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A NEW METHOD OF THE THERMAL RESISTANCE MEASUREMENTS OF MONOLITHIC SWITCHED REGULATORS

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Abstract: The problem of measurements of the thermal resistance (R_{th}) of monolithic switched regulators (MSR) is considered in the paper. A new method of measuring this thermal parameter is proposed and the proper measuring set is presented. The results of measurements of R_{th} of the considered devices are compared with the similar results obtained with two other known methods.

Keywords: thermal resistance, switched voltage regulators, new measuring method

1. INTRODUCTION

The thermal resistance R_{th} is one of the most important parameter of semiconductor devices and ICs. This parameter characterises the ability of a device to abstract the heat generated in this device.

If the thermal resistance of a device and the power dissipated inside it are known, the inner device temperature T_j, limiting the device SOA at the thermal steady-state and influencing its reliability, can be calculated. The thermal resistance is also an important parameter of electrothermal macromodels (ETMs) of semiconductor devices and ICs [1].

The thermal resistance is defined as follows

$$R_{th} = \frac{T_j - T_0}{P_{th}} \tag{1}$$

where P_{th} denotes the power dissipated in the considered device, T_0 is the temperature of the reference point (case or ambient).

The value of the inner temperature of a device can be estimated by optical, chemical or electrical methods [2]. The optical method can be used to measure temperature distribution in the device or the electronic module [3], whereas from the electrical methods [4, 5, 6, 7] only the information about average temperature of the device can be obtained. Among these methods, only the electrical methods are non-destructive ones and they can be used for measuring packaged devices [8].

Using the electrical methods of measuring the device thermal resistance, the value of the inner temperature T_j can be obtained by measuring the value of any electrical thermo-sensitive parameter of the known and unique dependence on temperature. Typically, the voltage across the p-n junction operating in the forward-mode at the constant value of the current of the small value, is chosen for this purpose [9, 10].

In the electrical methods measuring the thermal resistance of ICs, eg. [9, 10], the same substrate diode is typically used as the heating and thermosensitive element. In such methods, the power is dissipated in another way than that existing during the typical operating mode of a monolithic switched regulator (MSR). On the other hand, the way of power dissipation can influence, even strongly, the device thermal resistance value [1, 11].

In the paper, the monolithic dc voltage switched regulators LT1073 [12] and L296 [13] are considered. These ICs are composed of the power bipolar transistor (switch) as well as some control and protection blocks situated on the same chip.

In the measuring method of the thermal resistance of the monolithic switched regulators, proposed earlier by the authors [14], the heat power is dissipated in the forward-biased p-n body diode. In the second stage of the measurements, the voltage across the same diode is used as the thermo-sensitive parameter. Note, that in the method from [14], the power is dissipated in an other way than that existing during the typical operating mode of the considered regulators.

In the paper a new method of the measurement of the thermal resistance of the monolithic switched regulators in their real operation conditions is proposed. The method is explained in detail for two selected devices - the regulator LT1073 and the regulator L296. The proposed method is the modification of the former one, proposed by the authors for the LT1073 regulator [15]. In the method proposed in this paper, the electrical power dissipated in the device is calculated in such a way that multiplication and integration of the device terminal currents and voltages are not necessary, unlike the method from [15]. The accuracy of this method was verified by comparing the thermal resistance values obtained with this method and two other known methods, e.g. [14].

2. IDEA OF THE METHOD

In the proposed method the MSR operates in the switched voltage stabilizer with dc-dc converter, which is the typical application circuit of the investigated class of devices. The general block diagram of the measuring set is shown in Fig.1.

