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## A NEW MEASUREMENT METHOD OF THE TRANSIENT THERMAL IMPEDANCE OF THE MONOLITHIC SWITCHED REGULATOR LT1073

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### ABSTRACT

The transient thermal impedance  $Z(t)$  of the monolithic switched regulator LT1073 is investigated in the paper. A new method of measuring this thermal parameter of the device in its real operation conditions is proposed and the proper measuring set is described, too. The results of the  $Z(t)$  measurements of the device operating at its various cooling conditions are presented. Apart of this, the measuring results corresponding to the steady-state obtained both by the proposed method and by the other known methods are compared.

### 1. INTRODUCTION

The transient thermal impedance  $Z(t)$  is one of the most important parameter of semiconductor devices and ICs. This parameter characterises the ability of a device to abstract of the heat generated in this device. If a time dependences of both the transient thermal impedance of a device and the power dissipated inside it are known, the inner device temperature  $T_j$  limiting the device SOA and influencing its reliability can be calculated. The transient thermal impedance is also an important parameter of electrothermal macromodels (ETMs) of semiconductor devices and ICs [1]. Therefore, the accuracy of estimation of the transient thermal impedance affects the accuracy of modelling nonisothermal characteristics of such devices and ICs obtained after the ETM.

In the paper [2] two measuring methods of  $Z(t)$  of power transistors using the cooling or the heating curve are described. Our further considerations are based on the cooling curve, according to which the transient thermal impedance is defined by

$$Z(t) = \frac{T_j(t=0) - T_j(t)}{P_{th}} \quad (1)$$

where  $T_j(t=0)$  denotes the device inner temperature corresponding to the moment of switching-off the heating power  $P_{th}$  dissipated at the steady-state.

The most popular model of a device transient thermal impedance is of the form [1, 3]

$$Z(t) = R_{th} \cdot \left[ 1 - \sum_{i=1}^N a_i \cdot \exp\left(-\frac{t}{\tau_{thi}}\right) \right] \quad (2)$$

where  $R_{th}$  denotes the thermal resistance,  $\tau_{thi}$  is the  $i$ -th thermal time constant and the sum of  $a_i$  factors have to be equal to 1, whereas  $N$  is the number of the thermal time constants.

The value of the inner temperature of a device can be estimated by optical, chemical or electrical methods [4]. The optical method can be used to measure temperature distribution in the device or the electronic module [5], whereas from the electrical methods [6, 7, 8, 9] only information about average temperature of the device can be obtained. Among these methods, only electrical methods are non-destructive ones and they can be used for measuring of packaged devices [10].

Using the electrical methods of measuring the device transient thermal impedance, the value of the inner temperature  $T_j$  can be obtained from the measurements of a value of any electrical thermo-sensitive parameter of the known dependence on temperature. A voltage across the p-n junction operating in the forward-mode at the constant value of the current of the small value, is typically chosen to this end [11, 12].

In the paper, the monolithic dc voltage switched regulator LT1073 [13] is considered. This IC is composed of the power bipolar transistor (switch) as well as some control and protection blocks situated on the same chip. As it results from the authors' investigations [14, 15], the inner temperature of LT1073 affects the electrical characteristics of this regulator operating in the BOOST converter. The knowledge of the transient thermal impedance of LT1073 is indispensable for the correct designing of the considered class of switched power supplies.

In the measuring method of the thermal resistance of the monolithic switched regulator LT1073, proposed earlier by the authors [16], 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 [16], the power is dissipated in an other way than that existing during the typical operating mode of the LT1073.

On the other hand, the way of the power dissipation can influence, even strongly, the device thermal resistance value [1, 17].

In the paper, a new method of the measurement of the transient thermal impedance of the LT1073 regulator obtained in its real operation conditions is proposed for the first time. The accuracy of this method was verified by comparison of the thermal resistance values obtained by this method and other known methods, e.g. from [16].

## 2. THE GENERAL CONCEPTION OF THE METHOD

In the proposed method the regulator LT1073 operates in the switched voltage stabilizer with BOOST converter which is the typical application circuit of the investigated device. The general conception of the measuring set is presented in Fig.1.

