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## INVESTIGATION OF TRANSIENT THERMAL CHARACTERISTICS OF MICROWAVE TRANSISTORS

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### Abstract

The transient thermal characteristics of modern microwave transistors may strongly influence the performance of many microwave circuits. In the paper, the method and the exemplary results of measurements of transient thermal impedance of microwave transistors are presented. Special attention is devoted to measurements in very short time periods after step change of power. The presented results are not available in typical datasheets of microwave transistors. Apart from measurements, an analytical approximation of thermal impedance is presented and the exemplary sets of its parameters obtained by curve fitting.

Keywords: transient thermal impedance, microwave transistors, measurement systems.

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### 1. Introduction

Thermal problems are of great and still growing importance in electronics. They occur mainly in semiconductor devices and integrated circuits, and need to be taken into consideration at various stages of design, production, testing and operation of electronic equipment.

Two groups of thermal phenomena should be considered. The first is the influence of the inside temperature on the characteristics and parameters of electronic devices and consequently, on the performance of electronic equipment. The second is the self-heating phenomenon – the inside device temperature depends not only on the ambient temperature but also on the power dissipated (dependent on the currents and voltages). Both phenomena are coupled together resulting in involved electro-thermal interactions (reported sometimes as a “thermal feedback”) in electronics circuits.

In this paper the transient thermal characteristics of modern microwave transistors are discussed. The current state of development of microwave transistors and the significance of their thermal characteristics are briefly outlined in Section 2.

The special, but very important class of microwave circuits operates in a pulse regime in which fast thermal transients in transistors may occur. In Section 3 a dynamic lumped thermal model of transistors described by their transient thermal impedance is discussed, including a possible method of measurement of this characteristic.

Section 4 is the main, experimental part of the paper. The laboratory system for measurements of transient thermal impedance of microwave transistors and representative examples of the obtained transient thermal characteristics are presented. In Section 5 the discussion of the results and some concluding remarks are given.

## 2. Microwave transistors and their thermal characteristics

Many microwave circuits, for example in radar systems, wireless communication, microwave heating, laser excitation *etc.*, are based on discrete microwave transistors as active, amplifying devices. Microwave transistors are under steady development. Bipolar, LDMOS and MESFET transistors made of silicon and gallium arsenide are most commonly used. Modern developments contain mainly heterojunction transistors – bipolar (heterojunction bipolar transistors – HBT) and field effect (heterojunction FET – HFET, high electron mobility transistors – HEMT), based on such semiconductor materials as SiGe, SiC, GaAlAs and GaN [1, 2].

The electrical characteristics of transistors are temperature-sensitive [3, 4, 5], therefore special circuit solutions are usually used to minimize the effect of external temperature changes on the performance of microwave subcircuits. Apart from the ambient temperature variations, the self-heating phenomenon, resulting from power dissipation, may influence the microwave transistor characteristics [4, 5, 6, 7]. It is particularly important for power microwave transistors working with the values of dissipated power ranging from several watts to over 100 W.

In many microwave power circuits, for example in radar transmitters, a pulse mode of operation is employed [3, 8, 9, 10]. The peak values of power dissipated in transistors is very high and, according to the small duty ratio, the average power does not exceed the values specified by maximum ratings. In such a mode of operation, the inside device temperature changes substantially during the supply power pulse. As a consequence, the temperature-sensitive parameters of transistors are changed periodically. Those changes should be minimized by proper design of the conditions of transistor operation. It is necessary to take into account the dynamic thermal characteristics of transistors in the circuit design process.

The dynamic thermal characteristic of an electronic device is known as transient thermal impedance, defined as the inside temperature response to a step pulse of dissipated power [11, 12, 13]. Such characteristics are usually specified in manufacturer's data sheet of power low frequency devices but, as a rule, are not present in microwave transistor manufacturer specifications.

