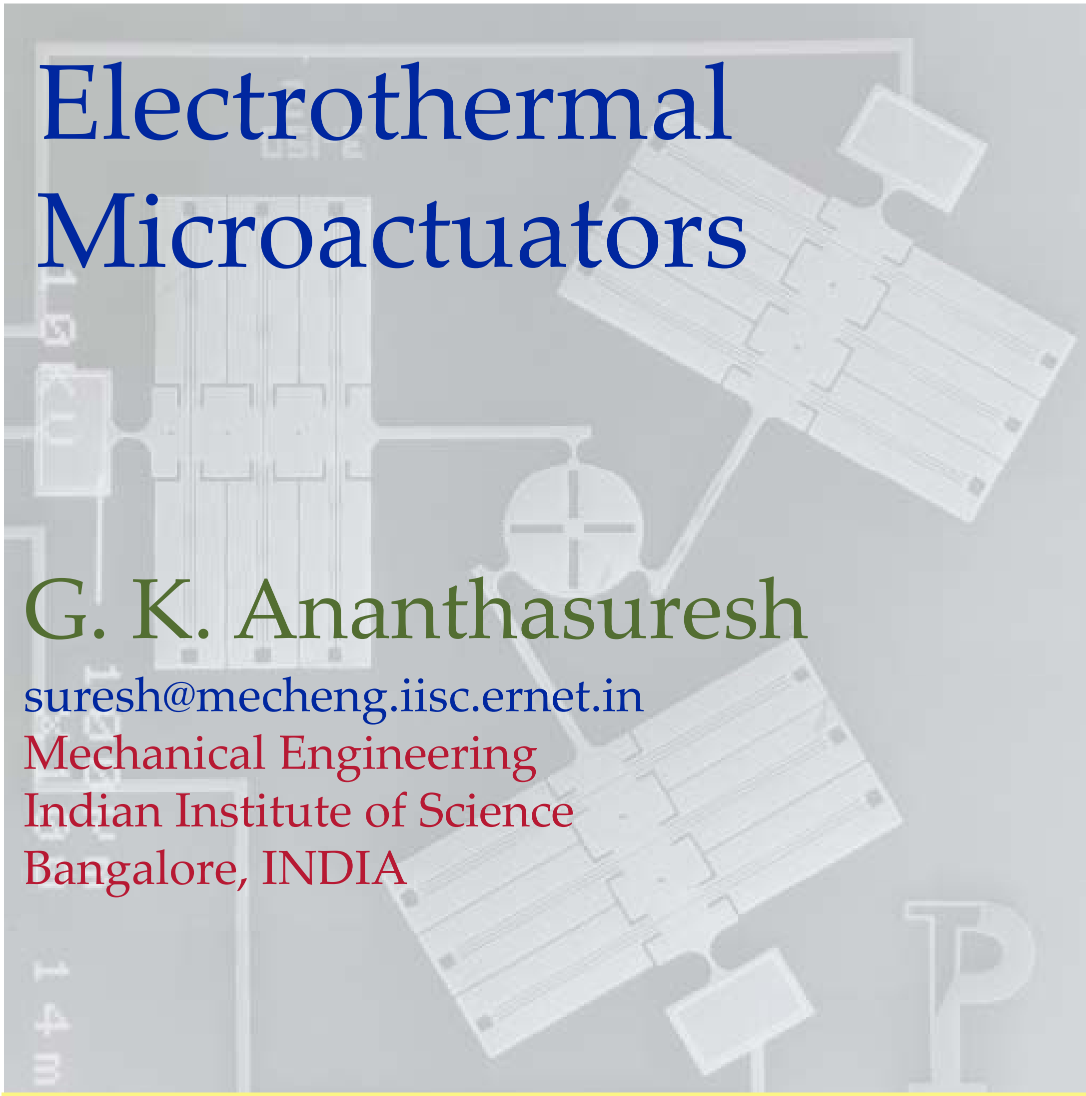

Electrothermal Microactuators

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Effects of heating on mechanical deformation

$$\alpha = \frac{d\varepsilon}{dT}$$

Temperature coefficient of expansion

$$\varepsilon(T) = \varepsilon(T_0) + \alpha(T - T_0)$$

Uniaxial thermal strain

$$\varepsilon_{mismatch}(T) = (\alpha_f - \alpha_s)(T - T_0)$$

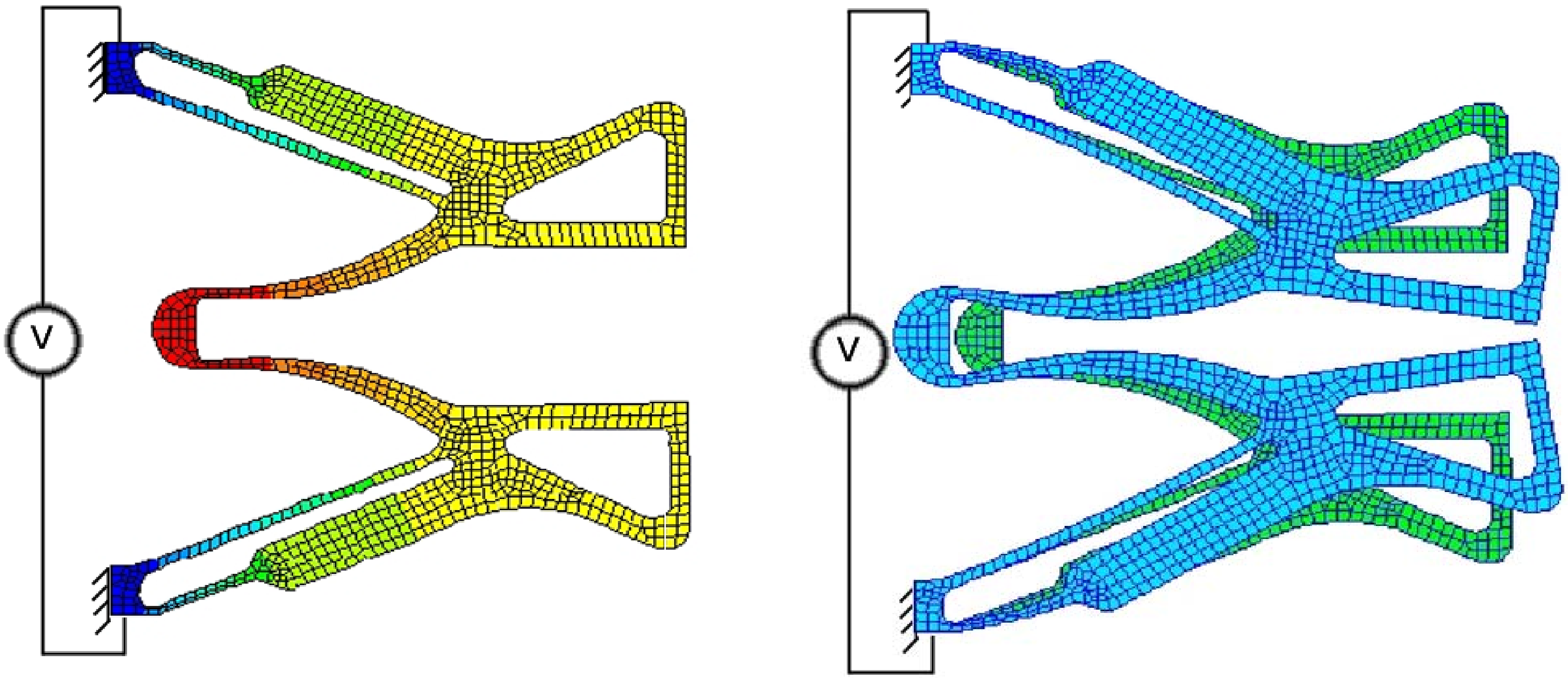
$$\sigma_{mismatch} = \left(\frac{E}{1-\nu}\right)\varepsilon_{mismatch}$$

Mismatched thermal strain and stress between a film and a substrate that are bonded to each other.

$$\varepsilon_z = -\left\{\alpha_f + 2\nu(\alpha_f - \alpha_s)\right\}(T - T_0)$$

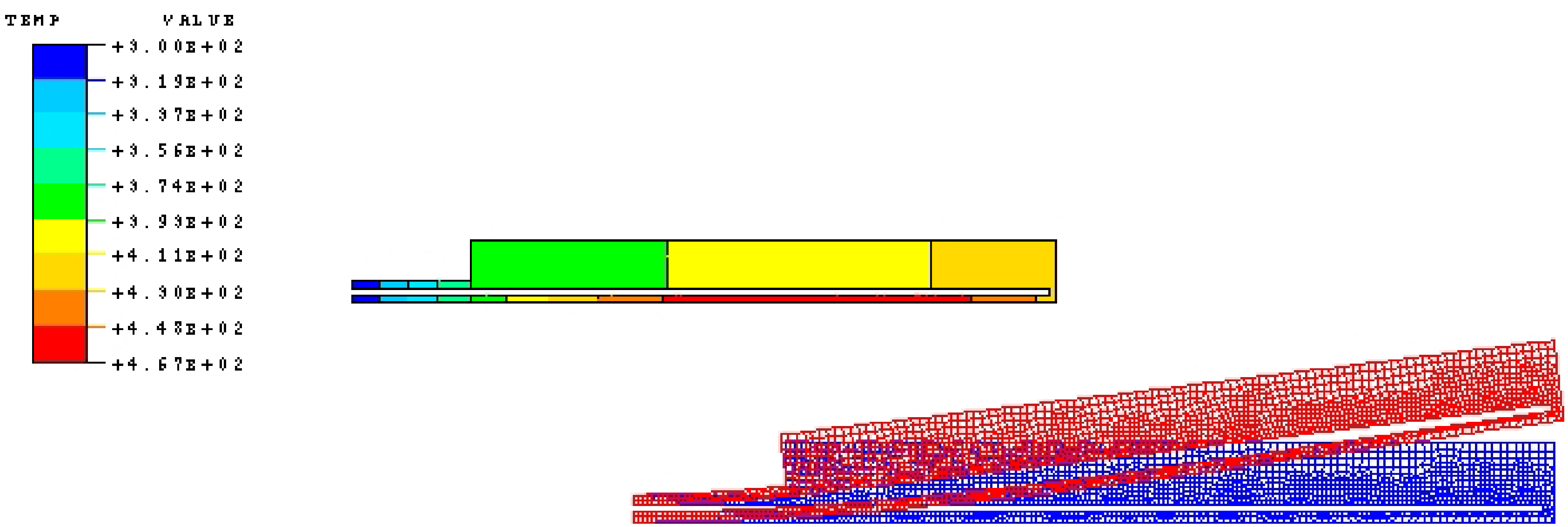
Total strain for a sandwiched film in the thickness (z) direction

Embedded actuation:
Actuator and mechanism are together.



