The International Journal Of Engineering And Science (IJES)
|| Volume || 4 || Issue || 6 || Pages || PP.11-23 || June - 2015 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Mechanical Characterization of Shape Memory Alloy Based RF MEMS switch using ANSYS

[1,] Pearl Antonette Mendez, [2,] Roopa Toms, [3,] Riya Cherian, [4,] Theresa Tomy, [5,] Minnie J Kappan, [6,] P.N.Jithin

[1, 2, 3, 4, 5,] (Department of Electronics & Communication, Rajagiri school of Engineering & Technology, Ernakulam, Kerala, India)

[6](Department of Mechanical Engineering, Rajagiri School of Engineering & Technology, Ernakulam, Kerala, India)

ABSTRACT

Conventional switches require considerable amount of actuation voltage for operation. So an RF MEMS switch which can be actuated by a lower voltage unlike the conventional switches can be used to solve this problem. RF MEMS switches offer a substantially higher performance than p-i-n or FET diode switches. They are extensively used in MEMS phase shifters, phased arrays and switching networks up to 120 GHz. Work is also extended to the analysis of the switch under various mechanical parameters like material properties, Young's Modulus, Poisson's ratio, loading properties etc. The development platform chosen is ANSYS software. The analysis category is structural-thermo-electric analysis. A switch is being simulated using ANSYS software and the switching action is analysed.

***KEYWORDS**: ANSYS, FEM, micro-fabrication, RF microelectro mechanical systems, SMA, surface micromachining*

Date of Submission: 22-May-2015 ⟷ Date of Accepted: 08-June-2015

I. INTRODUCTION

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro-fabrication. MEMS is similar to VLSI circuits in that it allows the execution of complex functions on a size scale orders of magnitude lower and at far less power than discrete circuits. However, MEMS enables this miniaturization on a class of sensors and transducers that traditionally were constructed on the model of a large, often cumbersome transducer or sensor coupled to a highly integrated VLSI readout circuit or processor. [1] A good example of this is the MEMS accelerometer, now one of the largest single MEMS application through its incorporation in air bags.The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move. The term used to define MEMS varies in different parts of the world. In the United States they are predominantly called MEMS, while in some other parts of the world they are called "Microsystems Technology" or "micromachined devices".

II. MEMS & MICROMACHINING

MEMS is a miniature device or an array of devices combining electrical and mechanical components and fabricated with IC batch-processing techniques [2]. Different MEMS fabrication techniques currently in use, include bulk micromachining, surface micromachining, fusion bonding, and LIGA, which is a composite fabrication procedure of lithography, electroforming, and molding. The most important technique for RF MEMS is surface micromachining. Surface micromachining consists of the deposition and lithographic patterning of various thin films, usually on Si substrates. Generally, the intent is to make one or more of the ("release") films freestanding over a selected part of the substrate, thereby able to undergo the mechanical motionor actuation characteristic of all MEMS. This is done by depositing a "sacrificial" film (or films) below the released one(s), which is removed in the last steps of the process by selective etchants. The variety of materials for the release and sacrificial layers is great, including many metals (Au, Al, etc.), ceramics (SiO and Si N), and plastics (photoresist, polymethyl methacrylate (PMMA), etc.). Depending on the details of the MEMS process and the other materials in the thin-film stack, the release and sacrificial layers can be deposited by evaporation, sputtering, electrodeposition, or other methods.

MEMS switches are surface-micromachined devices which use a mechanical movement to achieve a short circuit or an open circuit in the RF transmission-line. RF MEMS switches are the specific micromechanical switches which are designed to operate at RF to mm-wave frequencies (0.1 to 100 GHz) [3]. The advantages of MEMS switches over PIN diode or FET switches are [4]

***Near-Zero Power Consumption*:** Electrostatic actuation requires 30-80 V, but does not consume any current, leading to a very low power dissipation (10-100 nJ per switching cycles). On the other hand, thermal/ magnetic switches consume a lot of current unless they are made to latch in the down-state position once actuated.

***Very High Isolation*:** RF MEMS metal-contact switches are fabricated with air gaps, and therefore, have very low off-state capacitances (2-4 fF) resulting in excellent isolation at 0.1-60GHz. Also, capacitive switches with a capacitance ratio of 60-160 provide excellent isolation from 8-100GHz.

***Very Low Insertion Loss*:** RF MEMS metal-contact and capacitive switches have an insertion loss of 0.1dB up to 100GHz.

***Linearity and Intermodulation Products*:** MEMS switches are extremely linear devices and therefore re-sult in very low intermodulation products in switching and tuning operations. Their performance is 30-50 dB better than PIN or FET switches.

***Potential for Low Cost*:** RF MEMS switches are fabricated using surface micromachining techniques and can be built on quartz, Pyrex, LTCC, mechanical grade high-resistivity silicon or GaAs substrates.

RF MEMS switches also have their share of problems, and these are:

***Relatively Low Speeds*:** The switching speed of most electrostatic MEMS switches is 2-40 μs, and thermal/magnetic switches are 200-3, 000 μs. Certain communication and radar systems require much faster switches.

***High Voltage or High Current Drive*:** Electrostatic MEMS switches require 30-80 V for reliable operation, and this requires a voltage up-converter chip when used in portable telecommunication systems. Thermal/ magnetic switches can be actuated using 2-5 V, but require 10-100 mA of actuation current.

***Power Handling*:** Most MEMS switches cannot handle more than 200 mW although some switches have shown up to 500 mW power handling (Terravicta and Raytheon). MEMS switches that handle 1-10 W with high reliability simply do not exist today.

***Reliability*:** The reliability of mature MEMS switches is 0.1-40 Billion cycles. However, many systems require switches with 20-200 Billion cycles. Also, the long term reliability (years) has not yet been addressed. It is now well known that the capacitive switches are limited by the dielectric charging which occurs in the actuation electrode, while the metal contact switches are limited by the interface problems between the contact metals, which could be severe under low contact forces (in electrostatic designs, the contact forces are around 40-100 μN per contact).

