Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

Simulation of Thermal Sensor for Satellite Thermal Control Using Comsol

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Abstract: Complex space missions use satellites which are of small intricate size and compact design. These sizes lie in the dimension of pico and nano meters. The complexity involved in efficiently controlling the increase in temperature rise resulting from heat flux from space radiation and internal heat generation increases with the decrease in size of the satellite. Even an infinitesimal rise in temperature needs to be detected. This paper focuses on the development of a Microelectronical mechanical systems (MEMS) mechanism which involves a bimetallic microbeam, a piezoelectric crystal and Field effect transistor(FET) to detect the rise in temperature and actuate the temperature control system. The relation between their individual response to parameters like temperature rise, stress and voltage is used to detect the temperature rise. The interaction between the three components is modeled by the application modes in comsol and the voltage output across the FET which will actuate the thermal control system is obtained.

Keywords: Bimetallic, piezoelectric, transistor, thermal sensor

1. Introduction

Analysis of the mishaps during space missions have shown that the major reasons for failure is the excessive heating of the satellite. The success of any space mission requires a very efficient temperature control system[1]. The function of a thermal control system is to regulate the temperature of the entire satellite in the ranges considered safe for the smooth functioning of the satellite so as it achieves all its assigned targets. It is of prime importance that the sensor actuating the system should be efficient to detect temperature rise and transfer the response without any time lag such that the regulation is spontaneous. The design of such a sensor becomes more complicated if the size of the satellite is small. MEMS devices pose a good solution to this problem .The interaction between these components facilitates the conversion of mechanical energy to electrical energy at the microscopic level[2]. In the proposed model this conversion is achieved by the thermal structural interaction of the bimetallic beam and the piezoelectric effect of the crystal .The output voltage obtained from the piezoelectric crystal this voltage then sets up a current in the FET, this current actuated the temperature control system.

2. Mechanism

The bimetallic microbeam is the driving component of the system. In response to the temperature rise of the system the bimetallic beam deflects due to the difference in thermal expansion coefficients of the two materials. At one end the beam is fixed to the body of the satellite, this end is the temperature detecting end. The deflection in the beam causes it to impinge on the piezoelectric crystal. A normal force proportional to the stress developed in the beam acts on the crystal .This develops a compression in the piezoelectric crystal and at the lattice level will induce a polarization. The arrangement is such that this force will act on the flat horizontal surface of the crystal. As a result the voltage is obtained between this face which bears the impact of the beam and the corresponding opposite face. This voltage with the help of two electrodes is fed to the FET end terminals. This voltage acts as a biasing voltage between the gate and source terminals. This voltage increases the bias above the threshold voltage required for the current to flow between the source and drain. This current then flows into the temperature control system which deploys the designed respective mechanism to regulate the temperature. The geometric representation of the model is shown in Figure1. The arrangement is such that set up facilitates easy contact between the three components when there is rise in temperature. In the absence of temperature rise the three components are isolated from each other; the contact takes place only once there is rise in temperature.

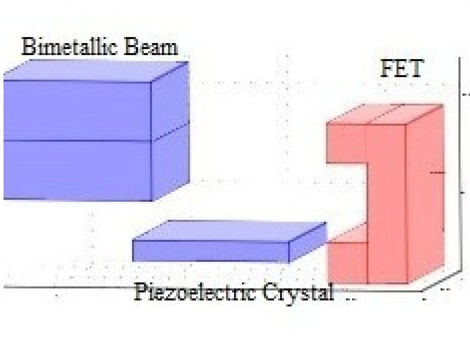

Figure1. Schematic construction of the mechanism

4. Use of Comsol Multiphysics:

The simulation of the entire mechanism is done using the application modes in comsol Multiphysics. Using the Mems module the bimetallic beam consisting of iron and copper is simulated using the thermal structural interaction in the three dimensional mode. This module facilitates the modelling for the stress developed and the resulting strain. The Quartz piezoelectric crystal is modeled using the structural mechanics module in which the piezoelectric application mode along with the geometry of the crystal is added to the initial simulation.

A third application mode from the electrostatics mode which is conductive media dc is added and the geometry of the MOSFET is imported from the model library present in comsol. The solver then solves all of the three geometries simultaneously or as desired using the solver manager tool.

