CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Semiconductor devices are now gradually upgraded in term of electrical performances, power densities, transistor dimensions and the packaging size. These patterns of advancement generate greater amount of heat. Therefore, thermal management within the semiconductor device and surrounding packaging must be improved progressively in order to remove the heat generated. With this issue occurs in semiconductor world, the research to find out high-conductivity materials become more important. Since the semiconductor device is affected by the temperature within and surrounding the packaging, thermal management become the main subject in designing semiconductor devices. Heat spreader plays an important role in thermal management of a semiconductor device because it is a medium to remove heat from the chip to heat sink. Heat spreader with high thermal conductivity can removes heat effectively. At the same time, it must have a low coefficient of thermal expansion so that the heat spreader does not excessively expand.

1.2 PROBLEM STATEMENT

Semiconductor devices nowadays generate greater amount of heat. Thus, a material with excellent heat removal is needed to be used as heat spreader. Materials like copper and aluminium have excellent heat removal, however, easily expanded when subjected to a very high temperature. An expanded heat spreader creates a force or pressure that can change the shape of semiconductor device. As the result, the semiconductor device is malfunctioned. Thermal conductivity indicates a material ability to remove heat and coefficient of thermal expansion shows how much a material expands in respond to temperature. A material with higher thermal conductivity and lower coefficient of thermal expansion than copper and/or aluminium are needed to provide a better heat removal with less or no expansion on the heat spreader.

1.3 OBJECTIVES AND SCOPE OF STUDY

The objectives and scope of studies for this project are as follows:

1. To investigate the heat transfer from chip to heat sink via heat spreader.
2. To study the current heat spreader properties that is thermal conductivity and coefficient of thermal expansion.
3. To design the heat spreader by using copper-carbon composite.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 HEAT SPREADER

A heat spreader is located between a chip and a heat sink of a semiconductor device as shown in Figure 2.1. Heat spreader is added for chip protection and also to allow better thermal performance. Heat spreader acts as a primary heat exchanger that moves heat between a heat source (chip) and a secondary heat exchanger (heat sink). Heat sink has a larger contact surface compare to heat spreader. Therefore, the heat flow per unit area (heat flux density) of heat sink is less than heat flux density of heat spreader. So, heat spreader is usually used only if the heat source has a very high heat flux density or when heat sink cannot removes the heat effectively. Copper is the most common material for heat spreader. Copper heat spreader is selected because it is an excellent thermal conductor. Diamond is the best material but limited due to high cost. Another alternative is heat spreader made of diamond coating. Heat spreader can also be made from composite such as Cu-Mo.

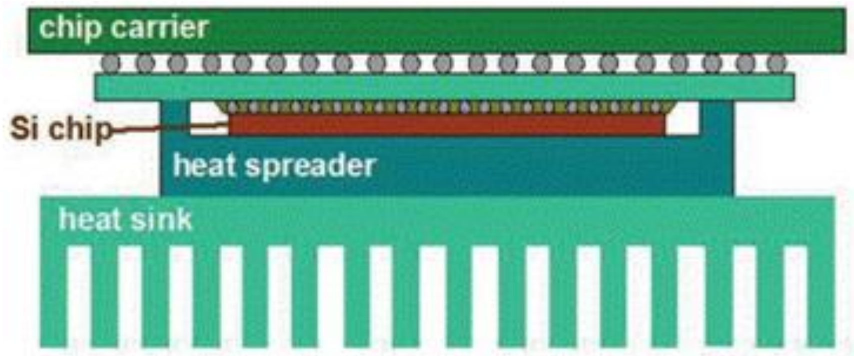

Figure 2.1**:** Basic Construction of a Semiconductor Device [3]

2.2 THERMAL CONDUCTIVITY

Thermal conductivity, *k*, is a property that indicates a material ability to conduct heat. Thermal conductivity is used mostly in Fourier's Law for heat conduction.
Heat conduction is defined by the equation below:

$$H = \frac{\Delta Q}{\Delta t} = k \times A \times \frac{\Delta T}{x} \tag{1}$$

where $\frac{\Delta Q}{\Delta t}$ is the rate of heat flow, *k* is the thermal conductivity, *A* is the total surface area of conducting surface, ΔT is temperature difference and *x* is the thickness of conducting surface separating the two temperatures.

The heat conduction equation is then rearranged to gives thermal conductivity equation, that is,

$$k = \frac{\Delta Q}{\Delta t} \times \frac{1}{A} \times \frac{x}{\Delta T} \tag{2}$$

where $\frac{\Delta T}{x}$ is the temperature gradient. Therefore, thermal conductivity is defined as the quantity of heat, ΔQ, transmitted in time Δt through a thickness *x*, in a direction normal to a surface of area *A*, due to a temperature difference ΔT, under steady state conditions and when the heat transfer is dependent only on the temperature gradient.

Thermal conductivity also can be defined as a flux of heat (energy per unit area per unit time) divided by a temperature gradient (temperature difference per unit length) as shown by the equation below.

$$k = \frac{\Delta Q}{A \times \Delta t} \times \frac{x}{\Delta T} \tag{3}$$

The typical units for thermal conductivity are W/(m·K) (SI unit) and Btu·ft/(h·ft²·°F) (English unit). Table 2.1 shows the thermal conductivity of various types of materials [1, 2].

