International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 18 (2017) pp. 7675-7681
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Automated Control of Die-to-Case Thermal Resistance in Integrated Circuit Packages of Pulse Voltage Converters

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Abstract

The article highlights the topicality of the problem of controlling the die-to-case thermal resistance in the integrated circuit packages of pulse voltage converters which determines the quality of the product. The review of the existing methods and procedures of controlling the junction-to-case thermal resistance of the semiconductor devices is given. Their high labor intensity, sufficient duration of the control process and the impossibility of using pulse voltage converter ICPs for automated control of microcircuits in the conditions of mass production are shown. The objective of this article is to propose and justify a method that is a modification of the standard method enabling to apply it in automated control. As a result of the study, it was established that the junction-to-case thermal resistance of the pulse converter chip can be significantly accelerated. The proposed method is based on the determination of junction temperature by the electrical parameters of one of the *p*-*n*-junctions in the structure of the pulse voltage converter packages. The materials of the article can be useful for developers and users of automated tools for controlling electrical parameters of semiconductor devices and integrated circuits.

Keywords: pulse voltage converter, junction-to-case thermal resistance, *p*-*n*-junction, automated control

INTRODUCTION

High-frequency pulse voltage converters are used in secondary power supplies, which are available practically in all products of the electrical and radio engineering industry – in computers, televisions, in various automated devices and systems. There are several dozens of such integrated circuit packages (ICPs) in the electrical aircraft equipment. Failure of one ICP can lead to serious consequences.

The most important parameter determining the quality of semiconductor device manufacturing is its junction-to-case thermal resistance. The junction-to-case thermal resistance determines the amount of overheating (temperature rise) of the active region of the die with respect to the case temperature. Defective mounting of the die to the case can result in an excess of the permissible temperature of the device, in accelerating the degradation processes and forming defects in instrument structures and, consequently, in failure of the semiconductor device under operating conditions. According to International Rectifier (IR) Company, the world's largest manufacturer of high-power transistors and diodes, and Cree, the largest manufacturer of high-power LEDs, the failure of high-power semiconductor components is caused by the following main reasons: 20% – the impact of external climatic factors, 20% – mechanical impact and 60% – violation of thermal regimes. Overheating of a semiconductor device die directly depends on its thermal resistance. Junction temperature is used to calculate reliability and to estimate the service life of semiconductor devices. The reliability of the device deteriorates exponentially with temperature increase. As a rule, the temperature increase by 10-15° C can shorten the life of the product by more than 50%. For these reasons, it is necessary to determine the junction temperature accurately when the semiconductor device is operating in the nominal mode.

The junction-to-case thermal resistance is not only an indicator of reliability, but also an indicator of the level of quality of the technological process of manufacturing semiconductor devices. Therefore, one of the main tasks of the output control in the production of semiconductor devices and the input control in the manufacture of radio electronic equipment is to determine the thermal resistances of semiconductor devices.

The structure of integrated circuit packages of high-frequency pulse voltage converters (PVC) has transistorized keys that commute currents up to 10 A and more, which can lead to ICP overheating. The control of junction-to-case thermal resistance of power transistors is regulated by standards, and the corresponding methods are in principle suitable for controlling junction-to-case thermal resistance of PVC ICPs, but due to the limited number of ICP pins access to the basic terminals of transistors is usually impossible.

The analysis of the PVC ICP structure indicates the presence of *p*-*n*-junction between some pins, whose properties can be used to control the junction temperature and the entire die while determining the junction-to-case thermal resistance of these integrated circuit packages.

GOST 24461-80 [1] is the main normative document governing the method of controlling junction-to-case thermal resistance of power diodes *Rthjc*. It considers two options for determining the thermal resistance of diodes, each of which contains two stages. At the first stage, the temperature dependence of the temperature-sensitive parameter is determined in both variants. At the second stage, the temperature difference between the die and the case is determined in different ways. The junction-to-case thermal resistance is defined as the ratio of the temperature difference between the die and the case to the heating power in the steady-state nominal mode.

