Coupled Multi-Physics Modeling of Micro-Machined Electro-Thermo-Mechanical Actuator

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Abstract:

Electro-thermal actuation mechanism continues to attract attention of MEMS designers as a reliable method of delivering high displacements and high actuation forces [1].

The main purpose of this work is to conduct a coupled multi-physics FEA of a micro-machined electro-thermo-mechanical actuator (µETMA) in order to determine a nature of a common failure mode, suggest a better fabrication process and compute performance characteristics, such as actuation current, working temperature, actuation force and displacement, characteristic response time, etc.

Two designs of µETMA have been considered so far: design for PolyMUMPs and design for MetalMUMPs processes [2].

Comprehensive coupled multi-physics modeling of the device should include the following phenomena: initial relaxation of the structure due to residual stresses inherent to micro-fabrication methods, computation of electric current through the structure with semiconductor and metallic types of conductivity, Joule's heating, radiation and natural convection, thermal expansion, modal analysis, air-structure interaction, etc. Current paper presents only several analyses accomplished so far.

It has been determined that common mode failure observed with polysilicon devices is caused by run off temperature behavior due to exponential temperature dependence of the conductivity.

Introduction

Electro-thermal actuation mechanism continues to attract attention of MEMS designers as a reliable method of delivering high displacements and high actuation force [1]. However, design of such devices presents some difficulties due to the fact that several physical phenomena are tightly coupled, and therefore more than ever designer experience and intuition must be supplemented with multi-physics coupled-field analysis. ANSYS Multiphysics affords such kind of modeling and is used throughout this work.

Electro-thermo-mechanical actuators are based on simple physical principles: potential difference applied to a conductor causes electric current and Joule heating. Increased temperature gives rise to mechanical deformations. By varying applied potential difference one can control the position of the actuator. Design objective is to increase useful mechanical displacements and minimize energy losses.

Typical applications of µETMA include optical and electrical switches, variable optical attenuators, micro-tweezers and micro-manipulators, etc.

The problem, which was observed in the laboratory with µETMA fabricated from polysilicon with PolyMUMPs process [2] was that controlling of the actuator position required extremely fine control of the driving voltage, and slight fluctuations in voltage caused distraction of the devices.

The objective of this work was to model this phenomenon, determine the cause of it, and rectify the design.

Device fabricated by PolyMUMPs process

Design.

Scanning electron microphotograph of the device under investigation is shown in Figure 1. A disk of 500 µm in diameter is suspended 2 µm above the substrate on four narrow (5 µm) and long (500 µm) tethers. Schematic cross-sectional view of the tether illustrates that device is made of two polysilicon layers. Poly 1 layer is 1.5 µm thick and

has 20 MPa tensile residual stresses. Poly 2 layer is 2 μm thick and exhibits 150 MPa compressive residual stresses. Both polysilicon layers have thermal expansion coefficient about $\alpha=2.9*10^{-6}$ K^{-1}. Polysilicon is a semiconductor material, and therefore it's resistivity exponentially decreases with temperature rise. Measured resistivity of the polysilicon deposited in PolyMUMPs process follows the following thermal dependence:

$$\rho = 3.2*10^{-18} * T^{2/3} * e^{(0.6eV/kT)} , [Ohm * m] \tag{1}$$

where T is an absolute temperature, eV is an electron-volt = $1.6*10^{-19}$ J, k is the Boltzmann constant.
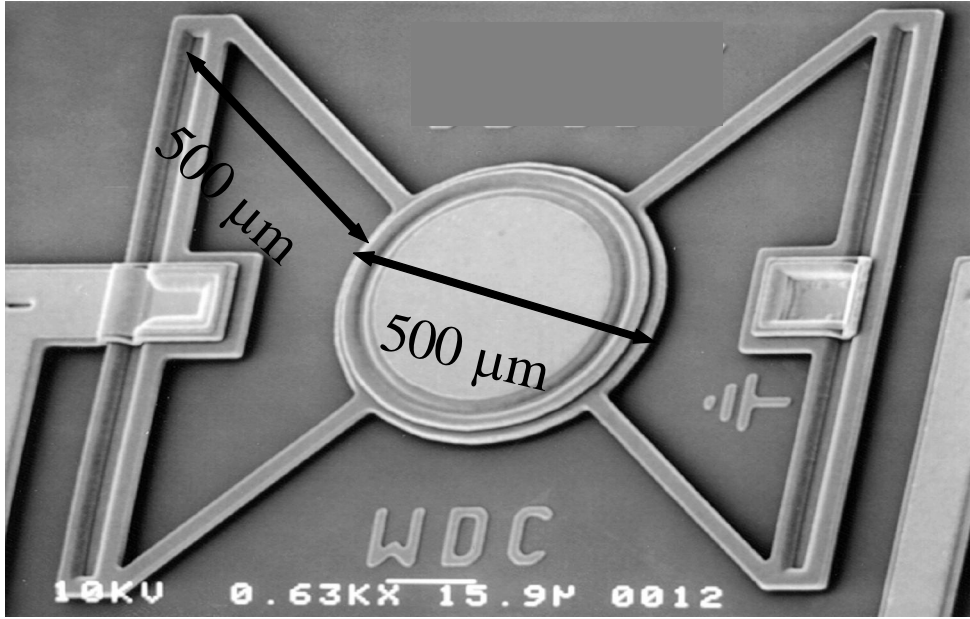

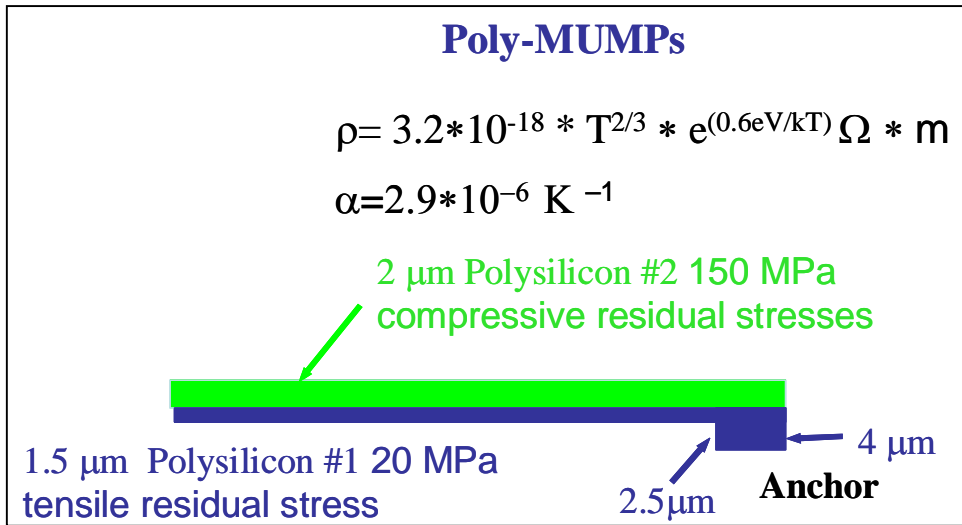**Figure 1. Scanning electron microphotograph of the μETMA fabricated with PolyMUMPs process.**

Figure 2. Schematic cross-sectional view of the tether illustrates that device is made of two polysilicon layers

Model.