## 3. Transient thermal impedance

### 3.1. General features

There are two possible descriptions of dynamic thermal characteristics of any device. The first is based on the heat conduction equation (distributed model) and the second – on the concept of transient thermal impedance (lumped model). The latter is of course the simpler one and is acceptable if the dimensions of the active region of a device (for example the conducting channel in a FET transistor or the base region with adjacent junctions in a bipolar transistor) are much smaller than the whole device including the package and heat sink. The transient thermal impedance (or thermal resistance in the DC case) is generally accepted as a sufficiently accurate description of typical semiconductor devices.

Transient thermal impedance is defined by the following formula [11, 12, 13], for  $p(t) = P_o \cdot 1(t)$ :

$$Z_{j-o}(t) = \frac{T_j(t) - T_o}{P_o}; \text{ for } t \geq 0, \quad (1)$$

where  $T_j$  – inside temperature,  $T_o$  – reference temperature (for example the ambient or case temperature).

The transient thermal impedance curve can be approximated by the expression [11], [12], [14]:

$$Z_{j-o}(t) = \sum_{i=1}^L K_i \cdot \left[ 1 - \exp\left(-\frac{t}{\tau_i}\right) \right]. \quad (2)$$

The above description is very convenient for the purpose of calculation of inside temperature changes for the known waveform of dissipated power  $p(t)$ . The following formula is to be used:

$$T_j(t) = T_j(t_o) + \int_{t_o}^t W_{j-o}(t-x) \cdot p(x) \cdot dx, \quad (3)$$

where  $p(t) = 0$  for  $t < t_o$ .

The function  $W_{j-o}(t)$  can be easily obtained from the analytical expression (2) for thermal impedance [11, 14]:

$$W_{j-o}(t) = \frac{dZ_{j-o}}{dt} = \sum_{i=1}^L B_i \cdot \exp(\alpha_i \cdot t) \quad (4)$$

with

$$B_i = K_i/\tau_i; \quad \alpha_i = -1/\tau_i. \quad (5)$$

### 3.2. Measurement method

The thermal impedance curve for a given device, in specified cooling conditions can be obtained experimentally and several possible measurement methods may be applied [11, 13, 15]. The measurement methods for low-frequency power devices can be found in manufacturer's application notes or other documents (for example [16, 17]). The inside temperature  $T_j(t)$  is measured indirectly with the use of a properly chosen temperature-sensitive electrical parameter. The typical measurement method corresponds to the definition given by Eq. (1). After a step pulse of dissipated power, the temperature-sensitive parameter is measured in the short break of power dissipation. Calibration of the temperature-sensitive parameter is necessary before the main measurement. The device under test is periodically switched between the "heating mode" and "measurement mode" of operation. The switching frequency is limited because of the electrical transient states accompanying the switching process. As a consequence, the fast thermal transients cannot be measured accurately. This restriction is of minor importance for typical, low frequency power devices.

Fast thermal transients can be particularly important for microwave transistors, therefore another measurement method should be chosen. The measurements presented in this paper are based on the cooling-curve approach [15, 18]. The device under test is heated-up by the constant power dissipation  $P_o$  until the thermal steady-state is achieved. Next, the power is switched-off and changes of the temperature-sensitive parameter are recorded. The waveform of the inside temperature for cooling process  $T_{jch}(t)$  is obtained, using the known calibration curve.

The shape of  $T_{jch}(t)$  is related to the transient thermal impedance by the formula:

$$T_{jch}(t) = P_o \cdot [K_{j-o} - Z_{j-o}(t)], \quad (6)$$

where  $K_{j-o}$  is the steady-state thermal resistance corresponding to  $Z_{j-o}$  and is obtained from (6) for  $t = 0^+$  (when  $Z_{j-o} = 0$ ).

