A Transient Thermal Tester as an Alternative to Thermocouples for Characterizing Heat Sinks

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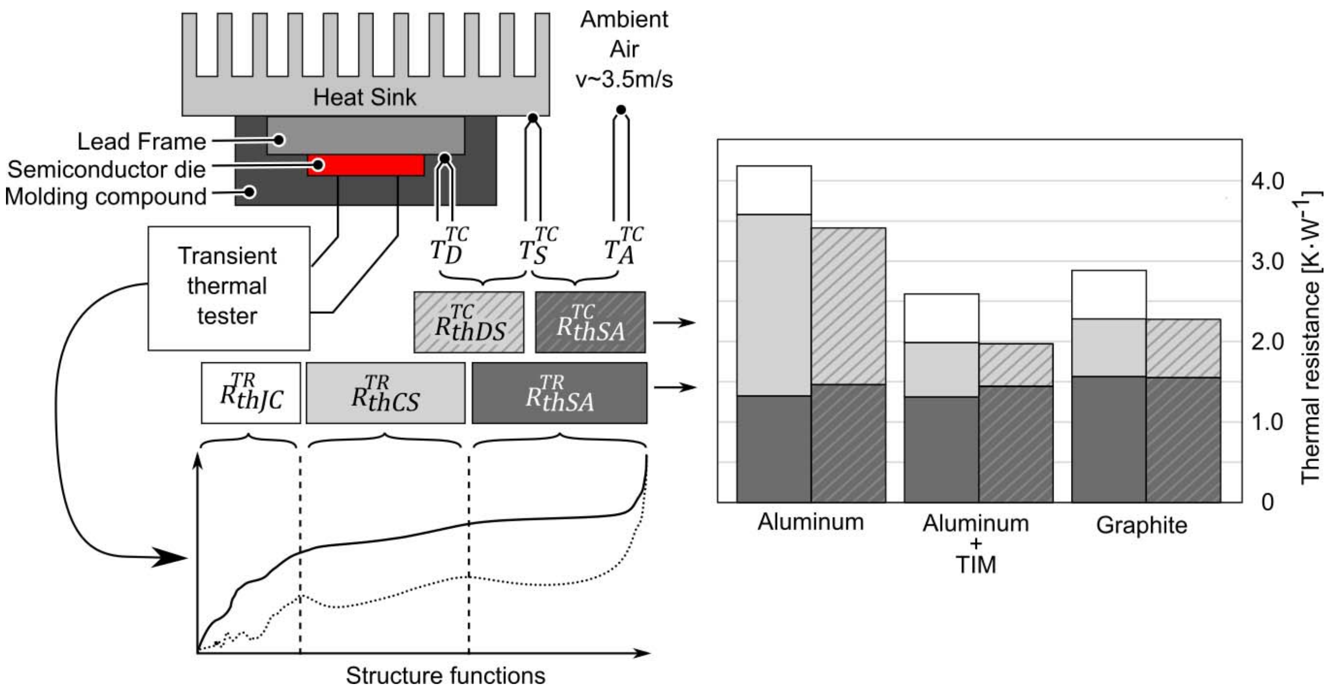

Abstract

Graphite and aluminum heat sinks were characterized in an experimental setup that allowed simultaneous measurements using thermocouples and a transient thermal tester. Both methods result in the same conclusion about the relative performance of the heat sinks, but the thermocouple method under predicts the total resistance by approximately 0.6 K·W^{-1} due to its inability to capture the true junction temperature. The sink-to-ambient resistances show a good agreement. The case-to-sink resistance determined by the transient thermal tester is comparable to the device-to-sink resistance determined using thermocouples, but explaining this trend requires further work. The transient thermal tester eliminates the time consuming and error-prone installation of thermocouples, but comes with higher equipment cost.

Keywords

Heat sink characterization, transient thermal tester, structure functions, thermocouple measurement, graphite heat sinks, natural graphite sheet.

Nomenclature

R_{thJC}^{TR} - Junction-to-case thermal resistance measured by a transient thermal tester [K·W^{-1}]

R_{thCS}^{TR} - Case-to-sink thermal resistance measured by a transient thermal tester [K·W^{-1}]

R_{thSA}^{TR} - Sink-to-ambient thermal resistance measured by a transient thermal tester [K·W^{-1}]

T_D^{TC} - Device thermocouple reading [°C]

T_S^{TC} - Heat sink thermocouple reading [°C]

T_A^{TC} - Inlet ambient air thermocouple reading [°C]

R_{thDS}^{TC} - Device-to-sink thermal resistance measured by thermocouples [K·W^{-1}]

