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Transverse Thermoelectric Properties of Cu/Mg2Si and Ni/Mg2Si Artificially Anisotropic Materials

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Transverse Thermoelectric Properties of Cu/Mg2Si and Ni/Mg2Si Artificially Anisotropic Materials

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Master of Science
in
Applied Physics

by

David James Nyce Esch

B.A. Physics Goshen College, 2011

May, 2015

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Abstract

In this thesis the spark plasma sintering process (SPS) was used to press Mg_2Si powder with Ni and Cu slices into alternating layer stacks. These stacks, once cut at an angle, are an artificially anisotropic material. This anisotropy provides transverse thermoelectric properties to the sample. The transverse transport properties were measured along with the individual component transport properties. The SPS process provided malleable samples that gave a power factors of 6.71×10^{-6} for the Ni/Mg_2Si stack and 1.50×10^{-6} for the Cu/Mg_2Si stack. These fall short of the theoretical calculations which would give the power factors as .0254 for the Ni/Mg_2Si stack and .211 for the Cu/Mg_2Si stack. It is theorized that eddy currents and interface resistances between the layers are the causes for these discrepancies.

Material Science, Thermoelectric, Transverse Thermoelectric, Artificially Anisotropic, Applied Physics, Spark Plasma Sintering

[Chapter 1] Introduction

Standard or longitudinal thermoelectrics have been used for years to convert waste heat into electrical energy, used as refrigerators, and for power generation in remote environments such as space exploration. In fact, Radioisotope Thermoelectric Generators (RTGs) have been used to power deep-space satellites using incredibly large temperature differences generated by radioactive Pu compounds. [1] Traditional thermoelectric devices use both n-type and p-type semiconductors connected by metal contacts in a structure as given in Figure 1.1. [2]

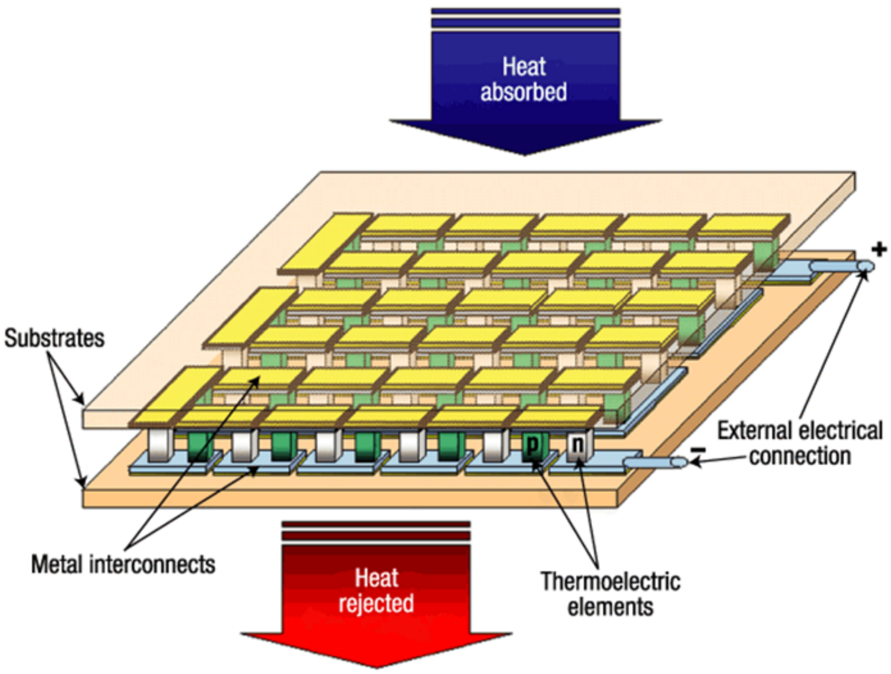

Figure 1.1. Standard longitudinal thermoelectric device. The device is formed from individual n- and p- type semiconductors connected electrically in series and thermally in parallel [2].

The efficiency with which these devices convert heat and electrical energy is determined by the transport properties of the two materials. These transport properties are: the Seebeck coefficient S, the electrical conductivity σ, and the thermal conductivity κ. These parameters are combined to form a unitless "figure of merit" or ZT defined as the Seebeck coefficient of the material squared multiplied by its electrical conductivity and divided by the material thermal conductivity multiplied by the temperature. [3]

$$ZT = \frac{S^2 \sigma T}{\kappa} \tag{1.1}$$

A ZT of at least 1 is required to make a useful device; however, most materials do not have this high of a ZT. The best thermoelectrics are BiTe alloys at room temperature and PbTe or SiGe alloys at high temperatures. $Bi_{2-x}Sb_xTe_3$ has been shown to have a ZT of 1.2 at room temperature, [2] while $Pb_2Sr_xTe_{3+x}$ doped with Na has been shown to have a ZT of 2.2 at 915 K. [5] Compared with the compound Mg_2Si, used in this thesis, has a high Seebeck coefficient, electrical conductivity and thermal conductivity giving a ZT of about 0.002 at room temperature. [6]

There are limitations with the longitudinal thermoelectrics. The geometry for the longitudinal thermoelectrics cannot be changed easily. Making tubular longitudinal thermoelectrics would be difficult. Another limitation for longitudinal thermoelectrics is that since a p-type and n-type semiconductors as well as metal contacts are needed the range of materials one can use is restricted. Without both a n-type, a p-type, and a highly electrically conductive metal Ohmicly connecting the semiconductors the longitudinal method cannot work.

Transverse thermoelectrics are built in a totally different manner. Instead of needing both a n-type and a p-type semiconductor, all transverse thermoelectrics require is any combination of a metal and a semiconductor. Both materials must be stacked together in an alternating pattern and then turned at an angle as in Figure 1.2.

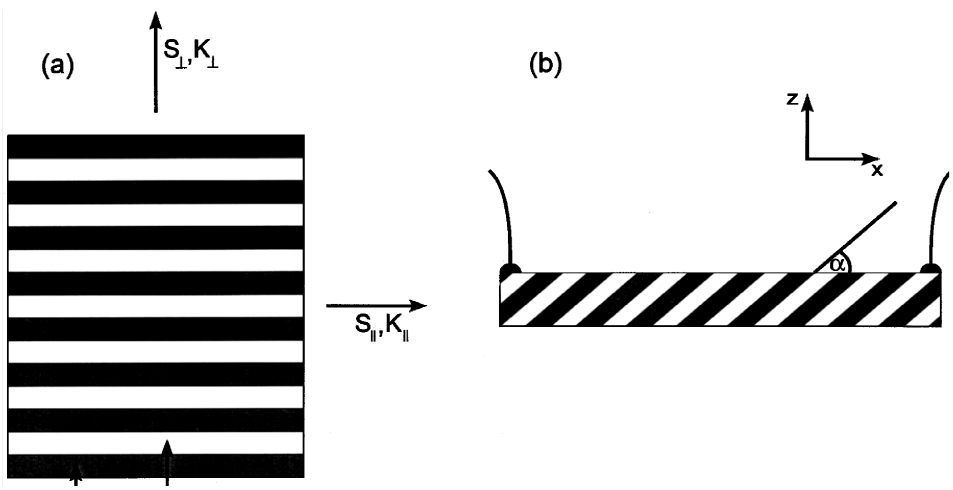

Figure 1.2. Fabrication of a transverse thermoelectric material. (a) The material is formed by stack alternating layers of a semiconductor and a metal (b) An artificially anisotropic material is formed by cutting the stack at an angle α with respect to the layers. Heatflows along the z axis and a potential difference is directed in the x direction. [7]

This new geometry and structure has two important benefits. First, the geometry of this sample is adjustable. It can be cut into a variety of useful geometries to fit a variety of applications It could be in the shape of a tube (to fit around an exhaust pipe) or a long, slender sheet (to fit on top of a car seat). The other strength is that the layers can be almost any material. It works best for metals and semiconductors but it could be made out of two metal alloys. [3] This versatility in the component materials is its greatest strength. The only requirement is that the layers stick together and make as close to an Ohmic contact as possible.

This new geometry is greatly beneficial in that the transport coefficients in the perpendicular and parallel directions are now combinations of the individual transport coefficients of each material, labelled A and B. The perpendicular and parallel transport coefficients have the forms:

$$S_{\perp} = \frac{S_A \kappa_B + p S_B \kappa_A}{\kappa_B + p \kappa_A} \ , \ S_{\parallel} = \frac{S_A \sigma_A + S_B \sigma_B p}{\sigma_A + \sigma_B p} \tag{1.2}$$

$$\sigma_{\perp} = \frac{\sigma_A \sigma_B (1+p)}{p \sigma_A + \sigma_B} \ , \ \sigma_{\parallel} = \frac{\sigma_A + \sigma_B p}{1+p} \tag{1.3}$$

Here p is the ratio of the thickness of layer A to that of layer B. The thermal conductivities have the same form as the electrical conductivities. The derivation of equations (1.2) and (1.3) are given in Appendices [A-F].

The transport coefficients are now anisotropic and can be written in tensor form. After being rotated each transport coefficient tensor will have diagonal components. The tensor that is formed after the rotation of the layers is

$$[S] = \begin{bmatrix} S_{\parallel} \cos^2 \alpha + S_{\perp} \sin^2 \alpha & 0 & \frac{1}{2}\left(S_{\parallel} - S_{\perp}\right) \sin 2\alpha \\ 0 & S_{\parallel} & 0 \\ \frac{1}{2}\left(S_{\parallel} - S_{\perp}\right) \sin 2\alpha & 0 & S_{\parallel} \sin^2 \alpha + S_{\perp} \cos^2 \alpha \end{bmatrix} \tag{1.4}$$

All of the transport properties have this same tensor form as the Seebeck coefficient tensor in equation (1.4).

With this new geometry comes a new heating scheme. The heat will be applied in the *z* direction while the electric current will flow in the *x* direction. This allows us to think of the thermal conductivity as dominated by phonons instead of dominated by the electrons. This decoupling of the heat flow should reduce the thermal conductivity.

This new geometry will give rise to a new *ZT* value. The Seebeck coefficient will be only the *zx* term from the tensor. The electrical conductivity will consist of the *xx* component while the thermal component will consist of the *zz* component giving us

$$ZT = \frac{S_{ZX}^2 \sigma_{XX} T}{\kappa_{ZZ}} \tag{1.5}$$

It is worthwhile to mention that the *zx* component of the Seebeck coefficient will eventually simplify to the difference between the two materials' Seebeck coefficients multiplied by a combination of the conductivities

$$S_{ZX} = \frac{1}{2}\left(\frac{S_A\sigma_A + S_B\sigma_B p}{\sigma_A + \sigma_B p} - \frac{S_A\kappa_B + pS_B\kappa_A}{\kappa_B + p\kappa_A}\right)\sin 2\alpha = \frac{p(S_A - S_B)(\kappa_A\sigma_A - \kappa_B\sigma_B)\sin 2\alpha}{2(\kappa_B + p\kappa_A)(\sigma_A + \sigma_B p)} \quad (1.6)$$

Therefore, in theory, the *ZT* will increase if you have Seebeck coefficients with opposite signs (an n-type and p-type semiconductor being one example).

It is also worthwhile to mention that the parallel component of the thermal conductivity has an additional factor. This factor is due to Peltier heating from circulating currents. This additional factor consists of the figure of merit of a standard longitudinal thermoelectric device, $Z_{AB}T$. This enlarges the parallel thermal conductivity which will cause a reduction in the transverse figure of merit. [8]

$$\kappa_{\parallel} = \frac{\kappa_A + \kappa_B p}{1+p}(1+Z_{AB}T) \quad (1.7)$$

Previous papers published on artificially anisotropic thermoelectrics mostly have been theoretical and computational. [8-10] There have been some experimental papers published as well. [3,7, 11-13] The processes that have been used to create an artificially anisotropic material range from soldering together layers [14] to vacuum injection of molten semiconductor into a metal mold [12].

The purpose to these experiments is to attempt to create a new kind of thermoelectric. This transverse thermoelectric geometry has the potential to increase its figure of merit more so than the traditional longitudinal geometry. Given the flexibility this geometry, transverse thermoelectrics can be shaped to fit a multitude of power generation and cooling needs. Also with its ability to use almost any set of materials, transverse devices could be made with both cost effective as well as environmentally friendly materials. And finally, the method with which we produce these devices, the spark plasma sintering method, would be simple to include in a factory setting.

[Chapter 2] Method

In this thesis, spark plasma sintering (SPS) has been used to produce the transverse thermoelectric element using a combination of sliced metal disks and powdered semiconductor material. Transport property measurements of individual components were made using an apparatus made by ZEM-3 ULVAC. Room temperature measurements of parallel, perpendicular, and transverse Seebeck coefficients and electrical conductivities were made using a home-made setup. The thermal conductivity was not measured. All theoretical calculations were done using equations (1.2) – (1.6) in *Mathematica*. [Appendix G] Calculations were done with literature values as well as experimental values measured in the laboratory.

<u>[Section 2.1] Fabrication</u>

SPS was used to fabricate the multi-layers stacks. SPS works by applying uniaxial pressure with two conductive hydraulic rams. These rams press down on a graphite die with a 10mm hole containing the sample with tens to hundreds of megapascals of pressure. The sample is then heated by passing a current through it. The sample is internally heated by its own resistance through the process of Joule heating. This allows for rapid heating and cooling. The rapid heating allows intense densification to occur as long as the grain size of the powder used for the sample is small enough. Usually nanopowders are used to obtain maximum densification. This process decreases impurities and the direction of the current facilitates the crystalline formation of the semiconductor during pressing. [15] Prior to pressing the stack; the Ni, Cu and Mg_2Si were processed to fit inside the graphite die.

The Ni and Cu rods were machined to approximately 9.6 mm in diameter so as to fit inside the graphite die in which the sample was pressed. The graphite die has a hole that is 10 mm in diameter but graphite foil must be put between the die and the sample or else the sample will fuse directly to the die. These machined rods are cut into slices with thicknesses of about 0.5 mm. They were cut using a Buehler Isomet 4000 Linear Precision Saw. The Isomet was equipped with an abrasive cut-off wheel which was made of silicon carbide. The Ni rods were cut at an average thickness of .501 mm with a maximum thickness of .585 mm and a minimum thickness of .441 mm. The Cu rods were cut at an average thickness of .563 with a maximum thickness of .709 and minimum thickness of .414.

The Mg_2Si was ground into a powder and put through a sieve to guarantee a maximum particle size of 75 μm. The Mg_2Si block crystals were ground in a glove box filled with argon gas using an agate mortar and pestle. The powder was then put through a 75 µm sieve. The purpose of this process is to ensure that the particles being pressed in the SPS system are as small as possible to ensure maximum densification and optimal crystalline structure in the layers. The powder was kept inside the argon atmosphere until needed to reduce oxidation.

Once the metal layers were cut and the powder was sieved the sample was assembled inside the graphite die. There are two plungers, one in the top and one in the bottom as well as a graphite sheath. The sheath was cut to size and inserted into the hole. Then one plunger was placed in the bottom. Then the sample was built, starting with a metal layer on bottom. Then approximately 0.0705 g of powder was put on top of this metal layer (actual masses given in Table 2.1.1). A long graphite rod was used to compact the Mg_2Si powder before adding another metal layer. In this way the stack was built, alternating metal and powder, ending with a metal layer on top. Lastly, a second plunger was placed on top.

Cu/Mg2Si Stack			**Ni/Mg2Si stack**		
Copper thickness	*Max*	0.709	Nickel thickness	*Max*	0.585
[mm]	*Mean*	0.5634	[mm]	*Mean*	0.5012
	Min	0.414		*Min*	0.441
Mg2Si mass	*Max*	0.072	Mg2Si mass	*Max*	0.0709
[g]	*Mean*	0.0709	[g]	*Mean*	0.0705
	Min	0.0702		*Min*	0.07

Table 2.1.1. Statistics for the thicknesses and masses of the Cu, Ni, and Mg_2Si for each sample

The die was lightly compacted in a cold press and then inserted into the SPS system. A two stage vacuum system was used to evacuate the pressing chamber. The chamber was then evacuated to 5×10^{-5} Torr before initial pressing. At this point the hydraulic rams increased the pressure, at a rate of 40 MPa per minute, till the pressure reached the 80 MPa. Both the Ni/Mg_2Si and Cu/Mg_2Si samples had a set pressure of 80 MPa. Once the pressure reached the set point argon gas was pumped into the chamber. Then the temperature was increased to the temperature set point at a rate of 100 °C per min. The temperature set points were 700 °C for the Cu/Mg_2Si and 800 °C for the Ni/Mg_2Si. Once the temperature reached the temperature set point then the sample was held for a set period of time. The Cu/Mg_2Si sample was held for 3 minutes while the Ni/Mg_2Si sample was held for 4 minutes and 10 seconds. The pressure was held until the sample had been pressed to the maximum density. This is the point in which the sample will no longer compact, which is determined by monitoring the ram position. When this maximum compression was reached the temperature set point was ramped down at the same rate. After which the pressure set point was ramped down at a rate of 20 MPa per minute to reduce stress on the sample. This process results in a cylindrical layered stack covered in graphite. The sample is polished so as clean off all of the graphite as well as to gain as good a connection as possible when soldering and electroplating.

[Section 2.2] Transport Measurements

Experiments using a linear transport property testing apparatus made by ZEM-3 ULVAC were performed. All of the materials (Mg_2Si, Cu, and Ni) were tested for their individual Seebeck coefficients and electrical conductivities. The ZEM-3 uses two metal contacts on the end of stabilizing bars. The sample was set to rest the bottom bar, called the stage, and the top bar squeezes down from the top securing the sample. Thermocouples were then attached at the side as shown in Figure [2.2.1]. This allows a current to be passed through the sample and the voltage to be read by the thermocouples giving the resistance of the sample. Also, there is a heater under the bottom metal contact, allowing for a change in temperature to be put across the sample. Reading the voltage from the thermocouples in this setup would allow the measurement of the Seebeck coefficient. In this way the ZEM-3 gives the longitudinal thermoelectric properties of the pure samples.

Figure [2.2.1] Picture of the ZEM-3 apparatus. The samples stage is visible with both stabilizing arms as well as the thermocouples.

Mg_2Si powder was prepared in the manner described above and pressed in the SPS. The Mg_2Si powder was pressed for 5 minutes at 800 °C under 80 MPa. A rectangular prism was cut out of the pressed cylinder with the slow diamond saw and was polished to dimensions 3.68 mm x 5.2 mm x 9.396 mm. It was polished using a metal block holder that was machined to have a right angle so as to make the sample as perfect a rectangular prism as possible. With this polishing the sample could be loaded into the ZEM for measurement.

Cu and Ni rectangles were also cut using the linear precision saw, polished, and then set up in the ZEM in the same manner as the Mg_2Si. The copper sample had dimensions of 3.445 mm x 1.423 mm x 9.399 mm (width x depth x height). While the Ni sample had dimensions of 3.947 mm x 1.347 mm x 9.624 mm. The ZEM has a built in package that measures the Seebeck coefficient and electrical conductivity for different temperatures. This data was analyzed in excel and the properties at room temperature were extrapolated over the temperature range.

Then, transport measurements were performed at different sample stages. Seebeck coefficients and conductivities were measured with perpendicular, parallel, and transverse geometries for both samples. All measurements were made in atmosphere and at room temperature. When changing the samples geometry, both cutting and nickel plating of the samples were performed.

The perpendicular measurements were made after the SPS step. For the Seebeck coefficient measurement; wires, thermocouples, and a heater were attached, as shown in Figure 2.2.2. Copper wires were soldered to the top and bottom of the sample. Our thermocouples were attached using GE varnish to the top and bottom of the sample. The thermocouples were type T and made by an undergraduate assistant of Dr. Stokes' using a spark welder. The sample was placed on top of a heat sink using thermal paste and a heater was placed on top of the sample the same way. A heater, three 100 Ω resistors connected in parallel on a ceramic plate, was held on top by a specially made brace. Enough thermal paste was used that it oozed out the sides when pressure was applied.

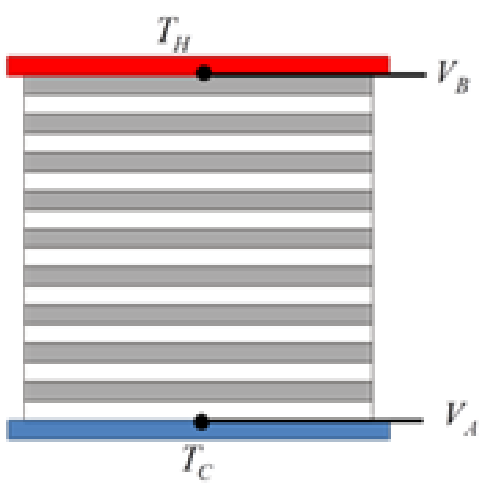

Figure 2.2.2. Experimental setup for measuring the perpendicular Seebeck coefficient

The copper wires and thermocouples were attached to individual Keithley 2182A nanovoltmeters. A simulated 23°C reference point was used for the nanovoltmeters connected to the thermocouples. The heater was connected to a Keithley 2400 sourcemeter. The current through the heater started at 10 mA, increased at a rate of 10 mA ending at the compliance of the meter (about 210 mA). The voltage across the sample and the temperature at the top and bottom were recorded three times at each current set point.

The conductivity measurement was done after the Seebeck coefficient measurement. Once the GE varnish had been cleaned off, two more copper wires were soldered to the top and bottom of the sample, as shown in Figure 2.2.3. These two leads were connected to the sourcemeter to apply a current and the other two leads were connected to a nanovoltmeter to measure the voltage resulting from the applied current. Currents started at 1 mA and were incremented by 1 mA till 10 mA at which point the increment changed to 10 mA resulting in a final current of 100 mA. The voltages and temperatures in both experiments were recorded using a LabView program utilizing a VISA interface connection for each nanovoltmeter.