***Packaging*:** MEMS switches need to be packaged in inert atmospheres (Nitrogen, Argon, etc..) and in very low humidity, resulting in hermetic or near hermetic seals. Hermetic packaging costs are currently relatively high, and the packaging technique itself may adversely affect the reliability of the MEMS switch. Microassembly and Analog Devices have both developed excellent packages for RF MEMS switches. The Microassembly package is based on gold-to-gold thermo-compression at 250◦C while the Analog Devices package is based on glass-to-glass seal at 400−450◦C. Other companies which have packaged switches are Terravicta (ceramic package) and Omron (glass-to-glass).

***Cost*:** While MEMS switches have the potential of very low cost manufacturing, one must add the cost of the packaging and the high-voltage drive chip. It is therefore hard to beat a $0.3-0.6 single-pole double throw 3 V PIN or FET switch, tested, packaged and delivered.

III. ACTUATION TECHNIQUES

Devices capable of motion greatly broaden the potential applications for MEMS. Desirable characteristics of MEMS actuators include [5]

- Force generation in millinewton range
- Displacement of 10m or more
- Linear response to input signals
- Fabrication compatible with standard surface micromachining
- Reliable, with long life time

Actuation methods can be broadly classified by physical stimulus that under lies the actuation. Most common physical stimuli are electric fields, magnetic fields and thermal effects. Actuation methods induced by electric fields include electrostatic and piezoelectric. The common magnetic field induced actuation methods are magneto static and magnetostrictive. For thermally driven actuation, methods include difference in thermal coefficients of expansion between two materials, shape memory materials and liquid-to-vapour phase change.

Shape memory alloy (SMA) materials posses the ability to repeatedly return to a shape 'learned' at a high temperature when deformed at a low temperature. The most common shape memory alloy is made from titanium and nickel (also known as Nitinol). SMA actuators can generate forces of millinewtons and larger, and can have large displacements [6]. Integration with standard MEMS fabrication processes is not difficult. Major disadvantages include power required for heating and slow response time.

IV. ANSYS

ANSYS offers a comprehensive range of engineering simulation solution sets providing access to virtually any field of engineering simulation that a design process requires. The tool puts a virtual product through a rigorous testing procedure before it becomes a physical object. It is a finite element modelling package for solving mechanical problems like static/dynamic structural analysis, heat transfer fluid problems, and acoustic electromagnetic problems. ANSYS uses multi-physics analysis tools for accurate and fast results. It also uses Structural Analysis tools to characterize static and dynamic behaviour of device, to determine stress, deformation and resonance of MEMS devices. The main features of this virtual prototyping and modular simulation system is innovative, reliable and high quality products and processes, fewer physical prototypes and test setups for faster return on investment due to reduced development time, more flexible and responsive information based development process, enabling the modification of designs at later stages of development and seamless working exchange of data regardless of location, industry, CAD environment.

V. FINITE ELEMENT ANALYSIS

Finite element method (FEM) is a numerical technique for finding approximate solutions to partial differential equations. It is a method for dividing up a very complicated problem into small elements that can be solved in relation to each other. FEM approximates partial differential equations with a system of algebraic equations for steady state problems and a system of ordinary differential equations for transient problems. The finite element method is originally developed to study the stresses in complex aircraft structures. Then it is applied to other fields of continuum mechanics, such as heat transfer, fluid mechanics, acoustics, electromagnetics, geo-mechanics, and biomechanics. FEA is used in industries, such as aerospace, automotive, biomedical, bridges and buildings, electronics and appliances, heavy equipment and machinery, micro electro mechanical systems (MEMS) and sporting goods. In the FEA the structure is modelled by the assemblage of small pieces of structure.

These pieces with simple geometry are called finite elements. In FEA, the variation of the field variable on the element is approximated by the simple functions such as polynomials. The actual variation on the element is almost certainly more complicated. So FEA provides an approximate solution.

Table 1: material properties of switches

Material	Al	Nitinol	Polyimide	Au	Ni	Cu
Young's modulus (10^3)	70.00	75.00	2.50	78.00	200.00	130.00
Poisson ratio	0.35	0.31	0.34	0.44	0.31	0.34
Density (10^{-15})	2.70	6.50	1.42	19.28	8.90	8.96
Thermal coefficient (10^{-6})	23.10	11.00	20.00	14.20	13.40	16.50

Thermal conductivity (10^6)	237.00	18.00	0.12	315.00	90.70	401.00

VI. SMA Actuated RF MEMS Switch

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 5volts, 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 [7].

6.1 Switch Design

The model of proposed SMA switch is shown in figure I. The switch is of series type which basically consists of a free end cantilever Polyimide beam and Nitinol pads. Nitinol was chosen as the SMA material in the model since it is the most used SMA material for actuation purposes. Two Nitinol pads are attached to the cantilever as shown in figure 1; one at the top and the other at the bottom [7].

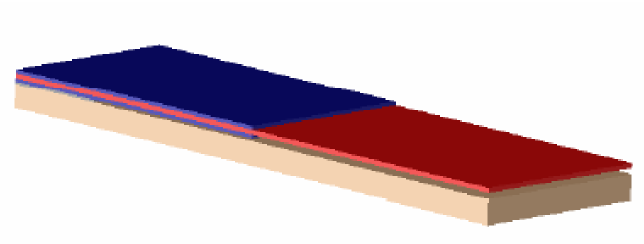

Fig 1: SMA actuated RF switch model

6.2 Working Principle

Initially the lower Nitinol actuator is initially deformed in the longitudinal direction. When a voltage is applied to the lower actuator, current will pass through the actuator causing it to warm 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[7].

6.3 Finite Element Model of Switch

ANSYS Multiphysics software is chosen to perform the dynamic simulation for its ability to coupled field problems. The behavior 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.

6.3.1 Design Optimization

The foremost purpose of this optimization design is to maximize the deflection for a constant applied voltage to the actuator. ANSYS software includes a parametric solver that was used to perform optimization based on the criteria shown in table II.