Heatuator: Series connection

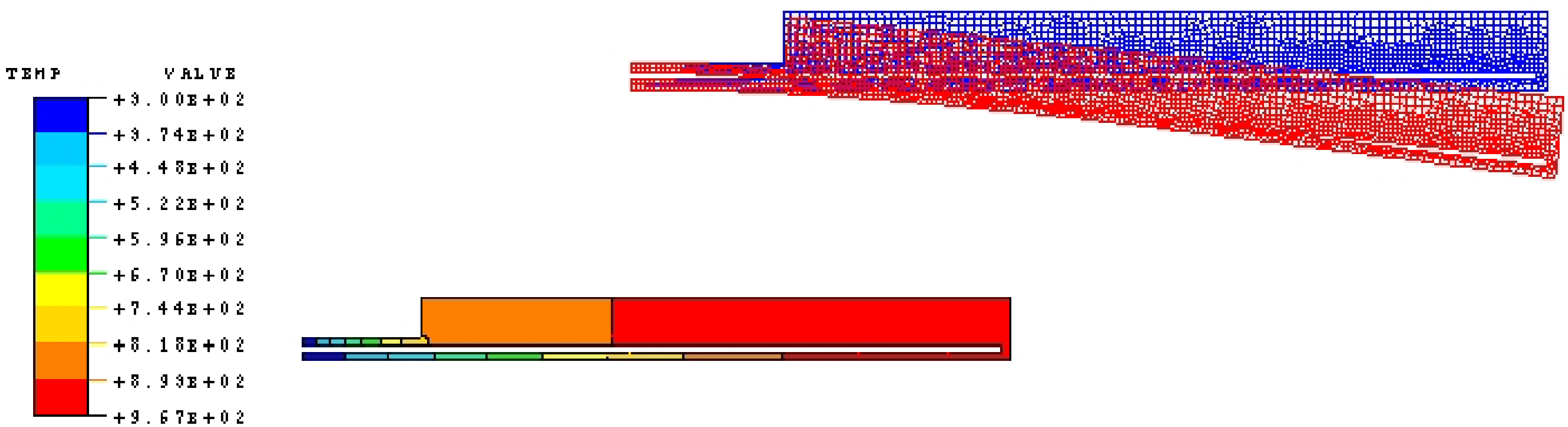
(Guckel et al., 1992; Comtois and Bright, 1996)



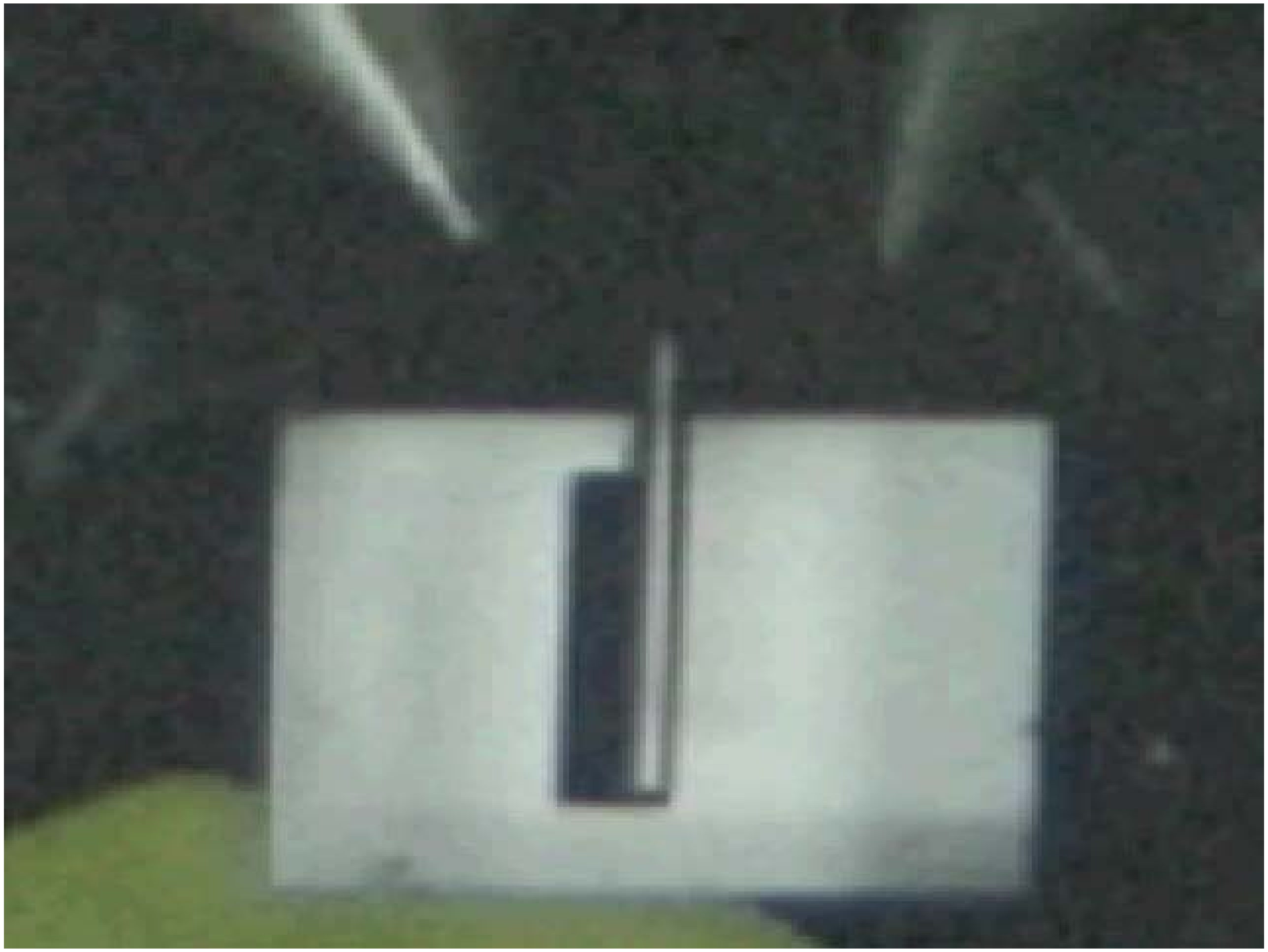
Heatuator: parallel connection

(Moulton and Ananthasuresh, 1997)

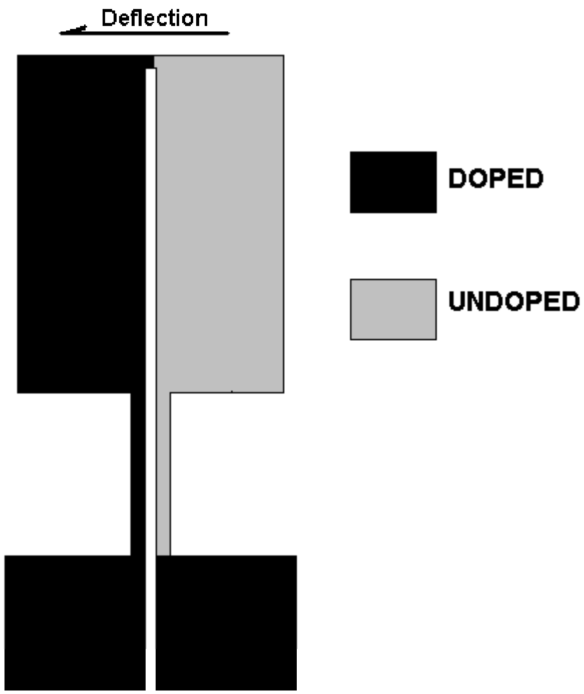
Parallel connection

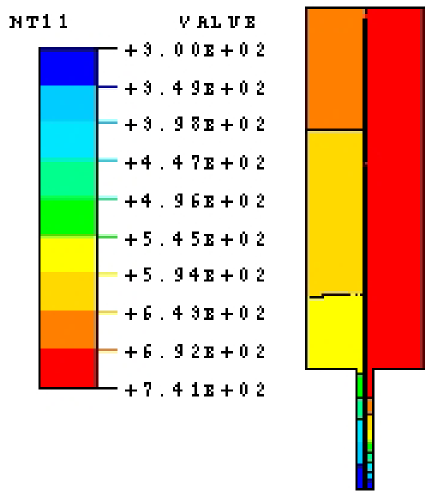


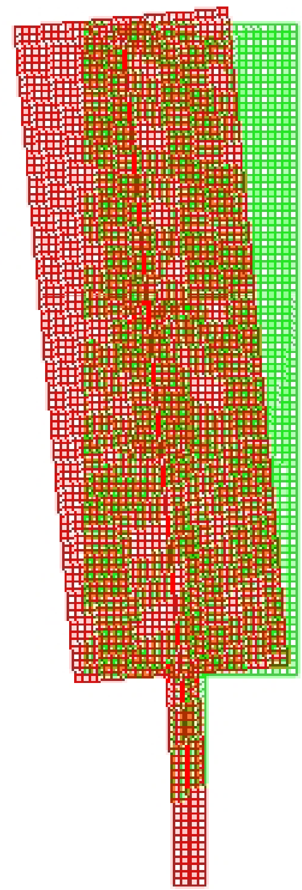
Heatuator: working



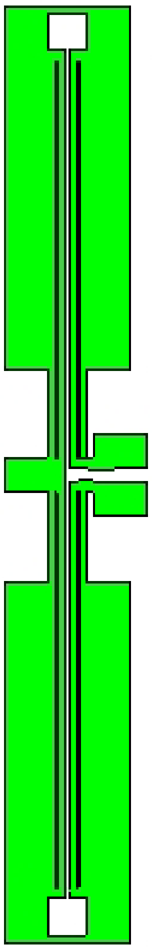
Heatuator with elective doping (if made with silicon)