Table 2.1: Thermal Conductivity of Some Common Materials

Materials	**Thermal Conductivity, W/(m·K)**
Lead	35.3
Aluminum	237
Gold	318
Copper	385
Silver	429
CNT	> 2000
Carbon	160

2.3 COEFFICIENT OF THERMAL EXPANSION

The energy that is stored in the intermolecular bonds between atoms changes during heat transfer. As the stored energy increases, the length of the molecular bond also increases. Therefore, solids expand in response to heating and contract on cooling. This response to temperature changes is called coefficient of thermal expansion. The coefficient of thermal expansion is used:

- in linear thermal expansion
- in area thermal expansion
- in volumetric thermal expansion

These characteristics are closely related. The volumetric thermal expansion coefficient can be measured for all materials of condensed matter (liquids and solid state). The linear thermal expansion can only be measured in the solid state and is common in engineering applications. Some substances have a negative expansion coefficient, and will expand when cooled, for example, freezing water.

The thermal expansion coefficient is a thermodynamic property of a substance. It relates the change in temperature to the change in a material's linear dimensions. It is the fractional change in length per degree of temperature change.

$$\alpha = \frac{1}{L_0}\frac{\partial L}{\partial T} \tag{4}$$

where L_0 is the original length, L the new length, and T the temperature. Table 2.2 shows coefficient of thermal expansion for some common materials [8, 9].

Table 2.2: Coefficient of Thermal Expansion of Some Common Materials

Coefficient of Linear Thermal Expansion, *α*		**Coefficient of Volumetric Thermal Expansion, *β***
Material	**α in 10^{-6}/ °C at 20 °C**	**β(=3α) in 10^{-6}/°C at 20 °C**
Lead	29.0	87.0
Aluminium	23.0	72.0
Gold	14.0	42.0
Copper	16.5	49.5
Silver	18.0	54.0
CNT	1.0	3.0
Carbon	7.1	21.3

2.3.1 Linear Thermal Expansion

$$\frac{\Delta L}{L_0} = \alpha_L \Delta T \tag{5}$$

The linear thermal expansion is the one-dimensional length change with temperature.

2.3.2 Area Thermal Expansion

The change in area with temperature can be written:

$$\frac{\Delta A}{A_0} = \alpha_A \Delta T \tag{6}$$

For exactly isotropic materials, the area thermal expansion coefficient is very closely approximated as twice the linear coefficient.

$$\alpha_A \cong 2\alpha_L \tag{7}$$

$$\frac{\Delta A}{A_0} = 2\alpha_L \Delta T \tag{8}$$

2.3.3 Volumetric Thermal Expansion

The change in volume with temperature can be written:

$$\frac{\Delta V}{V_0} = \alpha_V \Delta T \tag{9}$$

The volumetric thermal expansion coefficient can be written

$$\alpha_V = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{10}$$

where T is the temperature, V is the volume, ρ is the density, derivatives are taken at constant pressure p; β measures the fractional change in density as temperature increases at constant pressure.

For exactly isotropic materials, the volumetric thermal expansion coefficient is very closely approximated as three times the linear coefficient.

$$\alpha_V \cong 3\alpha_L \tag{11}$$

$$\frac{\Delta V}{V_0} = 3\alpha \Delta T \tag{12}$$

2.4 RULE OF MIXTURE

Rules of Mixtures are mathematical expressions which give some property of the composite in terms of the properties, quantity and arrangement of its constituents. They may be based on a number of simplifying assumptions, and their use in design should temper with extreme caution [4, 5].

For a general composite, total volume V, containing masses of constituents M_a and M_b, the composite density is;

$$\rho = \frac{M_a + M_b}{V} = \frac{M_a}{V} + \frac{M_b}{V} \qquad (13)$$

In terms of the densities and volumes of the constituents;

$$\rho = \frac{V_a \rho_a}{V} + \frac{V_b \rho_b}{V} \qquad (14)$$

But $V_a / V = v_a$ is the volume fraction of the constituent a, hence:

$$\rho = v_a \rho_a + v_b \rho_b \qquad (15)$$

The density in the equation above can be replaced with thermal conductivity or coefficient of thermal expansion. Therefore, thermal conductivity and coefficient of thermal expansion of a mixture can be expressed as;

$$k = v_a k_a + v_b k_b \qquad (16)$$

$$\alpha = v_a \alpha_a + v_b \alpha_b \qquad (17)$$

2.5 RELATED WORKS

Taikyoeng and Young calculate the thermal conductivity of nanocomposites embedded with carbon nanotubes (CNTs) based on the representative volume element (RVE) concept [6]. The RVE, which encompasses a single CNT, was constructed assuming that the CNTs are distributed in polymeric material homogeneously, and also assuming that the CNTs have no interaction with other CNTs. This research describes the thermal characteristics of nanoscale materials - CNTs filled nanocomposites - as a case study and measured their thermal conductivity, for the purpose of validation of numerical results.

