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BUILDING AN ASTM D5470 STANDARD APPARATUS AND TESTING PERFORMANCE OF DIFFERENT THERMAL INTERFACE MATERIALS

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ABSTRACT

The goal of this research project is to design a cost-effective thermal interface material (TIM) testing apparatus alternative to more expensive, commercially available testing units. The TIM tester will follow the ASTM standard D5470-12 for testing the thermal properties of different TIMs. TIMs are used between two solid surfaces to enhance the heat transfer by displacing air gaps from the interface. TIM has a higher thermal conductivity than air and therefore can lower the contact resistance at the interface of interest to prevent overheating of the system. The ASTM D5470 setup consists of two meter bars and heat flow is made one-dimensional using proper insulation. The temperature gradients in each meter bar, heat flow, and the TIM's thickness was measured to determine its thermal resistance and conductivity through fundamental heat transfer analysis.

Keywords: Thermal interface material, thermal conductivity, thermal resistance, heat transfer.

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1. Introduction

One of the greatest challenges inhibiting the development of electronic devices is the excessive heat buildup created by micro electrical components. Central processing unit (CPU) manufacturers like Intel enhance the power capabilities of their products every year while shrinking them in size. There is not an end in sight to these continuous improvements, so the demand is greater than ever to develop methods and materials that are capable of dissipating the heat produced from these micro electrical components. Heat sinks that contact these components are frequently used to quickly transfer heat from the device to its surroundings. However, the surface roughness on the faces of the heat source and the heat sink prevent them from perfectly mating. Figure 1 illustrates the situation created by the surface roughness and non-flatness at the heat source-heat sink interface.

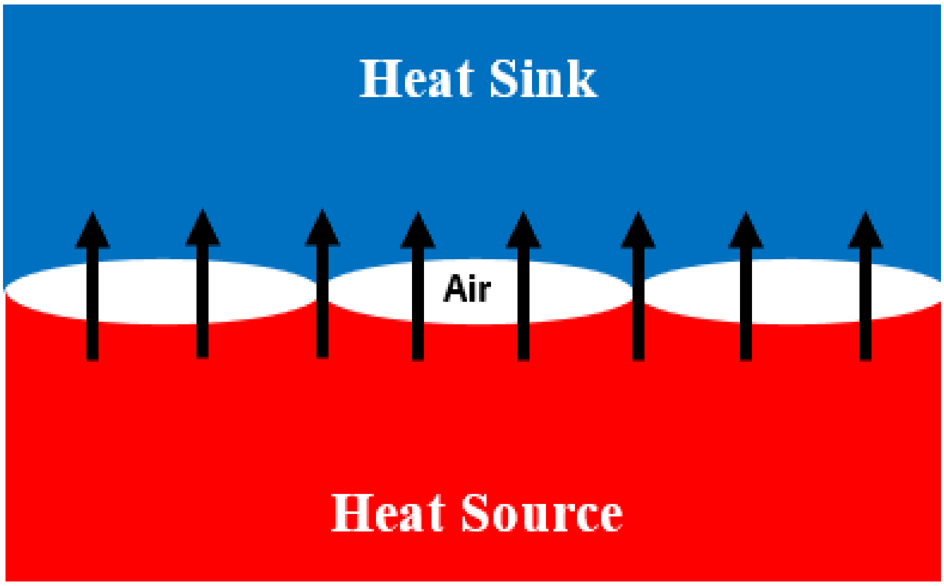

Figure 1. An imperfect mating surface is created by the roughness and/or non-flatness of the heat source and heat sink surfaces. As a result, air pockets with low thermal conductivity develop and prevent effective heat transfer.

It is possible to polish the surfaces that are in contact so that the surface roughness is reduced, but this process adds time and cost to manufacturing [1]. Instead, thermal interface materials (TIMs) have been developed to combat the thermal dissipation issue. TIMs possess high thermal conductivities and are able to deform in order to fill the air pockets created at the interface. Additionally, TIMs must be able to withstand the variable thermal loading over time. Figure 2 illustrates how TIMs fill the air pockets and increase the rate of heat transfer.