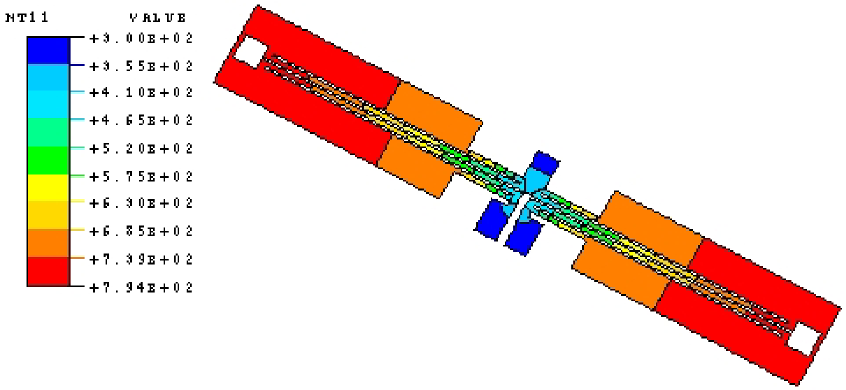


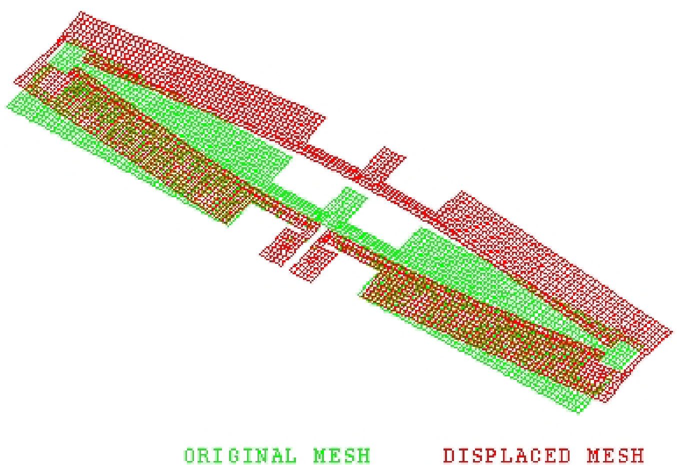


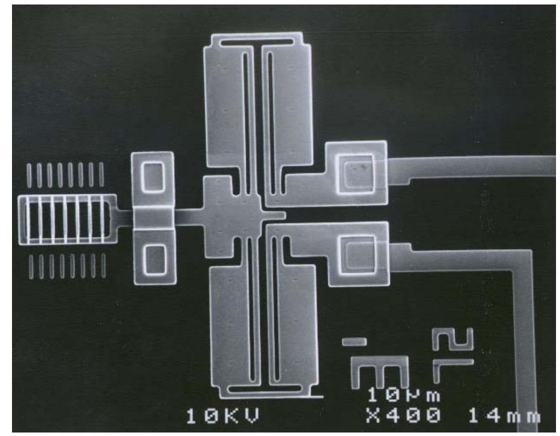


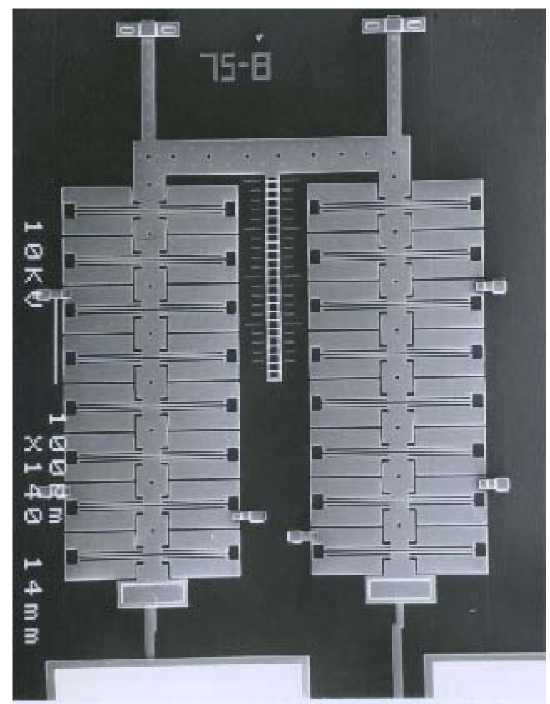
ETC expansion block





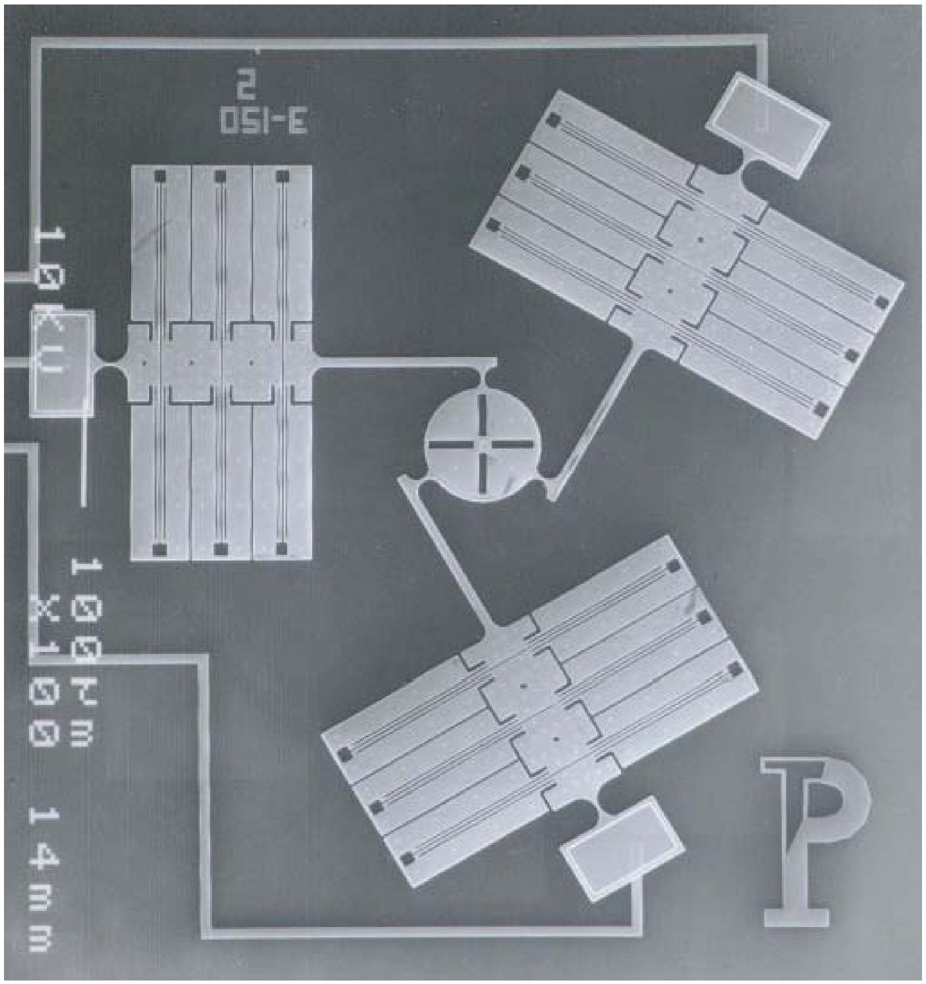






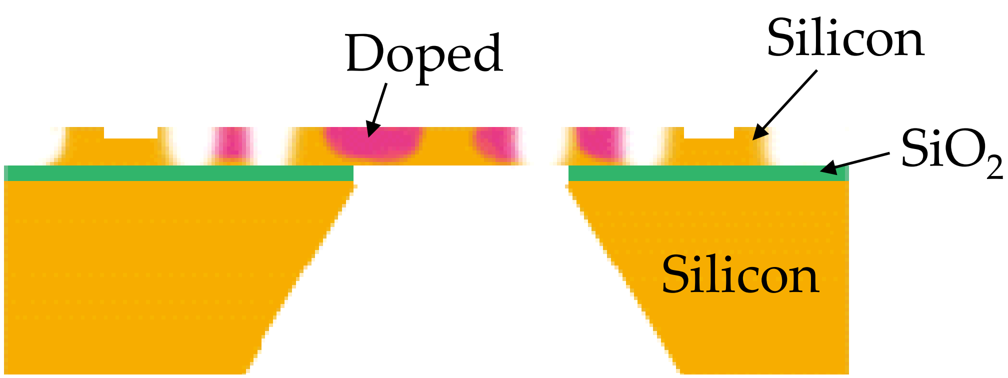
G.K. Ananthasuresh, Indian Institute of Science

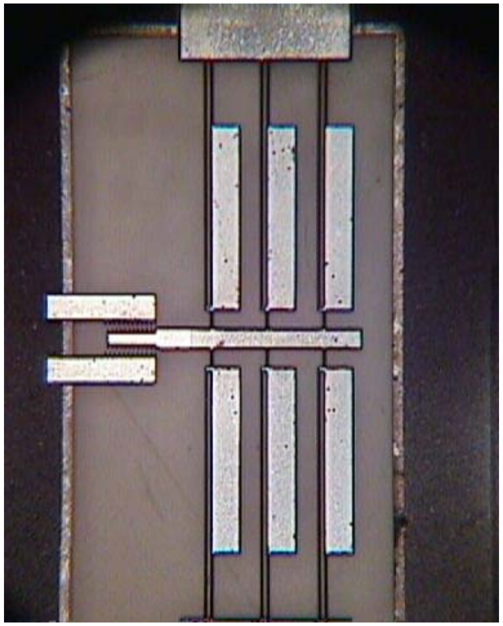
ETC Parallel micro manipulator

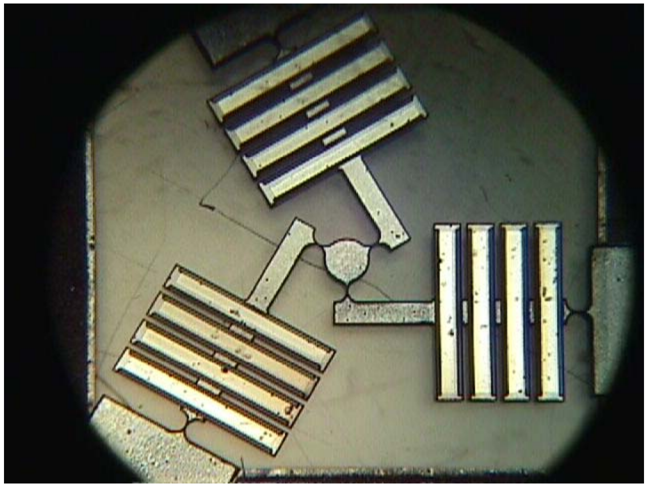


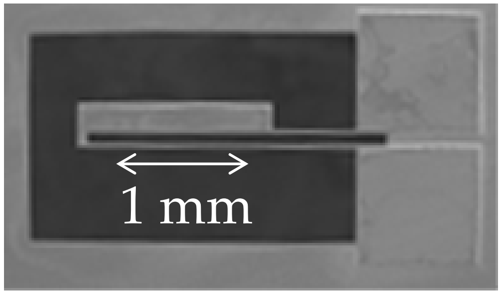
With three degrees of freedom; Made using MUMPs, polysilicon.

