Thermoelectric and Piezoelectric Energy Harvesting

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What to remember:

- Thermoelectric
  - Composite materials show promise, further improvements under way
  - Next steps focus on device prototyping

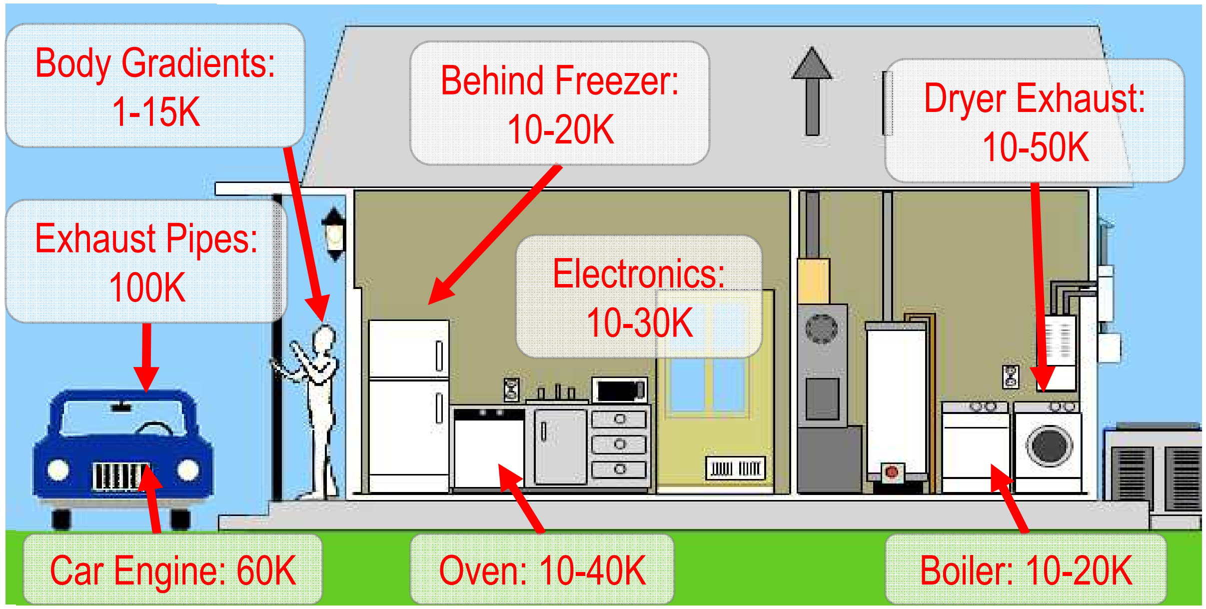
- Piezoelectric
  - Low-frequency resonance attained (~31Hz)
  - Voltage output achieved from HVAC duct (22 mV_{rms})
  - Integration of harvester & capacitor under way

Energy Harvesting from Waste Heat

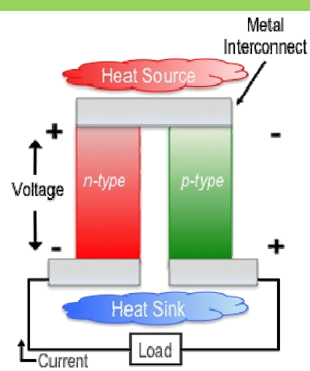
Alternate applications

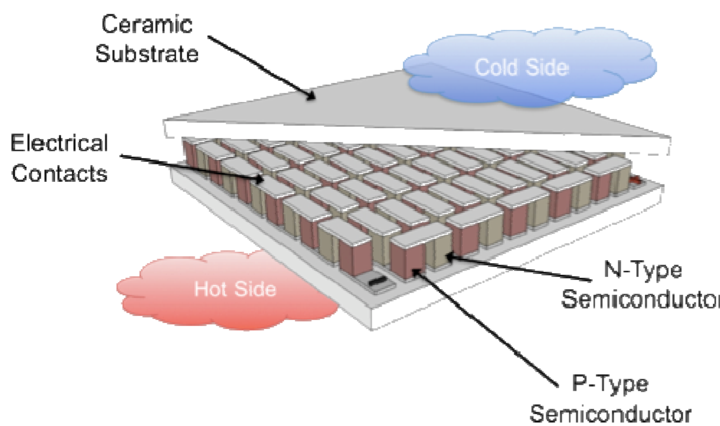
Location	Source	Gradient
Factories	Exhaust pipes, Boilers, condensers	10-80K
Vehicles	Engine Exhaust pipes	60K >100K
Airplanes	Cabin to External	10-50K

Residential temperature gradients



Thermoelectric Energy Harvesting





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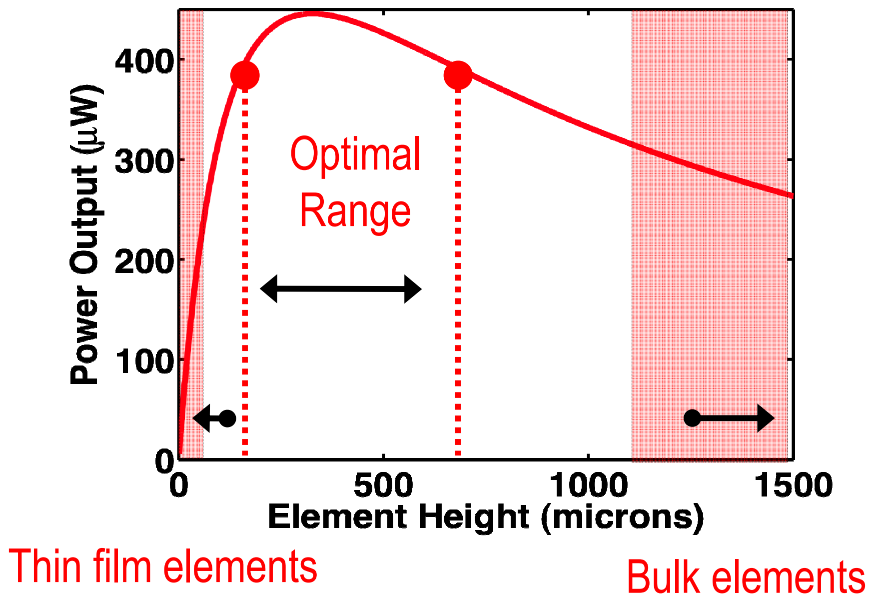
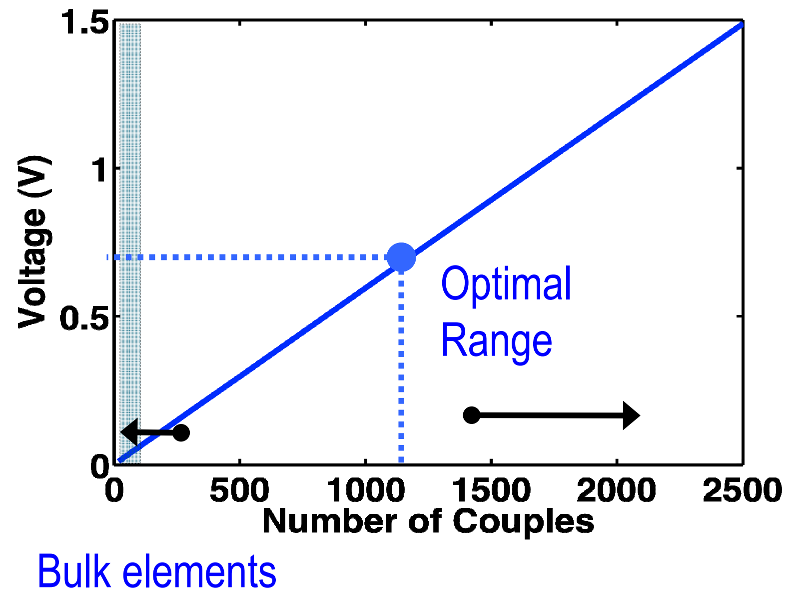
Design of Thermoelectric Devices

