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Thermoelectric effects and applications: an advanced physics laboratory experiment

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Abstract

We developed a simple, inexpensive undergraduate laboratory experiment covering concepts and applications related to thermoelectric effects. Students use commercially available thermoelectric plates for producing electric current or for cooling and heating, then utilize them to perform experimental investigations that involve cooling. These investigations include studying supercooling and flash-freezing of water, as well as the temperature dependence of the resistivity of metals and semiconductors. The experiment allows students to easily add more components to investigate additional phenomena, thus lending itself as a potential open-ended 'final project' in the lab. The activities emphasize experiment design and scientific investigation. They also develop some of the main goals of advanced physics laboratories, such as the exposure to new technologies and experimental skills, data collection and automation/control, as well as data analysis and the clear communication of the results. This experiment can be integrated into the physics curriculum of electronics or advanced laboratory courses at the sophomore or higher levels.

Keywords: advanced laboratory physics, physics education, thermoelectric effect, Peltier cooling, Seebeck effect

(Some figures may appear in colour only in the online journal)

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1. Introduction

Advanced labs serve an important role in the physics curriculum. They allow students to start learning and practicing scientific investigations and the design of experiments, as well as prepare them to join the skilled workforce [1, 2]. More specifically, students develop experimental skills and expertise, learn to design apparatus, generate and acquire data, analyze data properly [3], and communicate their findings in a succinct and clear way through lab reports and oral presentations [4, 5]. These skills are acquired through direct hands-on practice in advanced labs, where the students conduct the experiments with instructors' guidance.

The thermoelectric Seebeck and Peltier effects were discovered about two centuries ago, where the flow of electric current across a junction of dissimilar conductors (or semiconductors) can create a temperature gradient across the junction, and vice versa [6]. Yet, these effects still have many modern applications ranging from scientific devices [7], to cooling electronic/computer parts, and simpler consumer products, like camping coolers, among numerous others [8]. Furthermore, the field continues to evolve [9] and attract research, like the spin-dependent Seebeck effect [10, 11].

The experiment described here has the general theme of studying and using the thermoelectric effect. It can be divided into two main parts: (a) studying/understanding the behavior of the thermoelectric devices and (b) using thermoelectric cooling (TEC) and heating in other investigations. Both parts will be introduced here, preceded by a brief description of the lab settings.

1.1. Lab settings

This experiment was integrated either into the sophomore electronic instrumentation laboratory at Miami University or in the senior advanced physics lab at Birzeit University. The sophomore electronic instrumentation lab especially teaches the students experimental skills and knowledge that helps them in their future research or careers that involve technology [12]. Miami's 'Electronic Instrumentation Laboratory' is designed to give extensive exposure to basic electronic devices, tools, and concepts. These include the use of operational amplifiers and semiconductor devices for different purposes, the use of software to run equipment as well as acquire and analyze data, low-resistance measurements and noise reduction, and the use of modern microcontrollers. Thus, the 'thermoelectric effects' experiment served to build upon and enhance some of the skills that the students learned throughout the semester and allowed them to gain insight into some fundamental science through these experiments. In the advanced physics lab, students were expected to contribute more in the design of the experiments and to propose/conduct extra activities and deeper analysis. This experiment is easily integrated in both types of lab courses.

1.2. Thermoelectric effects

There is a host of effects associated with the flow of energy (heat) and electric charge through materials. The best-known effect of current flow in materials is Joule heating effect, where a current (I) flowing through an 'ohmic' conductor (i.e. a conductor with a linear relation between current and voltage). The current will add energy to the conductor thus heating it according to $P = I^2R$, where R is the resistance of the conductor and P the power dissipation [13].

Yet there are multiple lesser known effects that are related to the flow of charge and energy in materials, such as the Seebeck [14], the Peltier [15], and the Thomson [16, 17] effects. Furthermore, these effects are also influenced by magnetic fields and give rise to new thermomagnetic

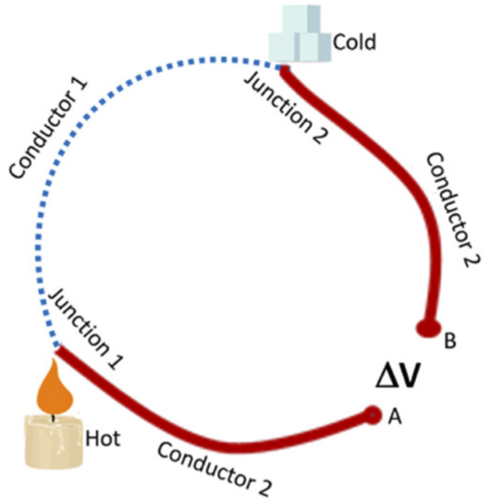

Figure 1. Thermoelectric or Seebeck effect. A temperature gradient between junction 1 and junction 2, which connect two different conductors, creates a potential difference ΔV between points A and B.

effects as well. Such thermomagnetic effects are somewhat similar to the Hall and the spin Hall effects and are still the subject of intense research [18]. We will focus here on the Peltier and the Seebeck effects only as they are quite useful in cooling, heating, and other temperature control applications.

