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ELECTRICAL AND HEAT FLOW SIMULATION OF MEMS STRUCTURES USING SPICE

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Abstract: The Cantilevers and beams are the very basic structures used in MEMS. This paper describes the use of PSPICE circuit simulator for simulations in 2 domains – Electrical and Thermal. The analogy between heat flow and electrical circuits give us an electrical equivalent circuit that can simulate the thermal heat flow. The steady-state and transient simulations of a heatuator have been done using PSPICE giving thermal time constants of the order of 40 μ-sec.

Keywords: Heat Flow simulation by PSPICE, MEMS simulation using PSPICE.

1. INTRODUCTION

The Cantilevers and beams are the very basic structures used in MEMS. Diffused or poly-silicon resistors are incorporated either as piezoresistive sensors or for heating the structure. The heat flows towards the fixed end(s) of the cantilever or beam resulting in a steady state temperature profile. The analogy between heat flow and electrical circuits gives us the pairs, Temperature ⇔ Voltage, Heat flow ⇔ Current, Thermal mass ⇔ Capacitor, Thermal resistance ⇔ Resistance, and Fixed ends ⇔ Ground. Thus, an electrical equivalent circuit can simulate the thermal heat flow.

2. DOMAINS – ELECTRICAL, THERMAL AND MECHANICAL

PSPICE simulation of appropriate analogous electrical circuits can obtain results in 3 domains viz. Electrical, Thermal and Mechanical. A beam (Figure 1.) has been shown in all the 3 physical domains.

3. INTERACTION BETWEEN THE 3 DOMAINS

Various interactions between the 3 domains are shown in the Figure 2 and these are

(1) Electrical→ Thermal : Temperature rise due to I^2R heating,

(2) Thermal → Electrical : Change in resistance due to Temperature Coefficient of Resistance (TCR),
(3) Thermal → mechanical : Strain due to expansion (linear coefficient of expansion)
(4) Mechanical → Electrical : Change in resistance due to piezoresistivity
(5) Mechanical → Thermal : If there is bending, then heat flow will change due to change in gap conduction
(6) Electrical → Mechanical : Change in mechanical strain due to piezoelectric effect (if any)

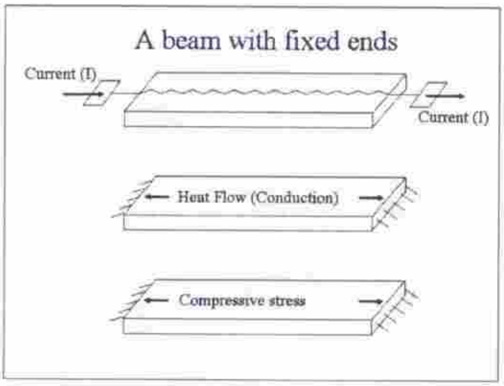


Figure 1. A beam with fixed ends with Electro-Thermal heat-actuation. The 3 domains are (1) Electrical, (2) Heat Flow and (3) mechanical

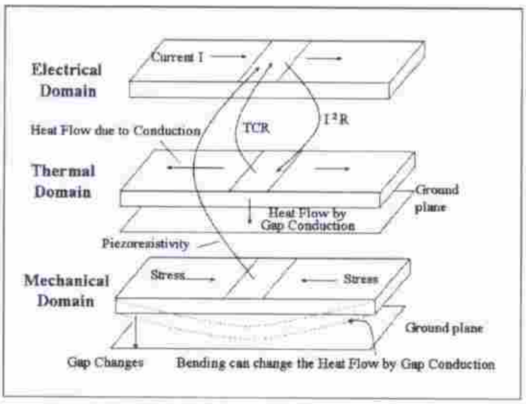


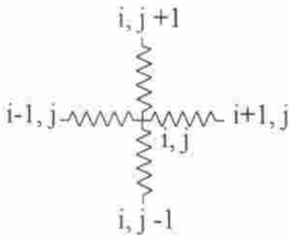
Figure 2. Various cross-interactions between the 3 domains

4. PSPICE IMPLEMENTATION OF THE DOMAINS

The simulation of the electrical and thermal equivalent circuits of the MEMS structure are done simultaneously using circuit analysis program PSPICE. Each mesh element shares the electrical, heat and mechanical parameters. In PSPICE circuit simulations each of the domains is implemented by a 4-star connected at every mesh point. The Laplacian operator

$$\mathbf{\Delta}\,\psi = \frac{\delta^2 \psi}{\delta\, x^2} + \frac{\delta^2 \psi}{\delta\, y^2}$$

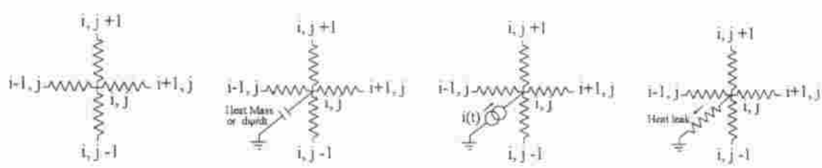
is implemented by 4-star connected resistors