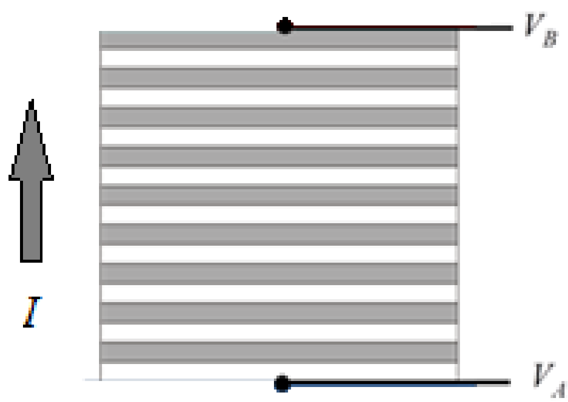

Figure 2.2.3. Experimental setup for measuring the perpendicular electrical conductivity

Cutting methods were determined by trial and error. Other Cu and Ni stacks were pressed to serve as test cases. Ni and Cu stacks were cut with the slow diamond saw as well as an abrasive slurry wire saw from South Bay Technology. A Ni stack was also cut using the linear precision saw Buehler IsoMet 4000. After these tests the slow diamond saw was used exclusively for the Cu stacks and the wire saw was used exclusively for the Ni stacks.

After this, the samples previously described were cut to enable parallel measurements. The Cu/Mg_2Si was cut using a slow diamond saw. An 8 inch diamond blade of .012 inch width and medium grit was used. The speed was kept at 100 rpm while the weight position was set at

150 on an arbitrary scale from the fulcrum giving cutting times of about an hour. The purpose was to cut off two sides to create two flat sides on which to attach leads and thermocouples. The Ni/Mg_2Si sample was substantially more brittle so a wire saw was used to cut it. A stainless steel wire of .01 inch diameter was used with silicon carbide abrasive slurry giving cutting times of 5.5 and 11.5 hours. In both cases the mounting of the samples was achieved with graphite pads on top of blocks of aluminum connected by melted wax. All samples were allowed to cool before cutting.

The sides that were revealed after these cuts were plated with nickel. This is done because a solid layer to measure our voltage is needed to produce an isopotential. If the wires were soldered directly to the layers then the measurement would have been flawed since we would not have known if the side was an isopotential or not. A Caswell electroplating system was used for this purpose. The surface area of the sample was determined before plating since the current needed depends on the surface area (1 A for 16 inch^2). The current was always higher than necessary for the surface area being plated because the current will drop during the plating procedure and if it drops too far the plate would become uneven. In general the system was used for about an hour each time giving us about a .001 inch plate layer.

Once the sides were plated then the parallel measurements were made. The setup is almost the same as the perpendicular measurements except that the leads and thermocouples were attached to the newly plated sides instead of the top and bottom, as shown in Figure 2.2.4. It must be noted that the plating was polished off of the other sides making sure that the potential wasn’t that of the nickel plating but that of the sample.

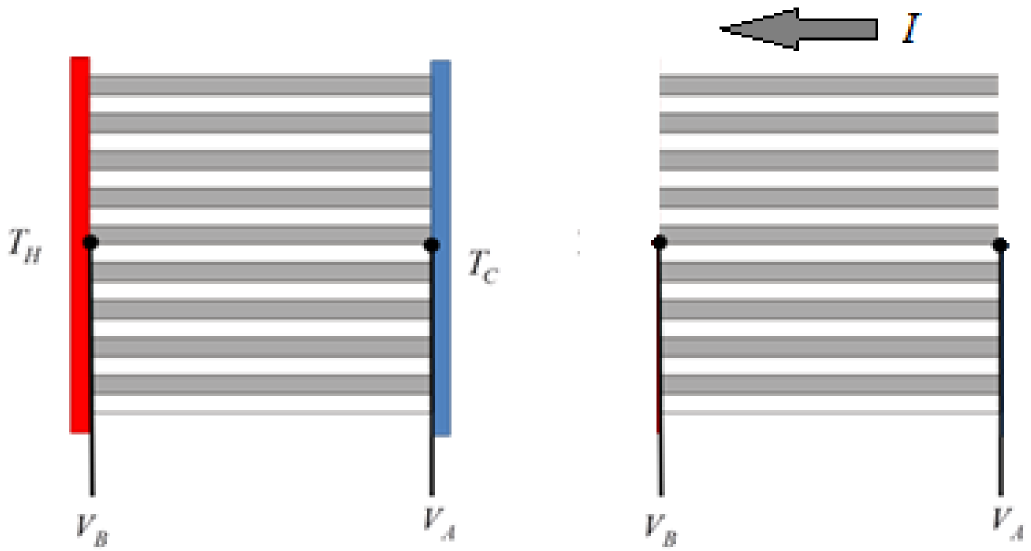

Figure 2.2.4. Experimental setups for measuring parallel transport properties

After the parallel measurements were made, the plating was polished off. Then the samples were cut again, this time making a rectangular prism with slanted layers of 35°. Once again the Cu/Mg_2Si stack was cut using the slow diamond saw but this time the weight position was changed to 100 on the arbitrary scale, giving cut times from 2 hours to 21 minutes. The Ni/Mg_2Si stack was cut using the wire saw with the same parameters as above, giving cut time ranging from 4 hours to about 2 hours. The angle was determined by a plastic sample holder that was built by a 3D printer to be exactly 35°.

The rectangular prism was then plated within the Caswell plating system. The plating was then polished off of the sides, except for the ends. The ends were plated so that they would act as isopotentials, giving us the voltage across the sample.

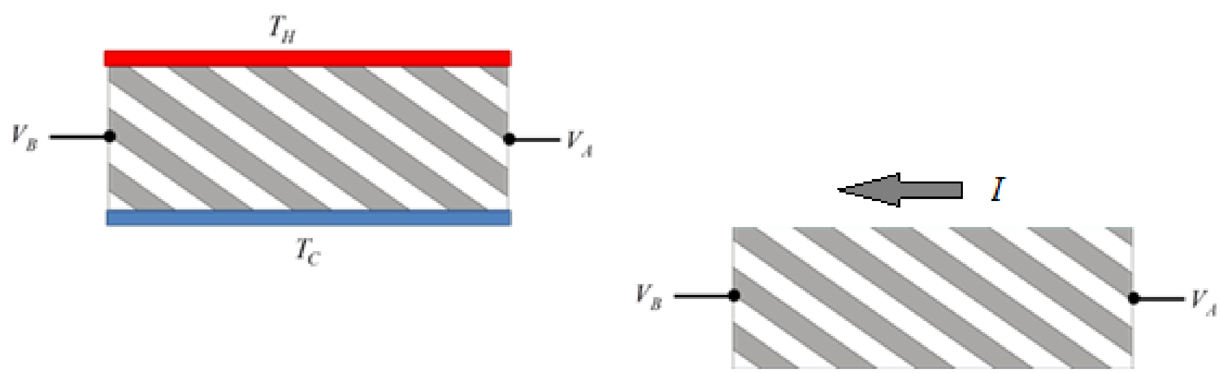

Figure 2.2.5. Experimental setups for measuring transverse transport properties

The transverse Seebeck coefficient measurement (Figure 2.2.5) was different from the perpendicular and parallel measurements in that the thermocouples were attached on the top and bottom while the two wires were soldered to the plated sides. The conductivity experiment was much the same as before with two leads being attached to each of the plated ends, one set providing the current while the other measured the voltage.

[Chapter 3] Results

All of the measurements made are used to evaluate the efficacy of our thermoelectric device but those were not the only results of the experiments. During the experimental process more than the two final stacks were pressed. The extra stacks were used during our experiments with cutting methods.

The Ni stack that was cut by the linear precision saw ended up delaminating with the fragments spraying around the inside of the chamber. The Ni stack which was cut by the slow diamond saw ended up delaminating as well. The wire saw was the only saw which successfully cut the Ni stacks without delamination. The Cu stack that was cut by the wire saw ended up breaking multiple wires during the cutting process. The wire always broke by being caught by the Cu metal, not on the Mg_2Si. The Cu stack that was cut on slow diamond saw did not delaminate and this process was therefore chosen for that stack.

[Section 3.1] Theoretical

The best angle for the ZT and the power factor was determined for both samples using both the CRC handbook values for the transport coefficients as well as the experimental determined transport coefficients from the ZEM. These calculations are attached in Appendices [G, H]. For the Ni/Mg_2Si sample the best angle was 28° giving a ZT of .37 for the ZEM values while the CRC values had a ZT of .41. The best angle for the power factor of the Ni/Mg_2Si sample is 35.3°. The Cu/Mg_2Si sample would maximize its ZT, at about 1.2, with an angle of 21.4° while at an angle of 35.3° the power factor would be maximized. Figures 3.1.1 and 3.1.2 give the best angles for the ZT and the power factor of both material values for transport properties determined from the CRC values as well as the values from the ZEM.

Also in Appendix [G], there is a calculation of the adjusted figure of merit including the term for the Peltier heating due to the circulating currents inside the layers. The change in the ZT when including this term is on the order of .1%. This is a negligible change in the ZT but it is worthwhile to note that with materials which have a higher longitudinal thermoelectric figure of merit this change will be more substantial.

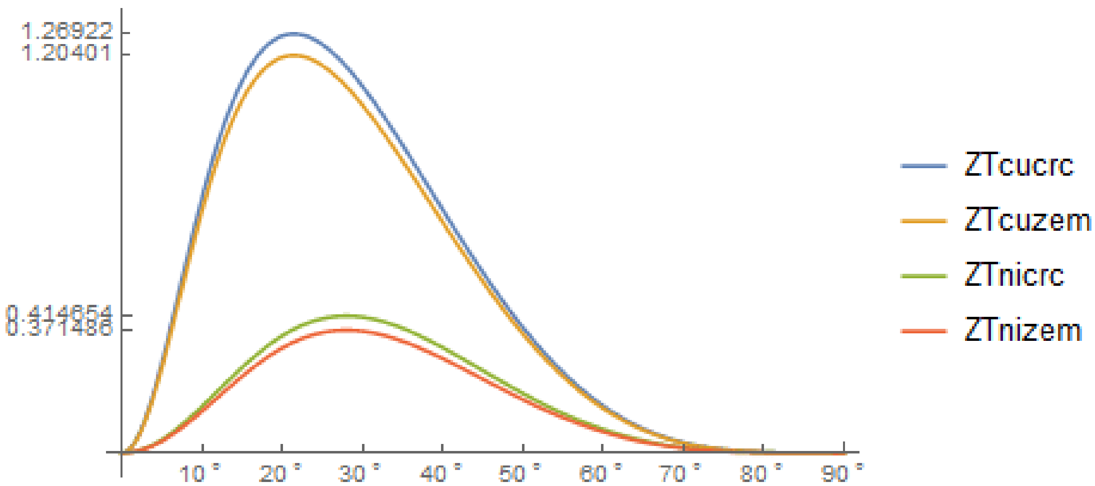

Figure 3.1.1. Theoretical ZT graphed vs. angle of the layers for all theoretical stacks. (a) ZTcucrc is the ZT of the copper stack using the CRC handbook values, (b) ZT cuzem is the ZT of the copper stack using the ZEM values, (c) ZTnicrc is the ZT of the nickel stack using the CRC values, and (d) ZTnizem is the ZT of the nickel stack using the ZEM values

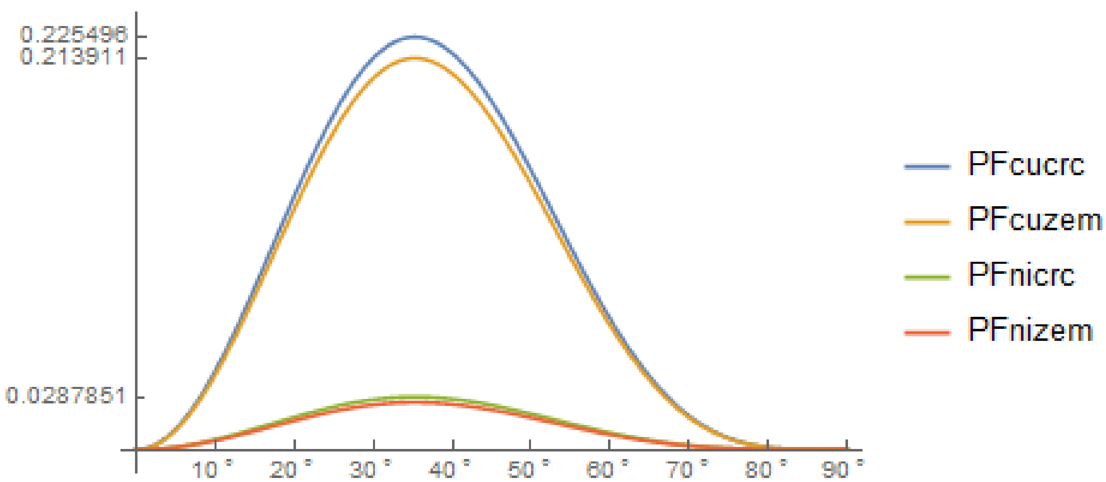

Figure 3.1.2. Theoretical power factor graphed against the angle of the layers for all theoretical stacks. All names are the same as Figure 3.1.1. (see above)

There were two sets of transport properties calculated for the Ni/Mg_2Si stack. One set with the experimentally determined Seebeck coefficient and conductivity and the other with values taken from the CRC handbook. [16] The transport properties for the Cu/Mg_2Si stack were also determined with both ZEM and CRC values. All of this data is in Table 3.1.1.

		Ni stack, ZEM	Ni stack, CRC	Cu stack, ZEM	Cu stack, CRC	Units
Perpindicular	Seebeck Coefficient	-2.15E-04	-2.15E-04	-2.24E-04	-2.24E-04	V/K
	Electrical Conductivity	934	934	934	934	S/m
Parallel	Seebeck Coefficient	-1.15E-05	-1.95E-05	5.40E-06	1.83E-06	V/K
	Electrical Conductivity	4.16E+06	5.00E+06	2.70E+07	2.94E+07	S/m
Transverse	Seebeck Coefficient	9.54E-05	9.19E-05	1.08E-04	1.06E-04	V/K
	Electrical Conductivity	2.79E+06	3.36E+06	1.81E+07	1.97E+07	S/m
	Power Factor	0.0254	0.0283	0.2109	0.2223	W/(m*K^2)

Table 3.1.1. Theoretical transport properties at room temperature

[Section 3.2] Experimental

The ZEM measurements of the pure Ni and Cu were different than the CRC handbook values. The values that were determined are given in Table 3.2.1. All material properties are given with the only duplicates being the Seebeck coefficient and electrical conductivity of the metals. The thermal conductivity data used has been taken from other sources either the CRC handbook or from Fu et. al. in the case of the Mg_2Si. [17]

	Mg2Si	Cu	Ni	Units	Source
Seebeck Coefficient	-2.29E-04	5.40E-06	-1.15E-05	V/K	ZEM
		1.83E-06	-1.95E-05		CRC Handbook
Electrical Conductivity	500.6	5.41E+07	8.31E+06	S/m	ZEM
		5.88E+07	1.00E+07		CRC Handbook
Thermal Conductivity	5.65	390	90	W/(m*K)	CRC Handbook, except for Mg2Si

Table 3.2.1. Transport coefficients, for the components, used to calculate the theoretical transport properties

The room temperature measurements of the Cu/Mg_2Si and Ni/Mg_2Si stacks are given in Table 3.2.2. They were derived from the data in Appendices [L, M]. They are categorized by the symmetry of each experiment as well as whether the entire sample was plated or merely the ends were plated. The experimental power factor was determined by squaring the Seebeck coefficient and multiplying by the electrical conductivity.

		Ni Stack	Cu Stack	Units
Perpindicular	Seebeck Coefficient	-8.78E-05	-8.09E-05	V/K
	Electrical Conductivity	878	5.29	S/m
Parallel	Seebeck Coefficient	-6.99E-06	-6.90E-07	V/K
	Electrical Conductivity	2.37E+07	2.36E+07	S/m
Transverse	Seebeck Coefficient	-2.32E-05	-4.17E-06	V/K
plating	Electrical Conductivity	56429	54688	S/m
on ends	Power Factor	3.05E-05	9.52E-07	W/(m*K^2)

Table 3.2.2. Transport coefficients measured at room temperature

The Figures 3.2.1 - 3.2.4 show how the measurements were derived. The Seebeck coefficient was derived by graphing the negative voltage against the change in temperature. The slop of the best fit line of this graph is the Seebeck Coefficient. The electrical conductivity was obtained by first graphing the voltage versus the current passed through the sample. The slope gives us the resistance which can be changed into the conductivity by taking the length divided by the resistance and the cross sectional area.

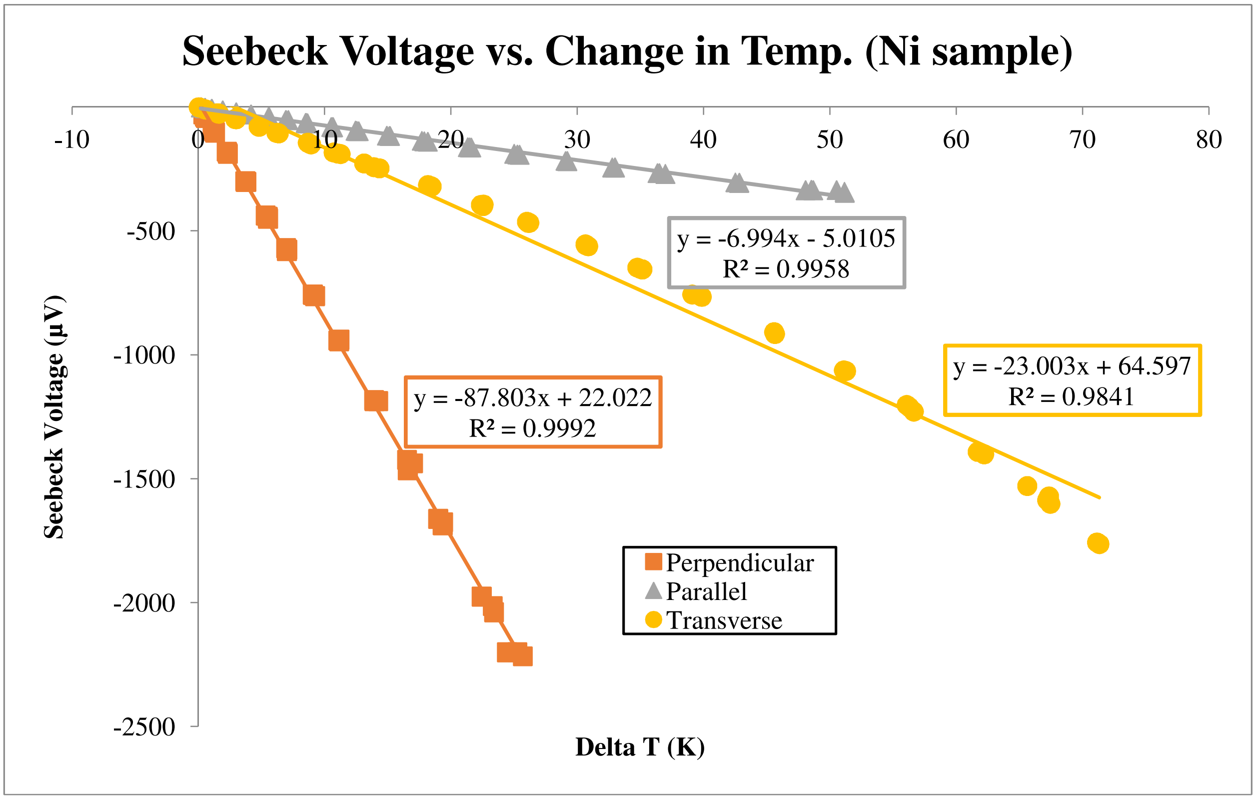

Figure 3.2.1. Graphed the Seebeck voltage versus the change in temperature for the Ni/Mg_2Si sample. The graph's slope is the Seebeck Coefficient. The Seebeck coefficient is given in here in µV/K.

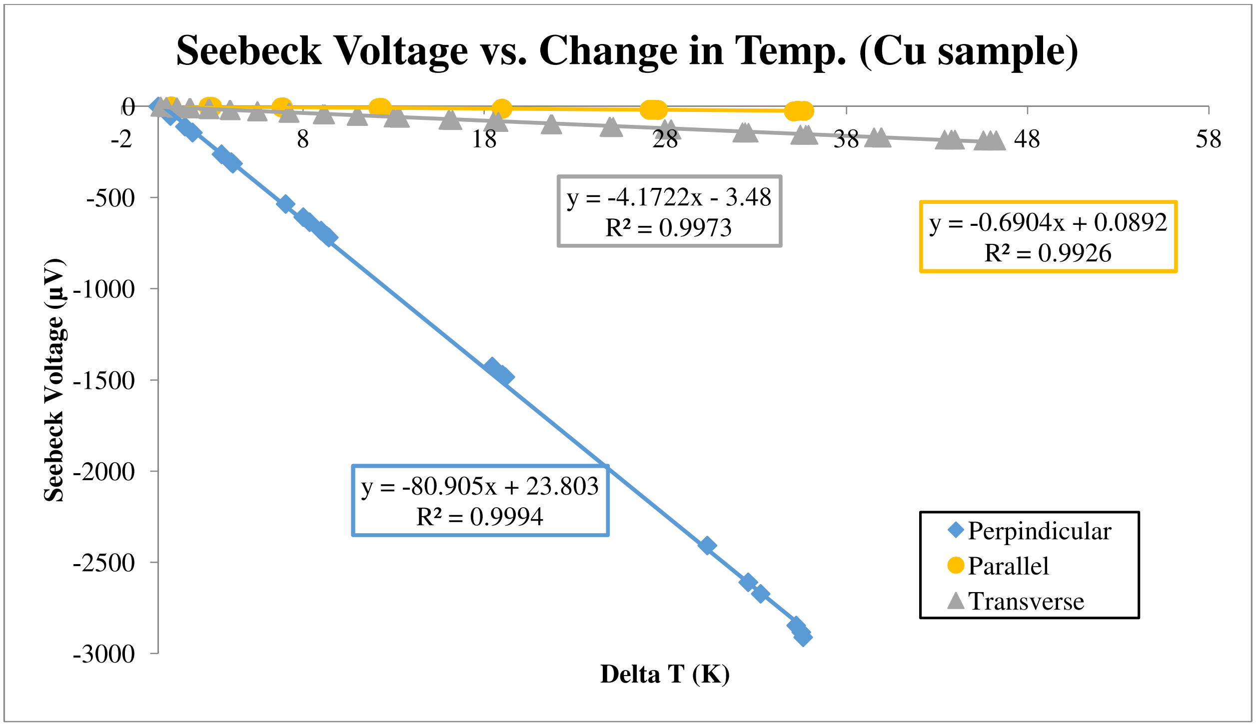

Figure 3.2.2. Graphed the Seebeck voltage versus the change in temperature for the Cu/Mg_2Si sample. The graph's slope is the Seebeck Coefficient. The Seebeck coefficient is given in here in µV/K.