Devices made with PennSOIL



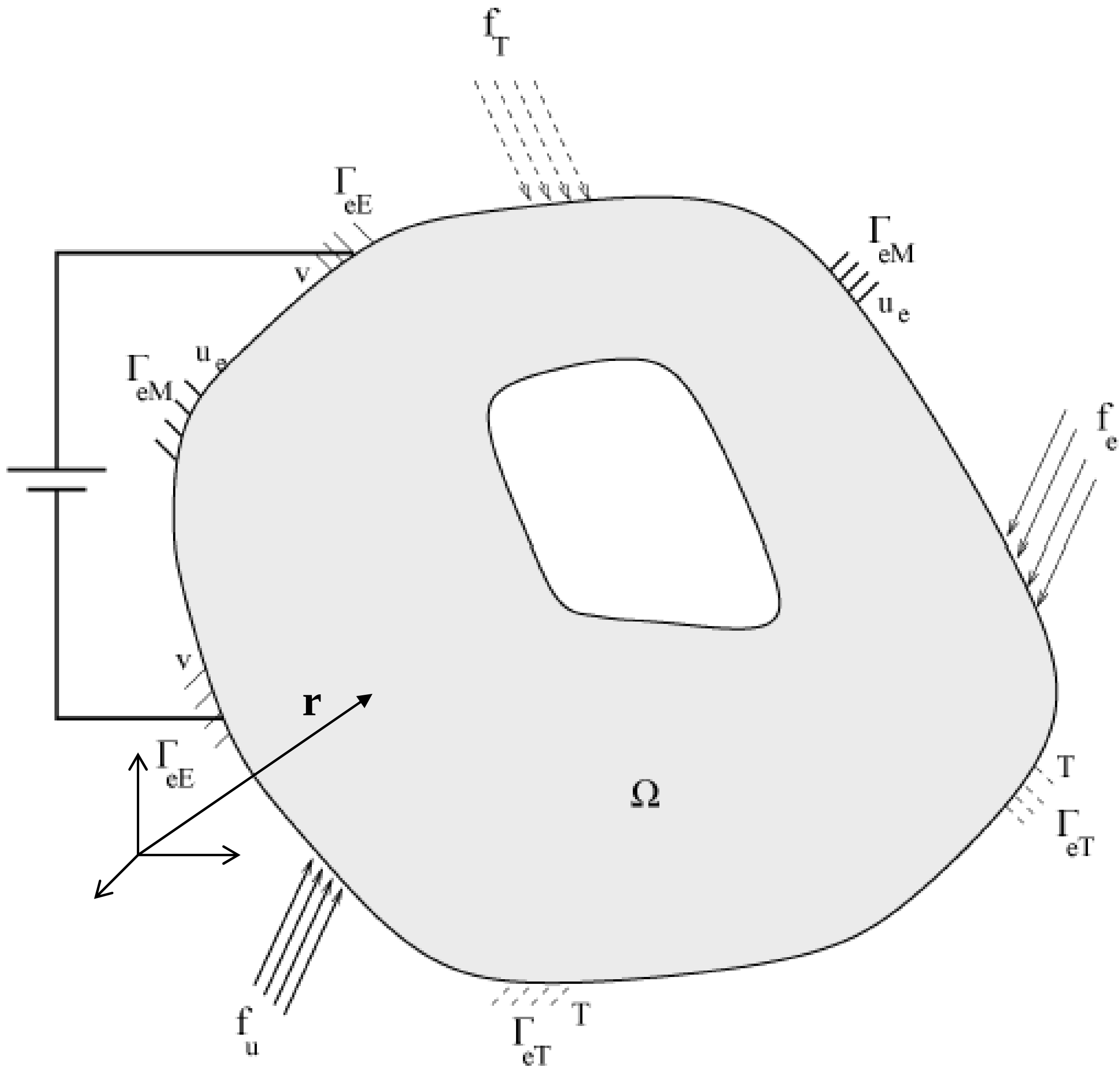






Modeling

V



Governing equations (steady-state)

Electrical Domain

$$\nabla \cdot (\tilde{k}_e \nabla v) + i_e = 0 \quad \text{in } \Omega$$

$$v = v_e \quad \text{on } \Gamma_{eE}$$

$$\bar{n} \cdot (\tilde{k}_e \nabla v) = f_e \quad \text{on } \Gamma_{nE}$$

Elastic Domain

$$\nabla \bullet \tilde{\sigma} + \bar{F} = 0 \quad \text{in } \Omega$$

$$\tilde{\sigma} = \tilde{E}[\tilde{\varepsilon} - \alpha(T - T_0)\tilde{I}] \quad \text{in } \Omega$$

$$\tilde{\varepsilon} = \frac{\nabla \bar{u} + (\nabla \bar{u})^T}{2} \quad \text{in } \Omega$$

$$\bar{u} = \bar{u}_e \quad \text{on } \Gamma_{eM}$$

$$\tilde{\sigma}\, \bar{n} = \bar{f}_u \quad \text{on } \Gamma_{nM}$$

Thermal Domain

$$\nabla \cdot (\tilde{k}_t \nabla T) + \dot{q}_T = 0 \quad \text{in } \Omega$$

$$\dot{q}_T = \tilde{k}_e \nabla v \cdot \nabla v \quad \text{in } \Omega$$

$$T = T_e \quad \text{on } \Gamma_{eT}$$

$$\bar{n} \cdot (\tilde{k}_t \nabla T) = f_T \quad \text{on } \Gamma_{nT}$$

Inter-domain Coupling

$\tilde{k}_e(T)$, $q_T(v)$, $\tilde{E}(T)$, $\alpha(T)$,

Nonlinearity

$\tilde{k}_e(T)$, $\tilde{k}_t(T)$, $f_T(T)$,

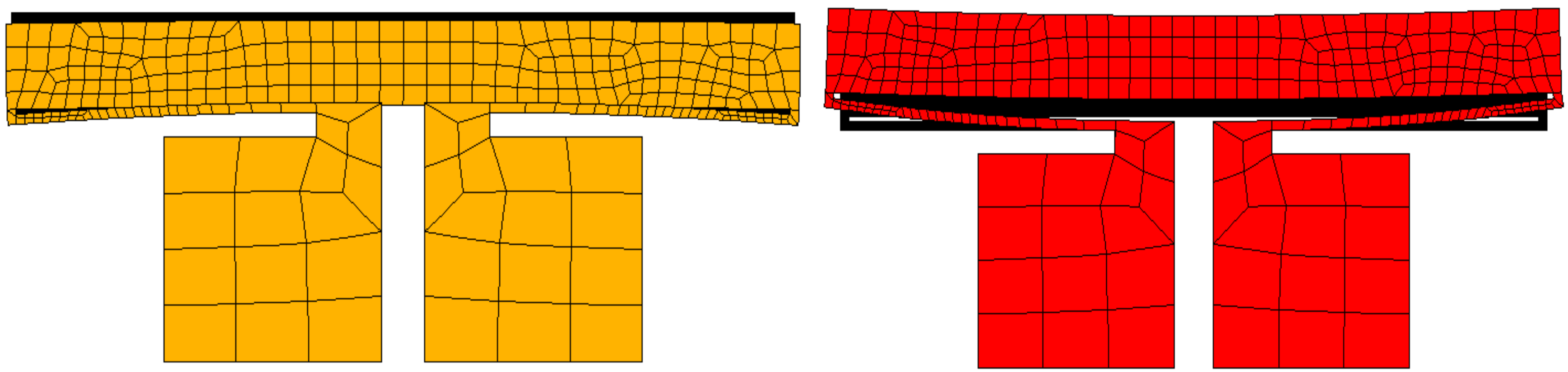
$\tilde{E}(T)$, $\alpha(T)$.

Thermal modeling

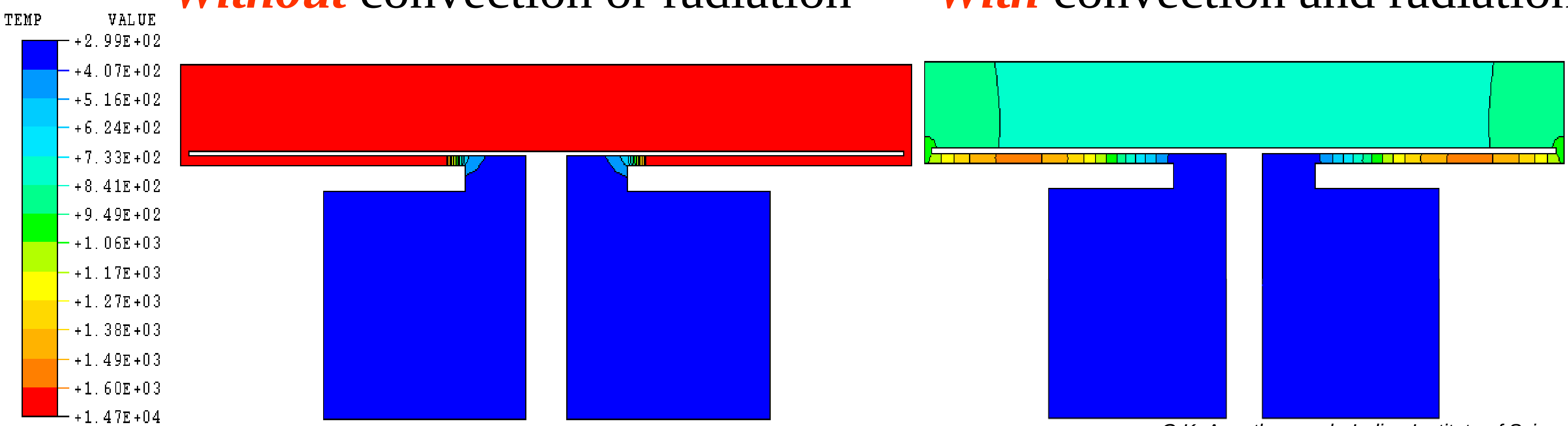
- Convection
  - Temperature dependence of heat transfer properties.
  - Size dependence of heat transfer properties.
- Radiation
  - View / Shape factors.
  - Radiation heat transfer between parts of the same device at different temperatures.
- Boundary Conditions
  - Essential Boundary conditions at the device anchor.
  - Natural Boundary conditions at the device anchor.
- Conduction through trapped air volume
  - Conduction between parts of the same device at different temperature with an intervening trapped air volume.
  - Conduction from the underside of the device to the substrate through the air trapped between them.
- Temperature dependence of thermo-physical Properties

Why convection and radiation ?

Thermal Expansion Device (TED), Cragun & Howell (1998)



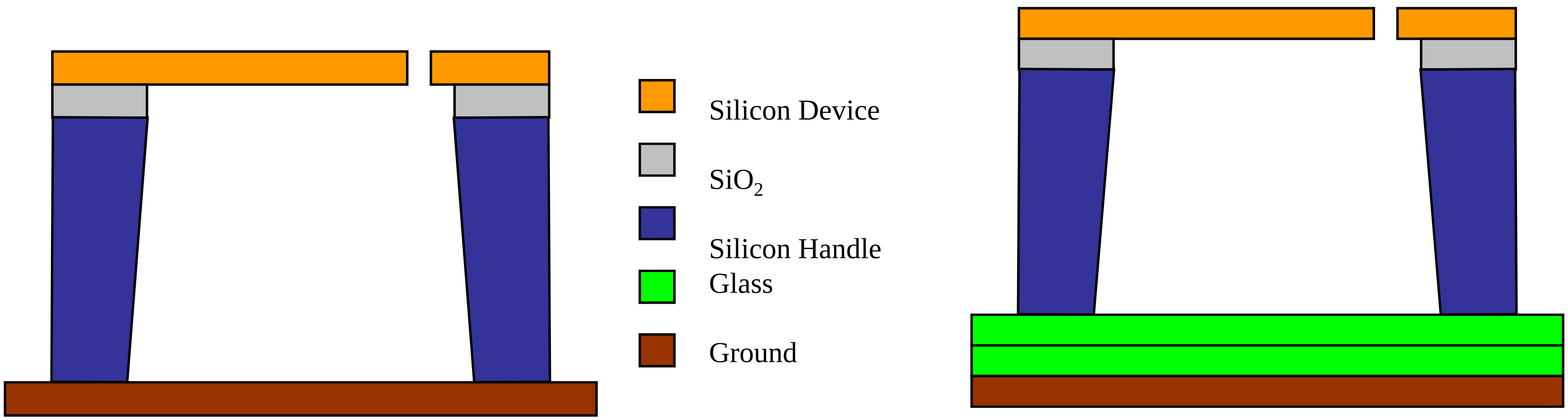
Without convection or radiation ***With*** convection and radiation



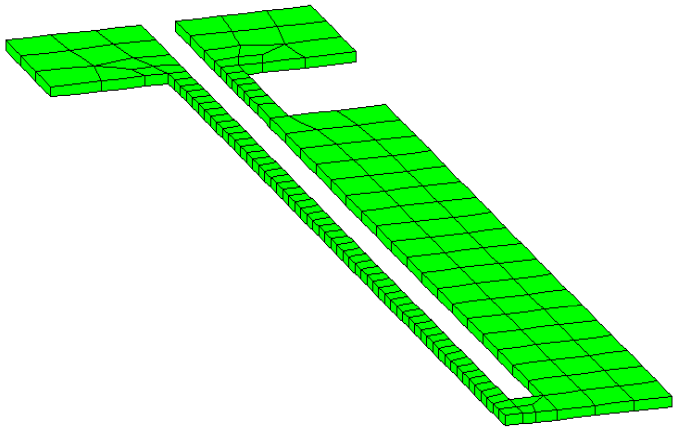
EBC v/s NBC

Essential Boundary C
Thermally Grounded

Natural Boundary C
Not Thermally Grounded



The Finite Element model



20 node, **3-D** **Continuum** elements in ABAQUS

Fully Coupled Electro-Thermal Analysis

Sequentially Coupled Thermo-Elastic Analysis

With temperature dependent material properties and heat transfer coefficients.