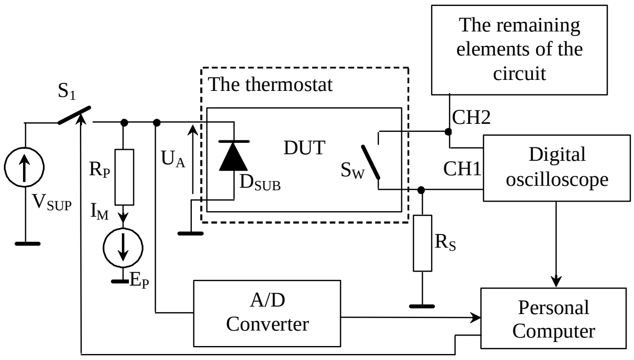

Fig.1. The block diagram of the measuring set

The measurement is realized in three stages. In the first stage (the switch S_1 is opened) the calibration of the thermal characteristic $U_A(T_A)$ of the body diode (D_{SUB}) existing in the investigated regulator (DUT) is performed. The characteristic $U_A(T_A)$ is measured for different values of the ambient temperature T_A, at the fixed current I_M of a small value. According to the considerations included in [16], the slope F of this characteristic is determined from

$$F = \frac{U_{AK} - U_{go}}{T_A} - 1{,}5 \cdot \frac{k}{q} \qquad (2)$$

where U_{AK} denotes the forward biased diode voltage, U_{go} = 1.206 V for silicon, T_A is the ambient temperature, k – the Boltzmann constant and q denotes the electron charge.

In the second stage, the switch S_1 is permanently switched-on and switched-off. When the switch S_1 is switched-on, the electrical power is dissipated mainly in the power bipolar transistor – represented here by the switch S_W. Due to the dissipated power, the inner temperature of the MSR rises over the ambient temperature. When the switch S_1 is switched-off, the voltage U_A across the body diode is measured. At the thermal steady-state the electrical power P_{th} dissipated inside the regulator (switch S_1 is closed) and the voltage U_{AL} on the diode D_w (switch S_1 is opened) are measured.

In the third stage, the thermal resistance is calculated from

$$R_{th} = \frac{U_{AL} - U_{AK}}{P_{th} - U_{AL} \cdot I_M} \cdot F^{-1} \qquad (3)$$

where U_{AL} denotes the U_A voltage in the steady-state when the switch S_1 is in the off stage, P_{th} is the power dissipated in the MSR when the switch S_1 is in the on stage.

Due to the power dissipated in the investigated device in the form of a rectangular wave of the frequency higher than 10 kHz [12, 13]. Therefore, the average value of the power is taken into account to calculate the thermal resistance according to Eq. (1). Such an approach is correct, because as it was proved in [17], the identical values of the device inner temperature at the steady-state are obtained when the time dependence of the power of the rectangular high-frequency wave or of the Heaviside function of the magnitude equal to the average value of the dissipated power are used.

3. PRACTICAL REALIZATION OF THE METHOD

A way of realizing the method depends on the application circuit of the considered regulator. In this Chapter the measuring sets of the pulse voltage regulator operating in the Boost converter (LT1073) and the buck converter (L296) are presented and described.

3.1. LT1073 regulator

To realize the proposed method, the measuring set for LT1073 regulator, presented in Fig.2, has been worked out and tested.

In Fig.2 the block A represents the elements of the application circuit of the LT1073, the block B represents the source of the measuring current, the block C – represents the switch S_1 along with its control circuit and the block D represents the measuring amplifier.

The power transistor (switch S_w) and the body diode existing in the considered regulator are situated between the terminals 3, 4 and 1, 2, respectively.

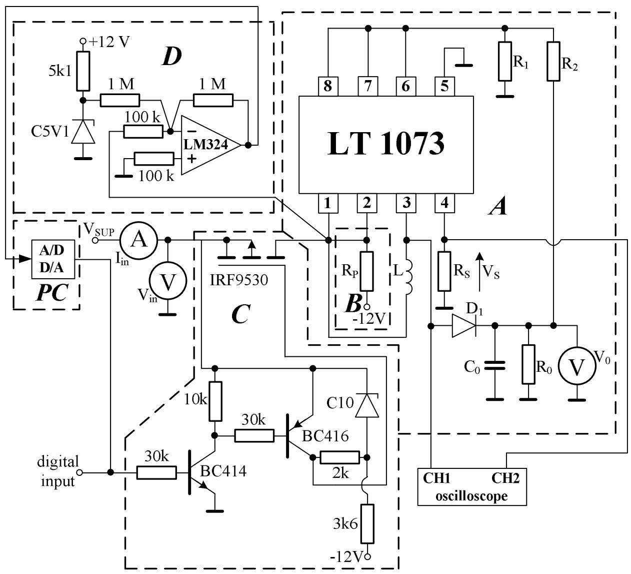

Fig.2. The measuring set for the regulator LT1073

The regulator LT1073 operates in the typical application circuit of the switched stabilizer with the boost converter. The resistors R_1 and R_2 realize the feedback loop, whereas the resistor R_S is used to measure the current of the switch S_w. The power network (block A) is also composed of the diode D, the impedance coil L, the output capacitance C_0 and the load resistance R_0.