They measured the thermal conductivity by employing ASTM E1225, which was based on temperature difference between the reference and the specimen at steady state and room temperature. For verification of uniform dispersion of the CNTs, morphological characterization was performed by using a field emission scanning electronic microscope (FESEM). They found that the numerically predicted thermal conductivity is closely matches the experimental one and that the numerical tool employed in the study is superior to other analytical and numerical methods.

Taikyeong and Young again predicted the effective thermal conductivity of the polymeric composites filled with carbon nanotubes (CNTs) by using the asymptotic expansion homogenization technique (AEH), which makes it possible to localize and homogenize a heterogeneous medium [7]. In the present study, CNT embedded epoxy composites are taken into account as the heterogeneous system. The representative volume element (RVE) employed in the homogenization process is constructed by assuming that the CNTs are dispersed homogeneously in the polymer matrix. It is presumed that the RVE contains a single CNT and that there is no direct interaction between neighboring CNTs.

The thermal conductivity measurement was carried out by employing ASTM E1225, which was based on temperature difference between the reference and the specimen at steady state and room temperature. The dispersion state of CNTs in the composites is morphologically characterized by the field emission scanning electronic microscope (FESEM). In order to consider the orientation state of CNTs, the bounding approach is adopted by using the orientation tensor. They found that the numerically homogenized thermal conductivity is higher than that obtained by the analytic model. Predicted conductivities are also compared with experimental results as well as analytic results. The homogenization technique yields the effective thermal conductivity accordant with experimental results. In the case that a heterogeneous material has anisotropic properties or geometrical complexity, the homogenization technique is an efficient method to obtain averaged material properties equivalent to those of the real heterogeneous medium.

CHAPTER 3

METHODOLOGY

The process flow for the project is shown by the flowchart below.

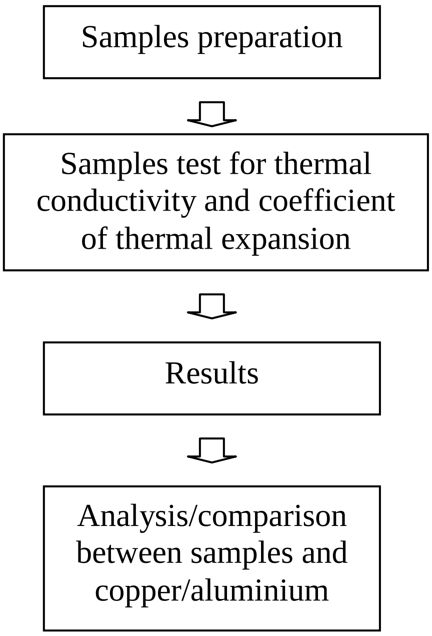

Figure 3.1 Project Flowchart

3.1 SAMPLE DETERMINATION

The materials chosen are copper and carbon because copper has excellent thermal conductivity and carbon has low coefficient of thermal expansion. There are three samples with different composition to be produced (refer Table 3.1). By using rule of mixture, the amount needed for copper and carbon for each composition is determined. The sample is designed as a cylindrical bar with 2.5 cm diameter and 1.5 cm height as shown by Figure 3.2. Each sample has two cylindrical bars. This design is chosen because Hilton Heat Conduction Unit (which will be used to test the sample thermal conductivity later on) can fit only a sample of 3.0 cm in length and

2.5 cm diameter. 1.5 cm length of bar is made because the mould can not fill up the amount of copper-carbon powder mixture needed to form 3.0 cm length.

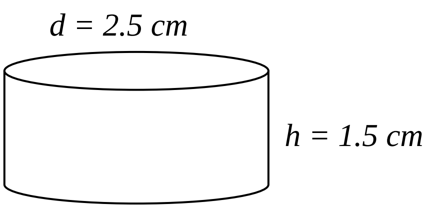

Figure 3.2: Design of Copper-Carbon Sample

Volume of the cylindrical bar is;

$V = \pi r^2 h \times 2$

$= \pi\,(2.5\text{ cm} / 2)^2\,(1.5\text{ cm}) \times 2$

$= 14.7\text{ cm}^3$

Contacting surface area is;

$A = \dfrac{\pi D^2}{4}$

$= \dfrac{\pi\,(2.5\text{ cm})^2}{4}$

$= 4.91 \times 10\text{-}4\text{ cm}^2$

The mass of copper and carbon needed to form the cylindrical bar is determined by using rule of mixture;

$$\rho = v_{cu}\rho_{cu} + v_c\rho_c \tag{18}$$

$$v_{cu} + v_c = 1 \tag{19}$$

$$v_{cu} = V_{cu} / V \tag{20}$$

$$v_c = V_c / V \tag{21}$$

$$m_{cu} = \rho_{cu} V_{cu} \tag{22}$$

$$m_c = \rho_c V_c \tag{23}$$

Substitute (20) into (22) and (21) into (23), so the mass of copper and carbon is given by;

$$m_{cu} = \rho_{cu} v_{cu} V \tag{24}$$

$$m_c = \rho_c v_c V \tag{25}$$

where ρ_{cu} = 8.93 g/cm^3 and ρ_c = 2.26 g/cm^3.