R_{thSA}^{TC} - Sink-to-ambient thermal resistance measured by thermocouples [K·W^{-1}]

1. Introduction

The motivation for this study originates in our work related to the development of natural graphite sheet (NGS) heat sinks. In [1] we used thermocouples to evaluate the performance of two geometrically identical heat sinks manufactured from aluminum and NGS and found out that the NGS heat sink shows significantly lower thermal resistance at the interface between the heat source and the heat sink. The thermocouple method suffers from many shortcomings related to mounting of thermocouples – it is intrusive, labor intensive and the temperature readings are prone to errors arising (mainly, but not only) from the imperfect contact between the thermocouple and the measured surface [2]. To validate the previous results we decided to use the transient thermal tester, which has been shown to be able to measure the interface and heat sink thermal resistances [3], and eliminates the labor-intensive installation of thermocouples. The goal of this work is to compare the two methods and assess their potential from the heat sink development perspective.

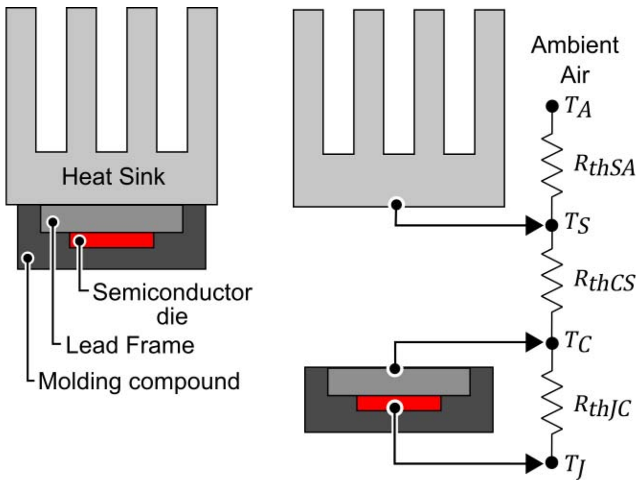

Figure 1: Left: a typical power electronics cooling layout. Right: Thermal resistances network

2. Theoretical background

The performance of electronics cooling systems is typically expressed in terms of thermal resistance whose general definition is

$$R_{th12} = \frac{T_1 - T_2}{P} \quad \left[\frac{K}{W}\right], \qquad \textit{Eq. 1}$$

where T_1 and T_2 are the temperatures at the locations of interest and P is the dissipated power. For a general air-cooled semiconductor cooling assembly shown in Figure 1, the most important thermal performance metric describing the quality of the whole heat transfer path is the junction-to-ambient thermal resistance for which the semiconductor junction temperature T_J and the inlet ambient air temperature T_A are substituted into Eq. 1 instead of T_1 and T_2, respectively. To assess the heat transfer through the individual parts of the assembly, the junction-to-ambient resistance is usually broken down into junction-to-case (R_{thJC}), case-to-sink (R_{thCS}), and sink-to-ambient (R_{thSA}) resistance, which requires knowing the case temperature T_C and the sink temperature T_S. While the definition of T_J and T_A is straightforward, the case and sink temperatures pose a complication. Strictly speaking a thermal resistance should be used only between two isothermal surfaces, but both the case and the sink surface are not isothermal and the definition of T_C and T_S is ambiguous. In simulations, average values are typically used. Measurement of these temperatures is difficult due to the limited access to install sensors such as thermocouples.

From the heat sink development perspective, it is necessary to evaluate not only the sink-to-ambient resistance, but also the case-to-sink resistance as the latter is, among other parameters, dependent on the surface finish and mechanical properties of the heat sink, especially in applications without an electrically insulating layer between the device and the heat sink.

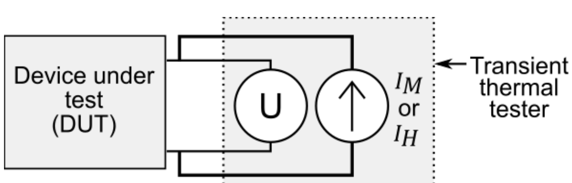

Figure 2: Schematic visualization of transient thermal tester

3. Measurement methods

Although heat sinks typically are characterized in a standalone configuration with a simple resistive heater used as the heat source, both methods in our work use a real-world power semiconductor (a diode). This lets us capture the case-to-sink resistance in realistic conditions and include the effect of the package and chip size on the performance of the heat sink, which is mainly applicable to graphite heat sinks whose low through-plane thermal conductivity can limit heat spreading in the base plate.