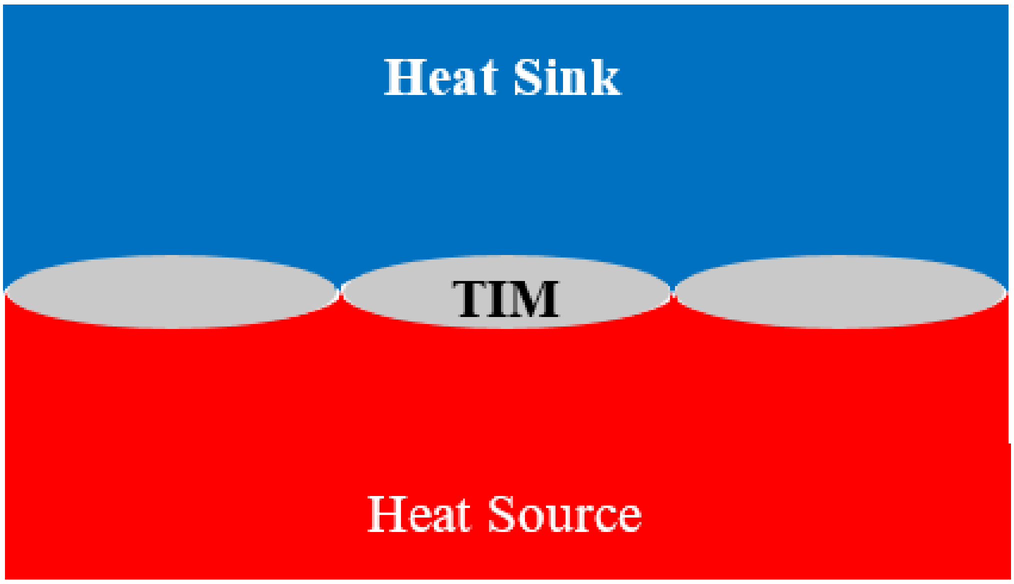

Figure 2. The ideal TIM possesses a high thermal conductivity and is able to deform so that it displaces the air pockets that are normally present at the interface.

Since the demand for better TIMs is great, ASTM standard D5470-12 was developed and describes the methods used and conditions required to test the thermal conductivity and thermal impedance of various TIM types [2]. Thermal impedance is a material's resistance to heat flow and is dependent on its thickness. Commercial manufacturers have developed highly automated testing machines that can determine a TIM's thermal properties are available for purchase, but they are very expensive.

The great cost for a commercial TIM testers has prompted many institutions develop their own TIM testers at a fraction of the cost. Extensive research of other institutions' designs revealed that common design challenges include [3-8]:

1. Measuring in-situ thickness during testing.
2. Applying heating and cooling during testing.

3. Applying and measuring constant, uniform pressure during testing.
4. Determining length of meter bars and location of temperature sensors.
5. Choosing proper insulation to simulate one-dimensional heat flow.
6. Maintaining meter bar alignment.
7. Maximizing overall precision of the device

The main objective of this work is to design and build a TIM testing device according to ASTM D 5470 standard guidelines and test thermal performance of various traditional and potential TIMs.

1.1 Calculation of thermal Resistance and thermal Conductivity

ASTM D5470-12 specifies two main methods of measuring thermal conductivity for a TIM. One relies on knowing the heat flow in the meter bars (method 1), and one relies on knowing the thermal conductivity of the meter bar material (method 2). We chose to use method 1 for our design. In this method, total thermal resistance also known as thermal impedance was calculated using equation 1 at different TIM thicknesses.

$$R_{th} = \frac{\mathrm{A}}{\mathrm{Q}} * (\mathrm{T_H} - \mathrm{T_C}) \qquad (1)$$

Where A is the cross-sectional area of the meter bar contacting the TIM specimen, Q is the heat flow applied to the apparatus, T_H is the temperature of the surface of the hot meter bar contacting the TIM specimen, and T_C is the temperature of the surface of the cold meter bar contacting the TIM specimen. T_H and T_C can be linearly extrapolated from thermocouple measurements along the meter bar as long as those measurements are in an area of uniform heat flux and the distances between thermocouples is known. Equations 2 and 3 are used to calculate $\mathrm{T_H}$ and $\mathrm{T_C}$, respectively.

$$\mathrm{T_H} = \mathrm{T_2} - \frac{\mathrm{d_2}}{\mathrm{d_1}} * (\mathrm{T_1} - \mathrm{T_2}) \qquad (2)$$

$$\mathrm{T_C} = \mathrm{T_3} + \frac{\mathrm{d_4}}{\mathrm{d_3}} * (\mathrm{T_3} - \mathrm{T_4}) \qquad (3)$$

T_1, T_2, T_3, and T_4 are temperatures measured by the thermocouples in the hot and cold meter bars, and d_1 is the distance between T_1 and T_2, d_2 is the distance from T_2 to the surface of the TIM in contact with the hot meter bar, d_3 is the distance between T_3 and T_4 and d_4 is the distance from T_3 to the surface of the TIM in contact with the cold meter bar. Total thermal resistance measurements are plotted versus measured thickness, and the reciprocal of the slope of the line created by the plot is the thermal conductivity of the specimen. The general schematic for this method is shown in Figure 3.