Table 3.1: Mass of Copper and Carbon Needed for Each Composition

Composition (%)	Cu-10C	Cu-15C	Cu-20C
m_{cu}, g	118.35	111.78	105.20
m_c, g	3.33	5.00	6.66

3.2 SAMPLE PREPARATION

Since the mould for 2.5 cm diameter bar is not available in the lab, a new mould is needed. The material used for mould is mild steel and processed by using Conventional Lathe machine. The mould is 7.0 cm in length and has diameter of 2.5 cm. The mould basically has three parts that are mould, plunger and base (Figure 3.3). The samples then are processed by using Hand Press machine (Figure 3.4) at UTP laboratory. All samples are pressed at force equal to 75 kN.

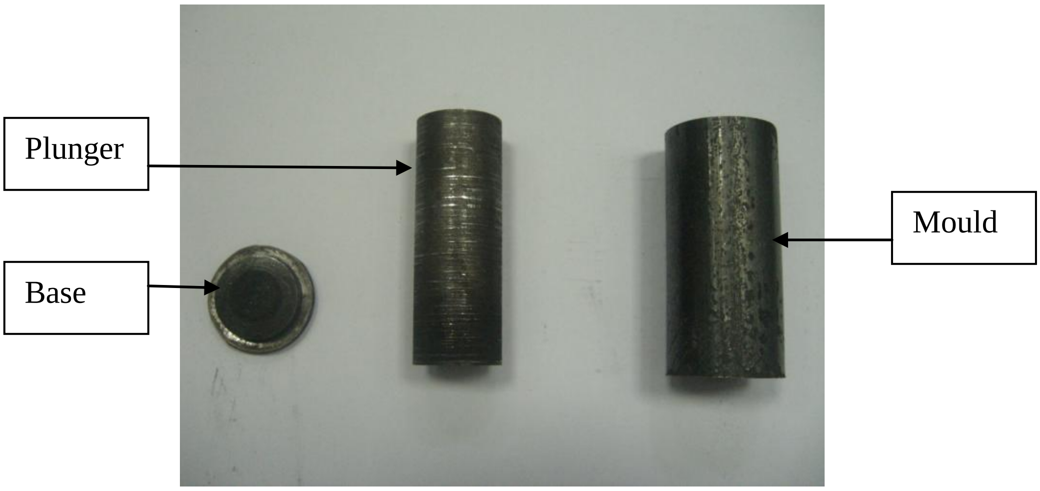

Figure 3.3: Plunger, Mould and Base

Figure 3.4: Hand Press Machine

3.3 SAMPLE TESTING

Samples test is conducted by employing ASTM E1225 which is by using Hilton Heat Conduction Unit (Figure 3.5) at UTP laboratory. The construction of the module is shown in Figure 3.6. The heat is supplied from power supply to module and transferred to cooling water. The instrumentation provided permits accurate measurement of temperature and power supply. Fast response temperature probes, with a resolution of 0.1^{o}C give direct digital read out in ^{o}C. The power control circuit provides a continuously variable electrical output 0-100 Watts with direct readout.