The voltage across the forward biased substrate diode connected between the terminals 2 and 5 is treated as the thermosensitive parameter.

The source of the measuring current I_M is realized by the resistor R_p situated between the terminal number 2 of the regulator and the source of the negative supply.

The main task of the transistor IRF9530 situated in the block C is to switch the supply of the regulator between its two operation conditions: the normal operating condition and the measuring one. The other elements existing in the same block ensure the changing of the output voltage of the A/D converter (TTL standard) to the value which guarantees switching-on and switching-off the transistor at any value of the input voltage V_{SUP}. The voltage across the forward biased body diode is measured by the A/D converter. The measuring amplifier (the block D) operating in the adder configuration is indispensable to assure the high accuracy of the measurement. This adder adapts the level of the measuring voltage to the range of A/D conversion.

In the method the average power is calculated from

$$P_{th} = V_{in} \cdot I_{in} - \frac{V_o^2}{R_o} \cdot \left[1 + V_D \cdot \left(1 - \frac{t_{on}}{T_S}\right)\right] - I_{in}^2 \cdot \left(R_L + R_S \cdot \frac{t_{on}}{T_S}\right) \quad (4)$$

where V_{in}, I_{in} are the average values of the input voltage and current respectively, V_o, V_D are the output voltage of the stabilizer and the voltage across the diode during its switching-on respectively, T_S denotes the period of the signal controlling the switch, whereas t_{on} is the turn-on time of the switch. The values of V_D, t_{on}, T_S are obtained from waveforms of the voltage at the terminal number 3 of the LT1073. This waveform has to be measured immediately before the power pulses are switched –off.

Eq. (4) was formulated by subtracting the average power dissipated in the load resistance and the elements existing in the measuring set, from the power received from the supply source V_{SUP}. The commutation power dissipated in the diode when it was switched, was omitted in Eq. (4).

3.2. L296 regulator

Fig.3 presents the circuit for measuring the thermal resistance of the monolithic voltage regulator L296. This circuit is composed of the identical blocks as these existing in the circuit shown in Fig.2, except the block A, represents the application circuit of the considered device. In this block the capacitor C_{OSC} along with the resistor R_{OSC} determine the value of the frequency of the signal controlling the power switch existing in the L296 regulator. The elements R_k and C_k are responsible for the frequency compensation of the error amplifier, whereas the capacitor C_{SS} operates in the soft start circuit. Apart from the regulator L296, there are some additional elements, such as: the diode D_1, the inductor L, the output capacitor C_0 and the load resistance R_0 in the power network existing in the buck converter.

The average power dissipated in the regulator is described by Eq (4).

The low level of the voltage at the digital input ensures that the regulator operates in the typical application circuit (Buck), whereas the high level of this voltage (at the same input terminal) causes switching-off the supply of the regulator and polarization of the substrate diode in the forward mode.