Thermal Boundary Conditions and Scaling : Case Studies

- Same *Maximum Temperature* ***at Steady State***
  - EBC + Meso
  - NBC + Meso
  - EBC + Micro
  - NBC + Micro

Made using PennSOIL

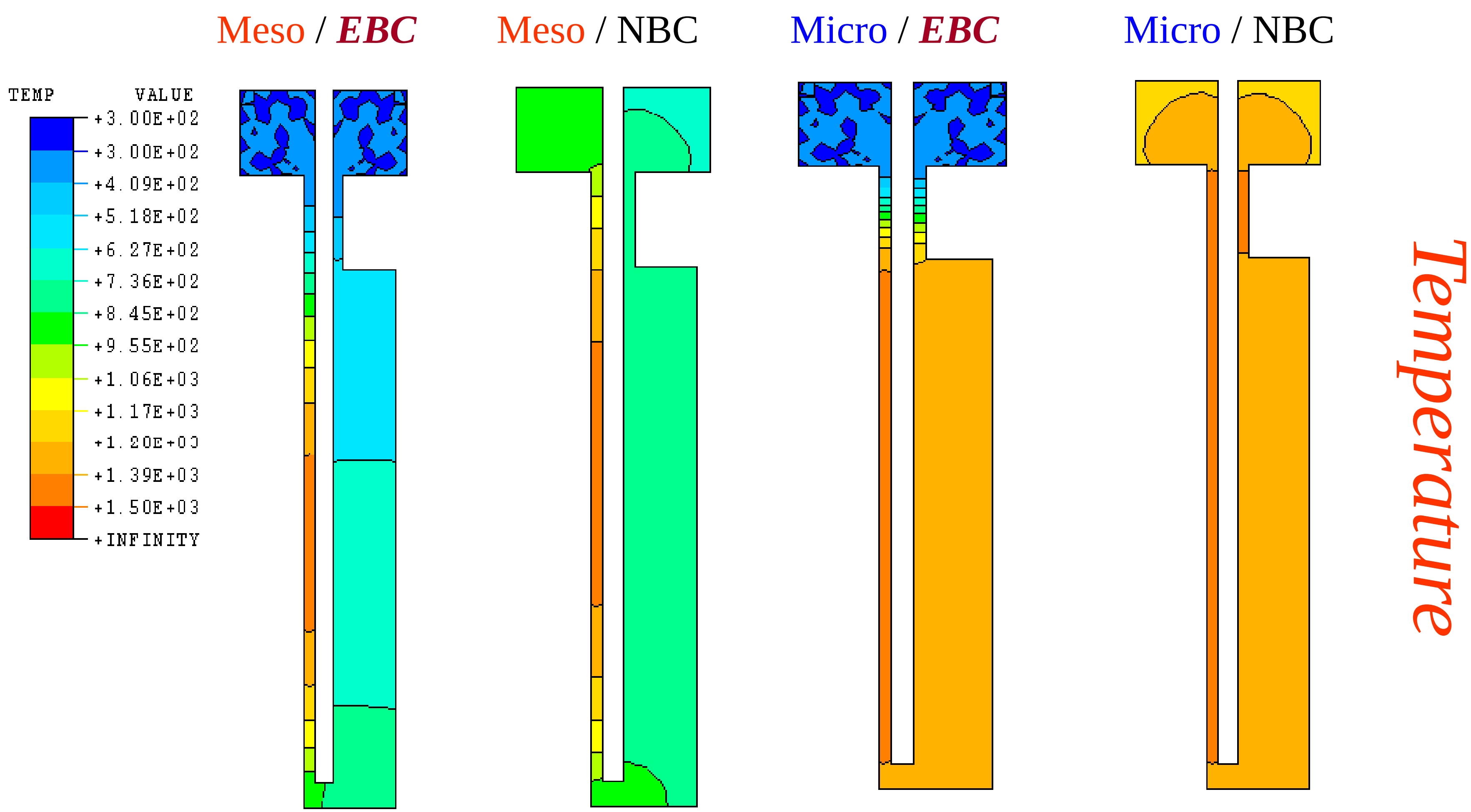
Made using MUMPs

- Same ***Power Input***
  - EBC + Meso
  - NBC + Meso
  - EBC + Micro
  - NBC + Micro

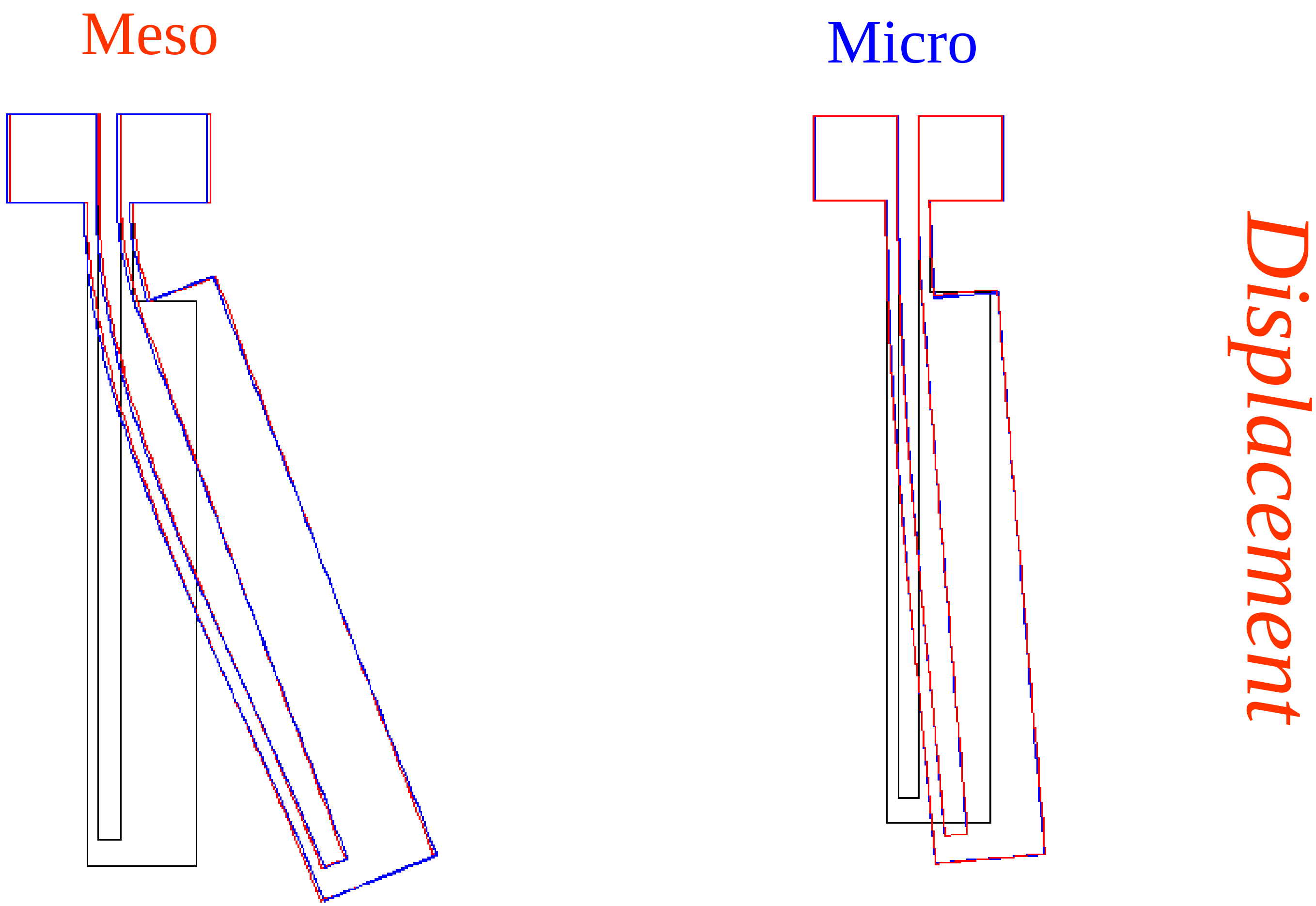
- Same ***Applied Voltage***
  - EBC + Meso
  - NBC + Meso
  - EBC + Micro
  - NBC + Micro