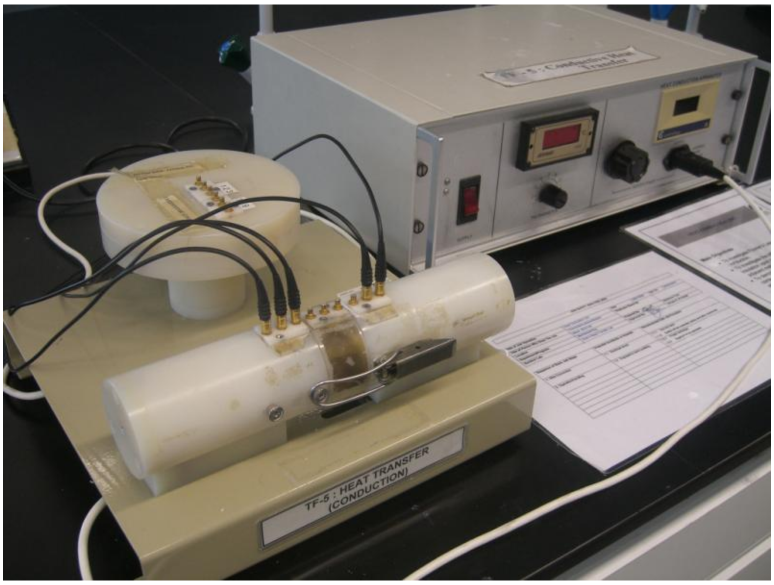

Figure 3.5: Hilton Heat Conduction Unit

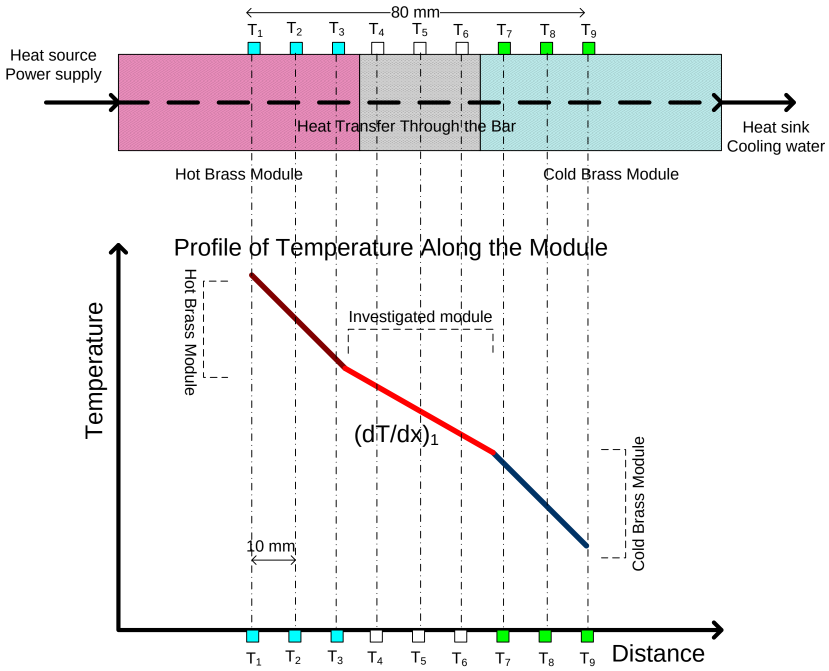

Figure 3.6: Heat Transfer Along Bar Module [10]

The linear module consists of two permanent bars and a removable bar. The construction of the linear module can be seen at Figure 3.5. The heat is generated from electrical power supply and heat the hot brass module. The heat transferred along the bar and to the environment through the cooling water. The temperature profile at steady state along the module can also be seen in Figure 3.5. The temperature reading of thermocouple 1 to 9 is plotted versus the distance. The Temperature of hot brass module will rise up when the power supply is turned on. Due to temperature different, the heat will be transferred to the next module by conduction. At steady state the heat in will be equal to heat out and shows the constant profile along the time. The hot and cold brass module has the same temperature gradient because is built with some material, but the removable can be fixed with many kinds of tested material. In this case, copper-carbon modules.

Procedure

1. Cu-10C module is arranged for simple bar. Both ends are coated with special conduction gel for reducing resistance before inserting the module.
2. The tap water is passed through the cold sink by setting the water flow rate about 0.5 liter per minute.

3. All thermocouples arrangements are checked to make sure they are correctly connected.
4. The main supply is switched on.
5. All 9 thermocouple readings at ambient condition are recorded.
6. The heater power input is set at 5 Watts.
7. The system is allowed to reach a steady state. This condition is reached when all 9 temperature readings are not changing with time.
8. The power and temperatures are recorded in Table xx when the steady state condition is attained.
9. Steps 7 – 9 is repeated by changing the power input to 10, 15 and 20 Watts.
10. The graph of recorded temperature (T) versus position of the bar (x) is plotted.
11. The thermal conductivity of copper-carbon, k, is determined by obtaining the slope of the plot.
12. Step 1 – 11 is repeated for Cu-15C and Cu-20C.

CHAPTER 4

RESULTS AND DISCUSSION

The composite is said a better material when it has better properties of thermal conductivity and coefficient of thermal expansion compare to copper and aluminium. Specifically, the thermal conductivity must at least better than aluminium that is 237 W/(m·°C) and the coefficient of thermal expansion must be less than copper that is 16.5 x 10^{-6}/ °C.

4.1 RESULTS

4.1.1 Sample 1 (90% copper, 10% carbon)

Figure 4.1**:** Sample 1 (90% copper, 10% carbon)

Table 4.1: Temperature Data for Sample 1

Test	**1**	**2**	**3**	**4**
Power, Q/t (W)	5	10	15	20
T_1 (°C)	26.8	29.1	32.0	34.9
T_2 (°C)	26.5	28.9	31.8	34.2
T_3 (°C)	26.8	29.3	31.8	34.4
T_4 (°C)	26.3	29.2	31.8	32.8
T_5 (°C)	25.2	27.3	30.1	31.0
T_6 (°C)	25.2	26.1	28.2	29.0
T_7 (°C)	23.8	23.8	23.9	24.0
T_8 (°C)	24.0	23.6	23.8	23.8
T_9 (°C)	23.7	23.4	23.8	23.7

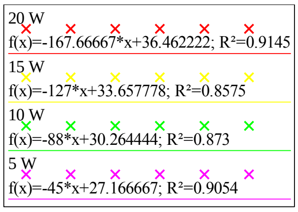

Figure 4.2: Temperature versus Position for Sample 1

Table 4.2: Thermal Conductivity of Sample 1

Test	**Power (Watt)**	**Slope (°C/m)**	**Thermal Conductivity, k = Power / (Slope x Area) (W/m °C)**
1	5	45.0	226.3
2	10	88.0	231.4
3	15	127.0	240.6
4	20	167.7	242.9

Thermal conductivity and coefficient of thermal expansion of sample 1 is 235.3 W/m °C and 15.56 x 10^{-6}/ °C respectively (see **Appendix 1**).