3.1. Thermocouples

Measuring the thermal resistances listed in Section 2 requires attaching thermocouples to the locations outlined in Figure 1, which is challenging and often impossible. It is common practice to choose more accessible locations and either assume a negligible temperature difference between the desired and the measured locations, which introduces a systematic error in the measurement, or build a numerical model and use it to determine the difference between the desired and measured locations, which requires accurate information about the geometry and material properties. In this work we were not able to use the latter approach as the necessary material properties were not known or were uncertain.

The dissipated power can be determined by measuring the current through and the voltage drop across the device.

3.2. Transient thermal tester

The transient thermal tester uses the semiconductor chip as the temperature sensor. Analogously to a thermocouple measurement, which uses the voltage across the two wires to determine the temperature of the joint, the transient thermal tester uses the forward voltage (or other temperature sensitive property) of the chip to determine its temperature. The relation between the forward voltage and the temperature is obtained in the calibration process, during which the device is clamped to a controlled temperature source (aluminum plate with internal liquid channels), a constant measuring current I_M is applied, and the forward voltage is measured at varying device temperatures. In principle, the transient thermal tester is an accurate four-point resistance meter consisting of a DC power supply and a voltmeter (Figure 2). The measurement starts with

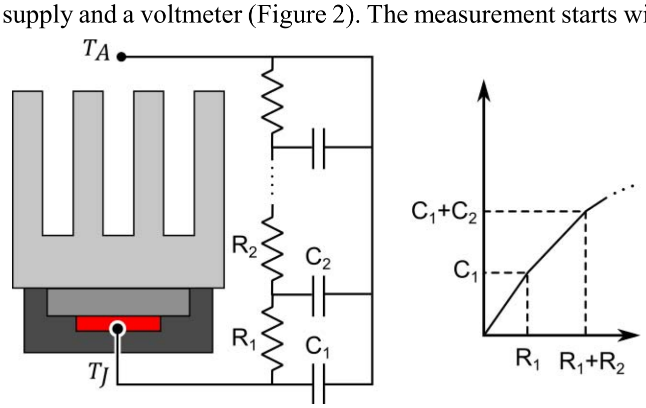

Figure 3: Physical meaning of structure functions. Left: equivalent 1-D R-C network, right: small part of the structure functions

