<u>İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY</u>

DESIGN AND SIMULATION OF ELECTROSTATICALLY ACTUATED MEMS CANTILEVER BEAM SWITCH

M.Sc. Thesis by
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ELEKTRİKSEL OLARAK AKTİVE OLAN KİRİŞ TİPİ ANAHTARLARIN TASARIM VE SİMULASYONU

YÜKSEK LİSANS TEZİ

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May 2011

Ayşe Özgül Ertanır

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SUMMARY

In recent years, nanotechnology becomes a major issue in our lifetimes with growing technology. Especially MEMS (Micro Electro Mechanical System) is important searching area for nanotechnology because of its wide range of application such as medical, telecommunication, automotive, defense and aerospace areas. Low-cost, small size and light weight is advantages of the MEMS. As the communication technology evolves day by day, the demands for low cost, low power, multifunctional and higher-speed data communication circuits are increasing enormously. With the potential to enable wide operational bandwidths, eliminate off-chip passive components, make interconnect losses negligible, and produce almost ideal switches and resonators in the context of a planar fabrication process compatible with existing IC processes, micromachining and Micro-Electro-Mechanical Systems (MEMS) has emerged to overcome the aforementioned problems of communication circuits. Cantilever beam switch is this kind of MEMS switch which is actuated by electro-statically. For this purpose pull- in voltage is important parameter for cantilever beam design. Pull-in voltage value depends on dimension of the beam, material properties of the beam. Therefore this parameter values is calculated correctly. Cantilever beam switch's working does not depends on only electrical parameters also mechanical properties such as damping ratio, tip deflection, stress are effect the system. For modeling this kind of switch, parallel plate capacitor parameter is used. Several simulation will be examined for correct analyse. In fabrication part different dimension cantilever beam swithes is used for see how it depence parameter relation. After design, simulation and fabrication, MEMS cantilever beam switch capacitance, voltage values are measured in real time.

ELEKTRİKSEL OLARAK AKTİVE OLAN KİRİŞ TİPİ MEMS ANAHTARLARIN TASARIM VE SİMÜLASYONU

ÖZET

Teknolojinin ilerlemesi ile birlikte nanoteknoloji uygulamaları da hayatımıza girmistir. Son yıllarda mikro elektromekanik sistemler (MEMS) nanoteknoloji alanının önemli calişma basamaklarından biri haline gelmiştir. Özellikle, sağlık, telekominikasyon, otomotiv, savunma, uzay ve havacılık gibi alanlarda geniş çapli uygulamalar bulunmaktadir. MEMS' in tercih sebeplerinin başında ise düşük maliyet, küçük boyutlu ve düşük ağırlıklı olması gelmektedir. Teknolojinin ilerlemesi özellikle kominikasyon sisteminde ki gelişmelere olanak sağlamıştır. Bu nedenle MEMS, RF (radio frekanslari) uygulamalarında tercih edilmeye baslanmıştır. Çünkü düşük maliyetli, düşük güç tüketen, çok fonksiyonlu ve yüksek hızlı bilgi transferi sağlayan komünikasyon sistemlerine olan ihtiyaç oldukça fazla artmaktadır. RF devlerinde yüksek bant genişliğine olanak sağlaması, kırmık dışındaki pasif elemanları ortadan kaldırması, IC üretimine uygun fabrikasyon sağlaması ve ideale çok yakın anahtarlama yapıları ile günümüzde çokça tercih edilmeye başlanmıştır. Bu anahtarlama yapılarından biri olan kiriş tipi anahtar elektriksel kuvvet ile aktive hale gelmektedir. Dolayısıyla kapanma gerilimine uygun olarak, anahtarının boyutları kullanılan malzeme özellikleri hesaplanarak tasarımı yapılmalıdır. Özellikle bu elektriksel kuvvet doğrultusunda sistemde mekanik olarak da titreşim, ani ivmelenme, sönümleme, stres ve bükülmeler meydana gelmektedir. Sadece elektriksel analizler değil mekanik analizlerde önem kazanmaktadır. Paralel plaka kapasitörlerinden yola çıkılarak kiriş tipi anahtarın tasarımı ve simülasyonları yapılmıştır. Ayrıca farklı boyutlar için farklı gerilim değerlerinde kapasite ölçümleri yapılarak, anahtarda baskın parametreleri araştırılacaktır. Böylece sistemde istenilen verileri sağlayabilecek MEMS tasarımı yapılabilmektedir.

1. 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 microfabrication. 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 [1].