Finite element model of this device consists of 5,000 brick coupled-field SOLID5 elements and is shown in Figure 3. Residual stresses were modeled (as they are) as thermal stresses. Initial operating temperature of the device was assumed to be 300 K. Reference temperature for Poly 1 layer was set to 338 K to model tensile residual stress, and reference temperature for Poly 2 layer was set to 0.1 K to model compressive residual stress.
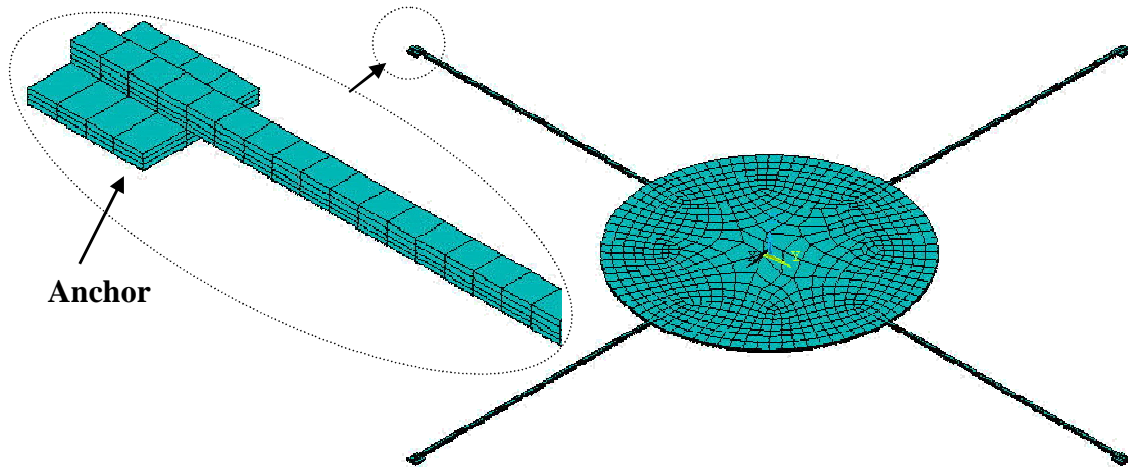

Figure 3. Finite element model of the PolyMUMPs μETMA consists of 5,000 brick coupled-field SOLID5 elements. Fix Ux, Uy and Uz DOF BCs and appropriate electrical BCs were assigned to bottom surface of the anchors
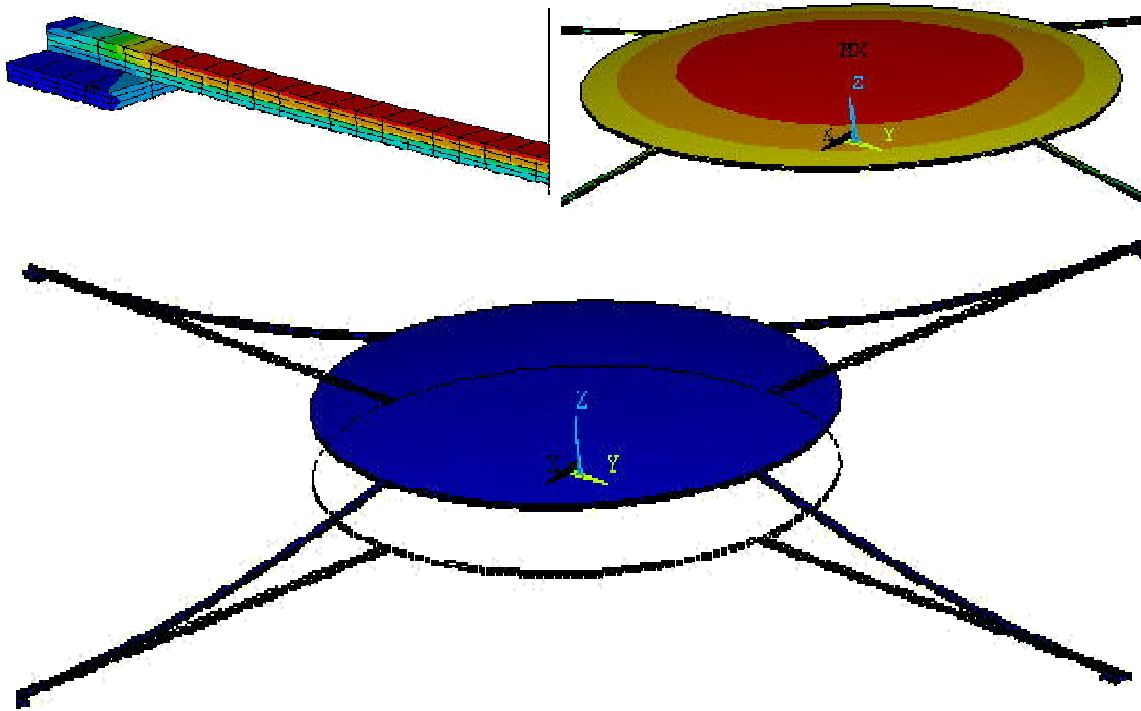