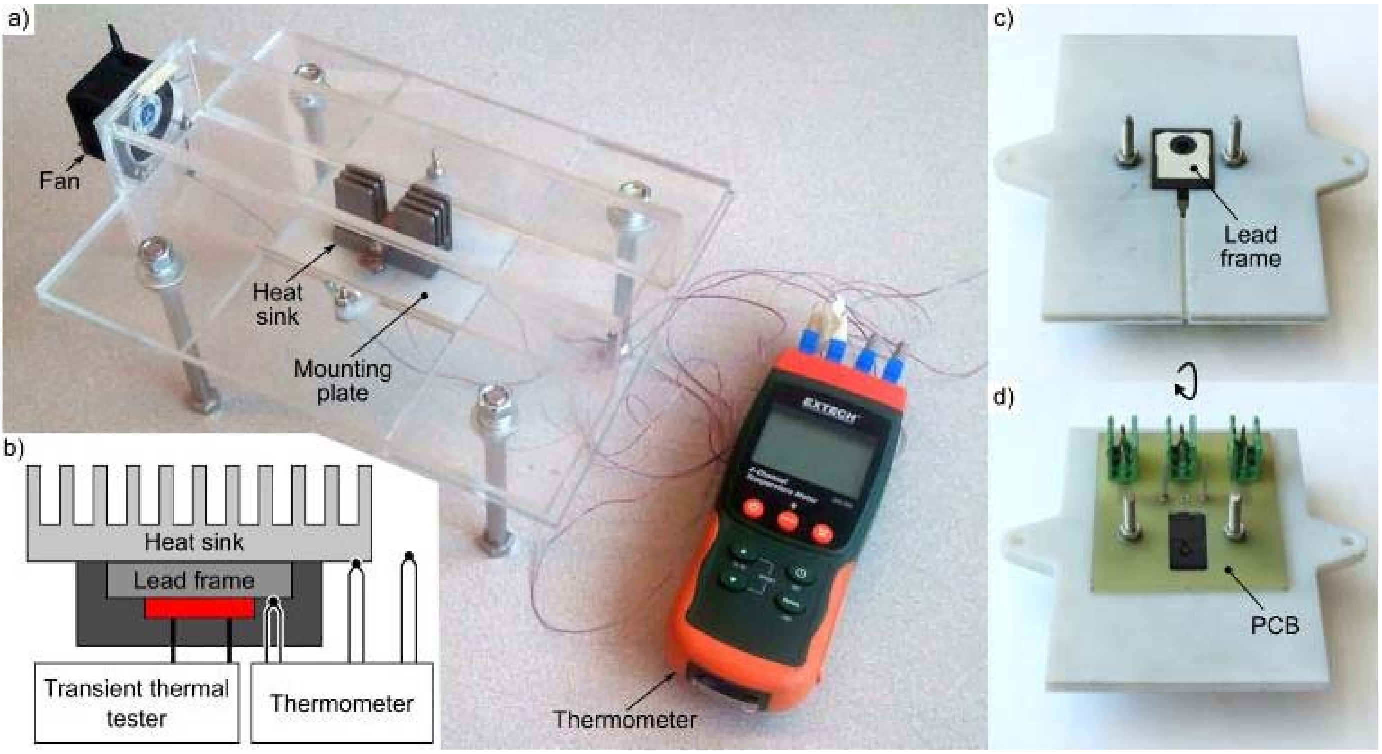

Figure 4: Experimental setup. a) a photograph of the whole setup (the transient thermal tester is not shown), b) scheme showing the two measurement methods, c) detail of the mounting plate and d) bottom of the mounting plate (rotated by 180°)

the heating phase, in which a heating current I_H is passed through the device under the test (DUT) until it reaches steady-state. The dissipated power is determined in the same way as in the thermocouple method, by measuring the voltage and current through the DUT. The current is then lowered to the measuring current I_M, which results in the DUT gradually cooling down. The transient temperature profile of the chip is recorded and deconvoluted into a curve called the structure function from which the thermal resistances can be determined. While the details of the deconvolution are complex [4], the basic idea is to numerically generate an equivalent 1-D R-C thermal network whose transient response is identical to the experimentally obtained response of the measured system. The structure function is a graphical visualization of individual resistor and capacitor pairs (Figure 3), while the differential structure function is a derivative of the capacitance with respect to resistance.

4. Measurement

The experimental setup shown in Figure 4 was designed to allow a simultaneous measurement using thermocouples (Extech SDL200 thermometer) and the transient thermal tester (Mentor graphics T3ster with a 50A-30V Booster). It consisted of an acrylic wind tunnel with 4cm axial fan and a mounting plate with a plastic frame, printed circuit board and the semiconductor device (IXYS DSEI 30-06A diode). The current probes of the transient thermal tester were connected using the three-pin connectors while the voltage probes were attached directly to the device terminals using test leads. Graphite and aluminum heat sinks were attached to the mounting plate using an insulated metal bracket and two M3 bolts tightened to 0.05 Nm resulting in a contact pressure of approximately 0.5 MPa. The geometry and manufacturing method of the heat sinks was described in [1], however the heat sinks in this study were not identical (7 fins instead of 9, lower graphite density).

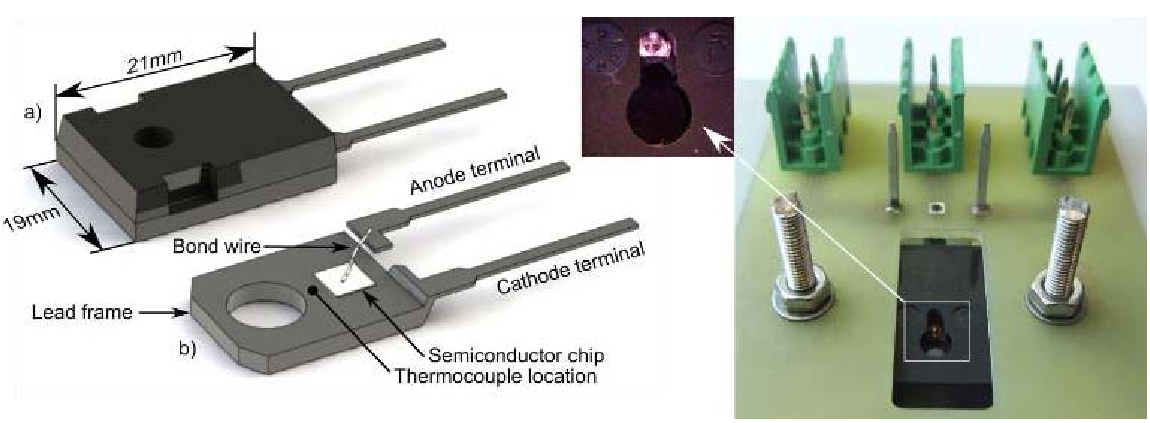

Figure 5: a 3D CAD visualization of a) the device (diode) and b) its internal structure. Right: The device mounted on the printed circuit board with the detail of the thermocouple location (picture before attaching the thermocouple)

