# Thermoelectric Generator/Cooler Experiment Lesson Plan

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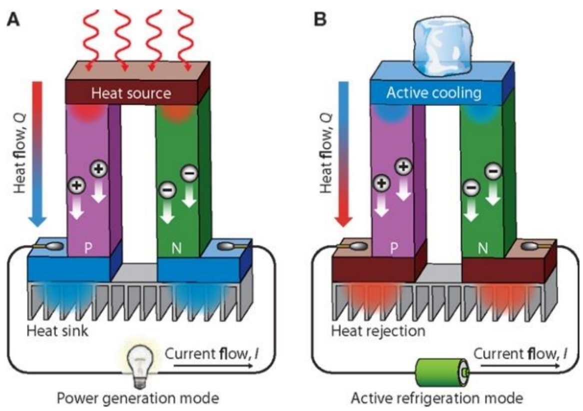

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## Overview
Students will characterize a thermoelectric (TE) module and utilize the power generated to power an LED.

## Outline
Pre-Lab (45 min): Learn about thermoelectric devices, answer questions about TE characteristics
Experimental Procedure (1.5 hours): Measure Seebeck coefficient, power LED, charge a cell phone, examine Peltier effect

## Supplies

| Included in Kit | Not Included |
|---|---|
| Thermoelectric modules (5) | Hot plates |
| Thermocouples (12) | Screw driver |
| Voltage stepper (1) | Calculator |
| Power bricks / adaptors (5) | Ruler |
| Screw jacks (5) | Voltmeter |
| Thermal grease (1) | |
| LEDs | |
| Tape | |
| Alligator clips | |

## 1. Overview

In 2014, Africa produced 77% of its energy from thermal power stations utilizing coal (33%), natural gas (32%), and oil (12%) [2]. A conventional thermal power station converts ~40% of the fuel heating value to useable energy, while the remaining 60% is wasted if no appropriate recovery is implemented. A thermoelectric (TE) generator is a device that can harvest heat by converting a temperature difference to a potential difference, thereby yielding an output of electricity. Advantages of TE generators include a long lifetime, no moving parts, no operation emissions, low maintenance, and high reliability [3]. However, a typical TE generator only has an energy conversion efficiency of ~5%, which limits its current application to places where reliability outweighs efficiency. Such applications include space missions to other planets, as well as power sources for remote sensing, control, safety surveillance and metering stations [4]. To make a TE generator a viable option for large-scale waste heat recovery, its performance must be increased by at least a factor of 2 [3]. TE generators can be improved by enhancing the intrinsic material properties, as well as by optimizing the device structure. An example of the latter can be seen in the TE modules sent with the present experiment kit. A schematic of the included module can be found in **Figure 1**. Such a design can dissipate heat quickly through the heat sink and fan, and maintain a greater temperature difference compared with a bare TE device. The enhancement of the intrinsic properties of the materials used in the TE device has the potential to improve the device performance significantly and is an on-going topic of discussion in the research community.

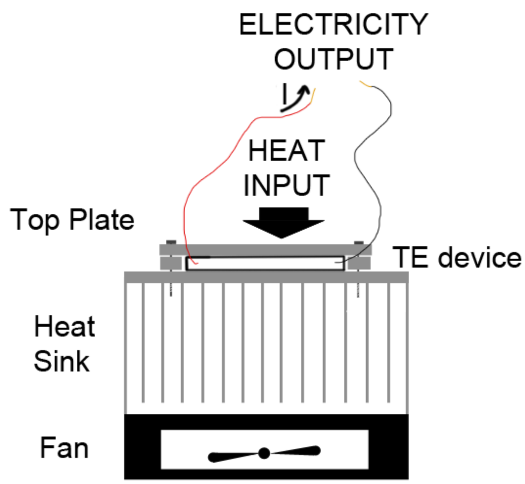


**Figure 1.** A schematic of the TE module included in the experiment kit. A TE device is sandwiched between an aluminum top plate and a heat sink. A fan is attached to the heat sink to improve heat dissipation for cooling applications. Electricity is output through the black and red wires.

A TE device can be used as both an electric generator (as discussed in the previous paragraph) or as a cooler, which uses the reverse process to the generator. By applying a potential difference to a TE device, a temperature difference is created. Peltier coolers, as they are often referred, are widely used to cool scientific devices such as lasers and charge-coupled devices (CCDs), as well as commercial products such as portable refrigerators and water fountains.

The materials employed in a TE device make the cooling and electricity generation functions possible. **Figure 2** shows a schematic of a TE device. The device is composed of many pairs of p-type and n-type semiconductors, with each pair connected by a conductive metal, typically copper or nickel (gray rectangles in Figure 2). All pairs are sandwiched between two ceramic substrates. The entire device is then sealed by silicone (not shown in the figure). The TE device included in this experimental kit uses antimony bismuth telluride as the p-type semiconductor, while the n-type semiconductor is selenium bismuth telluride. The semiconductor pairs and conductive metal sitting on the top and bottom of the pairs form a continuous path for electric charges to move.

This experimental kit seeks to familiarize students with the function of TE devices and their intrinsic properties. The remainder of this document will introduce various fundamental concepts associated with TE devices:

- **Section 2 -** Discusses the physical principles of how TE devices work, i.e. why a temperature differential produces a voltage potential and vice versa, and the ideal material to achieve maximum performance.
- **Section 3 -** Introduces the figure of merit (FoM), which is used to describe the performance of a TE device.
- **Section 4 -** Discusses the various material properties that affect the overall performance of a TE device. Scattered throughout these sections are five "Pre-lab" questions, designed to reinforce the concepts discussed. At the completion of Section 4, the experimental procedure and corresponding discussion can be found.

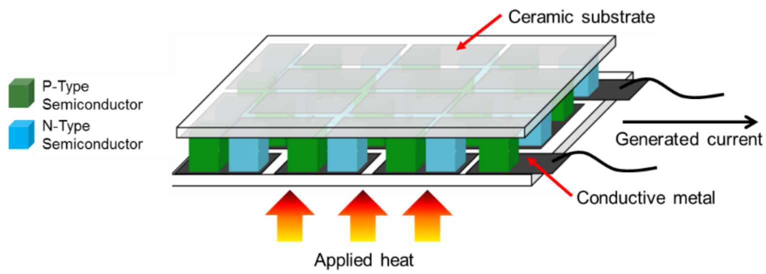


**Figure 2.** A schematic of a thermoelectric device [5]

## 2. Characteristics of Thermoelectrics

### 2.1. Seebeck Effect

Thermocouples, one of the most popular instruments used for temperature measurements, utilize the Seebeck effect to measure temperature. The *Seebeck effect* describes the generation of a voltage potential between two dissimilar metals due to an applied temperature differential. A thermocouple is composed of two dissimilar metals attached to a voltmeter, as illustrated in **Figure 3a**. Different metals have different electron densities. Imagine a thermocouple where Metal B has a higher electron density than Metal A. Since Metal B has more electrons than Metal A, electrons will diffuse from Metal B to Metal A (**Figure 3b**). Metal B is left with a positive charge, while Metal A is left with a negative charge, resulting in a voltage potential.