1.2.1. The Seebeck Effect. When two conductors are connected together to form two junctions (known as a thermocouple), a potential difference will develop across points A and B, if the junctions are maintained at different temperatures (figure 1). This effect is the thermoelectric effect or the Seebeck effect, named after the scientist who first observed it in the early 19th century [6, 9]. If a 'load' is connected between points A and B a current flows through the circuit. So, the Seebeck effect concerns the conversion of thermal energy into electric energy, where a temperature gradient creates an electro-motive-force, or a voltage. This effect has many applications in temperature measurement and in small scale power generation.

1.2.2. The Peltier effect. The Peltier effect is practically the reverse of the Seebeck effect: when a current flows through a thermocouple junction (i.e. a voltage applied across the junction) a temperature gradient develops across the junction [8, 19]. In a way, the Peltier effect is basically a heat pump that extracts heat from one side of the junction and 'deposits' that heat on the other side causing one side to cool down and the other side to heat and so making this effect useful in cooling and heating applications. Yet, in practice it is mainly used for cooling because there are other, more efficient ways for heating applications. Some of the common cooling applications of the Peltier effect are cooling electronic equipment and refrigeration (such as in a portable cooler, for example) [20].

It is important to notice that both the Peltier and Seebeck effects are reversible, which means that if you reverse the current flow direction then the cold and hot ends of the thermocouple will switch. This is unlike the Joule heating effect, where thermal energy is generated whether you run current in one direction or the other through a conductor.

1.2.3. Other thermoelectric effects. Another thermoelectric effect is the Thomson effect [17]. It is directly related to the Seebeck and the Peltier effects, except that it refers to the cooling and heating effects when an electric current flows in a conductor that has a temperature gradient across its ends. In particular, the Thomson effect occurs in a *single* conductor, without a need for a thermocouple and leads either to cooling or heating, depending on the relative directions of current flow and temperature gradient. Both Peltier and Seebeck effects depend on external magnetic fields, which leads to two additional thermoelectric (or thermomagnetic) effects. Even though the Seebeck effect was demonstrated about two centuries ago, the associated thermomagnetic effects are quite contemporary and are being heavily studied across the world [21]. They are somewhat similar to the Hall effect and the spin Hall effect [22].

1.2.4. Materials and designs for Peltier-effect-based cooling and heating. Simple thermocouples are made of two dissimilar metals connected together, such as copper and constantan, a copper-nickel alloy. These thermocouples generate relatively small voltages of a few to a few tens of micro-volts per kelvin (K) of temperature difference between the ends. Semiconductor materials are especially important in Peltier and Seebeck effects applications because they have much larger 'Seebeck coefficients' that lead to stronger thermoelectric effects (figure 2) [23, 24]. Parts A and B of figure 2 show how semiconductor-based Peltier cooling works. It is important to notice that the free charge carriers move against the current direction in the n-type elements and with the current direction in the p-type elements. Thus the free charge carriers always move in the same direction (e.g. from the top to the bottom of each element in the figures), which is crucial in the Peltier and Seebeck effects [19, 20, 23].

The cooling and power generation effects associated with a single junction are still too small for applications, even when using semiconductors. Instead, a large array of these junctions is usually used in order to produce an appreciable cooling effect in commercial Peltier coolers (figure 2(C)). All junctions are connected thermally in parallel, where, for example, the top part will be cold for all elements and the bottom part will be hot for all of them, or vice versa. Electrically, the junctions are connected in series, so the same current flows through all of them. This is important in order to maximize the cooling because the Peltier effect is proportional to the actual current flowing into a thermocouple.

1.3. Using thermoelectric coolers in other investigations

TECs were used in three simple studies that required a change in temperature. These studies included the behavior of water droplets when cooled below their freezing temperature as well as the resistance variation with temperature in both a metal and a semiconductor.

