3D Printing Nanostructured Thermoelectric Devices

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Objectives

The ultimate goal of this project is to enable 3D printing of nanostructured thermoelectric devices on flexible substrates and measure the properties of the devices.

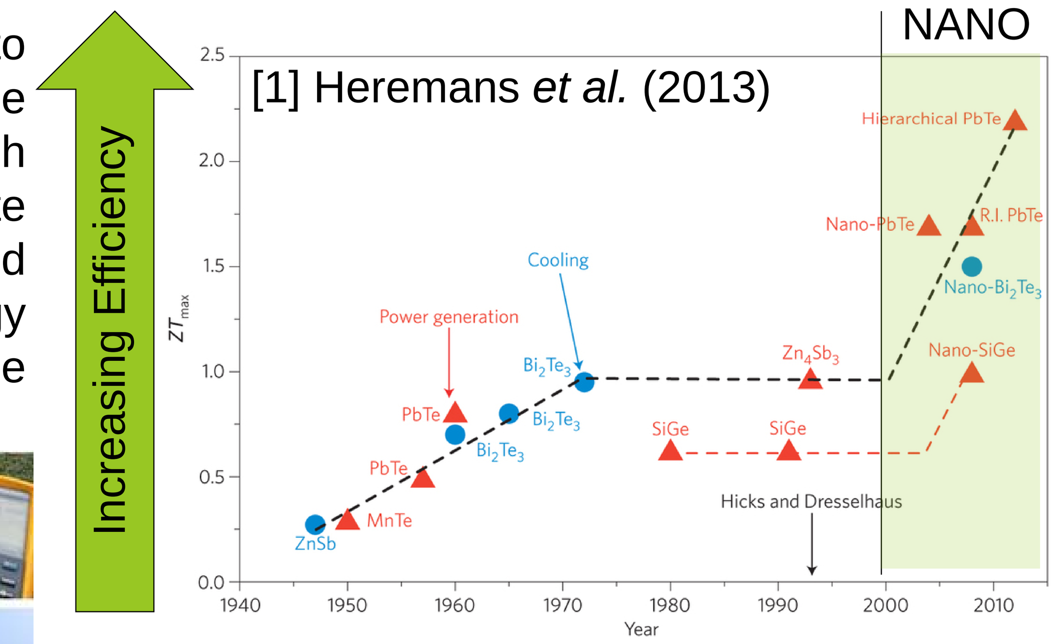
Task 1: *Fabricate a inkjet 3D printer that can print customized thermoelectric device and synthesis suitable nanostructured inks*

Task 2: *Simulation of the Harman method to ensure the preciseness of TE measurement*

Task 3: *Measure the TE efficiency of different samples*

Background

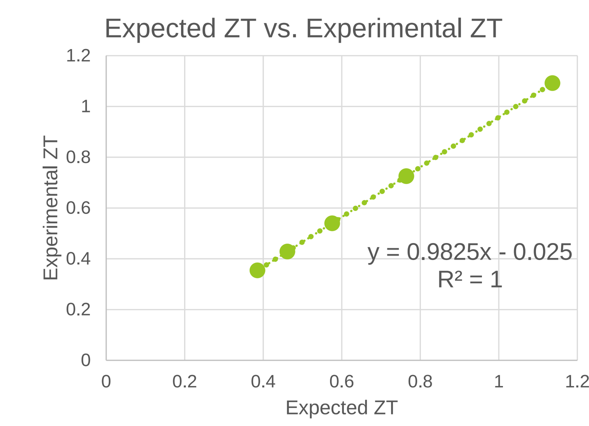
Thermoelectric materials can convert thermal energy to electrical energy and vice versa. Applications include electronic cooling, reducing energy consumption through waste heat recovery, and power generation in remote systems. Conventional thermoelectrics are rigid and planar. New applications such as wearable technology would benefit from the development of flexible thermoelectrics.



Nanostructuring improves the efficiency of thermoelectric materials by decoupling thermal and electrical transport.

Simulation of Harman Method

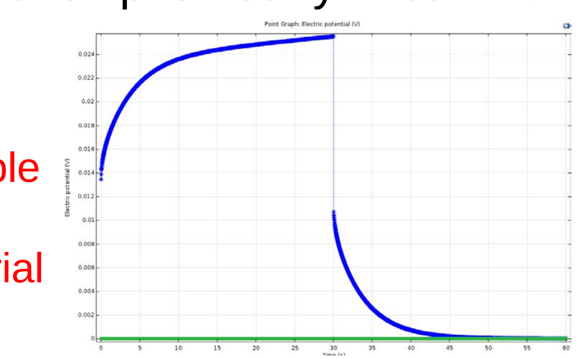
1. Validate Harman method for standard geometry & conditions