## 4. Measurement of thermal impedance curves

### 4.1. Measurement system and procedure

The measurement set-up is built-up from the following elements:

- Heating supply circuit;
- Measurement supply circuit;
- Source of reference voltage;
- Electronic switch;
- Amplifier;
- PC with AD/DA card (measurement card);
- Temperature chamber.

The principle of operation of the set-up for measuring transient thermal characteristics is presented in Fig. 1.

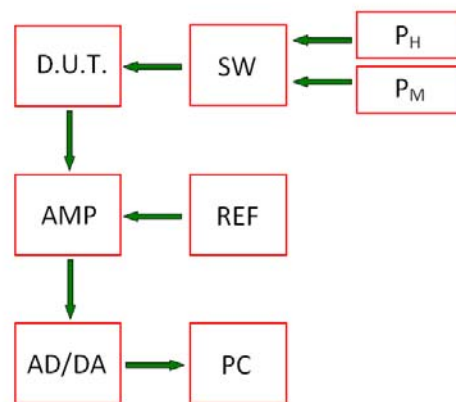


Fig. 1. Principle of operation of the measurement set-up: D.U.T. – device under test, SW – switch,  $P_H$  – heating signal,  $P_M$  – measurement signal, AMP – measurement amplifier, AD/DA – measurement card, PC – computer.

The heating supply circuit consists of two independent voltage and current sources. The value of the power delivered by the heating supply circuit to the transistor under test during the heating phase can be set between 0 and 90W. The current value at which the temperature-sensitive parameter is measured can be set between 100  $\mu$ A and 4 mA depending on the transistor under test. Measurement of the base to emitter voltage  $V_{BE}$  (for BJT and HBT) or threshold gate-to-source  $V_{GS}$  voltage for FET transistors, which serve as the temperature-sensitive parameters, is carried out in differential mode in relation to the reference voltage (the corresponding  $V_{BE}$  or  $V_{GS}$  voltage of an additional, non-powered transistor). The obtained voltage difference is amplified (amplification can be adjusted from 18 to 89 V/V).

The above measurement circuit is controlled by the PC via the National Instruments NI6115 X-PCI measurement card. It is a 12-bit card with 2 analog outputs and 4 analog inputs with a maximum sampling rate of 10 MHz per channel. The PC with AD/DA card performs: amplified voltage conversion into a digital signal, control of switching between heating and measurement mode device supply, conversion of acquired temperature-sensitive voltage into temperature rise  $\Delta T_j(t)$ .

A temperature chamber with internal air circulation system 3213/15 made by FEUTRON allows ambient temperature control in the range of  $-40^\circ\text{C}$  up to  $180^\circ\text{C}$  with  $\pm 0.1^\circ\text{C}$  precision. The internal temperature of the chamber was additionally controlled by temperature meter 1522 manufactured by Hart Scientific with a thermistor probe of  $\pm 0.01^\circ\text{C}$  accuracy.

All measured transistors except for SMD transistors were placed on a ribbed heatsink, type A4062, made of aluminium alloy. The difference between the heatsink surface temperature

and ambient temperature did not exceed 1K, therefore the measured thermal impedance is in fact the junction-to-case impedance  $Z_{j-c}(t)$ .

The details of the measurement system are described in [18].

#### 4.2. Exemplary results

Transient thermal characteristics of different types of transistors mounted in different packages have been measured. The total number of transistors under measurement was 20. Some transistors were measured at several values of the ambient temperature from 20°C to 90°C. In the paper the exemplary results of transient thermal curves obtained for transistors BJT (LKE21050T), HBT (IBM43RF0100), MESFET (FLC097W), HFET (SHF0289) and LDMOS (PTF10122) are shown.

In Fig. 2 the difference between transient thermal impedance curves of two types of transistors for a short period are presented. The measurement results presented in Fig. 3 are in the form of temperature change curves in the cooling phase.

The values of thermal resistance for these transistors are 35 K/W and 16 K/W respectively.

As shown in Fig. 3, the changes of the inside temperature after power turn-off can be very fast, approaching 1 K/μsec for FLC097W (MESFET).