1.3.1. Supercooling and flash-freezing of water droplets cooled below their freezing temperature. Water is said to be supercooled/undercooled when it remains liquid below its ice melting temperature of 0 °C. This phenomenon was first demonstrated by Gabriel Fahrenheit in the early 18th century [25, 26]. He also observed a rapid increase of the water temperature when it finally freezes. This rapid freezing process is called flash freezing, and the temperature rises to the equilibrium melting point when flash freezing occurs. The occurrence of flash freezing depends on the initial nucleation of ice and some special conditions [23]. Flash freezing of a small water droplet on a cooled surface depends on the heterogeneous nucleation of ice on its surface, as well as on the droplet volume and the contact angle with the cooled surface [27–29].

1.3.2. Resistance $R(T)$ in metals and semiconductors. The variation of a material's resistivity with its temperature depends mainly on the energy band structure of that material. The conduction band in metals is partially filled with electrons. These free electrons are the vehicle for

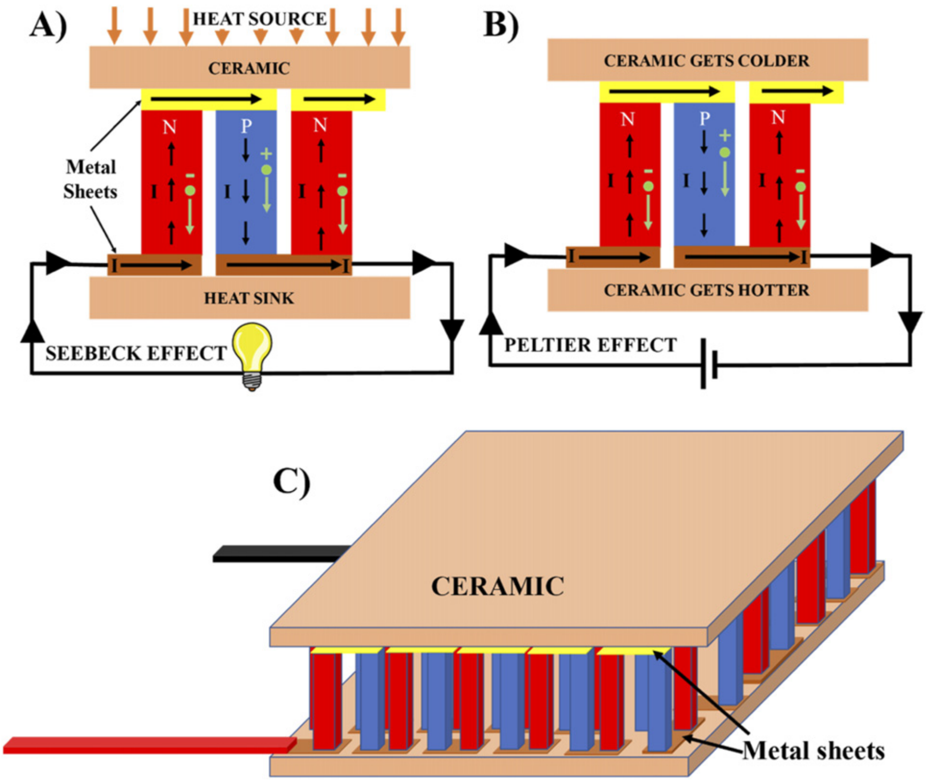

Figure 2. Schematic representation of thermoelectric devices that use p- and n-type semiconductors, which are significantly better than metal or alloy-based devices, both to produce power and for cooling. (A) A thermoelectric device of one junction is used for producing electrical power (Seebeck effect). (B) A thermoelectric device of one junction is used for cooling (Peltier effect). (C) A TEC device of many junctions [19, 20, 23].

conducting electricity, so metals are excellent conductors. On the other hand, insulators have their valence bands full and their conduction bands empty with a large energy gap separating the two bands, thus having no free electrons to conduct electricity and heat. Semiconductors are just like insulators, but with a relatively small energy gap that is not much larger than the thermal energy ($\frac{3}{2}k_{\mathrm{B}}T$) of an electron.

The resistivity of a metal increases linearly with its temperature due to the increase in lattice vibrations that cause a decrease in the mean free path of free electrons [30]. In the case of intrinsic semiconductors: there are no free electrons to carry the current at low temperature, since the conduction band is empty. The increase in temperature thermally excites electrons to the conduction band, which also creates holes in the valence band. These free electrons and holes can carry the current and cause the resistivity to decrease. This decrease in resistivity follows an exponential curve resembling the Boltzmann factor that has half of the energy gap (E_{g}) divided by Boltzman constant (k_{B}) [30] in its exponent.