Figure 4. Relaxed state of μETMA, Von Misses stresses in anchor and deformation of the disk. The only boundary conditions are Fix All DOF at the bottom patches of the anchors.

Results and Discussions

Static stress-strain analysis demonstrates that upon final release device should relax to a steady state: the rim is located 21 µm and center is 31 µm above the fabricated position. A deformation of the device due to the residual stresses is shown in Figure 4. This matches experimental results very well.
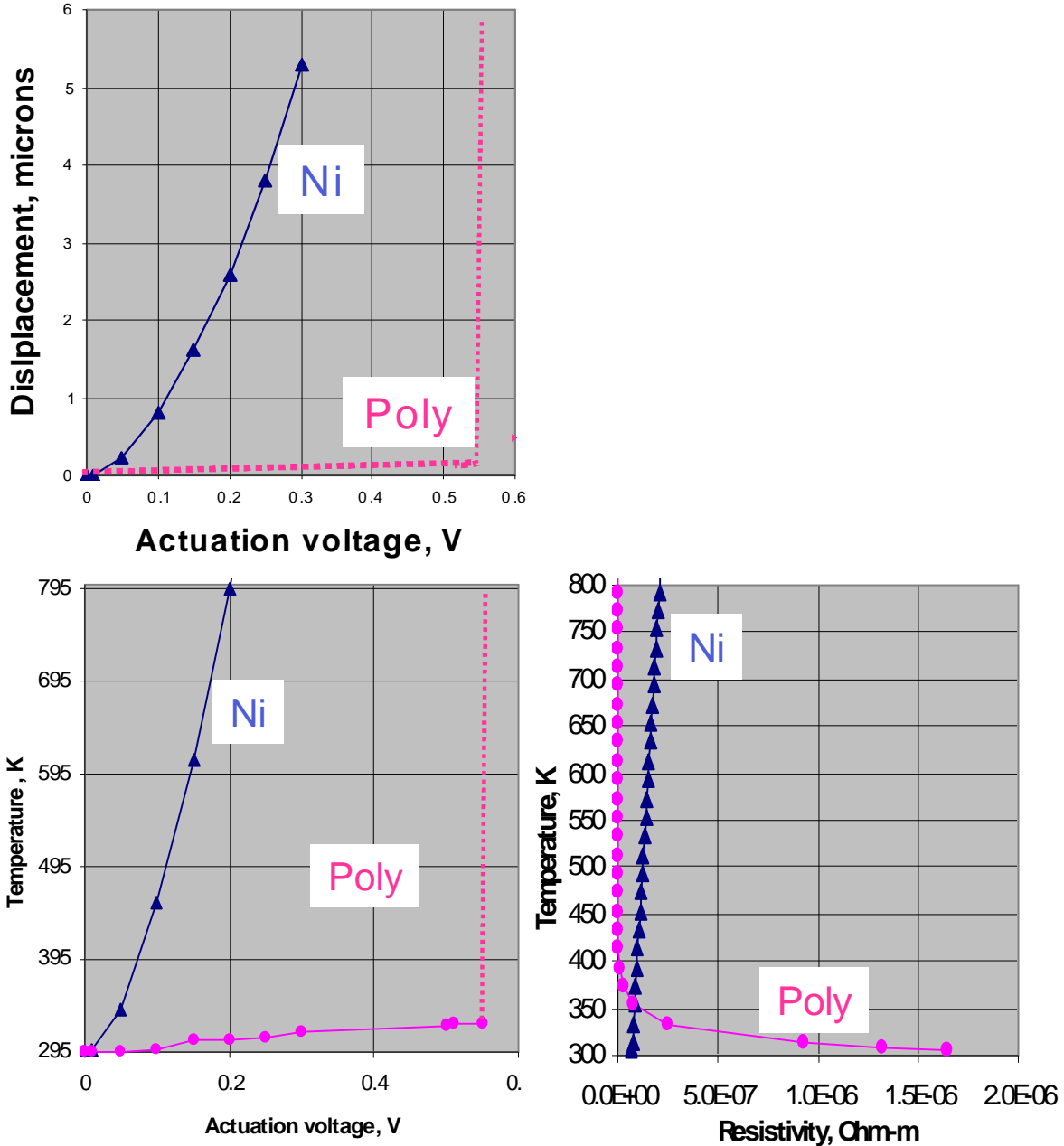