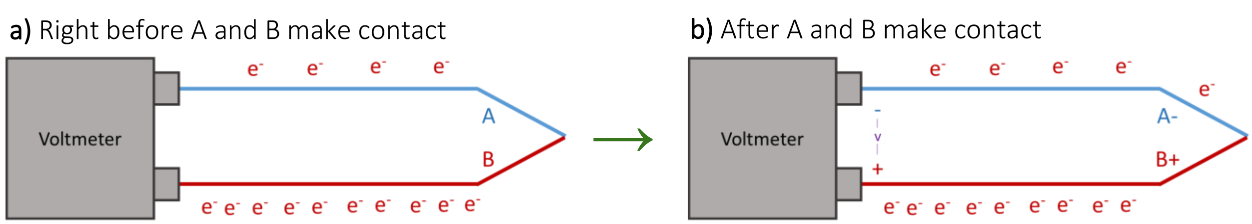


**Figure 3.** Electrons migrating to Metal A from Metal B when the two dissimilar metals are in contact.

When the junction of a thermocouple is exposed to a heat source, the electrons will have more kinetic energy to diffuse (**Figure 4a**). This means that more electrons will diffuse from Metal B to Metal A, leaving Metal B with a larger positive charge and Metal A with a larger negative charge, and therefore creating a larger voltage potential (**Figure 4b**).

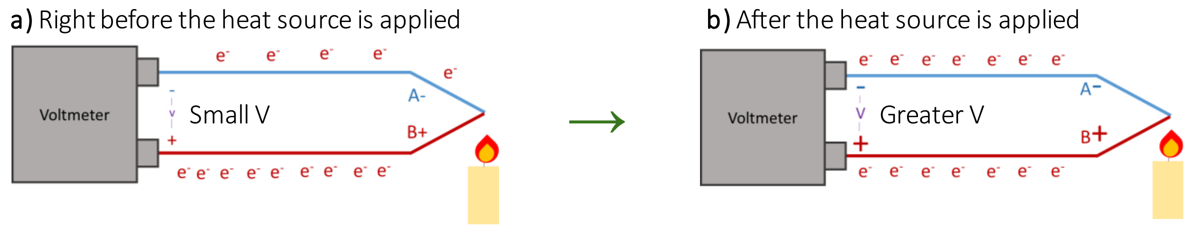


**Figure 4.** More electrons migrate from Metal B to Metal A when thermocouple is exposed to a heat source

A similar effect is observed in the doped semiconductors utilized in TE devices. **Figure 5a** shows a semiconductor that is doped with electrons (also known as an n-type semiconductor). When one side of the semiconductor is heated up, the heated electrons have more kinetic energy than the cold electrons. As a result, the heated electrons move to the cold side of the semiconductor, as seen in **Figure 5b**. This diffusion establishes an excess of electrons on the cold side, leaving the hot side with a positive charge and the cold side with a negative charge. This generation of a charge gradient or potential difference from an applied thermal gradient is again a result of the Seebeck effect.

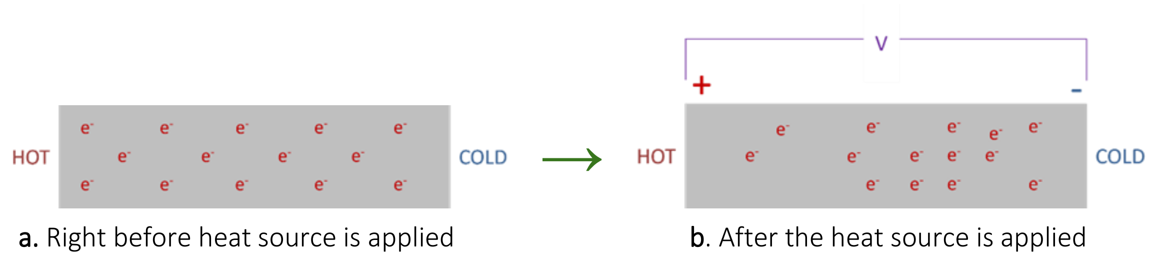


**Figure 5.** Seebeck effect in an electrically conductive and thermally insulating n-type semiconductor

In a p-type semiconductor, positively charged holes are the majority charge carriers. When one side is heated, holes in a p-type semiconductor move towards the cold side, leaving the hot side with a negative charge and the cold side with a positive charge. In a TE device, the potential difference generated by a single pair of legs (i.e. one n-type and one p-type) is rather small. By connecting the n-type and p-type semiconductors in series, as illustrated in **Figure 6**, a larger overall potential difference can be obtained, as the total voltage is the sum of the individual voltages when connected in series. Note that the implementation of both n-type and p-type semiconductors is essential to the success of a TE device. Using only n-type semiconductors or metals would yield a negligible potential difference.

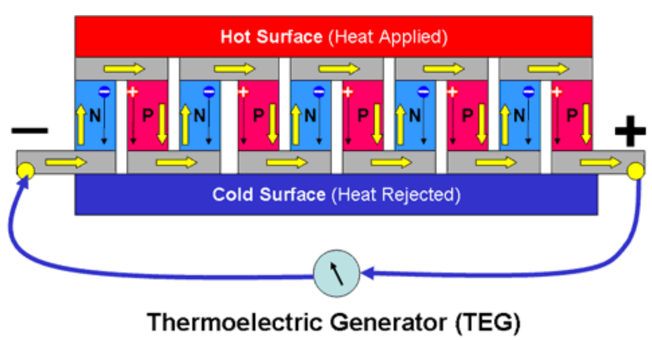


**Figure 6.** A schematic of an array of paired n-type and p-type semiconductors [6].

### 2.2. Peltier Effect

The *Peltier effect* is the opposite of the Seebeck effect, where an applied voltage generates a temperature gradient.

### 2.3. Ideal Thermoelectric Material

The ideal thermoelectric material is thermally insulating and electrically conducting. Unfortunately, such a material is difficult to attain, as most materials are either both thermally and electrically conducting or insulating. If a thermally and electrically conductive material were utilized, both sides of the material would become hot. As a result, electrons would be evenly distributed throughout the material and no voltage potential would be created (**Figure 7**).