Power Dependence



Voltage Dependence



Design Choice:

- Traditional technologies don't optimize for power output
- For waste heat sources, it is best to optimize for maximum power
  - Requires 100-500 μ m element sizes

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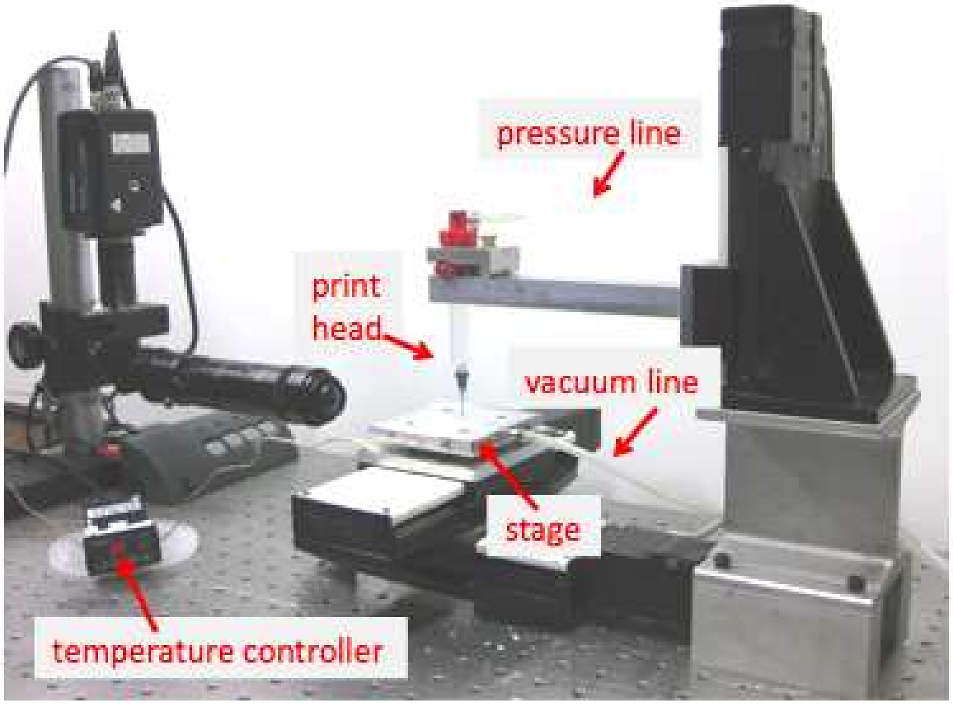
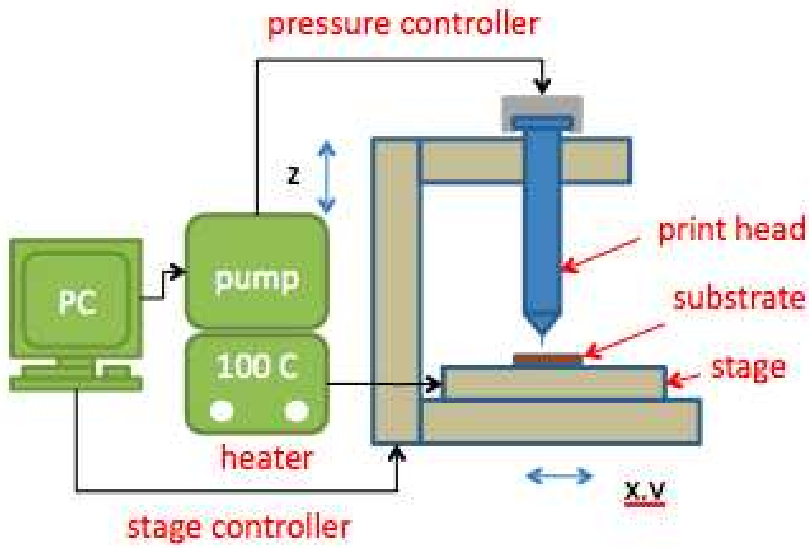
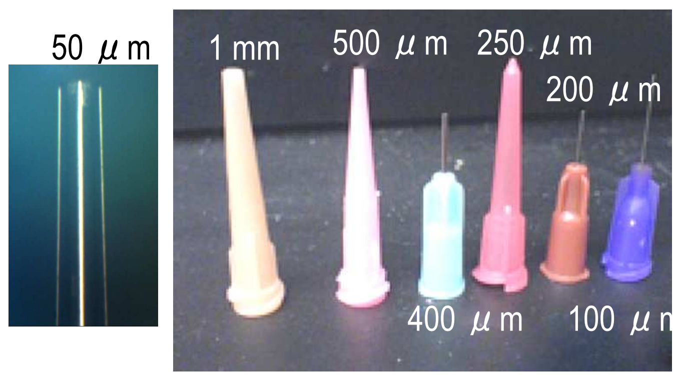
Direct-Write Dispenser Printing

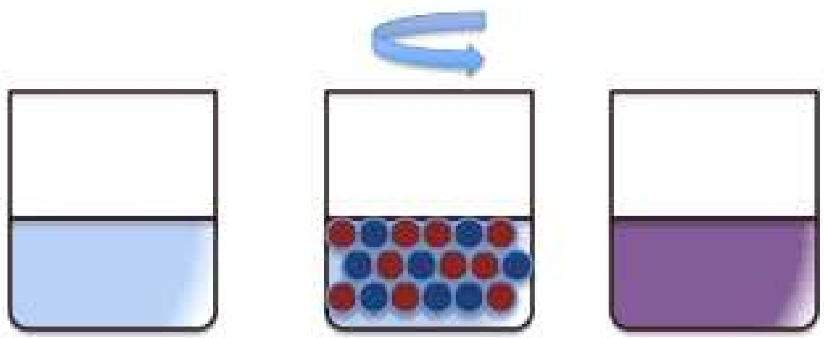




- 3 axis (X, Y, Z) Dispenser Printer
- 5 μm resolution stage
- Feature size limited by syringe tip size