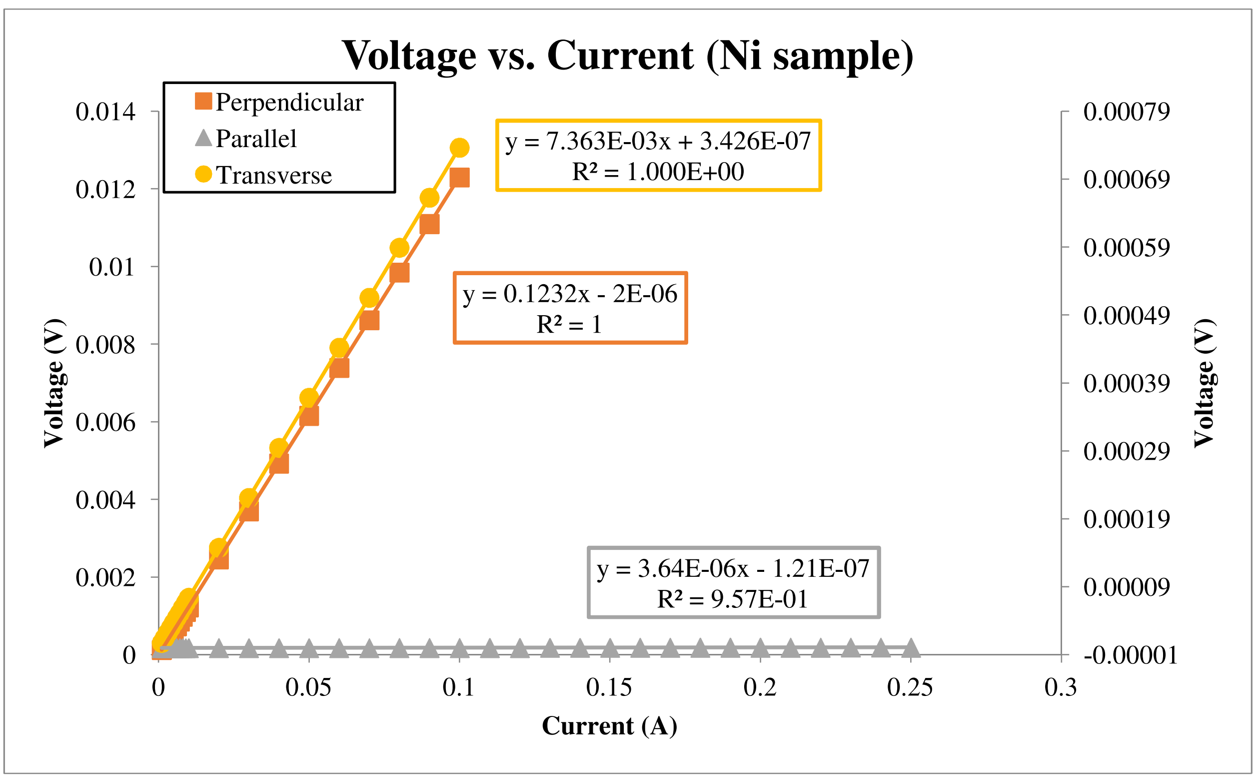

Figure 3.2.3. Graphed the voltage against the current giving the resistance for all geometries of the Ni/Mg_2Si sample. The slope of each trend line is the resistivity value for each geometry.

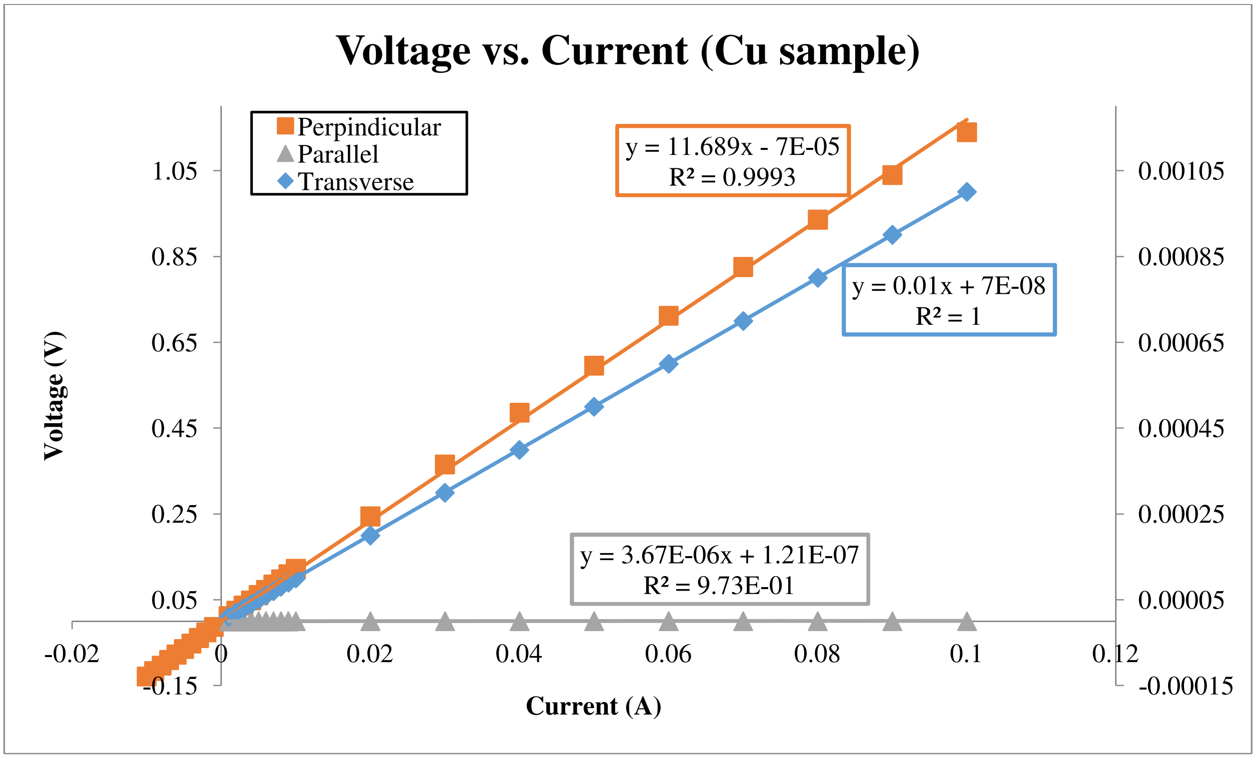

Figure 3.2.4. Graphed the voltage against the current giving the resistance for all geometries of the Ni/Mg_2Si sample. The slope of each trend line is the resistivity value for each geometry.

[Chapter 4] Discussion

An interesting fact is that using our current theory, the potential ZT of the Cu/Mg_2Si stack is 1.2 while the Ni/Mg_2Si is .37. This difference stems from our equation for the zx-component Seebeck coefficient, which when simplified gives the cumulative Seebeck coefficient as a function as the individual Seebeck coefficients difference. Since Cu has a positive Seebeck coefficient while both Ni and Mg_2Si have negative Seebeck coefficients. This causes the theoretical Seebeck coefficient of Cu/Mg_2Si is higher by a factor of ten. Having material Seebeck coefficients that are opposite in sign mean that their magnitude will add and is therefore a desirable outcome.

A comparison between both sets of theoretical values using only the ZEM and the experimental values is given in Table 4.1.

	Perpendicular Seebeck		**Parallel Seebeck**		**Transverse Seebeck (Szx)**	
	μV/K		μV/K		μV/K	
	Experimental	Calculated	Experimental	Calculated	Experimental	Calculated
Mg_2Si/Cu	-80.9	-224	-0.690	5.40	-4.17	108
Mg_2Si/Ni	-87.8	-215	-6.99	-11.5	-23.2	95.4
	Perpendicular Conductivity		**Parallel Conductity**		**Transverse Conductivity (σxx)**	
	S/m		S/m		S/m	
	Experimental	Calculated	Experimental	Calculated	Experimental	Calculated
Mg_2Si/Cu	5.29	934	2.36E+07	2.70E+07	5.47E+04	1.81E+07
Mg_2Si/Ni	878	934	2.37E+07	4.16E+06	5.64E+04	2.79E+06

Table 4.1. Comparison of calculated theoretical transport properties with the measured experimental transport properties

Most of the experimental values are either very close or similar to their calculated values, with a few notable exceptions. The experimental perpendicular conductivity for the Cu/Mg_2Si is much smaller than the calculated value. The transverse Seebeck coefficients for both stacks are of the opposite sign. The magnitude of the Seebeck coefficient of the Cu/Mg_2Si stack is also much lower than its calculated value aside from the change in sign. Lastly, the transverse conductivities for both samples are much smaller than they should be.

One explanation for the discrepancies in the theoretical and experimental values is eddy currents. Eddy currents are flows inside each layer that are parallel to the interfaces. This causes additional Joule heating inside the layer dissipating some of the electrical power applied. These eddy currents are caused by the interfaces. The jump discontinuities at the interfaces give a perpendicular electric field. With non-anisotropic materials the eddy currents are not created but when the seebeck tensor is anisotropic, this causes eddy currents to form. The eddy currents were calculated in COMSOL by Charles Crawford. [18]

These interface resistances are most likely caused by small gaps between the layers. Small air pockets or small imperfections in the crystal lattice at the junction points between the semiconductor and the metal are one cause of these interface resistances. Also, a deformation in the lattice of either the metal or the semiconductor due to the SPS process can cause the interface resistance. If a factor is added into each of the transport coefficients during their definition and then use the experimental value as the true value the resistance from each transport coefficient can be found. The derivations of the transport coefficients are given in Appendices [A-F].

The imperfect interfaces give both a thermal and electrical resistance affecting both the heat and electric currents. The calculated resistances are given in Table 4.2 along with what is called the equivalence term. The equivalence term is a relative term to the resistance. The equivalence term is defined at the end of each of the Appendices [A-F]. The equivalence term is how large or small the resistance term has to be to not affect the transport coefficients.

		Resistance	Equivalence Term
Ni Stack	Perpendicular Seebeck	6.79E-05	4.70E-05
ZEM Values	Perpendicular Conductivity	7.73E-04	7.17E-03
	Parallel Seebeck	4.24E-04	2.75E-04
	Parallel Conductivity	5.83E-05	2.75E-04
Cu Stack	Perpendicular Seebeck	7.71E-05	4.70E-05
ZEM Values	Perpendicular Conductivity	1.25	7.09E-03
	Parallel Seebeck	-4.03E-06	3.55E-05
	Parallel Conductivity	-2.80E-04	3.55E-05

Table 4.2. Calculated interface resistances for perpendicular and parallel transport coefficients alongside their respective equivalence terms

For the perpendicular Seebeck coefficient if the resistance is larger than the equivalence term then there is a reduction in the measured perpendicular Seebeck coefficient. If the resistance for the perpendicular conductivity is larger than its respective equivalence term then there is a reduction in the measured conductivity. Also, if the resistance for the parallel Seebeck coefficient is smaller than its corresponding equivalence term then there is a decrease in the parallel Seebeck coefficient. But for the parallel conductivity if the resistance is smaller than its equivalence term then the conductivity will increase.

The resistances were calculated using the experimental values, see Appendix [K]. The purpose of finding these values is to see if the electrical resistance terms (resistances derived from perpendicular conductivity and parallel transport properties) were the same or not. The perpendicular Seebeck resistance is the only thermal resistance so it cannot be compared with other like values. But the resistances calculated from the perpendicular conductivity, the parallel Seebeck coefficient, and the parallel conductivity are all electrical resistance terms.

The electrical resistances for the copper stack are not consistent. This is most likely due to contact resistances in the soldered connections for the measurements. It could also have been due to the contact between the nickel plating on the copper sample. Furthermore, the perpendicular conductivity experiment should be rerun to test if this extremely divergent result is in fact correct. The electrical resistance terms for the nickel stack are within one power of ten from each other. This could be due to the contact resistances of the solder and the plating as before.

Another analysis was performed using the experimental perpendicular and parallel Seebeck coefficients and electrical conductivities. Using these values and the transverse transport coefficient definitions from Reitmaier [3], the transverse coefficients were calculated. These calculated transverse values were then compared with the experimental transverse values. These calculations and comparisons are in appendix [L]. None of the experimental transverse values equaled the transverse values calculated from our experimental perpendicular and parallel components. The Ni stack experimental values are closer to the calculated values than the Cu stack values are. The most likely causes for these differences are the eddy currents caused by the interface resistances. These eddy currents would change their character depending on the angle between the interface and the direction of the current; hence the difference between the transverse, perpendicular and parallel components.

[Chapter 5] Conclusion

During the course of these experiments, it has been proven that a transverse thermoelectric device, using artificially anisotropic materials, can be produced from the spark plasma sintering method using both solid metal disks and powdered semiconductor. This method makes a better semiconductor structure but still leaves resistances at the material interfaces inside of the sample. While the crude room temperature measurements were successful, the next step would be to perform these experiments within a more controlled system. This controlled system should consist of cryogenically cooling the bottom of the sample to provide a better heat sink.

Our room temperature experiments have found discrepancies that are best explained by eddy currents caused by the resistances at the interfaces. If further studies are conducted on this topic and they find that both eddy currents as well as interface resistances are insufficient to cause the error then the theory itself must be reevaluated as a whole. During this study it was found that Ni and Mg_2Si have lower interface resistance than Cu and Mg_2Si. Further studies should also attempt different combinations of metals and semiconductors to find a combination that has a lower interface resistance between the layers. If and when we, as a field, are able to produce samples that meet with the expectations of the theory then artificially anisotropic materials could provide vast improvement over the current state-of-the-art longitudinal thermoelectric devices.

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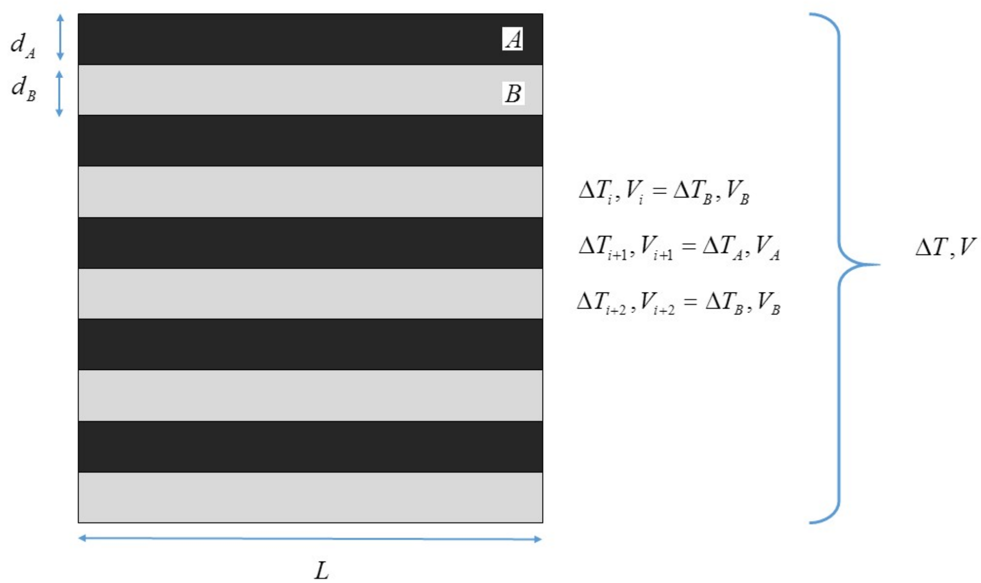
Appendices

[A] Perpendicular Seebeck Coefficient Derivation

Assuming that our sample has *N* layers of materials *A* and *B* with thicknesses d_A and d_B. We will also assume that the thickness has a length, *L*, and a width, *W*, that is the same for all layers. (The width is into the page)



(Figure A.1)

We start with the total potential from the top to the bottom of the sample through all the layers.

$$V = \sum_{i=1}^{2N} V_i \tag{A.1}$$

Since we only have two kinds of alternating layers, this simplifies to

$$V = NV_A + NV_B \tag{A.2}$$

Now, our perpendicular Seebeck coefficient as

$$S_\perp = \frac{V}{\Delta T} \tag{A.3}$$

We need our voltage in terms of ΔT and the Seebeck coefficients of each layer. This is given by

$$V_A = S_A \Delta T_A \text{ and } V_B = S_B \Delta T_B \tag{A.4}$$

In addition to this our total ΔT is given by

$$\Delta T = N\Delta T_A + N\Delta T_B \tag{A.5}$$

Substituting equations A.2, A.4, and A.5 into A.3 gives us

$$S_{\perp} = \frac{N(S_A \Delta T_A) + N(S_B \Delta T_B)}{N\Delta T_A + N\Delta T_B} = \frac{S_A \Delta T_A + S_B \Delta T_B}{\Delta T_A + \Delta T_B} \tag{A.6}$$

Fourier's law gives the heat flow rate in terms of our ΔT

$$\dot{Q} = \frac{\kappa A}{d} \Delta T \tag{A.7}$$

Rearranging this gives the ΔT in terms of the thermal conductivities and thicknesses of each slab. The cross sectional area and heat flow rate are constant; therefore, we have

$$\Delta T_A = \frac{\dot{Q}}{A} \frac{d_A}{\kappa_A} \text{ and } \Delta T_B = \frac{\dot{Q}}{A} \frac{d_B}{\kappa_B} \tag{A.8}$$

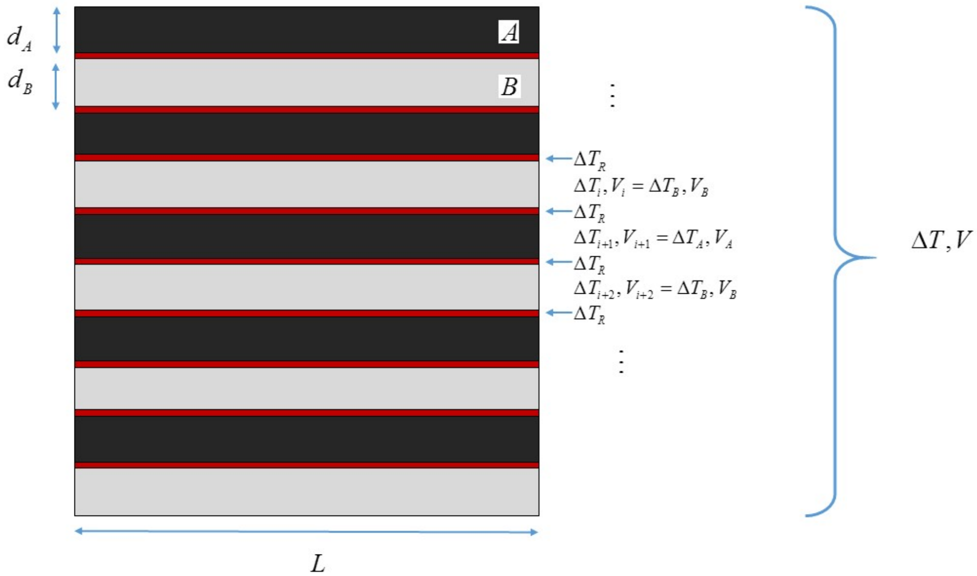
Substituting into equation (A.6) gives us

$$S_{\perp} = \frac{S_A \frac{\dot{Q}}{A} \frac{d_A}{\kappa_A} + S_B \frac{\dot{Q}}{A} \frac{d_B}{\kappa_B}}{\frac{\dot{Q}}{A} \frac{d_A}{\kappa_A} + \frac{\dot{Q}}{A} \frac{d_B}{\kappa_B}} = \frac{S_A \frac{d_A}{\kappa_A} + S_B \frac{d_B}{\kappa_B}}{\frac{d_A}{\kappa_A} + \frac{d_B}{\kappa_B}} = \frac{S_A d_A \kappa_B + S_B d_B \kappa_A}{d_A \kappa_B + d_B \kappa_A} \tag{A.9}$$

Simplifying with $p = \frac{d_B}{d_A}$ gives us

$$S_{\perp} = \frac{S_A \kappa_B + S_B \frac{d_B}{d_A} \kappa_A}{\kappa_B + \frac{d_B}{d_A} \kappa_A} = \frac{S_A \kappa_B + p S_B \kappa_A}{\kappa_B + p \kappa_A} \tag{A.10}$$

If we should think about a thermal interface resistance included into our $S_{\perp}$ will be reduced by the interface resistance, R_{TI}



(Figure A.2)

