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Thermal investigations of PCM enhanced electronics cooling

Abstract

The paper presents experimental results of PCM (Phase Change Material) enhanced cooling system. The investigations were focused on obtaining the best results of the cooling system during its start-up. The latent heat of phase change material was used to decrease temperature of the cooled electronic device. Comparison of a standard heat sink available on the market and the same heat sink filled with PCM applications was done. Temperature was monitored and registered during device start-up until its thermal steady state. It was done using contact and IR temperature measurement methods. PCMs usage enabled to absorb heat during electronic device start-up. The paper proves that using PCMs it is possible to delay temperature rise during electronic devices heating.

Keywords: Heat exchange, phase change materials, thermal impedance, cooling of electronic systems.

1. Introduction

Thermal management is one of the most important issues for electronic devices producers. The market of electronic devices grows very fast as well as power densities dissipated in electronic components. Dimensions of the devices and their packages are getting smaller. Electronic devices are operating well in specified range of temperature. Overheating of electronic elements leads to their shorter lifetime, malfunction (e.g. logic errors in microprocessors) or even immediate breakdown. As the result of above pointed facts, there is a need to design and produce cooling systems that would better fulfil the thermal management requirements.

Two types of cooling systems are used today: active and passive. The first one uses external power to move the cooling medium. Fans and pumps are widely used in air and liquid cooling systems. This enables to increase heat exchange thanks to the forced convection. It significantly increases the power dissipation in comparison with the second type of cooling systems – passive one. Such systems do not need any additional electrical power and are very reliable while no moving mechanical parts are used. Nevertheless heat transfer coefficient characterizing these cooling systems is usually a few times smaller.

Usage of PCM gives a chance to change this. PCM has a great potential in cooling systems applications. PCM has high value of latent heat and therefore during heating up and phase change it can absorb additional energy. Such materials are usually very light. Nevertheless some disadvantages can be found. The most of the PCMs have poor thermal conductivity. There are various applications of PCMs. Phase changing materials are used in electronics for thermal management e.g. batteries. They operate efficiently in quite narrow temperature range and PCMs can help in maintaining low batteries temperature **Błąd! Nie można odnaleźć źródła odwołania.**. Phase changing materials are often used in different fields than electronics cooling. Energy storage applications are one of the typical areas of PCM's application [5]. Heat exchanging devices can also potentially be equipped with phase changing elements in order to increase their performance [7].

Practically, all cooling systems use 3 ways of transporting heat to ambient. The first is convection. It can be natural convection without forcing the air movement (or any other cooling medium) or forced convection where cooling medium motion is caused by external device (e.g. pump, fan etc.). The second is heat conduction from an object with the higher temperature to an object with the lower temperature. In cooling systems heat is spread through the substrate very often what helps also to dissipate heat. The last third method is cooling by thermal radiation. It uses electromagnetic waves to transfer internal energy to ambience. In most of the cases heat radiation is emitted in the infrared region. In the paper one presents the experimental results of storing heat in order to decrease device temperature in start-up conditions. During the start-up, the power devices are subjected to the huge thermal stress. Such a stress can be measured or simulated using methods known in literature [4].

Comparison of a transistor cooling using the traditional radiator and the radiator enhanced by PCMs was done and chosen results are presented. The criterion for comparison is junction temperature of a device.

Thermal measurements and characterisation of integrated circuits and packages can be done using methods well known in the industry. The series of JEDEC JESD51 standards are in use today [1, 2]. Especially the JESD51-1 standard entitled "Integrated Circuit Thermal Measurement Method - Electrical Test Method (Single Semiconductor Device)" is a kind of reference for electronic devices testing in industry [1, 2, 3]. Standard Electrical Test Method (ETM) can be used for thermal characterization of integrated circuits housed in electric packages or to compare such circuits or packages. According to the JESD51-1 norm, the thermal resistance characterising electronic devices and circuits can be used:

$$R_{\theta JX} = \frac{T_J - T_X}{P_H} \tag{1}$$

where:

- $R_{\theta JX}$ – device junction to ambience thermal resistance
- T_J – the junction temperature
- T_X – the ambient temperature
- P_H – power dissipated in the device

Thermal resistance (1) represents thermal way between heat source (i.e. junction of a transistor) and ambience (this can be any other reference point that lies in the area of the researchers' interest) in a very simple way. Thermal resistance describes ability to remove heat from the device in steady state.