It is recommended to use a direct voltage u_F for diodes or an open voltage u_T for thyristors and symmetric thyristors as a temperature-sensitive parameter. Junction temperature T_J is determined by the calibration characteristic of the device. The semiconductor device is graded in the thermostat when a measuring current which does not affect the thermal equilibrium is flowing.

The concept of thermal resistance requires adopting simplified assumptions, such as a unidimensional heat flow, which fails to accurately simulate the three-dimensional thermal conductivity in a real device. The actual devices contain material and boundary layers with thermal resistances and heat capacities, which lead to a complex heat flow.

The methods recommended by the standard [1] for measuring thermal resistance are applied only for single diodes in laboratory conditions because of the high labor-intensiveness. They are not used for automated control in a batch production.

GOST 24461-80 [2] is the main normative document regulating the method of controlling junction-to-case thermal resistance of power transistors R_{thjc},. It is similar to [1] in many respects and because of the high labor intensity it is also not used for automated control in the conditions of mass production.

The following foreign standards should be highlighted: the US military standard MilStd 883C Method 1012.1 [3] and the international standard EIA/JEDEC JESD51-1 standard [4]. Based on the standard [4], the well-known T3Ster [5] and its Chinese counterpart TRA-200 HEO-200 [6] were developed.

In accordance with the standard [4], the semiconductor device is heated by a step (pulse) of heating power and the temperature of *p-n*-junction $T_J(t)$ is measured during the heating of the object until a steady state is reached. To measure $T_J(t)$ the heating power is periodically switched off for a short time (by several units or tens of microseconds) and the temperature-sensitive parameter is measured – the voltage drop at the *p-n*-junction with a small direct current. Based on the transient thermal performance (TTP) of $T_J(t)$, the components of thermal resistance corresponding to the individual layers of the structure or design of the object are determined. Information about the thermal parameters of the object is obtained in one time scan, which usually does not exceed several hundred seconds in duration, with a total number of temperature readings not exceeding 2000 (200 readings per decade). The error in measuring the TTP is conditioned by the quantization error of the analog-to-digital converter and to the effect of transient thermal and electrical processes when the semiconductor device is switched from the warm-up mode to the measurement mode. To more accurately identify the thermal parameters by TTP, A. Poope and V. Szekely proposed the so-called apparatus of structure functions [7, 8].

To reduce the influence of electrical transients, the linear law of modulation is applied, when pulses of heating current of preset amplitude and constant period of repetition, the duration of which is changed linearly, are passed through the diode. In the pauses between the heating pulses, the direct voltage at the *p-n*-junction is measured with a small current. This makes it possible to reduce the influence of electrical transients, since in this case it is not the absolute value of the transition temperature that is measured, but the rate of its change. However, due to the small steepness of the variation in the average heating power, this method has a low accuracy in measuring thermal resistance and does not allow determining the components of the thermal resistance.

In recent years, methods have been actively developed that are based on the analysis of the frequency thermal characteristics, i.e., the dependence of the amplitude and phase of changing the junction temperature $T_J(\omega)$ on the frequency when the device is heated with the power, which varies according to the harmonic law $P(t) = P_0 + P_m \sin\omega t$. These methods [9-22, 26-33] allow measuring the thermal resistance of individual layers of a semiconductor device structure: die, die holder, solder layer or conductive glue and case base. Based on the calculation of the amplitudes and phases of the fundamental harmonics of the heating power and the temperature of the *p-n*-junction, transient heat transfer resistance (thermal impedance) modulus and the phase shift φ between the *p-n*-junction temperature and the heating power are determined. Then, the dependence of the thermal impedance modulus on the heating power modulation frequency $Z_{thjc}(\omega)$ is taken and the parameters of the thermal circuit are determined. By analogy with electrical circuits, thermal impedance is considered as the complex number $\underline{Z}_{thjc} = Z_{thjc} e^{j\varphi}$, the real part of which determines thermal resistance $R_{thjc} = Re[\underline{Z}_{thjc}]$.