Including this resistance will add two temperature drops to our sum in equation (A.5) to

$$\Delta T = N\Delta T_A + N\Delta T_B + 2N\Delta T_{TR} \tag{A.11}$$

This ΔT_{TR} is defined with a resistance instead of conductivities, like (A.7), meaning

$$\Delta T_{TR} = \frac{Q}{A} R_{TR} \tag{A.12}$$

changing equation (A.9) to

$$S_\perp = \frac{S_A \frac{\dot{Q}}{A}\frac{d_A}{\kappa_A} + S_B \frac{\dot{Q}}{A}\frac{d_B}{\kappa_B}}{\frac{\dot{Q}}{A}\frac{d_A}{\kappa_A} + \frac{\dot{Q}}{A}\frac{d_B}{\kappa_B} + \frac{2\dot{Q}}{A}R_{TR}} = \frac{S_A \frac{d_A}{\kappa_A} + S_B \frac{d_B}{\kappa_B}}{\frac{d_A}{\kappa_A} + \frac{d_B}{\kappa_B} + 2R_{TR}} = \frac{S_A d_A \kappa_B + S_B d_B \kappa_A}{d_A \kappa_B + d_B \kappa_A + 2\kappa_A \kappa_B R_{TR}} \tag{A.13}$$

This can be simplified with $p = \frac{d_B}{d_A}$ although the previous result would be more useful

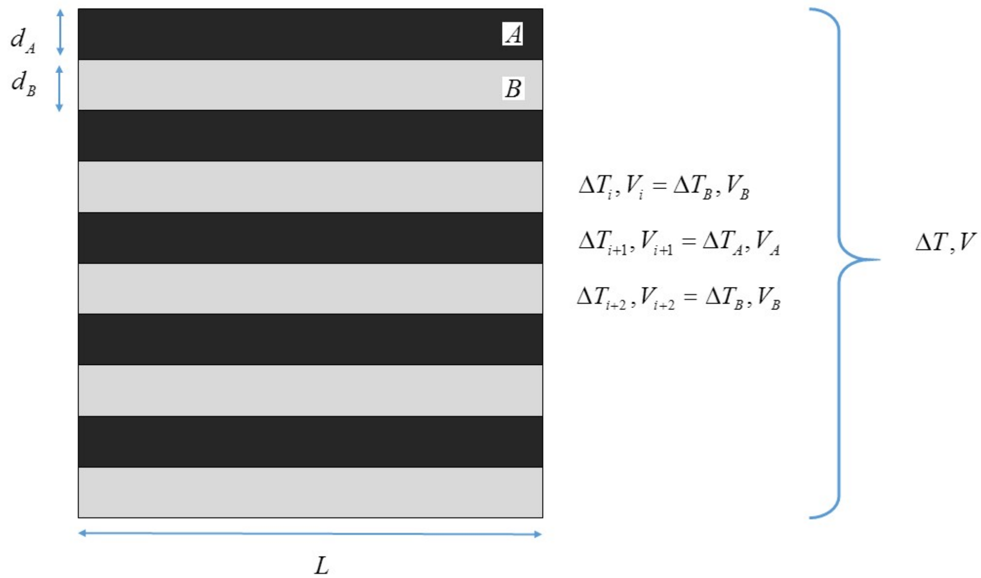
$$S_\perp = \frac{S_A \kappa_B + S_B \frac{d_B}{d_A}\kappa_A}{\kappa_B + \frac{d_B}{d_A}\kappa_A + 2\frac{\kappa_A \kappa_B}{d_A}R_{TR}} = \frac{S_A \kappa_B + pS_B \kappa_A}{\kappa_B + p\kappa_A + 2\frac{\kappa_A \kappa_B}{d_A}R_{TR}} \tag{A.14}$$

This thermal resistance could be neglected if

$$R_{TH} \ll \frac{1}{2}\left(\frac{d_A}{\kappa_A} + \frac{d_B}{\kappa_B}\right) \tag{A.15}$$

[B] Parallel Seebeck Coefficient Derivation

Assuming that our sample has *N* layers of materials *A* and *B* with thicknesses d_A and d_B. We will also assume that the thickness has a length, *L*, and a width, *W*, that is the same for all layers. (The width is into the page)



(Figure B.1)

We start with the total current flowing from the left to the right of the sample through all layers.

$$I = \sum_{i=1}^{2N} I_i \tag{B.1}$$

Since they have only two kinds of alternating layers, (B.1) simplifies to,

$$I = NI_A + NI_B \tag{B.2}$$

Now, our parallel Seebeck coefficient is defined as

$$S_{\parallel} = \frac{V}{\Delta T} \tag{B.3}$$

Since we need to find a total voltage we will transform the total current into total voltage with ohm's law

$$\frac{V}{R} = \frac{NV_A}{R_A} + \frac{NV_B}{R_B} \tag{B.4}$$

We can define the resistances in terms of their conductivities and the physical parameters of our sample.

$$R_A = \frac{L}{\sigma_A W d_A},\ R_B = \frac{L}{\sigma_B W d_B} \tag{B.5}$$

Our total resistance is the inverse addition of our individual resistances

$$\frac{1}{R} = \frac{N}{R_A} + \frac{N}{R_B} = \frac{N\sigma_A W d_A}{L} + \frac{N\sigma_B W d_B}{L} = \frac{NW(\sigma_A d_A + \sigma_B d_B)}{L} \tag{B.6}$$

Also we can define our voltages in terms of their Seebeck coefficient

$$V_A = S_A \Delta T\ ,\ V_B = S_B \Delta T \tag{B.7}$$

Substituting equations (B.5), (B.6), and (B.7) into equation (B.4) gives us

$$\frac{VNW(\sigma_A d_A + \sigma_B d_B)}{L} = \frac{S_A \Delta T N \sigma_A W d_A}{L} + \frac{S_B \Delta T N \sigma_B W d_B}{L} \tag{B.8}$$

Simplifying this expression,

$$V(\sigma_A d_A + \sigma_B d_B) = S_A \Delta T \sigma_A d_A + S_B \Delta T \sigma_B d_B \tag{B.9}$$

$$V = \frac{S_A \Delta T \sigma_A d_A + S_B \Delta T \sigma_B d_B}{\sigma_A d_A + \sigma_B d_B} \tag{B.10}$$

Substituting equation (B.10) into our equation for the parallel Seebeck coefficient gives

$$S_{\square} = \frac{S_A \Delta T \sigma_A d_A + S_B \Delta T \sigma_B d_B}{\Delta T(\sigma_A d_A + \sigma_B d_B)} \tag{B.11}$$

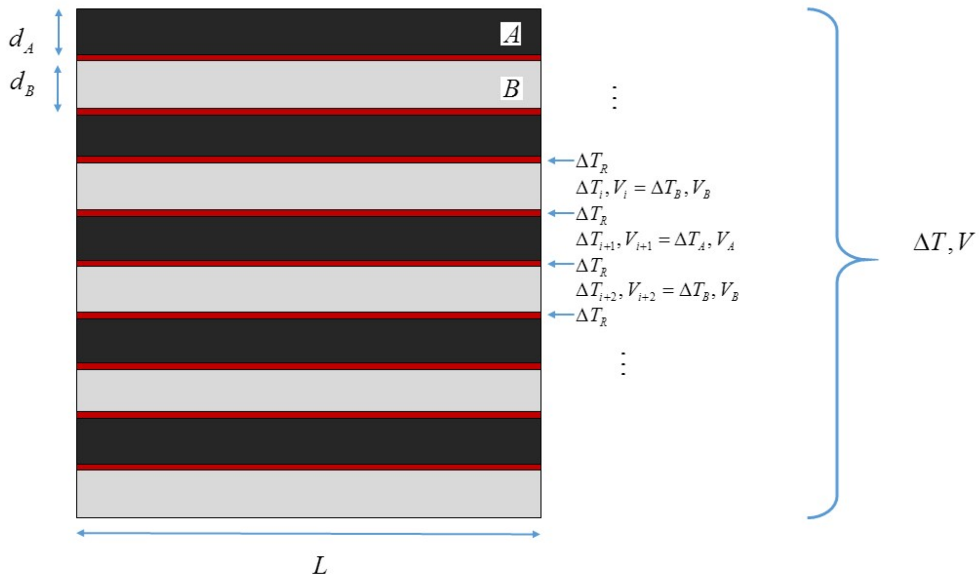
Simplifying it gives us our definition

$$S_{\square} = \frac{S_A \sigma_A d_A + S_B \sigma_B d_B}{\sigma_A d_A + \sigma_B d_B} \tag{B.12}$$

If we want our expression in terms of the relative thickness, $p = \frac{d_B}{d_A}$ then equation (B.12) becomes

$$S_{\square} = \frac{S_A \sigma_A + S_B \sigma_B p}{\sigma_A + \sigma_B p} \tag{B.13}$$

If we should think about an electrical interface resistance included into our $S_{\square}$ will be reduced by the interface resistance, R_{EI}



(Figure B.2)

This interface resistance adds an additional term into our total resistance giving,

$$\frac{1}{R} = \frac{N}{R_A} + \frac{N}{R_B} + \frac{2N}{R_{EI}} \tag{B.14}$$

$$\frac{1}{R} = \frac{N\sigma_A W d_A}{L} + \frac{N\sigma_B W d_B}{L} + \frac{2N}{R_{EI}} = \frac{NW(\sigma_A d_A + \sigma_B d_B + 2L/WR_{EI})}{L} \tag{B.15}$$

Which leads to an adjusted equation (B.10)

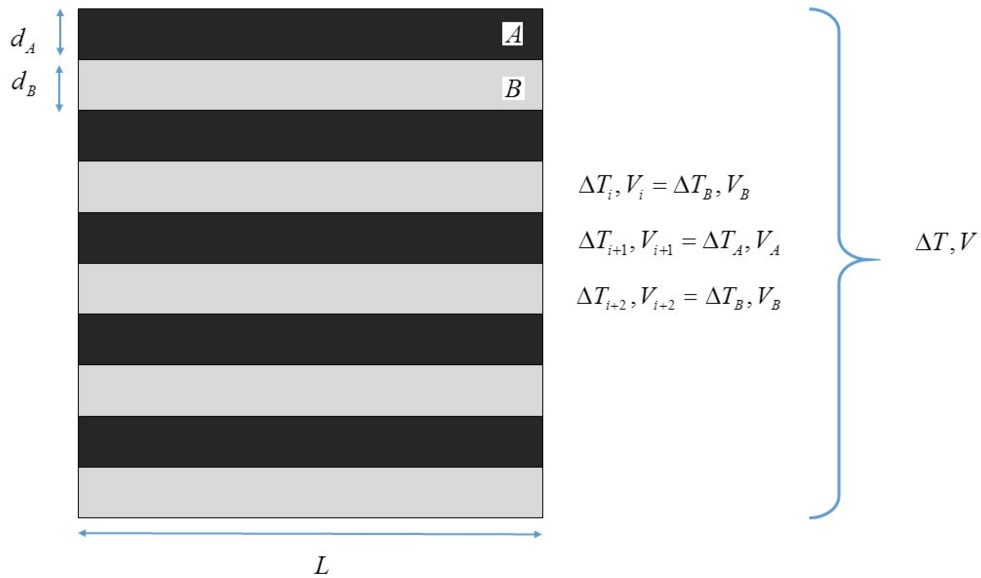
$$S_{\parallel} = \frac{S_A \sigma_A d_A + S_B \sigma_B d_B}{\sigma_A d_A + \sigma_B d_B + 2L/WR_{EI}} \tag{B.16}$$

This electrical interface resistance can be safely neglected if the following condition is met

$$R_{EI} \gg \frac{2L}{W}\left(\frac{1}{\sigma_A d_A + \sigma_B d_B}\right) \tag{B.17}$$

[C] Perpendicular Electrical Conductivity

Assuming that our sample has *N* layers of materials *A* and *B* with thicknesses d_A and d_B. We will also assume that the thickness has a length, *L*, and a width, *W*, that is the same for all layers. (The width is into the page)



(Figure C.1)

The total electrical resistance going through the sample is equal to the sum of the resistances of the layers.

$$R_\perp = \sum_{i=1}^{N} R_i \tag{C.1}$$

Since our sample has alternating *N* layers of materials *A* and *B*,

$$R_\perp = NR_A + NR_B \tag{C.2}$$

Our total electrical resistance can be given as an electrical conductivity. Also substituting in for the length traveled, $l = N(d_A + d_B)$, as well as for the cross sectional area, $A = WL$.

$$R_\perp = \frac{l}{\sigma_\perp A} = \frac{N\left(d_A + d_B\right)}{\sigma_\perp WL} \tag{C.3}$$

The electrical resistances of the materials can be converted to electrical conductivities as well.

$$R_A = \frac{l}{\sigma_A A} = \frac{d_A}{\sigma_A WL} \text{ and } R_B = \frac{l}{\sigma_B A} = \frac{d_B}{\sigma_B WL} \tag{C.4}$$

Substituting equations (C.3) and (C.4) into equation (C.2) we get

$$\frac{N(d_A+d_B)}{\sigma_\perp WL}=\frac{Nd_A}{\sigma_A WL}+\frac{Nd_B}{\sigma_B WL} \tag{C.5}$$

Simplifying (C.5) gives

$$\frac{(d_A+d_B)}{\sigma_\perp}=\frac{d_A}{\sigma_A}+\frac{d_B}{\sigma_B} \tag{C.6}$$

Then getting $\sigma_\perp$ by itself,

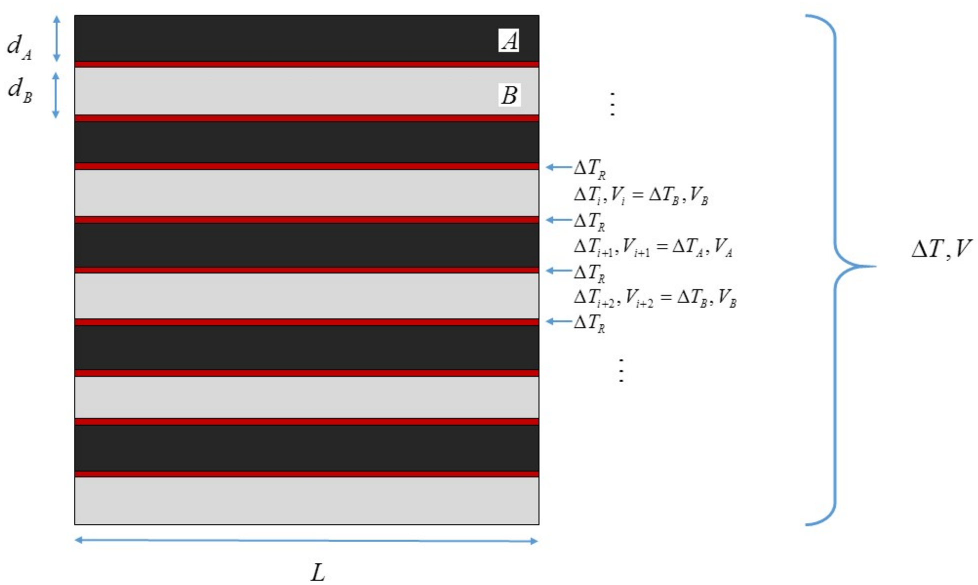
$$\frac{(d_A+d_B)}{\sigma_\perp}=\frac{d_A\sigma_B+d_B\sigma_A}{\sigma_A\sigma_B} \tag{C.7}$$

$$\sigma_\perp=\frac{\sigma_A\sigma_B(d_A+d_B)}{d_B\sigma_A+d_A\sigma_B} \tag{C.8}$$

If we would want to include a term for relative thickness of the layers $p=\frac{d_B}{d_A}$ then (C.8) becomes,

$$\sigma_\perp=\frac{\sigma_A\sigma_B(1+p)}{p\sigma_A+\sigma_B} \tag{C.9}$$

If we should think about an electrical interface resistance included into our $\sigma_\perp$ will be reduced by the interface resistance, R_{EI}



(Figure C.2)

This changes equation (C.2) to

$$R_\perp = NR_A + NR_B + 2NR_{EI} \tag{C.10}$$

Leading to a changed equation (C.5)

$$\frac{N(d_A + d_B)}{\sigma_\perp WL} = \frac{Nd_A}{\sigma_A WL} + \frac{Nd_B}{\sigma_B WL} + 2NR_{EI} \tag{C.11}$$

$$\frac{(d_A + d_B)}{\sigma_\perp} = \frac{d_A}{\sigma_A} + \frac{d_B}{\sigma_B} + 2WLR_{EI} \tag{C.12}$$

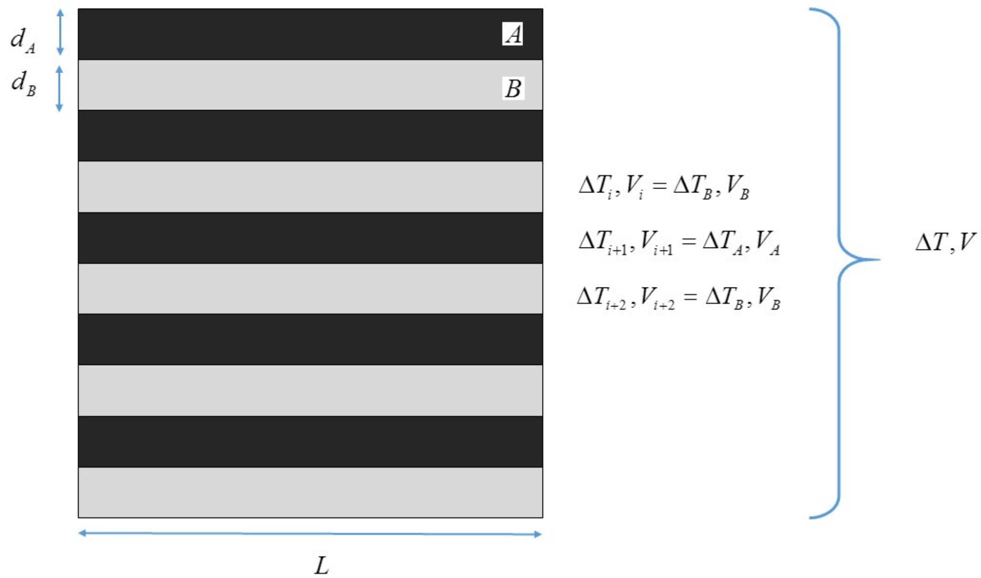
$$\sigma_\perp = \frac{\sigma_A \sigma_B (d_A + d_B)}{d_B \sigma_A + d_A \sigma_B + 2WL\sigma_A \sigma_B R_{EI}} \tag{C.13}$$

If the following condition is met then the electrical interface resistance can be safely neglected

$$R_{EI} \ll \frac{1}{2WL}\left(\frac{d_A}{\sigma_A} + \frac{d_B}{\sigma_B}\right) \tag{C.14}$$

[D] Parallel Electrical Conductivity

Assuming that our sample has *N* layers of materials *A* and *B* with thicknesses d_A and d_B. We will also assume that the thickness has a length, *L*, and a width, *W*, that is the same for all layers. (The width is into the page)



(Figure D.1)

The total electrical resistance moving from one side to the other is the parallel addition of many resistances.

$$R_{\Box} = \left(\sum_{i=1}^{N} \frac{1}{R_i} \right)^{-1} \tag{D.1}$$

Which gives us,

$$\frac{1}{R_{\Box}} = \frac{N}{R_A} + \frac{N}{R_B} \tag{D.2}$$

Defining the electrical resistance in terms of the electrical conduction gives,

$$R_A = \frac{L}{\sigma_A W d_A} \text{ and } R_B = \frac{L}{\sigma_B W d_B} \text{ and } R_{\Box} = \frac{L}{\sigma_{\Box} W N (d_A + d_B)} \tag{D.3}$$

Substituting into equation (D.2) gives

$$\frac{\sigma_{\Box} W N (d_A + d_B)}{L} = \frac{N \sigma_A W d_A}{L} + \frac{N \sigma_B W d_B}{L} \tag{D.4}$$

Simplifying this gives us

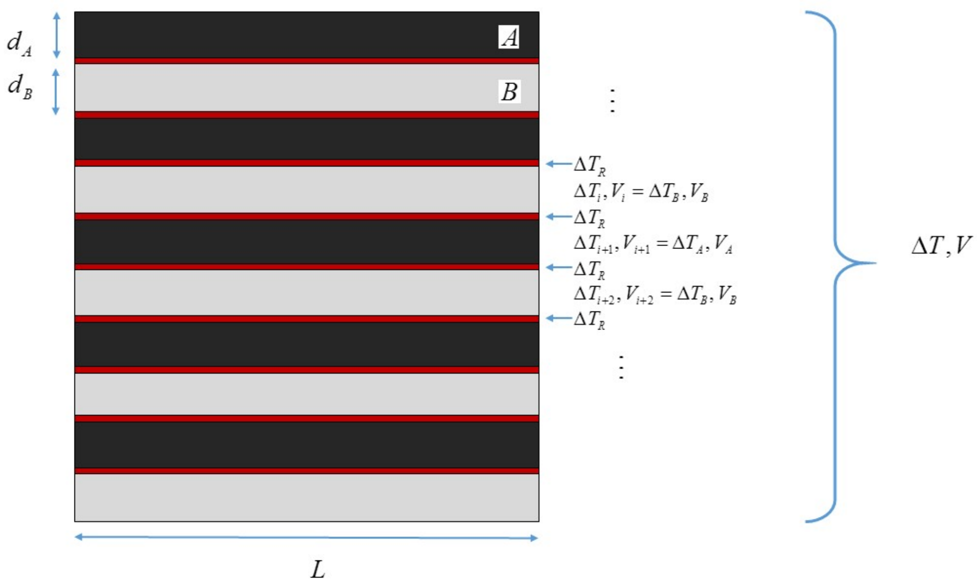
$$\sigma_{\Box}(d_A + d_B) = \sigma_A d_A + \sigma_B d_B \tag{D.5}$$

$$\sigma_{\square} = \frac{\sigma_A d_A + \sigma_B d_B}{d_A + d_B} \tag{D.6}$$

Inserting a term for the relative thickness $p = \frac{d_B}{d_A}$ our equation is modified to

$$\sigma_{\square} = \frac{\sigma_A + \sigma_B p}{1 + p} \tag{D.7}$$

If we should think about an electrical interface resistance included into our $\sigma_{\square}$ will be reduced by the interface resistance, R_{EI}