4. Application Modes and Physical Equations

4.1 Thermal Structural Interaction of Bimetallic Beam

For an isotropic, linearly elastic body, the surface stress components must be in equilibrium with the given external loads and within the body they must satisfy the following equilibrium equations:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + X = 0$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + Y = 0$$

$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + Z = 0$$

The displacements must match the geometrical boundary condition. The effect of temperature must be included in the stress-strain components:

$$\epsilon_x = \frac{1}{E}\left[\sigma_x - \vartheta\left(\sigma_y + \sigma_z\right)\right] + \alpha\Delta T$$

$$\epsilon_y = \frac{1}{E}\left[\sigma_y - \vartheta\left(\sigma_z + \sigma_x\right)\right] + \alpha\Delta T$$

$$\epsilon_x = \frac{1}{E}\left[\sigma_z - \vartheta\left(\sigma_x + \sigma_y\right)\right] + \alpha\Delta T$$

The beam is made of two different materials having different moduli of elasticity and expansion coefficient. The difference in the thermal stress developed in the two materials is given by:

$$(\acute{\alpha}_1 Y_1 - \acute{\alpha}_2 Y_2) \times \Delta T$$

Here ΔT is the rise in temperature and $\acute{\alpha}_1$, $\acute{\alpha}_2$ are the expansion coefficients and Y_1, Y_2 are the moduli of elasticity. This difference in the stress is the reason why the beam deflects, thereby impinging on the piezoelectric crystal to produce voltage.

4.2 Piezoelectric Crystal

Piezoelectric materials are anisotropic and the elastic field in such materials is coupled with the electric field. The linear constitutive relations expressing the coupling between the elastic field and the electric field can be written as:

$$T = C^E S - h^T E$$

$$D = hS + b^S E$$

Where T is the stress tensor, D is the electric displacements, S is the strain tensor, and h is the piezoelectric coupling constant, E is the electric field, b^S is the dielectric constant at constant strain, C^E is the elastic stiffness tensor evaluated at constant E field and h^T is the transpose of h.

The electric field E is related to the electric potential $\emptyset$ by $E = -\nabla\emptyset$. The displacement and potential for each element can be expressed, respectively, as

$$u = N_u \hat{u}$$

$$\emptyset = N_\emptyset \widehat{\emptyset}$$

Where u is the displacement vector, N_u and N_Φ the interpolation functions for the variables of u and $\emptyset$, ^ denotes the nodal point values.

Putting the strain–displacement relation in terms of the nodal displacement yields $S = B_u \hat{u}$ where $\boldsymbol{B_u}$ is the product of the differential operating matrix relating $\boldsymbol{S}$ to the shape function matrix $\boldsymbol{N_u}$. Similarly let $E = -\nabla\emptyset = -\nabla N_\emptyset \widehat{\emptyset} = -B_\emptyset \widehat{\emptyset}$. The equation of motion for a piezoelectric body can be derived from the principle of minimum potential energy by means of a variational functional. The resultant equations can be represented in matrix form from the assembly of all the individual finite-element equations.

$$[M_{uu}]\ddot{u} + [K_{uu}]u + [K_{u\emptyset}]\emptyset = \{F\}$$
$$[K_{u\emptyset}^T]u + [K_{\emptyset\emptyset}]\emptyset = \{Q\}$$

Where $[M_{uu}] = \int \rho\, N_u^T N_u dV$ is the kinematically constant mass matrix, $[K_{uu}] = \int B_u^T C^E B_u\, dV$ the elastic stiffness matrix, $[K_{u\emptyset}] = \int B_u^T h^T B_\emptyset\, dV$ the piezoelectric coupling matrix, $[K_{\emptyset\emptyset}] = \int B_\emptyset^T b^S B_\emptyset\, dV$ the dielectric stiffness matrix,

$$\{F\} = \int_V N_b^T f_b\, dV + \int_{S_1} N_{S_1}^T f_S dS_1 + N_u^T f_c$$

mechanical force,

$$\{Q\} = -\int_{S_2} N_{S_2}^T q_S dS_2 - N_\emptyset^T q_c$$

Electrical charge, $\mathbf{f}_b$ the body force, $\mathbf{f}_s$ the surface force, $\mathbf{f}_c$ the concentrated force, $\mathbf{q}_s$ the surface charge and $\mathbf{q}_c$ the point charge[4].

The electric field boundary condition requires that the electrode surface is zero.

$$\widehat{\emptyset}_i = \widehat{\emptyset}_{i+1} = \cdots = \text{constant} \qquad \sum Q_i = 0$$

These equations represent the Finite element method model[3] of the crystal. The solver uses finite element method, these equations play an important role in the simulation.

3.3 MOSFET

The charge Q generated from the crystal will flow across the electrodes which connect the MOSFET to the MOSFET with the help of connected electrodes. These electrodes are connected across the gate and source of the FET. The charge develops a biasing voltage between them and the current flows from drain to source.

