Finite Element Analysis of Micro – Electro – Mechanical Systems by using the ANSYS software

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Abstract: - Microelectromechanical Systems (MEMS) is the technology of the very small, and merges at the nano-scale into "Nanoelectromechanical" Systems (NEMS) and Nanotechnology. MEMS are also referred to as micro machines, or *Micro Systems Technology* (*MST*). MEMS are separate and distinct from the hypothetical vision of Molecular nanotechnology or Molecular Electronics. MEMS generally range in size from a micrometer (a millionth of a meter) to a millimeter (thousandth of a meter). At these size scales, the standard constructs of classical physics do not always hold true. Due to MEMS' large surface area to volume ratio, surface effects such as electrostatics and wetting dominate volume effects such as inertia or thermal mass. Finite element analysis is an important part of MEMS design.

Key-Words: - Finite Element Analysis, Micro – Electro – Mechanical Systems, ANSYS software, Coupled problems, Microactuator; Bistable electromagnetic actuation; UV-LIGA technology; Simulation

1. Introduction

Micro-electro-mechanical systems (i.e., MEMS) are integrated systems of microelectronics (IC), microactuator and, in most cases, microsensors [1]. MEMS technology offers unique advantages including miniaturization, mass fabrication and monolithic integration with microelectronics, and makes it possible to fabricated small devices and systems with high functionality, precision and performance. More important, MEMS technology can enable new circuit components and new functions [2] and [3]. Therefore, MEMS have attracted considerable attention since 1987 [1]. Microactuators are the key part of MEMS. For many MEMS devices such as switches, optical attenuators, pumps, valves, etc., microactuators are required to realize their physical functions. The controlled actuation or motion of microactuators can be achieved by several kinds of actuation mechanisms. Electrostatic, piezoelectric, magnetostrictive, magnetic, thermomechanical actuators have been reported [4], [5], [6], [7] and [8]. Among the different actuation principles, the electrostatic actuation is predominantly employed for the electrostatic microactuators' characteristics of simple structures, small energy loss and being compatible with integrated circuit processes [9] and [10]. However, electrostatic actuation mechanism has the disadvantages of high driving voltage and small displacement [11]; the high driving voltage has an adverse effect on the lifetime of devices [12].

The electromagnetic actuators have received much attention for their capabilities of realizing both large force and displacement and suitability in harsh environment [13] and [14], thus electromagnetic actuators with various structures have been fabricated [7], [15] and [16]. Compared with electrostatic microactuators, the electromagnetic ones increase the displacement with low actuation voltage that can effectively enhance the stability of the devices. The disadvantage of such devices is that they have higher power consumption, which is obviously an unfavorable factor for the heat dissipation of the microactuators with a compact structure. The high power consumption mainly comes from holding the state of the devices. To overcome the disadvantage above, electromagnetic actuation with bistable mechanisms was suggested. A type of latching electromagnetic microactuator with two stable states for reducing power consumption has been demonstrated by Ruan et al. [17]. The device was based on preferential magnetization of a permalloy cantilever in a permanent external magnetic field. But the force for the stable states came from the magnetizing cantilever in a magnetic field, which led to a low efficiency of electromagnetic effect. Ren and Gerhard [18] reported a bistable magnetic microactuator, where the device employed lateral movement and the motion was based on the bending of the cantilever. In this paper, an electrical - thermal MEMS microactuator will be presented.

2. Microsystem Analysis Features

ANSYS Multiphysics has an extremely broad physics capability directly applicable to many areas of microsystem design. Coupling between these physics enables accurate, real world simulation of devices such as electrostatic driven comb drives.

The ability to compute fluid structural damping effects is critical in determining the switching response time of devices such as micromirrors.

Electro-thermal-structural effects are employed in thermal actuators.

Fluid (CFD) capabilities are used to compute flow and free surface droplet formation useful in the design of ink-jet printer nozzles, and lab-on-chip applications.