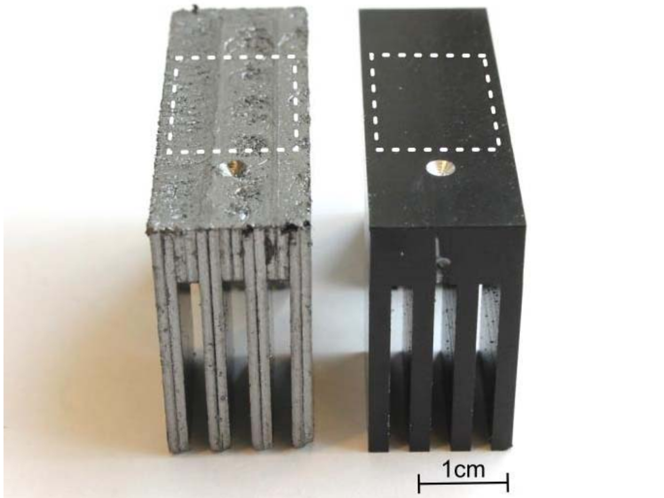

Figure 6: Location of the heat sink thermocouple. Graphite heat sink (left) and aluminum heat sink (right). The dashed lines show the position of the device

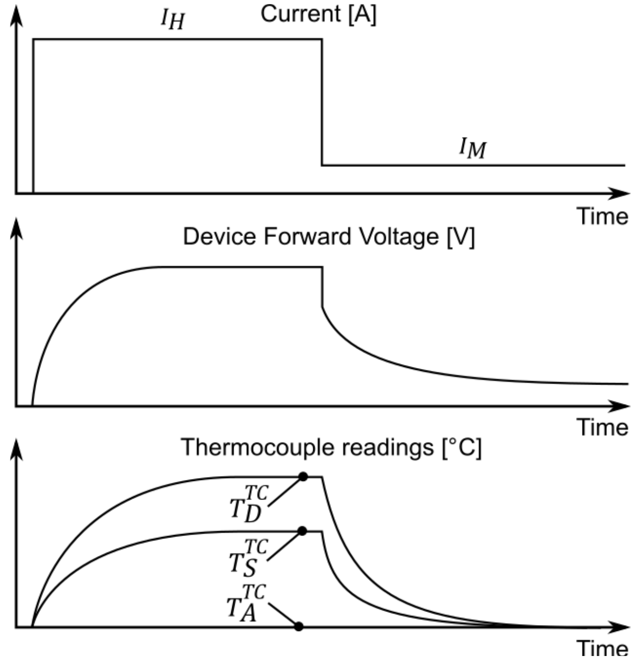

Figure 7: Visualization of the temporal profile of the current through the device (top), device forward voltage (middle), and thermocouple readings (bottom)

Four thermocouples (Omega 5SRTC, T-type, 36 AWG) were used to measure the temperature of the device, heat sink, inlet air, and outlet air. The location of the device thermocouple shown in Figure 5 was chosen to be as close to the chip as possible while minimizing the risk of damaging the bond wire. The copper lead frame of the diode was exposed by machining off a portion of the molding compound and a small dent 1 mm in diameter was then drilled to assure a good thermal contact with the thermocouple.

The heat sink thermocouple was mounted at the base in a 2-mm dent as shown in Figure 6. Both the device and the heat sink thermocouples were attached using a two-part epoxy (J-B Weld).

A single test started by the heating phase, in which the transient thermal tester ran the heating current through the device. When steady-state was reached, the thermocouple readings were recorded and subsequently the heating current was reduced to the measuring current and the cooling curve of the device junction was recorded. The measurement procedure is illustrated in Figure 7.

Three configurations were measured: i) aluminum heat sink without thermal interface material (TIM), ii) aluminum heat sink with the Shin-Etsu G751 TIM, and iii) graphite heat sink without TIM. Each configuration was tested at 5A, 7A, and 10A heating currents and an air speed of approximately 3.5 m s^{-1}. To investigate repeatability, measurements were repeated three times with re-mounting of the heat sinks and additional runs were performed without re-mounting, resulting in 36 data points.