TABLE II: DESIGN VARIABLES

Length of beam	400 µm
Width of beam	90 µm
Thickness of beam	2 µm
Length of pads	150 µm
Width of pads	90 µm
Thickness of pads	1 µm

6.3.2 Boundary Conditions

The boundary conditions are given in table III which is applied on both upper and lower pads. It is important to note that no boundary condition is applied on beam.

TABLE III. BOUNDARY CONDITIONS

Upper pad	Lower pad
U_X=0	U_X=0
U_Y=0	U_Y=0
U_Z=0	U_Z=0
V=0	V=5 volts

TABLE IV. VARIOUS DIMENSIONS OF PADS AND BEAM FOR SMA SWITCH

Dimensions (µm)	Set 1	Set 2	Set 3
Length of beam	150	250	400
Width of beam	90	90	90
Thickness of beam	1	1	1
Length of pads	50	150	300
Width of pads	90	90	90
Thickness of pads	1	1	1

VII. SIMULATION AND RESULTS

After completing the simulation in ANSYS environment, very good results are obtained and shown in power graph. Nodal solution is obtained which shows different colors in the graph indicating actuation values at different nodes.

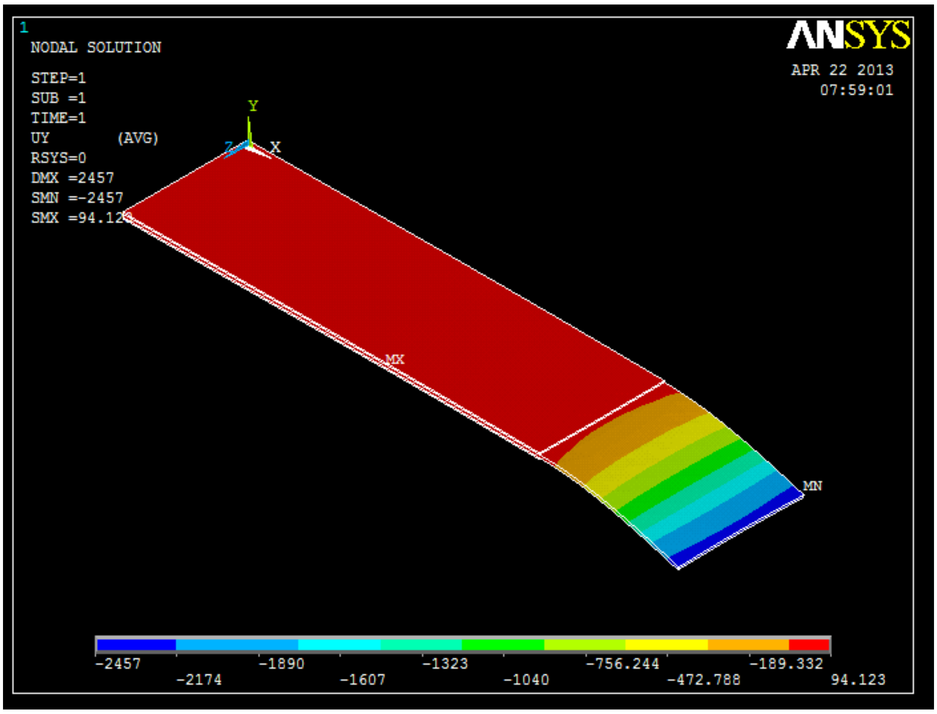

Fig 2: Maximum deflection plot for nitinol pads and aluminium beam (dimension set 1)

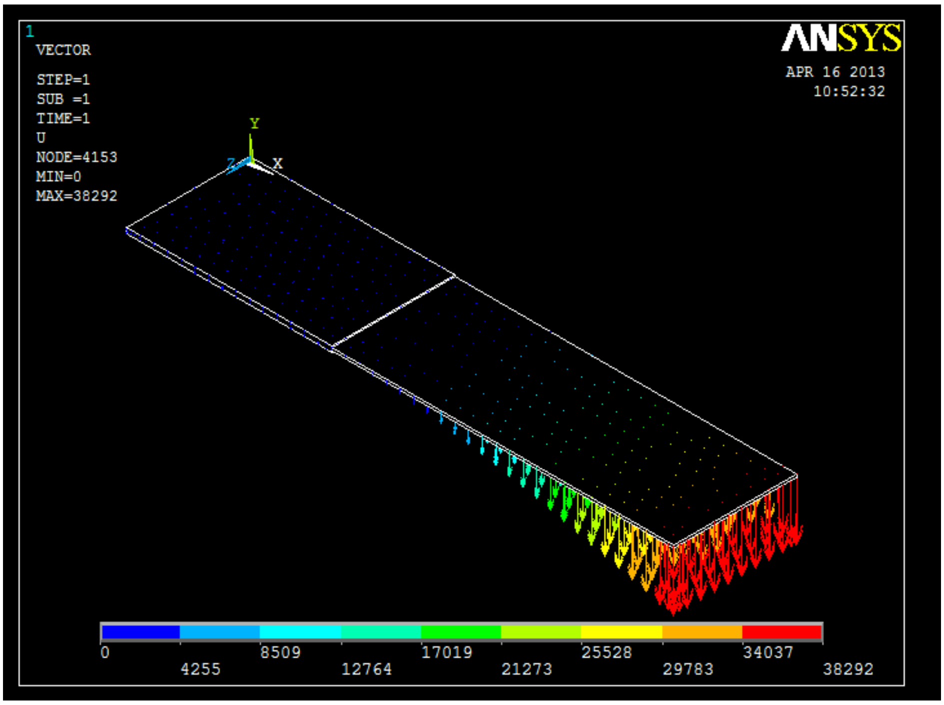

Fig 3: Maximum deflection – vector plot- Nitinol pads and aluminium beam (dimension set 1)