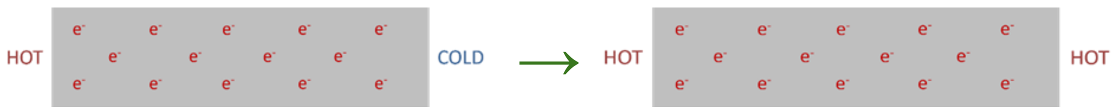


**Figure 7.** Electrically and thermally *conductive*

On the other hand, if a material is both thermally and electrically insulating, the electrons on the hot side would have difficulty moving to the cold side (**Figure 8**). The voltage generated from this type of material would be much smaller compared with that generated by a thermally insulating and electrically conductive material.

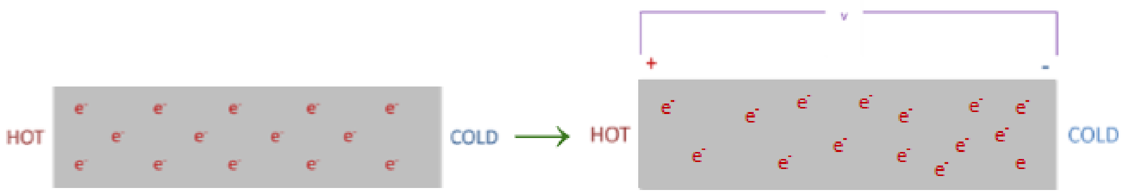


**Figure 8.** Electrically and thermally *insulating*

**Pre-lab Question 1**
*Give an example of a material that is both thermally and electrically conductive.*

*Give an example of a material that is both thermally and electrically insulating.*

## 3. Figure of Merit

The performance of a thermoelectric device can be described by the Figure of Merit (zT), which is a dimensionless parameter described as:

$$zT = \frac{\alpha^2 T}{\rho \kappa} \tag{1}$$

Here, $\alpha$ represents the Seebeck coefficient [Units: V/K], $\rho$ represents the electrical resistivity [Units: Ωm], $\kappa$ represents the thermal conductivity [Units: W/m-K], and $T$ represents the average temperature between the hot and cold sides [Units: K]. Note that the electrical resistivity is inversely related to the electrical conductivity ($\rho = 1/\sigma$). The Seebeck coefficient is a material property that describes the voltage potential produced for a given temperature difference [7].

The Figure of Merit is used to compare thermoelectric devices composed of different materials in order to maximize the performance of the device. A higher value of zT corresponds to a superior performance and zT values greater than 3.0 are needed for TE generators to be competitive [3]. Typically, zT is close to 1. **Figure 9** shows how zT changes with temperature for different thermoelectric materials. It is important to note that the trends displayed are nonlinear because the values of $\alpha$, $\rho$, and $\kappa$ also vary with temperature. As seen in Figure 9, thermoelectric materials operate in a certain range. For example, bismuth telluride ($Bi_2Te_3$) operates from 0-700 K. The zT values peak between 300-500 K, which indicates that $Bi_2Te_3$ is useful for applications near room temperature [8].

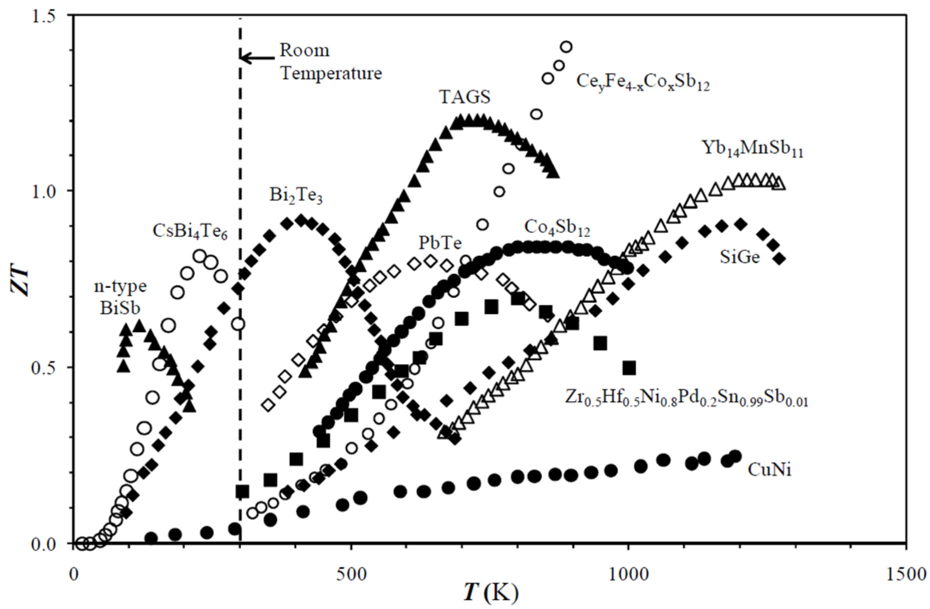


**Figure 9.** zT *vs.* temperature for various thermoelectric materials [8]

**Prelab Question 2**

*Show that the Figure of Merit, zT, is dimensionless. Hint: (1 W=1 $V^2/\Omega$).*

$$zT = \frac{\alpha^2 T}{\rho\kappa}$$

**Prelab Question 3**

***Table 1*** *below shows the experimental results for a single crystal of various thermoelectric materials* [9]. *The symbols ⫽ and ⊥ indicate the direction in which measurements were taken, parallel and perpendicular to the cleavage plane of the crystal, respectively. Using the values in the chart, calculate the zT values for some of the crystals, using the temperatures listed. (Hint: there are 2 ways to calculate the zT values. One is easier than the other.)*

**TABLE 1** Experimental Results for Single Crystal

| Column | n-p | $T$ (°C) | $C_p$ | $\rho$ | $\mu_H$ | $\alpha$ | $\kappa$ | $Z$ |
|---|---|---|---|---|---|---|---|---|
| $Bi_2Te_{3//}$ | n | 582 | 2.3 | 10 | 212 | 240 | 2.0 | 2.9 |
| $Sb_2Te_{3\perp}$ | p | 575 | 21 | 3.2 | 244 | 92 | 1.6 | 1.6 |
| $Sb_2Te_{3//}$ | p | 605 | 10 | 1.9 | 313 | 83 | 5.6 | 0.6 |
| $Bi_8Sb_{32}Te_{60}$ | p | 540 | 4.8 | 10 | 176 | 194 | 1.3 | 3.0 |
| $Bi_{10}Sb_{30}Te_{60}$ | p | 540 | 3.5 | 13 | 177 | 225 | 1.4 | 2.9 |
| $Bi_9Sb_{31}Te_{60}$ | p | 530 | 3.9 | 8.89 | 190 | 206 | 1.5 | 3.2 |
| $Bi_{40}Sb_{57}Te_3$ | n | 580 | 4.0 | 11 | 140 | 223 | 1.6 | 2.8 |
| $Bi_{40}Te_{58.5}Se_{1.5}$ | n | 580 | 4.3 | 11 | 150 | 230 | 1.7 | 2.9 |