Experiment

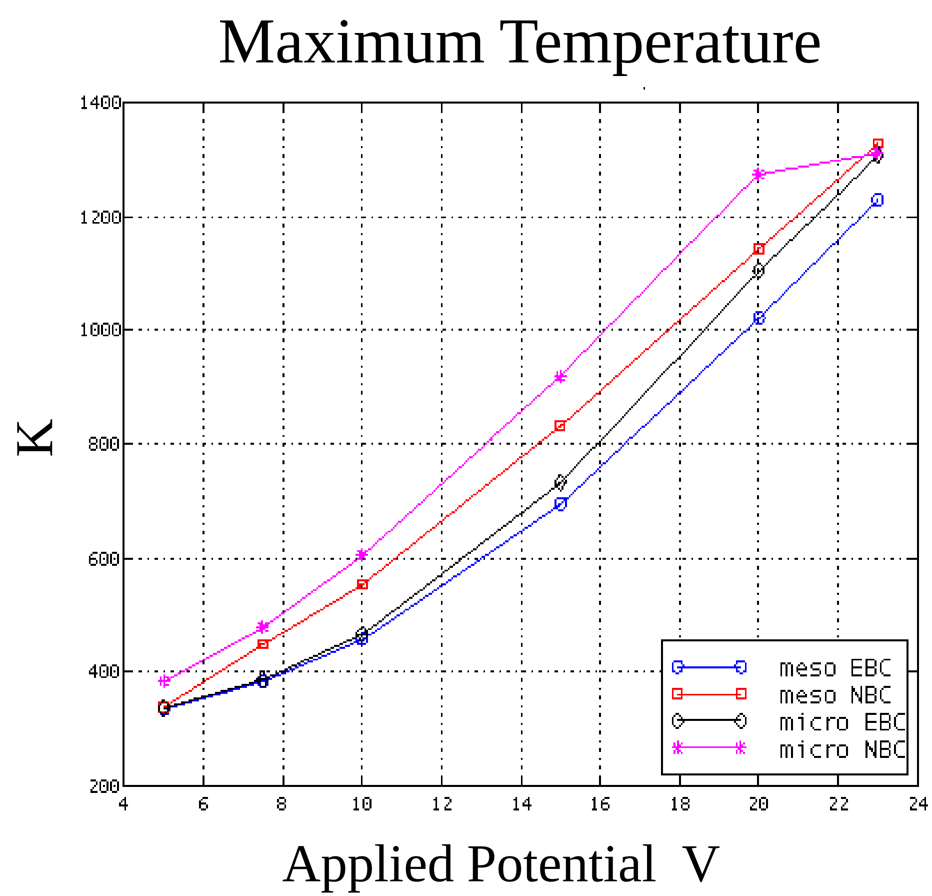
Same *Maximum Temperature*

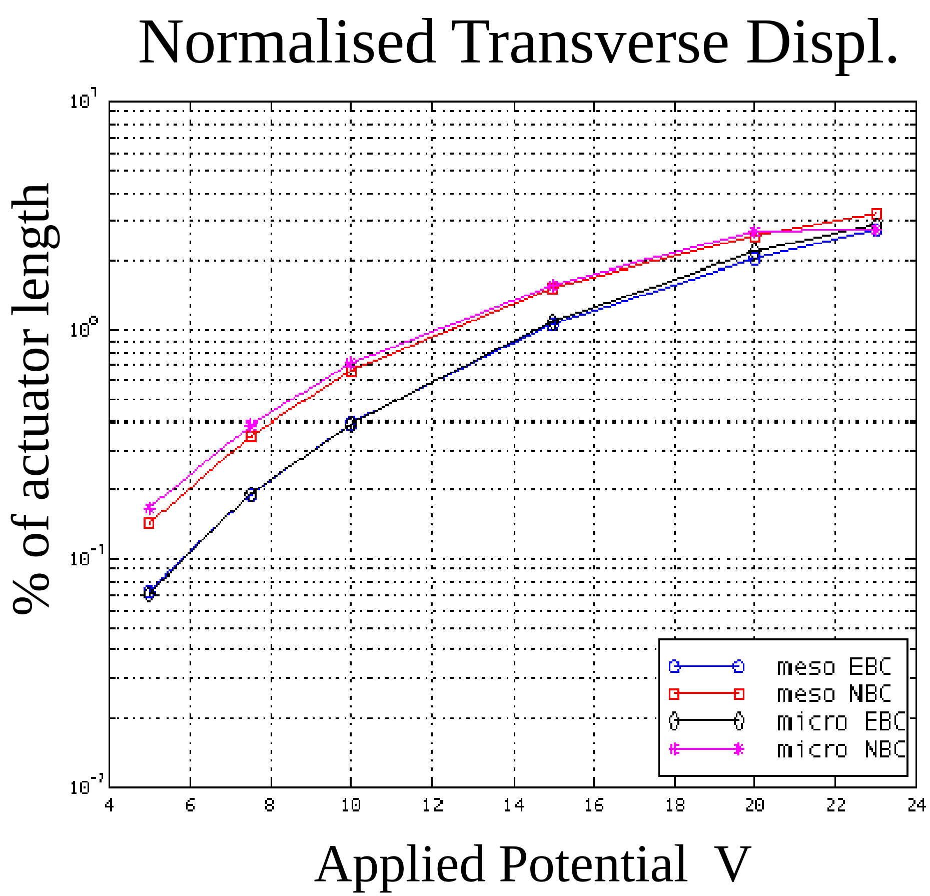


Same *Maximum Temperature*

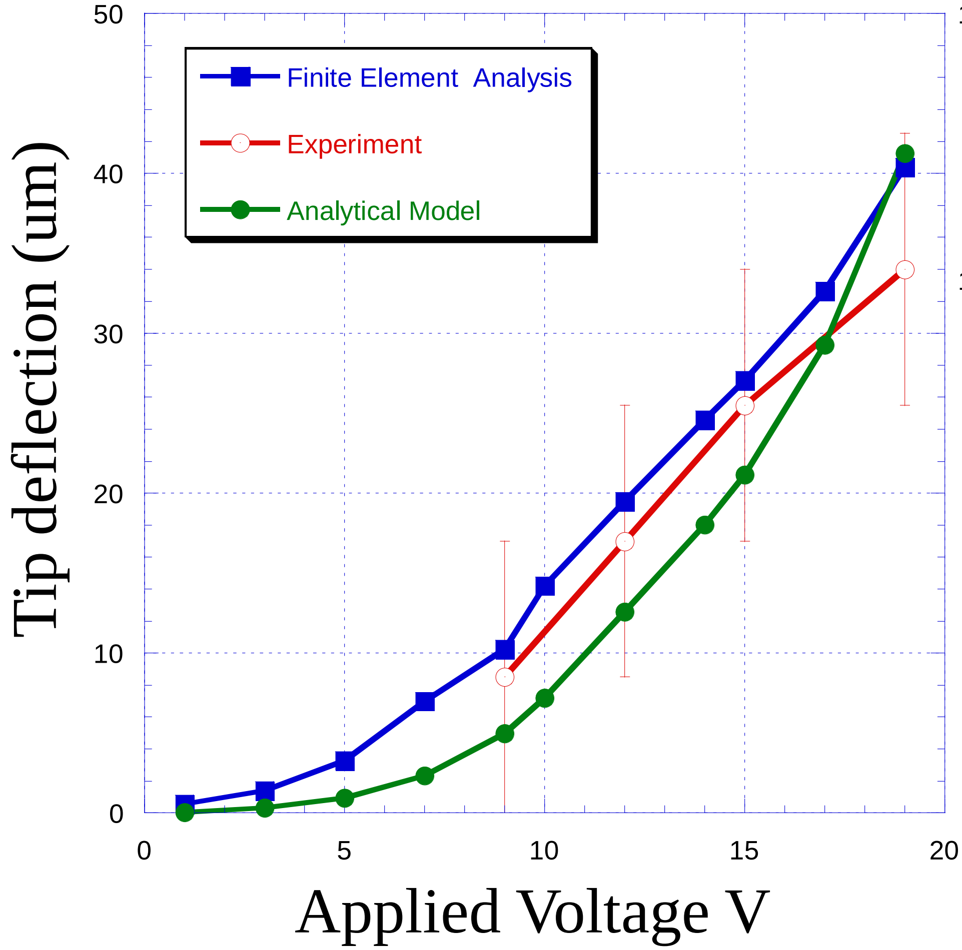


Same *Applied Voltage*

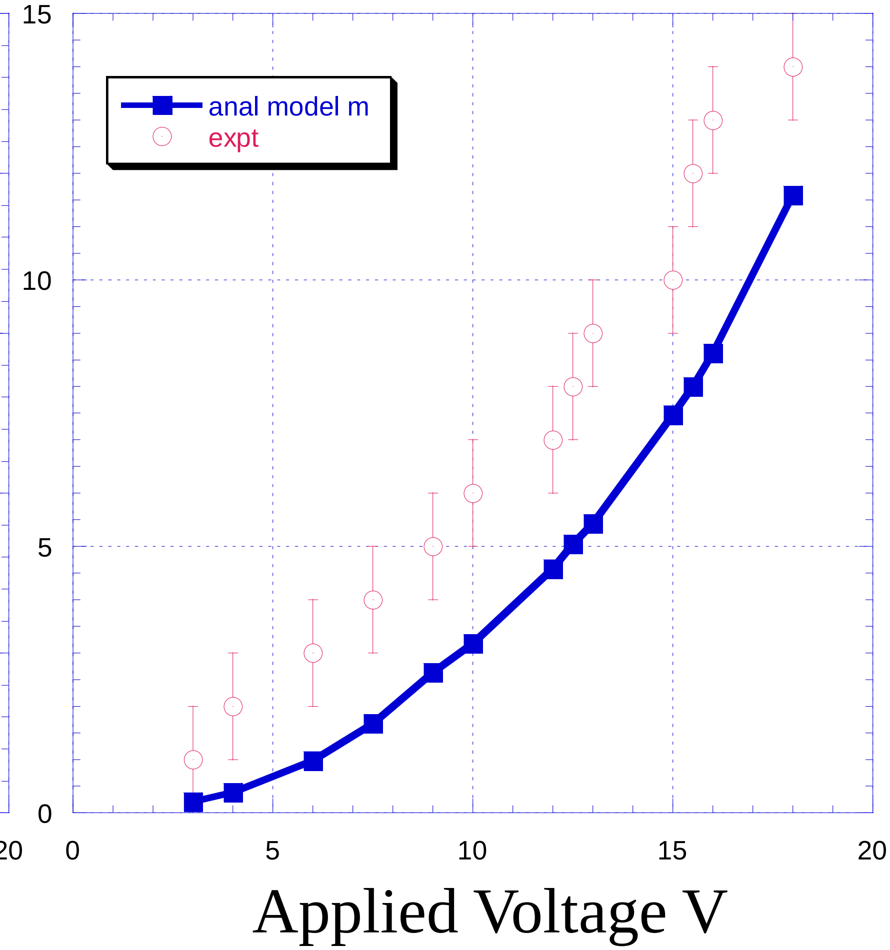




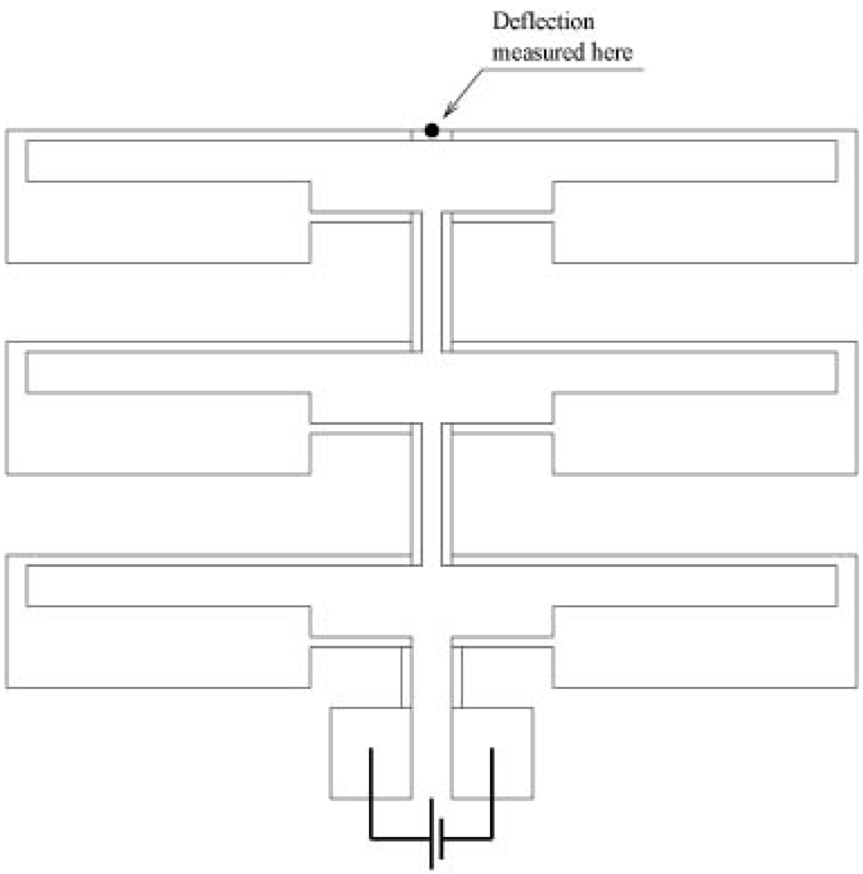
Meso scale *EBC*

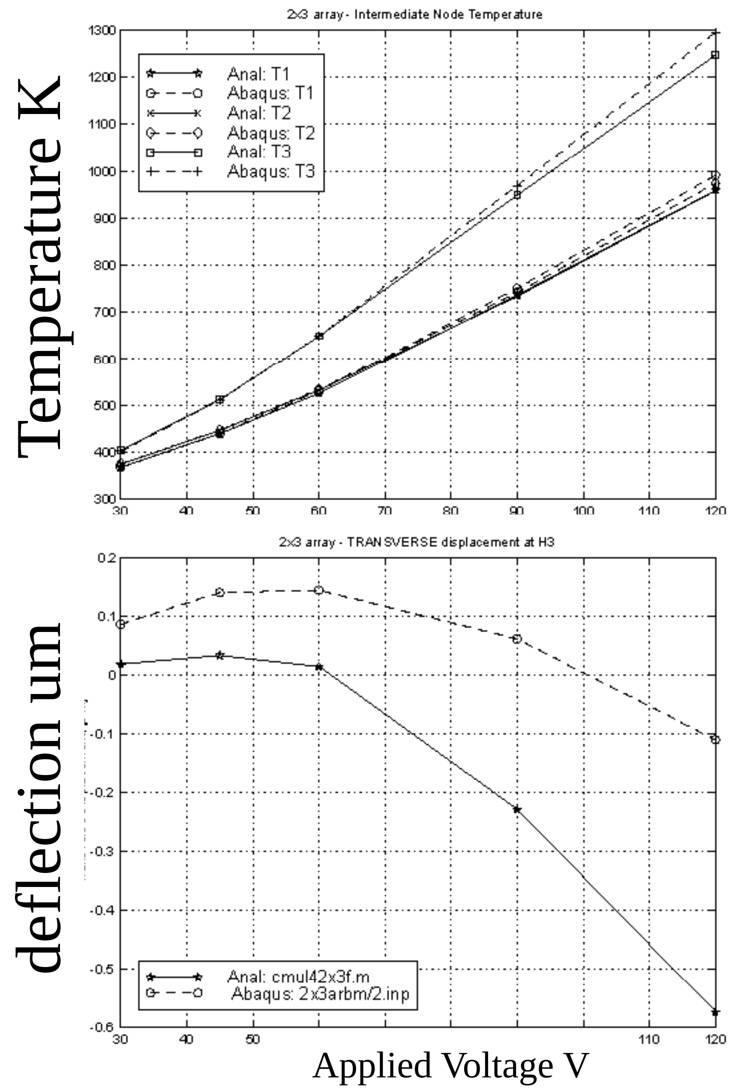


Meso scale **NBC**