It should be noted that the considered methods for determining the thermal parameters of the diodes do not comply with GOST 25529. In accordance with GOST 25529, the transient thermal resistance of the $Z_{(th)t}$ is the difference quotient, i.e. the ratio of the change in the junction temperature and temperature at the reference point at the end of a predetermined time interval to the step change in the dissipated power of the diode causing temperature change at the beginning of this interval, and the transient junction-to-case thermal resistance of the diode $Z_{(th)t}$ is the transient thermal resistance when the temperature of the diode case is the temperature at the reference point. In accordance with this standard, the junction-to-case thermal resistance of the diode R_{thjc} is defined as difference quotient of the effective junction temperature and the temperature at the reference point to the dissipated power of the diode in a steady state.

Continuing the analogy of the thermal parameters of the diode with the parameters of the electrical circuits, one can compare the TTP $T_J(t)$, determined under the standard [4], with the time characteristic of the circuit $h(t)$, and the thermal impedance $\underline{Z}_{thjc}$ with the complex frequency response $K(j\omega)$. Then the dependence of the thermal impedance modulus on the heating power modulation frequency $Zthjc(\omega)$ will be similar to the $K(\omega)$ – amplitude-frequency characteristic of the electrical circuit.

The thermal characteristics of the diode considered differ in the form of the argument of the analyzed junction temperature-time or frequency dependency. They are of interest in the study of dynamic modes of diode operation. However, the thermal resistance R_{thjc}, which is determined in the steady-state thermal regime, is used much more often. It is given in the reference data of diodes and integrated circuit packages of high-frequency PVC.

Many patents are known [9, 10, 14 - 17, 20, etc.], oriented to the frequency method of measuring thermal resistance. Based on the patent [9], a “hardware-software test and measurement complex for the diagnostics and control of power semiconductor devices in a state of high conductivity” was developed and manufactured at the Department of Automation of the Mordovia State University, which allows determining of a junction-to-case thermal resistance in the steady-state thermal regime R_{thjc} along with the main passport parameters of a semiconductor device. On the basis of patents [11, 14] “a thermal resistance meter for light-emitting diodes and LED modules” was developed [12].

The process of determining the thermal resistance by these methods is quite long-lasting (measured in minutes) and therefore their application for automated control under conditions of mass production is not feasible. In a number of works, essentially different methods for determining the thermal resistances of semiconductor devices have been proposed, for example, measuring the thermal parameters of digital integrated circuits using the temperature dependence of the signal propagation time [20, 21]. They demonstrate the possibility of using digital integrated circuits of the signal propagation time delay as a temperature-sensitive parameter in the measurement of the TTP, which varies over a wide range and depends on the temperature, is shown. Application of this method is complicated by the necessity to measure short time intervals with picosecond accuracy. This method cannot be used for automated control of the thermal parameters of PVC integrated circuit packages.

METHODOLOGY

To reduce the duration of tests when arranging automated control of thermal resistances R_{thjc} of mass-produced semiconductor devices and PVC integrated circuit packages, the authors propose to apply the standard method [1], modifying it in a certain way. The modification is as follows.

In a particular batch to be controlled, or at the beginning of the production of single-phase semiconductor devices or integrated circuit packages, one item is chosen as the reference and its thermal resistance R_{thjc} and the thermal time constant τ are determined by the known laborious method [1]. Then the reference item is connected to the tester first without load, and then with a nominal load for a time comparable to the thermal time constant of the semiconductor device or integrated circuit package. In this case, before and at the end of the heating, the value of the temperature-sensitive parameter is measured, which is the direct voltage drop across the *p-n*-junction (diode) at a given small measuring current. The duration of heating, the value of the measuring current and the difference of the two voltages are stored in the tester memory and subsequently these data are used as a reference in the automated testing of other semiconductor devices or integrated circuit packages of this batch. If at the end of the time interval, taken for measuring, voltage difference of the controlled items at the *p-n*-junction ΔU for a given small measuring current coincides with the reference ΔU_r, then it can be assumed that they coincide when the steady-state conditions are reached, assuming the heating processes are identical. Thus, the thermal resistance of the controlled item can be equated to the value known to the reference item. To exclude the impact of the initial temperature of the item, the voltage at the *p-n*-junction is measured twice: before and after heating. The proposed method does not require long heating of the controlled item to establishing thermal equilibrium. In this case, the tester measures only voltages, currents and time, which greatly simplifies its implementation.