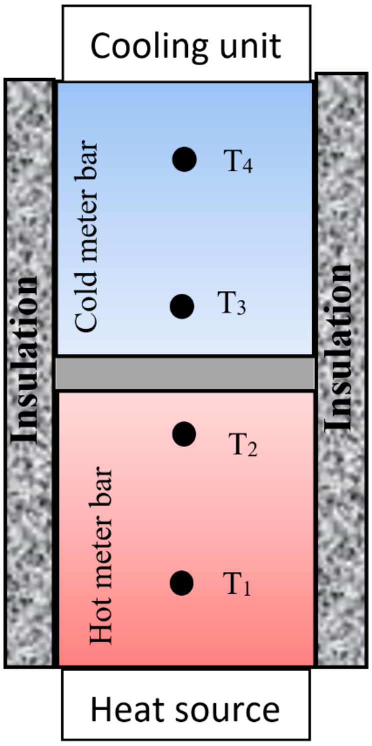

Figure 3. General schematic of a typical TIM tester setup.

2. Experimental setup

A steady-state thermal test setup was designed and built first. The design followed the guidelines outlined in ASTM D5470 standard. Figures 4 and 5 show the isometric view of the final design and the actual setup in operation, respectively. In our previous paper [9], we explained the detailed design of each component of the TIM tester.

The TIM tester consists of two round meter bars (1.5-inch diameter) through which heat travels. The bar is made of aluminum 6061-T6 alloy, which has a thermal conductivity of about

167 W/m.K. The overall length, width, and height of the unit without the press screw is 15” x 6” x 16”, respectively.

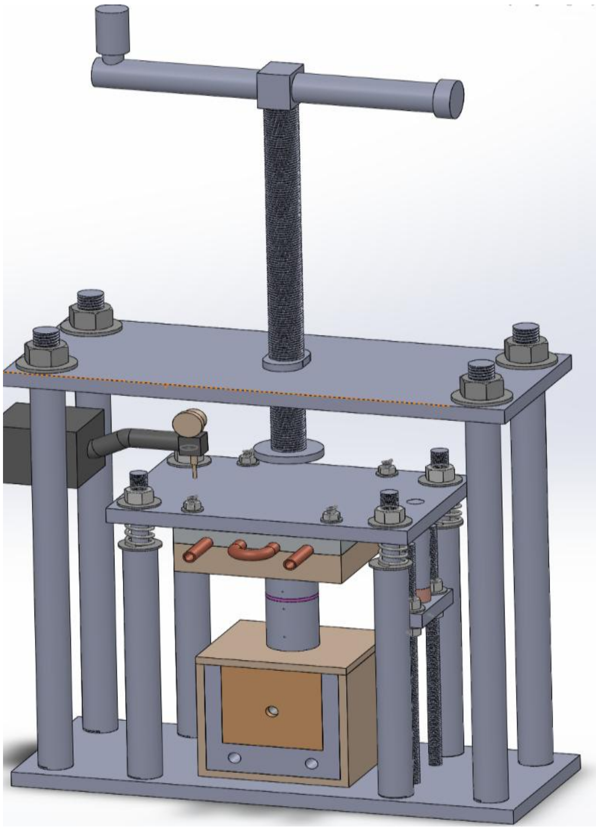

Figure 4. Isometric view of the final design. The outer housing is used to support the manual press screw that applies the compressive load onto the middle plate of the inner housing. A precision dial indicator is positioned above the middle plate of the inner housing. As the middle plate is compressed, the change in thickness can be recorded as the dial indicator probe freely glides down. The dial indicator clamp (black box) is attached to one of the support bars, and the clamp’s flexible arms can be adjusted to change the height of the dial indicator [9].