Two alternative methods of thermal characterisation of electronic devices are proposed in the standards mentioned above. Dynamic mode (another name is Pulsed Mode) is the first one. It consists of providing pulsating heating in the specific duration time and temperature measurements in parallel. The second optional method is a static one. In this approach the power step is applied to the investigated device. The temperature is measured since the power step begins up to the thermal steady state.

Thermal resistance is a steady state parameter and thus cannot - in general case - present the dynamic behaviour of tested circuits. A convenient parameter for dynamic characterization of the devices is the thermal impedance Z_{th} [6, 7, 8].

The device and the cooling system can be characterised in details by using the thermal impedance, which can be presented in the form of:

$$Z_{th}(s) = \frac{T(s)}{P(s)} = \frac{T_{step}(s)}{P_0 \mathcal{L}\{1(t)\}} = \frac{s}{P_0} T_{step}(s) = \frac{s}{P_0} \int_0^\infty T_{step}(t) e^{-st} dt \tag{2}$$

where $\mathcal{L}$ is the Laplace transform (for $s = \mathrm{j}\omega$, where ω is the angular frequency), T_{step} represents temperature response to the heating or cooling step function, and P_0 is the power delivered to the investigated device in the steady state.

According to JESD51-1 standard the same methods can be used to measure transient response and thus to determine thermal impedance. Using power step function, a researcher should be aware that in some cases in steady state temperature fluctuates and this can affect the results. Usually it is recommended to use cooling instead of heating step function (not always possible – depending on the research conditions). Using Laplace transform one can shift analysis from the time to the frequency domain. The result is the function of thermal impedance versus frequency. This is often presented as the Nyquist plot.

2. Measuring setup

Measuring setup includes T3Ster Transient Thermal Tester offered by MICRED/Mentor Graphics [3, 4, 11]. T3Ster is commonly used by many semiconductor manufacturers. The equipment is considered as the reference tool for testing electronic devices from the thermal point of view. T3Ster uses JEDEC static-test method. The system enables to apply thermal excitations to the semiconductor device and register temperature responses.

T3Ster enables to measure temperature of the investigated device in a few ways. Typically, the internal parasitic diode is used for MOS transistors. For the investigations bipolar junction transistors (BJT), one uses emitter p-n junction as the temperature sensor. It is due to well-defined dependence of temperature and voltage drop on the p-n junction.

The system enables to power the tested device from T3Ster's internal power source. Typically, it is the unit step function power. An external power source can also be connected but for the investigations presented in this paper, the internal one was sufficient. T3Ster also contains a measuring circuit with A/D converter and enables to register temperature response of the investigated device.

The integral part of the system is its software. There are two applications. The first one (T3ster) is used for setting up measurement and performing the basic result analysis. The second application (T3ster Master) enables detailed analysis of the performed measurements. As the result the pulse thermal impedance, thermal time constants, the Nyquist plot and so called structure function are calculated. The results characterise thermal properties of the semiconductor device and the cooling system.

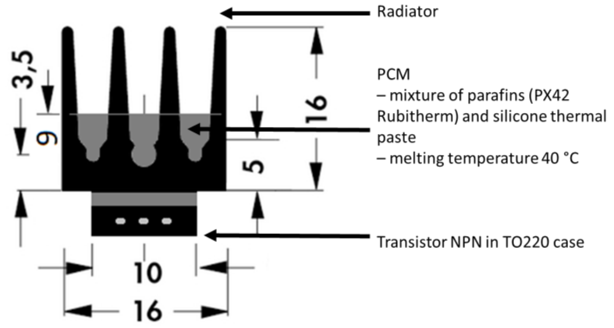

Fig. 1. Investigated transistor

The decision was made to use latent heat storage powder containing phase change material. It has supporting structure what makes that after melting PCM is not leaking. The main material is a mixture of different kinds of paraffin. They are closed in hydrophilic silica microcapsules what makes they act like a solid state in whole operating range. Remarkable is that it has long lifetime without significant drop of the performance during phase change cycling. The material is called PX42 and produced by Rubitherm [12]. It does not have one melting temperature while it is a mixture of the different kinds of paraffin. The melting range is (38…43)°C. During reverse phenomenon of phase change (congealing), temperature range is equal to (43…37)°C. Its heat storage capacity is at the level of 105 kJ/kg while specific heat capacity is equal to 2 kJ/kg·K.