The equation taken for the voltage V_{GS} is given by

$$(V_{GS} - v(x) - V_t) \times (Wdx) \times C_{ox} = dq$$

Here V_{GS} is the gate –source potential difference. dq is the charge flowing across the small element of the MOSFET.

The driving voltage V_{GS} can be expressed as a function of the charge Q flowing from the crystal in terms of the capacitance C_{ox} assuming that the Substrate of the MOSFET is at zero potential we get $Q = C_{ox} \times V_{GS}$. This V_{GS} is responsible for the current to flow from drain to source.

4. Results

For an assumed linear increase of temperature, the variation of stress is shown in figure 2. The maximum stress value developed is 2.5e08 Pa.

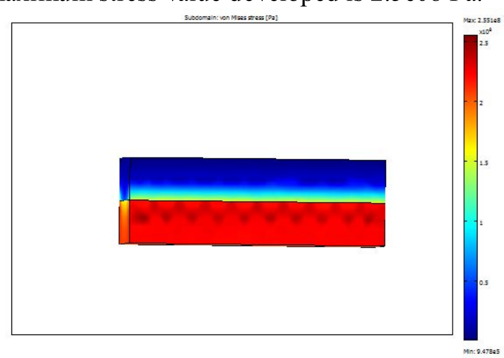

Figure 2. Stress Distribution in the Bimetallic Strip

This range is below the fracture region of the stress so the mechanism can safely work for over wide spectrum of temperature ranges. The displacement on the boundary surface is shown in figure 3. The min and max are 1.78e-03m and 2.247e-03m. Figure 4 shows the electric displacement which gives rise to charges inside the crystal as a result of the incident stress acting on it. This lies in the standard conduction region of the FET and can be used as an actuator switch for the FET.

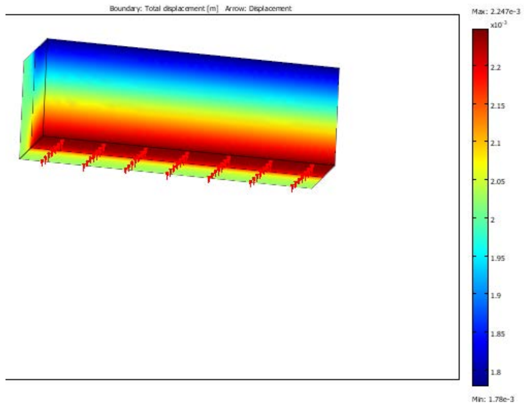

Figure 3. Displacement in the Bimetallic Strip

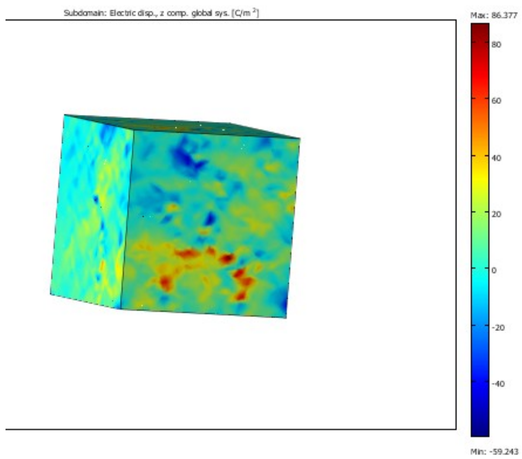

Figure 4. Electric Displacement in Piezoelectric Crystal

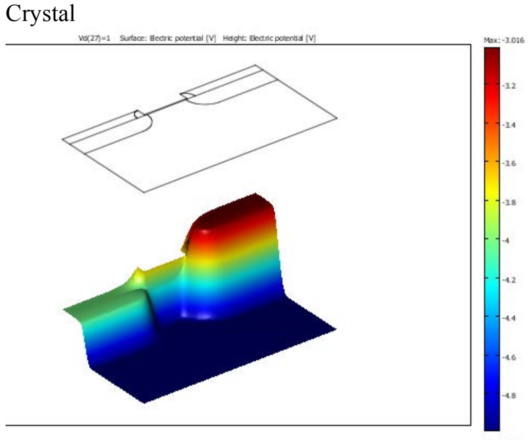

Figure 5 Voltage distribution across MOSFET

5. Conclusion

This paper demonstrates the simulation of the proposed mechanism .It shows that the quantities like stress, displacement and voltage which govern the working of this mechanism lie in feasible ranges. This mechanism therefore can be practically implemented in micro and nano satellite which are more susceptible to damage due to heat.

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