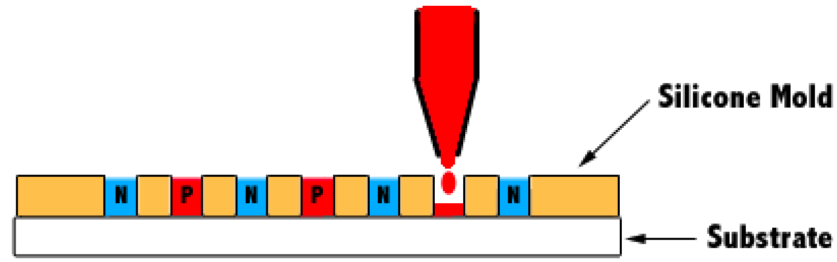
Dispenser Printed Thermoeletrics



Polymer Resin

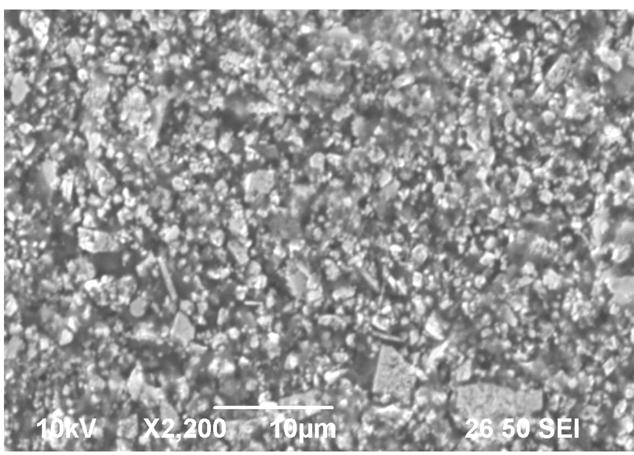
Add Active Particles

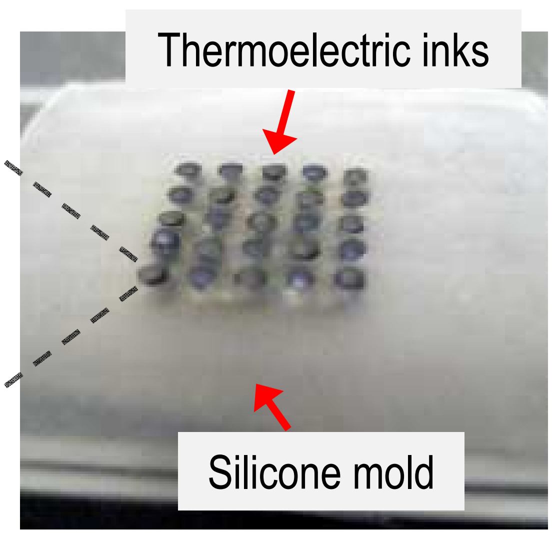
Ink



Print

SEM Image of Printed Thermoelectric Materials





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Initial Material Properties

If bulk material properties could be retained (ΔT = 10 K):
Predicted Power = 237.6 μW, Voltage = 1.18 V

Bulk

N-type Bi_2Te_3
α : 195 μV/K
ρ : 1.35e-5 Ω-m
λ : 1.4 W/m-K

P-type Bi_2Te_3
α : 230 μV/K
ρ : 1.75e-5 Ω-m
λ : 1.2 W/m-K

Current best material properties (ΔT = 10 K)
Predicted Power = 61.2 μW, Voltage = 1.33 V

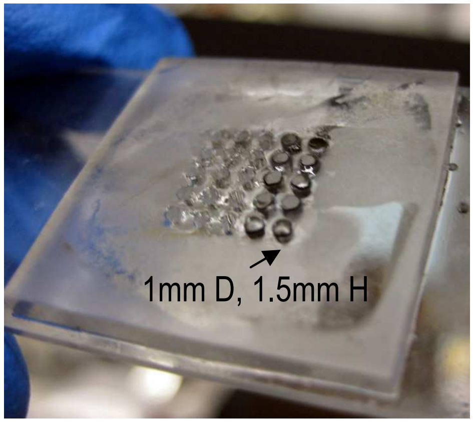
Current

N-type Bi_2Te_3
α : 200 μV/K
ρ : 2.5e-4 Ω-m
λ : 0.5 W/m-K

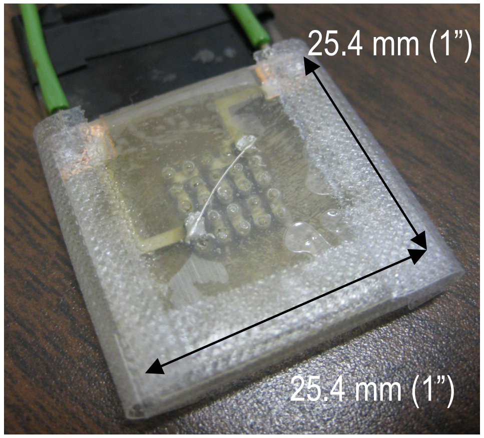
P-type $Bi_{0.5}Sb_{1.5}Te_3$
α : 250 μV/K
ρ : 2.5e-4 Ω-m
λ : 0.5 W/m-K

Preliminary Findings

- Existing bulk devices cannot meet the requirements for low waste heat sources to power
- Dispenser printing is a viable technique for creating the optimal size factors
- Initial materials show promising behavior
- Further work is being performed on materials optimization & device fabrication



Printed Thermoelectric Pillars

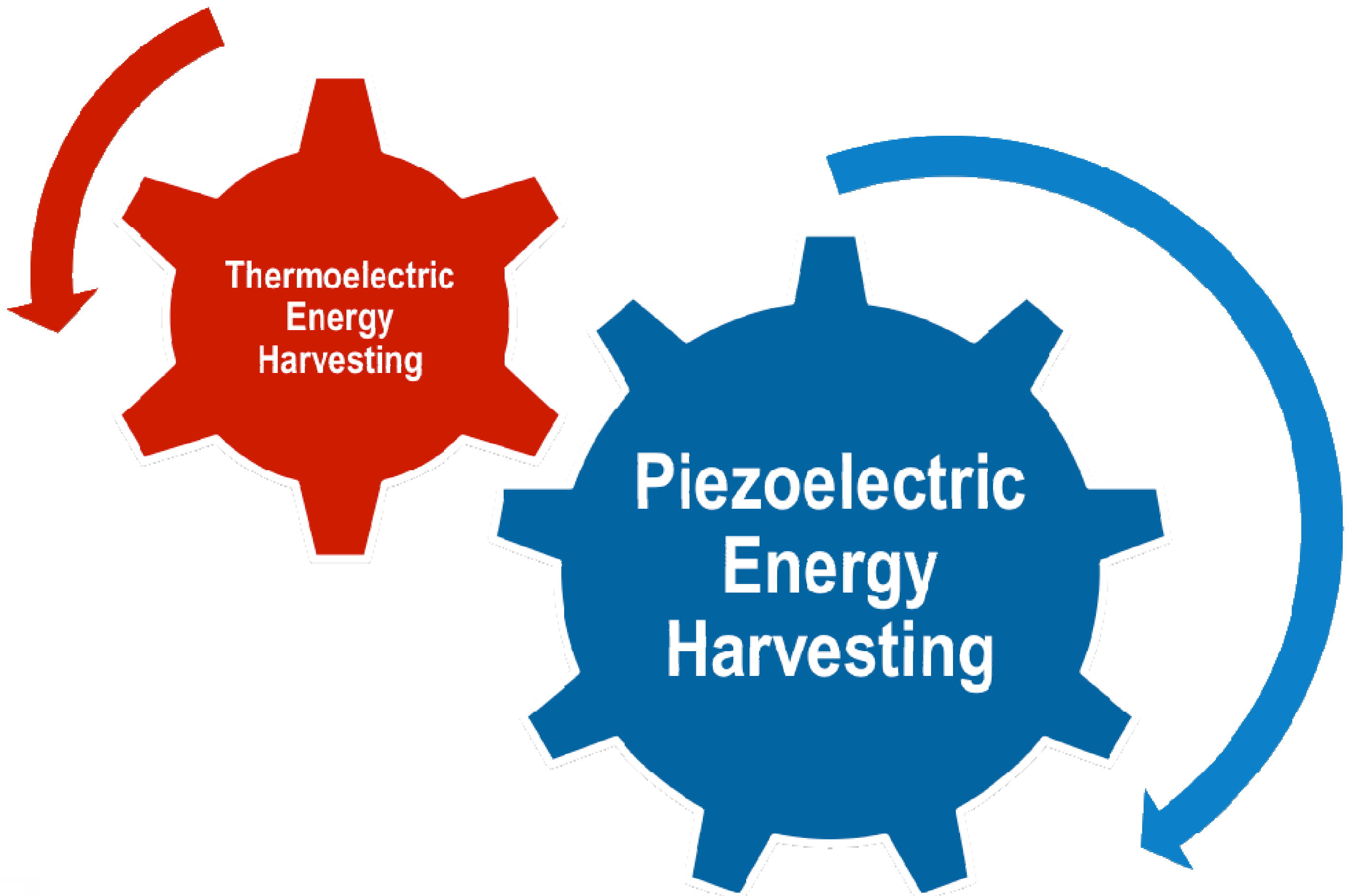


Device Prototype

Predicted Performance (10K gradient)