Column n-p, type of conduction; $T$ (°C), saturation temperature in °C; $C_p$, carrier concentration $10^{19}$ cm$^{-3}$; $\rho$, resistivity $\mu\Omega$ m; $\mu$ H, mobility of carriers cm$^2$ v$^{-1}$ sec$^{-1}$; $\alpha$, absolute Seebeck coefficient $\mu$V K$^{-1}$; $\kappa$, thermal conductivity W m$^{-1}$ K$^{-1}$; $Z$: figure-of-merit $10^{-3}$ K$^{-1}$.

| Crystal | zT value (dimensionless) |
|---|---|
| $Bi_2Te_{3//}$ | |
| $Bi_8Sb_{32}Te_{60}$ | |
| $Bi_{10}Sb_{30}Te_{60}$ | |
| $Bi_{40}Sb_{57}Te_3$ | |
| $Bi_{40}Sb_{58}Te_{1.5}$ | |

<u>Note:</u> Figure 7 is obtained from bulk materials while Table 1 is obtained from single crystals of the TE materials. Table 1's $Bi_2Te_3$ zT value is much higher at 580°C than the bulk sample in Figure 7. This is because bulk TE materials demonstrate lower composition homogeneity, undesired defects, and random orientation of grains. These traits lower the zT value [9].

## 4. Material Properties

The Figure of Merit (zT) depends on $T$, $\alpha$, $\rho$, and $\kappa$. These variables are not independent, as each variable may influence another.

### 4.1. Electrical Conductivity (σ or 1/ρ)

Thermoelectric devices utilize p-type and n-type semiconductors to create a voltage potential for electricity to flow through the device. P-type semiconductors are doped to have an excess of positive holes, while n-type semiconductors are doped to have an excess of negative electrons. Doping controls the electrical conductivity of semiconductors by introducing an impurity with a different number of electrons than the host material. For example, silicon (Si) has 4 valence electrons, with all electrons bound to the silicon lattice as seen in **Figure 10**. In p-type silicon, one of the silicon atoms is replaced with a boron atom that has 3 valence electrons. In this case, there is a missing electron, also known as a *hole*. Holes are the majority carriers for p-type silicon. In n-type silicon, a silicon atom is replaced with a phosphorous atom that has 5 valence electrons. In this case, there is an extra electron. Electrons are the majority carriers in n-type silicon.

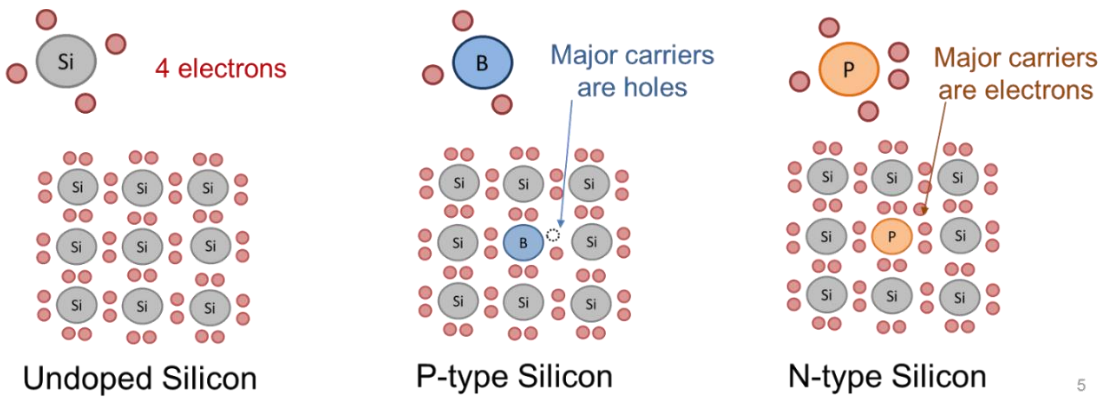


**Figure 10.** Three types of silicon lattices

For thermoelectric materials, such as bismuth telluride, doping is more complicated, but the concept is the same. Doping with antimony makes p-type bismuth telluride, while doping with selenium makes n-type bismuth telluride. Conductivity of n- and p-type materials ($\sigma_n$ and $\sigma_p$, respectively; [Units: 1/Ω-m]) and doping are directly related by the following equations:

$$\sigma_n = N_e e \mu_e \tag{2.1}$$

$$\sigma_p = N_h e \mu_h \tag{2.2}$$

where $N_e$ and $N_h$ represent the number of electrons and holes, $e$ represents the charge of an electron [$1.6\text{x}10^{-19}$ C], and $\mu_e$ and $\mu_h$ represent the mobility of the electrons and holes [Units: $m^2$/V-s].

### 4.2. Thermal Conductivity (κ)

Thermal conductivity describes the ability of a material to transfer heat and can be defined based on contributions from phonons and electrons:

$$\kappa = \kappa_L + \kappa_e \tag{3}$$

### 4.2.1. Thermal Conductivity from Electrons ($\kappa_e$)

Electrons are good at transporting heat and electricity. As previously mentioned, for thermoelectric devices, a thermally insulating (i.e. low thermal conductivity) and electrically conducting material is desired to enhance the performance of the device. As a result, metals are typically not desirable due to their electron arrangement allowing for a high degree of thermal conductivity. The contribution to the thermal conductivity from electrons may be reduced by decreasing the number of electrons, as well as scattering the electrons. This, however, would increase the electrical resistivity and thus, potentially decrease the zT value.

### 4.2.2. Thermal Conductivity from Phonons ($\kappa_L$)

Phonons are vibrations of atoms in a crystal. Phonons are the primary carriers of heat and non-metallic materials. Individual atoms in the lattice can vibrate longitudinally and transversely, as seen in **Figure 11**. The combination of these vibrations form a “wave” in the material, called a phonon. In general, increased vibrations and length of vibrations increases the thermal conductivity. Therefore, in order to reduce the thermal conductivity of TE materials, research has focused on scattering these “waves” by introducing defects and microstructures. Different defects and microstructures scatter different phonons and reduce the thermal conductivity, which may increase the zT value. Some defects and microstructures, however, could also scatter electrons and increase the electrical resistivity, leading to a potential decrease in zT. Finding a balance between the thermal conductivity and the electrical conductivity is one of the major challenges associated with improving the performance of thermoelectric devices.

