closed cases.

The purpose of this work was to test methods for indirect measurement of the integrated microwave power amplifiers thermal parameters based on HBT by the standard and modulation methods at various currents and to analyze the obtained dependencies.

2. METHODS FOR MEASURING THE THERMAL RESISTANCE OF INTEGRATED MICROWAVE AMPLIFIERS

The thermal properties of semiconductor devices are usually characterized by the thermal resistance (TR) "junction-to-case" $\mathrm{R}_{\mathrm{Tjc}}$, defined as the ratio of the temperature increment ΔT_{j} of the HBT *p-n*-junction to the thermal power dissipated in it:

$$R_{Tjc} = \frac{T_j - T_c}{P} = \frac{\Delta T_j}{P},$$

where T_{j} – *p-n*-junction temperature of the transistor, included in the amplifier; T_{c} – fixed case temperature; P – power dissipated in the amplifier.

According to OST 11 0944-96 [7] for BT and HBT, a measurement object pulsed heating mode is used, which is connected according to the circuit with a common base. The junction temperature T_{j} is determined in the pauses between heating current pulses I_{heat} by measuring a temperature sensitive parameter (TSP) that is linearly dependent on the junction temperature T_{j}. As a TSP for BT and HBT, a direct voltage U_{eb} is used at the emitter junction when a small fixed measuring current flows through it. The measurement error of TR by this method according to estimates [7] is more than 12% with a confidence level of 0.95. One of the reasons for this is the transient electrical process that occurs when switching the BT or HBT from the heating mode to the TSP measurement mode [8]. Another reason is the uncertainty in setting the duration of heating pulses, which, according to the standard [7], should be 3–5 times higher than the "transition-to-case" thermal constant τ_{Tjc}, but the standard does not provide a method for measuring τ_{Tjc}.

These shortcomings are absent in the modulation method with the object heating by heating current pulses, the duration of which is changed according to the harmonic law [9]:

$$\tau(t) = \tau_{av}(1 + a\sin 2\pi ft),$$

where τ_{av} – average pulse duration; *a, f* – coefficient and frequency of heating power modulation.

The heating power modulation causes sinusoidal oscillations of the transition temperature T_{j}, averaged over the period, with a phase shift φ relative to the variable power:

$$T_{\mathrm{j}}(t) = T_{\mathrm{j0}} + T_{\mathrm{m}}\sin(2\pi ft - \varphi),$$

where T_{j0} – junction temperature constant; T_m – variable component amplitude of the junction temperature at the modulation frequency *f*.

Thermal impedance is defined as the amplitudes ratio of the junction temperature variable components and the heating power The thermal impedance dependence on the modulation frequency of the heating power has features in the form of flat sections and inflection points determined by the components of the TR of the object [10]. The modulation method has a advantages number compared to the standard method [11]: it allows measuring the TS components, and this method significantly reduces the requirements for maintaining the temperature of the object body constant. Both methods are implemented in a hardware-software complex, which includes a microprocessor-based thermal resistance meter, a computer, and specialized software [11].

3. HARDWARE-SOFTWARE COMPLEX FOR MEASURING THERMAL RESISTANCE

The modulation method for measuring TR is implemented in a hardware-software complex (HSC), the functional diagram of which is shown in **Fig. 1**. The HSC works as follows. The operator enters data on the measurement modes and parameters, which are transferred to the microcontroller via the USB interface. The microcontroller, together with a digital potentiometer (DP) and a heating current source Iheat, generates pulses with the amplitude, repetition period and pulse-width modulation frequency set by the operator. The heating current pulses passing through the collector-emitter circuit of the transistor heat the object of measurement with a power that varies according to the harmonic law. The amplitude of the variable power component is determined based on the amplitude of the heating current pulses set by the operator and the measured voltage at the object, which is fed through a differential amplifier (DA) to the input of the analog-to-digital converter (ADC) built into the microcontroller.