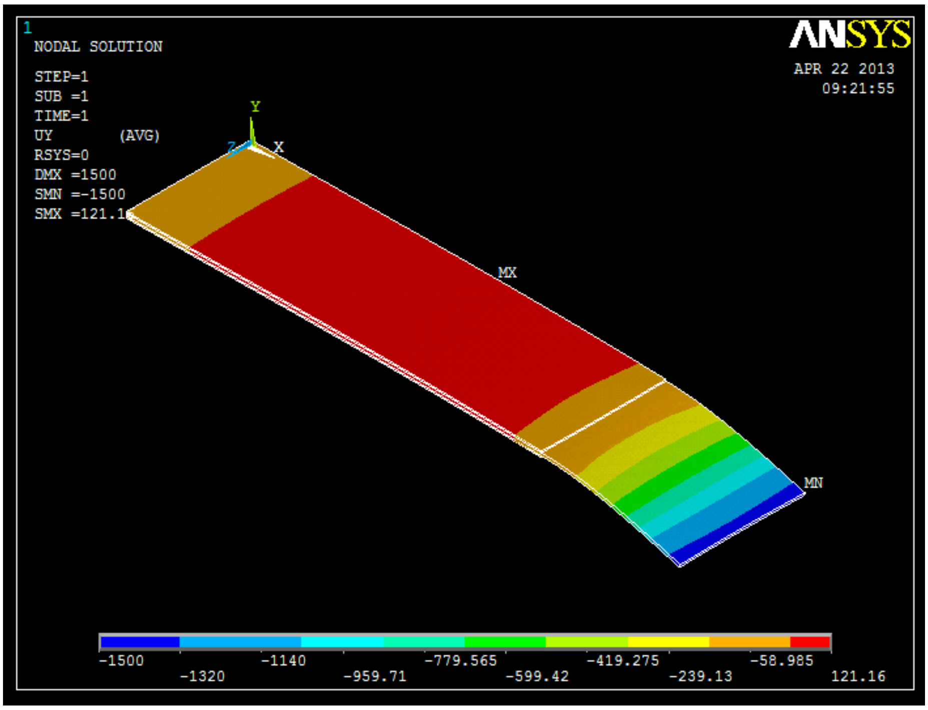

Fig 4: Maximum deflection plot for nitinol pads and copper beam (dimension set 1)

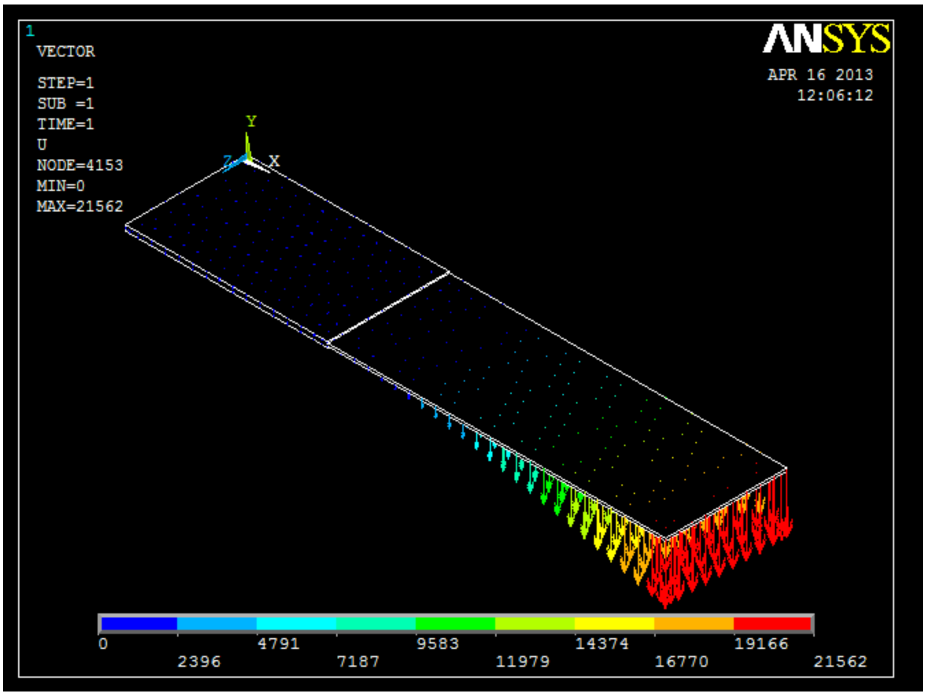

Fig 5: Maximum deflection – vector plot- Nitinol pads and copper beam (dimension set 1)

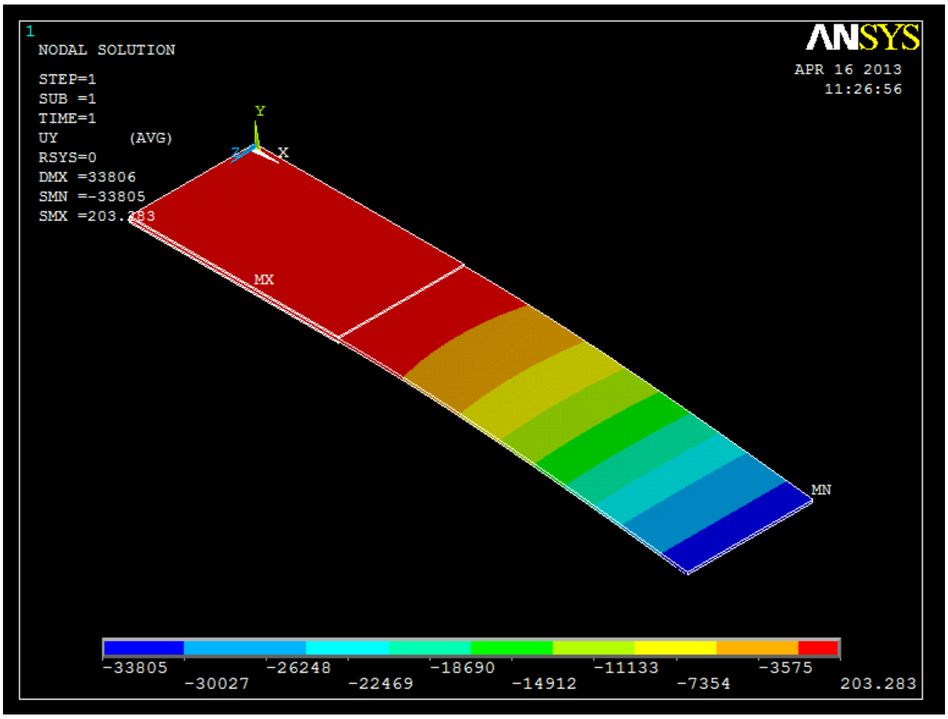

Fig 6: Maximum deflection plot for nitinol pads and gold beam (dimension set 1)