To select a thermo-sensitive parameter of the best features, the available terminal current-voltage characteristics of the LT1073 have been examined. It was noticed that six junctions are available for a user, but unfortunately, these junctions are reverse biased during normal operating conditions of the LT1073. Finally, the voltage across the forward biased p-n body diode ( $D_{SUB}$ ) operated at the constant value of the current has been chosen as a thermo-sensitive parameter.

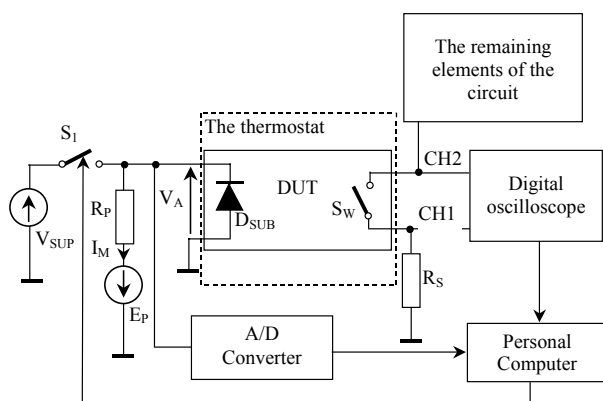


Fig.1. The block diagram of the general conception of the measuring set

The measurement is realized in four stages. In the first stage (the switch  $S_1$  is opened) the calibration of the thermometric characteristic  $V_{AK}(T_A)$  of the body diode ( $D_{SUB}$ ) existing in the investigated regulator (DUT) is performed. The characteristic  $V_{AK}(T_A)$  is measured for different values of the ambient temperature  $T_A$ , at the fixed current  $I_M$  of the small value. According to the

considerations included in [18], the slope  $F$  of this characteristic is determined from

$$F = \frac{V_{AK} - V_{go}}{T_A} - 1,5 \cdot \frac{k}{q} \quad (3)$$

where  $V_{AK}$  denotes the forward biased diode voltage corresponding to the current  $I_M$  and the temperature  $T_A$ ,  $V_{go} = 1.206$  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 switching-on and switching-off. The on-time is one thousand times longer than the off-time. When switch  $S_1$  is switched-on, the electrical power is dissipated mainly in the power bipolar transistor – represented here by the switch  $S_{\mu}$ . Due to the dissipated power, the inner temperature of the LT1073 rises over the ambient temperature. When the switch  $S_1$  is switched-off, the voltage  $V_A$  across the body diode is measured. At the thermal steady-state the electrical power of the average value equal to  $P_{th}$  dissipated inside the regulator (switch  $S_1$  is closed) and the voltage  $V_{AL}$  on the diode  $D_w$  (switch  $S_1$  is opened) are measured. The second stage is finished, when the thermal steady-state is achieved.

During the third stage the switch  $S_1$  is finally switched-off ( $t = 0$  is assumed) and the values  $V_{AL}(t)$  are measured until (due to the device cooling) the inner temperature equals the ambient one.

In the fourth stage, the transient thermal impedance is calculated from

$$Z(t) = \frac{V_{AL}(t=0) - V_{AL}(t)}{P_{th} - V_{AL} \cdot I_M} \cdot F^{-1} \quad (4)$$

Due to the power dissipated in the investigated device is of the form of the rectangular wave of the frequency equal to 19 kHz [13], therefore the average value of the power is taken into account to calculate the transient thermal impedance according to Eq. (1). Such approach is correct, because as it was proved in [19], the identical time dependences of the device inner temperature are obtained when the time dependence of the power of the Heaviside function or the rectangular high-frequency wave (19 kHz) of the same value are used.

## 3. DESCRIPTION OF THE METHOD

To realize the proposed method, the measuring set 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, 5, respectively.

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 (the block A) is also composed of the diode  $D_1$ , the impedance coil  $L$ , the output capacitance  $C_0$  and the load resistance  $R_0$ .