5. Data processing

The raw data for a single measurement included the thermocouple readings (device temperature T_D^{TC}, heat sink temperature T_S^{TC} and inlet ambient air temperature T_A^{TC}), dissipated power P, and the cooling curve. For the thermocouple method, the device-to-sink R_{thDS}^{TC} and sink-to-ambient R_{thSA}^{TC} thermal resistances were calculated by using T_D^{TC}, T_S^{TC}, and T_A^{TC} in Eq. 1. The cooling curves obtained from the transient thermal tester were processed using the T3ster Master software to get structure functions (SF's) and differential structure functions (DSF's). As illustrated in Figure 8, by identifying the C (Case) and S (Sink) points it is possible to determine the junction-to-case R_{thJC}^{TR}, case-to-sink R_{thCS}^{TR}, and sink-to-ambient R_{thSA}^{TR} thermal resistances. R_{thJC}^{TR} is typically obtained using the Transient Dual Interface Method (TDIM) [4][5][6], which requires measuring the device on a cold plate with a without a TIM. The principle of the method is that when an identical device is measured under different boundary conditions, the initial parts of the structure functions, which describe the heat flow within the device, will overlap and only when the heat has reached the

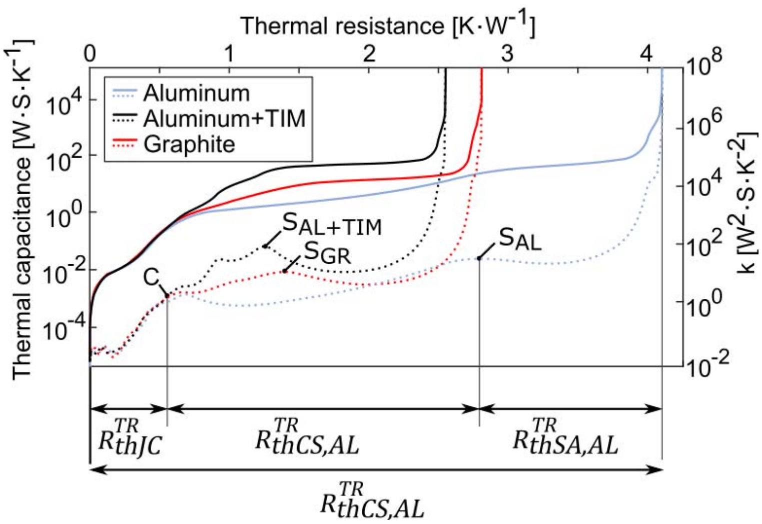

Figure 8: Structure functions (solid, left axis) and differential structure functions (dotted, right axis) of aluminum and graphite heat sinks. Measurement was made at 5A heating current, 0.2A measuring current and 3.5m/s approximate air speed

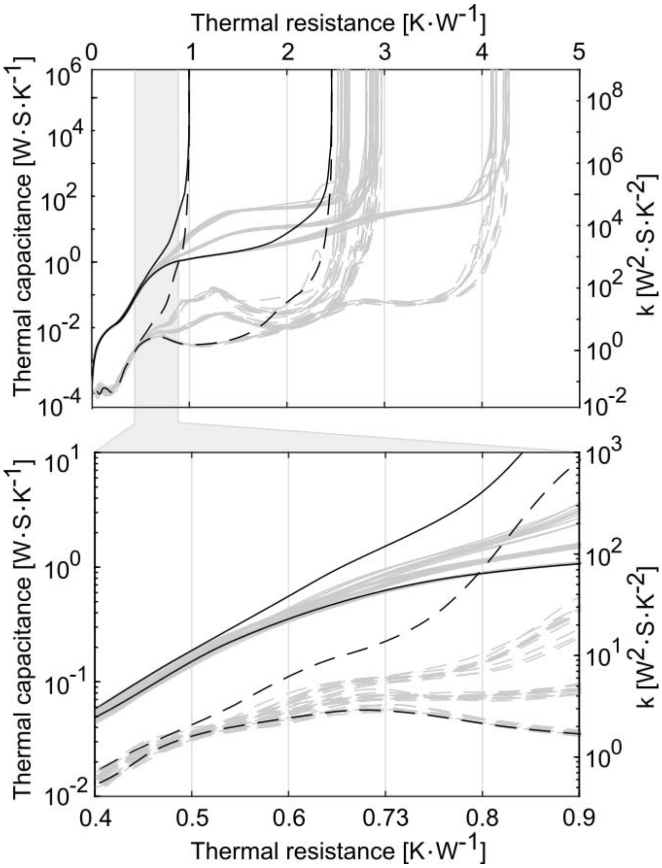

Figure 9: Compilation of all SF's (solid lines) and DSF's (dashed lines). Grey – measurements with heat sinks, black – measurements on a temperature controlled plate. The bottom figure is a detail of the top one