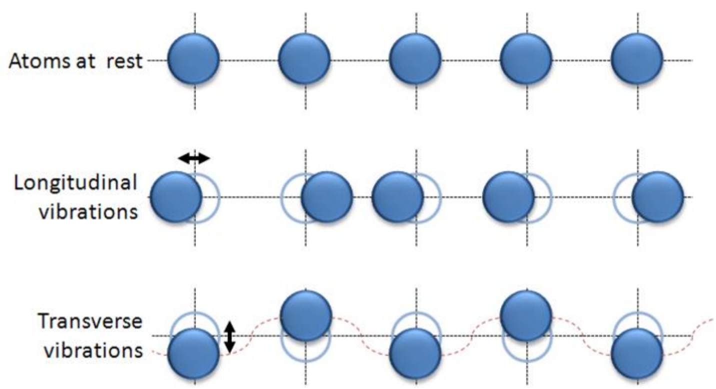


**Figure 11.** Phonons in the lattice formed from longitudinal and transverse vibrations [10]

**Prelab Question 4**

*Looking back at Table 1, the thermal conductivity for $Bi_2Te_3$ is 2.0 W/m-K. Meanwhile, $Bi_{10}Sb_{30}Te_{60}$, $Bi_{19}Sb_{31}Te_{60}$, and $Bi_{18}Sb_{32}Te_{60}$ all have thermal conductivities less than 2.0 W/m-K. What could be a possible explanation for this?*

### 4.3. Seebeck Coefficient (α)

The Seebeck coefficient is a measure of the voltage difference generated by a temperature gradient across a thermoelectric device/material, and can be described by:

$$\alpha = \frac{V}{\Delta T} \tag{4}$$

Here, $\alpha$ represents the Seebeck coefficient [Units: V/K], $V$ represents the voltage difference [Units: V], and $\Delta T$ represents the temperature difference between the hot and cold sides [Units: K]. The Seebeck coefficient is measured by prescribing a hot and cold temperature to opposite ends of the sample, creating a temperature gradient across the sample (**Figure 12**). The temperature on the hot side is varied while the cold side is typically kept at room temperature. The voltage is then measured. Thermocouples are typically used to measure the temperature of each surface. A potential source of error when using thermocouples may result from the "cold finger effect", where the temperature of the thermocouple can alter the temperature measurement.

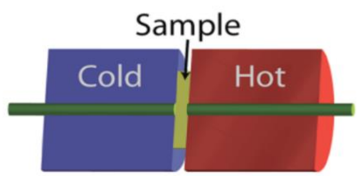


**Figure 12.** Setup used to measure the Seebeck coefficient of a sample [7]

In the following experiments, the Seebeck coefficient will be measured using a technique like the one described above.

**Prelab Question 5**

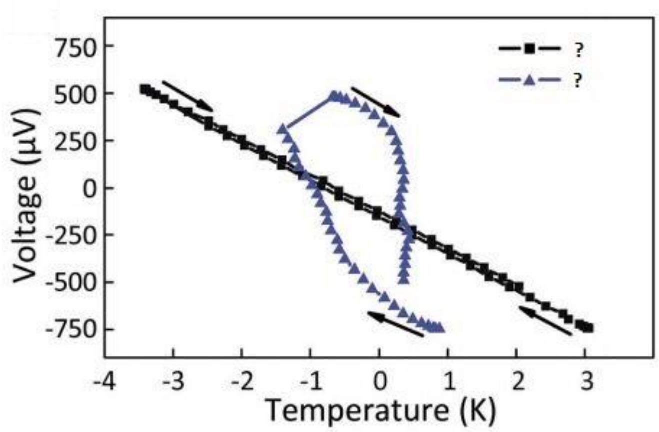


**Figure 13.** Sample of voltage vs temperature data used to calculate the Seebeck coefficient [7]

*The Seebeck coefficient for thermoelectrics is often measured with increasing temperature, then decreasing temperature, and vice versa. Good thermal contact between the surfaces and the thermocouples and/or heater is important for accurate measurement of the Seebeck coefficient. Using **Figure 13**:*

- *Which data was measured using good thermal contact? Label on the above plot.*

- *Calculate the Seebeck coefficient using the data obtained with the good thermal contact.*

# References


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# Experimental Procedure

Materials Required:

- 1x calculator per group
- 1x hot plate per group
- 1x Voltmeter per group
- 1x Screw driver
- 1x Ruler per group
- 1x Cell phone charging cable
- 1x Stopwatch
- 5x Thermoelectric (TE) modules (included)
- 2x Thermocouples (included)
- LEDs of various colors (included)
- Screw jack (included)
- Voltage stepper (included)
- 6x Alligator clips (included)
- Power bricks & adaptors (included)
- 1x Tape (included)

## I. Device Characterization

In this portion of the experiment, you will characterize the TE module by determining the Seebeck coefficient. This will be done by examining the voltage generated at five applied temperature differentials. One characterization will need one hotplate, one TEG module, one voltmeter, two thermocouples, and two alligator clips. It is recommended that 3-5 students work with one TEG module.

**Instructions**

1. Using the tape, attach one thermocouple to the surface of the hot plate and one thermocouple to the top surface of the TE module, which is exposed to air. (It may be easier to remove the fan.)

2. To induce a temperature differential across the TE module, place the flat side of the TE module on a hot plate set to ~40 °C (**Caution:** Try not to exceed 150 °C due to the sensitivity of the TE).

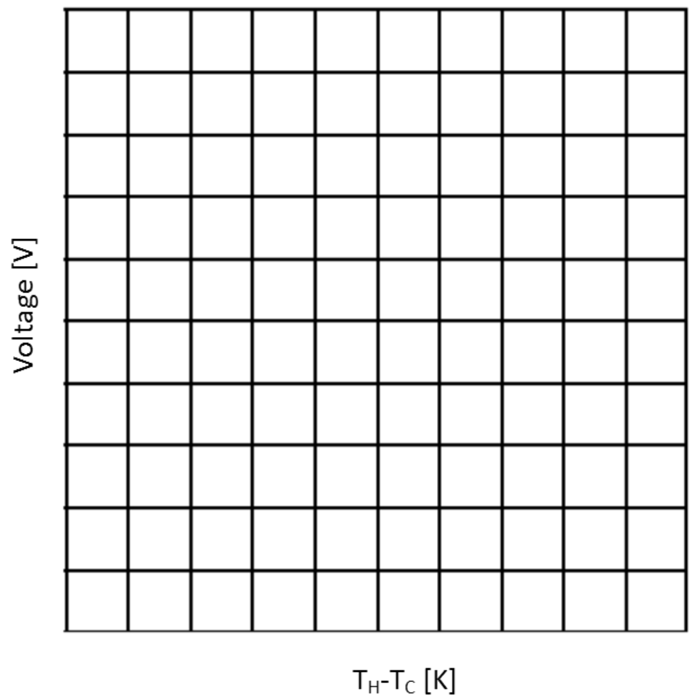
3. Measure the output voltage for five temperature gradients using the voltmeter. Increase the temperature difference in increments of approximately 5-10 °C. Record the measurements in the table below.