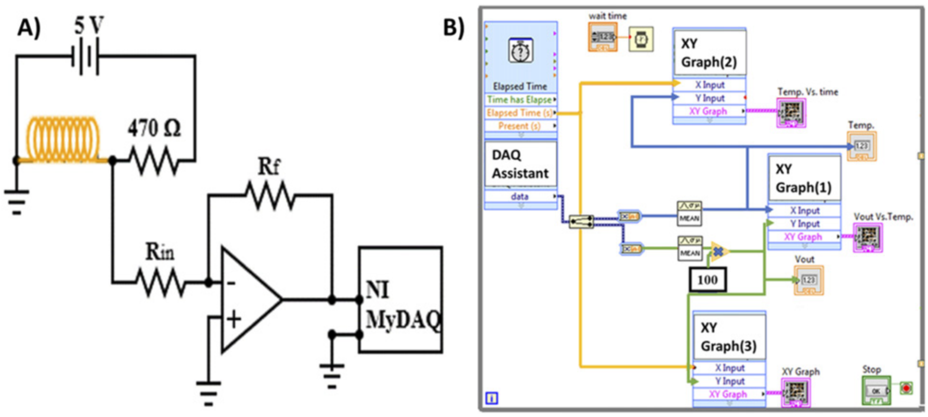

Figure 3. Circuit and software tools used in measurements. (A) A Simple electrical circuit for measuring the resistance of the copper wire. (B) A basic LabVIEW program to monitor and record the data. This program saves the data and gives three data graphs: (1) XY graph (1): monitors the output voltage variation as a function of temperature. (2) XY graph (2): monitors the temperature variation. (3) XY graph (3): monitors the voltage variation as a function of time.

2. Experimental setup and measurements

We used a TEC1-12706 thermoelectric cooler (TEC)—purchased through Amazon-that has 127 pairs of p- and n-type pins and a surface area of its flat face of 40 mm × 40 mm. The TEC was placed on an aluminum block that is immersed in water as a heat sink. The TEC was biased using a DC power supply. A 'type K' thermocouple was placed on the TEC surface and connected to a National Instruments 'MyDAQ' data acquisition unit to collect the temperature readings using LabVIEW software. Applying the DC bias over the TEC in one direction decreases the temperature of the top side (compared to the heat sink) while reversing the bias polarity increases the temperature (e.g. in figure 2(B)) running the current clockwise causes the top side to get colder than the bottom, while running a counter clockwise current makes the top side of the TEC device hotter than the bottom).

Temperature measurements were made for four different configurations:

(a) Temperatures at set TEC currents: nothing was placed on the surface (except the thermocouple), and the temperature was monitored with the current through the cooler.

(b) Temperature gradients to generate electricity: the TEC was placed between two thermally isolated 'reservoirs', where a hole in Styrofoam was used to keep hot water on one side and ice-and-water on the other. Each of these sides was in direct thermal contact with the TEC fixed in the Styrofoam hole (see figure 5(A)) below). The generated thermoelectric voltage and current were studied as functions of the temperature difference.

(c) A water droplet was placed on the TEC surface and its temperature was monitored while cooling, using a small thermocouple immersed in the droplet.

(d) A thin metal wire and a semiconductor (thermistor) were placed on the surface and their resistances were monitored as the temperature was changed:

1. Resistance of a metal wire placed on the surface. About 1 m of thin copper wire (gauge 32, diameter 0.2 mm) was made into a coil, put in thermal contact with the TEC top surface, and connected in series to a 470 Ω resistor and connected to a 5 V power

supply in a voltage divider configuration [31] (figure 3(A)). An inverting amplifier made with a type 741 operational amplifier with a gain (G) of about −15 was used to determine the voltage drop at the copper wire, $V_{cu} = \frac{V_{out}}{G}$. After that, we monitor the change in the voltage with temperature while varying the TEC current gradually for the two cases (heating and cooling) via a LabVIEW program (figure 3(B)). The resistance of the copper wire is then calculated using:

$$R_{cu}\ (\Omega) = \frac{V_{cu} \times 470\ \Omega}{(5\ \mathrm{V} - V_{cu})}.$$

2. Resistance of a semiconductor. A TTC 502 thermistor was placed on the surface and connected in series to a 100 kΩ resistor and a 5 V power supply in a voltage divider configuration. The change in the semiconductor voltage with the temperature gave the resistance of the semiconductor sample as:

$$R_{SC}\ (\Omega) = \frac{V_{out} \times 100\ \mathrm{k}\Omega}{(5\ \mathrm{V} - V_{out})}.$$

For those who do not want to use a computerized data acquisition setup, the resistance of the thermistor can be measured with a multi-meter and recorded manually without the need for computerized data recording. In this case, the multi-meter needs to be connected in the place of the 'NI MyDAQ' unit shown in figure 3(A). It should be noted here that a multi-meter will also have to be used to measure the potential difference across the thermocouple in order to measure the temperature manually. A manufacturer-provided calibration curve can then be used to find the matching temperature.