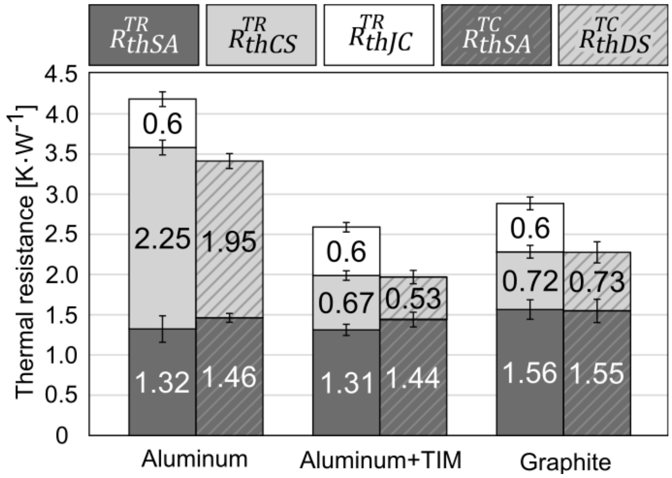

Figure 10: Comparison of the thermal resistances measured by thermocouples (hatched bars) and the transient thermal tester (solid fill). The error bars represent the minimum and maximum measured values (not the typical standard deviation)

device case, they will diverge. Thus, the divergence point (C point in Figure 8) is used for determining R_{thJC}^{TR}. Since the heat sink measurements performed in this work also provide three different boundary conditions, we had two options of determining the R_{thJC}^{TR}: i) from heat sink measurements, and ii) from a standalone measurement of the device on a cold plate using the TDIM. We collected the data for both and plotted it in Figure 9, which shows that the curves diverge slightly sooner for the TDIM method. For the purposes of this paper we used a graphically determined R_{thJC}^{TR} value of 0.6 K/W; however, a more rigorous approach should be implemented in the future to assure consistent results from different operators.

To determine the magnitude of the case-to-sink resistance R_{thCS}^{TR} we followed the work of Poppe et al. [3] and assumed the point S (Figure 8) to be at the local maximum of the DSF, which demarcates the left limit of the flat section of the SF. Poppe et al. also proposed using TDIM for determining the heat sink resistance, which is not expected to be suitable for graphite heat sinks as TIM does not significantly improve the heat transfer at the interface.

6. Results

Figure 10 shows a summary of all the measured thermal resistances, where the height of the bars corresponds to the average values and the error bars show the minimum and maximum values of our measurements instead of the typical standard deviation. The major conclusions are: i) measuring using thermocouples leads to underpredicting the total resistance due to inability to capture the true junction temperature, ii) if used for relative comparison of the heat sinks, both method result in the same conclusions (i.e. the aluminum heat sink with TIM shows the lowest total resistance followed by graphite and aluminum without TIM), iii) the average sink-to-ambient resistances (darkest grey bars) measured by the two methods are in a good agreement, iv) the average device-to-sink resistance measured by thermocouples corresponds to the case-to-sink resistance measured by the transient thermal tester.

The absolute difference between the average sink-to-ambient resistances (R_{thSA}^{TR} and R_{thSA}^{TC}) measured by the two methods is 0.14, 0.13, and 0.02 K·W^{-1} for the aluminum without TIM, aluminum with TIM, and graphite heat sinks, respectively, which corresponds to the relative difference of 10%, 10%, and 1%, respectively. All the relative differences reported in this paper use the transient thermal tester values as the reference value. Analyzing the data on the individual measurement basis instead of the averages, which is relevant because the data was gathered at the same time using the same testbed, reveals the maximum absolute difference between the method to be 0.25, 0.20, and 0.17 K·W^{-1}, which translates to the maximum relative difference of 20%, 15%, and 11%, respectively. The comparison suggests that the methods agree significantly better in the case of the graphite heat sink.

The absolute difference between the average case-to-sink resistance measured by thermocouples R_{thCS}^{TR} and the average device-to-sink resistance measured by the transient thermal tester R_{thDS}^{TC} is 0.31, 0.15 and 0.01 K·W^{-1} for the aluminum without TIM, aluminum with TIM, and graphite heat sinks, respectively, which corresponds to 14%, 22%, and 1% relative difference. Performing the comparison for individual measurements instead of the averages yields the maximum absolute differences between R_{thDS}^{TC} and R_{thCS}^{TR} to be 0.39, 0.22, and 0.35 K·W^{-1}, which corresponds to 17%, 31%, and 49% relative difference. The scatter of the data is much higher than in the case of sink-to-ambient resistance, which can be also inferred from Figure 10 where the magnitude of the medium grey bars is affected by not only one, but a sum of two error bars.