There are some disadvantages of this material. The first one is its thermal conductivity equal to 0.1 W/m·K which is comparable to wood. The second disadvantage is that PCMs are only 60% of whole material. To decrease influence of the first disadvantage, the PCM capsules were mixed with thermal conducting silicon paste which thermal conductivity equals to 2.8 W/m·K. This led to fill the space between capsules with PCM and increase overall thermal conductivity. Proportion 1/5 (thermal paste/PCM) was enough to fill the space between the capsules.

3. Experimental results

Investigations were done for BJT which was cooled down by typical radiator and this radiator was filled with PCM and thermal paste mixture. In both cases as a measuring tool T3Ster Transient Thermal Tester was used. Transistor was powered using T3Ster internal power supply. The temperature was measured as a voltage drop at the transistor's p-n junction with the known thermal coefficient of 2 mV/K. The measuring setup was closed in a cubic box (0.3×0.3×0.3 m^3) with insulated walls in order to eliminate external influence on the heat exchange between the transistor, the radiator and surrounding air. A power step input equal to $P_0(t=\infty) = 1.6$ W was applied using T3Ster internal power source.

In the first approach power step was applied and junction temperature was measured for 120 minutes. Thermal responses are presented in Fig. 2 in the logarithmic scale. Comparing both results (cooling using radiator with and without PCM), one can see that in the steady state, junction temperature is higher when the radiator with PCM was used. Nevertheless the question is what happens during the start-up. If one looks at the thermal response plot in the logarithmic scale, both plots (with and without PCMs) look almost the same.

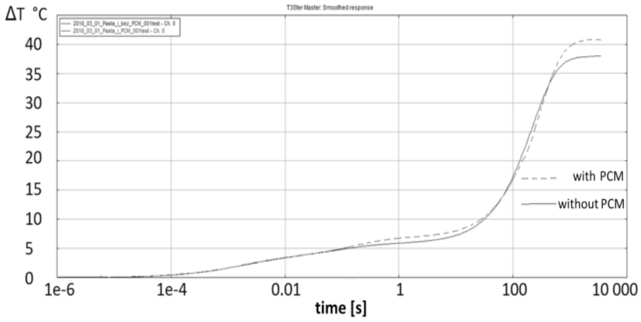

Fig. 2. Thermal response of the cooling setup with and without PCM in the logarithmic scale (ΔT junction minus ambient temperature)

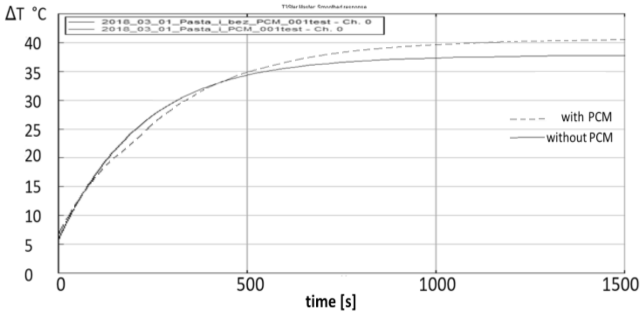

Fig. 3. Thermal response of the cooling setup with and without PCM the in linear scale (ΔT junction minus ambient temperature)

One can further analyse the heating curves versus time in the linear scale (Fig. 3). It can be seen that below t=500 s, junction temperature of the transistor mounted on the radiator with PCM is a few Celsius degree lower than in the case without PCM. Such an effect has an advantage in various applications. This way of operation gives possibility of using the proposed solution in some military applications, for example in weapons that are of single use in relatively short time. Second application could be frequency converters which are often used in the industry. Max. Inrush Current is very important for these devices and this parameter could be increased thanks to application of PCMs.

The thermal impedance in form of the Nyquist plot was determined as well (Fig. 4). When one compares plots for radiator with PCM and without it can be found a few characteristic differences. In the region of higher frequencies one can observe additional circle resulting from usage of additional PCMs that were placed between radiator fins. One can also observe that the plot for the case with PCMs tends to cross 0x axis in a value about 23.3 K/W when the value for the case without PCMs is slightly worse and equals to about 25 K/W.