| **TE Surface Temperature ($T_C$) [°C]** | **Hot Plate Temperature ($T_H$) [°C]** | **$\Delta T$ ($T_H$-$T_C$) [°C]** | **Voltage [V]** |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

** **Caution:** Hot plate will be warm. Do not touch surface. Try not to allow $T_H$ to exceed 150 °C.

**Questions**

1. Plot a graph of the measured voltages as a function of the applied temperature differential on the chart below. Do the results display an approximately linear trend?




   a. Recall from Equation 4 that the Seebeck coefficient can be calculated using $\alpha = V/\Delta T$. As best as you can, draw a linear best-fit line through your 5 data points and the origin of the plot. Use the slope of this line to calculate the Seebeck coefficient.
      i. Note: If the results display an approximately linear trend, the Seebeck coefficient calculated from the slope should be similar to the Seebeck coefficient calculated from each individual data point.

2. The Seebeck coefficient you calculated in Question 1 was for the whole TE *module*, whereas the values displayed in Table 1 of Pre-lab Question 3 are for individual TE *materials*. The Seebeck coefficient of a TE module can be determined based on the Seebeck coefficients of the p- and n-type semiconductors the module is composed of and the number of p- and n-type semiconductor pairs, using the following equation:

$$\alpha_{module} = N(\alpha_p - \alpha_n) \tag{5}$$

Assume your TE module is composed of 127 p- and n-type semiconductor pairs (*N* = 127), the p-type semiconductor is approximately $Bi_8Sb_{32}Te_{60}$ and the n-type semiconductor is approximately $Bi_{40}Sb_{57}Te_3$ (see Appendix A for determination of materials). Using the values found in Table 1, estimate the Seebeck coefficient of the module. Note: the Seebeck coefficient for n-type semiconductors is negative.

3. Calculate the percent error between the experimentally determined Seebeck coefficient and the value calculated in Question 2 above. What are some possible sources of error?

$$\%\ Error = \frac{|\alpha_{exp} - \alpha_{theoretical}|}{\alpha_{theoretical}} \times 100 =$$

4. The zT value of a TE module can be calculated using a similar expression to that found in Equation 1. Recall that Equation 1 is used to determine the zT value of a thermoelectric *material*. Minor modifications must be made to account for the many p- and n-type semiconductor pairs.

$$(zT)_{module} = \frac{\alpha_{module}^2 T}{K_{mod} R_{mod}} \tag{6}$$

Calculate the experimental zT value for the TE module, using your experimental Seebeck coefficient and letting $K_{mod} = 0.176$ W/K and $R_{mod} = 3.5\,\Omega$ (see Appendix B for the experimental measurement of these parameters).

5. Now calculate the theoretical zT value for the module, using the theoretical Seebeck coefficient calculated in Question 2, material and thermal properties for each semiconductor (using the same materials as in Question 2) and assuming L = 1 mm and A = 1 mm$^2$.

$$K_{mod} = N\left(\frac{\kappa_p A}{L} + \frac{\kappa_n A}{L}\right) \tag{7}$$

$$R_{mod} = N\left(\frac{L\rho_p}{A} + \frac{L\rho_n}{A}\right) \tag{8}$$

Here, $K_{mod}$ is the thermal conductance of the module, $R_{mod}$ is the electrical resistance of the module, $\kappa_p$ and $\kappa_n$ are the thermal conductivities of the p- and n-type semiconductors, respectively, $\rho_p$ and $\rho_n$ are the electrical resistivities of the p- and n-type semiconductors, respectively, $A$ is the area of each semiconductor leg, and $L$ is the length of each semiconductor leg.

6. How do your calculated zT values from Question 4 and Question 5 compare? How do these values compare with Figure 9? Would you expect the zT value of the module to be similar to the value for the individual materials? (Hint: think about the effect of other components present in a real device)

## II. Device Applications

Lighting an LED

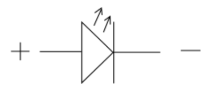
In this portion of the experiments, you will use the thermoelectric module to power a light-emitting diode (LED). As observed in Part I, the voltage produced by a single TE module is < 1 V. Therefore, in order to power a LED (> 1.8 V), you will need to connect multiple TE modules together. One experiment will need one hotplate, at least three TEG modules, LEDs, and at least four alligator clips. It is recommended that an entire lab class works on this experiment due to the availability of the modules.

**Questions**

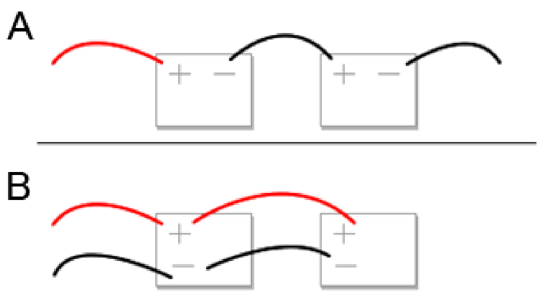
1. Based on the measured voltage differences you recorded in Part I, how many TE modules are required to power a 2 V LED using your largest temperature difference ($T_H$ ~ 80 °C)?

2. Will you connect the TE modules in parallel or in series?

3. Draw a circuit diagram below that can be used to power the 2.0 V LED. Each TE module can be represented as a voltage source.

   Note the symbol for an LED: 

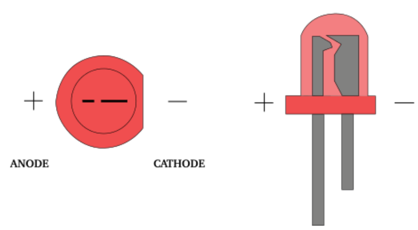

4. Using your circuit diagram from the previous question, choose the correct wiring configuration from below.




**Instructions**

1. Using the wiring diagram you selected in Question 4 (either A or B) and the correct number of TE modules to power the LED (as determined in Question 1), connect the wires of the TE modules together using the alligator clips.

2. Attach the 2 remaining wires to the legs of the LED. An LED has one long leg and one short leg, as seen below. Be sure to properly connect the positive and negative legs in your circuit (use the diagram you drew in Question 3).




3. Carefully place all TE modules on the hot plate(s), ensuring that the wiring connections are not broken. Set the hot plate(s) to ~80 °C.