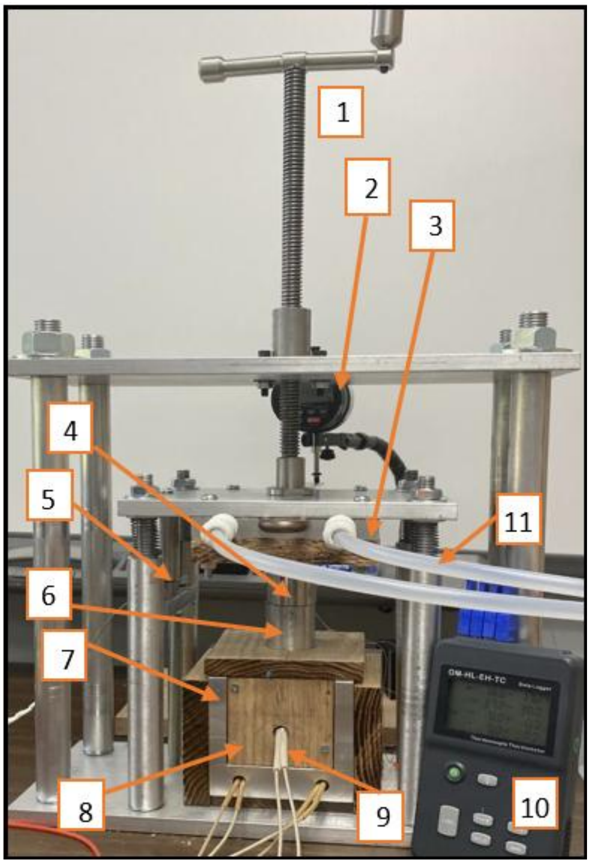

Figure 5: (1) press screw, (2) dial caliper, (3) cold plate, (4) cold meter bar, (5) load cell, (6) hot meter bar, (7) guard heater, (8) heater block surrounded by insulation, (9) cartridge heaters, (10) temperature data logger

The top meter bar is attached to the cold plate. The cold plate is connected to a chiller, which provides cold water to the plate and maintains a constant temperature boundary condition. The bottom meter bar is drilled to insert the cartridge heater, which provides heat to the bar. Wooden strips are used to reduce the heat loss from the heater. The test sample (TIM) was placed between two meter bars, and fiberglass insulations were used to wrap around the meter to reduce the heat loss to the surroundings and to make the heat flow one-dimensional. The pressure was applied on the top meter bar through the press-screw, and a load cell was used to detect the applied load and then converted to pressure. The meter bars were drilled to make holes for thermocouples. Each meter bar had two thermocouples, one inch apart. The temperature drop across the sample (TIM) was calculated by extrapolating thermocouple readings.

Total automation is an appealing feature of most commercial TIM units and consequently is why they are so expensive. Our design is considerably less expensive since more work is required by the user to conduct the test and collect data, but this also introduces additional uncertainty.

3. Results

The following tests were conducted to determine the thermal properties of various TIMs and accuracy of our device producing consistent results.

1. Thermal grease testing
2. Graphite sheet testing
3. Graphite sheet repeatability tests

The testing protocols used were in accordance with ASTM D5470-12 and are reiterated in the following sections for each test.

3.1 Thermal Grease TIM Testing

Thermal greases are the most widely used TIMs. Greases are generally consists of a polymeric matrix, loaded with conductive particles (metals or ceramics) to enhance the thermal conductivity. Greases are viscous liquids, and they flow well at the interface at a lower pressure and thus offer a low resistance thermal connection between the adjoining components. Greases can be electrically conductive or non-conductive depending upon its composition.

To measure the thermal conductivity of the grease, the thermal resistance was measured at three different thicknesses. For these tests, the device reached steady-state without the grease, and the dial caliper was zeroed, then the thermal grease was applied to the meter bar faces. The meter bars were pressed together until excess grease spilled out of the interface, and the excess grease was removed. The thickness of the grease being tested was determined from the reading given by the dial caliper. Once the device reached steady-state, temperature measurements were recorded, and the grease was compressed further to achieve a new thickness, where it was allowed to reach steady-state again.