3. Results and analysis

3.1. Temperature at set TEC currents (Newton's law of cooling and heating)

Figure 4 shows the variation of the temperature when changing the current: the temperature approaches its new equilibrium value asymptotically, both when cooling and heating. This is in agreement with Newton's law of cooling and heating, which states that the rate of change of temperature is proportional to the temperature difference between the object, T, and its surroundings, T_s. So, if T_F and T_0 are the final and initial temperatures, respectively [32, 33]:

$$\frac{\mathrm{d}T}{\mathrm{d}t} \propto (T - T_s)$$

$$T = T_F + (T_0 - T_F)e^{-kt}.$$

This results in an exponential and asymptotic approach of the temperature to the new value dictated by the TEC settings and the surroundings. The figure shows the behavior for both heating and cooling. Starting from zero current, the temperature of the surface was 25 °C. The current was then increased from zero to 1.0 A in steps of 0.5 A. The asymptotic approach to the final temperature is clear in each of these two steps. The current is then dropped from 1.0 A down to 0 A and the same asymptotic behavior is observed.

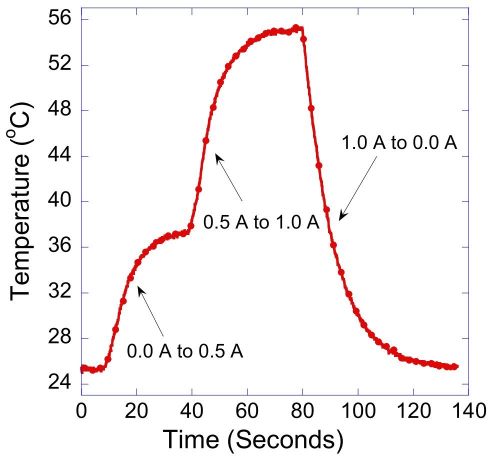

Figure 4. $T(t)$ variation when the thermocouple is placed on the thermoelectric plate while it is heated or cooled gradually by changing the applied current.

3.2. Thermoelectric power generation via a TEC

The second set of activities in lab exercise involves the study of electric power generation by imposing a temperature difference between the bottom and the top of the thermoelectric plate. In fact, the TEC can be used as a thermoelectric generator for a limited temperature difference range. This range is limited by the ceramic plate materials and properties, solder joints, thermoelectric legs dimensions, and the wires used on the device. Nesarajah and Frey [34] showed in detail the differences between TEC and thermoelectric power generation. In our experiment, the TEC was directly in thermal contact with hot water from the right and cold water with ice on the left, as shown in figure 5(A). The temperature of each side was measured using liquid thermometers. The TEC was connected to a resistor of 2 ohms and a resistance decade box in a voltage divider configuration. The induced voltage and current from the TEC device were measured by measuring the voltage difference across the 2 Ω resistor using the DAQ unit. Figure 5(B) shows the current–voltage (I–V) characteristics of the TEC for two temperature differences. It shows a linear behavior with a slope of about -0.31 V A^{-1}. From the equation of the straight line, the maximum power achieved is about 50 mW (by maximizing the $P = I \times V$ equation) at a current of about 0.5 A. Figure 5(C) shows a plot of the induced open circuit voltage vs the temperature difference. The TEC in this setup can be used to produce a voltage of 0.45 V at a temperature difference of about 85 °C. Finally, figure 5(D) shows a plot of the TEC's dissipated electrical power as a function of the temperature difference. It shows that the TEC dissipates approximately 200 mW of power at a temperature difference of about 85 °C. The behavior in both figures 5(C) and (D) is consistent with the TEC1-12706 Peltier model datasheet [35] and some previous work on it [34]. Furthermore, we note that no hysteresis occurs in either of them. So, these TEC devices can be used as thermoelectric generators in some applications when a sufficiently large temperature gradient is maintained across their sides.