4. Hopefully your LED is glowing nice and bright for you! If not, make sure you connected the LED legs to the proper wires. Perhaps try reversing. If your LED is still not lit, try adding another TE module for added voltage. Another method is to increase the temperature of the hot plate. Note that you can increase the temperature up to ~150 °C and that the cold side will get hot (temperature

difference will go down) overtime. After successfully lighting your LED, try testing with the other color LEDs, varying the number of TE modules required to obtain the necessary voltage.

Charging a Cell Phone

In this section, you will use a voltage stepper to yield a voltage large enough to charge a cell phone. Cell phones require 5.0 V to charge. As seen in the previous section, this would require many TE modules. As an alternative, you can use a voltage stepper to adjust an input voltage ranging between ~1.5 – 6.0 V to 5.0 V. You will do this using the experimental setup from the previous section (i.e. powering an LED).

**Instructions**

1. Connect the USB end of a phone charger into the voltage stepper and the other end to a cell phone.

2. Keep the TE modules on the hot plate(s) and the temperature set to ~80°C. Disconnect the LED from the circuit created in the previous section. In its place, connect the voltage stepper using alligator clips to connect the wires to the metal plates on the voltage stepper. Hopefully your phone has started charging!

**** Caution: Do not charge your phone for a prolonged period of time using the TE generator. The unstable current and voltage produced by the TE generator can be harmful your device's battery.**

When you are finished, turn off the hot plate(s). Once the TE modules have cooled, remove them from the hot plate(s) and disconnect the modules by removing the alligator clips.

**Questions**

5. If your cell phone shows that it's charging, keep it plugged in and run some apps. Do you see the percentage of your battery increase or decrease? (An old cell phone that drains battery fast would be ideal to observe the effect quickly) Explain what you observed.

6. Name a few potential research directions for thermoelectric generators.

## III. Peltier Cooler

The experiments thus far have demonstrated the Seebeck effect (i.e. generating a voltage from an applied temperature differential). Thermoelectric generators are a viable option for waste heat recovery. TE modules, however, can also be used in reverse, taking advantage of the Peltier effect (i.e. using an applied potential difference to produce a temperature differential). Peltier coolers, as they are often referred, can be utilized as an effective heat pump. This brief experiment will demonstrate this effect. One experiment will need one TEG module, one screw jack, one power brick, one timer, and two thermocouples. It is recommended that 3-5 students work with one TEG module.

**Instructions**

1. Attach the screw jack to the TE module by inserting the red wire into the positive side of the jack and the black wire into the negative side of the jack and using the screw driver to tighten the screws. Ensure that the wires will not come loose. If connected properly, heat will be pumped from the top plate to the heat sink.

2. Tape a thermocouple to the top and bottom surfaces of the TE module.

3. Connect the power brick to the inlet in the screw jack. Plug the power brick into a wall outlet using the power adaptor.

4. Record the temperature of each surface every 10 seconds for ~2-3 minute in the table below.

| **Time [s]** | **Temperature ($T_H$)** [°C] | **Temperature ($T_C$)** [°C] |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

5. After completing measurements, physically observe the temperature difference created by touching your finger to the surface. Frost may appear on the surface.

**Questions**

1. How long did it take for the temperatures to reach steady values? What was the temperature difference at steady conditions?

2. What are some potential applications of Peltier Coolers, other than those mentioned in the introduction?

# Appendix A

## Materials characterization of a commercial TEG module

***Objectives***

1. Use energy-dispersive X-ray spectroscopy (EDS) to determine elemental composition;
2. Use the information obtained to find materials properties, such as electrical conductivity, in the literature.

***Methods***

Materials Preparation: The sample for EDS was prepared by removing the legs from the thermoelectric module and placing onto a conductive carbon tape.

Characterization: EDS was performed using FEI Varios 460L at NC State Advanced Instrumentation Facility (AIF).

***Results***

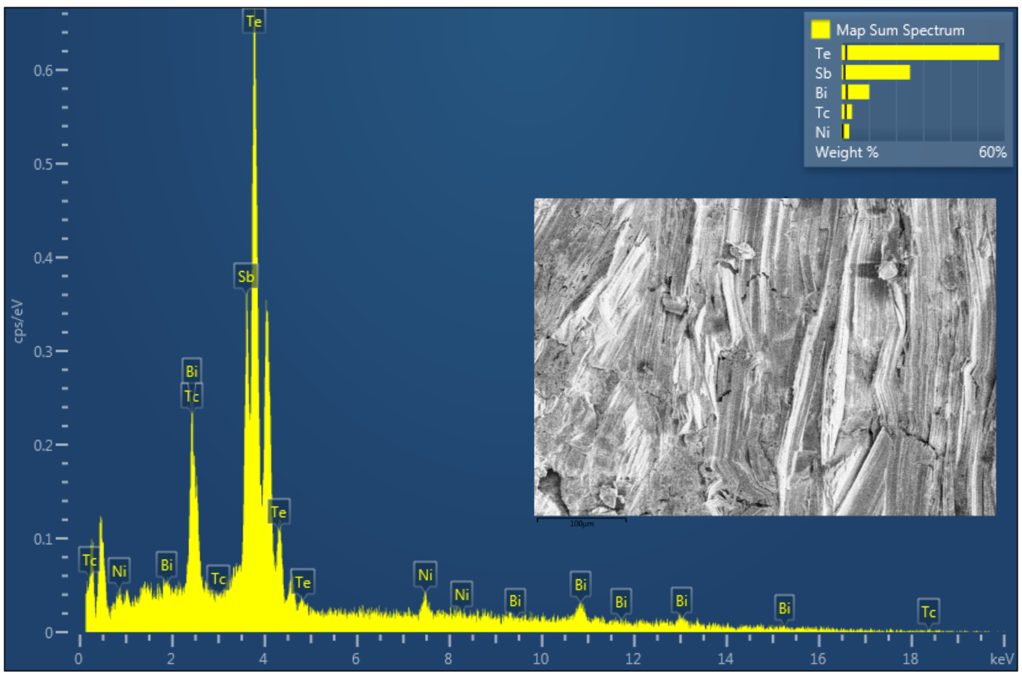



**Figure A-1.** An energy-dispersive X-ray spectrum of the p-type leg of a commercial thermoelectric module. The inset is a secondary electron scanning electron microgram of the region measured for EDS.

Based on the weight percentage of the elements present in Figure A-1, this leg was determined to be approximately $Bi_6Sb_{25}Te_{60}$, which is a p-type thermoelectric material.