4.1.2 Sample 2 (85% copper, 15% carbon)

Figure 4.3: Sample 2 (85% copper, 15% carbon)

Table 4.3: Temperature Data for Sample 2

Test	**1**	**2**	**3**	**4**
Power (W)	5	10	15	20
T_1 (^oC)	27.1	29.2	32.2	34.6
T_2 (^oC)	26.3	29.1	31.8	34.0
T_3 (^oC)	26.8	29.2	32.0	34.4
T_4 (^oC)	26.6	29.1	31.6	34.1
T_5 (^oC)	25.1	28.7	29.8	30.5
T_6 (^oC)	24.3	24.5	25.0	25.2
T_7 (^oC)	24.0	23.7	23.7	24.1
T_8 (^oC)	23.8	23.7	24.2	23.8
T_9 (^oC)	23.9	23.7	23.9	24.0

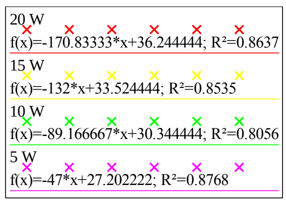

Figure 4.4: Temperature versus Position for Sample 2

Table 4.4: Thermal Conductivity of Sample 2

Test	Power (Watt)	Slope ($^oC/m$)	Thermal Conductivity, k = Power / (Slope x Area) (W/m ^oC)
1	5	47.0	216.7
2	10	89.2	228.3
3	15	132.0	231.4
4	20	170.8	238.5

Thermal conductivity and coefficient of thermal expansion of sample 2 is 228.7 W/m ^oC and 15.09 x 10^{-6}/ °C respectively (see **Appendix 2**).

4.1.3 Sample 3 (80% copper, 20% carbon)

Figure 4.5: Sample 3 (80% copper, 20% carbon)

Table 4.5: Temperature Data for Sample 3

Test	1	2	3	4
Power (W)	5	10	15	20
T_1 (^oC)	26.9	29.1	32.1	34.2
T_2 (^oC)	26.7	29.3	32.2	34.2
T_3 (^oC)	27.1	29.2	32.2	34.1
T_4 (^oC)	26.5	29.2	31.2	34.1
T_5 (^oC)	25.4	27.5	27.2	27.7
T_6 (^oC)	23.8	23.9	24.3	24.3
T_7 (^oC)	23.8	23.8	23.8	23.9
T_8 (^oC)	24.0	23.9	23.6	23.8
T_9 (^oC)	23.9	23.7	23.8	23.8

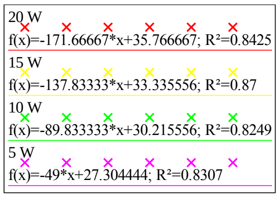

Figure 4.6: Temperature versus Position for Sample 3

Table 4.6: Thermal Conductivity of Sample 3

Test	**Power (Watt)**	**Slope (^{o}C/m)**	**Thermal Conductivity, k = Power / (Slope x Area) (W/m ^{o}C)**
1	5	49.0	207.8
2	10	89.8	226.8
3	15	137.8	221.7
4	20	171.7	237.2

Thermal conductivity and coefficient of thermal expansion of sample 3 is 223.4 W/m ^{o}C and 14.62 x 10^{-6}/ °C respectively (see **Appendix 3**).

4.2 DISCUSSION

From Table 4.1, the temperature of sample 1 at position 1 to 6 increases as the power input increases. This is because greater power input provides greater amount of heat. However, temperatures at position 7, 8 and 9 are about the same even with increasing power input because the brass module is cooled down with water flow. Figure 4.2 shows that the slope increases as the power input increases. This occurs because the temperature different between point 1 to point 9 are increasing when more power input is supplied. Table 4.2 summaries that thermal conductivity which is inversely proportional to the slope increases as power input increases. The same situation applies to sample 2 and sample 3 as shown by Figure 4.4 - Figure 4.6 and Table 4.3 – Table 4.6.

4.2.1 Thermal Conductivity Comparison

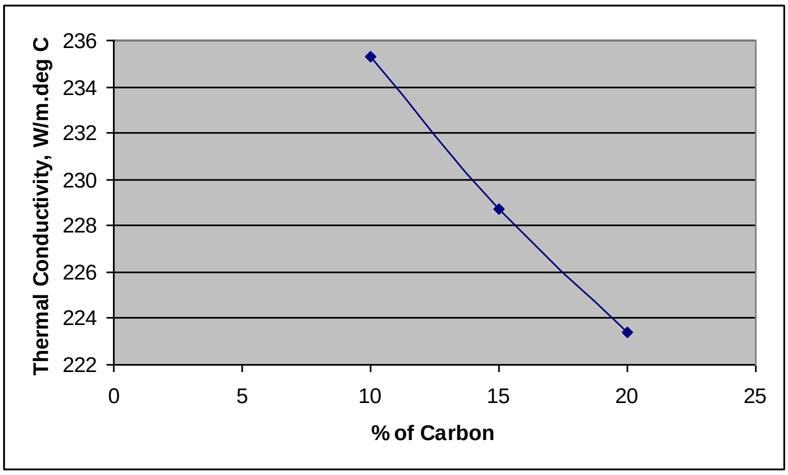

Figure 4.7: Thermal Conductivity versus Percentage of Carbon

Generally, the test gives a constant result as shown by Figure 4.7. The thermal conductivity is reduced when percentage of carbon added is increased. Sample 1 has the best thermal conductivity since it contained the least percentage of carbon. Even though the thermal conductivity is reduced, it is still acceptable because the value is about the same as thermal conductivity of aluminium which also been used as heat spreader (Figure 4.8). In fact, the thermal conductivity of all samples should be higher than aluminium. The value reduced due to some errors in experiment.