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 two kinds of the operation conditions: the normal operating condition and the measuring one. The other elements existing in the same block ensure a change 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 on the forward biased body diode is measured by the A/D converter. The measuring amplifier (block D) operating in the adder configuration is indispensable to ensure the high measurement accuracy. This adder adapts the level of the measuring voltage to A/D conversion range.

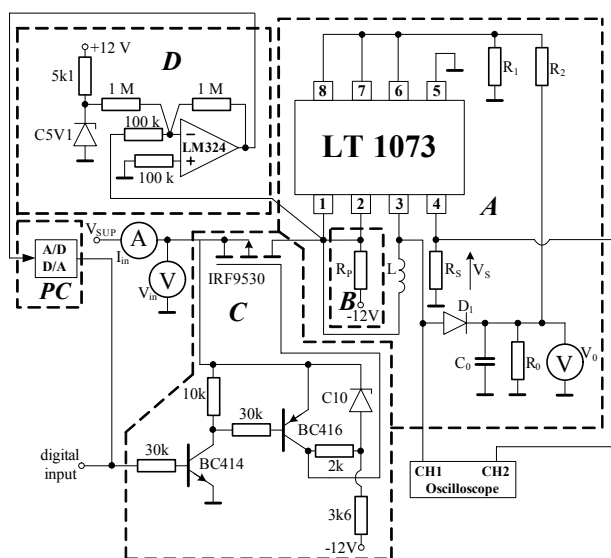


Fig.2. The electrical diagram of the measuring set

The computer program, controlling the operation conditions of the measuring set, realizes two tasks:

- generation in the digital output of the A/D and D/A converter card the pulse train controlling the transistor switch,
- reading the voltage across the forward biased body

diode from the A/D converter during the time (very short) when the transistor IRF9530 is switched-off.

In the second stage of the measurements, the electrical power  $P_{th}$  of the form of the rectangular wave of the duty factor equal to 1, which causes an increase of the regulator inner temperature, is dissipated in the LT1073. Practically, almost the whole power  $P_{th}$  is dissipated in the transistor (switch  $S_w$ ). The shape of the power  $P_{th}$  is much irregular unlike the shape of the power (rectangular wave) dissipated during the realisation of the classical pulse methods of measurements of the transient thermal impedance of semiconductor devices [16, 17]. Therefore, in the proposed method the value of the heating power  $P_{th}$  is calculated by averaging the voltage and current courses existing on the transistor switch  $S_w$ .

In the method, the average power is calculated from

$$P_{th} = V_{in} \cdot I_{in} - \frac{V_o^2}{R_o} \cdot \left[ 1 + V_D \cdot \left( 1 - \frac{t_{on}}{T_S} \right) \right] - I_{in}^2 \cdot \left( R_L + R_S \cdot \frac{t_{on}}{T_S} \right) \quad (5)$$

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 oscillogram of the voltage at the terminal number 3 of the LT1073. This oscillogram has to be measured immediately before the power pulses are switched-off.

The second stage of the method is finished, when two values of the voltage  $V_A$  measured one after an other in the interval time equal to one minute, differ from each other less than 2 mV. This means that the inaccuracy of the inner temperature estimation is not greater than 1 K.

#### 4. VERIFICATION OF THE METHOD

To verify the correctness of the proposed method, measurements of the transient thermal impedance and the thermal resistance of the LT1073 as a function of the dissipated power at various cooling conditions of this regulator, have been performed. As it results from [18], linearity of the thermometric characteristic depends on the value of the body diode current. To obtain the linear thermometric characteristic in the widest range of temperature changing, some  $V_{AK}(T_A)$  dependencies at the various current values  $I_M$  were measured (Fig.3).

As seen, the most linear characteristic corresponds to the value of the current  $I_M = 1 \mu A$ . At this current value the highest value of the characteristic slope  $F=dV_{AK}/dT$  is observed. For the lower current value ( $I_M = 10 \text{ nA}$ ) the linearity of  $V_{AK}(T_A)$  characteristic is restricted by the recombination component of the body diode current, whereas the nonlinearity of the characteristic corresponding to the much higher value of current ( $I_M =$

100 mA) results from the existence of the diode series resistance and its dependence on temperature.

