SMA Actuated RF MEMS Switch

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Abstract
This paper presents the design optimization and fabrication of a low-voltage series radio frequency (RF) Micro-electromechanical (MEMS) switch. The simulation shows that the use of a pre-strained SMA beam to actuate switching allows the excitation voltage to be relatively much lower compared to that needed for electrostatic actuation. The switch structure has been optimized by the calculation of the dependence of gap size on both the length and the modulus of elasticity of cantilever beam. The paper also describes two ways in which the response of the SMA actuator is improved. To allow rapid heating without over heating the beam a temperature sensor along with a controller are implemented in the design.

Keywords
RF Switch, MEMS, SMA, Nitinol

Nomenclature

M_s : *Martensitc start temperature*

M_f : *Martensitc finish temperature*

A_s : *Austenitic start temperature*

A_f : *Austnitic finish temperature*

T = *Operation temperature*

ε_T : *Strain, where T could be any phase temperature (Ms, As..)*

ε_{tr} = *Transtition temperature*

C = *Stress to temperature coefficient*

Δ = *Transformation strain*

σ = *Stress*

1. Introduction

The continuous advance in microelectro-mechanical systems (MEMS) technology attracted researchers towards the development of MEMS devices for radio frequency (RF) applications. RF MEMS devices have a broad range of potential applications in wireless communication, navigation and sensor systems. They could be used in switches, phase shifters, signal routings, impedance matching networks, exciters, transmitters, filters, and IF/RF receivers [1]. Compared with the common electronic solid state switches (FET's and PIN diodes), RF MEMS based switches are characterized by very low insertion loss, low power consumption, high isolation (up to 100 GHz), low fabrication cost, and very low intermodulation. The literature shows more than 32 different types of RF MEMS with a variety of actuation mechanisms (electrostatic, magnetostatic, piezoelectric or thermal), contact modes (capacitive or metal-to-metal), and circuit implementation (shunt or series) [2].

Electrostatic actuation is the most used actuation scheme in RF MEMS. However, this type of triggering requires a relatively high DC voltage (up to 30 volts) and thus requires an additional CMOS integrated up-converter to raise the usually used 5 volts control voltage to the required level. The current paper focuses on the design and fabrication of RF MEMS switch using Shape Memory Alloys (SMA) based actuator. Shape memory alloys are thermally activated. At low temperatures the crystalline structure of the alloy is in the martensitic phase which provides flexibility and allows relatively large deformations. When the temperature is raised, transformation to austenitic phase takes place and the material loses its flexibility and thus the strain is recovered. Usually heating of SMA actuators is based on joule's heating effect and the voltage needed could be around 5 volts, which makes it superior to the electrostatic actuator in that sense. In addition to the low driving voltage, SMA actuators provide high energy density and large forces. Unfortunately, the drawback of SMA actuators is their relatively high response time (~50 ms) compared to the electrostatic actuators that have a response time on the order of micro seconds. The paper provides a scheme to improve the performance of SMA actuation of the RF switch by allowing rapid heating

and fast cooling of the SMA beam. Applying high currents results in rapid heating but requires temperature monitoring in order to avoid overheating of the SMA layer. A thermodiode temperature sensor with a feedback control is used to monitor the temperature of the SMA wire. As for rapid cooling, different methods are available, including water immersion, heat sinking and forced air cooling. Heat sinking is herein used to improve the cooling rate and thus provide faster switching time.

2. Design and Fabrication of the RF Switch

2.1 Switch design

The model of the proposed SMA switch is shown in figure 3. The switch is of series type which basically consists of a free end cantilever Polyimide[1] beam. We used Nitinol as the SMA material in our model since it is the most used SMA material for actuation purposes. Two Nitinol beams are attached to the cantilever as shown in figure 1; one at the top and the other at the bottom.

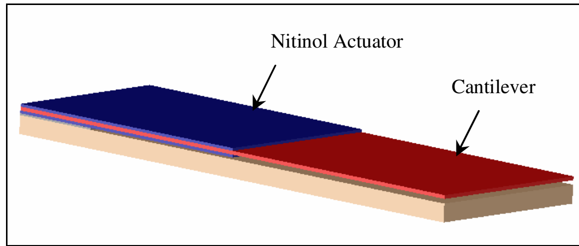

Figure 1: RF switch model

At the equilibrium position, the lower nitinol actuator is initially deformed in the longitudinal direction. When a voltage applied to the lower actuator, current will pass through the actuator causing it to heat up by joule heating and thus retain its initial deformation and contracts. The contraction of the beam causes the cantilever to bend down wards and metal-to-metal contact will occur. To enhance switching time, the upper nitinol actuator is heated up and the strain induced in the pull down phase will be retained and will aid the cantilever to go back to its equilibrium position in smaller time.