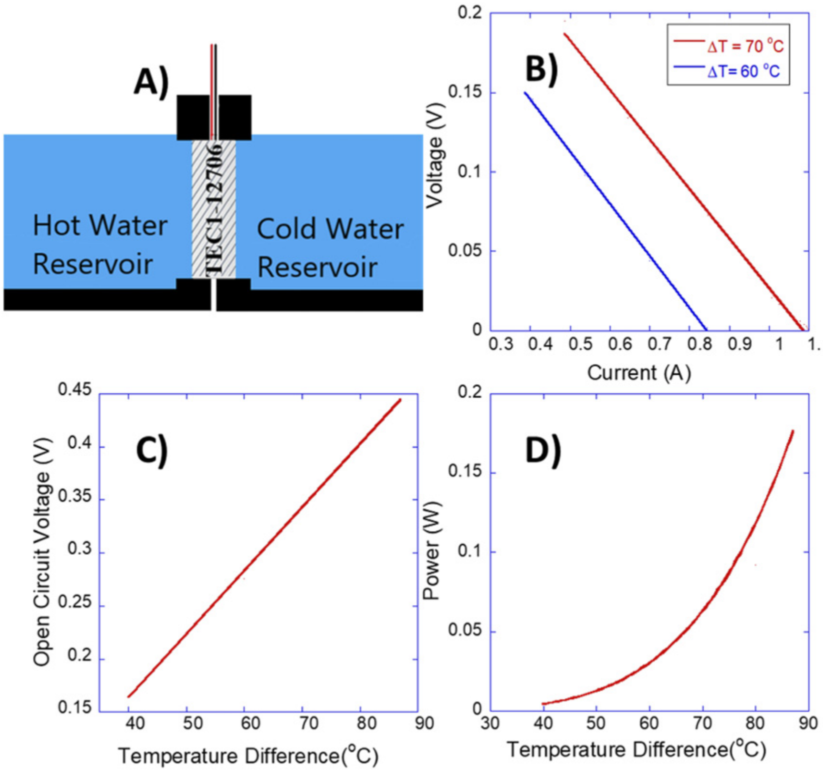

Figure 5. (A) Experimental set-up to measure the open-circuit voltage and the dissipated power from the TEC TEC1-12706, where the TEC was directly in thermal contact with the water (hot and cold) from both sides. (B) The I–V characteristics for the TEC at temperature differences of 60 °C (lower line) and 70 °C (upper line). (C) The open-circuit voltage vs the temperature difference. (D) The dissipated electrical power vs the temperature difference.

4. Further results and analysis

4.1. Water droplets: supercooling, flash freezing, and melting

The shape and behavior of water droplets on surfaces have attracted significant research attention and have many applications [36, 37]. The supercooling and flash-freezing of water are also fascinating phenomena that are worth studying and understanding. Figure 6 shows two pictures of a 40 μl water droplet taken before (left) and after freezing (right). The thin thermocouple is seen inserted in the droplet from the left. To get a clearer idea about what happens when the droplet freezes, figure 7 shows the temperature behavior as recorded by the thermocouple in a water droplet placed on the TEC plate while cooling (red circles). The figure also shows the temperature variation as recorded by the thermocouple when there is no water droplet on the TEC plate (blue). Water is relatively insulating, so the thermocouple is likely to be measuring the temperature of the water in its direct vicinity within the water droplet.

There are two striking observations in the figure: (1) the temperature of the water droplets falls smoothly to well below 0 °C, while it is still in the liquid phase-as observed visually and through a digital camera. This is known as supercooling. (2) There is a significant difference

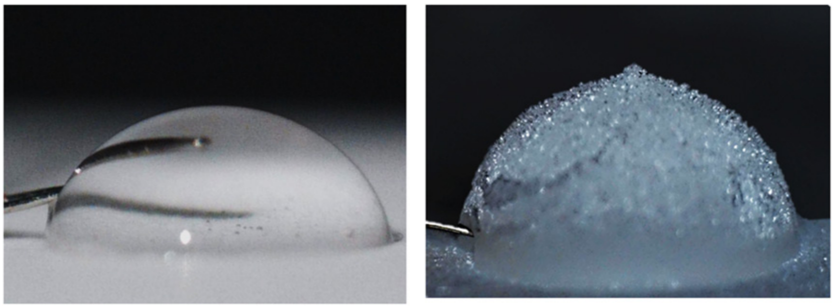

Figure 6. A picture of the water droplet during the cooling of the thermoelectric plate. (Left) Before the beginning of the freezing process. (Right) After the flash-freezing process.