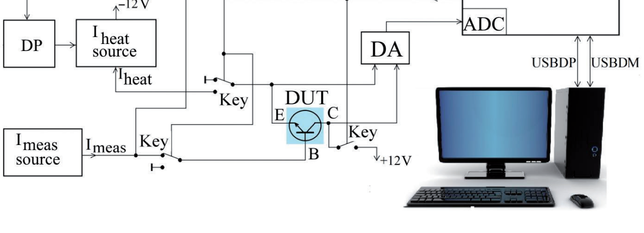

Fig. 1. *Functional diagram of the hardware-software complex.*

The impact on the object of variable power, which changes according to a harmonic law, causes a change in the temperature of the active region of the transistor die (*p-n*-junction) according to the same law, but with a phase shift relative to the heating power. The measurement of the junction temperature is carried out indirectly based on the measurement of a temperature-sensitive parameter (TSP), which is used as a direct voltage U_{eb} between the emitter and the base of the transistor when a fixed measuring current Imeas flows through the emitter junction. The transition temperature is measured in pauses between heating pulses with a time delay relative to their trailing edge, which is necessary to complete transient electrical processes. The junction temperature is measured by a 16-bit ADC that communicates with the microcontroller via the SPI (Serial Peripheral Interface) serial peripheral interface. To ensure the flow of heating current pulses through the transistor through the collector-emitter circuit, and in the pauses between pulses through the base-emitter circuit, electronic switches Key on field-effect transistors controlled by a microcontroller are used.

By the HSC it is possible to measure the TR not only by the modulation method, but also by the standard method according to OST 11 0944-96, using heating of the object by a series of heating current pulses with a constant duration. Since the duration of the heating pulses must be such that the die has time to reach a stationary temperature regime, while the case temperature remains unchanged, a special regime is provided in the HSC to determine this optimal duration. It is based on the measurement and analysis of the transient thermal characteristic (TTC), that is, the dependence of $Z_T(\tau)$ of the transient TR on the duration τ of the heating current pulses and includes the passage of heating pulses through the object with a duration increasing according to a logarithmic law. In this case, the pause between pulses exceeds the pulse duration by a factor of 4–5, which is quite sufficient for the die temperature to return to its initial value after each pulse. After each heating pulse with a certain time delay, the response to this effect is measured – the change in the transition temperature. To determine the optimal pulse duration, smoothing and differentiation of the measured TTC is applied.

4. MEASUREMENT OF THE MICROWAVE AMPLIFIER THERMAL RESISTANCE BY THE STANDARD METHOD

The objects of study were integrated microwave amplifiers based on InGaP/GaP HBT type MMG3014NT1 with a limiting frequency of 4 GHz and a maximum operating current of 300 mA [12]. During measurements, the object was connected to a source of heating pulses according to a common-base circuit. Heating was carried out by a series of heating current pulses flowing through the "collector-emitter" circuit. The voltage U_{eb} used as the TSP was measured with a time delay of 40 μs relative to the end of each heating current pulse. The temperature coefficient of the forward voltage drop was measured by the standard method and for the HBT MMG3014 is – 1.78 mV/K.

To determine the optimal duration of the heating current pulses, the transient thermal characteristic (TTC) was first measured by passing heating current pulses, with a change in duration τ from 0.1 to 300 ms with a step constant on a logarithmic scale of 50 pulses per decade. The results of the PTC measurements are presented in the upper window in **Fig. 2**. The features of the TTC were identified by calculating $[dZ_T/d\tau]^{-1}$ as a function of the pulse duration τ. The result of such processing of TTC is shown in the lower window in Fig. 2. The maximum of the graph in the lower window corresponds to the optimal pulse duration, the value of which for the studied HBT MMG3014 turned out to be 5.5 ms. At the pulse duration determined in this way, the measurements were carried out by the standard method. The thermal resistance R_{Tjc} was determined by calculating the temperature difference of the die before and after the heating pulse, followed by averaging over all pulses. To eliminate the influence of the delay time on the measurement results, extrapolation of the TSP values by the end of each heating pulse was used; it was assumed that the process of object die cooling is described by a root dependence [8].