The following figure (Fig. 1) explains how ANSYS Multiphysics capabilities fits into the Microsystem/MEMS design process:

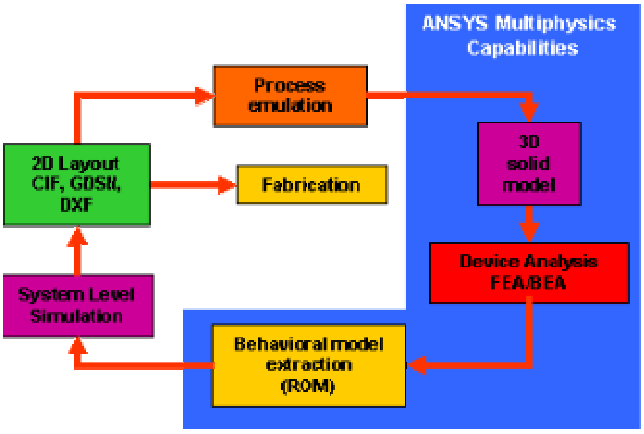

Fig. 1: ANSYS Multiphysics integration into the Microsystem/MEMS design process.

A sample of the features included in ANSYS Multiphysics are listed below:

1. Structural static, modal, harmonic, transient mechanical deformation.
2. Large deformation structural nonlinearities.
3. Full contact with friction and thermal contact.
4. Linear & non linear materials.
5. Buckling, creep.
6. Material properties: Temperature dependent, isotropic, orthotropic, anisotropic.
7. Loads/Boundary conditions: Tabular, polynomial and function of a function loads.
8. Plasticity, viscoplasticity, phase change.
9. Electrostatics & Magnetostatics.
10. Low Frequency Electromagnetics.
11. High Frequency Electromagnetics. (Full wave, frequency domain).
12. Circuit coupling - voltage & current driven.
13. Acoustic - Structural coupling.
14. Electrostatic-structural coupling.
15. Capacitance and electrostatic force extraction.
16. Fluid-Structural capability to evaluate damping effects on device response time.
17. Microfluidics: Newtonian & non Newtonian continuum flow
18. Free Surface VOF with temperature dependent surface tension.
19. Charged particle tracing in electrostatic and magnetostatic fields.
20. Electro-thermal-structural coupling.
21. Piezoelectric & Piezoresistive transducers: Direct coupled structural-electric physics. Full isotropic, orthotropic parameters.
22. Advanced themrolelectirc effect such as Seebeck, Peltier & thermocouple.

3. ANSYS MEMS Applications Overview

ANSYS Multiphysics can be applied to a broad range of Microsystem/MEMS analysis. The following table (Tab. 1) shows the analysis capability relevant for a range of applications.

Microsystem Application	ANSYS Multiphysics Capability
Inertial Devices: Accelerometers & Gyroscopes	Structural modal, Static, Transient, Electrostatic-Structural, Reduced order macro modeling for system level.
Surface Acoustic Wave Devices	Acoustic - Structural coupling
MicroStripline Components	High Frequency electromagnetics.
Micro-patch and Fractal Antennas	High Frequency electromagnetics.
Piezo Inkjet Printheads	Thermal actuation: Electro-thermal - structural coupled physics. Thermal-structural coupled physics
Thermal Inkjet Printheads	Piezoelectric actuation: Direct coupled structural-electric physics. VOF Free surfaces & capillary action.
Micro mass spectrometers	Electromagnetics & charged particle tracing
Electrostatic comb drives	Electrostatic - structural coupling. Capacitance extraction.
Microfluidic Channels	Newtonian/non-Newtonian continuum flow
Piezoelectric actuators	Full isotropic & orthotropic parameters
Pressure transducers:	Capacitance based: Electrostatic structural coupling. Piezo-resistive based: Electro-Structural indirect coupling
Electromechanical RF filters	Electrostatic - structural coupling. Capacitance extraction.
Micromirror technology	Electrostatic - structural coupling. Fluidic structural capability to evaluate damping effects
Micro-grippers	Electro-Thermal-structural
Micro TIP field emitters	Electrostatics & charged particle tracing
Micro-Gear assemblies	Mechanical with complex contact, friction.
Thermoelectric actuators	Electro-thermal - structural coupled physics
Magnetostrictive actuators	Low Frequency electromagnetics