Figure 5. Computed behavioral curves showing temperature of the devices as a function of actuation voltage, maximum disk displacement as a function of applied voltage and resistivity as a function temperature.

The next step in analysis was to compute the location of the disk as a function of the applied voltage via coupled electro-thermo-mechanical analysis. However, convergence was impossible to achieve after potential difference

reached about 540 mV. Behavioral curves relevant to understanding this phenomenon are shown in Figure 5. It turns out, that at around this potential difference temperature of the device reaches about 340 K. Around this temperature resistivity of the polysilicon begins decreasing very rapidly (exponentially) after even small further rise of the temperature. Thermal power is proportional to V^2 / R and therefore temperature also increases very rapidly with increase of applied voltage. These two non-linearities (exponential and quadratic) working together lead to extremely fast increase of the temperature of the device with even small incremental increase of the driving voltage. This "run away" behavior causes melting of the devices in experimental set up and manifests itself as a convergence problem in FEA.

Because described behavior is a natural one for a semiconductor material, it can be concluded that no design can guarantee reliable operation of the µETMA fabricated from polysilicon. Therefore another process, MetalMUMPs shell be considered for fabrication of such a device.
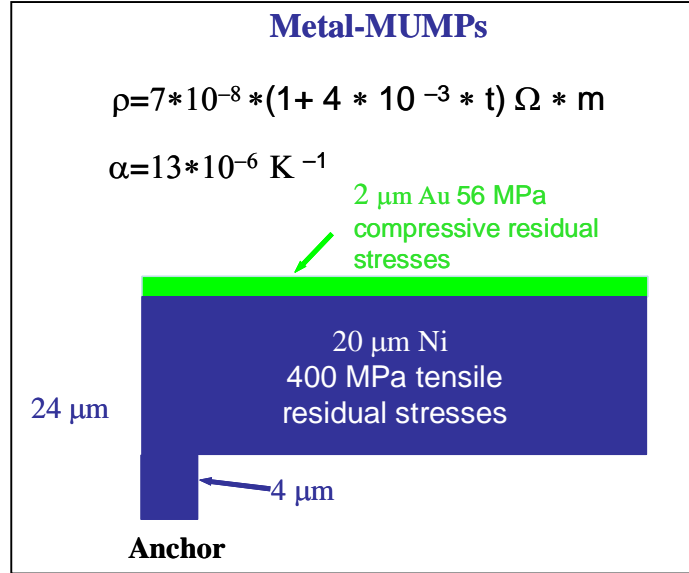

Figure 6. Schematic cross-sectional view of the tether illustrates that device is made of two metal layers

Device for fabrication by MetalMUMPs process

Design.

