Thermoelectric and Piezoelectric Effects for Energy Harvesting

Thermoelectric Effect

The thermoelectric effect is the conversion between phonons, the quasi-particles carrying heat energy, into conduction electrons. This effect is modeled by two coupled differential equations:

\[ Q = -\kappa + \Pi S \sigma \frac{dT}{dx} - \Pi \sigma \left( \frac{d\varphi}{dx} \right) \]
\[ J = -S \sigma \frac{dT}{dx} - \sigma \left( \frac{d\varphi}{dx} \right) \]

\( Q \) is the heat flux and \( J \) is the electrical flux. Here, \( \kappa \) is the peltier coefficient which represents the thermal energy per charge, and \( S \) is the seeback coefficient which is a material property accounting for the temperature gradient. \( \sigma \) is the electrical conductivity and \( \varphi \) is the thermal conductivity. \( T \) is the temperature, \( x \) is the position, and \( \varphi \) is the electron potential.

From these equations, the drude model can be used to provide theoretical calculations for the peltier and seeback coefficients. However, these values are off by an order of magnitude. This discrepancy arises from the fact that electrons do not behave as an ideal gas. First, electrons are bound to the atoms until enough energy is applied to the system via phonon interactions. This means the electrons follow quantum statistics, namely the Fermion statistics. Secondly, the phonons also have quantized energy states associated with them. However, their interactions resemble those of light waves, meaning the phonons follow the Bose-Einstein statistics.

The main figure of merit for thermoelectric materials is as follows:

\[ zT = \frac{S^2 T}{\rho \kappa} \]

Piezoelectric Effect

The piezoelectric effect is the direct conversion of mechanical stress into electricity. This occurs as a result of the alignment of the dipole moments in a crystal lattice. When stress is applied, the atoms will shift out of alignment, and the dipoles formed will align. Once the stress is released, the dipoles begin to relax again. When placed in an area of prevalent vibrations, an oscillating electric field will form, driving a resulting current.

There are several figures of merit that represent how well a material performs. This is a result of the large number of different types of piezoelectric materials that account for different types of vibrational modes, shown below. These can be applied to various situations, such as flexural to mechanical vibrations, shear stress to flow etc.

Further, the piezoelectric effect can be enhanced through the bandgap structure of the material. As stress is applied to the material, in general, the bandgap decreases, making it easier for electrons to move from the valence band into the conduction band. When junctions are used, where two materials with different electronic structures are attached, then the bandgap alignment can also facilitate the promotion of electrons to the conduction band and increase the overall efficiency.

The main figure of merit used to determine the ability for the material to function as a piezoelectric is as follows.
This value provides a dimensionless value that can be used to gauge how well a material will perform as a thermoelectric. This figure accounts for the thermal conductivity as well as the conversion from heat into electricity. Currently, alloys provide the most efficient materials. To further increase this efficiency, fabrication at the nanoscale can help through something known as phonon drag. With small sizes, the phonons will take on quantized momentum, which reduces the overall energy of the phonons and increasing the chances that the phonons interact with electrons.

This can then be used to calculate the overall efficiency of the thermoelectric material using the following equation.

\[
\eta = \frac{\Delta T \sqrt{1 + zT} - 1}{T_H \sqrt{1 + zT} + 1}
\]

The original Carnot efficiency equation is modified with the figure of merit to represent a more accurate maximum efficiency. However, even with a perfect figure of merit, the system will always be ultimately limited by the Carnot efficiency due to the heat engine it uses. With a nuclear reactor operating at 300 degrees Celsius, approximately 10% of the wasted heat. Once optimized, these materials may provide more efficient energy conversion than traditional systems. However, if this is not possible, these materials will provide ways of preventing heat loss in larger heat engines.

\[
k^2 = \frac{d^2 E_y}{\xi_e}
\]

This is a ratio between the amount of stored electrical energy to input mechanical energy. The higher this value is, the more efficient the conversion between the two forms of energy is.

Piezoelectric materials offer a niche system of harvesting wasted mechanical energy. In a car, driving at 10 m/s with lead zirconate titanate (PZT) placed in the tires, 240 mW of power could be produced. While large scale energy generation may not be viable, smaller systems to improve efficiency will benefit from these materials.