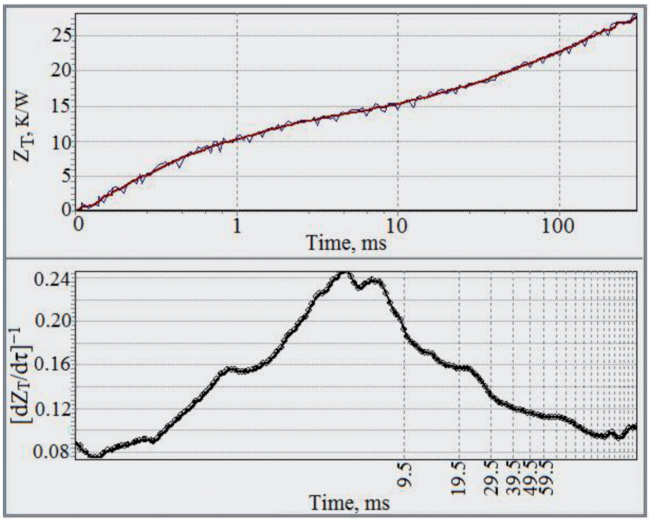

Fig. 2. *Transient thermal characteristic (top) and the result of its processing (bottom).*

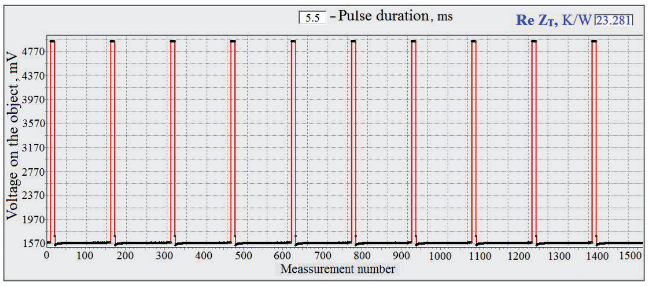

Fig. 3. *The shape of the voltage on the object when measuring the TC of the microwave amplifier MMG3014 standard method at* I_{heat} *= 200 mA.*

The result of measuring the TR of the MMG3014 microwave amplifier at I_{heat} =200 mA is shown in **Fig. 3**. Regardless of the set pulse duration, the voltage at the top of the pulses was measured 10 times with subsequent averaging. To determine the change in the junction temperature caused by the heating pulse, the TSP value was measured 10 times before each heating pulse and 130 times after it. The interval between adjacent TSP measurements was 13 μs, which was determined by the capabilities of the external ADC and SPI interface. The measured value of TC at I_{heat} = 200 mA turned out to be 23.28 K/W. TC measurements at various I_{heat} values showed that with an increase in the I_{heat} amplitude, the value of R_{Tjc} decreases significantly.

5. MEASUREMENT OF THERMAL RESISTANCE BY THE MODULATION METHOD

In this method, the object is heated by a sequence of heating current pulses with a given repetition period and a duration that varies according to a harmonic law. To determine R_{Tjc}, the dependence of the real part Re $Z_T(f)$ of the thermal impedance on the modulation frequency of the heating power f was measured (upper window in **Fig. 4**). The inflection point on the dependence Re $Z_T(f)$ is determined by the thermal resistance "junction-to-case" R_{Tjc}. To determine this component, a plot of the dependence of the inverse derivative Re $Z_T(f)$ on frequency from Re Z_T was plotted (lower window in Fig. 4). The maximum on the graph corresponds to the TR R_{Tjc} component.