[1] The choice of Polyimide is based on the optimization that will be illustrated later

2.2 Constitutive relations of SMA

Many constitutive models have been proposed for the stress-train relations as a function of temperature. In this study, a simplified model is used for simulation purposes and that approximates the stress-strain curve as multi-linear segments with variable modulus of elasticity that is dependant on the operating temperature. The stress-strain curve for a given temperature is as shown in figure 2. The model is determined by the following parameters [3, 4, 5, 6].

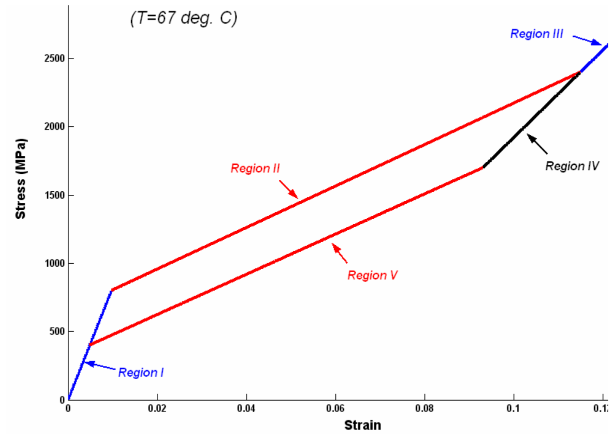

Figure 2: Stress Strain curve at a given temperature

a) *Transition Stresses:*

$$\sigma_{Ms} = C(T - M_s) \quad (1)$$

$$\sigma_{Mf} = C(T - M_f) \quad (2)$$

$$\sigma_{As} = C(T - A_s) \quad (3)$$

$$\sigma_{Af} = C(T - A_f) \quad (4)$$

b) *Transitions Strains*

$$\varepsilon_{Ms} = \frac{C(T - M_s)}{E_A} \quad (5)$$

$$\varepsilon_{Mf} = \Delta + \frac{C(T - M_f)}{E_M} \quad (6)$$

$$\varepsilon_{As} = \Delta + \frac{C(T - A_s)}{E_M} \quad (7)$$

$$\varepsilon_{Af} = \frac{C(T - A_f)}{E_A} \quad (8)$$

The constitutive relations for the five regions depicted figure 2:

1) Region I

$$(0<\varepsilon_I<\varepsilon_{Ms})$$

$$\sigma_I = E_A \varepsilon_I \quad (9)$$

2) Region II

$$(\varepsilon_{Ms}<\varepsilon_{II}<\varepsilon_{Mf})$$

$$\varepsilon_{tr,II} = \Delta\left(\frac{\varepsilon_{II}-\varepsilon_{Ms}}{\varepsilon_{Mf}-\varepsilon_{Ms}}\right) \quad (10)$$

$$\sigma_{II} = \sigma_{Ms} + \left(\frac{\varepsilon_{tr,II}}{\Delta}\right)(\sigma_{Mf}-\sigma_{Ms}) \quad (11)$$

3) Region III

$$\varepsilon_{Mf}<\varepsilon_{III}<\varepsilon_{\max})$$

$$\varepsilon_{tr,III} = \Delta \quad (12)$$

$$\sigma_{III} = \sigma_{Mf} + E_M(\varepsilon_{III}-\varepsilon_{Mf}) \quad (13)$$

4) Region IV

$$(\varepsilon_{As}<\varepsilon_{IV}<\varepsilon_{Mf})$$

$$\varepsilon_{tr,IV} = \Delta \quad (14)$$

$$\sigma_{IV} = \sigma_{Mf} + E_M(\varepsilon_{IV}-\varepsilon_{Mf}) \quad (15)$$

5) Region V

$$(\varepsilon_{Af}<\varepsilon_V<\varepsilon_{As})$$

$$\varepsilon_{tr,V} = \Delta - \left(\Delta\left(\frac{\varepsilon_{As}-\varepsilon_{tr,V}}{\varepsilon_{As}-\varepsilon_{Af}}\right)\right) \quad (16)$$

$$\sigma_V = \sigma_{Af} + \left[\left(\frac{\varepsilon_{tr,V}}{\Delta}\right)(\sigma_{As}-\sigma_{Af})\right] \quad (17)$$

Figure 2 shows the stress strain curve for different temperatures. It should be noted that increasing the temperature is equivalent to reducing the applied stress.