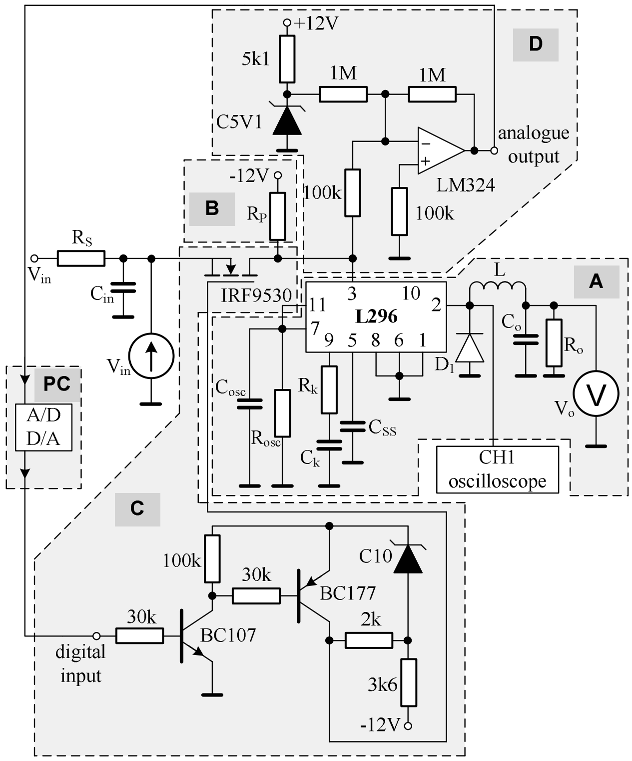

Fig.3. The measuring set for L296

4. VERIFICATION OF THE METHOD

To verify the correctness of the proposed method, the measurements of the thermal resistance of the regulators LT1073 and L296 as a function of the dissipated power, at various cooling conditions of these regulators, have been performed.

The results of the thermal resistance measurements of the regulator LT1073 as a function of the dissipated power obtained both: by the proposed method (triangles), the method from [14] (squares) and the infrared method (circles) are presented in Fig. 4. The investigated device was situated on the universal PCB (105x65 mm) oriented horizontally.

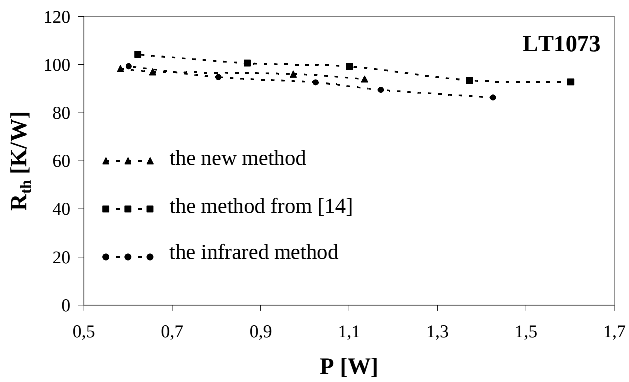

Fig.4. The measuring results of the thermal resistance of the LT1073 on the dissipated power

As seen, the thermal resistance values obtained with all the considered methods are nearly the same. Note, that the thermal resistance slightly decreases with an increase of the electrical power. The values of the R_{th} obtained with the infrared method are lower than the other results obtained with the electrical methods. This is so, because in the infrared method, the case temperature of the regulator LT1073, instead of its inner one, has been taken into account to obtain the R_{th} value of the considered device.

In Fig.5 the results of measurements of the dependence of the thermal resistance on the regulator input voltage V_{SUP} (see Fig. 2) at different cooling conditions of the regulator LT1073 are presented. The voltage regulator under test operates in the measuring set presented in Fig.2. The load resistance R_0 is equal to 150 Ω. During the investigations the LT1073 was situated on the PCB of the dimensions: 110x105 mm oriented horizontally (curve a) or vertically (curve b). Apart from this, the curve c presents the situations, when horizontally oriented PCB is additionally situated inside the typical metal box of the dimensions 83x148x150 mm. The curve d concerns the LT1073 operating along with the aluminium heat-sink of the dimensions 18,5x11,5x1 mm, adhesive to the device case, whereas the PCB was oriented horizontally.

As seen, the values of the R_{th} are lower of about 5% when the PCB is oriented vertically. However, when the LT1073 is placed inside the box, an increase of its thermal resistance of about 10% is observed. The use of the external heat-sink causes a decrease of the thermal resistance value of the LT1073 even more than 20%.