Comparison of ZT for materials with different k_{TE}

Result: the relationship is nearly linear with a slope ~1

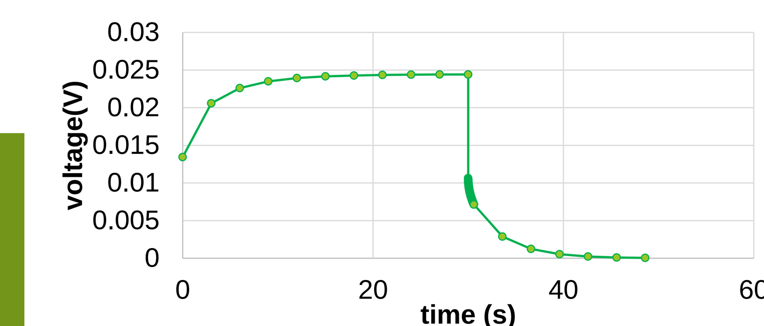
Thus, the Harman Method is applicable to most of the common TE material



Expected ZT: COMSOL built-in value

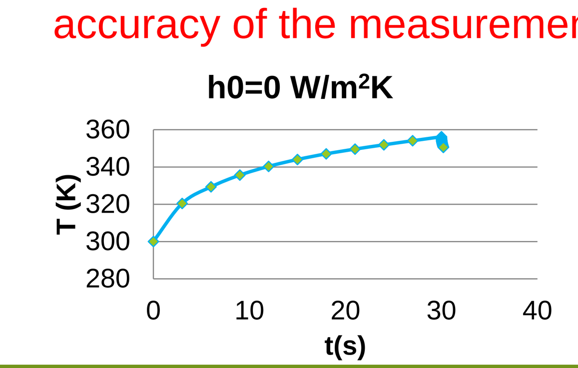
Experimental ZT: Value extracted from simulated data analysis using Harman method

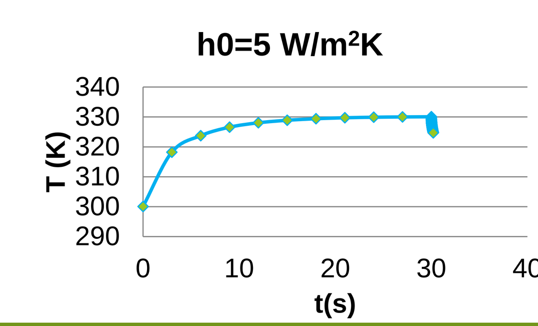
2. Impact of heat losses and comparison of simulation methods (two-step study: stationary+ transient)



The voltage difference reaches the steady state with heat loss from the side walls. Although the times need to reach steady are different, all of them are less than 30s. Heat losses from the sides of the sample impact the accuracy of the measurements.

- Heat losses from the sides of the sample enables the voltage to reach steady value
- **Stationary study**: steady state total voltage
- **Transient study**: no sourcing current though the sample.
- Assuming constant properties: S(T0), σ (T0), T0 is the ambient temperature 300K
- Smaller time step size (0.001s) during the transient process



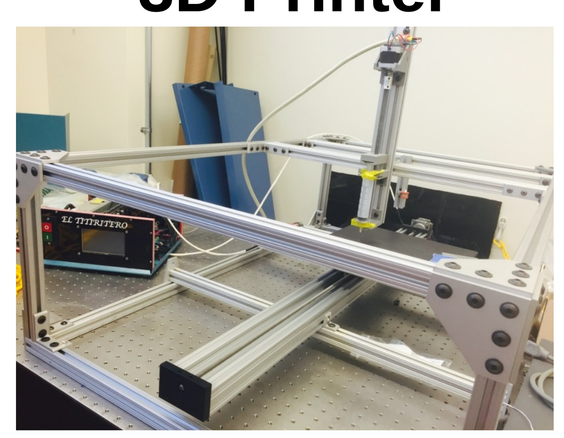


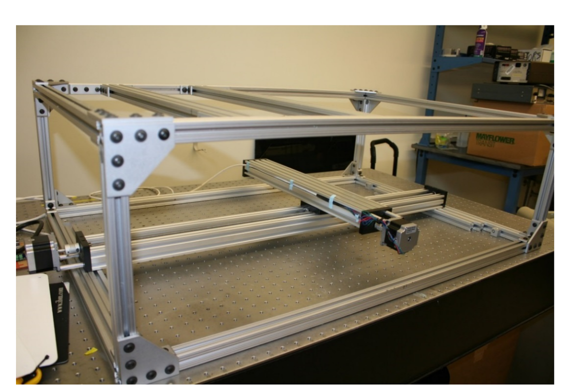
Comparison of the temperature with and without the heat flux