Tab. 1: The analysis capability o ANSYS relevant for a range of applications

4. Problem Definition

This paper demonstrates how to analyze an electrical-thermal actuator used in a micro-electromechanical system (MEMS). The thermal actuator is fabricated from polysilicon and is shown below.

The thermal actuator works on the basis of a differential thermal expansion between the thin arm and blade.

The required analysis is a coupled-field multiphysics analysis that accounts for the interaction (coupling) between thermal, electric, and structural fields.

A potential difference applied across the electrical connection pads induces a current to flow through the arm and blade.

The current flow and the resistivity of the polysilicon produce Joule heating (I^2R) in the arm blade.

The Joule heating causes the arm and the blade to heat up.

Temperatures in the range of 700 - 1300°K are generated.

These temperatures produce thermal strain and thermally induced deflections.

The resistance in the thin arm is greater than the resistance in the blade.

Therefore, the thin arm heats up more than the blade, which causes the actuator to bend towards the blade.

The maximum deformation occurs at the actuator tip. The amount of tip deflection (or force applied if the tip is restrained) is a direct function of the applied potential difference.

Therefore, the amount of tip deflection (or applied force) can be accurately calibrated as a function of applied voltage.

These thermal actuators are used to move micro devices, such as ratchets and gear trains.

Arrays of thermal actuators can be connected together at their blade tips to multiply the effective force.

The main objective of the analysis is to compute the blade tip deflection for an applied potential difference across the electrical connection pads. Additional objectives are to: Obtain temperature, voltage, and displacement plots, Determine total current and heat flow.

5.1 Given

Dimensions are in micrometers. The thermal actuator has an overall length of approximately 250 micrometers, and a thickness of 2 micrometers.

The given potential difference across the electrical connection pads is 5 volts. In Tab.2 are given the characteristic magnitudes of the actuator

Material Properties for Polysilicon	
Young's modulus	169e3 GPa
Poisson's ratio	0.22
Resistivity	2.3e-5 ohm-µm
Coefficient of thermal expansion	2.9e-6/^{o}K
Thermal conductivity	150e6 W/m^{o}K

Tab. 2: Characteristic magnitudes of the actuator

5.2 Approach and Assumptions

Coupled-field problems can be solved using the direct method or the sequential method. The direct method performs the coupled-field analysis in one step using coupled-field elements. The sequential method performs the coupled-field analysis in multiple steps, where the results from one step are used as input to the next step. Coupled field elements are not required for the sequential method.
This paper uses the direct method to evaluate the actuator. The direct approach is the most efficient method for this problem. However, if it were necessary to include the effects of temperature-dependent material properties and/or thermal radiation, it would probably be more efficient to use the sequential method. The nonlinear thermal-electric problem could be solved using SOLID98 elements with only the TEMP and VOLT degrees of freedom active, and the mechanical problem could be solved using SOLID92 elements. The temperatures calculated in the thermal analysis could be applied as loading to the mechanical model using the LDREAD command.
It must defined the element type as SOLID98 using the default degrees of freedom [KEYOPT(1)]: UX, UY, UZ, TEMP, VOLT, MAG. The element simulates the coupled thermal-electric-structural response. The MAG degree of freedom is not required for this analysis so it will not be assigned a magnetic material property.
To define material properties for this analysis, it must be converted the given units for Young's modulus, resistivity, and thermal conductivity to µMKSV units. The units have been converted to µMKSV, and are shown in the following table (Tab. 3).