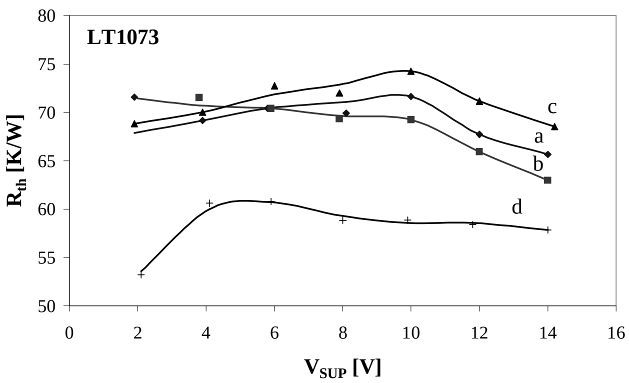

Fig.5. The dependence of the LT1073 thermal resistance on the regulator input voltage for its various cooling conditions

In Fig.6 the measured dependence of the thermal resistance of the regulator L296 on the dissipated power inside them is presented. In this figure triangles denote the results obtained with the proposed method, squares – the results obtained with the method from [14] whereas circles – the results obtained by the infrared method. The investigated device was situated on the PCB (125x74 mm) oriented horizontally.

As seen, the measuring results obtained with the new method and the method from [14] fit well to each other. The values of the thermal resistance measured with the use of the infrared method are about 2 K/W lower than these obtained with the electrical methods. This difference results from the fact that in the infrared method the temperature of the device surface instead of the device inner temperature is measured. In the whole considered range of the dissipated power the thermal resistance degreases with an increase of the dissipated power.

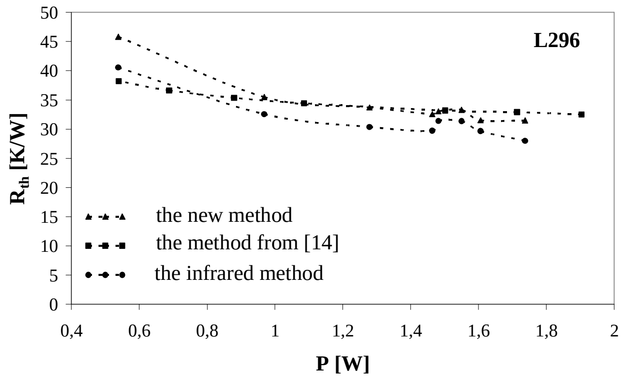

Fig.6. The measuring results of the thermal resistance of the regulator L296 on the dissipated power

In turn, in Fig.7 the dependence of the thermal resistance of the regulator L296 on the voltage at its input obtained with the new method and the infrared one at various cooling conditions of the device is presented. In this figure the measuring results of the device operating without the heat-sink and on the aluminium heat-sink (20x36x1 mm) are denoted by the broken and the solid lines, respectively. The device load resistance R_0 was equal to 5.1 Ω and 2.55 Ω for device operating without and with the heat-sink, respectively.

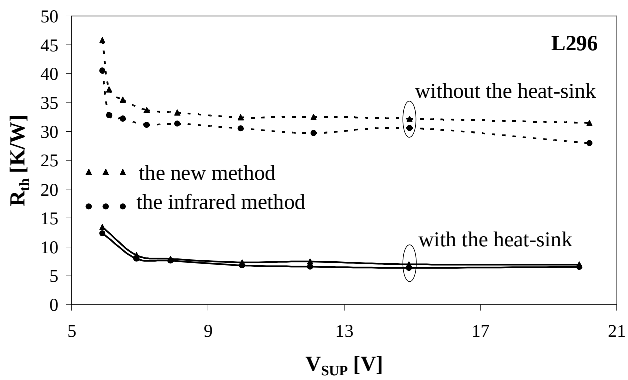

Fig.7. The measuring results of the thermal resistance of the regulator L296 on the regulator input voltage

As seen, the device thermal resistance decreases with an increase of the input voltage. When the heat-sink is used, a five-time-degrease of the device thermal resistance is observed.

5. CONCLUSIONS

In the paper the new method of measuring the thermal resistance of the monolithic switching regulators is proposed. The correctness of this method was proved experimentally. The values of the thermal resistance of the regulators LT1073 and L296 measured with the new method and with the other methods have been compared. The differences are less than a few percentage, but the new method gives the lower values of R_{th}.

As it was shown, the value of the thermal resistance of the considered regulators depends on both the supply voltage and the manner of their mounting. The considered range of the change of the supply voltage as well as the use of the metal heat-sink leads to the change of the thermal resistance.