The generalized equation containing the 2^{nd} order and 1^{st} order derivatives; a term in ψ and a forcing function i(t) is given below

$$\mathbf{\Delta}\,\psi - \mathbf{B}\,\frac{\delta\,\psi}{\delta\,t} - \mathbf{C}\,\psi = \mathbf{i(t)}$$

The 4-star connected equivqlent circuit that implements the above equation is given below. The time derivative "dψ/dt" is implemented by a capacitor connected to the node point (i,j) and ground. The capacitor is also used as analog of "heat mass". A resistor connected between node point (i,j) and ground implements a heat loss by gap-conduction. A current source (as a function of time) implements a "heat source" connected to the node point. Thus a genralised implementation of a 2^{nd} order Laplacian or Poisson's equation is shown below in figure 3.



(a) Laplacian operator (b) 1^{st} Derivative term (c) Input function (d) term prpoprtional to ψ

Figure 3. Implementation of different terms in a Laplace or Poisson equation

5. PSPICE SIMULATION OF HEATUATOR

The heatuator, used for demonstrating use of PSPICE for Electro-Thermal simulations, is shown in figure 4 - narrow and wide arms have widths of 10 um and 30 um respectively while the length and thickness are same for both arms – 2 μm and 100 μm. The mesh of 10 μm x 10 μm is constructed and each mesh is constructed out of the equivalent circuit consisting of 4-star connected resistors and a capacitance to ground as given in section 3 above. The electrical mesh and heat-flow mesh interact with each other and give us both electrical and heat quantities – we are interested in temperature profile of the heatuator for a 10 mA current through the device.

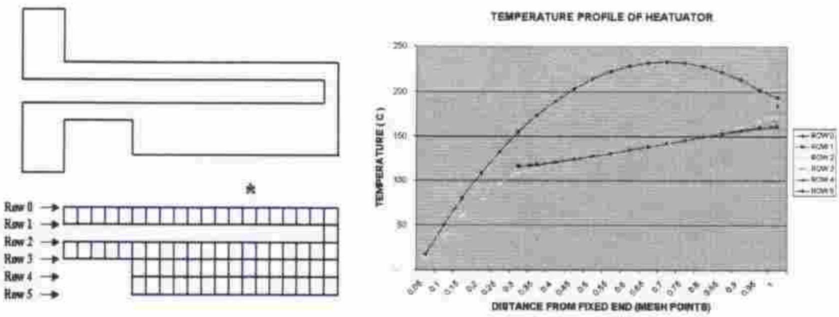


Figure 4. A polysilicon Electro-Thermal heat-actuator having arms with different widths.The star * shows the mesh location that has the maximum temperature. .

The simulation using PSPICE for the temperature profile is given figure 5. The transient simulation is straight forward in PSPICE and is obtained by giving a pulse of 10 mA with a pulse width of 200 micro-seconds (figure 5). The thermal mass acts as a 'capacitance' and gives a time constant of 40 μS for the narrow arm and 100 μ-sec for the wide arm.

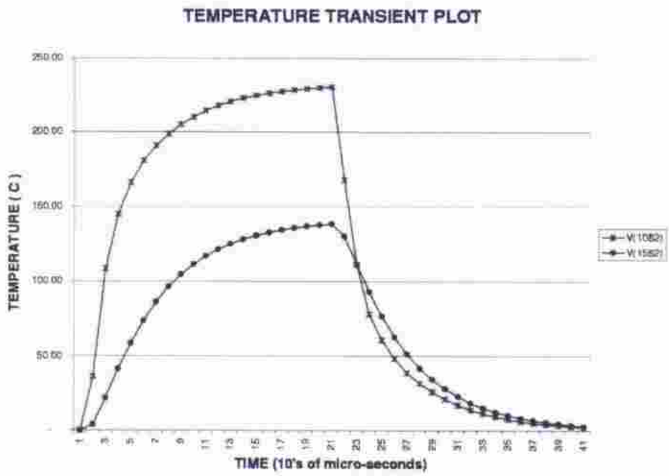


Figure 5. PSPICE transient simulation of the heatuator at its hottest point in the narrow arm (top curve) and a point below that in the wider arm (lower curve). Time constants for the two regions are ~40 μSec and ~100 μSec respectively

6. CONCLUSIONS

Electrical and Thermal simulation for a heatuator structure have been performed using PSPICE circuit simulator. Once the mesh sub-circuits are defined then a variety of simulation options of PSPICE become available. This paper has used only DC and Transient simulation and estimated the thermal time constant of the heatuator MEMS structure. The sub-circuit definitions include non-linearities and cross coupling between various domains. Thus, a set of meshes will act in a manner similar to that a multiphysics element acts in ANSYS.