Material Properties for Polysilicon (µMKSV units)	
Young's modulus	169e3 MPa
Poisson's ratio	0.22
Resistivity	2.3e-11 ohm-µm
Coefficient of thermal expansion	2.9e-6/oK
Thermal conductivity	150e6 pW/µm^{o}K

Tab. 3: Units' conversion

Next, the model is meshed with the coupled field elements. Then, voltages are applied to the electrical connection pads and set their temperature to an assumed 30^{o}C. Next, the electrical connection pads are mechanically fixed in the X, Y, and Z directions. Finally, the solution is obtained and post processing of the results to achieve the analysis objectives, as stated above.

6. Results

The geometry to be modelled appears in the next figure (Fig. 2):

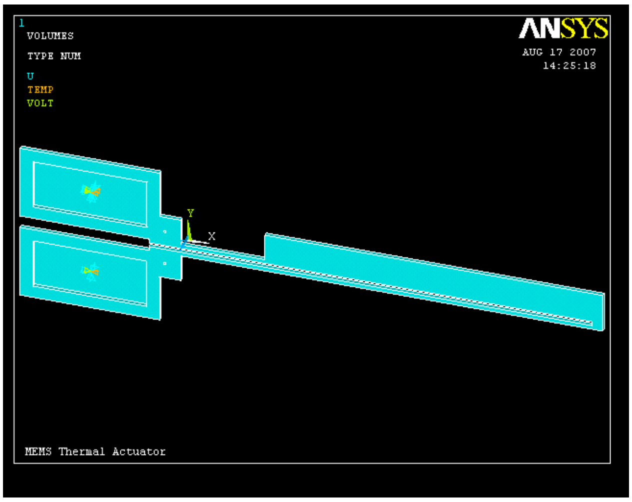

Fig. 2: Geometry to be modelled

The next figure presents a zoom of meshing (Fig. 3):

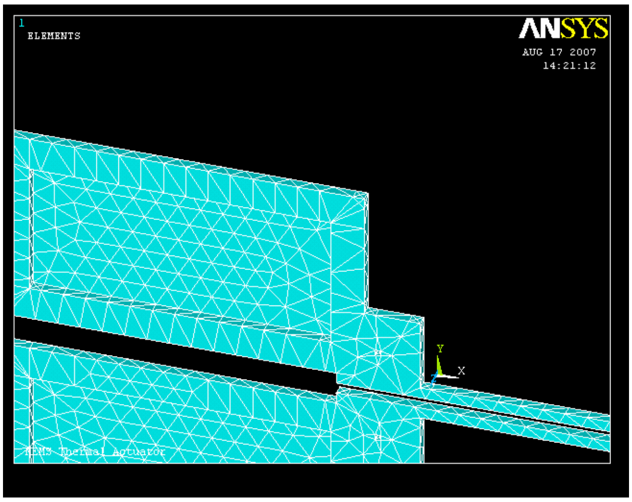

Fig. 3: Zoom of meshing

First, the temperature results will be plotted. This is one of the objectives of this analysis (Fig. 4):