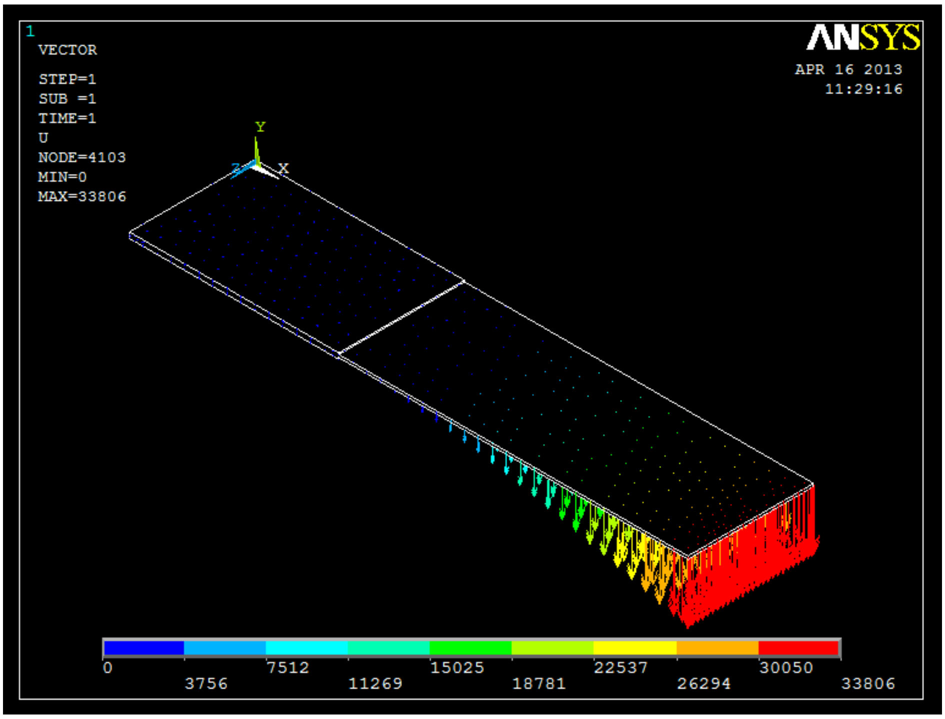

Fig 7: Maximum deflection- vector plot for nitinol pads and gold beam (dimension set 1)

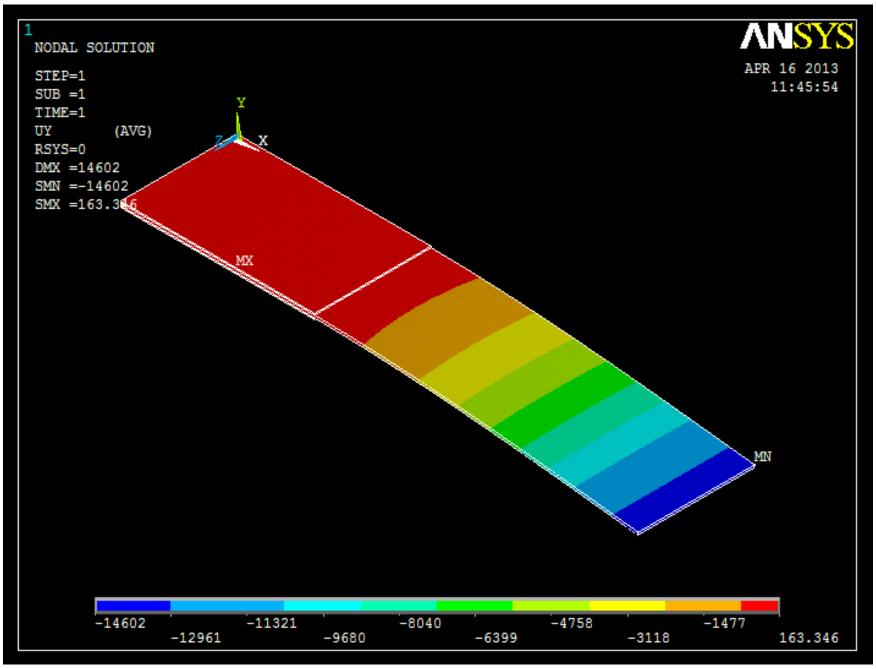

Fig 8: Maximum deflection plot for nitinol pads and nickel beam (dimension set 1)

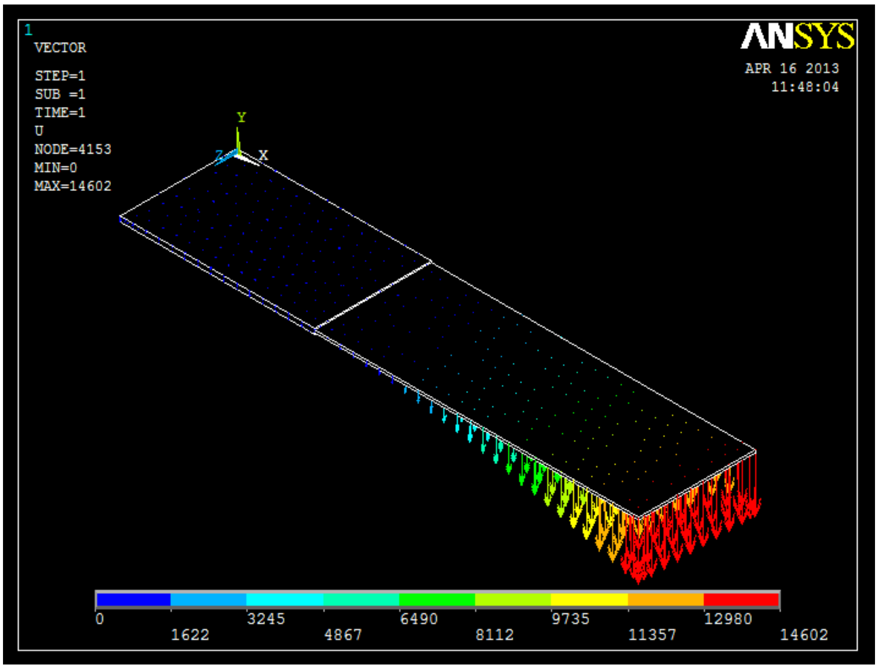

Fig 9: Deflection plot – vector plot for nitinol pads and nickel beam (dimension set 1)