Picocube Demand	Predicted
Power : 10 μW avg. Voltage : ***0.7 V (DC conv)***	Power : 61 μW. Voltage : ***1.33 V***

Switch gears



Ambient Vibrations in the Built Environment

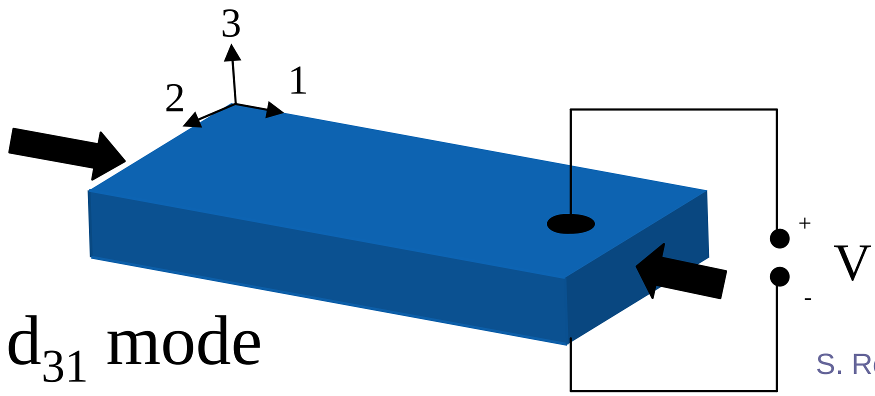
- Vibrations in buildings are low *acceleration,* low *frequency*

Acceleration and frequency of several vibration sources in buildings

	acceleration (g's)	frequency (hz)
Washing machine	0.31	85
Clothes dryer	0.36	121
Small microwave oven	0.23	121
External windows by street	0.07	100
HVAC Etcheverry roof	0.25	185
HVAC duct Etcheverry 5th floor	0.34	29
Refrigerator	0.02	59

S. Roundy, PhD Thesis UC Berkeley 2003.
Romy Fain, UC Berkeley undergraduate.

Piezoelectricity



d_{31} mode

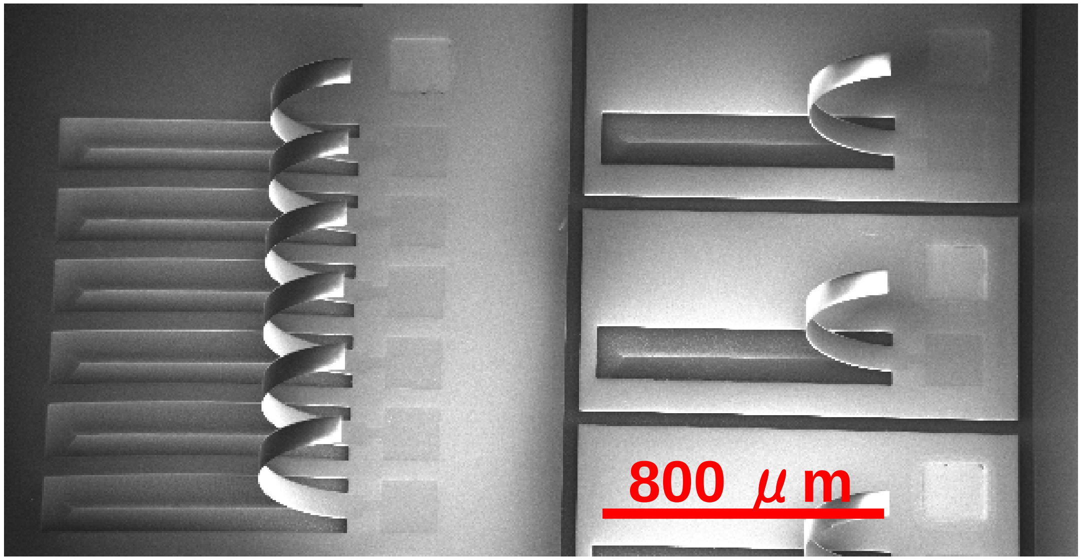
S. Roundy, PhD Thesis UC Berkeley 2003

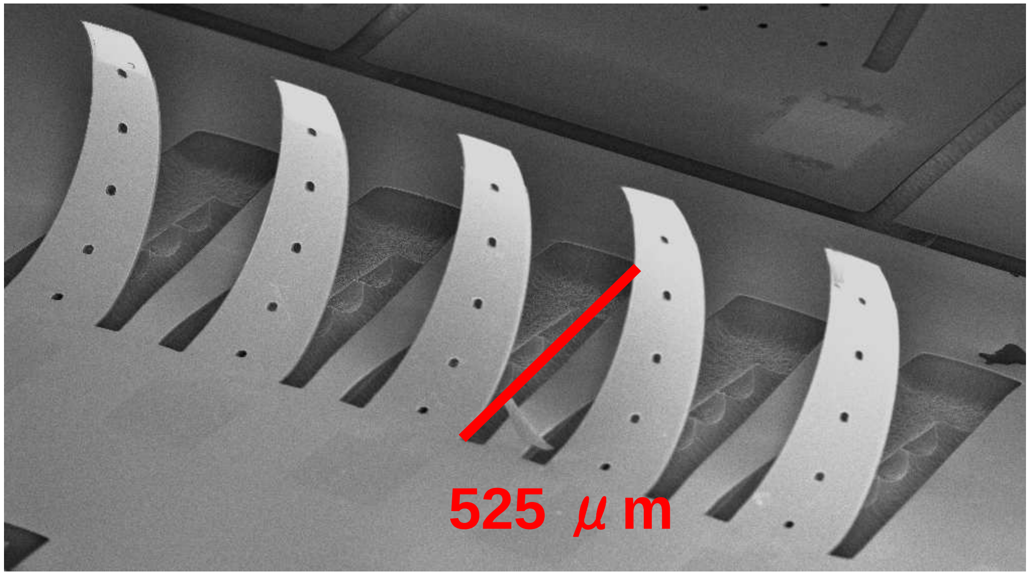
D_i = electric displacement
S_i = strain
T_i = stress
E_i = electric field
d_{31} = piezoelectric constant
ε_{33} = permittivity (at constant stress)
s_{11} = elastic compliance (at constant electric field)