(Figure D.2)

This additional resistance adds another term into our equation (D.2)

$$\frac{1}{R_{\square}} = \frac{N}{R_A} + \frac{N}{R_B} + \frac{2N}{R_{EI}} \tag{D.7}$$

$$\sigma_{\square}(d_A + d_B) = \sigma_A d_A + \sigma_B d_B + \frac{2L}{WR_{EI}} \tag{D.8}$$

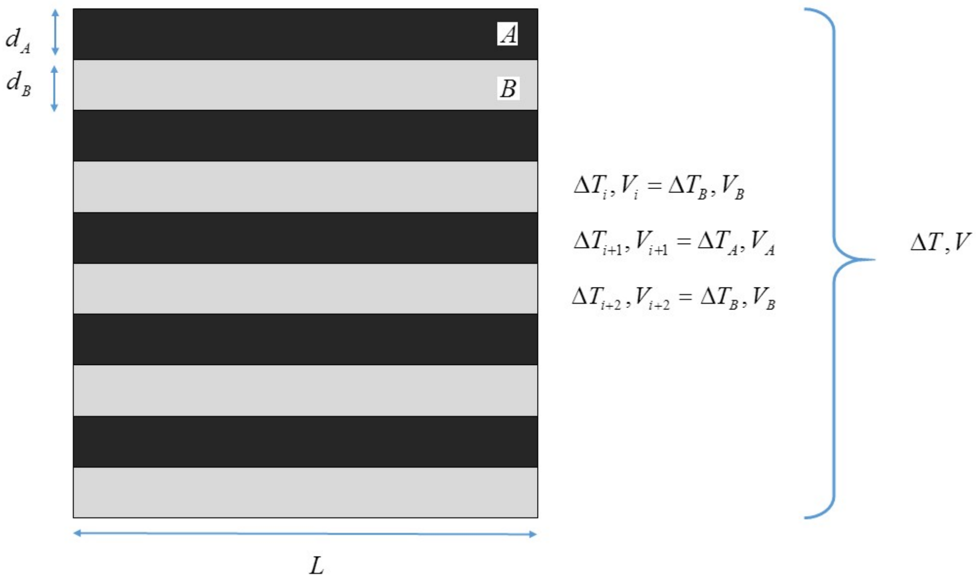
$$\sigma_{\square} = \frac{\sigma_A d_A + \sigma_B d_B + 2L/WR_{EI}}{(d_A + d_B)} \tag{D.9}$$

One could neglect the interface resistance if the following condition is met

$$R_{EI} \square \frac{2L}{W}\left(\frac{1}{\sigma_A d_A + \sigma_B d_B}\right) \tag{D.10}$$

[E] Perpendicular Thermal Conductivity

Assuming that our sample has *N* layers of materials *A* and *B* with thicknesses d_A and d_B. We will also assume that the thickness has a length, *L*, and a width, *W*, that is the same for all layers. (The width is into the page)



(Figure E.1)

The total thermal resistance going through the sample is equal to the sum of the resistances of the layers.

$$R_\perp = \sum_{i=1}^{N} R_i \tag{E.1}$$

Since our sample has alternating *N* layers of materials *A* and *B*,

$$R_\perp = NR_A + NR_B \tag{E.2}$$

Our total thermal resistance can be given as a thermal conductivity. Also substituting in for the length traveled, $N(d_A + d_B)$,

$$R_\perp = \frac{N\left(d_A + d_B\right)}{\kappa_\perp LW} \tag{E.3}$$

The thermal resistances of the materials can be converted to thermal conductivities as well.

$$R_A = \frac{d_A}{\kappa_A LW} \text{ and } R_B = \frac{d_B}{\kappa_B LW} \tag{E.4}$$

Substituting equations (E.3) and (E.4) into equation (E.2) we get,

$$\frac{N(d_A + d_B)}{\kappa_\perp LW} = \frac{Nd_A}{\kappa_A LW} + \frac{Nd_B}{\kappa_B LW} \tag{E.5}$$

Simplifying (E.5) gives,

$$\frac{(d_A + d_B)}{\kappa_\perp} = \frac{d_A}{\kappa_A} + \frac{d_B}{\kappa_B} \tag{E.6}$$

Then getting $\sigma_\perp$ by itself,

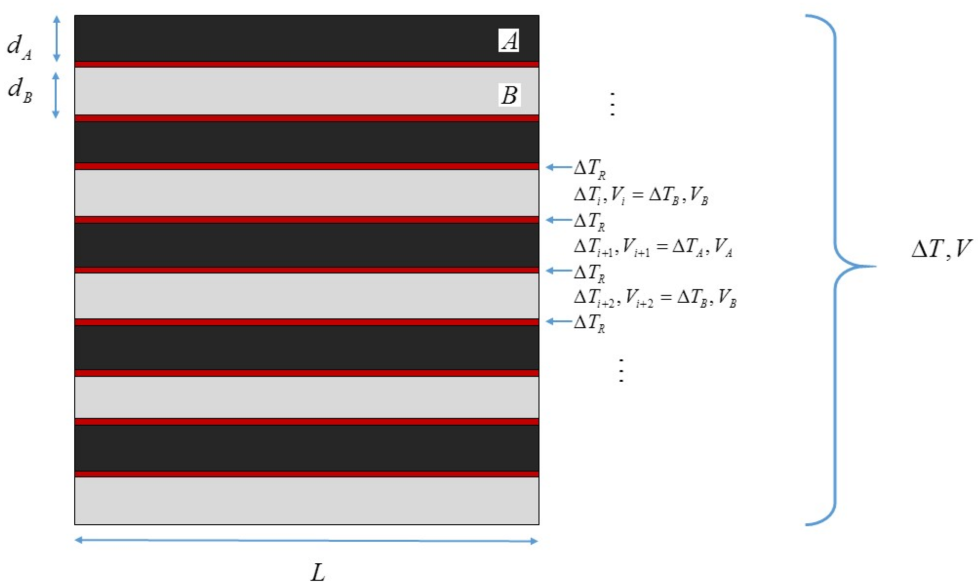
$$\frac{(d_A + d_B)}{\kappa_\perp} = \frac{d_A \kappa_B + d_B \kappa_A}{\kappa_A \kappa_B} \tag{E.7}$$

$$\kappa_\perp = \frac{\kappa_A \kappa_B (d_A + d_B)}{d_B \kappa_A + d_A \kappa_B} \tag{E.8}$$

If we would want to include a term for relative thickness of the layers $p = \frac{d_B}{d_A}$ then (E.8) becomes,

$$\kappa_\perp = \frac{\kappa_A \kappa_B (1 + p)}{p\kappa_A + \kappa_B} \tag{E.9}$$

If we should think about a thermal interface resistance included into our $\kappa_\perp$ will be reduced by the interface resistance, R_{TI}



(Figure E.2)

Adding this interface resistance would change our equation (E.2) to

$$R_\perp = NR_A + NR_B + 2NR_{TI} \tag{E.10}$$

Following the same derivation this leads to

$$\frac{(d_A + d_B)}{\kappa_\perp} = \frac{d_A}{\kappa_A} + \frac{d_B}{\kappa_B} + 2WLR_{TI} \tag{E.11}$$

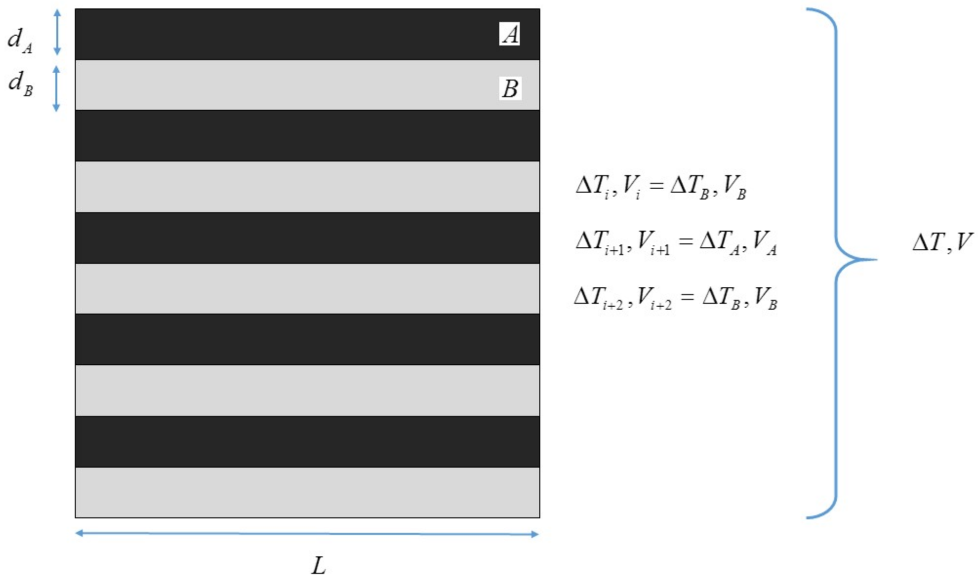
$$\kappa_\perp = \frac{\kappa_A \kappa_B (d_A + d_B)}{d_B \kappa_A + d_A \kappa_B + 2WL\kappa_A \kappa_B R_{TI}} \tag{E.12}$$

This thermal resistance can be ignored if the following condition is met

$$R_{TI} \ll \frac{1}{2WL}\left(\frac{d_A}{\kappa_A} + \frac{d_B}{\kappa_B}\right) \tag{E.13}$$

[F] Parallel Thermal Conductivity

Assuming that our sample has *N* layers of materials *A* and *B* with thicknesses d_A and d_B. We will also assume that the thickness has a length, *L*, and a width, *W*, that is the same for all layers. (The width is into the page)



(Figure F.1)

The total thermal resistance moving from one side to the other is the parallel addition of many resistances.

$$R_{\parallel} = \left(\sum_{i=1}^{N} \frac{1}{R_i} \right)^{-1} \tag{F.1}$$

Which gives us,

$$\frac{1}{R_{\parallel}} = \frac{N}{R_A} + \frac{N}{R_B} \tag{F.2}$$

Defining the thermal resistance in terms of the thermal conduction gives,

$$R_A = \frac{L}{\kappa_A W d_A} \text{ and } R_B = \frac{L}{\kappa_B W d_B} \text{ and } R_{\parallel} = \frac{L}{\kappa_{\parallel} W N (d_A + d_B)} \tag{F.3}$$

Substituting into equation (F.2) gives

$$\frac{\kappa_{\parallel} W N (d_A + d_B)}{L} = \frac{N \kappa_A W d_A}{L} + \frac{N \kappa_B W d_B}{L} \tag{F.4}$$

Simplifying this gives us

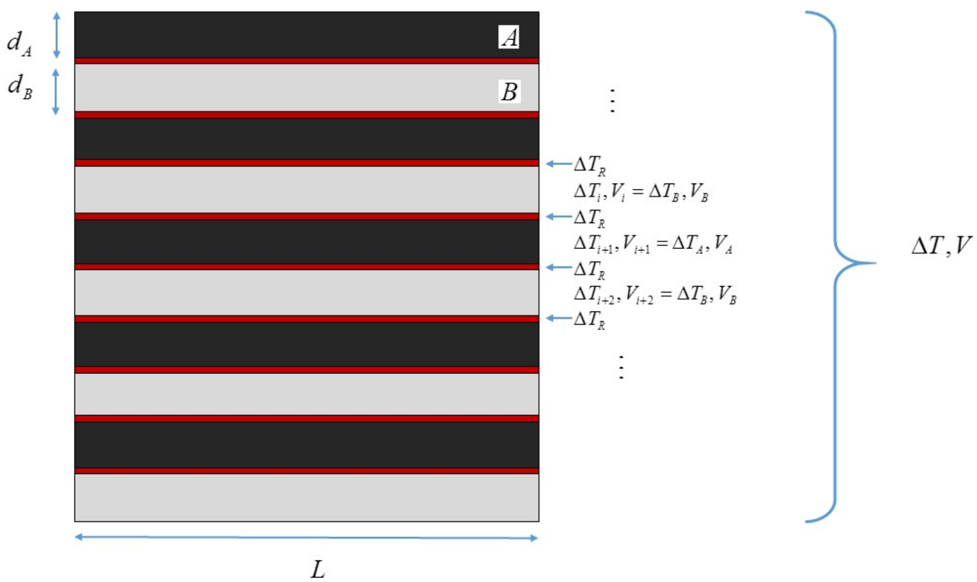
$$\kappa_{\parallel} (d_A + d_B) = \kappa_A d_A + \kappa_B d_B \tag{F.5}$$

$$\kappa_{\parallel} = \frac{\kappa_A d_A + \kappa_B d_B}{d_A + d_B} \tag{F.6}$$

Inserting a term for the relative thickness $p = \frac{d_B}{d_A}$ our equation is modified to

$$\kappa_{\parallel} = \frac{\kappa_A + \kappa_B p}{1 + p} \tag{F.7}$$

If we should think about a thermal interface resistance included into our $\kappa_{\parallel}$ will be reduced by the interface resistance, R_{TI}



(Figure F.2)

We have to adjust equation (F.2) in order to include this term

$$\frac{1}{R_{\parallel}} = \frac{N}{R_A} + \frac{N}{R_B} + \frac{2N}{R_{TI}} \tag{F.8}$$

This will simplify to a similar equation as (F.7) with our additional term

$$\frac{\kappa_{\parallel} WN(d_A + d_B)}{L} = \frac{N\kappa_A W d_A}{L} + \frac{N\kappa_B W d_B}{L} + \frac{2N}{R_{TI}} \tag{F.9}$$

$$\kappa_{\parallel} = \frac{\kappa_A d_A + \kappa_B d_B + {}^{2L}\!/_{WR_{TI}}}{(d_A + d_B)} \tag{F.10}$$

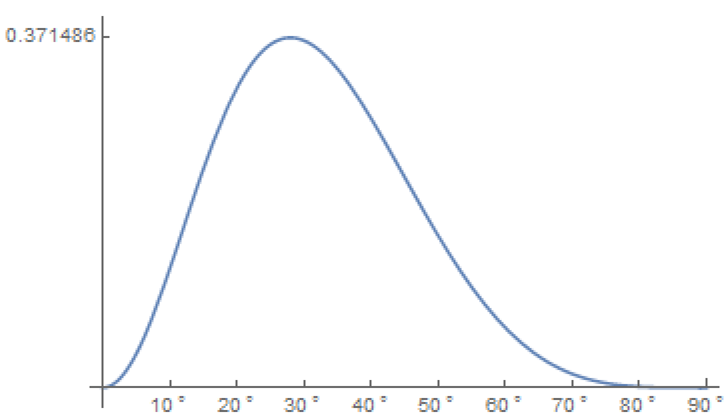
This resistance can be safely ignored if condition (F.11) is met

$$R_{TI} \approx \frac{2L}{W}\left(\frac{1}{\kappa_A d_A + \kappa_B d_B}\right) \tag{F.11}$$

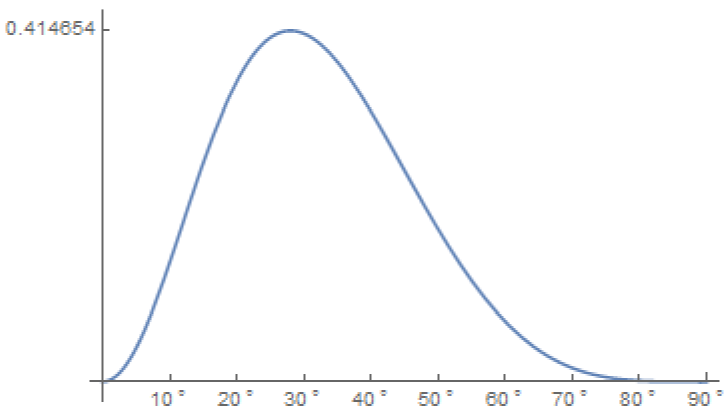
[G] Angular Dependence of the Figure of Merit

This is a Mathematica print-out used to calculate the optimal angle for the figure of merit of both samples. Both CRC handbook values and experimental ZEM values were used.

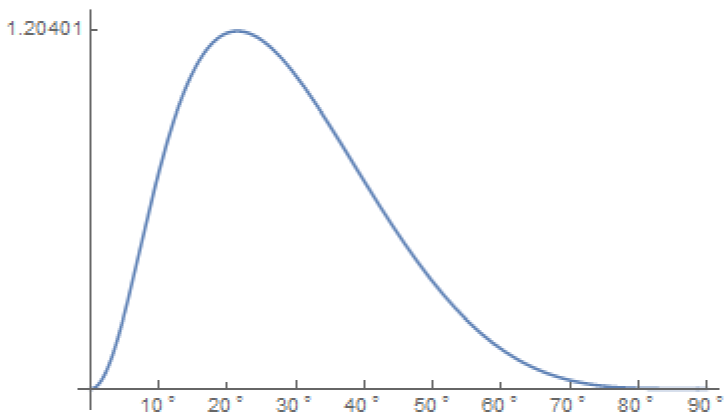
```
Off[Solve::ifun]
Spara := (Sa * σa + ρ * Sb * σb) / (σa + ρ * σb)
Sperp := (Sa * κb + ρ * Sb * κa) / (ρ * κa + κb)
κpara := (κa + ρ * κb) / (1 + ρ)
κperp := (κa * κb * (1 + ρ)) / (ρ * κa + κb)
σpara := (σa + ρ * σb) / (1 + ρ)
σperp := (σa * σb * (1 + ρ)) / (ρ * σa + σb)
Szx := .5 * (Spara - Sperp) * Sin[2 * α]
σxx := σpara * Cos[α] ^ 2 + σperp * Sin[α] ^ 2
κzz := κpara * Sin[α] ^ 2 + κperp * Cos[α] ^ 2
Z := Szx ^ 2 * σxx / κzz

(* Ni Angular Dependance of Z with experimental values *)
Sa := -2.29 * 10 ^ -4
σa := 500.6
κa := 5.65
Sb := -11.5127 * 10 ^ -6
σb := 8.31298 * 10 ^ 6
κb := 90
ρ := 1
Solve[D[Z, α] == 0, α];
ZTnizem = Z * 300;
Plot[Z * 300, {α, 0, π / 2},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {0.3714856742944023`}}]
0.4885058616295843` / π * 180;
α := 27.98932413877697` Degree
Z * 300;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```



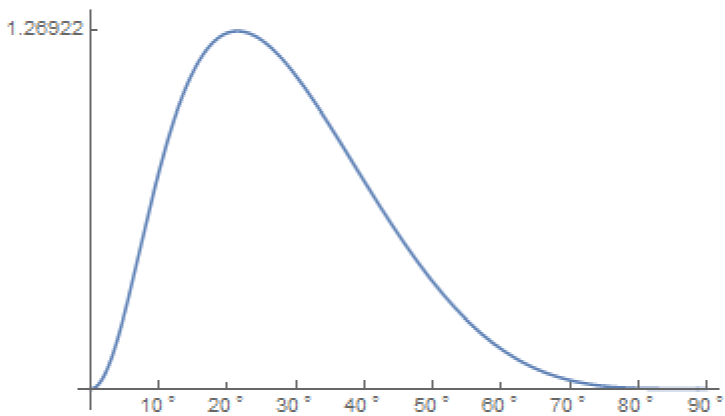
```
(* Ni Angular Dependance of Z with CRC handbook values *)
Sa := -2.29*10^-4
σa := 500.6
κa := 5.65
Sb := -19.5*10^-6
σb := 1*10^7
κb := 90
ρ := 1
Solve[D[Z, α] == 0, α];
ZTnicrc = Z*300;
Plot[Znicrc, {α, 0, π/2},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {0.4146536314169404`}}]
0.4886804863283252`/π*180;
α := 27.999329397013565` Degree
Z*300;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```



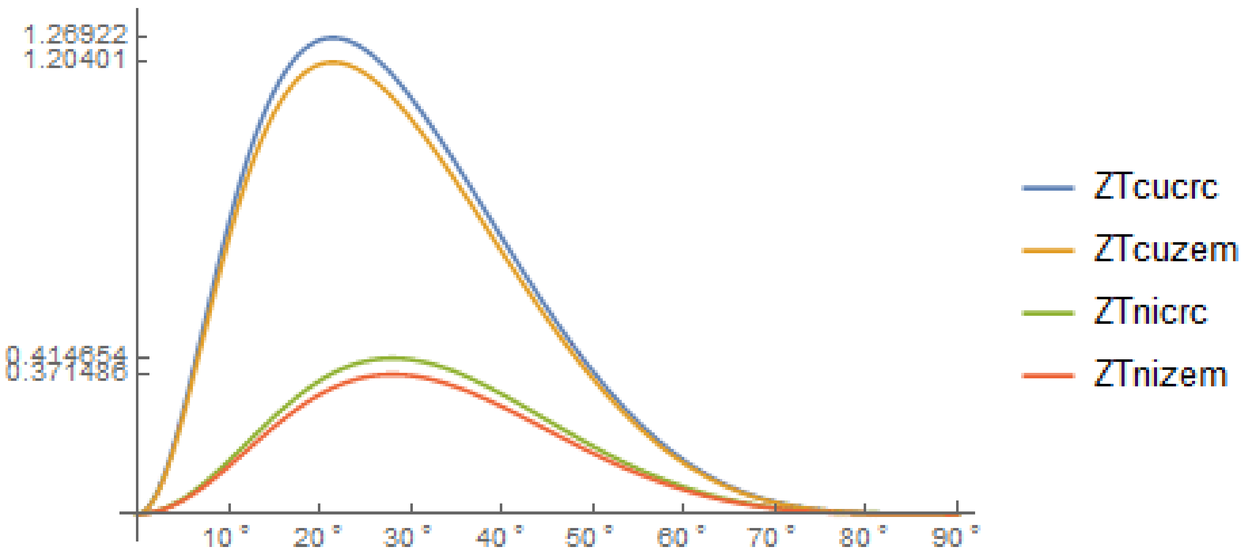
```
(* Cu Angular Dependance of Z with experimenal values *)
Sb := -2.29*10^-4
σb := 500.6
κb := 5.65
Sa := 5.39856*10^-6
σa := 5.40936*10^7
κa := 390
ρ := 1
Solve[D[Z, α] == 0, α];
ZTcuzem = Z*300;
Plot[Z*300, {α, 0 Degree, 90 Degree},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {1.204009528419901`}}]
0.3742963156163024`/π*180;
α := 21.445599172110736` Degree
Z*300;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```