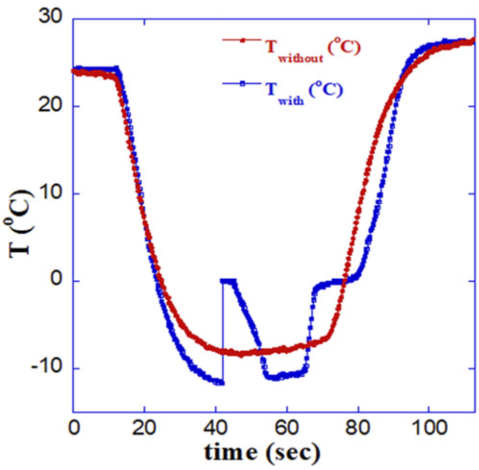

Figure 7. (Red circles) Temperature variation when the thermocouple is placed on the thermoelectric plate (without a water droplet) while it cooled. (Blue squares) Temperature variation when the thermocouple is placed inside a water droplet during cooling.

between the cooling curves with a water droplet on the surface and without it. Specifically, the curve for the water droplet displays two flat regions at $T = 0$ °C, one immediately after flash-freezing and the second while warming to room temperature after turning off the cooling current. As the temperature reaches about -11 °C it suddenly rises to 0 °C. This sudden jump in temperature occurs when a fraction of the water droplet freezes instantly. This is the well-known flash freezing of supercooled water, after which the rest of the droplet freezes relatively slowly. After the flash-freezing temperature jump, the temperature stays at zero for a bit, while the entire droplet freezes and then the temperature of the ice eventually starts dropping again to the expected equilibrium value for the particular TEC settings (nearly -17 °C). The temperature was allowed to stabilize at this value for about half a minute, then the cooling current

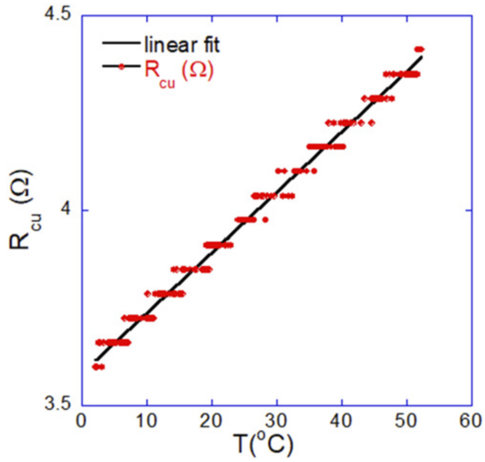

Figure 8. Temperature dependence of the resistance of a copper (Cu) wire. The red circles are the measured data points, and the line is the least-squares fit to the data. The step-like appearance of the data is due to the limited resolution of the measurement.

was turned off, and the temperature of the ice droplet started to rise immediately. Yet, the temperature curve flattens out again at 0 °C and stays there until the vicinity of the thermocouple melts. At this point the temperature starts to climb again toward room temperature.

4.2. Resistance change with temperature in a metal and a semiconductor

Figure 8 shows the resistance of a copper wire as a function of temperature. The resistance of the wire is quite low and increases linearly with temperature. According to the resistance variation for metals $R = R_0(1 + \alpha(T - T_0))$, plotting the relative resistance as a function of temperature results in a straight line with slope equal to αR_0 with α the temperature coefficient of resistivity. The best fit in figure 8 gives the value for $\alpha = (3.95 \pm 0.02) \times 10^{-3}\ ^\circ\mathrm{C}^{-1}$, which agrees well with the literature value of $3.93 \times 10^{-3}\ ^\circ\mathrm{C}^{-1}$ for copper at 20 °C [6, 38].

In metals the Fermi level falls within the conduction band, so there is an abundance of free electrons to conduct a current. The limiting factor for the conductivity is the presence of collisions between electrons and the rest of the crystal. While a part of the resistance is due to collisions with crystal imperfections that is temperature independent, the linear dependence arises from the well-known lattice vibrations and is known as phonon scattering [39–41].

Semiconductors, on the other hand have a much higher resistivity that varies exponentially with temperature, as seen in figure 9(A). We used a type TTC-502 thermistor as a semiconductor and found its resistance to decrease rapidly with increasing the temperature. This behavior stems from the fact that the Fermi level falls between the valence band and the conduction band in semiconductors. For an intrinsic semiconductor at low-temperature, electrons will not have enough thermal energy to excite them into the conduction band and thus cannot contribute to the conductance since they are confined to the 'localized' valence band. As temperature increases, more electrons get thermally excited to the conduction band leaving behind a 'hole' for each of them. These electron–hole pairs contribute to conduction, and the resistance drops (i.e. the conductance increases) with the increase in their numbers. The probability of being thermally excited from a lower valence band to a higher energy level of the conduction band drops exponentially with the energy gap (E_g), which is the energy