$$D_3 = d_{31}T_1 + \varepsilon_{33}^{T} E_3$$

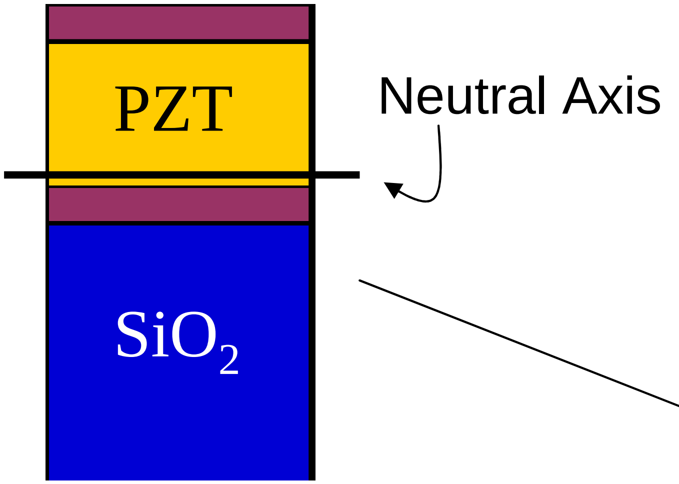
$$S_1 = s_{11}^{E} T_1 + d_{31} E_3$$

First generation prototypes





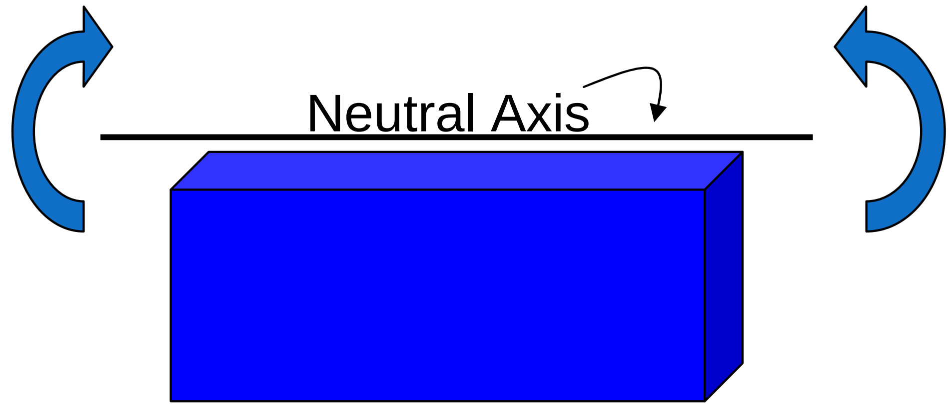
Curvature of beams - stress compensation

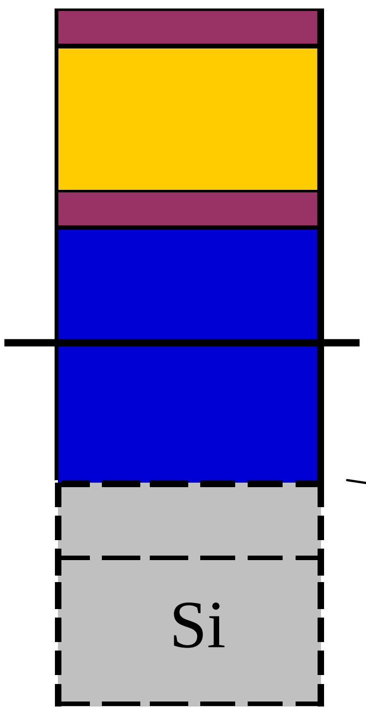


(not to scale)

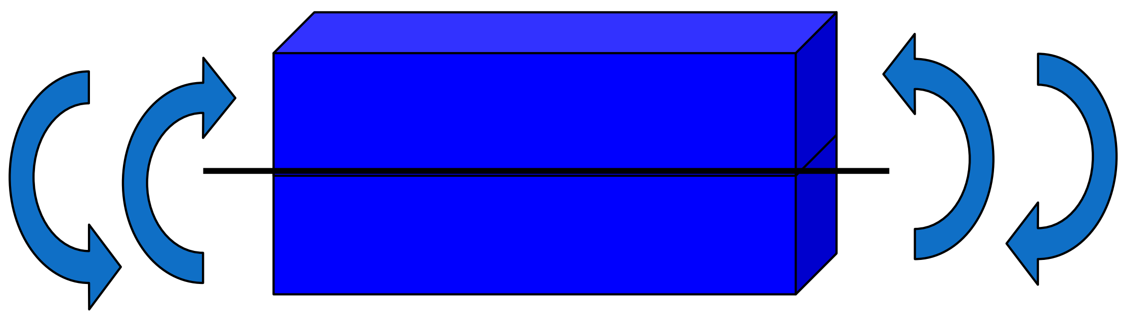
$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n}\left(\overline{Q_{ij}}\right)_k \left(z_k^3 - z_{k-1}^3\right)$$