Apart from measurements, the computer procedure based on optimization algorithms was used to identify the coefficients in the analytical approximation of thermal impedance (Eq. 2). In Figs 4 and 5, the comparison of the measured  $Z_{j-c}(t)$  with the analytical approximation (Eq. 2) for optimal set of parameters  $K_i$ ,  $\tau_i$ , assuming  $L=4$ , for two types of transistors, is presented. It is seen that the approximation in Eq. (2), for  $L=4$  is very good.

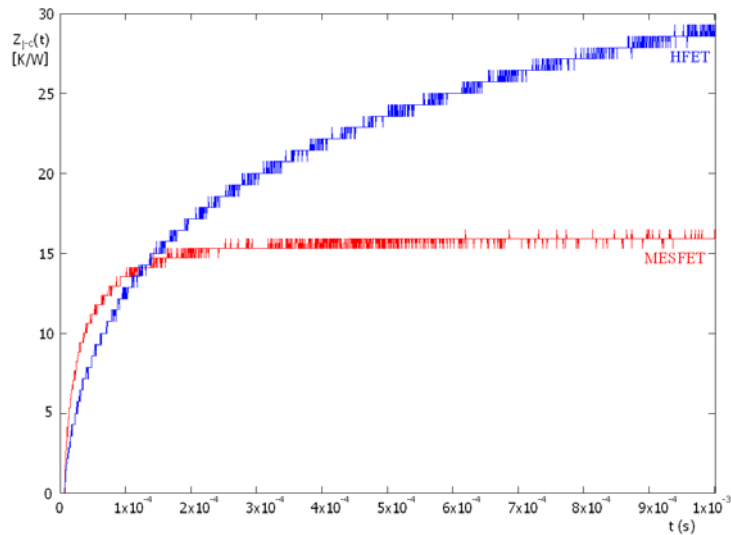


Fig. 2. Transient thermal impedance curve of transistor MESFET (FLC097W) and HFET (SHF0289).

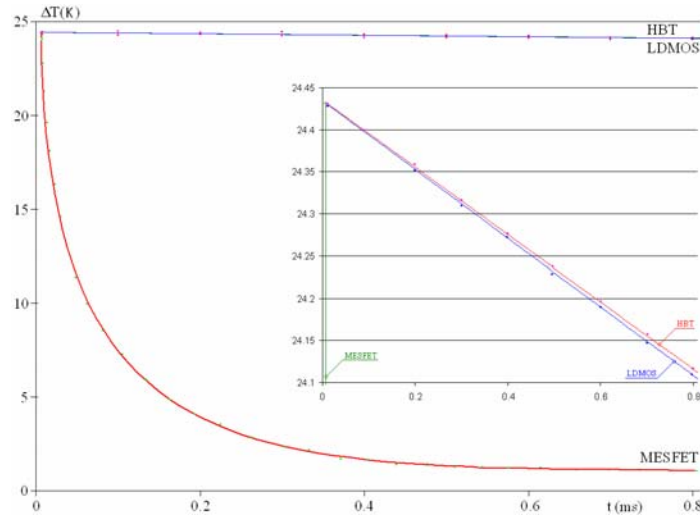


Fig. 3. Cooling curve of transistor MESFET (FLC097W), HBT (43RF0100) and LDMOS (PTF10122).