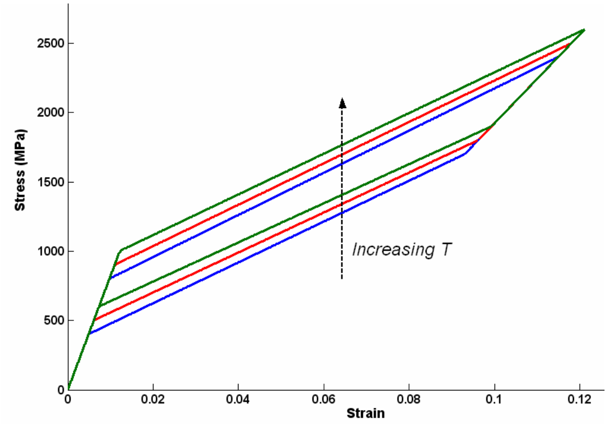

Figure 3: Stress Strain curve of Nitinol for different T

2.3 Temperature Control

Large currents heat SMA layer quickly and reduce contraction time. However, applying large currents for too long leads to overheating which can destroy the shape memory effect and in extreme cases lead to break of the SMA layer. In order to prevent such damage a thermodiode is used to sense the temperature. When the temperature of the SMA reaches a certain value the controller automatically cuts-off the current to the SMA element.

Thermo-diode Sensor

If a voltage source is connected to a p-n junction diode, current will flow continuously and the junction is sid to be forward-biased, provided that the applied voltage V is greater than the forward bias voltage V_s of the diode. The voltage dependence on temperature of the diode is given by:

$$V = \left(\frac{\eta KT}{e}\right)\ln\left(\frac{I}{I_s}+1\right) \quad (18)$$

where

η: Non ideality multiplicative factor
e: Electron charge (C)
K: Boltzman's constant (J/K)
T: Absolute temperature

Equation (18) indicates that the voltage is directly proportional to absolute temperature. Because diode voltage V is a function of current, a stable constant current source is essential.

In the current application the pn-junction will be placed in contact with the shape memory alloy and an amplifier circuit is used to measure the forward bias voltage across a thermodiode. Figure 4 shows

the basic circuit for the thermodiode; resistors R_1 and R_2 limit the current I which flows through the junction. The output from the differential opamp is linearly related to temperature and is converted into a digital value by analog to digital conversion (data acquisition card).

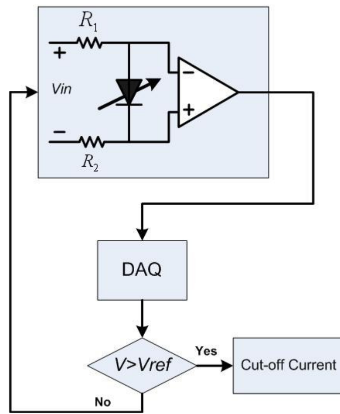

Figure 4: Controller flow chart

The value of the voltage is monitored and when the voltage value exceeds *Vref*, the voltage corresponding to the rating temperature, the voltage input to the SMA layer drops to zero to cut-off the current.

2.4 Switch Dynamic model

A simplified dynamic model for the switch is given by [2]. The motion's equation:

$$\underline{M}\,\underline{\ddot{X}} + \underline{B}\,\underline{\dot{X}} + \underline{K}\,\underline{X} = \underline{Fc} \qquad (19)$$

where $\ddot{X}$, $\dot{X}$, and X are the displacement, velocity, and acceleration vectors. *M, B, and K* are the mass, damping and stiffness matrices. *Fc* is the control force vector that results when the SMA actuator contracts to retain its pre-deformed strain.

This model is implemented in finite element software to solve for both the deflection of the cantilever tip and for the time it takes for contact.