$$\{M\} = [B]\{\varepsilon^o\} + [D]\{\kappa\}$$



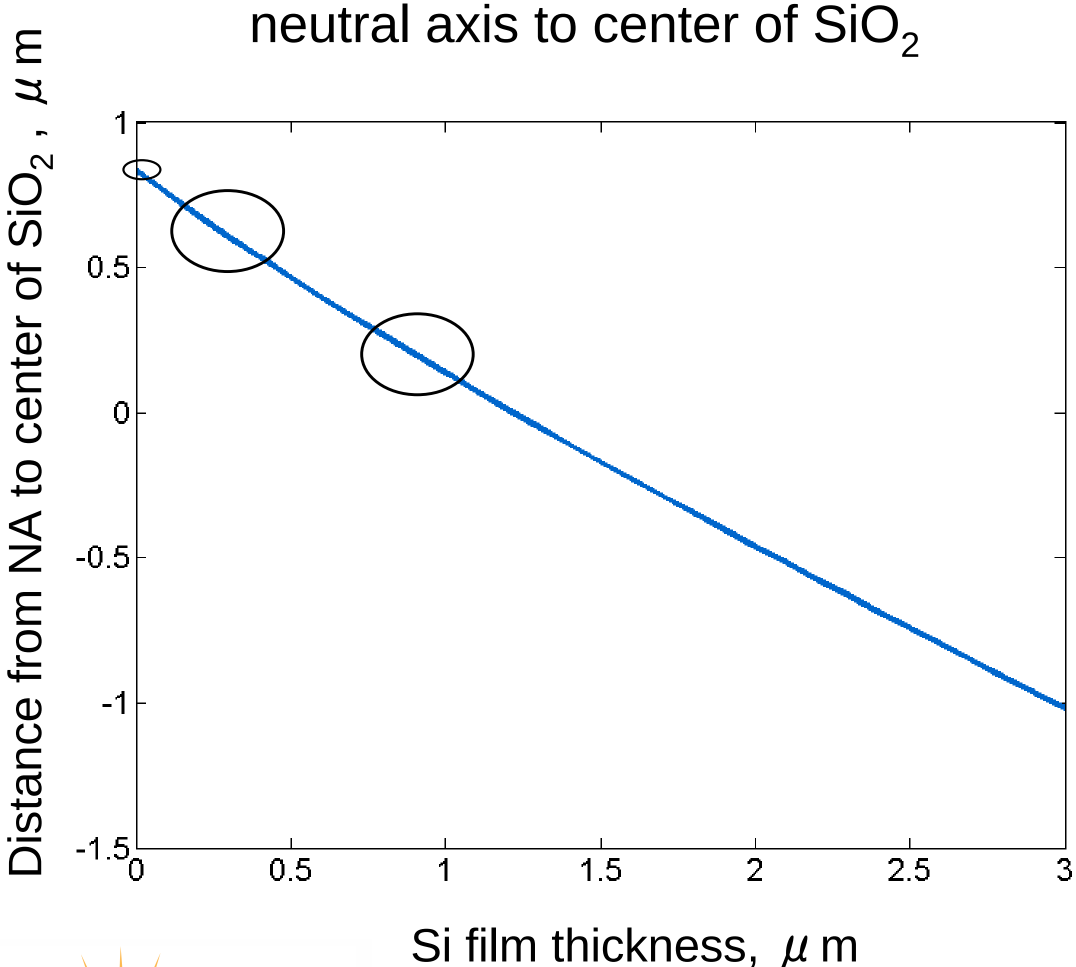


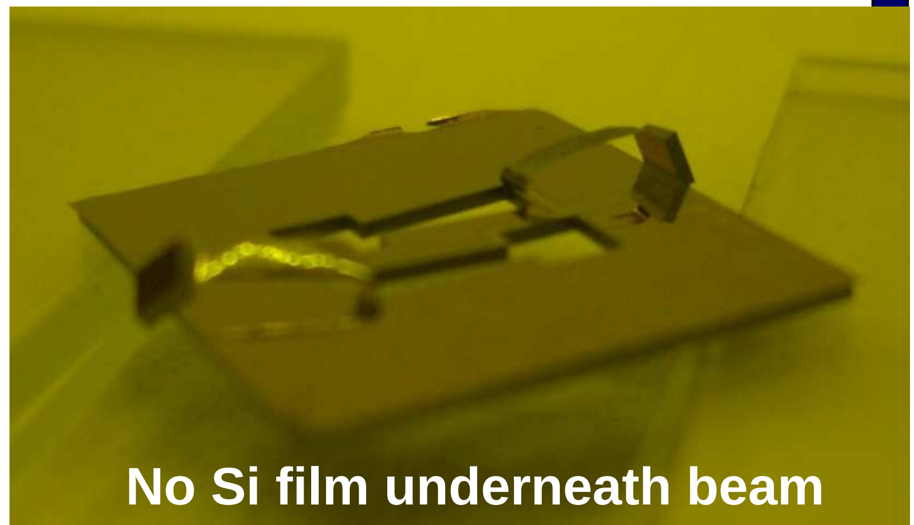
Electrode	~200 nm
PZT	~ 800 nm
Electrode	~160 nm
SiO_2	~ 1400 nm
Si	~250 – 1200 nm