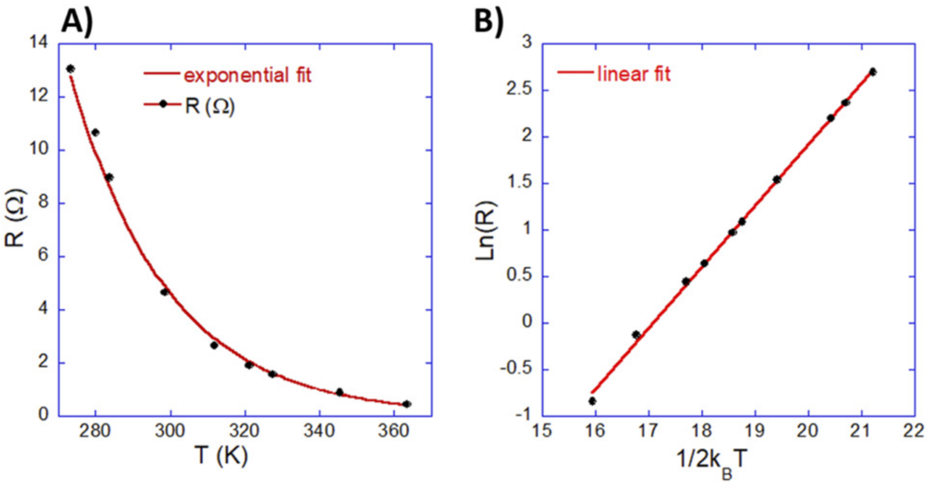

Figure 9. Temperature dependence of resistance of a thermistor of type TTC-502. (A) Raw data of the resistance of the thermistor as a function of the temperature along with a best fit exponential curve. (B) Ln(R) as a function of $(1/2k_BT)$ where R is the resistance of the TTC-502 thermistor, e is the electron charge, k_B Boltzmann constant, and T is the absolute temperature.

difference between the two bands. So, the intrinsic carrier density (free charge-carrier density) is proportional to the Boltzmann factor $n_i(T) = Ae^{\left(\frac{-E_g}{2k_BT}\right)}$, where k_B is the Boltzmann constant, A is a constant that depends on the semiconductor material, and T is the absolute temperature [30]. Assuming no significant change in the mobility, the conductance of the semiconductor is: $\sigma = en_i\,(T)\,(\mu_e + \mu_p)$, where μ_e and μ_p are the electron and hole mobilities, respectively. The resistivity is $\rho\,(T) = \frac{1}{\sigma} = \frac{1}{Ae(\mu_e+\mu_p)}e^{\left(\frac{E_g}{2k_BT}\right)}$, and thus the resistance has the form $R\,(T) = R_0e^{\left(\frac{E_g}{2k_BT}\right)}$, where R_0 is a constant.

Figure 9(B) shows a plot of the natural logarithm of the resistance, ln(R), as a function of $\frac{1}{2k_BT}$. Since $\ln(R) = \ln(R_0) + \frac{E_g}{2k_BT}$, the slope of this straight line is the energy gap (in eV) between the conduction and valence bands in the semiconductor. Our data shows an energy gap of (0.66 ± 0.01) eV, where the uncertainty is the 'standard deviation in the slope of the line, as obtained from the LINEST function in Excel'. This is within 1% of the energy gap of germanium (0.67 eV) which is used in the TTC-502 thermistor [42].

We do caution that simply placing the thermistor in contact with the TEC surface will most likely give the wrong energy gap value, as it happened with our initial experiments. This is likely due to the poor thermal contact between the thermistor and the TEC plate. The thermistor has a painted surface and is shaped like a lentil seed and so does not lend itself to a good thermal contact with the flat TEC plate. Therefore the actual temperature of the thermistor seems to have been always closer to room temperature than the temperature registered by the thermocouple placed on the TEC surface. We solved this problem by placing the thermistor in a small water beaker placed on the TEC surface. Water insured a very good thermal contact with the thermistor and gave excellent results.

4.3. Further experiments

One main advantage of this experiment is that it lends itself naturally to being extended as an open-ended project, where students can easily augment the experiment with different additions. Some possibilities that our students chose in the past were to connect a solar panel to power the TEC unit, to use a temperature control circuit like a Schmitt trigger to build a heating/cooling system, to use a hot coffee cup to produce electric energy, and multiple others.

5. Conclusion

Commercially available TEC devices have been used as simple and inexpensive tools to experiment with the Seebeck and Peltier thermoelectric effects. The temperature variation was found to follow Newton's law of cooling and heating. The cooling and heating ability of the devices was used to study the resistance change with temperature in a metal and a semiconductor by characterizing the temperature behavior for each of them, thus allowing us to extract the thermal coefficient of the resistance, α, for the metal and the energy gap, E_g, of the semiconductor. This experiment can be used as a sophomore electronics experiment or as an open-ended project in more advanced laboratories.

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