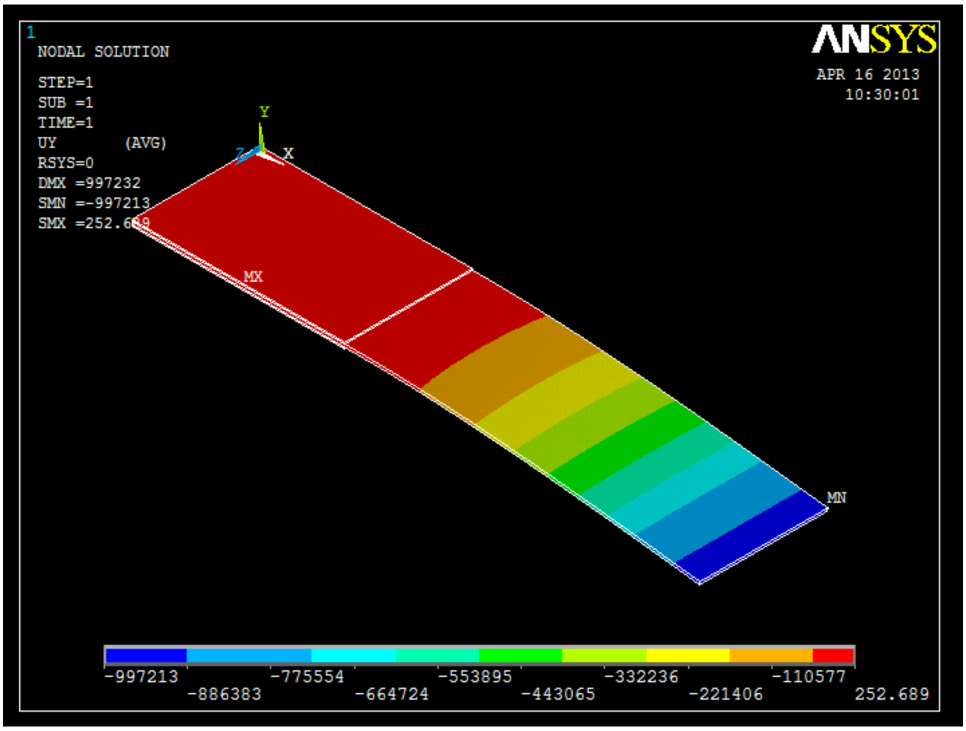

Fig 10: Maximum deflection plot for nitinol pads and polyimide beam (dimension set 1)

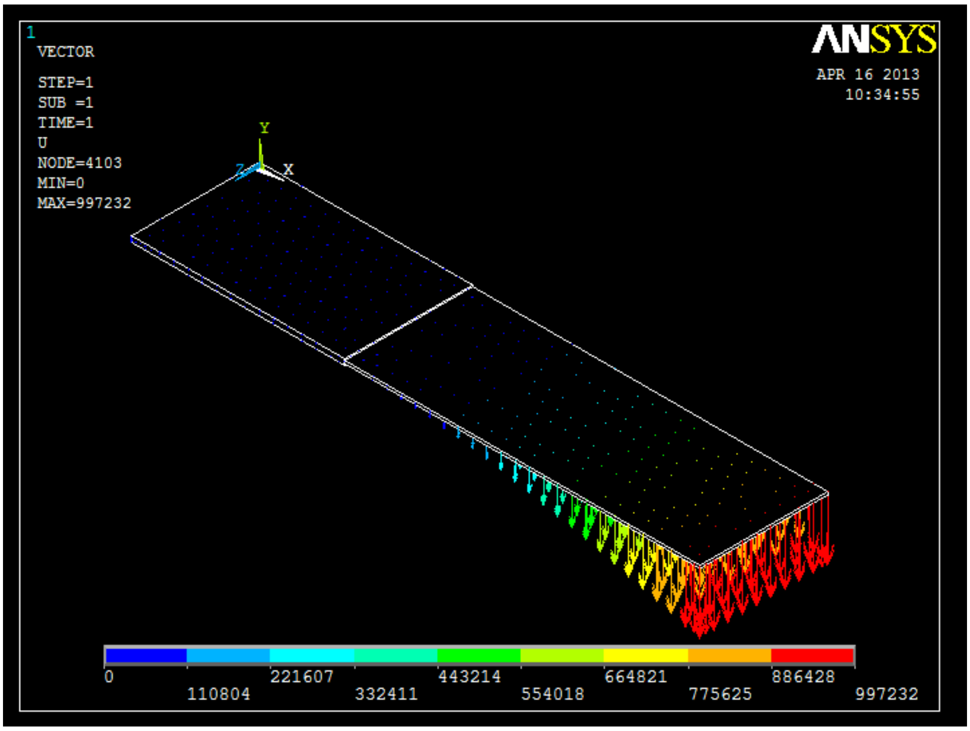

Fig 11: Maximum deflection – vector plot for nitinol pads and polyimide beam (dimension set 1)

Vector plot exhibits the direction of actuation as shown in figure. From the figure it is clear that maximum actuation is at node 4153 is along downward. It also shows that maximum actuation is at the end of beam. Same analysis is performed at various dimensions as shown in the table IV and using various materials for the beam.