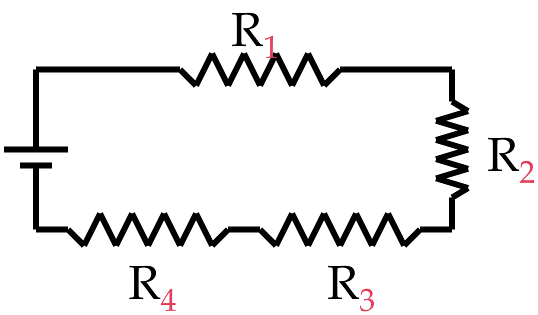


More complicated geometry

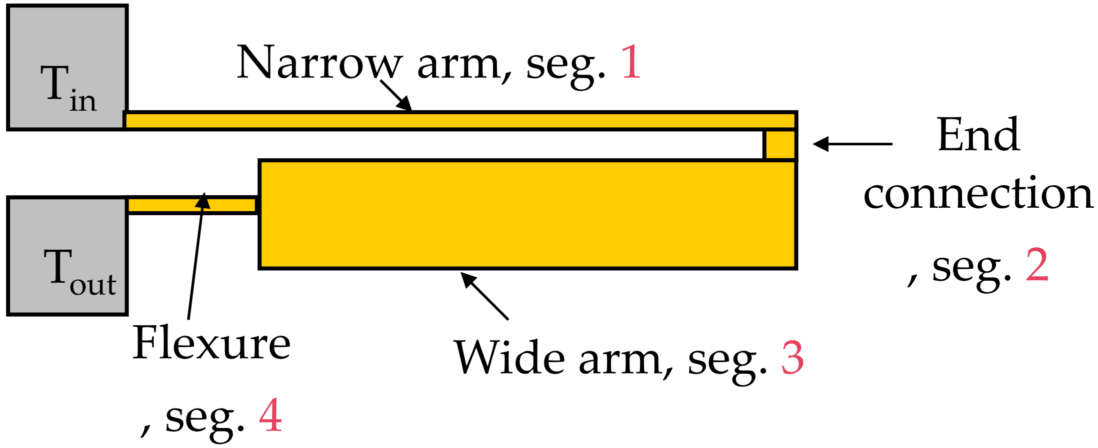




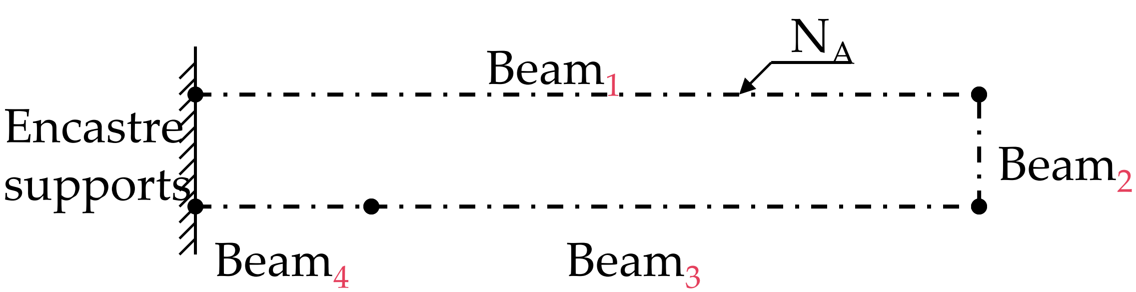
One dimensional approximation



Electrical Model



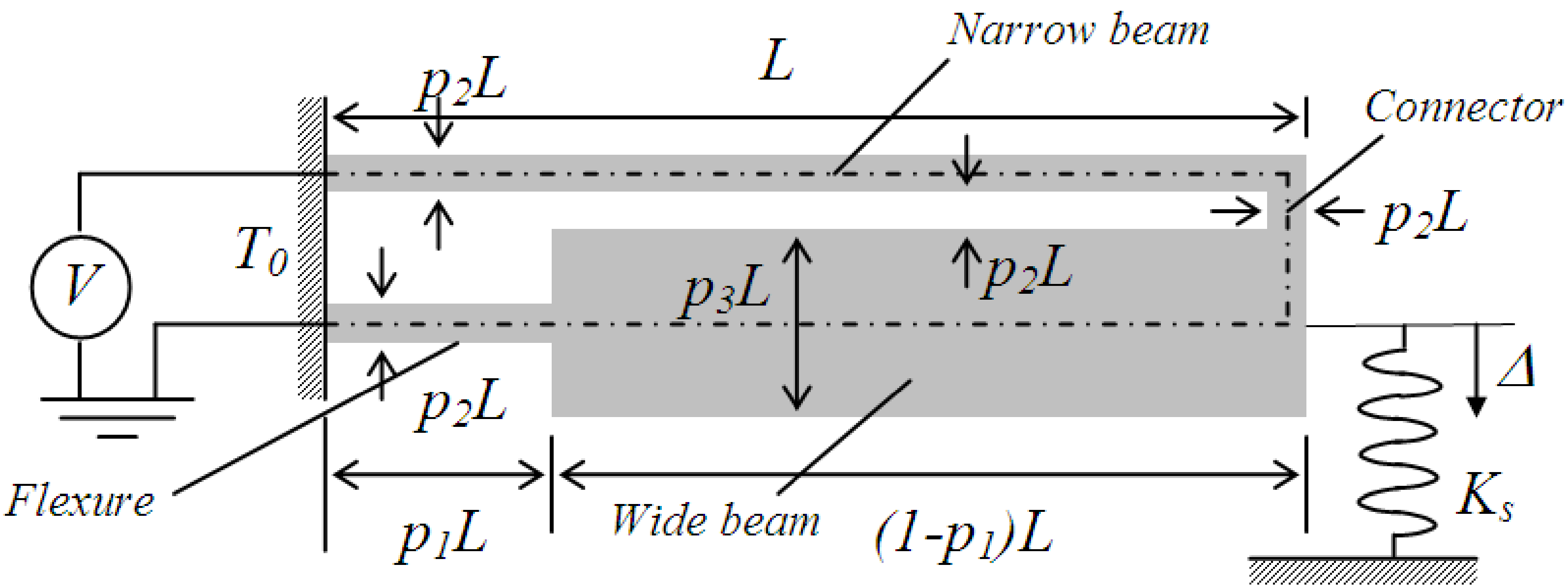
Thermal Model



Elastic Model

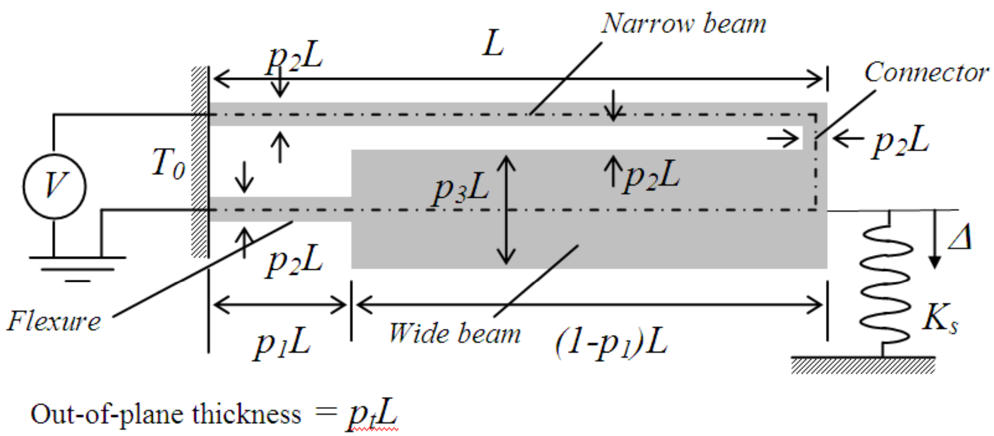
(Maizel's theorem to compute the output deflection)