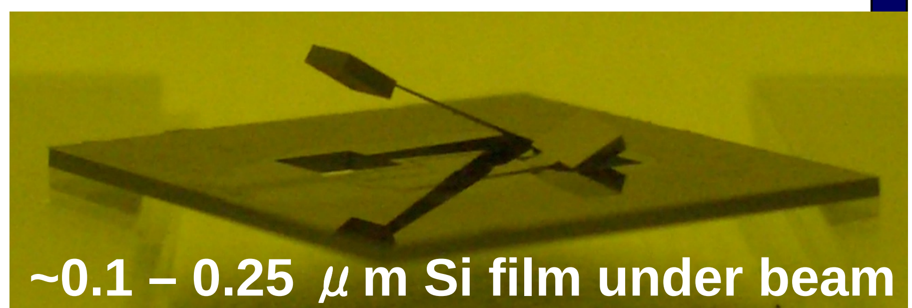


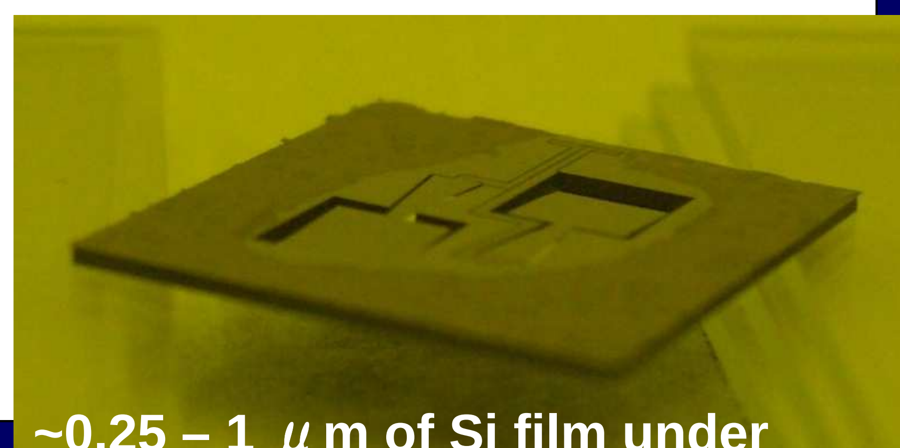
Stress compensation results

Si film thickness vs distance from neutral axis to center of SiO_2









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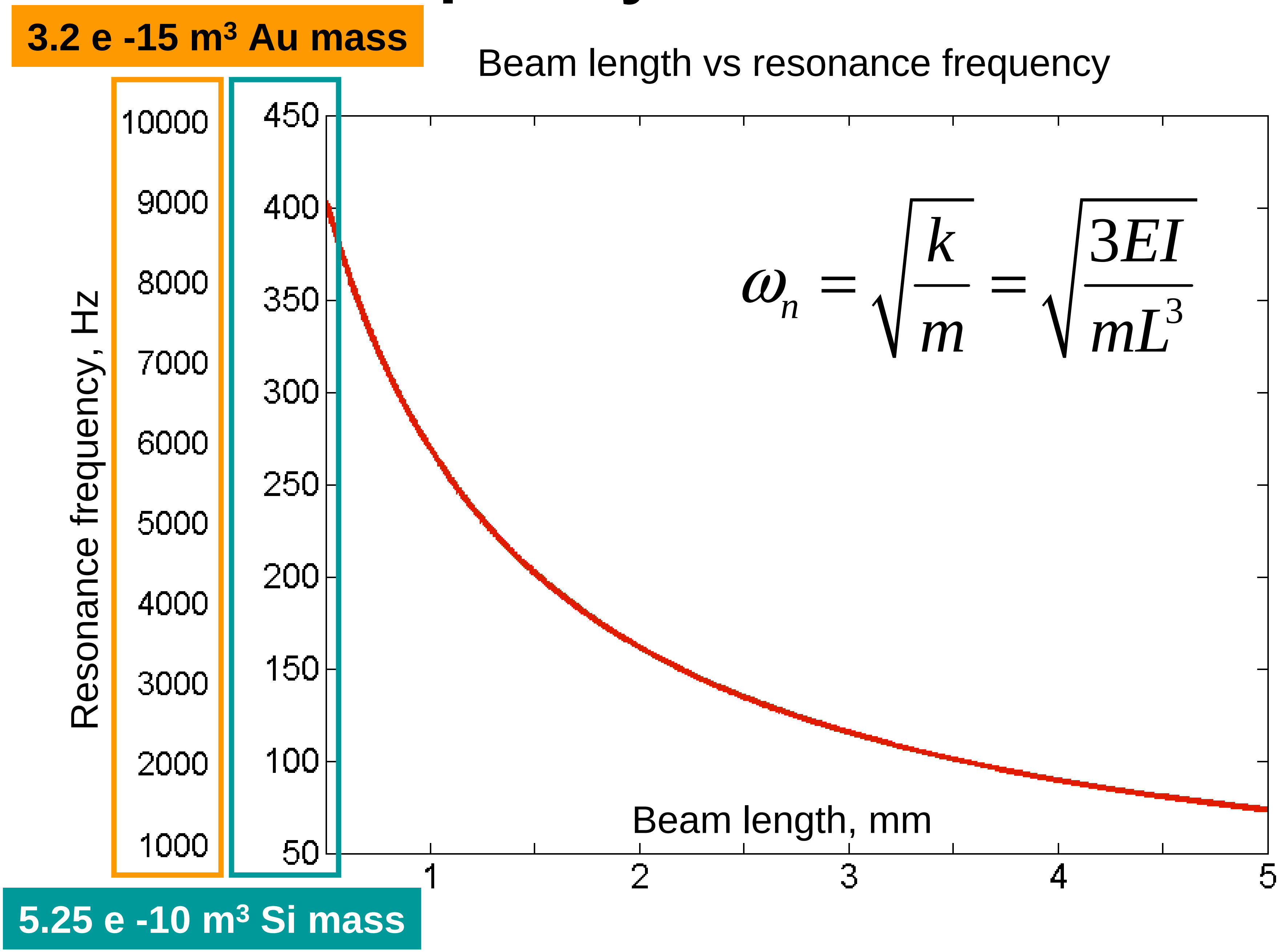
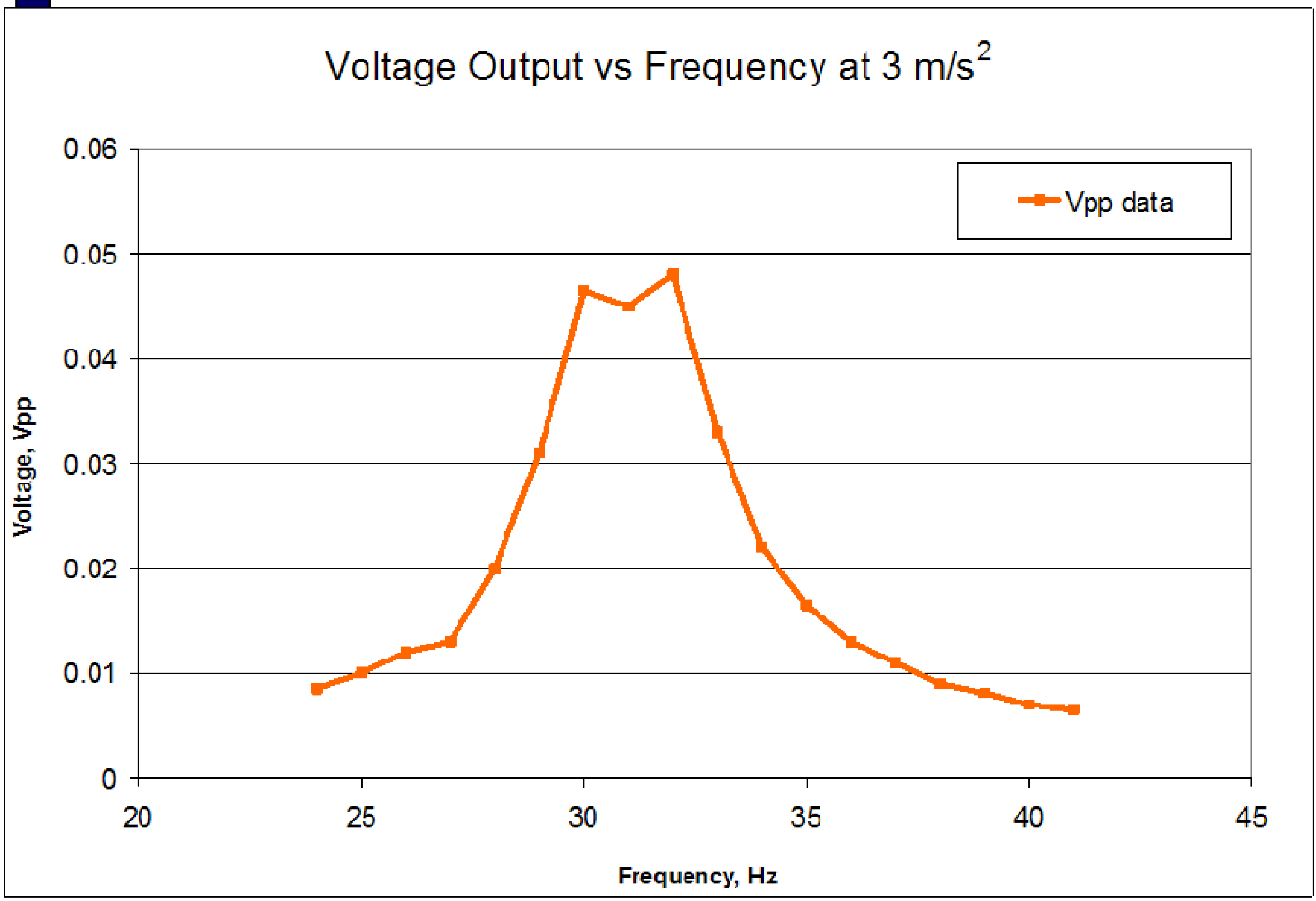
Frequency reduction

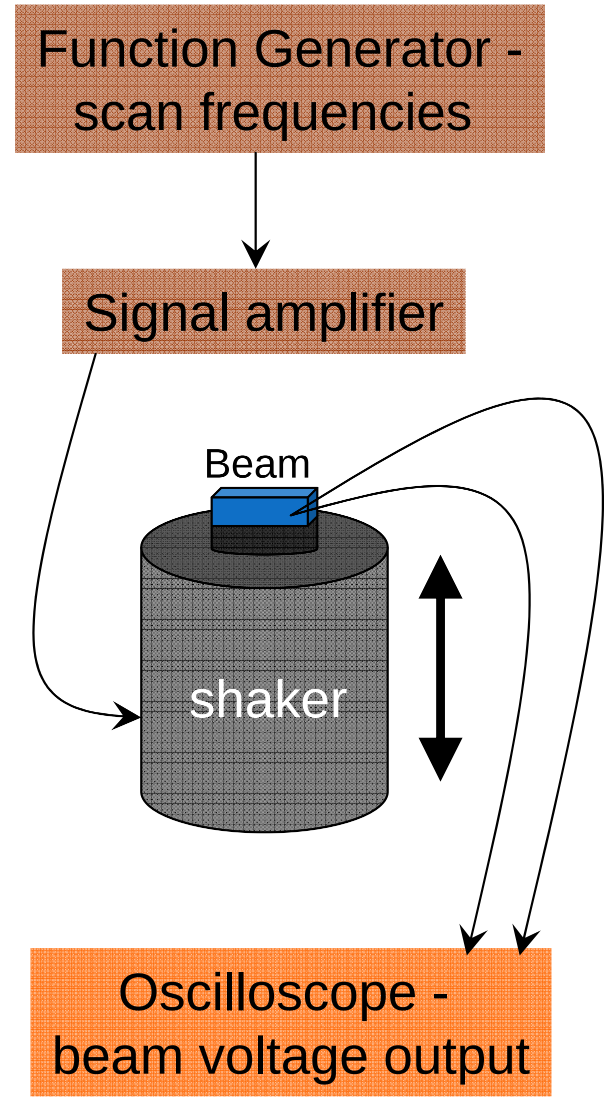


$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{3EI}{mL^3}}$$

Data confirms low resonance frequency

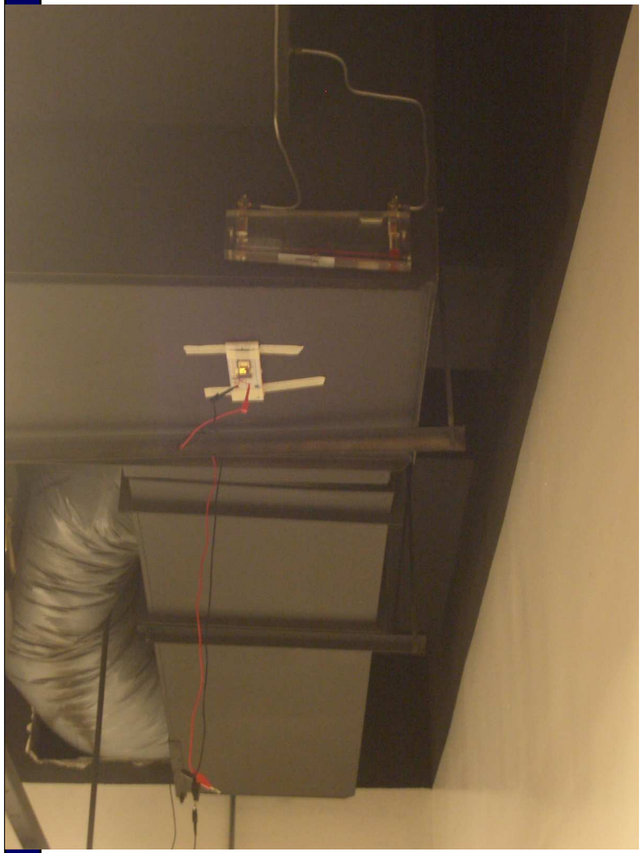
Model predicts 31 Hz if Si film t = 0.25 microns, higher freq if Si film is thicker.