Due to the long electrical time constant characterizing the power block (typically about 10 - 20 ms) the proposed method can be used to monitor the inner temperature of the regulator during its typical operating conditions, which could be used in designing the external system of the thermal protection of the power supplies including the considered regulators.

REFERENCES

[1] J. Zarębski, Modelling, Simulations and Measurements of Electrothermal Characteristics in Semiconductor Devices and Electronic Circuits, Proc. of Gdynia Maritime Academy, Gdynia 1996, (in Polish)

[2] S. Rubin and F. Oettinger, Thermal Resistance Measurement on Power Transistors. National Bureau of Standards, NBS 400-14, U.S. Dept. of Commerce, 1979.

[3] M. Janicki, P. Kawka, G. De Mey and A. Napieralski, “IGBT Hybrid Module Thermal Measurements and Simulations”. 8-th International Conference Mixed Design of Integrated Circuits and Systems MIXDES 2001, Zakopane, 2001, p. 249.

[4] V. Székely, M. Rencz and B. Courtois, “Thermal investigations of ICs and microstructures”, Sensors and Actuators A Physical, Vol. A 71, no. 1-2, 1998, pp. 1-2.

[5] V. Székely, “Thermal testing and control by means of built-in temperature sensors”. Electronics Cooling, Vol. 4, No. 3, 1998, pp. 36-39.

[6] V. Székely, M. Rencz and B. Courtois, “Thermal investigations of IC's and microstructures”, Microelectronics Journal, Vol. 28, No 3, pp. 205-207, 1997.

[7] J. Glinianowicz, F. Christiaens, E. Beyne and Z. Staszak, “Measurement Circuits for Transient Thermal Characterisation on Power Transistors and Transformers”, XVII-th National Conference Circuit Theory and Electronic Networks, Wrocław – Polanica Zdrój, 1994, p.359.

[8] K. Górecki and J. Zarębski, „Microcomputer System for Measuring Thermal Parameters of a Class of Semiconductor Devices and Integrated Circuits”. Metrology and Measurement Systems, No. 4, 2001, pp. 379-396. (in Polish)

[9] V. Szekely, M. Rencz, “Increasing the accuracy of thermal transient measurements”, IEEE Transactions on Components & Packaging Technologies, vol.25, no.4, Dec. 2002, pp.539-46.

[10] F. F. Oettinger, D. L. Blackburn, “Semiconductor Measurement Technology: Thermal Resistance Measurements”, U. S. Department of Commerce, NIST/SP-400/86, 1990.

[11] F.F. Oettinger, D.L. Blackburn, S. Rubin, “Thermal characterization of power transistors”, IEEE Trans. on El. Dev., ED-23, No. 8, 1976, pp.831-838.

[12] LT1073- Micropower DC/DC Converter Adjustable and Fixed 5 V, 12 V. Linear Technology corporation, 2000.

[13] Designing with the L296 Monolithic Power Switching Regulator. AN244/1288, SGS-Thomson, STMicroelectronics, 1996.

[14] K. Posobkiewicz, K. Górecki and J. Zarębski, “Measurements of the Thermal Resistance of Monolithic Voltage Regulators”. Proceedings of Gdynia Maritime University, No. 53, 2004, pp. 105-112 (in Polish).

[15] K. Górecki, J. Zarębski, “A New Method of the Measurement of the Thermal Resistance of the Monolithic Switched Regulator LT1073”, 6 Seminario International de Metrologia Eletica VI Semetro, Rio de Janeiro, 2005, p. 53.

[16] K. Górecki, J. Zarębski, „Investigation of the Thermometric Characteristics of Semiconductor Devices with p-n Junction”. Metrology and Measurement Systems, No. 4, 2001, pp. 397-411. (in Polish)

[17] K. Górecki and J. Zarębski, „Calculation of an Inner Temperature of Power Semiconductor Devices Controlled by High Frequency Signal” XXVIII International Conference on Fundamentals of Electrotechnics and Circuit Theory IC-SPETO’2005, Ustroń, 2005, Vol. 2, pp. 253-256. (in Polish)