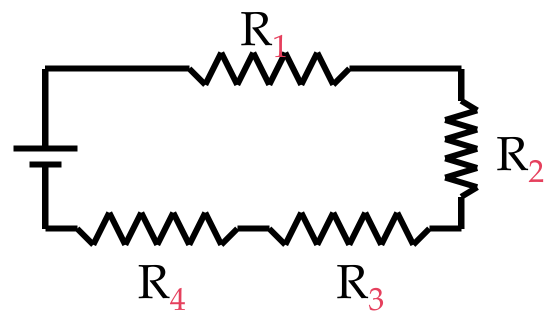
Parameters for analytical modeling of electro-thermal-compliant actuator



Out-of-plane thickness $= p_tL$

Electrical analysis





$$R_i = \frac{\rho_e L_i}{A_i} \text{ for } i = 1,2,3,4$$

$$R = R_1 + R_2 + R_3 + R_4 = \frac{\rho_e}{L}\left\{\frac{1}{p_t p_2} + \frac{1}{p_t} + \frac{(1-p_1)}{p_t p_3} + \frac{p_1}{p_t p_2}\right\} = \phi_e \frac{\rho_e}{L}$$

Notice how resistance, current, and dissipated power vary with scaling.

$$J = \frac{V}{R} = \frac{LV}{\phi_e \rho_e}$$

$$P_e = J^2 R = \frac{LV^2}{\phi_e \rho_e}$$

Coupling between electrical and thermal analysis

$$\dot{Q}_{e_i} = \frac{J^2 R_i}{A_i L_i} = \frac{L^2 V^2}{\phi_e^2 A_i^2 \rho_e} \qquad i = 1, 2, 3, 4$$

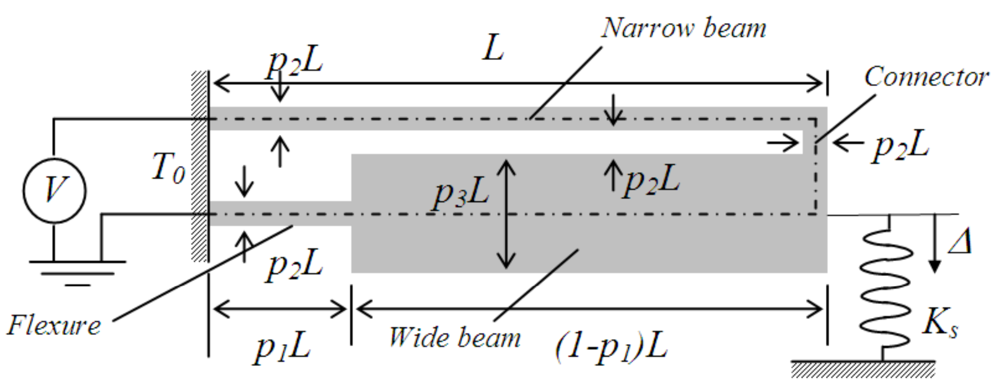
$$\dot{Q}_{e_1} = \frac{V^2}{\phi_e^2 p_t^2 p_2^2 L^2 \rho_e}$$

$$\dot{Q}_{e_2} = \frac{V^2}{\phi_e^2 p_t^2 p_2^2 L^2 \rho_e}$$

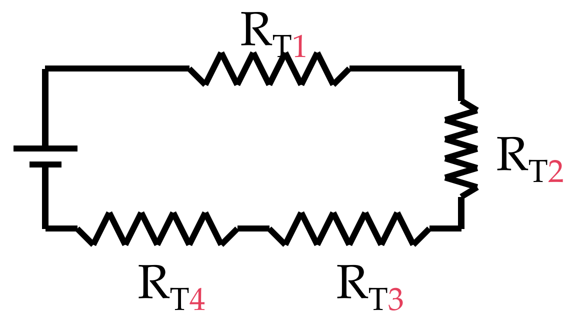
$$\dot{Q}_{e_3} = \frac{V^2}{\phi_e^2 p_t^2 p_3^2 L^2 \rho_e}$$

$$\dot{Q}_{e_4} = \frac{V^2}{\phi_e^2 p_t^2 p_2^2 L^2 \rho_e}$$

Thermal analysis



Out-of-plane thickness $= p_tL$



$$\frac{d^2T_i(x)}{dx^2} + \frac{\dot{Q}_{e_i}}{k_t} = 0 \qquad i = 1,3,4$$

Temperature profile in the connector is not modeled as it is negligibly short.

$$T_i(x) = -\frac{\dot{Q}_{e_i}}{2k_t}x^2 + a_i x + b_i \quad i = 1,3,4$$

Six constants to be evaluated from the boundary conditions.

Boundary conditions to solve for constants

$$T_i(x) = -\frac{\dot{Q}_{e_i}}{2k_t}x^2 + a_i x + b_i \quad i = 1,3,4$$

1. Temperature raise at the left end is zero.

$$T_1(x=0) = T_0 \quad \Rightarrow \quad b_1 = T_0$$

2. Temperature raises at the interface of first and third segments are equal.

$$T_1(x=L_1) = T_3(x=0) \quad \Rightarrow \quad -\frac{\dot{Q}_{e_1}}{2k_t}L^2 + a_1 L + T_0 = b_3$$

3. Thermal equilibrium of the second segment

$$-k_t A_1 \left.\frac{dT_1}{dx}\right|_{x=L_1} - k_t A_3 \left.\frac{dT_3}{dx}\right|_{x=0} + \dot{Q}_{e_2} A_2 L_2 = 0$$

$$-k_t p_t p_2 L^2 \left(-\frac{\dot{Q}_{e_1}}{k_t} L + a_1 \right) - k_t p_t p_3 L^2 a_3 + \dot{Q}_{e_2} p_t p_2^3 L^3 = 0$$

Boundary conditions (contd.)

$$T_i(x) = -\frac{\dot{Q}_{e_i}}{2k_t}x^2 + a_i x + b_i \quad i = 1,3,4$$

4. Temperature raises at the interface of third and fourth segments are equal.

$$T_3(x = L_3) = T_4(x = 0) \Rightarrow -\frac{\dot{Q}_{e_3}}{2k_t}(1-p_1)^2 L^2 + a_3(1-p_1)L + b_3 = b_4$$

5. Heat flux continuity at the interface of third and fourth segments.

$$k_t A_3 \left.\frac{dT_3}{dx}\right|_{x=L_3} - k_t A_4 \left.\frac{dT_4}{dx}\right|_{x=0} = 0 \Rightarrow k_t p_t p_3 L^2 \left(-\frac{\dot{Q}_{e_3}}{k_t}(1-p_1)L + a_3 \right) - k_t p_t p_2 L^2 a_4 = 0$$

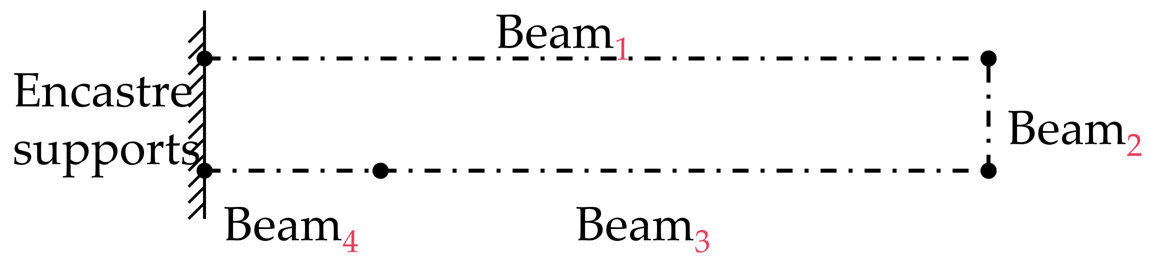
6. Temperature raise at the end of the fourth segment is zero.

$$T_4(x = L_4) = T_0 \Rightarrow p_1 L a_4 + b_4 = \frac{\phi_{t_5} V^2}{\phi_e^2 \rho_e k_t} + T_0 = c_5$$

Total temperature raise = $T_{\max} = \phi_{t\max} \dfrac{V^2}{\rho_e k_t}$

Notice the lack of scaling effect!

Elastic analysis



Maizel's theorem to find the vertical deflection at the tip.

$$\Delta = \sum_{i=1}^{4} \left[\int_0^{L_i} \hat{F}_{axial_i}(x)\, \alpha \left\{ T(x)_i - T_0 \right\} dx \right]$$

$$\frac{\Delta}{L} = \phi_\Delta V^2 \frac{\alpha}{\rho_e k_t}$$

Notice on what quantities the relative deflection depends.

With convection included, it would be different.

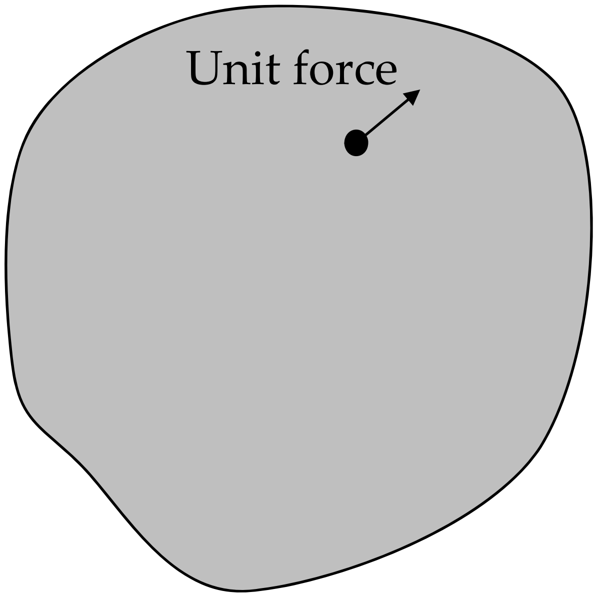
Maizel's theorem in 3D

$$\Delta = \int_V \left(\hat{\sigma}_x + \hat{\sigma}_y + \hat{\sigma}_z \right) \left(\alpha \left(T - T_0 \right) \right) dV$$

$\hat{\sigma}_x$ = normal stress in the x direction due the application of a unit force at the point of interest in the direction of interest

Similarly, for $\hat{\sigma}_y, \hat{\sigma}_z$

$T(x, y, z)$ = temperature distribution obtained from thermal analysis



With convection included…

Without convection…

$$\frac{\Delta}{L} = \phi_\Delta V^2 \frac{\alpha}{\rho_e k_t} \propto L^0$$

$$\frac{d^2 T_i(x)}{dx^2} + \frac{\dot{Q}_{e_i}}{k_t} = 0 \qquad i = 1..4$$

With convection…

$$\frac{\Delta}{L} \propto \frac{1}{\sqrt{L}}$$

$$T \propto \frac{\dot{Q}L}{h} \propto \frac{V^2}{\rho_e h L} \propto \frac{1}{L}$$

$$\frac{d^2 T_i(x)}{dx^2} - \frac{h p_i (T_1 - T_0)}{k_t A_i} + \frac{\dot{Q}_{e_i}}{k_t} = 0 \qquad i = 1..4$$

Main points

- Electro-thermal-elastic actuation is easy to implement in practice.
  - Large forces and displacements
  - Slow
- Coupled modelling is sequential, usually…
  - Temperature-dependent properties make it nonlinear.
- Reduced order modelling is convenient and useful.