**TABLE 27.7** Experimental Results for Single Crystal

| Column | n-p | $T$ (°C) | $C_p$ | $\rho$ | $\mu_H$ | $\alpha$ | $\lambda$ | $Z$ |
|---|---|---|---|---|---|---|---|---|
| $Bi_2Te_{3//}$ | n | 582 | 2.3 | 10 | 212 | 240 | 2.0 | 2.9 |
| $Sb_2Te_{3\perp}$ | p | 575 | 21 | 3.2 | 244 | 92 | 1.6 | 1.6 |
| $Sb_2Te_{3//}$ | p | 605 | 10 | 1.9 | 313 | 83 | 5.6 | 0.6 |
| $Bi_8Sb_{32}Te_{60}$ | p | 540 | 4.8 | 10 | 176 | 194 | 1.3 | 3.0 |
| $Bi_{10}Sb_{30}Te_{60}$ | p | 540 | 3.5 | 13 | 177 | 225 | 1.4 | 2.9 |
| $Bi_9Sb_{31}Te_{60}$ | p | 530 | 3.9 | 8.89 | 190 | 206 | 1.5 | 3.2 |
| $Bi_{40}Sb_{57}Te_3$ | n | 580 | 4.0 | 11 | 140 | 223 | 1.6 | 2.8 |
| $Bi_{40}Te_{58.5}Se_{1.5}$ | n | 580 | 4.3 | 11 | 150 | 230 | 1.7 | 2.9 |

Column n-p, type of conduction; $T$ (°C), saturation temperature in °C; $C_p$, carrier concentration $10^{19}$ cm$^{-3}$; $\rho$, resistivity $\mu\Omega$ m; $\mu$ H, mobility of carriers cm$^2$ v$^{-1}$ sec$^{-1}$; $\alpha$, absolute Seebeck coefficient $\mu$V K$^{-1}$; $\lambda$, thermal conductivity W m$^{-1}$ K$^{-1}$; $Z$: figure-of-merit $10^{-3}$ K$^{-1}$.

Table 27.7 was extracted from the *Thermoelectrics Handbook: Macro to Nano* [1]. Material properties of $Bi_6Sb_{25}Te_{60}$ may be approximated by the properties for $Bi_8Sb_{32}Te_{60}$ in the table. A few properties of interest include the electrical resistivity (10 μΩ-m), Seebeck coefficient (194 μV/K), thermal conductivity (1.3 W/m·K), and figure-of-merit (3.0 x $10^{-3}$ K$^{-1}$). The EDS spectrum of the n-type leg in the module was not collected. It was assumed to be $Bi_{40}Sb_{57}Te_3$, which has an electrical conductivity of 9 x $10^4$ S/m, Seebeck coefficient of 223 μV/K, thermal conductivity of 1.7 W/m·K, and figure-of-merit of 2.9 x $10^{-3}$ K.

**Reference**


1. Rowe, D. M. (2006). *Thermoelectrics handbook: macro to nano*. Boca Raton, FL: Taylor & Francis, pp 27-16.

# Appendix B

## Experimental measurement of TE module thermal conductance and electrical resistance

### Thermal Conductance Measurement

The thermal conductivity of a material describes how well a material conducts heat. A low thermal conductivity material conducts heat at a lower rate, or has a higher resistance to heat conduction. Heat conduction is governed by Fourier's Law, which states that the rate of heat transfer is proportional to the rate of change of temperature in the direction of heat transfer, and is represented using

$$Q = -\kappa A \frac{dT}{dx} \tag{B-1}$$

where $Q$ represents the heating power [W], $\kappa$ represents the thermal conductivity [W/m-K], $A$ represents the area of heat transfer, and $\frac{dT}{dx}$ represents the temperature rate of change in the direction of heat flow. For the simplest of cases (rectangular system), a linear temperature profile exists across the thickness and the above equation can be simplified to

$$Q = -\kappa A \frac{\Delta T}{\Delta x} \tag{B-2}$$

where $\Delta T$ represents the temperature difference between 2 given points, and $\Delta x$ represents the distance between the same 2 points. The thermal conductivity of a material can be determined by rearranging Fourier's Law to solve for $\kappa$:

$$\kappa = q'' \frac{\Delta x}{(T_1 - T_2)} \tag{B-3}$$

where $q''$ represents the heat flux (heating power per unit area) and $T_1$ represents the hotter temperature. Finally, the thermal conductance ($K$) of a sample specimen can be determined based on the dimensions of the sample, according to

$$K = \frac{kA_{sample}}{\Delta x} \tag{B-4}$$

A simple steady state heat transfer problem can be used to determine the unknown thermal conductivity of a material.

***Objectives***

1. Measure the thermal conductance of the TE module using steady state heat transfer principles

***Methods***

A steady state heat transfer system was utilized to measure the thermal conductance of the TE module at approximately room temperature. The setup utilized a heating pad to supply a constant heat flux to the sample material (i.e. the TE module). The temperature of the module was measured on the top and bottom to determine the temperature difference. Figure B-1 displays a schematic of the experimental setup. The thermal compound noted in Figure B-1 was used to minimize the contact resistance between the heating pad and the TE module.

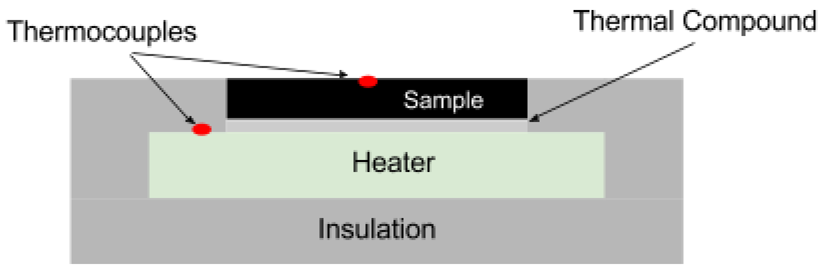



**Figure B-1:** Schematic of experimental setup to measure thermal conductance

***Results***

The experimental procedure was first validated using a reference specimen with known thermal conductivity. After validating the procedure, the thermal conductivity of the TE module was measured 3 times and an average was taken to represent the thermal conductivity of the module. The average thermal conductivity was found to be 0.425 W/m-K. The thermal conductance was then calculated using Equation B-4, based on the measured dimensions of the module. The thermal conductance of the module is approximately 0.176 W/K.

**Electrical Resistance Measurement**

***Objectives***

1. Measure the electrical resistance of the TE module using Ohms Law

***Methods***

Ohms Law ($V = IR$) was used to determine the electrical resistance of the TE module at room temperature. The electrical leads of the TE module were connected to a power supply and a very small voltage potential was applied to the device. The current was measured and used to calculate the resistance in combination with the voltage. This was repeated for 4 different voltage potentials, all of which were less than 1V to minimize the temperature difference generated across the device (i.e. by the Peltier effect).

***Results***

The resulting resistances measured from each of the four trials were used to determine an average resistance of the module. The electrical resistance was found to be approximately 3.5Ω.