MetalMUMPs is a single structural layer process, utilizing nickel as a structural material, Fig. 6. Thick (20 µm) layer of nickel is covered with thin (2 µm) layer of gold for providing good ohmic contacts and high reflectivity. Nickel has a tensile residual stress of 400 MPa, while gold layer is under compressive stress of 56 MPa. Design rules for MetalMUMPs process dictate 50 µm widths of the tethers. Nickel and gold have $13*10^{-6}$ K^{-1} and $1.41*10^{-6}$ K^{-1} thermal expansion coefficients, respectively. In contrast with semiconductor materials, metallic resistivity increases with temperature rise following linear law. Measure thermal dependence of resistivity for MetalMUMPs nickel is as follows:

$$\rho = 7*10^{-8} *(1+ 4*10^{-3}*T), \ [Ohm*m] \tag{2}$$

Model.

Finite element model of the device designed for MetalMUMPs process is very similar to previously described PolyMUMPs model. Residual stresses were modeled setting reference temperature of nickel layer to 450 K to create tensile residual stress, and to 250 K for the gold layer to model compressive residual stress.

Results and Discussions

Upon the final release MetalMUMPs device relaxes to a steady state: rim is located 2 μm and center is 3.3 μm above the fabricated position, resulting in much flatter disk than afforded by a PolyMUMPs device.

Coupled electro-thermo-mechanical analysis converges quite rapidly with default solver settings. Simulated behavioral curves are shown in Figure 5. For example 1 μm displacement is achieved upon application of 120 mV that causes temperature rise up to about 500 K, electrical current through each tether about 135 mA, and thermal power about 16 mW. Typical temperature distribution across the device is shown in Figure 7.
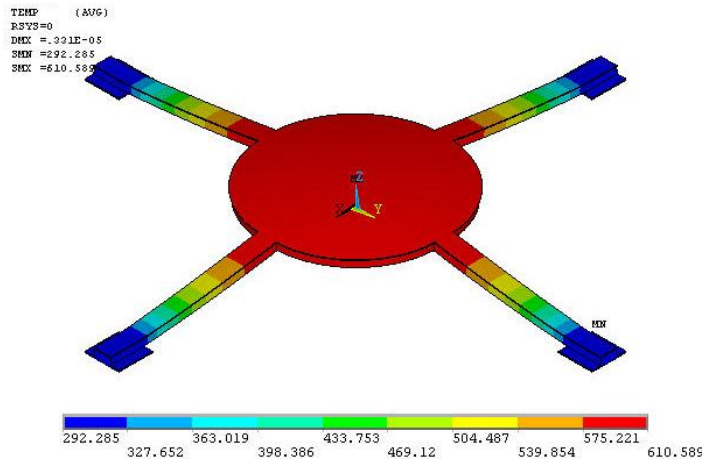

TEMP   (AVG)
RSYS=0
DMX =.331E-05
SMN =292.285
SMX =610.589

| 292.285 | | 363.019 | | 433.753 | | 504.487 | | 575.221 |
| | 327.652 | | 398.386 | | 469.12 | | 539.854 | | 610.589 |

Figure 7. Typical temperature distribution in MetalMUMPs device

Modal analysis of the MetalMUMPs device determines that the first mode has a resonance frequency 44.3 kHz. Intended operation of the device is associated with the first mode, therefore upper limit of the actuation speed can be determined as ¼ of the period of the first mode, which turns out to be 5.6 μs. Perhaps real actuation speed will be limited by other factors, such as thermal losses and mechanical damping. In order to determine these, more realistic modeling should be done, including transient analysis taking into account radiation, convection, and thermal losses to the substrate, fluid-structure interaction modeling, etc.

Conclusion

FEA of μETMA designed for PolyMUMPs and MetalMUMPs micro fabrication processes has been carried out. It's been determined that common mode failure observed with polysilicon devices is caused by run off temperature behavior due to exponential temperature dependence of the conductivity. Some functional parameters of the device designed for MetalMUMPs process have been computed. It is suggested that this process is much better suited for fabrication of μETMA.

References

1. Transducers'03, The 12th International Conference on Solid-State Sensors, Actuators and Microsystems, Boston, June 18-23, 2003

2. PolyMUMPs and MetalMUMP micro-fabrication processes are offered by Cronos/MEMSCAP, Inc. More information can be found at www.memsrus.com