2.5 Finite Element Model

ANSYS software is chosen to perform the dynamic simulation for its ability to coupled field problems. The behaviour of SMA is different from any other material integrated within ANSYS material library. To model the SMA material properties, the material is assumed to behave as multi-linear elastic whose modulus of elasticity is dependant on temperature. The ANSYS macros are used to implement the constitutive equations presented earlier (refer to *Constitutive relations for SMA*). Figure 5 shows the stress-strain curves for different temperatures as for the new material implemented in ANSYS.

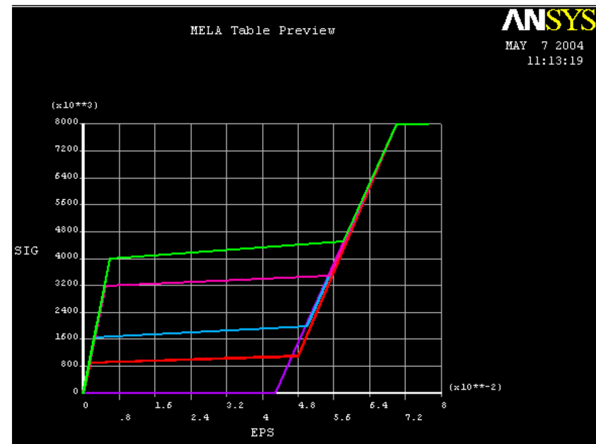

Figure 5: Stress Strain curve of nitinol in ANSYS

For the finite element model, coarse mesh was used since the geometry is not complex. Figure 6 shows this meshed finite element model of both the SMA layer and the cantilever beam.

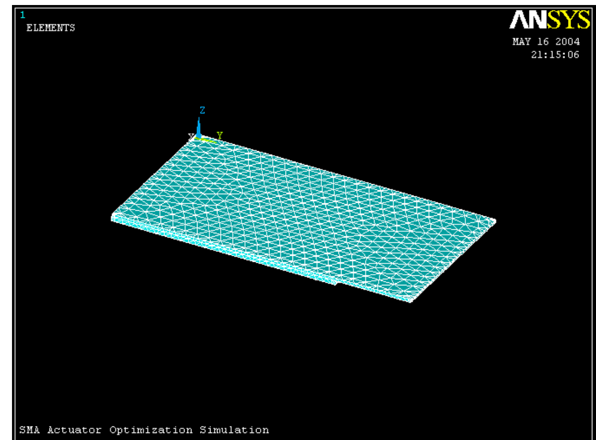

Figure 6: Finite element model in ANSYS

2.6 Design Optimization

The main purpose of this optimization scheme is to maximize the deflection for a constant applied voltage to the actuator (5 volts). ANSYS software includes a parametric solver that was used to perform the optimization based on the following criteria:

- **Design Variables:**
  - Length of beam *(150 μm<L< 400 μm)*
  - Modulus of elasticity of the cantilever material *(50 GPa<E<270 GPa)*

- **State Variables**
  - Width of the cantilever (*90 μm <W<100 μm)*
- **Objective Function**
  - Maximizing the deflection of the cantilever beam: *(Max. (X_{tip}))*

2.7 Simulation and Results

For the optimization parameters stated earlier and for an input voltage of 5 volts, the following results are obtained.

2.7.1 Optimization Parameters

- *E = 75 GPa*
- *W=90 μm*
- *L=150 μm*

2.7.2 Results

- Switching time = *1 ms*
- Maximum tip deflection = *0.4 μm*
- Maximum von-miss stress = 28 MPa