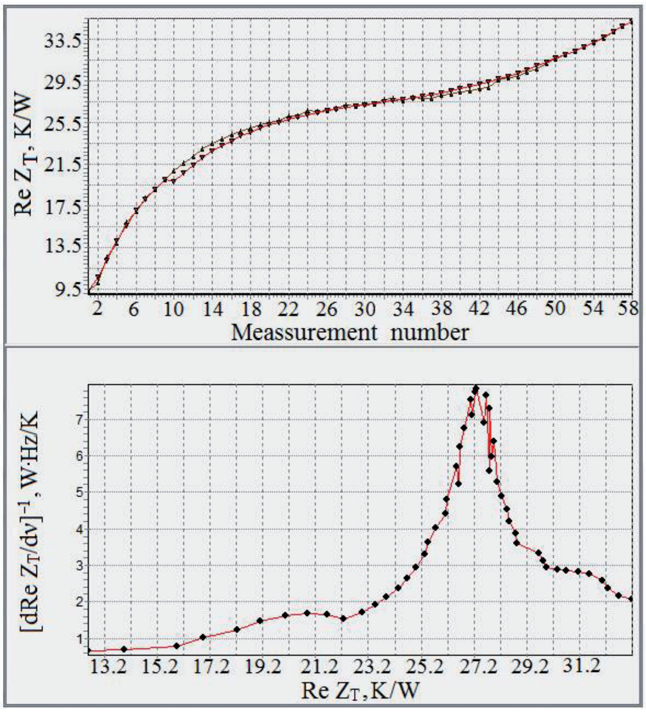

Fig. 4. *Frequency dependence of the real part Re* $Z_T(f)$ *thermal impedance of the MMG3014 microwave amplifier.*

To assess the inhomogeneity of the distribution of the heating current over the die structure of the MMG3014 microwave amplifier, the dependence Re $Z_T(f)$ was measured at different values of the amplitude of the heating current pulses. The results of processing the obtained dependences are shown in **Fig. 5.** For the convenience of

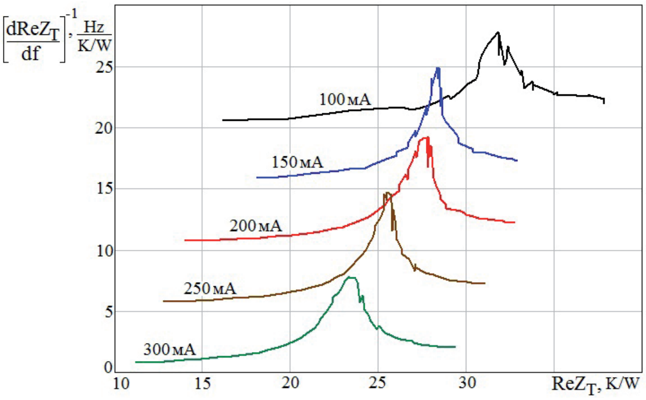

Fig. 5. *Dependence of* $(\text{dRe}Z_T/\text{d}f)^{-1}$ *on the real part of the thermal impedance Re* Z_T *microwave amplifier MMG3014 at different amplitudes of* I_{heat}.

perceiving the graphs, all of them are shifted relative to each other along the ordinate axis by 5 units. It can be seen that with an increase in Iheat from 100 to 300 mA, the maxima, whose position relative to the Re Z_T axis determines the thermal resistance R_{Tjc}, shift to the beginning of the abscissa axis. This indicates that with an increase in the amplitude of the heating current pulses, the values of the thermal resistance R_{Tjc} of the microwave power amplifier based on the HBT significantly decrease.

The results of measurements of R_{Tjc} at different values of RTjc, obtained by the modulation method, are shown in **Fig. 6.** The solid line 1 shows the result by the least squares method. Line 2 shows the result of processing the R_{Tjc} values obtained by the standard method. It can be seen that the nature of the dependence of R_{Tjc} on Iheat for both methods is the same, but there is a significant difference between the measured values of R_{Tjc}. The reason for this difference is that, in addition to the die in which the HBT is formed, the power amplifier has matching elements with active and capacitive resistance. When using the modulation method, the object is heated by a sequence of pulses with a repetition period of about 100 µs, and when using the standard method, by single pulses with a duration of several milliseconds. Due to the different nature of the current flow through the matching capacitive elements, the HBT die is heated by a series of short current pulses more than when heated by single pulses.