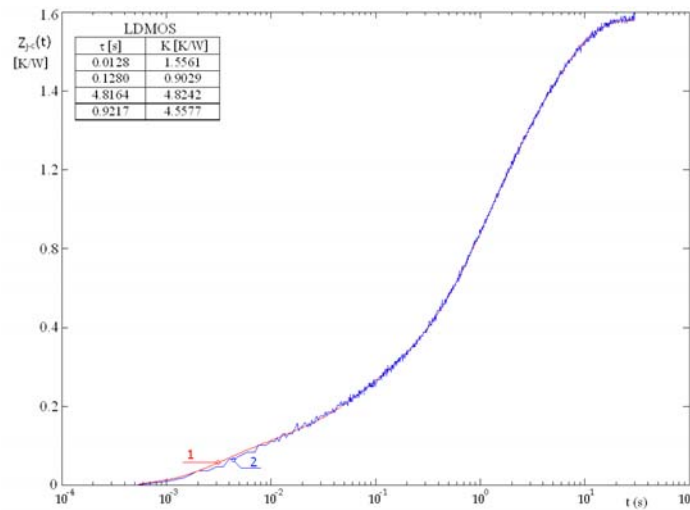


Fig. 4. A comparison of measured thermal impedance (blue curve – 2) and its analytical approximation (red curve – 1) of transistor LDMOS-PTF10122. Thermal resistance is  $K_t = 1.58$  K/W.

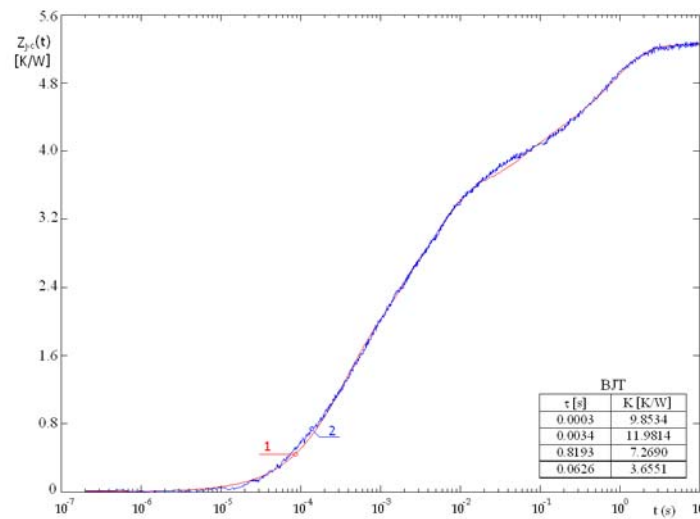


Fig. 5. A comparison of measured thermal impedance (blue curve – 2) and its analytical approximation (red curve – 1) of transistor BJT-LKE21050T. Thermal resistance is  $K_t = 5.2$  K/W.

### 4.3. Discussion of accuracy

The accuracy of the measurements of consecutive values of thermal impedance according to definition (1) is relatively easy to evaluate. It depends on the accuracy of measurements of quantities present in Eq. (1), the heating power  $P_o$  (resulting from measurements of proper current and voltage), the reference temperature  $T_o$  and the samples of inside temperature  $T_j(t)$ . The accuracy of  $T_j$  measurement results from the accuracy measurement of the temperature-sensitive parameter and from the accuracy of the calibration curve.

Based on principles of transient thermal characteristics measurements and the construction of the multitasking measurement system, the evaluation of parameter errors and factors that have strong influence on final measurement results of transistor internal temperature increment curve was conducted. The estimation of the total error  $\delta Z_{j-c}$  of measurement of  $Z_{j-c}(t)$  (in the sense described above), gives the values  $\delta Z_{j-c}$  not exceeding 2% for the range of measurements, where  $T_j(t) - T_o > 5K$  for all the measurements described in Section 4.2. For low values of the temperature rise (corresponding to points of time in close vicinity of 0), the error  $\delta Z_{j-c}$  approaches 6%.

The more important question is the accuracy of calculations of the inside temperature  $T_j(t)$  of a device in which the known power  $p(t)$  is dissipated. Such calculation can be performed on the formula (3) for the assumption of a lumped, linear thermal model, where  $W_{j-o}(t)$  is obtained directly from the known  $Z_{j-c}(t)$  curve. It is the main purpose the transient thermal impedance is introduced for. The problem is: to what extent the transient thermal impedance is an adequate description of involved, distributed thermal processes in the structure of a microwave transistor? This problem is generally very difficult to solve.