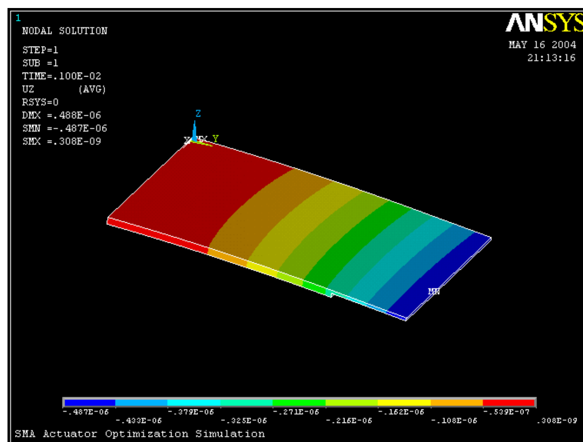

Figure 7: Cantilever Deflection

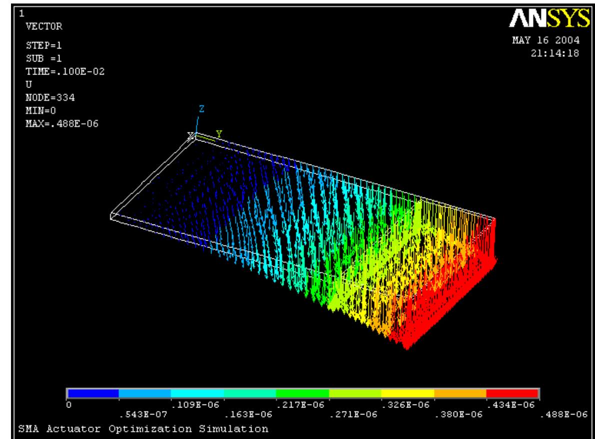

Figure 8: Magnitudes of Deflection ANSYS simulation

2.8 Switch fabrication

The summary of the steps proposed for the fabrication are as follows (figure 8) [7]:

- Begin with a ***Silicon substrate*** *-1-*
- Deposit the ***silicon nitride*** (Si_xN_y) as an insulating layer using chemical vapor deposition (CVD)
- Create a ***silicon dioxide*** (SiO_2) sacrificial layer by CVD
- Using positive photo-resist, the sacrificial layer is exposed to ultra violet rays through a mask
- The whole substrate is developed in a developer solution (H_2SO_4) to remove area of SiO_2 exposed to UV
- The first layer of metal (***Au***) is deposited using sputter deposition *-2-*
- Pattern the layer of Au by deep reactive ion etching (DRIE)
- Repeat above processes to deposit the heat sink metal *-3-*
- Deposit an SiO_2 layer
- Use lithography to pattern the SiO_2 then deposit the first Nitinol ***TiNi*** alloy metal by sputter deposition and repeat same process to deposit the second Au metal contact *–see 5-*
- Pattern the SiO_2 layer to open a window in the sacrificial layer
- Deposit the polyimide to form the cantilever beam *-4-*
- The last sacrificial layer is deposited by CVD

- Pattern the SiO_2 layer to deposit the second TiNi alloy metal
- Use DRIE to pattern the TiNi in the desired form
- Selective etch the SiO_2 layer in hydrofluoric acid (HF) leaving a free standing micro structure

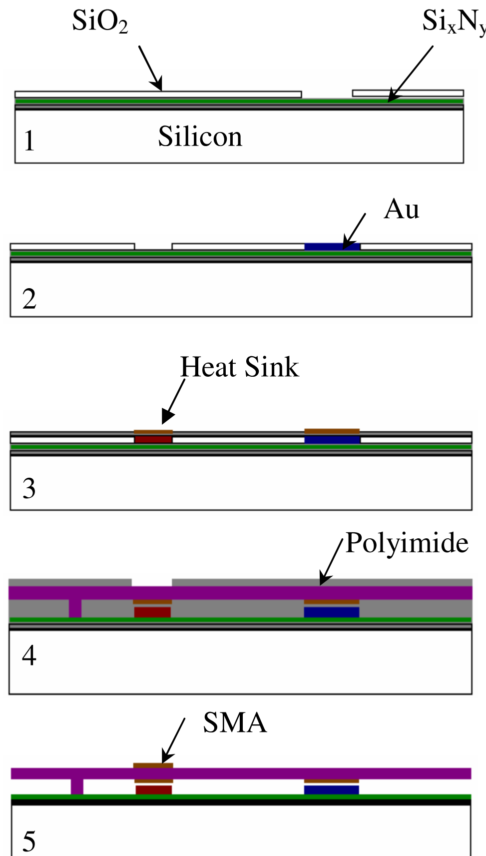

Figure 9: Fabrication process steps

3. Conclusion & Future Work

The results of finite element solution shows that using SMA for actuation of RF MEMS switches has a great advantage in terms of excitation voltage compared to the input voltage required for electrostatic actuation (5 volts compared to 20 volts needed in electrostatic actuated RF switches). Controlling the current passing through nitinol beams will increase the time response and thus allows lower switching time which is comparable to that of electrostatic actuated RF switches. The need for CMOS up-converters that are necessarily integrated with RF MEMS switches could be neglected when using SMA actuators instead of electrostatic actuators. The future work will explore using *inductive heating* to heat the SMA layer rather than joule heating. This type of heating proved to have much higher heating rate in the macro-world.

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