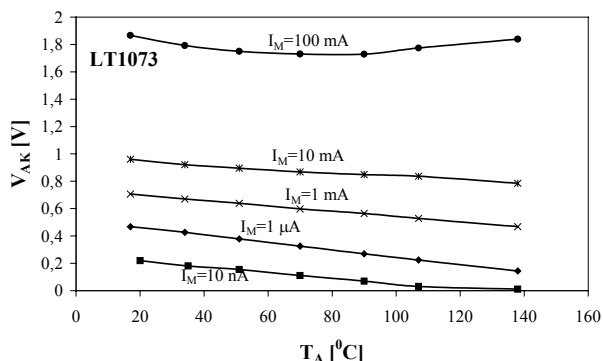


Fig.3. The thermometric characteristics of the LT1073 body diode

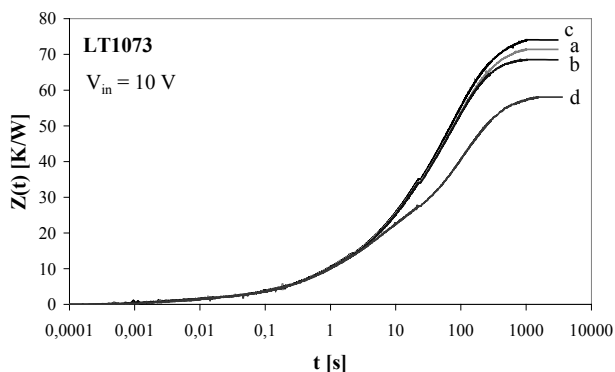


Fig.4. The measured dependences of the Z(t) of the LT1073 regulator for various cooling conditions

In Fig.4 the time dependences of the Z(t) of the LT1073 measured by the proposed method for the various cooling conditions, at  $V_{in} = 10\text{ V}$  are presented. The voltage regulator under test operates in the measuring set presented in Fig.2. The load resistance  $R_0$  is equal to  $150\ \Omega$ . During the investigations the LT1073 was situated on the PCB of the dimensions:  $110 \times 105\text{ mm}$  oriented horizontally (curve a) or vertically (curve b). Apart from this, the curve c concerns the situations, when horizontally oriented PCB is additionally situated inside the typical metal box of the dimensions  $83 \times 148 \times 150\text{ mm}$ . The curve d concerns the LT1073 operating along with the aluminium heat-sink of the dimensions  $18,5 \times 11,5 \times 1\text{ mm}$  adhering to the device case, whereas the PCB was oriented horizontally. As seen, for  $t < 10\text{ s}$  the measured curves are practically the same. So, the cooling conditions affect the Z(t) the most visible at the steady-state.

Using the Z(t) dependences from Fig.4 and the estimation method described in [20], the set of values of the coefficients existing in Eq. (1) was calculated

(Table 1).

Table 1. Coefficients existing in the Z(t) model for various cooling conditions of the LT1073

coefficient	Curve a	Curve b	Curve c	Curve d
$R_{th}$ [K/W]	72.1	68.6	74.3	58.2
$a_1$	0.135	0.135	0.135	0.14
$\tau_{th1}$ [s]	400	200	330	400
$a_2$	0.449	0.449	0.449	0.444
$\tau_{th2}$ [s]	92	92	92	122
$a_3$	0.247	0.247	0.247	0.207
$\tau_{th3}$ [s]	13	13	13	10
$a_4$	0.102	0.102	0.102	0.126
$\tau_{th4}$ [s]	1.4	1.4	1.4	1.4
$a_5$	0.042	0.042	0.042	0.052
$\tau_{th5}$ [s]	0.19	0.19	0.19	0.19
$a_6$	0.025	0.025	0.025	0.031
$\tau_{th6}$ [s]	0.007	0.007	0.007	0.007

As seen, the values of three the shortest thermal time constants are independent of the cooling conditions of the investigated regulator, whereas values of  $a_i$  and  $R_{th}$  change, e.g. the most longer thermal time constant  $\tau_{th1}$  changes itself twice (see differences between curves a and d).