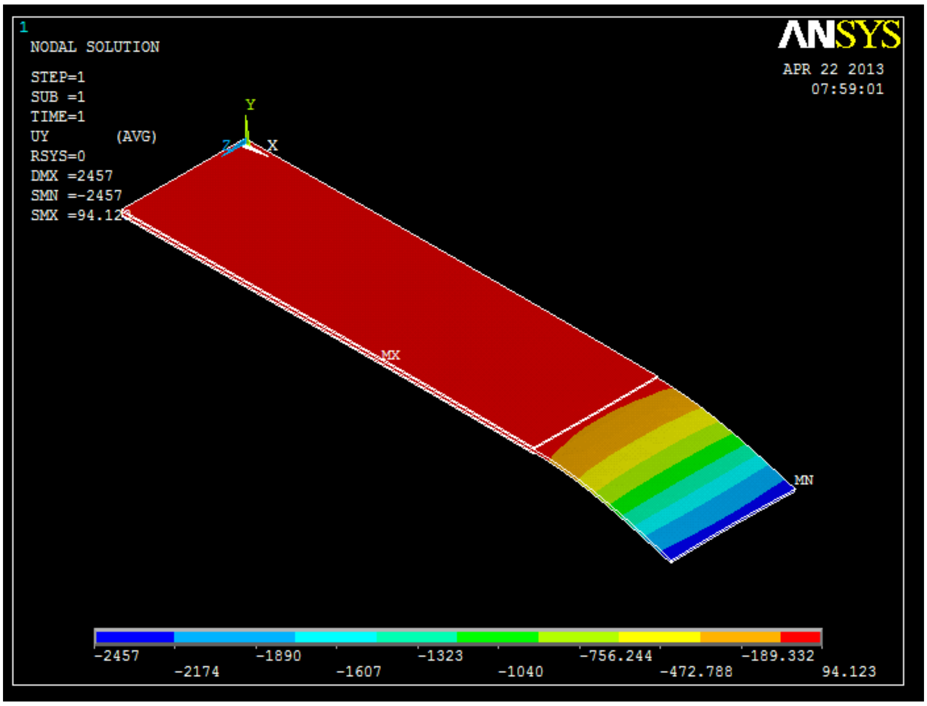

Fig 12: Maximum deflection plot for nitinol pads and aluminium beam (dimension set 2)

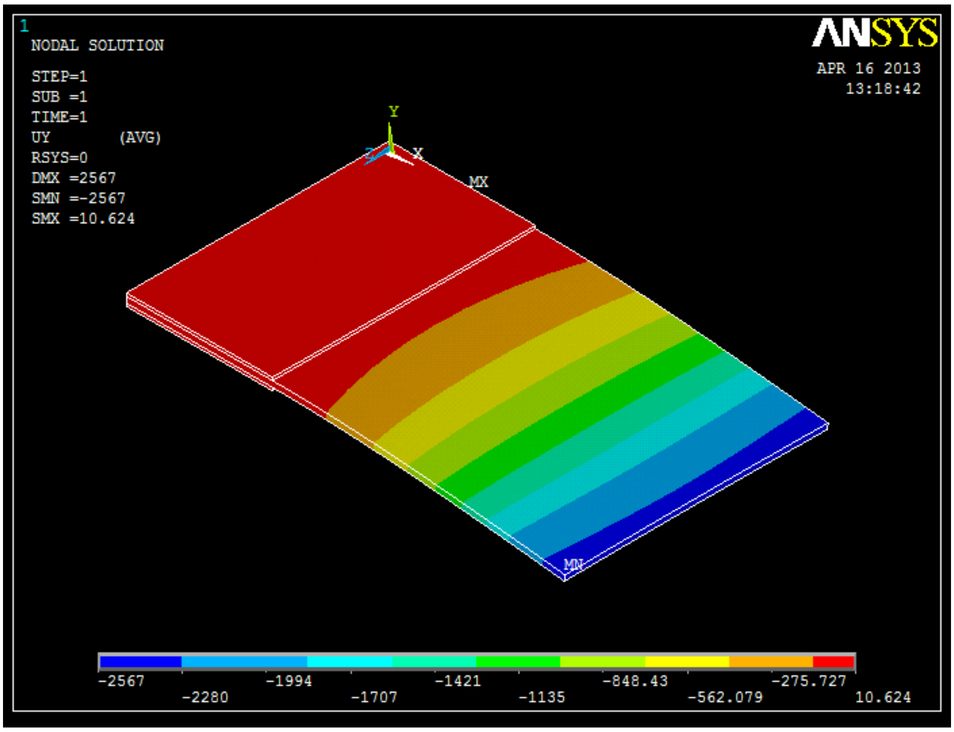

Fig 13: Maximum deflection plot for nitinol pads and aluminium beam (dimension set 3)

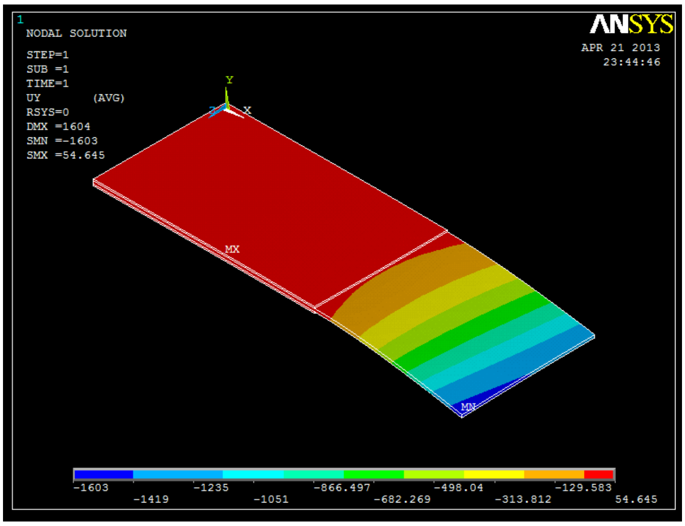

Fig 14: Maximum deflection plot for nitinol pads and Nickel beam (dimension set 2)