```
(* Cu Angular Dependance of Z with CRC handbook values *)
Sb := -2.29*10^-4
σb := 500.6
κb := 5.65
Sa := 1.83*10^-6
σa := 5.88*10^7
κa := 390
ρ := 1
Solve[D[Z, α] == 0, α];
ZTcucrc = Z*300;
Plot[Z*300, {α, 0 Degree, 90 Degree},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {1.2692177050094084`}}]
0.3742961336501091` / Degree;
α := 21.445588746215844` Degree
Z*300;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```




```
Plot[{ZTcucrc, ZTcuzem, ZTnicrc, ZTnizem}, {α, 0 Degree, 90 Degree},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree},
   {1.2692177050094084`, 1.204009528419901`, 0.4146536314169404`, 0.3714856742944023`}},
 PlotLegends → LineLegend["Expressions"]]
```




```
(* Ni Angular Dependance of Zadj with experimental values *)
Sa := -2.29*10^-4
σa := 500.6
κa := 5.65
Sb := -11.5127*10^-6
σb := 8.31298*10^6
κb := 90
ρ := 1
κpara
Solve[D[Z, α] == 0, α];
α := 0.4885058616295843`;
Z*300
Clear[α]
κparaadj
Solve[D[Zadj, α] == 0, α];
α := 0.48840351781800406`;
Zadj*300
Abs[Z - Zadj]*200/(Z + Zadj) "Percent Difference"
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```

```
47.825

0.371486

47.8816

0.37124

0.0661537 Percent Difference
```

```
(* Ni Angular Dependance of Z with CRC handbook values *)
Sa := -2.29*10^-4
σa := 500.6
κa := 5.65
Sb := -19.5*10^-6
σb := 1*10^7
κb := 90
ρ := 1
κpara
Solve[D[Z, α] == 0, α];
α := 0.48850183103967354`
Z*300
Clear[α]
κparaadj
Solve[D[Zadj, α] == 0, α];
α := 0.4884063586854767`
Zadj*300
Abs[Z - Zadj]*200/(Z + Zadj) "Percent Difference"
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]

47.825

0.414654

47.8778

0.414398

0.0617124 Percent Difference
```

```
(* Cu Angular Dependance of Z with experimenal values *)
Sb := -2.29*10^-4
σb := 500.6
κb := 5.65
Sa := 5.39856*10^-6
σa := 5.40936*10^7
κa := 390
ρ := 1
κpara
Solve[D[Z, α] == 0, α];
α := 0.3742963156163024`
Z*300
Clear[α]
κparaadj
Solve[D[Zadj, α] == 0, α];
α := 0.3741880852458984`
Zadj*300
Abs[Z - Zadj]*200/(Z + Zadj) "Percent Difference"
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
197.825

1.20401

198.1

1.20279

0.101718 Percent Difference
```

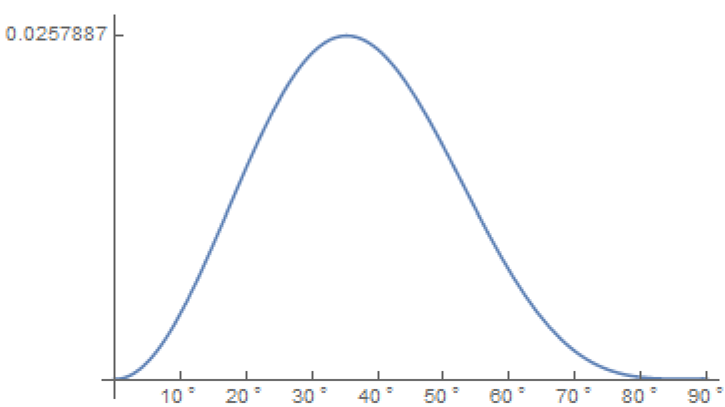
```
(* Cu Angular Dependance of Z with CRC handbook values *)
Sb := -2.29*10^-4
σb := 500.6
κb := 5.65
Sa := 1.83*10^-6
σa := 5.88*10^7
κa := 390
ρ := 1
κpara
Solve[D[Z, α] == 0, α];
α := 0.3742961336501091`
Z*300
Clear[α]
κparaadj
Solve[D[Zadj, α] == 0, α];
α := 0.37419095969200405`
Zadj*300
Abs[Z - Zadj]*200/(Z + Zadj) "Percent Difference"
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
197.825

1.26922

198.092

1.26796

0.0988451 Percent Difference
```

Created with the Wolfram Language

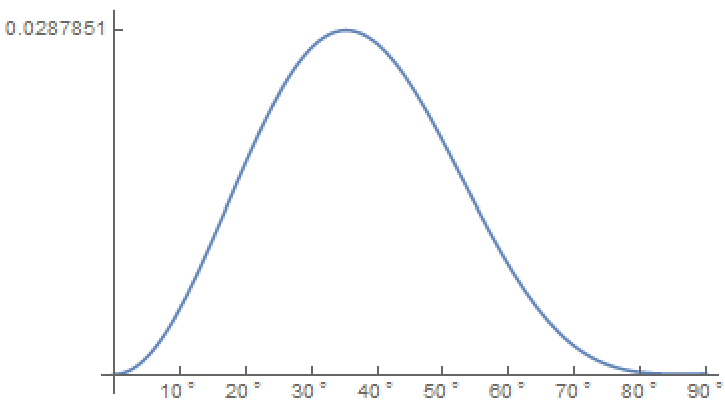
[H] Angular Dependence of the Power Factor

This is a Mathematica print-out used to calculate the optimal angle for the power factor of each sample. Both CRC handbook values and experimental ZEM values were used.

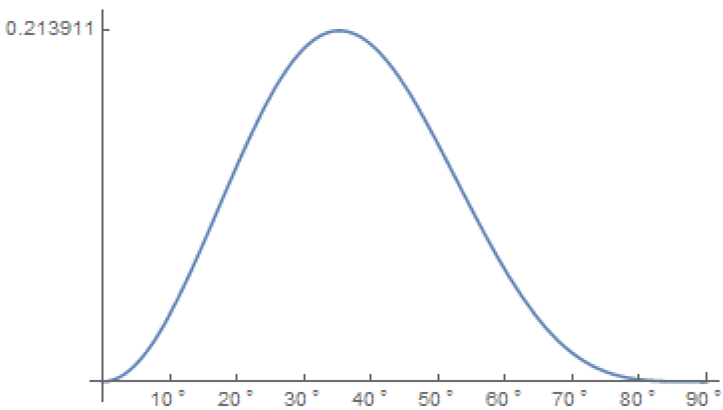
```
Off[Solve::ifun]
Spara := (Sa * σa + ρ * Sb * σb) / (σa + ρ * σb)
Sperp := (Sa * κb + ρ * Sb * κa) / (ρ * κa + κb)
κpara := (κa + ρ * κb) / (1 + ρ)
κperp := (κa * κb * (1 + ρ)) / (ρ * κa + κb)
σpara := (σa + ρ * σb) / (1 + ρ)
σperp := (σa * σb * (1 + ρ)) / (ρ * σa + σb)
Szx := .5 * (Spara - Sperp) * Sin[2 * α]
σxx := σpara * Cos[α] ^ 2 + σperp * Sin[α] ^ 2
κzz := κpara * Sin[α] ^ 2 + κperp * Cos[α] ^ 2
(* Ni Angular Dependance of the power factor with experimental values *)
Sa := -2.29 * 10 ^ -4
σa := 500.6
κa := 5.65
Sb := -11.5127 * 10 ^ -6
σb := 8.31298 * 10 ^ 6
κb := 90
ρ := 1
Solve[D[Szx ^ 2 * σxx, α] == 0, α];
PFnizem = Szx ^ 2 * σxx;
Plot[Szx ^ 2 * σxx, {α, 0, π / 2},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {0.02578865582004254`}}]
0.6155222867839857` / π * 180;
α := 35.266829228963466` Degree
Szx ^ 2 * σxx;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```



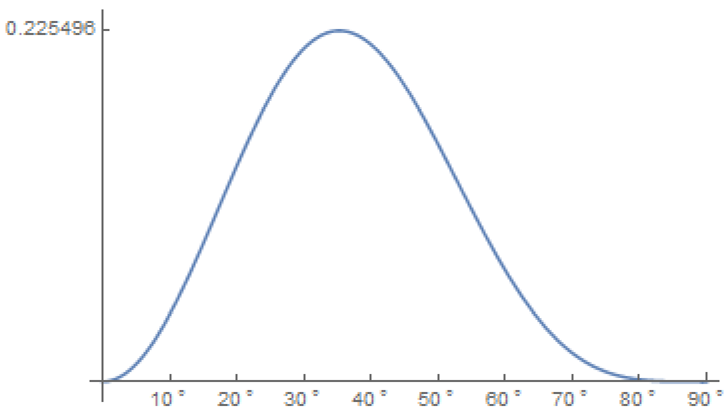
```
(* Ni Angular Dependance of the power factor with CRC handbook values *)
Sa := -2.29*10^-4
σa := 500.6
κa := 5.65
Sb := -19.5*10^-6
σb := 1*10^7
κb := 90
ρ := 1
Solve[D[Szx^2*σxx, α] == 0, α];
PFnicrc = Szx^2*σxx;
Plot[Szx^2*σxx, {α, 0, π/2},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {0.028785141232975712`}}]
0.6155151042206574`/π*180;
α := 35.266417698398676` Degree
Szx^2*σxx;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```



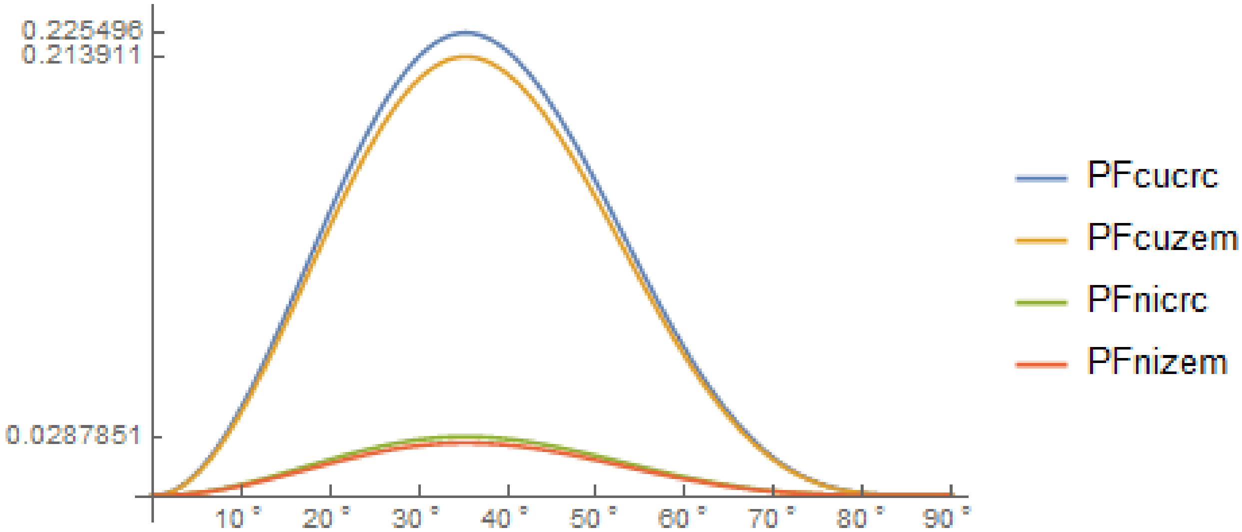
```
(* Cu Angular Dependance of the power factor with experimenal values *)
Sb := -2.29*10^-4
σb := 500.6
κb := 5.65
Sa := 5.39856*10^-6
σa := 5.40936*10^7
κa := 390
ρ := 1
Solve[D[Szx^2*σxx, α] == 0, α];
PFcuzem = Szx^2*σxx;
Plot[Szx^2*σxx, {α, 0, π/2},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {0.21391082953634766`}}]
0.6154862523938558`/π*180;
α := 35.264764610491696` Degree
Szx^2*σxx;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```



```
(* Cu Angular Dependance of the power factor with CRC handbook values *)
Sb := -2.29*10^-4
σb := 500.6
κb := 5.65
Sa := 1.83*10^-6
σa := 5.88*10^7
κa := 390
ρ := 1
Solve[D[Szx^2*σxx, α] == 0, α];
PFcucrc = Szx^2*σxx;
Plot[Szx^2*σxx, {α, 0, π/2},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree}, {0.2254958350832478`}}]
0.6154857286344618`/π*180;
α := 35.26473460128894` Degree
Szx^2*σxx;
Clear[Sa, Sb, σa, σb, κa, κb, α, ρ]
```




```
Plot[{PFcucrc, PFcuzem, PFnicrc, PFnizem}, {α, 0 Degree, 90 Degree},
 Ticks → {{10 Degree, 20 Degree, 30 Degree, 40 Degree, 50 Degree, 60 Degree,
    70 Degree, 80 Degree, 90 Degree},
   {0.2254958350832478`, 0.21391082953634766`, 0.028785141232975712`}},
 PlotLegends → LineLegend["Expressions"]]
```



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[I] Transport Property Calculations

This is a the Mathematica print-out that was used to calculate the theoretical values. The theoretical values are calculated using transport properties that were experimentally found with the ZEM as well as values from the CRC handbook. The equations are from Reitmeir et al [12]

```
(* Transport Property Equation Setup *)
Spara := (Sa * σa + ρ * Sb * σb) / (σa + ρ * σb)
Sperp := (Sa * κb + ρ * Sb * κa) / (ρ * κa + κb)
κpara := (κa + ρ * κb) / (1 + ρ)
κperp := (κa * κb * (1 + ρ)) / (ρ * κa + κb)
σpara := (σa + ρ * σb) / (1 + ρ)
σperp := (σa * σb * (1 + ρ)) / (ρ * σa + σb)
Szx := .5 * (Spara - Sperp) * Sin[2 * α]
σxx := σpara * Cos[α] ^ 2 + σperp * Sin[α] ^ 2
κzz := κpara * Sin[α] ^ 2 + κperp * Cos[α] ^ 2
```

Citation for numbers given

Copper

Cu Seebeck coef. = 5.39856E-6 {V/K} (ZEM data)

1.83E-6 {V/K} (CRC handbook)

Cu electrical conductivity = 5.40936E7 {S/m} (ZEM data)

5.88E7 {S/m} (CRC handbook)

Cu thermal conductivity = 390 {W/m*K} (CRC handbook)

Magnesium Silicide

Mg2Si Seebeck coef. = -2.27351E-4 {V/K} (ZEM data)

Mg2Si electrical conductivity = 467.14 {S/m} (ZEM data)

Mg2si thermal conductivity = 5.65 {W/m*K} (Fu, Zou, Longtin, Nie, Gambino, "Thermoelectric properties of magnesium silicide fabricated using vacuum plasma thermal spray", *Journal of Applied Physics.* Oct2013, Vol. 114 Issue 14) [note: I took the hotpress value, which should be the most accurate for the SPS method]

Nickel

Ni Seebeck coef. = -11.5127E-6 {V/K} (ZEM data)

-19.5E-6 {V/K} (CRC handbook)

Ni electrical conductivity = 8.31298E6 {S/m} (ZEM data)

1E7 {S/m} (CRC handbook)

Ni thermal conductivity = 90 {W/m*K} (CRC handbook)

```
(* Cooper Transport Properties *)
Scu2 := 1.83 * 10 ^ -6
Scu := 5.39856 * 10 ^ -6
σcu2 := 5.88 * 10 ^ 7
σcu := 5.40936 * 10 ^ 7
κcu := 390
(* Magnesium Silicide Transport Properties *)
Smg2si := -2.27351 * 10 ^ -4
σmg2si := 467.14
κmg2si := 5.65
(* Nickle Transport Properites *)
Sni2 := -19.5 * 10 ^ -6
Sni := -11.5127 * 10 ^ -6
σni2 := 1 * 10 ^ 7
σni := 8.31298 * 10 ^ 6
κni := 90

(* Ni/Mg2Si stack theoretical with experimental values*)
Sa := Sni
κa := κni
σa := σni
Sb := Smg2si
κb := κmg2si
σb := σmg2si
ρ := 1
α := 35 Degree
Sperp
σperp
Spara
σpara
Szx
σxx
Szx ^ 2 * σxx
Clear[Sa, Sb, σb, σa, κa, κb, α, ρ]

-0.000214602

934.228

-0.0000115248

4.15672 × 10^6

0.0000954148

2.78951 × 10^6

0.0253957
```

```
(* Ni/Mg2Si stack theoretical with CRC handbook values *)
Sa := Sni2
κa := κni
σa := σni2
Sb := Smg2si
κb := κmg2si
σb := σmg2si
ρ := 1
α := 35 Degree
Sperp
σperp
Spara
σpara
Szx
σxx
Szx^2*σxx
Clear[Sa, Sb, σb, σa, κa, κb, α, ρ]
```

-0.000215073

934.236

-0.0000195097

5.00023×10^{6}

0.0000918849

3.35551×10^{6}

0.02833

```
(* Cu/Mg2Si stack theoretical with experimental values *)
Sa := Scu
κa := κcu
σa := σcu
Sb := Smg2si
κb := κmg2si
σb := σmg2si
ρ := 1
α := 35 Degree
Sperp
σperp
Spara
σpara
Szx
σxx
Szx^2*σxx
Clear[Sa, Sb, σb, σa, κa, κb, α, ρ]
```

-0.000224027

934.272

5.39655×10^{-6}

2.7047×10^{7}

0.000107794

1.81491×10^{7}

0.210885

```
(* Cu/Mg2Si stack theoretical with CRC handbook values *)
Sa := Scu2
κa := κcu
σa := σcu2
Sb := Smg2si
κb := κmg2si
σb := σmg2si
ρ := 1
α := 35 Degree
Sperp
σperp
Spara
σpara
Szx
σxx
Szx ^ 2 * σxx
Clear[Sa, Sb, σb, σa, κa, κb, α, ρ]
```

-0.000224078

934.273

1.82818×10^{-6}

2.94002×10^{7}

0.000106141

1.97282×10^{7}

0.222257

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[J] Interface Resistances

This Mathematica printout is the program used to solve for the value of the interface resistance for both samples. Both CRC and ZEM values were used.

```
(* Transport Property Equation Setup *)
Sperp := (Sa * κb * da + db * Sb * κa) / (db * κa + da * κb + 2 * κa * κb * RT)
Spara := (Sa * σa * da + db * Sb * σb) / (σa * da + db * σb + (2 * L / W / RE))
σperp := (σa * σb * (da + db)) / (db * σa + da * σb + 2 * A * σa * σb * RE)
σpara := (σa * da + db * σb + 2 * L / W / RE) / (da + db)
EqTerm1 := .5 * (da / κa + db / κb)
EqTerm2 := 2 * L / W * (1 / (σa * da + σb * db))
EqTerm3 := .5 * (da / σa + db / σb) / A
EqTerm4 := 2 * L / W * (1 / (σa * da + σb * db))
(* Cooper Transport Properties (2 means crc) *)
Scu2 := 1.83 * 10 ^ -6
Scu := 5.39856 * 10 ^ -6
σcu2 := 5.88 * 10 ^ 7
σcu := 5.40936 * 10 ^ 7
κcu := 390
(* Magnesium Silicide Transport Properties *)
Smg2si := -2.27351 * 10 ^ -4
σmg2si := 467.14
κmg2si := 5.65
(* Nickle Transport Properites (2 means crc) *)
Sni2 := -19.5 * 10 ^ -6
Sni := -11.5127 * 10 ^ -6
σni2 := 1 * 10 ^ 7
σni := 8.31298 * 10 ^ 6
κni := 90
```

```
(* Ni/Mg2Si stack theoretical with experimental values
 approximate thickness is be set at .5 mm *)
Sa := Sni
κa := κni
σa := σni
Sb := Smg2si
κb := κmg2si
σb := σmg2si
da := .0005
db := .0005
L := 5.04*10^-3
W := 8.83*10^-3
A := 7.46*10^-5
EqTerm1
NSolve[Sperp == -8.7803*10^-5, RT]
EqTerm2
NSolve[Spara == -6.994*10^-6, RE]
EqTerm3
NSolve[σperp == 877.817, RE]
EqTerm4
NSolve[σpara == 2.37288*10^7, RE]
Clear[Sa, Sb, σa, σb, κa, κb, da, db, L, W, R, A]

0.0000470256

{{RT → 0.0000679108}}

0.00027463

{{RE → 0.000423933}}

0.00717428

{{RE → 0.000461036}}

0.00027463

{{RE → 0.0000583261}}
```

```
(* Ni/Mg2Si stack theoretical with CRC handbook values
 approximate thickness is set at .5 mm *)
Sa := Sni2
κa := κni
σa := σni2
Sb := Smg2si
κb := κmg2si
σb := σmg2si
da := .0005
db := .0005
L := 5.04*10^-3
W := 8.83*10^-3
A := 7.46*10^-5
EqTerm1
NSolve[Sperp == -8.7803*10^-5, RT]
EqTerm2
NSolve[Spara == -6.994*10^-6, RE]
EqTerm3
NSolve[σperp == 877.817, RE]
EqTerm4
NSolve[σpara == 2.37288*10^7, RE]
Clear[Sa, Sb, σa, σb, κa, κb, da, db, L, W, R, A]

0.0000470256

{{RT → 0.0000681635}}

0.000228302

{{RE → 0.000127579}}

0.00717422

{{RE → 0.000461104}}

0.000228302

{{RE → 0.000060953}}
```

```
(* Cu/Mg2Si stack theoretical with experimental values
 approximate thickness is set at .5 mm *)
Sa := Scu
κa := κni
σa := σcu
Sb := Smg2si
κb := κmg2si
σb := σmg2si
da := .0005
db := .0005
L := 4.61*10^-3
W := 9.59*10^-3
A := 7.55*10^-5
EqTerm1
NSolve[Sperp == -8.09*10^-5, RT]
EqTerm2
NSolve[Spara == -6.9037*10^-7, RE]
EqTerm3
NSolve[σperp == 5.28888, RE]
EqTerm4
NSolve[σpara == 2.36091*10^7, RE]
Clear[Sa, Sb, σa, σb, κa, κb, da, db, L, W, R, A]

0.0000470256

{{RT → 0.0000771374}}

0.0000355462

{{RE → -4.0316×10^-6}}

0.00708843

{{RE → 1.24507}}

0.0000355462

{{RE → -0.00027965}}
```

```
(* Cu/Mg2Si stack theoretical with CRC handbook values
 approximate thickness i set at .5 mm *)
Sa := Scu2
κa := κni
σa := σcu2
Sb := Smg2si
κb := κmg2si
σb := σmg2si
da := .0005
db := .0005
L := 4.61*10^-3
W := 9.59*10^-3
A := 7.55*10^-5
EqTerm1
NSolve[Sperp == -8.09*10^-5, RT]
EqTerm2
NSolve[Spara == -6.9037*10^-7, RE]
EqTerm3
NSolve[σperp == 5.28888, RE]
EqTerm4
NSolve[σpara == 2.36091*10^7, RE]
Clear[Sa, Sb, σa, σb, κa, κb, da, db, L, W, R, A]

0.0000470256

{{RT → 0.0000772599}}

0.000032701

{{RE → -8.96382×10^-6}}

0.00708842

{{RE → 1.24507}}

0.000032701

{{RE → -0.000166016}}
```