In addition, it can be seen from the figure that the thermal resistance R_{Tjc} of the MMG3014 HBT microwave amplifier noticeably decreases with an increase in the heating current amplitude. One of the most probable mechanisms of such a decrease is the equalization of the current distribution in the comb structure of the HBT during heating [13,14]. One of the main reasons for the inhomogeneous current distribution in the comb structures of BT and HBT in the active mode of operation is the voltage drop across the resistance of the current-carrying emitter tracks of metallization in relation to the thermal potential [14]. With an increase in the structure temperature and thermal potential, the effect of the voltage drop on the metallization resistance decreases and the inhomogeneity of the current density in the structure decreases. Thus, the steepness of the current dependence R_{Tjc} can serve as an indirect diagnostic parameter of the resistance of current-carrying metallization and the inhomogeneity of the current distribution in the HBT structure.

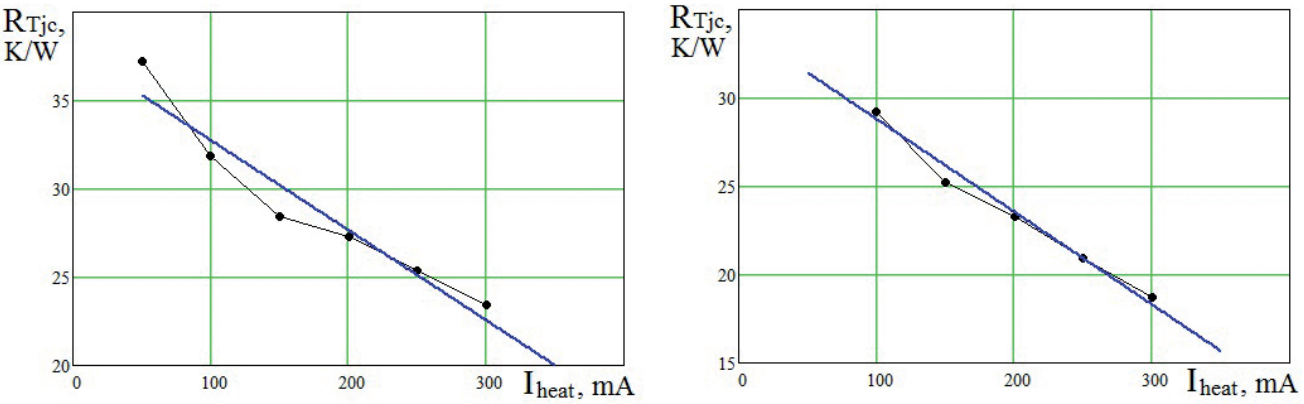

Fig. 6. *Dependence of the thermal resistance of the MMG3014 microwave amplifier, measured by various methods, on the amplitude of the heating current pulses: 1– standard method; 2 –modulation method.*

6. CONCLUSION

The results of comparative measurements of the junction-to-case TR of integrated microwave amplifiers (amplifier stages) based on InGaP/GaP HBT by the standard and modulation methods at different values of the heating current amplitude are presented. It is shown that the results of measuring the junction-case TR of integrated microwave amplifiers by both methods are in good agreement with each other. It has been established that with an increase in the amplitude of the heating current, the TS of the junction-case of integrated microwave amplifiers decreases, which is probably due to the alignment of the current distribution in the HBT structure during heating.

Thus, the steepness of the current dependence R_{Tjc} can serve as an indirect diagnostic parameter of the inhomogeneity of the current distribution in the HBT structure.

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