Figure 6 shows the calculated thermal resistance of thermal grease at three different thicknesses. In theory, the thermal resistance has a linear relationship with thickness as represented by the following equation 4.

$$\boldsymbol{R_{th} = R_c + \frac{L}{Ak}} \tag{4}$$

Where R_c is the contact resistance, L is the thickness, A is the cross-sectional area, and k is the thermal conductivity of the TIM material. The thermal conductivity is calculated from the inverse of the slope of linear fit curve. From the data, the thermal conductivity is calculated to be 6.27 W/m-K, which is typical for a thermal grease interface. Also, the results show that the thermal resistance decreased by about 50% as the thickness decreased from 1.44 mm to 0.33 mm. Greases offer reasonably low thermal resistance at low pressures. While thermal greases provide low thermal resistance, their practical limitations hinder long-term reliability and ease of use. They are often messy, challenging to apply uniformly, and difficult to remove during rework. Common failure mechanisms such as pump-out, phase separation, and dry-out can degrade performance over time, limiting their effectiveness as a thermal interface material (TIM) over the product's operational lifespan [1,10]. Additionally, if the grease is electrically conductive, any excess material that seeps out of the interface may pose a risk of electrical short circuits [10]

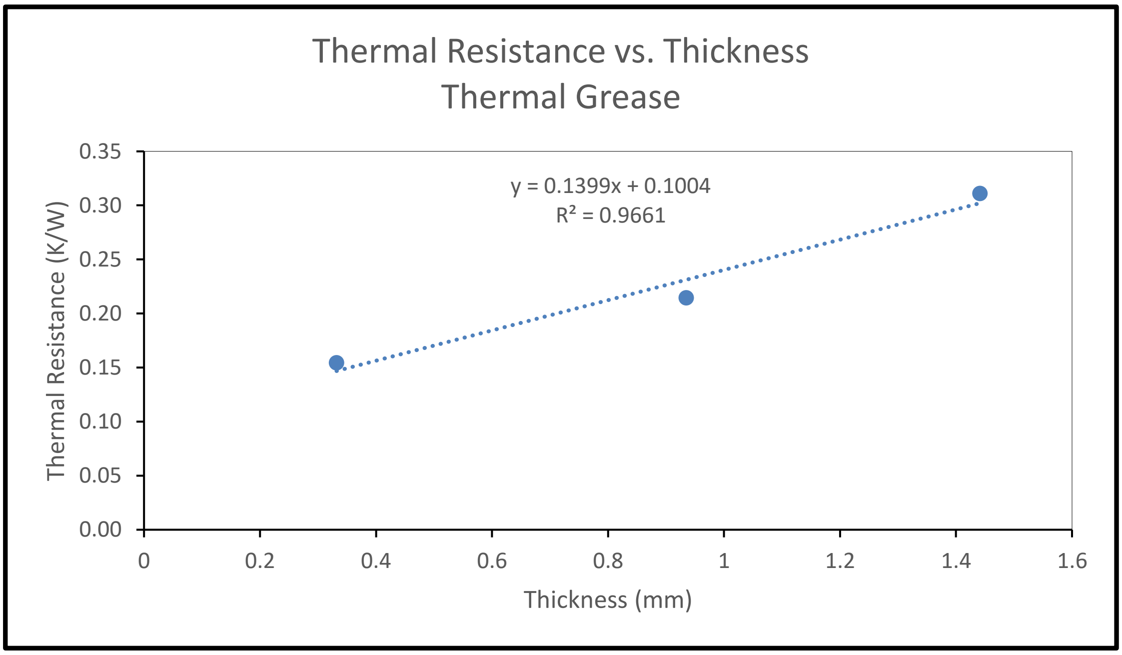

Figure 6: Thermal resistance increases with material thickness. The inverse of the slope should be the thermal conductivity of the material being tested.

3.2 Graphite Sheet TIM testing

Graphite sheet is another soft-solid TIM used in electrical applications. It has a relatively high thermal conductivity (35 W/m-K), and it deforms slightly when compressed to reduce air pockets at the heat sink interface. For these tests, the thermal resistance was calculated and plotted against various pressures. *Figure 7* displays the data from tests conducted at six different interface pressures on a single graphite sheet of thickness 1 mm. The thermal resistance decreases by about 9% in the lower pressure range (10-30 psi). After 30 psi, the thermal resistance does not change significantly with pressure. The results suggest that a very high pressure is not needed to achieve lower thermal resistance with graphite sheets. Unlike greases, graphite sheets do not suffer from issues such as pump-out, phase separation, or dry-out, which makes them especially suitable for applications requiring stable thermal performance over extended periods. Furthermore, they are clean, easy to handle, and suitable for rework processes.