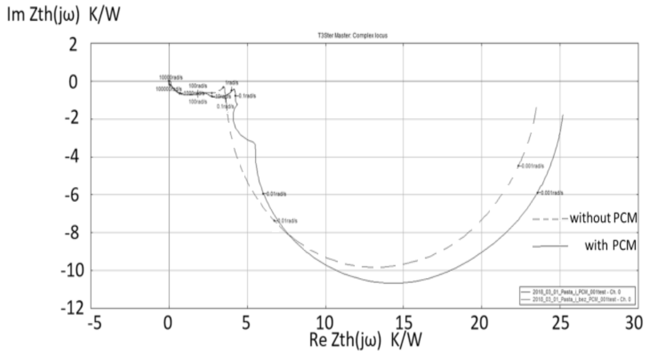

Fig. 4. Nyquist plot of the thermal impedance with and without PCM

Thermal resistance in steady state conditions (with PCMs) is worse while introducing PCM that causes decrease of the radiator area cooled by natural convection.

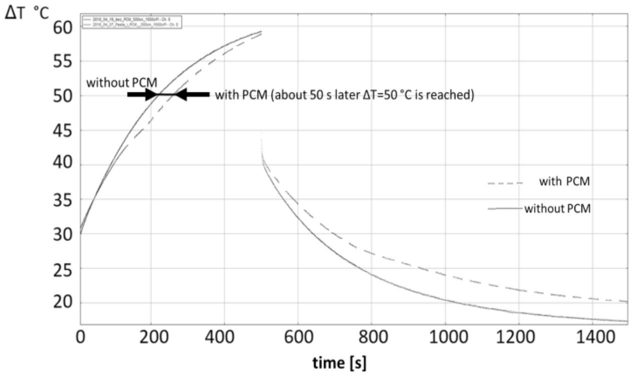

Fig. 5. One heating and cooling cycle for transistor and heat sink with and without PCM (*ΔT* junction minus ambient temperature)

In the next experiment, the cycles of heating as well as cooling taking respectively 500 s and next 1000 s were performed using the same method of temperature measurement as in above presented investigations (Fig.5). One can observe that temperature delay in time Δt equal to 50 s was reached for time $t \approx 200$ s and temperature difference $\Delta T \approx 50$°C. This is a very promising result for industrial applications. It can help in significant extension of overload time for e.g. frequency converters. Typically frequency converters available on the market can afford 1.5 × output current rating (i.e., 150% overload) for about 60 s with the cycle time of 300 s.

Infrared measurements simultaneously with contact ones were also performed. Nevertheless for comparison of cooling with and without PCM can be better analysed using contact temperature measurement method. In addition, thermographic image visualizes very well temperature distribution on the device and the radiator (Fig. 6).

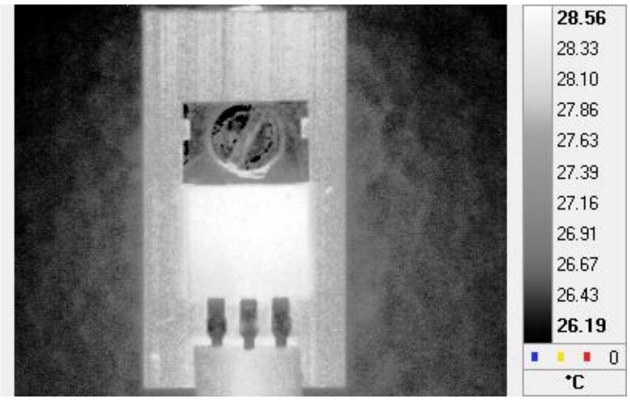

Fig. 6. The infrared image of the transistor with the heat sink with PCM during heating up, after t=1 s from heating start, for $P_0 = 1.6$ W

4. Conclusions

The aim of the investigations was to compare transistor cooling with typical radiator available on the market with cooling using the same radiator but with PCM enhancement. Some of the measurements were done using Transient Thermal Tester (contact method) and some with IR thermography. In this case contact methods are better while temperature inside the electronic device can be measured. Temperature measurement was done as the voltage drop on the p-n junction in the transistor that depends on temperature. It was the same transistor that was under the test. Investigations prove that in some cooling applications PCM's usage is advantageous. In the paper, the typical radiator was filled with Phase Change Material. This helped to introduce a temperature delay and to maintain lower temperature of a device longer. In comparison with standard radiator, PCMs enhanced radiator enabled to maintain for about 50 s longer the device temperature lower than 50°C. Decreasing device temperature leads to increase of its lifetime. Some disadvantages of the method were also found. In a steady state, temperature of the transistor when PCMs are used increases in comparison with standard radiator. In the future works this undesirable effect can be reduced or eliminated.

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Received: 12.12.2018 *Paper reviewed* *Accepted: 04.02.2019*

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