RESULTS

Let us consider the proposed method for controlling junction-to-case thermal resistance as exemplified by a diode. If the tested diode has thermal resistance higher than the reference diode, its die temperature at the time of measurement will be higher than of the reference one and voltage difference ΔU will be lower than the reference difference ΔU_r. However, the change in voltage U is not proportional to the change in thermal resistance. It is advisable to estimate how the temperature and the value of the temperature-sensitive parameter change with the change in the thermal resistance of the diode. If we assume that the averaged junction temperature of the diode, when heated by the rated current, changes practically exponentially in accordance with equation:

$$T_J=T_{kn}+T_{Jm}(1-e^{t/\tau}),$$

where T_{kn} is initial temperature of the case, $T_{Jm}=T_{kmax}+P\cdot R_{thjc}$ – maximum increment of junction temperature, τ – thermal time constant of the case heating, T_{kmax} – maximum maximum increment of increment of the case in a steady state in a steady state, P – heating power, then with twofold increase, for example, in R_{thjc}, maximum increment of junction temperature will change as follows:

$$T_{Jm} = T_{kmax} + 2P \cdot R_{thjc}.$$

If we assume that the case temperature increases slightly during heating, the change in junction temperature appears to be disproportionate to the change in thermal resistance and is described by equation:

$$T_J = T_{kn} + (T_{kmax} + P \cdot R_{thjc})(1 - e^{t/\tau}).$$

In accordance with this equation, Figure 1 shows junction temperature curve for three values of junction-to-case thermal resistance with reference value $R_{thjc,r} = 2$ °C/W. The curves correspond to $T_{kn} = 20$ °C, $T_{kmax} = 80$ °C, $\tau = 50$ c, P=5 W. In this case the established junction temperature will be higher than the case temperature by the value of $P \cdot R_{thjc}$.

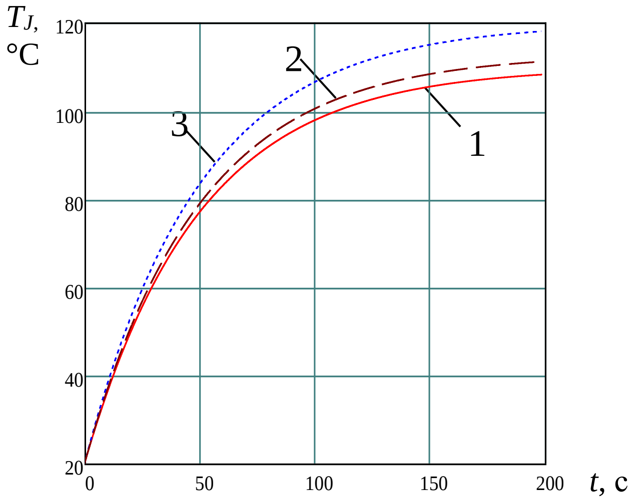

Figure 1: Temperature curve for various thermal resistances: 1 – $R_{thjc} = R_{thjc,н}$;

2 – $R_{thjc} = 1.3R_{thjc,н}$; 3 – $R_{thjc} = 2R_{thjc,н}$

The curve shows that by the time point equal to τ = 50 s, the junction temperature reaches 76.9°C at $R_{thjc} = R_{thjc,r}$, and 83.2 ° C at $R_{thjc} = 2R_{thjc,r}$, that is, with a twofold increase in thermal resistance the junction temperature at the time point equal to the thermal constant τ will increase by 7.6%

For integrated circuit packages of high-frequency PVC, there are no published or patented methods to control junction-to-case thermal resistance. However, the presence of available *p*-*n*-junction in the structure of these PVCs makes it possible to apply the proposed accelerated method for controlling the transition temperature (of the diode) and, accordingly, the die temperature and junction-to-case thermal resistance of PVC integrated circuit packages, assuming that the temperature of the *p*-*n*-junction will correspond to the PVC die temperature. Thus, in the integrated circuit package LM2676 (Texas Instruments) *p*-*n*-junction is available between GND and ON/$\overline{\text{OFF}}$. Using this junction, it is possible to arrange automated control of its temperature and junction-to-case thermal resistance of this integrated circuit package and other high-frequency PVCs as follows.