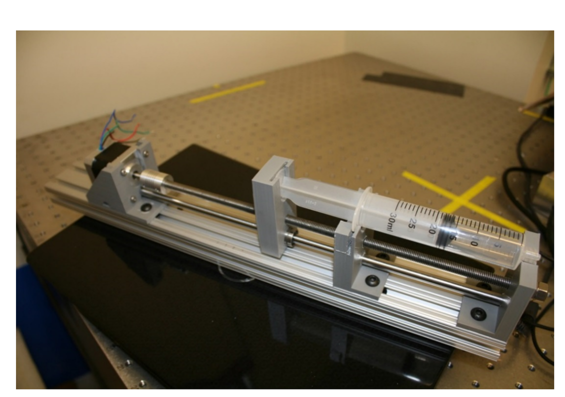
3D Printer Design & Fabrication

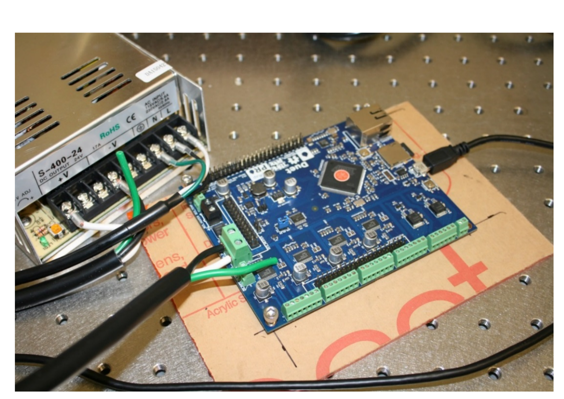
3D Printer Design & Components
- X-Y Motion Control: Printer Frame
- Ink Dispensing: Syringe Pump
- Control System

3D Printer









1. X-Y Motion Control: Printer Frame

Purpose: Movement of X and Y axis to pattern the 2D layout.

Our system uses two uniaxial stages with NEMA motors for automatic positioning. The plate is able to be heating in the further research.

2. Ink Dispensing: Syringe Pump

Purpose: Controlled deposition of the active material.

Our system uses a 3D printed syringe pump, one NEMA motor, and a 30 mL syringe to control the rate of deposition. Selection of the nozzle on the syringe impacts the deposition line width. The design is based on OpenSource.

3. Control System

Purpose: Control the ink dispensing and motion control to print the desired 3D structure.

Our system uses an Arduino DUET board to control the three motors (X,Y axis & syringe pump). Up to five extruders and 3 axis motor can be controlled by this system in the future work. The desired printing pattern is transferred to the Pronterface software using an SD card.

Bismuth Telluride Nanoink
Bismuth Telluride nanopowder （size：325 mesh）. About 200 mg nanoparticles were dispersed in 20 ml water containing 0.2% polymeric stabilizer Solsperse 46 000 (Lubrizol) and then sonicated for 2 min

4. Modified Substrate for Sample Control

Purpose: xxx.

xxx

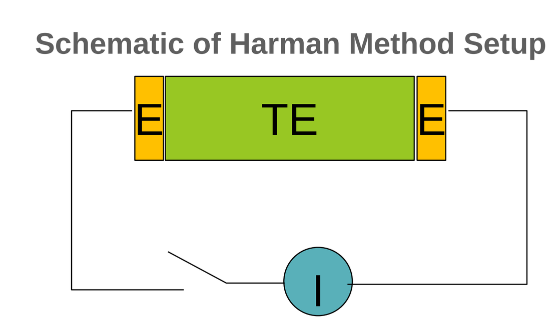
Modified Harman Method for Performance Characterization

The maximum efficiency of thermoelectric device is given by [2]:

$$\eta_{max} = \frac{T_H - T_C}{T_C} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}}$$

Thus efficiency is directly related to the figure of merit *ZT*, which is a lumped parameter including thermal conductivity k, electrical conductivity σ, Seebeck coefficient S, and temperature T: $ZT = \frac{S^2\sigma}{k}T$

The modified Harman method measures the Figure of Merit *ZT* directly, rather than evaluating each material property separately.