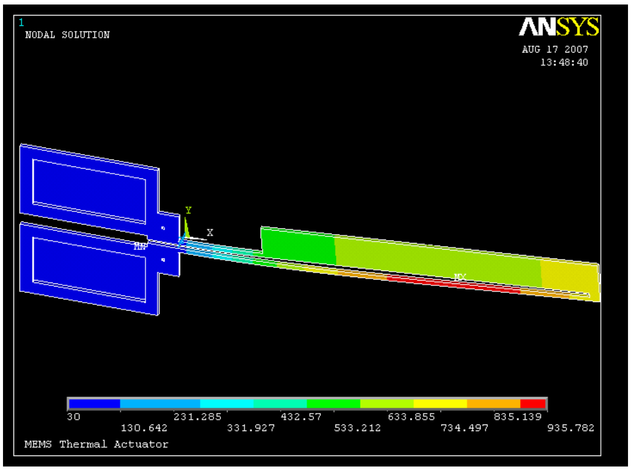

Fig. 4: Temperature results

It may be noted, that the electrical connection pads are the same color, reflecting the constant temperature boundary condition. It may be noted, also, that there is a change in color in the blade, as viewed from the pads end to the blade tip end, indicating that the voltage difference across the pads causes a temperature difference across the blade. Finally, it may be noted, that the thin arm is at higher temperatures than the blade.
Next, the voltage results will be plotted (Fig. 5):

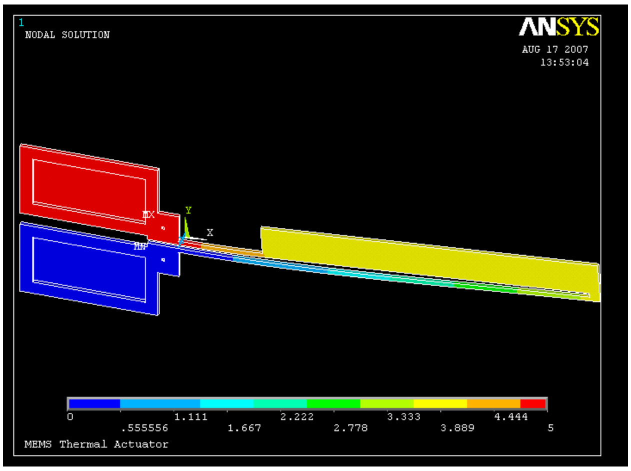

Fig. 5: Voltage results

It may be noted, that the electrical connection pads are distinctly two different colors, reflecting the voltage difference across the pads. It may be noted, also, that there is a change in color in the blade, as viewed from the pads end to the blade tip end, indicating that the voltage drop from pad 1 to pad 2 is distributed along the electrical conduction path of the actuator.

Finally, the displacement results will be plotted and more precisely those according to the Y – direction (Fig. 6):

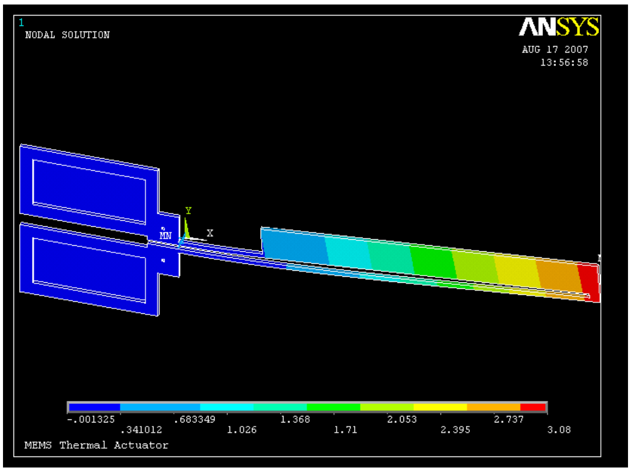

Fig. 6: Displacement results will be plotted and more precisely those according to the Y – direction.

It may be noted, that the electrical connection pads are the same color, reflecting that the pads are constrained in all directions. It may be noted, especially, the gradual change in color in the blade and thin arm, as viewed from the pads end to the blade tip end.
It may be noted, also, from the legend that the color

of the tip of the blade indicates a deflection of approximately 3.07 micrometers. This deflection results from the 5 volts applied across the pads.
The total heat flow is approximately 8.07e9 pW and the total current is approximately 3.23e9 pA.

7. Conclusion

In this paper, an electrical - thermal MEMS microactuator modelling was presented. The ambition of the author was to explain, how ANSYS Multiphysics capabilities fits into the Microsystem/MEMS design process. Basic characteristics of the behaviour of such a microactuator were identified. A further step of study will be to take into account the dependence of the electric conductivity on temperature.

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