First, for a single reference integrated circuit package from the batch planned for the automated control of junction-to-case thermal resistance, junction-to-case thermal resistance and the thermal time constant are determined in any way ([1], [2], etc.). After that, for a reference integrated circuit, connected to the tester, a direct voltage drop is measured on the *p*-*n*-junction at a small (measuring current) and the initial temperature, then the integrated circuit package is transferred to the mode providing die heating for a time equal to (0.5 ... 0.8)τ, and then quickly disconnect the integrated circuit package by means of the tester and at a small measuring current the direct voltage drop is measured again on the *p*-*n*-junction at the end of the heating process. Four values are stored in the memory of the tester controller: the duration of switching on, 2 voltages on the *p*-*n*-junction at a small measuring current and the value of this current. Using these values, the remaining integrated circuit packages are tested from the batch planned for the automated control of junction-to-case thermal resistance.

Processing of reference values can be carried out, following the standard method [1].

1. First, the temperature dependence of the temperature-sensitive parameter (voltage on the *p*-*n*-junction with a direct small measuring current) is established in the laboratory. The sequence of actions is the same as at the first stage of the standard method [1]. The obtained dependence $U_J(T)$ is used either for direct determination of thermal resistance, or it is approximated by a linear dependence:

$$U_J(T) = U_0 - K_T T.$$

An example of such a two-point approximation is shown in Figure 2. Linear approximation characterizes the dependence of $U_J(T)$ by two parameters: the temperature coefficient of the voltage K_T and initial voltage U_0:

$$K_T = (U_1 - U_2)/(T_2 - T_1),\ U_0 = U_1 + K_T T_1. \qquad (1)$$

In this case, the *p*-*n*-junction temperature is determined through the measured voltage U by equation:

$$T_J = (U_0 - U)/K_T. \qquad (2)$$

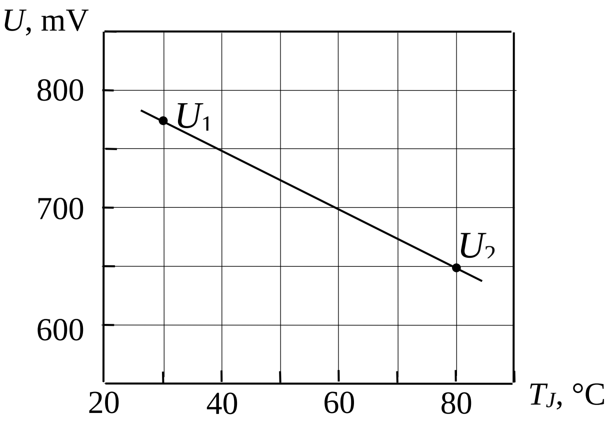

Figure 2: Temperature dependence of the temperature-sensitive parameter

2. At the second stage, the thermal resistance of the reference integrated circuit package is determined. To do this the reference integrated circuit package is installed into the tester, the heating mode is switched on, the temperature of the integrated circuit package case and time, after which the case temperature almost ceases to change are measured. Dividing the measured time by three, the approximate value of the thermal time constant τ is found. The heating of the integrated circuit package continues until complete cessation of the case temperature changes, and then the power of the integrated circuit package is disconnected and voltage is measured by means of the tester on the *p-n*-junction at low measuring current. Using the measured voltage and the dependence $U_J(T)$ or equations (1), (2), the temperature of *p-n*-junction T_J is determined. Junction-to-case thermal resistance is calculated by equation:

$$R_{thjc}=(T_J - T_C)/P_h\,,$$

where P_h is loss power (heat flow) in the heating mode, T_C is the case temperature in a steady state.