Physical explanation of the fact that the device-to-sink and case-to-sink resistances are of a comparable magnitude is not straightforward and outside of the scope of this paper. The biggest complication is the uncertainty in what temperature do the thermocouples pick up (imperfect contact, heat leakage) and what is the physical meaning of the measured resistances. The latter can be illustrated by comparing the case-to-sink (R_{thCS}^{TR}) and device-to-sink (R_{thDS}^{TC}) resistances in the aluminum with TIM case with the value of the interface resistance from the TIM manufacturer (Shin-Etsu, G751 [7]). Assuming the area of the TO-247 diode to be 314 mm^2, the reported specific thermal resistance of 17 K·mm^2·W^{-1} at 138 kPa (lower pressure than in this work) translates to 0.05 K·W^{-1}, which is approximately one order of magnitude lower than the measured value. A possible explanation is that R_{thCS}^{TR} and R_{thDS}^{TC} include also a part of the heat sink and lead frame resistance.

Since the measurements were not performed in a controlled environment, the fluctuations in ambient temperature could affect the results by disturbing the steady state, or by altering the cooling conditions during the recording of the cooling curves. The heat losses from the device into the printed circuit board, wind tunnel, and the ambient air have not been accounted for. Both points must be addressed in the future.

7. Discussion

The results of this work suggest that if the case-to-sink R_{thCS}^{TR} and device-to-sink R_{thDS}^{TC} resistances are used to judge the quality of the heat transfer through the device-heat sink interface, and sink-to-ambient resistances (R_{thSA}^{TR} and R_{thSA}^{TC}) are used to judge the ability of the heat sink to dissipate heat, both methods will result in similar conclusion within approximately 20%. This conclusion is, however, most likely case dependent and any change in the thermocouple method (thermocouple type, location and attachment) might result in different values. The validity of the proposed way to analyze the SF's is also not guaranteed and the future work could reveal a better method for relating the shape of the SF and DSF to the characteristics of a heat sink. Using SF's also brings a question of how to evaluate the uncertainty of the measurement, which is non-trivial due to the complex mathematical operations involved in the deconvolution of SF's and DSF's from the measured cooling curves.

Suitability of the methods for various applications is given by many factors. The thermocouple method is inexpensive and well known, but the installation of the thermocouples is time consuming and comes with challenges related to mounting and heat leakage through the thermocouple. The cost of a transient thermal tester is significantly higher, but it can be offset by other advantages: the need for intrusive installation of thermocouples is eliminated and since a transient response of the heat sink is measured instead of a simple steady-state performance, low-order thermal models for predicting the transient behavior of the heat sinks can be built based on the structure functions [3]. Additionally, other information describing the heat sink such as its heat capacity or the location of heat transfer bottlenecks can potentially be extracted from the shape of the structure functions, however, the extraction methods still need to be analyzed and developed. A promising, already documented method, is using the structure functions to calibrate a 3D numerical thermal model [8]., however, to the author's best knowledge, a study on how much information about a heat sink can be inferred using this approach is not available in the literature.

8. Conclusion

To validate our previous data gathered using thermocouples and to investigate the potential of using transient thermal tester for heat sink characterization, we designed a test bed that allowed heat sinks to be measured using the two methods at the same time, and collected the data for a graphite heat sink without TIM and an aluminum heat sink with and without TIM. The data suggest that the methods agree in determining the relative overall performance of the heat sinks i.e. they agree on which heat sink has the best performance. Breaking down the total thermal resistances reveals that the sink-to-ambient resistances measured by the two methods are in agreement, and that the case-to-sink resistance measured by a thermal transient tester and device-to-sink resistance measured by thermocouples show comparable values. The physical meaning of the case-to-sink and device-to-sink resistances is not obvious and requires further work as demonstrated by comparing the results to a specific interface resistance of the TIM measured by a specialized 1D heat flow device, which revealed approximately one order of magnitude difference. Other questions requiring further attention, such as quantifying the thermocouple errors, eliminating fluctuating ambient air temperature, and addressing heat losses have been identified. If developed into maturity, the proposed method can become a robust way to evaluate an in-situ performance of a heat sink, and, since the time-consuming installation of thermocouples is no longer needed, more heat sinks can be tested in reasonable time allowing for extended experimental parametric studies, which are highly valuable for developing heat sinks, as they include factors impossible to capture in simulations (such as variations in interface resistance or thermal properties). The equipment cost of the transient thermal tester is significantly higher than that of thermocouples and the feasibility should be judged on a per-case basis.

Contributions

M. Cermak – Concept, samples and test bed preparation, data analysis, publication; W. J. He – Data collection, transient thermal tester expertise; M. Bahrami – supervision.

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