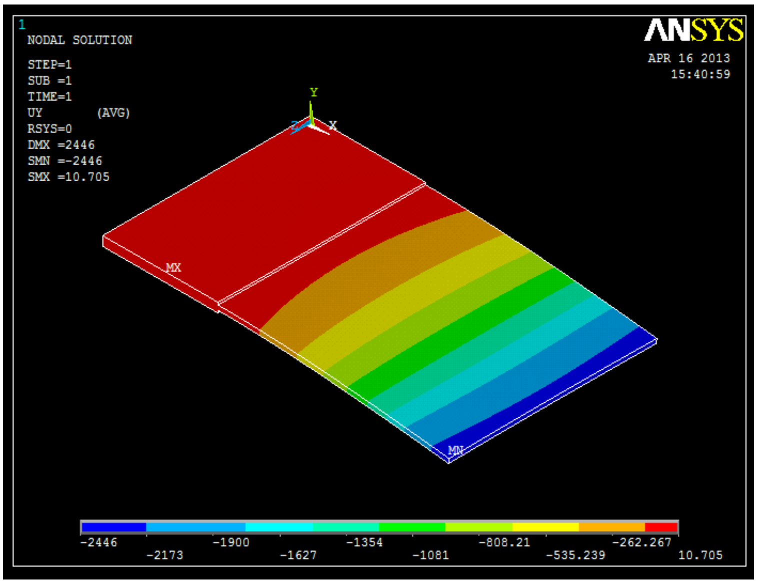

Fig 15: Maximum deflection plot for nitinol pads and Nickel beam (dimension set 2)

TABLE V: ACTUATION OBTAINED FOR DIFFERENT TYPES OF BEAMS WITH NITINOL PADS

MATERIAL (Pad & Beam)	MAXIMUM DEFLECTION IN µm		
Nitinol & Aluminium	2409	2567	2608
Nitinol & Polyimide	62433	62543	63864
Nitinol & Gold	2166	2249	2251
Nitinol & Nickel	1027	1604	2446
Nitinol & Copper	1032	1438	1500

VIII. SUMMARY OF RESULTS

The RF mobile switches to be compatible with integrated circuits (IC) must fulfill the three following conditions [8-10] Very small size, Low actuation voltage and Low power consumption. MEMS switches were first demonstrated in 1979 as electrostatically actuated cantilever switches [11]. The main disadvantage of this type of the switch was high actuation voltage [12,13]. Shape memory alloys (SMAs) are attractive engineering materials due to their ability to memorize shapes through a thermally induced solid state phase transition. They can be used to design switches with very low actuation voltages

Polyimide is having the maximum actuation compared to the four metals and hence can be used in a switch as the switching time will comparatively less compared to the other metals. Polyimide is also highly heat resistant. Aluminum metal gives highest actuation value (among the metals considered) but as it is readily oxidized, not used in fabrication process. Thus gold having next highest actuation value is used.

IX. CONCLUSION

An RF MEMS switch is simulated using shape memory alloy (SMA) which shows that the use of SMA beam to actuate switching, allows the excitation voltage to be relatively much lower (5 V) compared to that needed for electrostatic actuation (30 V). As a metal alloy of nickel and titanium, Nitinol exhibits the unique properties of shape memory and superelasticity. The stress on the beam due to the actuation voltage is also reduced increasing the switching life time. . The main applications of RF MEMS switches are Radar systems for defense applications, Automotive radars, satellite communication systems, wireless communication systems and instrumentation systems.

REFERENCES

[1]. Elliott R. Brown, RF-MEMS Switches for Reconfigurable Integrated Circuits, *IEEE Transactions on Microwave theories and circuits*, VOL. 46, NO. 11, NOVEMBER 1998, pp 1868-1880.
[2]. J. Bryzek, K. Petersen, and W. McCulley, "Micromachines on the march," *IEEE Spectrum Mag.*, p. 20, May 1994.
[3]. Gabriel M. Rebeiz, RF MEMS switches: status of the technology, *The 12th International Conference on Solid State Sensors, Actuators and Microsystems*, Boston, June 8-12, 2003, pp 1726-1729.
[4]. G. M. Rebeiz, RF MEMS–Theory, Design and Technology. Hoboken, NJ: Wiley, 2003.
[5]. Aamir F. Malik, M. Shoaib, S. Naseem*, S. Riaz, Modeling and Designing of RF MEMS Switch using ANSYS, *International Conference on Emerging Technologies IEEE-ICET* 18-19 October, 2008.
[6]. S.Ki Lee. Byungkyu Kim, "Design parametric study based fabrication and evaluation of in-pipe moving mechanism using shape memory alloy actuators", *Journal of Mechanical Science and Technology*, April 09, pp. 96-102, 2008.
[7]. G.K EI-Khoury & M.A. Hotait, 'SMA Actuated RF MEMS Switch', 2004.
[8]. Z. J. Yao, S. Chen, S. Eshelman, and D. Deniston, "Micromachined low-loss microwave switches," *IEEE J. Microelectromech. Syst*., Vol. 8, No. 2, , pp. 129–134. 1999.
[9]. D. Hah, and E. Yoon, "A low-voltage actuated micromachined microwave switch using torsion springs and leverage," *IEEE Transaction on Microwave Theory and Techniques*, Vol. 48,No. 12,. pp. 2540–2545. 2000.
[10]. J. Y. Park, G. H. Kim, K. W. Chung, and J. U. Bu, "Monolithically integrated micromachined RF MEMS capacitive"
[11]. K. E. Petersen, "Membrane switches on silicon," IBM J. Res. Develop., Vol. 23, No. 4, pp. 376–385, July 1979.
[12]. F. Plotz, S. Michaelis, R. Aigner, H.-J. Timme, J. Binder, and R. Noe, "A low-voltage torsional actuator for applications in RF microswitches," Sensors and Actuators A, Vol. 92, pp.312–317, 2001.
[13]. J. M. Huang, K. M. Liew, C. H. Wong, S. Rajendran, M. J. Tan, and A. Q. Liu, "Mechanical design and optimization of capacitive micromachined switch," Sensors and Actuators A, Vol. 93, pp. 273–285. 2001.