The results of the  $R_{th}$  measurements of the LT1073 as a function of the dissipated power obtained both: by the proposed method (triangles), the method from [16] (squares) and the infrared method (circles) are presented in Fig. 5. The investigated device was situated on the universal PCB ( $105 \times 65\text{ mm}$ ) oriented horizontally.

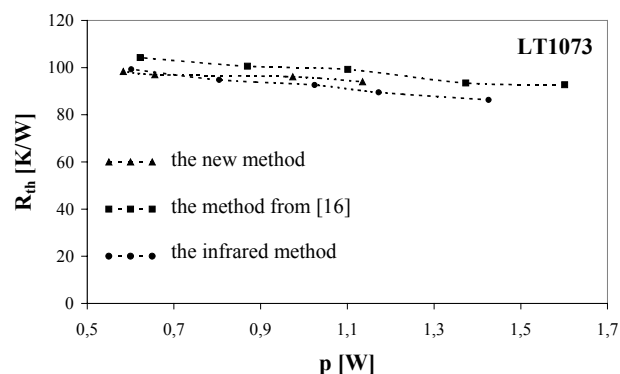


Fig.5. The measurement results of the  $R_{th}$  of the LT1073 on the power dissipated

As seen, the thermal resistance values obtained by all the considered methods are nearly the same. Note, that the thermal resistance slightly decreases with an increase of electrical power. The values of the  $R_{th}$  obtained by the infrared method are lower than other results measured by the electrical methods. This is so, because in the infrared method, the case temperature of the LT1073 instead of its

inner one has been taken into account to obtain the  $R_{th}$  value of the considered device.

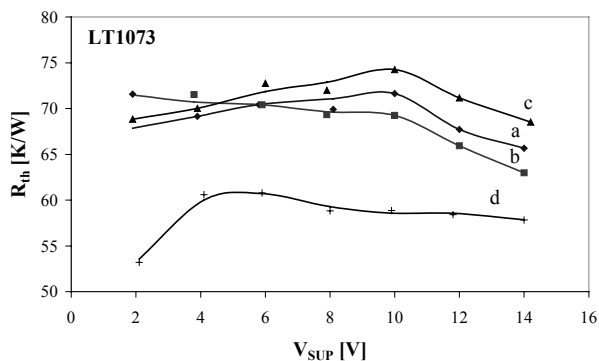


Fig.6. The dependence of the LT1073 thermal resistance on the regulator input voltage for its various cooling conditions

In Fig.6 the results of measurements of the dependence of the thermal resistance on the regulator input voltage  $V_{SUP}$  (see Fig. 2) at the same cooling conditions of the LT1073, as it was considered in Fig.4, are presented. 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. Using the external heat-sink causes decreasing of the thermal resistance value of the LT1073 even more than 20%.

## 5. CONCLUSIONS

In the paper the new method of measuring the transient thermal impedance of the monolithic regulator LT1073 is proposed. The correctness of this method was revealed experimentally.

To describe well the  $Z(t)$  according to Eq. (2), six thermal time constants of the values from 7 ms to 400 s are needed. Changing of the PCB orientation causes the changing of the longest thermal time constant only.

The values of the thermal resistance of the LT1073 measured by the new method and by the other electrical one [16] have been compared (Fig.4). The differences are less than a few percentage, but the new method gives lower values of the  $R_{th}$ .

As was shown, the value of the thermal resistance of the LT1073 depends on both the supply voltage and the manner of its mounting. The considered range of change of the supply voltage as well as the use of the metal box leads to the change of the thermal resistance of about 10%. It is worth to notice, that changing of the PCB area results in changing of the thermal resistance of the investigated device even more than 30%.

Due to the long thermal time constant characterizing the power block (typically about 10 - 20 ms) the proposed

method can be used to observe the inner temperature of the regulator during its typical operation conditions, which could be used in designing the external system of the thermal protection of the LT1073.

## 6. ACKNOWLEDGMENTS

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