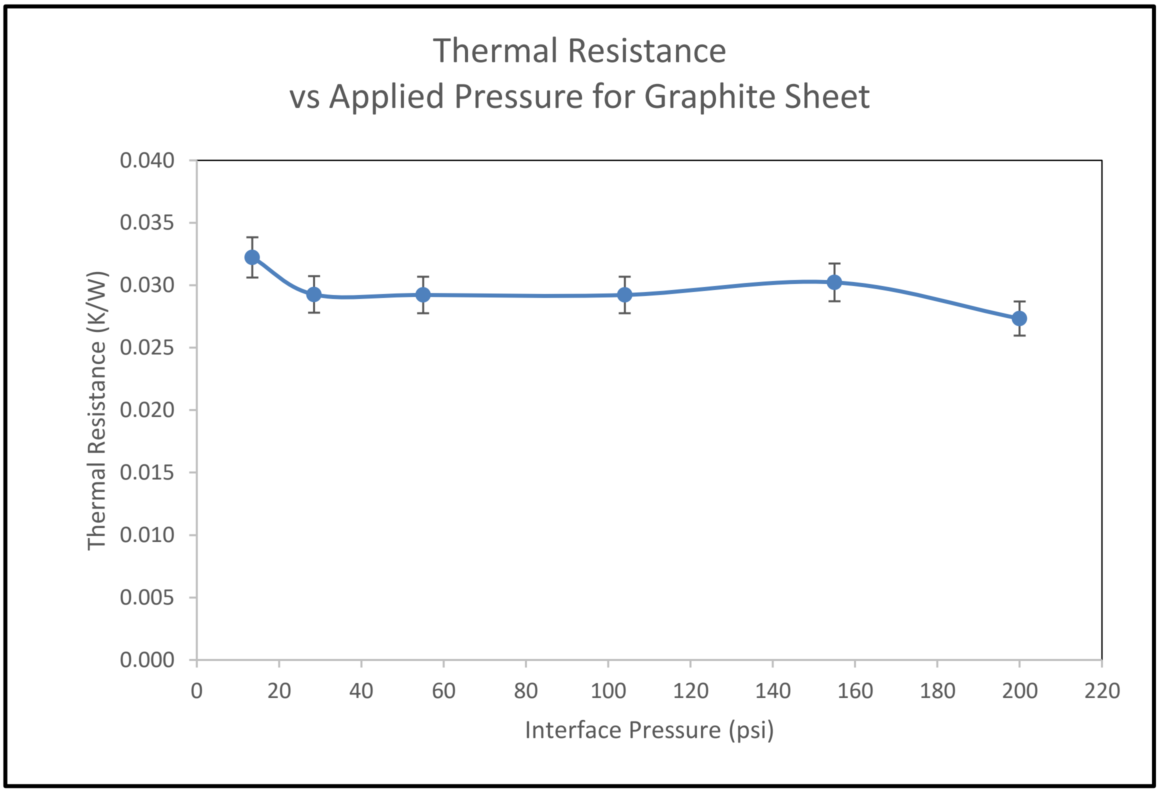

Figure 7: Thermal resistance of a single graphite sheet as a function of applied pressure. Beyond an interface pressure of around 30 psi, thermal resistance does not vary significantly.

3.3 Graphite Sheet Repeatability Tests

To determine if the setup would produce repeatable results, tests were performed with another graphite sample at the same or close to the same pressure three separate times. For each test, we allowed the temperatures to reach steady state. The heater block was turned off and was allowed to cool while the cold plate ran for 15 minutes. The graphite sample was removed, and it was reinserted between the meter bars. The heater block was turned back on, and steady-state temperatures were recorded again. This process was repeated two additional times for a total of three tests. The power from the power supply and the temperature of the cooling plate remained constant, so if a similar pressure was applied each time, similar results for thermal impedance should be obtained. For the three test results, the relative standard deviation (RSD) was calculated and found to be about 3.2%, which ensured the excellent repeatability of the test results.

4. Summary & Conclusion

A steady-state thermal test setup was designed and built using ASTM D5470 guidelines. The total cost of the TIM tester, including raw materials, parts, instruments, and the chiller pump, is $8,327, which is less than 20% of the cost of a commercial TIM testing device.

Thermal performance of various TIMs have been tested using the designed setup. Thermal resistances of thermal grease were measured at different thicknesses. The thermal conductivity of the grease was calculated to be 6.27 W/m.K, which indicated a high performing grease interface. Thermal resistance of the graphite sheet are presented as a function of applied pressure. Results show that graphite sheet have superior performance compared to thermal grease. Graphite sheets also eliminate common issues associated with thermal greases, such as pump-out and dry-out, enhancing long-term reliability. Repeatability testing shows that the measurements obtained from the TIM testing device are reasonably consistent.

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