3. At the third stage, the parameters determined with the help of the reference integrated circuit package are entered in the tester memory. To do this, after the reference integrated circuit package has completely cooled down, it is reconnected to the tester and the voltage on the *p-n*-junction is measured at a small measuring current. Then the heating mode is switched on for a time comparable to the thermal time constant (arbitrary in the range (0.5 ... 0.8) τ). Then quickly (by means of the tester) the power is cut off and the voltage drop is measured on the *p-n*-junction at a small measuring current. Four values are stored in the tester memory: heating duration, two voltages on the *p-n*-junction at a small measuring current and the value of this current. This completes the preparatory stages and it is possible to start automated control of all integrated circuit packages of this type or this batch.

The very process of automated control of junction-to-case thermal resistance is simplified as much as possible. It is necessary to insert the tested integrated circuit package into the tester adapter and run the controlling program. The tester organizes the necessary switching and measuring, determines the difference of the measured voltages and compares it with the reference one. If the difference in the measured voltages of the tested integrated circuit package coincides with the similar difference in the voltages of the reference integrated circuit package within the tolerance, then the junction-to-case thermal resistance of the tested integrated circuit package is considered to comply with the norm. In this way, junction-to-case thermal resistance can be controlled for each integrated circuit package of not only high-frequency PVC, but also of many other semiconductor products.

DISCUSSION

Applicability of the proposed method is conditioned by the permissible deviation of junction-to-case thermal resistance from the nominal value. In many cases, an excess of 30% is allowed. An increase in the junction temperature by 2.5% during control at the time τ corresponds to this excess of thermal resistance (Figure1). Such temperature changes can be easily recorded by an automated tester, which enables to organize the sorting of products.

However, it should be borne in mind that shortening the heating time leads to a significant decrease in the temperature dependence of the thermal resistance (Figure 1). Thus, if the same power is used for heating for a time of 0.2τ, a 30% increase in thermal resistance will result in a temperature increase of only by 1.5%. A compromise is required between the duration of the test and the accuracy of determining the thermal resistance. According to preliminary estimates, it is expedient to choose the heating time of the die in the range of (0.5 ... 0.8)τ.

When implementing the proposed algorithm for automated control of junction-to-case thermal resistance, it is necessary to fulfill a number of conditions.

First, it is required to minimize the time interval between switching off the heating power and measuring the voltage on the *p-n*-junction. Given that τ of the PVC ICPs makes usually a few seconds or more, the use of switching devices in the tester with a response time of milliseconds allows this condition to be met.

Secondly, it is necessary to ensure the stability of not only the heating time, but also the heating power. Obviously, for each part type of PVC integrated circuit package, a switching circuit should be selected in the heating mode and the power loss stabilization algorithm should be developed. This algorithm is implemented by software and hardware as part of the tester, taking into account the permissible variation in electrical parameters of integrated circuit packages. Modern automated test equipment, for example, based on the PXI platform (National Instruments), allows solving this problem.

Thirdly, the accuracy of the junction-to-case thermal resistance determination depends essentially on the stability of the characteristic of the temperature-sensitive element (*p*-*n*-junction) (Figure 2) within the batch of the tested integrated circuit packages of PVC of one part type. Unfortunately, the authors did not have enough PVC integrated circuit packages with the dies obtained in one technological process to make an objective conclusion.

Despite the fact that the implementation of the proposed method for automatic control of junction-to-case thermal resistance of PVC ICPs requires additional work, the method itself is distinguished by scientific novelty and efficiency.

CONCLUSION

The conducted analysis of the known procedures and methods of controlling junction-to-case thermal resistance of semiconductor devices demonstrated their high laboriousness and the duration of the control process, which does not allow them to be used for automated testing of integrated circuit packages of high-frequency PVCs.

A modified method is proposed that significantly accelerates the determination of the junction-case thermal resistance of the semiconductor diodes in automated testing.

The possibility of applying this modified method for the automated determination of the die-case thermal resistance of PVC ICPs using the *p*-*n*-junction built in their structure is shown.

An algorithm for applying the modified method for the automated determination of junction-to-case thermal resistance of PVC integrated circuit packages using test equipment is developed.

The proposed method is recommended for use in controlling the thermal resistances of various semiconductor products.

ACKNOWLEDGEMENTS

The work was performed with the financial support by the Ministry of Education and Science of the Russian Federation (project No. 8.1729.2017/4.6).

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