The evaluation of accuracy presented in this work is restricted to a comparison of the inside temperature waveforms  $T_{jc}(t)$  calculated for assumed power  $p(t)$  from Eq. (3), with the waveforms  $T_{jm}(t)$  measured (with the use of a temperature-sensitive parameter) for the same power excitation. In the calculations, the previously measured thermal impedance curves  $Z_{j-c}(t)$  are used.

Such comparison has been performed for several transistors under investigation and the discrepancy between the measured and calculated values of the inside temperature rise  $T_j(t) - T_o$  does not exceed 7%. The example of the comparison is presented in Fig. 6.

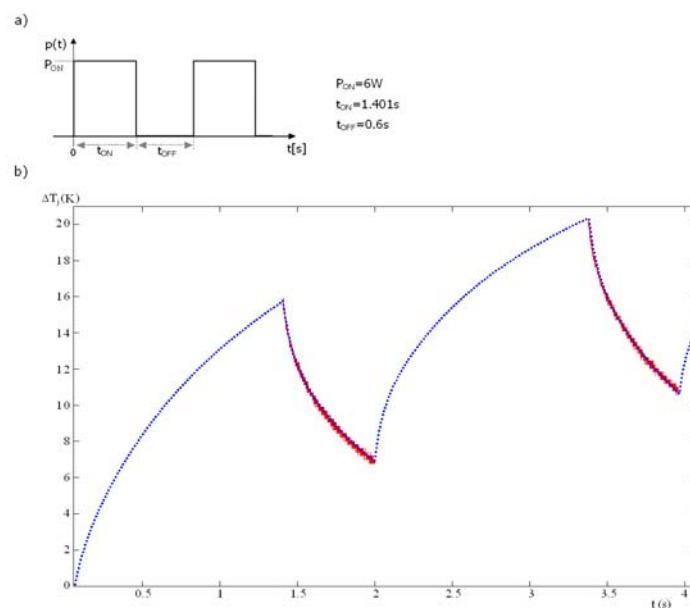


Fig. 6. Temperature rise of LDMOS transistor (b) during pulse power excitation with parameters shown in a) red curve – measurements, blue curve – calculations

## 5. Summary

In the paper, the method and results of the measurements of transient thermal characteristics of several types of modern microwave transistors are presented. Special attention is paid to the measurements of fast thermal transients occurring in transistors directly after a step change of dissipated power. The cooling curve measurement technique is adopted for this purpose. It is observed that the thermal transient in some transistors may be very fast-up to 1 K/ $\mu$ sec for 1W step change of power (see Fig. 3 for transistor MESFET). Such temperature changes may strongly influence the performance of pulse-power microwave amplifiers.

The transient thermal impedance curves may be approximated by the analytical description presented in Section 3 (Eq. 2). The set of coefficients in such description can be obtained by the “curve fitting” procedure. According to results presented in Section 4 the consistency of measured curves and analytical approximation can be very good (see Figs 4 and 5 ). The description of  $Z_{j-c}(t)$  by Eq. (2) can be used in calculations of waveforms of the inside device temperature by the convolution formula (Eq. 3) with the use of highly effective algorithms SARA [14, 19, 20].

Transient thermal impedance is a simplified thermal model that neglects the spatial distribution of temperature inside the transistor. The accuracy of such simplified description has been evaluated by the comparison of results of calculations, according to Eq. (3) for assumed waveform of power  $p(t)$  with the measurement results. The consistency of both results observed in several experiments is satisfactory (the example is given in Section 4.3, Fig. 6).

The precise measurement methods of dynamic thermal characteristics are necessary in many applications, where the temperature is an important factor of the system under investigation [11, 21, 22]. Therefore, the presented methods may find wide application, not only for microwave transistors and circuits.

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