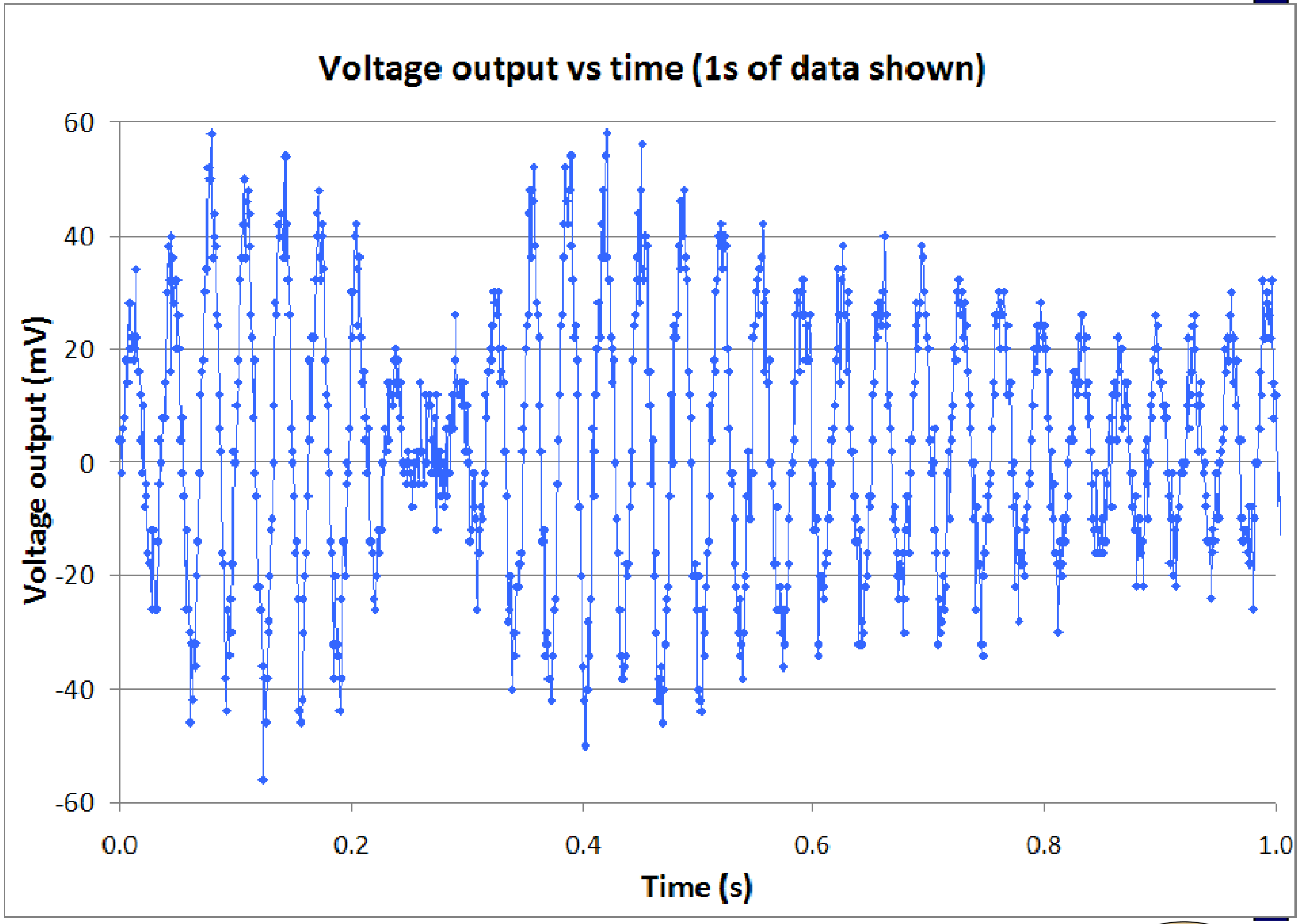




Preliminary results: ambient vibrations

Voltage output from energy harvester on duct ~22 mV_{rms}



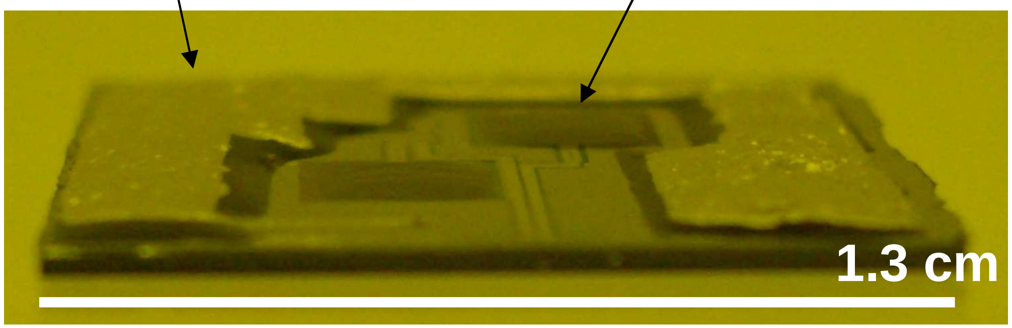


Printed mass, printed capacitor

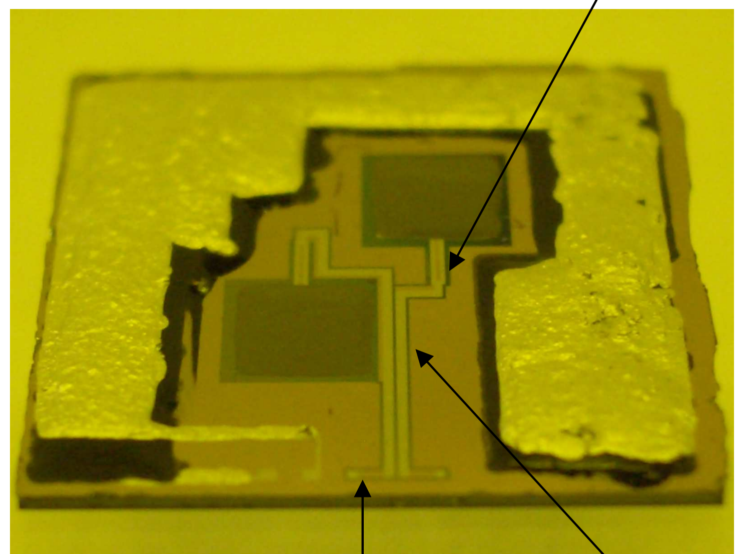
This is the first phase of work to integrate energy harvester with energy storage

Dispenser-printed capacitor sandwiched between current-collectors

Dispenser-printed proof mass



Beam structure



Electrode bond pads

Electrode leads

Take-aways

- Thermoelectric
  - Composite materials show promise, further improvements under way
  - Next steps focus on device prototyping

- Piezoelectric
  - Low-frequency resonance attained (~31Hz)
  - Voltage output achieved from HVAC duct (22 mV_{rms})
  - Integration of harvester & capacitor under way

Thank you! Questions?