When electrical current *I* flows though the sample, heat is generated or consumed at the junctions based on the Peltier effect, and an energy balance at steady state yields

Difference in the Seebeck coefficient between the sample and electrodes   Thermal conductivity

$$IST = k\Delta T \quad (1)$$

Rewriting equation (1) as a function of voltage drop at the electrodes $V_e = I\,R$

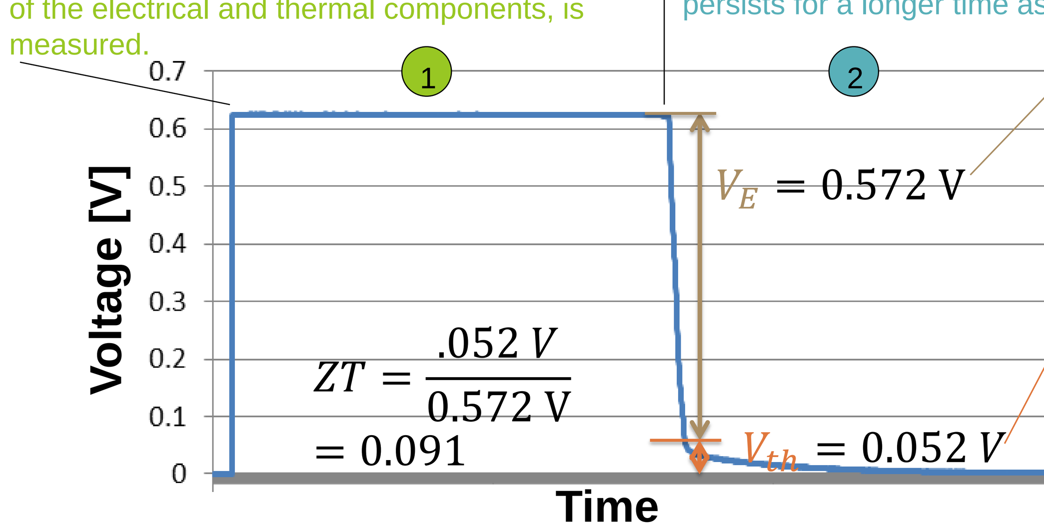
Electrical Conductivity

$$\frac{\sigma S}{k}T = \frac{\Delta T}{V_e} \quad (2)$$

Since the temperature rise is related to the thermal voltage (V_{th}) through the Seebeck coefficient, then $\Delta T = \frac{V_{th}}{S}$, then $\frac{\sigma S^2}{k}T = \frac{V_{th}}{V_e} = ZT$

Phase ①: Current flows through the TE material until the reaches the steady state. In this phase, the total voltage, which is the sum of the electrical and thermal components, is measured.

Phase ②: After the system reaches steady state, the current is shut off. The measured voltage drops rapidly as $I = 0$ (so $V_e = 0$), but the thermal component of the voltage ($V_{th} = S\,\Delta T$) persists for a longer time as the sample cools down.



The difference between the steady state voltage and the voltage shortly after the current stops is the electrical component of the voltage ($V_e = I\,R$)

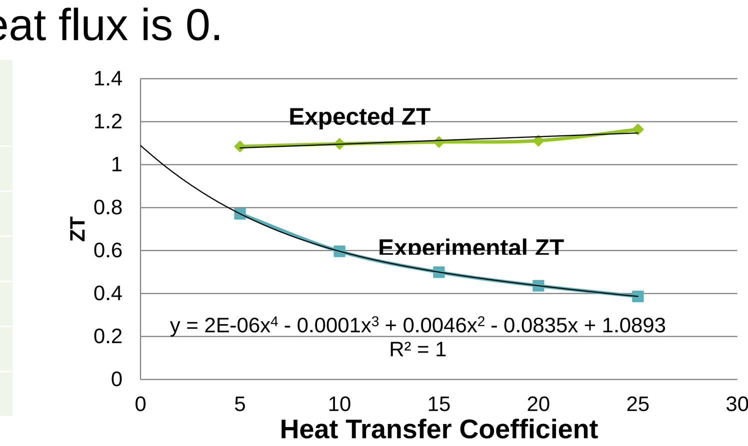
Immediately after the current stops, the sample retains the steady state temperature profile, thus the thermal component of the voltage can be measured from the slowly decaying voltage

Requirements for accurate results:
- System must reach steady state before turning off the source
- Sample design should ensure 1-D heat transfer
- Current must be small to minimize Joule heating

Results & Conclusions

The measured *ZT* value is impacted by the heat loss from the sides of the sample. In order to improve the precision of the Harman method, a extrapolation could be made when the heat flux is 0.

Heat Transfer Coefficient [W/m² K]	Expected (Input) ZT	Experimental ZT	error %
0	1.08	1.09	1%
5	1.085	0.77	-
10	1.10	0.60	-
15	1.11	0.50	-
20	1.11	0.44	-
25	1.16	0.39	-



For the baseline case, the *ZT* using the extrapolation method reasonably matches the expected *ZT* input into the simulations. For cases where the Seebeck coefficient and electrical conductivity are changed, there is increased error in the extracted *ZT* (4 - 12 %).

Additional work is needed to implement the Harman method in non-ideal measurement situations where heat losses are significant.

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References

[1]
[2]
[3]
[4]
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