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[K] Experimental Comparison

This Wolfram Mathematica printout shows the calculation of the transverse Seebeck coefficient and transverse electrical conductivity. It also shows the comparison of the experimental values with these calculated values from previous experiments.

```
α := 35 Degree
Szx := .5 * (Spara - Sperp) * Sin[2 * α]
σxx := σpara * Cos[α] ^ 2 + σperp * Sin[α] ^ 2

(* Ni values *)
Sperp := -8.7803 * 10 ^ -5
Spara := -6.994 * 10 ^ -6
σperp := 877.817
σpara := 2.37288 * 10 ^ 7
expSzx := -2.3242 * 10 ^ -5
expσxx := 56 429
Szx "Szx"
Szx / expSzx
σxx "σxx"
σxx / expσxx
Clear[Sperp, Spara, σperp, σpara, exp1Szx, exp2Szx, exp1σxx, exp2σxx]

0.0000379678 Szx

-1.63359

1.59226 × 10^7 σxx

282.17

(* Ni values *)
Sperp := -8.09 * 10 ^ -5
Spara := -6.9037 * 10 ^ -6
σperp := 5.28888
σpara := 2.36091 * 10 ^ 7
expSzx := -4.1722 * 10 ^ -6
expσxx := 54 688
Szx "Szx"
Szx / expSzx
σxx "σxx"
σxx / expσxx
Clear[Sperp, Spara, σperp, σpara, exp1Szx, exp2Szx, exp1σxx, exp2σxx]

0.0000347669 Szx

-8.33299

1.58419 × 10^7 σxx
```

```
289.679
```

Created with the Wolfram Language

[L] Ni/Mg_2Si stack data

Current (mA)	Voltage (V)	Current (A)		
1	0.000122	0.001		
2	0.000245	0.002		
3	0.000368	0.003		
4	0.000491	0.004		
5	0.000613	0.005		
6	0.000736	0.006		
7	0.000859	0.007		
8	0.000982	0.008		
9	0.00111	0.009		
10	0.00122	0.01		
10	0.00123	0.01		
20	0.00246	0.02		
30	0.0037	0.03		
40	0.00493	0.04		
50	0.00616	0.05		
60	0.00739	0.06		
70	0.00862	0.07		
80	0.00985	0.08		
90	0.0111	0.09		
100	0.0123	0.1		
Length	Resistance (Ohms)	R-Values	Conductivities (S/m)	
0.00805867	0.12318	1	876.8410713	all data
Radius	0.12277	0.99994	879.7693506	1 - 10 mA
0.00487333	0.12318	1	876.8410713	10 - 100 mA
Area			**877.8171644**	(average)
7.4611E-05				

Table L.1.Perpendicular Conductivity Data and Calculations. The conductivities were attained by dividing the length by the resistance and the area. Used three different ranges for the slopes

Voltage (V)	Top Temp (C)	Bottom Temp (C)	Delta T (C or K)	Seebeck Voltage (μV)
-0.000015899	22.96045	23.0679	-0.10745	15.899
-9.13413E-06	22.9448	23.0834	-0.1386	9.13413
-6.93464E-06	22.9925	23.0837	-0.0912	6.93464
3.03903E-05	23.506	23.1139	0.3921	-30.3903
3.87452E-05	23.6467	23.1427	0.504	-38.7452

Table continued on next page

4.46068E-05	23.7625	23.1641	0.5984	-44.6068
9.04052E-05	24.388	23.2653	1.1227	-90.4052
9.88659E-05	24.5455	23.2903	1.2552	-98.8659
0.000103215	24.6322	23.3078	1.3244	-103.215
0.000180364	25.7758	23.5278	2.248	-180.364
0.000185477	25.8673	23.5624	2.3049	-185.477
0.000189144	25.9184	23.584	2.3344	-189.144
0.000298718	27.6387	23.9202	3.7185	-298.718
0.000302149	27.7335	23.9511	3.7824	-302.149
0.000302093	27.7118	23.9687	3.7431	-302.093
0.000450568	29.9721	24.4597	5.5124	-450.568
0.000443037	29.9243	24.4447	5.4796	-443.037
0.000437557	29.7605	24.4435	5.317	-437.557
0.000569447	31.7298	24.7932	6.9366	-569.447
0.000575451	31.8697	24.8432	7.0265	-575.451
0.000581395	31.8815	24.8799	7.0016	-581.395
0.000756578	34.4797	25.4189	9.0608	-756.578
0.000758204	34.5252	25.4569	9.0683	-758.204
0.000762718	34.7097	25.4766	9.2331	-762.718
0.000938625	37.1936	26.0296	11.164	-938.625
0.000942096	37.1527	26.0705	11.0822	-942.096
0.000945446	37.2466	26.0964	11.1502	-945.446
0.00118631	41.056	26.8199	14.2361	-1186.31
0.00118282	40.7624	26.8638	13.8986	-1182.82
0.00118741	40.8402	26.9022	13.938	-1187.41
0.00142335	44.1584	27.6464	16.512	-1423.35
0.00146579	44.3054	27.73	16.5754	-1465.79
0.00143752	44.727	27.7492	16.9778	-1437.52
0.00166195	47.4327	28.4525	18.9802	-1661.95
0.00167489	47.8907	28.5139	19.3768	-1674.89
0.00168737	47.9074	28.5666	19.3408	-1687.37
0.00197529	51.8317	29.4111	22.4206	-1975.29
0.00201335	52.8061	29.5028	23.3033	-2013.35
0.00203837	53.0335	29.6296	23.4039	-2038.37
0.00220023	54.6402	30.2129	24.4273	-2200.23
0.00219911	55.4575	30.2129	25.2446	-2199.11
0.00221607	55.9607	30.2781	25.6826	-2216.07

Table L.2 Perpendicular Seebeck Coefficient Data. The Seebeck voltage is the negative measured voltage multiplied by 1×10^6 to obtain microvolts per kelvin.

Current (mA)	Current (A)	Voltage (V)	Widths (m)	Resistance (ohm)	R-Values
1	0.001	-1.28106E-07	0.00864	3.6442E-06	0.95714
2	0.002	-1.41485E-07	0.009769	9.1788E-06	0.54541
3	0.003	-1.0753E-07	0.00808	1.5163E-06	0.82604
4	0.004	-6.53556E-08	Height (m)	2.9292E-06	0.9593
5	0.005	-4.11791E-08	0.008042	2.1251E-06	0.8597
6	0.006	-7.06955E-08	Length (m)		
7	0.007	-1.02851E-07	0.005042		
8	0.008	-4.41199E-08	Average Area (m^2)	Conductivity (S/m)	
9	0.009	-7.26162E-08	7.48404E-05	1.849E+07	all data
10	0.01	-3.28422E-08	Area (m^2)	7.340E+06	1 - 10 mA
20	0.02	4.50852E-08	6.94829E-05	4.443E+07	10 - 120 mA
30	0.03	-2.0125E-08	7.85623E-05	2.300E+07	130 - 250 mA
40	0.04	2.13871E-08	6.49794E-05	3.170E+07	1 - 120 mA
50	0.05	3.12856E-08	Position (m)	2.499E+07	
60	0.06	5.99609E-08	0		
70	0.07	8.80367E-08	0.002521		
80	0.08	1.30509E-07	0.005042		
90	0.09	1.09092E-07			
100	0.1	1.3003E-07			
110	0.11	1.42447E-07			
120	0.12	1.1671E-07			
130	0.13	4.04151E-07			
140	0.14	4.43325E-07			
150	0.15	4.6826E-07			
160	0.16	5.31775E-07			
170	0.17	5.40568E-07			
180	0.18	5.90779E-07			
190	0.19	6.20354E-07			
200	0.2	6.63487E-07			
210	0.21	6.80944E-07			
220	0.22	6.99781E-07			
230	0.23	7.39553E-07			
240	0.24	7.47471E-07			
250	0.25	7.15436E-07			

Table L.3. Parallel Conductivity Data and Calculations. The conductivities were attained by dividing the length by the resistance and the area. Used three different ranges for the slopes

Voltage (V)	Top Temp (C)	Bottom Temp (C)	Delta T (C or K)	Seebeck Voltage (μV)
1.19099E-06	23.2285	23.0269	0.2016	-1.19099
1.24348E-06	23.2257	23.0226	0.2031	-1.24348
1.28529E-06	23.2274	23.0244	0.203	-1.28529
3.63437E-06	23.5657	23.0489	0.5168	-3.63437
3.74391E-06	23.582	23.0517	0.5303	-3.74391
3.79832E-06	23.5908	23.0523	0.5385	-3.79832
7.43711E-06	24.1613	23.1245	1.0368	-7.43711
7.67144E-06	24.1974	23.1318	1.0656	-7.67144
7.74576E-06	24.2098	23.1388	1.071	-7.74576
1.38344E-05	25.1988	23.2825	1.9163	-13.8344
1.39126E-05	25.2113	23.2852	1.9261	-13.9126
1.39668E-05	25.2227	23.2919	1.9308	-13.9668
0.000021569	26.454	23.4662	2.9878	-21.569
2.16855E-05	26.4763	23.4764	2.9999	-21.6855
2.16809E-05	26.4753	23.4807	2.9946	-21.6809
3.02593E-05	27.8491	23.6927	4.1564	-30.2593
3.02032E-05	27.8637	23.7028	4.1609	-30.2032
3.04043E-05	27.8951	23.7105	4.1846	-30.4043
4.13291E-05	29.6128	24.0114	5.6014	-41.3291
4.09207E-05	29.6139	24.0183	5.5956	-40.9207
4.08493E-05	29.5781	24.0245	5.5536	-40.8493
5.28359E-05	31.4667	24.356	7.1107	-52.8359
5.19368E-05	31.3116	24.3571	6.9545	-51.9368
5.19024E-05	31.26	24.3594	6.9006	-51.9024
6.41225E-05	33.1745	24.6958	8.4787	-64.1225
6.46118E-05	33.2493	24.7199	8.5294	-64.6118
6.54623E-05	33.3883	24.755	8.6333	-65.4623
8.05717E-05	35.6508	25.1353	10.5155	-80.5717
8.09878E-05	35.8438	25.1781	10.6657	-80.9878
8.10545E-05	35.7981	25.1919	10.6062	-81.0545
0.000095405	37.9664	25.5221	12.4443	-95.405
0.00009645	38.1045	25.5558	12.5487	-96.45
9.75164E-05	38.2773	25.5915	12.6858	-97.5164
0.000115312	40.8981	25.9815	14.9166	-115.312
0.000116594	41.2058	26.0418	15.164	-116.594
0.000116808	41.2035	26.076	15.1275	-116.808
0.000136203	44.1766	26.4893	17.6873	-136.203

Table continued on next page

0.000138296	44.4169	26.5437	17.8732	-138.296
0.000139806	44.7588	26.6015	18.1573	-139.806
0.000161662	48.6793	27.3471	21.3322	-161.662
0.000162841	48.8661	27.3899	21.4762	-162.841
0.000163043	49.02	27.4217	21.5983	-163.043
0.000188653	52.9563	27.9669	24.9894	-188.653
0.000191589	53.2743	28.0319	25.2424	-191.589
0.00019261	53.5078	28.0844	25.4234	-192.61
0.00021777	57.7447	28.685	29.0597	-217.77
0.000217623	57.9303	28.736	29.1943	-217.623
0.000218711	57.9919	28.7822	29.2097	-218.711
0.000244015	62.1592	29.4035	32.7557	-244.015
0.000243114	62.4191	29.4556	32.9635	-243.114
0.000243666	62.4919	29.51	32.9819	-243.666
0.000266511	66.3704	30.0233	36.3471	-266.511
0.000266759	66.5913	30.1016	36.4897	-266.759
0.000269787	67.1436	30.1804	36.9632	-269.787
0.000304154	73.6846	31.1795	42.5051	-304.154
0.000305836	74.0887	31.282	42.8067	-305.836
0.00030524	74.1797	31.3537	42.826	-305.24
0.000335446	80.2387	32.1774	48.0613	-335.446
0.000334115	80.7508	32.2226	48.5282	-334.115
0.000335525	80.9606	32.283	48.6776	-335.525
0.000345678	83.8844	32.717	51.1674	-345.678
0.000341881	83.8995	32.757	51.1425	-341.881
0.000334856	83.2086	32.6952	50.5134	-334.856

Table L.4. Perpendicular Seebeck Coefficient Data. The Seebeck voltage is the negative measured voltage multiplied by 1×10^6 to obtain microvolts per kelvin.

With plating all around			**With plating only on the ends**		
Current (mA)	Current (A)	Voltage (V)	Current (mA)	Current (A)	Voltage (V)
1	0.001	9.91192E-07	1	0.001	7.68853E-06
2	0.002	1.80292E-06	2	0.002	1.51253E-05
3	0.003	2.58322E-06	3	0.003	2.24075E-05
4	0.004	3.37612E-06	4	0.004	2.98171E-05
5	0.005	4.19612E-06	5	0.005	0.000037208
6	0.006	4.97869E-06	6	0.006	4.46253E-05
7	0.007	5.79372E-06	7	0.007	5.17028E-05
8	0.008	6.60041E-06	8	0.008	5.91426E-05
9	0.009	7.39769E-06	9	0.009	0.000066708
10	0.01	8.20389E-06	10	0.01	7.40678E-05
20	0.02	0.000016196	20	0.02	0.000147631

30	0.03	0.000024208	30	0.03	0.000221058
40	0.04	3.21738E-05	40	0.04	0.000294787
50	0.05	4.01808E-05	50	0.05	0.000368498
60	0.06	0.000048172	60	0.06	0.000442069
70	0.07	5.62005E-05	70	0.07	0.000515684
80	0.08	6.41752E-05	80	0.08	0.000589374
90	0.09	7.22141E-05	90	0.09	0.000663049
100	0.1	8.01851E-05	100	0.1	0.000736599

Resistances (ohm)	R-values	conductivity (S/m)
0.00079997	1	**519349.6057**
0.0073626	1	**56428.99303**
height (m)	length (m)	
0.003476	0.007163	
width (m)	area (m)	
0.00496	1.724E-05	

Table L.5. Transverse Conductivity data. The conductivities were obtained by dividing the length by the resistance and the area. The top conductivity is the totally plated value. The bottom conductivity is the sample which was only plated on the ends hence the value that has been used in the thesis.

Voltage, all plated (V)	Top Temp (C)	Bottom Temp (C)	Delta T(K)	Seebeck Voltage (µV)
5.31969E-07	23.257	23.2106	0.0464	-0.531969
5.77321E-07	23.286	23.1808	0.1052	-0.577321
6.65747E-07	23.3179	23.1744	0.1435	-0.665747
1.68367E-06	24.0087	23.3536	0.6551	-1.68367
1.77689E-06	24.0657	23.3138	0.7519	-1.77689
1.76807E-06	24.0566	23.3305	0.7261	-1.76807
3.26447E-06	24.994	23.5596	1.4344	-3.26447
3.52363E-06	25.1843	23.6074	1.5769	-3.52363
3.61613E-06	25.2575	23.634	1.6235	-3.61613
6.16164E-06	26.8742	24.0874	2.7868	-6.16164
6.1449E-06	26.9251	24.0159	2.9092	-6.1449
6.04418E-06	26.843	23.9047	2.9383	-6.04418
9.43008E-06	28.8088	24.3837	4.4251	-9.43008
9.72563E-06	29.0942	24.561	4.5332	-9.72563
9.94886E-06	29.2836	24.5659	4.7177	-9.94886
1.40262E-05	31.5008	25.0477	6.4531	-14.0262
1.40344E-05	31.5069	24.9499	6.557	-14.0344
0.000014159	31.5969	24.9788	6.6181	-14.159
0.000019867	34.7589	25.7362	9.0227	-19.867
2.06955E-05	35.0621	25.9409	9.1212	-20.6955
2.06781E-05	35.1493	25.8932	9.2561	-20.6781
2.63221E-05	38.0266	26.5608	11.4658	-26.3221
0.000027157	38.2471	26.7753	11.4718	-27.157
2.68181E-05	38.0879	26.3976	11.6903	-26.8181

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3.52777E-05	42.2465	27.5956	14.6509	-35.2777
3.52573E-05	42.1726	27.2912	14.8814	-35.2573
3.59183E-05	42.3416	27.5846	14.757	-35.9183
0.000043206	45.4642	28.3273	17.1369	-43.206
4.46394E-05	46.0724	28.3273	17.7451	-44.6394
4.49985E-05	46.2468	28.5756	17.6712	-44.9985
5.51387E-05	50.5645	29.2583	21.3062	-55.1387
5.65166E-05	51.0401	29.4631	21.577	-56.5166
5.71952E-05	51.1507	29.8526	21.2981	-57.1952
7.00743E-05	55.8268	30.7812	25.0456	-70.0743
7.11845E-05	56.0142	30.7808	25.2334	-71.1845
7.05417E-05	55.8675	30.8675	25	-70.5417
8.27636E-05	60.289	32.1174	28.1716	-82.7636
0.000083549	60.4734	32.1558	28.3176	-83.549
8.27942E-05	60.4349	31.9126	28.5223	-82.7942
9.77894E-05	65.6595	33.442	32.2175	-97.7894
0.000098924	65.7972	33.3854	32.4118	-98.924
9.85439E-05	65.8638	33.4861	32.3777	-98.5439
0.00011231	70.5257	34.5739	35.9518	-112.31
0.000114364	71.0299	34.8051	36.2248	-114.364
0.000113383	71.119	34.7822	36.3368	-113.383
0.000130912	77.3462	36.6322	40.714	-130.912
0.000130566	77.4784	36.1258	41.3526	-130.566
0.000130953	77.6114	36.1851	41.4263	-130.953
0.000153612	84.4975	37.9565	46.541	-153.612
0.000155115	84.6341	38.0165	46.6176	-155.115
0.000154375	84.3688	38.1114	46.2574	-154.375
0.00016667	88.6412	37.8957	50.7455	-166.67
0.000171288	89.3778	39.5327	49.8451	-171.288
0.000171141	89.645	39.1357	50.5093	-171.1405
0.000197187	96.6042	40.9851	55.6191	-197.187
0.000194079	95.824	40.3116	55.5124	-194.079
0.000192649	95.9567	40.9582	54.9985	-192.649
0.000214847	102.135	41.6553	60.4797	-214.847
0.000218036	103.195	41.7114	61.4836	-218.036
0.000219361	103.47	42.2706	61.1994	-219.361
0.000232901	107.239	43.6561	63.5829	-232.901
0.000233026	107.888	43.1331	64.7549	-233.026
0.000236515	108.278	43.5262	64.7518	-236.515
Voltage, ends plated (V)	Top Temp (C)	Bottom Temp (C)	Delta T (K)	Seebeck Voltage (µV)
8.46643E-07	23.2076	23.1874	0.0202	-0.846643
1.54089E-06	23.2573	23.2002	0.0571	-1.54089
1.65464E-06	23.2765	23.2027	0.0738	-1.65464