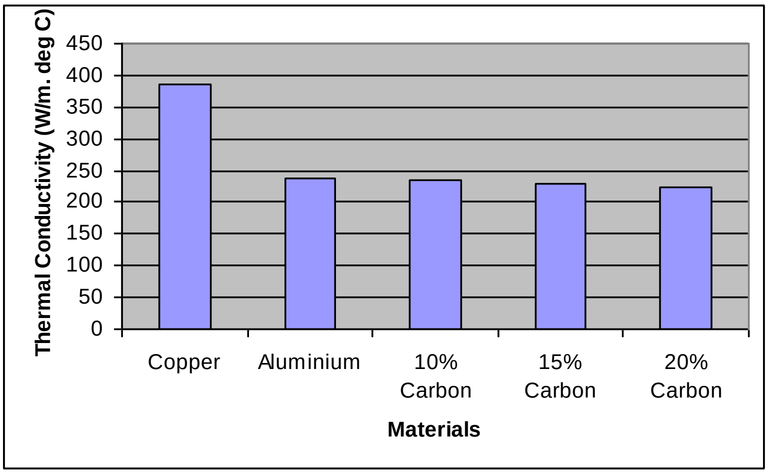

Figure 4.8: Thermal Conductivity Comparison

4.2.2 Coefficient of Thermal Expansion Comparison

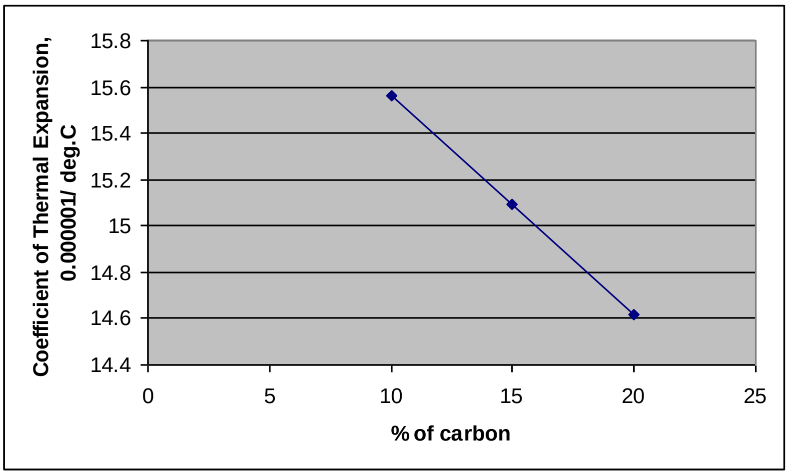

Figure 4.9: Coefficient of Thermal Expansion versus Percentage of Carbon

The coefficient of thermal expansion for all samples is calculated. According to Figure 4.9, coefficient of thermal expansion is reduced when more carbon is added to copper. Sample 3 possess the best coefficient of thermal expansion because it has the most percentage of carbon. All samples own better coefficient of thermal expansion compare to pure copper and aluminium (Figure 4.10).

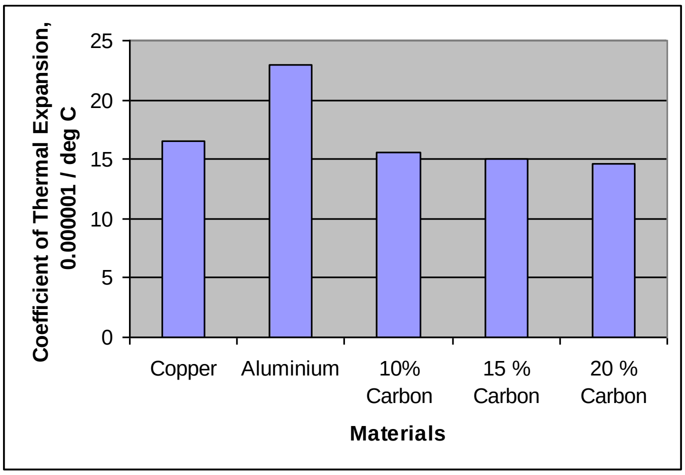

Figure 4.10: Coefficient of Thermal Expansion Comparison

4.2.3 Errors in Experiment

Random Errors

Random errors are statistical fluctuations in the measured data due to the precision limitations of the measurement device. Random errors usually result from the experimenter's inability to take the same measurement in exactly the same way to get exact the same number. Below are some random errors happen in this project:

- Measuring the weight of materials is somehow difficult especially carbon which is in small scale.
- The temperature readings of thermocouples are not steady.
- The particle size of both materials is not the same. Copper powder has particle size of 63 µm and particle size of carbon powder is smaller than 63 µm.
- The materials are not compressed at right pressure. Pressure higher than 75 kN/m^2 can not be applied because a crack or defect on the mould could happen

Systematic Errors

Systematic errors are reproducible inaccuracies that are consistently in the same direction. Systematic errors are often due to a problem which persists throughout the entire experiment. Below are some systematic errors happen in this project:

- The mixture of copper powder and carbon powder is not well compacted. Some carbon powder is attached on the mould.