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8.44729E-06	23.7294	23.2613	0.4681	-8.44729
9.7184E-06	23.8429	23.2886	0.5543	-9.7184
1.03071E-05	23.8791	23.2932	0.5859	-10.3071
2.50527E-05	24.9667	23.4481	1.5186	-25.0527
0.000026521	25.0634	23.459	1.6044	-26.521
2.70088E-05	25.0996	23.4636	1.636	-27.0088
4.81886E-05	26.5686	23.6673	2.9013	-48.1886
4.91915E-05	26.6587	23.6801	2.9786	-49.1915
4.92044E-05	26.6788	23.6838	2.995	-49.2044
7.86426E-05	28.7286	23.9665	4.7621	-78.6426
7.91505E-05	28.7822	23.9704	4.8118	-79.1505
0.00007928	28.7783	23.9795	4.7988	-79.28
0.000104526	30.378	24.1959	6.1821	-104.526
0.000104464	30.5069	24.2363	6.2706	-104.464
0.000106235	30.6164	24.2563	6.3601	-106.235
0.000144074	33.3442	24.6901	8.6541	-144.074
0.000146431	33.4785	24.7135	8.765	-146.431
0.00015096	33.6564	24.7427	8.9137	-150.96
0.000183338	35.7184	25.0248	10.6936	-183.338
0.000187936	36.1568	25.1023	11.0545	-187.936
0.000189798	36.4106	25.1538	11.2568	-189.798
0.000227666	38.5785	25.4594	13.1191	-227.666
0.00024239	39.486	25.608	13.878	-242.39
0.00024726	40.0433	25.7103	14.333	-247.26
0.000314663	44.6461	26.4784	18.1677	-314.663
0.000320337	44.9177	26.5196	18.3981	-320.337
0.000320723	45.0108	26.5481	18.4627	-320.723
0.000394957	49.6902	27.334	22.3562	-394.957
0.000399481	49.9113	27.3726	22.5387	-399.481
0.000393505	49.9581	27.3878	22.5703	-393.505
0.000467307	54.292	28.0938	26.1982	-467.307
0.000462998	54.0875	28.0813	26.0062	-462.998
0.000467569	54.2085	28.0974	26.1111	-467.569
0.000553977	59.5893	28.9509	30.6384	-553.977
0.000557509	59.6419	28.9871	30.6548	-557.509
0.00056191	59.9026	29.0431	30.8595	-561.91
0.000647995	64.529	29.7834	34.7456	-647.995
0.000654557	64.9557	29.8892	35.0665	-654.557
0.000655153	65.1279	29.9796	35.1483	-655.153
0.000756476	69.7166	30.626	39.0906	-756.476
0.000763616	70.6494	30.8666	39.7828	-763.616
0.000765844	70.8079	30.9589	39.849	-765.844
0.000908312	77.844	32.2706	45.5734	-908.312
0.000913558	77.9693	32.3453	45.624	-913.558

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0.000915852	78.0814	32.44	45.6414	-915.852
0.00106385	84.7964	33.6633	51.1331	-1063.85
0.00106527	85.0515	33.7791	51.2724	-1065.27
0.00106249	84.8941	33.8039	51.0902	-1062.49
0.00120215	91.055	34.9876	56.0674	-1202.15
0.00121098	91.385	35.1024	56.2826	-1210.98
0.00122882	91.8656	35.2348	56.6308	-1228.82
0.00139129	98.0855	36.3987	61.6868	-1391.29
0.00140125	98.8436	36.6401	62.2035	-1401.25
0.00152902	103.133	37.5198	65.6132	-1529.02
0.00157094	105.868	38.5329	67.3351	-1570.94
0.00158616	105.745	38.5606	67.1844	-1586.16
0.00160112	106.172	38.7308	67.4412	-1601.12
0.00176345	111.683	40.3542	71.3288	-1763.45
0.00175681	111.566	40.4303	71.1357	-1756.81
0.00175457	111.452	40.4995	70.9525	-1754.57

Table L.6. Transverse Seebeck Coefficient Data. The Seebeck voltage is the negative measured voltage multiplied by 1×10^6 to obtain microvolts per kelvin. The first section is the voltages when the sample was completely plated. The second section contain the voltages when the plating was only on the edges and is therefore the voltages that were used to calculated the Seebeck coefficient.

[M] Cu/Mg_2Si stack data

Current (mA)	Current (A)	Voltage (mV)	Voltage (V)
-10	-0.01	-128.7	-0.1287
-9	-0.009	-116	-0.116
-8	-0.008	-103.2	-0.1032
-7	-0.007	-90.37	-0.09037
-6	-0.006	-77.49	-0.07749
-5	-0.005	-64.6	-0.0646
-4	-0.004	-51.7	-0.0517
-3	-0.003	-38.79	-0.03879
-2	-0.002	-25.87	-0.02587
-1	-0.001	-12.94	-0.01294
1	0.001	12.23	0.01223
2	0.002	24.46	0.02446
3	0.003	36.71	0.03671
4	0.004	48.96	0.04896
5	0.005	61.24	0.06124
6	0.006	73.51	0.07351
7	0.007	85.73	0.08573
8	0.008	97.92	0.09792
9	0.009	110.1	0.1101
10	0.01	122.2	0.1222
20	0.02		0.2444
30	0.03		0.3656
40	0.04		0.4864
50	0.05		0.596
60	0.06		0.712
70	0.07		0.826
80	0.08		0.936
90	0.09		1.04
100	0.1		1.14

Resistances (Ohms)	Length	Conductivity (S/m)
11.689	0.004667	**5.288882951**
Radius	Area	R-Value
0.004902	7.54912E-05	0.99933

Table M.1.Perpendicular Conductivity Data and Calculations. The conductivity was attained by dividing the length by the resistance and the area.

Voltage (V)	Temp Top (C°)	Temp Bottom (C°)	Delta T (C° or K)	Negative Voltage (µV)
-1.446E-06	22.9248	22.9444	-0.0196	1.4456
6.409E-08	22.9434	22.9436	-0.0002	-0.0640896

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5.0927E-06	23.0161	22.9455	0.0706	-5.09271
4.226E-05	23.5911	23.0175	0.5736	-42.2598
5.2868E-05	23.7423	23.0612	0.6811	-52.8683
0.00010988	24.6223	23.1487	1.4736	-109.88
0.0001431	25.1579	23.2539	1.904	-143.1
0.00026207	27.0104	23.5155	3.4949	-262.067
0.00030599	27.7005	23.6679	4.0326	-305.986
0.00031298	27.8362	23.7064	4.1298	-312.976
0.00053513	31.21	24.1757	7.0343	-535.132
0.00060689	32.4125	24.4013	8.0112	-606.885
0.00063427	32.8661	24.5067	8.3594	-634.271
0.00068122	33.6603	24.6721	8.9882	-681.219
0.00070804	34.0668	24.7793	9.2875	-708.036
0.00071808	34.304	24.8855	9.4185	-718.084
0.00142513	44.9697	26.524	18.4457	-1425.13
0.00147071	45.7523	26.7431	19.0092	-1470.71
0.00148257	46.0369	26.8743	19.1626	-1482.57
0.00240642	59.2615	28.9504	30.3111	-2406.42
0.00260817	62.1608	29.5888	32.572	-2608.17
0.00267155	63.1475	29.8976	33.2499	-2671.55
0.00284612	65.8604	30.6477	35.2127	-2846.12
0.00288243	66.3502	30.8576	35.4926	-2882.43
0.00290996	66.8765	31.2815	35.595	-2909.96

Table M.2 Perpendicular Seebeck Coefficient Data. The Seebeck voltage is the negative measured voltage multiplied by 1×10^6 to obtain microvolts per kelvin.

Current (mA)	Current (A)	Voltage (V)		
1	0.001	9.2479E-08		
2	0.002	1.0736E-07		
3	0.003	9.5299E-08		
4	0.004	1.3099E-07		
5	0.005	1.3267E-07		
6	0.006	1.4023E-07		
7	0.007	1.4767E-07		
8	0.008	1.5373E-07		
9	0.009	1.6201E-07		
10	0.01	1.971E-07		
20	0.02	2.25E-07		
30	0.03	2.6225E-07		
40	0.04	2.8073E-07		
50	0.05	3.148E-07		
60	0.06	3.4156E-07		

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70	0.07	3.7443E-07		
80	0.08	3.9153E-07		
90	0.09	4.3838E-07		
100	0.1	4.9154E-07		
	Width (m)	Height (m)	Area (m^2)	position
x=0	9.43E-03	4.67E-03	4.40381E-05	0
width=diameter	9.80E-03	4.67E-03	4.57506E-05	0.002303333
x=L	9.55E-03	4.63E-03	4.42165E-05	0.004606667
Resistances (Ohms)	R-Values	Length (m)	Conductivities (S/m)	notes
3.67E-06	0.97338	0.00460667	2.78E+07	all of the data
1.01E-05	0.91441	Average Value of Area function	10051565.14	1 - 10 mA
3.09E-06	0.9888	4.5175E-05	33005284.95	10 - 100 mA
			2.36091E+07	average

Table M.3. Parallel Conductivity Data and Calculations. The conductivities were attained by dividing the length by the resistance and the area. Used three different ranges for the slopes. The average was the value used for the discussion.

Voltage (V)	Top Temp (C)	Bottom Temp (C)	Delta T (C or K)	Seebeck Voltage (µV)
6.70E-07	23.605	22.8945	0.7105	-6.70E-01
7.08E-07	23.6408	22.912	0.7288	-7.08E-01
1.39E-07	23.6558	22.9255	0.7303	-1.39E-01
1.60E-06	26.3157	23.5414	2.7743	-1.60E+00
1.75E-06	26.5323	23.6123	2.92	-1.75E+00
2.27E-06	26.6433	23.6639	2.9794	-2.27E+00
4.76E-06	31.6859	24.8846	6.8013	-4.76E+00
5.05E-06	31.7886	24.8973	6.8913	-5.05E+00
5.19E-06	31.8231	24.9509	6.8722	-5.19E+00
8.51E-06	38.7399	26.588	12.1519	-8.51E+00
7.79E-06	38.9099	26.6159	12.294	-7.79E+00
8.33E-06	38.8308	26.4891	12.3417	-8.33E+00
1.27E-05	47.3717	28.416	18.9557	-1.27E+01
1.26E-05	47.4822	28.4851	18.9971	-1.26E+01
1.25E-05	47.5278	28.5488	18.979	-1.25E+01
1.89E-05	58.7221	31.1368	27.5853	-1.89E+01
1.84E-05	58.5261	31.163	27.3631	-1.84E+01
1.81E-05	58.3267	31.2066	27.1201	-1.81E+01
2.69E-05	68.4351	33.3505	35.0846	-2.69E+01
2.34E-05	68.8651	33.5574	35.3077	-2.34E+01
2.40E-05	69.2317	33.5719	35.6598	-2.40E+01

Table M.4. Perpendicular Seebeck Coefficient Data. The Seebeck voltage is the negative measured voltage multiplied by 1×10^6 to obtain microvolts per kelvin.

Current (mA)	***Current (A)***	***Voltage totally plated (V)***	***Voltage only ends plated(V)***
1	0.001	5.90016E-06	1.02857E-05
2	0.002	0.000011886	2.02271E-05
3	0.003	1.78314E-05	3.02261E-05
4	0.004	2.39457E-05	0.000040163
5	0.005	2.99799E-05	0.000050151
6	0.006	3.58659E-05	6.02012E-05
7	0.007	4.19517E-05	7.02303E-05
8	0.008	4.80066E-05	8.03252E-05
9	0.009	5.39422E-05	9.01331E-05
10	0.01	5.98861E-05	0.000100106
20	0.02	0.000119861	0.000200043
30	0.03	0.00017989	0.00029984
40	0.04	0.000239962	0.000399683
50	0.05	0.000299922	0.000499888
60	0.06	0.000359868	0.000600001
70	0.07	0.000420137	0.000700112
80	0.08	0.00048016	0.000800292
90	0.09	0.000540439	0.000900798
100	0.1	0.000600517	0.00100113
R-Value	***Resistance (ohm)***	***Conductivity (S/m)***	
1	0.006046	**90490.90199**	plating around sample
1	0.0100042	**54687.83046**	plating only on ends of sample
	Width (m)	***Area (m^2)***	
	0.00266	9.5228E-06	
	Height (m)	***Length (m)***	
	0.00358	0.00521	

Table M.5. Transverse Conductivity data. The conductivities were obtained by dividing the length by the resistance and the area. The top conductivity is the totally plated value. The bottom conductivity is the sample which was only plated on the ends hence the value that has been used in the thesis.

Potential, full plating (V)	**Top Temp (C)**	**Bottom Temp (C)**	**Delta T (C or K)**	**Seebeck Voltage (μV)**
-4.68313E-07	23.0932	22.8799	0.2133	0.468313
-4.8493E-07	23.1124	22.8886	0.2238	0.48493
-5.25123E-07	23.1228	22.8921	0.2307	0.525123
-9.57526E-07	23.2423	22.9117	0.3306	0.957526
-1.02591E-06	23.2859	22.9199	0.366	1.02591
-1.15675E-06	23.3515	22.9266	0.4249	1.15675
-3.48727E-06	24.0761	22.9842	1.0919	3.48727
-3.42176E-06	24.0435	22.9882	1.0553	3.42176
-3.37988E-06	24.0522	22.9998	1.0524	3.37988
-6.60962E-06	25.1338	23.1	2.0338	6.60962

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-6.83783E-06	25.2209	23.1143	2.1066	6.83783
-6.97803E-06	25.2635	23.1247	2.1388	6.97803
-1.17934E-05	26.8436	23.2662	3.5774	11.7934
-1.19627E-05	26.9147	23.282	3.6327	11.9627
-1.21158E-05	26.9694	23.2953	3.6741	12.1158
-1.83411E-05	28.9986	23.4684	5.5302	18.3411
-1.87187E-05	29.1022	23.4871	5.6151	18.7187
-1.85578E-05	29.0697	23.4977	5.572	18.5578
-2.59475E-05	31.4294	23.7049	7.7245	25.9475
-2.63013E-05	31.571	23.7281	7.8429	26.3013
-2.66536E-05	31.6658	23.7426	7.9232	26.6536
-3.69363E-05	34.943	24.0521	10.8909	36.9363
-3.71424E-05	35.0183	24.0681	10.9502	37.1424
-3.69865E-05	34.9823	24.0722	10.9101	36.9865
-4.91572E-05	38.7316	24.3798	14.3518	49.1572
-4.94525E-05	38.8593	24.4086	14.4507	49.4525
-4.96284E-05	38.8541	24.4127	14.4414	49.6284
-0.00006086	42.2983	24.6676	17.6307	60.86
-6.23735E-05	42.7709	24.7223	18.0486	62.3735
-6.46736E-05	43.4072	24.7863	18.6209	64.6736
-7.80123E-05	47.4387	25.1447	22.294	78.0123
-7.86822E-05	47.5835	25.1737	22.4098	78.6822
-7.86221E-05	47.6486	25.2295	22.4191	78.6221
-0.000093121	51.8897	25.6227	26.267	93.121
-9.46803E-05	52.4112	25.6877	26.7235	94.6803
-0.000095645	52.6464	25.7197	26.9267	95.645
-0.000113868	57.9972	26.2123	31.7849	113.868
-0.000114541	58.1302	26.2123	31.9179	114.541
-0.000114414	58.1541	26.2723	31.8818	114.414
-0.000130613	62.8242	26.7496	36.0746	130.613
-0.000132175	63.2325	26.8275	36.405	132.175
-0.000134405	63.8411	26.9115	36.9296	134.405
-0.000158094	70.3963	27.6646	42.7317	158.094
-0.000159829	70.8405	27.7671	43.0734	159.829
-0.000159713	70.7811	27.8077	42.9734	159.713
-0.000176104	75.7319	28.4814	47.2505	176.104
-0.000178686	75.8467	28.5195	47.3272	178.686
-0.000179631	76.1378	28.5997	47.5381	179.631
-0.00020471	82.772	29.4766	53.2954	204.71

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-0.000205762	83.1792	29.5824	53.5968	205.762
-0.000205756	83.0678	29.6622	53.4056	205.756
-0.000230851	89.4993	30.7674	58.7319	230.851
-0.000231845	89.6925	30.9549	58.7376	231.845
-0.000231125	89.7224	31.0381	58.6843	231.125
-0.000257031	96.4648	32.1199	64.3449	257.031
-0.00025779	96.6735	32.176	64.4975	257.79
-0.000259263	96.9508	32.2504	64.7004	259.263
-0.000277841	102.184	32.8521	69.3319	277.841
-0.000284249	103.643	33.0585	70.5845	284.249
-0.000286119	104.124	33.167	70.957	286.119
-0.000324098	113.791	34.4599	79.3311	324.098
-0.00032434	113.904	34.5278	79.3762	324.34
-0.000325931	114.087	34.5739	79.5131	325.931
-0.000335509	116.25	34.9173	81.3327	335.509
-0.000336486	116.598	35.0043	81.5937	336.486
-0.000337628	116.791	35.0574	81.7336	337.628
Potential, plating on ends (V)	**Top Temp (C)**	**Bottom Temp (C)**	**Delta T (C or K)**	**Negative Voltage (V)**
9.11111E-07	23.2085	23.0898	0.1187	-0.9111111
1.04669E-06	23.2442	23.104	0.1402	-1.04669
0.000001099	23.2515	23.1065	0.145	-1.099
2.44591E-06	23.6893	23.2498	0.4395	-2.44591
2.65209E-06	23.7403	23.2768	0.4635	-2.65209
2.71892E-06	23.7538	23.286	0.4678	-2.71892
5.29177E-06	24.6054	23.5794	1.026	-5.29177
5.36472E-06	24.6254	23.5895	1.0359	-5.36472
5.40989E-06	24.6374	23.6067	1.0307	-5.40989
8.5388E-06	25.6752	23.9572	1.718	-8.5388
8.89261E-06	25.7748	24.0056	1.7692	-8.89261
9.02932E-06	25.8298	24.0318	1.798	-9.02932
1.34658E-05	27.3064	24.5455	2.7609	-13.4658
1.37954E-05	27.4032	24.5916	2.8116	-13.7954
1.38833E-05	27.4505	24.6038	2.8467	-13.8833
1.88545E-05	29.1235	25.1809	3.9426	-18.8545
1.90754E-05	29.2166	25.2214	3.9952	-19.0754
1.91663E-05	29.2345	25.2351	3.9994	-19.1663
2.57752E-05	31.4978	26.0357	5.4621	-25.7752
0.000025884	31.5881	26.0954	5.4927	-25.884

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2.59757E-05	31.5811	26.1169	5.4642	-25.9757
3.35377E-05	34.2303	27.0388	7.1915	-33.5377
3.37453E-05	34.2689	27.0388	7.2301	-33.7453
0.000033857	34.3237	27.0743	7.2494	-33.857
4.20789E-05	37.1784	28.0955	9.0829	-42.0789
4.25599E-05	37.3059	28.136	9.1699	-42.5599
4.28129E-05	37.4001	28.1905	9.2096	-42.8129
5.10066E-05	40.2021	29.1717	11.0304	-51.0066
5.07198E-05	40.1352	29.1812	10.954	-50.7198
5.05298E-05	40.1516	29.147	11.0046	-50.5298
5.93852E-05	43.1803	30.1893	12.991	-59.3852
6.04304E-05	43.5454	30.341	13.2044	-60.4304
6.12301E-05	43.809	30.4707	13.3383	-61.2301
7.24252E-05	47.8565	31.8354	16.0211	-72.4252
0.000072859	48.0219	31.9457	16.0762	-72.859
7.34126E-05	48.2604	32.0124	16.248	-73.4126
0.000083154	51.6735	33.1827	18.4908	-83.154
8.46467E-05	52.2072	33.4362	18.771	-84.6467
8.47066E-05	52.3249	33.5328	18.7921	-84.7066
0.000097475	56.6789	35.0177	21.6612	-97.475
0.000097355	56.8941	35.1371	21.757	-97.355
9.72726E-05	56.8498	35.1229	21.7269	-97.2726
0.000112102	61.7963	36.8406	24.9557	-112.102
0.000112108	62.0658	36.9516	25.1142	-112.108
0.000111288	61.8151	36.9052	24.9099	-111.288
0.000124008	66.5336	38.5726	27.961	-124.008
0.000125655	66.9419	38.6356	28.3063	-125.655
0.000126213	67.0899	38.7616	28.3283	-126.213
0.000142004	73.0745	40.8278	32.2467	-142.004
0.000142255	73.3513	40.9495	32.4018	-142.255
0.000142609	73.5996	41.0157	32.5839	-142.609
0.000153967	77.8555	42.4134	35.4421	-153.967
0.000155038	78.2829	42.539	35.7439	-155.038
0.000155458	78.6759	42.7775	35.8984	-155.458
0.000169505	84.0594	44.5533	39.5061	-169.505
0.000170469	84.6462	44.7163	39.9299	-170.469
0.000169256	84.5774	44.6799	39.8975	-169.256
0.000181007	89.9121	46.5048	43.4073	-181.007
0.000181246	90.4092	46.6187	43.7905	-181.246

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0.000181706	90.8419	46.8573	43.9846	-181.706
0.000186176	93.183	47.6321	45.5509	-186.176
0.000185733	94.0952	47.8414	46.2538	-185.733
0.000185833	93.8765	47.9358	45.9407	-185.833

Table M.6. Transverse Seebeck Coefficient Data. The Seebeck voltage is the negative measured voltage multiplied by 1×10^6 to obtain microvolts per kelvin. The first section is the voltages when the sample was completely plated. The second section contain the voltages when the plating was only on the edges and is therefore the second set of voltages were used to calculate the Seebeck coefficient.

Vita

David Esch was born in Cincinnati, Ohio. He went to high school in Millbury, Massachusetts graduating in 2007. He obtained his Bachelor of Arts degree in physics from Goshen College in 2011. He entered the University of New Orleans Physics graduate program in 2012, to pursue a Master of Applied Physics degree in material science. He joined Professor Kevin Stokes' research group in 2013.