- Some copper powder and carbon powder was left inside the containers (plastic bags) after being removed into the mould.
- The mixture of copper powder and carbon powder is not well compacted. Some carbon powder is attached on the mould.
- The materials are not compressed at right pressure. Pressure higher than 75 kN/m^2 can not be applied because a crack or defect on the mould could happen.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Heat is transfered from chip to heat sink via heat spreader. The heat spreader must have excellent thermal conductivity and low coefficient of thermal expansion to perfom excellent heat removal. The currently used heat spreader that are aluminium and copper has thermal conductivity of 237 W/(m·°C) and 385 W/(m·°C) respectively. Coefficient of themal expansion of copper is 16.5 10^{-6}/ °C and 23.0 x 10^{-6}/ °C for aluminium. All samples have better thermal conductivity compare to alumimium and lower coefficient of thermal expansion than copper. However, adding carbon to copper is not as easy as this project because carbon actually reduce its properties when subjected to a very high temperature (more than 300 ^{o}C). Therefore, sample 1 is the best since it contains less percentage of carbon and has better value for both properties (thermal conductivity more than 237 W/(m·°C) and the coefficient of thermal expansion less than copper 16.5 x 10^{-6}/ °C).

5.2 RECOMMENDATIONS

Several alterations can be done to improve the experiment especially to reduce the percentage error:

- The mass of copper and carbon powder must be measured repeatedly to get more data, for example five or ten readings. The final mass is then decided by averaging all data.
- The temperature for each thermocouple also must be decided by averaging the data.

- Use mould made of stainless steel instead of mild steel. Stainless steel is harder and stronger than mild steel. So it can withstand greater pressure to compact the powder mixture.
- Use mill ball machine to resize the particle. Te mixture should be process with mill ball machine first to resize the particle so that copper and carbon powder can be compacted nicely.

CHAPTER 6

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APPENDICES

Appendix 1: Thermal Conductivity and Coefficient of Thermal Expansion Calculation for Sample 1

$$k_{\text{average}} = \frac{226.3 + 231.4 + 240.6 + 242.9}{4}$$

$$= 235.3 \text{ W/m } ^{o}\text{C}$$

$$k_{\text{theoretical}} = v_{\text{cu}}k_{\text{cu}} + v_{\text{c}}k_{\text{c}}$$

$$= (0.90)(385) + (0.10)(160)$$

$$= 362.5 \text{ W/m } ^{o}\text{C}$$

$$\text{Percentage of error} = \frac{|\text{ Theoretical} - \text{Experimental }|}{\text{Theoretical}} \times 100\%$$

$$= \frac{|\ 362.5 - 235.3\ |}{362.5} \times 100\%$$

$$= 35.1\ \%$$

$$\alpha_{\text{theoretical}} = \text{v}_{\text{cu}}\alpha_{\text{cu}} + \text{v}_{\text{c}}\alpha_{\text{c}}$$

$$= (0.90)(16.5) + (0.10)(7.1)$$

$$= 15.56 \times 10^{-6} \ / \ ^{o}\text{C}$$

Appendix 2: Thermal Conductivity and Coefficient of Thermal Expansion Calculation for Sample 2

$$k_{\text{average}} = \frac{216.7 + 228.3 + 231.4 + 238.5}{4}$$

$$= 228.7 \text{ W/m } ^{o}\text{C}$$

$$k_{\text{theoretical}} = v_{cu}k_{cu} + v_{c}k_{c}$$

$$= (0.85)(385) + (0.15)(160)$$

$$= 351.3 \text{ W/m } ^{o}\text{C}$$

$$\text{Percentage of error} = \frac{|\text{ Theoretical} - \text{Experimental }|}{\text{Theoretical}} \times 100\%$$

$$= \frac{|\ 351.3 - 228.7\ |}{351.3} \times 100\%$$

$$= 34.9\ \%$$

$$\alpha_{\text{theoretical}} = \text{v}_{cu}\alpha_{cu} + \text{v}_{c}\alpha_{c}$$

$$= (0.85)(16.5) + (0.15)(7.1)$$

$$= 15.09 \times 10^{-6} \text{ / } ^{o}\text{C}$$

Appendix 3: Thermal Conductivity and Coefficient of Thermal Expansion Calculation for Sample 3

$$k_{\text{average}} = \frac{207.8 + 226.8 + 221.7 + 237.2}{4}$$

$$= 223.4 \text{ W/m } ^{o}\text{C}$$

$$k_{\text{theoretical}} = v_{cu}k_{cu} + v_{c}k_{c}$$

$$= (0.80)(385) + (0.20)(160)$$

$$= 340.0 \text{ W/m } ^{o}\text{C}$$

$$\text{Percentage of error} = \frac{|\text{ Theoretical} - \text{Experimental }|}{\text{Theoretical}} \times 100\%$$

$$= \frac{|\ 340.0 - 223.4\ |}{340.0} \times 100\%$$

$$= 34.9\ \%$$

$$\alpha_{\text{theoretical}} = \text{v}_{\text{cur}}\alpha_{\text{cu}} + \text{v}_{\text{c}}\alpha_{\text{c}}$$

$$= (0.80)(16.5) + (0.20)(7.1)$$

$$= 14.62 \times 10^{-6} \ / \ ^{o}\text{C}$$