1.1 Background and Motivation

In recent years, micro electro mechanical system (MEMS) becomes milestone for medical and commercial applications. Their low cost, small size, low energy consumption, standard semiconductor fabrication compatibility and life time have made it so usable devices. The application of MEMS can be seen most of the area in the life [1]. Especially in medical application, MEMS device is being used very commonly such as Bio-mems, hearing and seeing aids, DNA sequencing and bio-sensors. Also in communication industries RF MEMS switch is more useful than PIN diodes and FET devices. MEMS devices still researching issue. Because the design process of MEMS contains different layers such as fluidics, thermal effects, electrostatic and mechanics. Therefore, these domains are taken into consideration to simulate the performance of finished device [7]

Another fast growing area is communication technologies. As the communication technology evolves day by day, the demands for low cost, low power, multifunctional and higher-speed data communication circuits are increasing enormously. All these essential requirements enforce significant challenges on the current technology and illustrate the need for new designs and advanced architectures. The challenges of re-configurability, spectrum efficiency, security, miniaturization and cost minimization can only be met by ensuring that the transceiver/receiver is comprised of low-energy, low-cost, adaptive and high performance RF devices [10].

The interest of RF MEMS switch design is very suitable for CMOS standard process flow. Also, compatibility of RF device's parameter in the system is makes them useful in a same system. When an electrostatic force is applied to the RF MEMS switch pull-in occurs and it connects two lines in the system. Due to their advantages like low-power consumption, high isolation MEMS switches replace the conventional switches. Electrostatic actuation is the most preferable actuation method in MEMS switches because of its application is very simple and has a high efficiency [7]. For getting more reliable MEMS switch, material properties, electrostatic force, beam deflection, damping of the system is investigated mathematically. Also design parameter is found for different size of cantilever beam switch. After all that, MEMS process flow is searched and started its fabrication in the cleanrooms.

1.2 Pull - in Phenomenon

For cantilever beam switch is modeled like a parallel plate capacitor. Therefore, a bias voltage is necessary to ensure a linear force-capacitance range of operation. The calculation of the pull-in voltage whereby the sensing structure collapses due to electrostatic forces is an important design requirement. A linear, uniform approximate model of the nonlinear electrostatic pressure has been developed and used in conjunction with the load deflection model of a MEMS cantilever beam under uniform pressure to develop a highly accurate model to calculate the pull-in voltage [11]. For pull-in to occur, a certain amount of energy needs to be injected into the system. The modulated voltage pull – in techniques relies on this energy being accumulated in the mechanical system during the pull in process. For system reliability lower actuation voltage is needed and then the time for pull-in occur is longer [4].

1.3 Thesis Objectives and Organization

The objective this thesis is:

- In RF device for switching the signal cantilever beam switch more useful, cheaper and reliable at high frequencies than PIN Diodes and FET devices. To show that cantilever beam design is very important when calculating power ranges, dimension, working frequencies, pull-in voltage, deflection of the beam, stress in the beam, for this purpose choosing right beam material

- To modeling electrostatically actuated cantilever beam switch, parallel plate capacitor system model is investigated to calculate the pull-in voltage
- To observe relation between material properties, moment of inertia deflection, resonant frequency, material properties such as Young Modulus for process cantilever beam switch
- To check damping coefficient effect in the system, open loop system responses are investigated with damping and without damping system
- To process compability MEMS to traditional CMOS showed in process flow step
- To verify the mathematical equation for different size of MEMS cantilever beam switches masking design is done with using L-edit program
- To verify the design, Finite Element Modeling (FEA) is used in CoventorWare program. MEMS cantilever beam switch fabrication process is described in this program

The organization of the thesis is as follows. There is a general overview about MEMS such as its application, usage and market distribution in the world in Chapter 2. In Chapter 3, mathematical explanation about parallel plate capacitors then modeling and simulation of cantilever beam switch is studied. Also in this chapter cantilever beam design parameter's relation between them is investigated. In Chapter 4, cantilever beam switch process, layout and fabrication steps are showed. Finally, a summary of the conclusions, together with possible future work is given in Chapter 5.

2. MEMS OVERVIEW

In MEMS systems are became a major issue for growing technology and find a lot of application area with this growing technology. In this chapter, MEMS application areas are investigated.

2.1 Introduction

Microelectromechanical systems (MEMS) refer to devices that have characteristic length of less than 1 mm but more than 1 micron, that combine electrical and mechanical components and that are fabricated using integrated circuit batch-processing technologies. The multidisciplinary field has witnessed explosive growth during last decade and the technology is progressing at a rate that far exceeds that of our understanding of the physics involved. Electrostatic, magnetic, electromagnetic, pneumatic and thermal actuators, motors, valves, gears, cantilevers, diaphragms and tweezers of less than100 micron size have been fabricated. These have been used as sensors for pressure, temperature, mass flow, velocity, sound and chemical composition, as actuators for linear and angular motions, and simple components for complex system such as robots, lab-on-a-chip, micro heat engines and micro heat pumps [12].

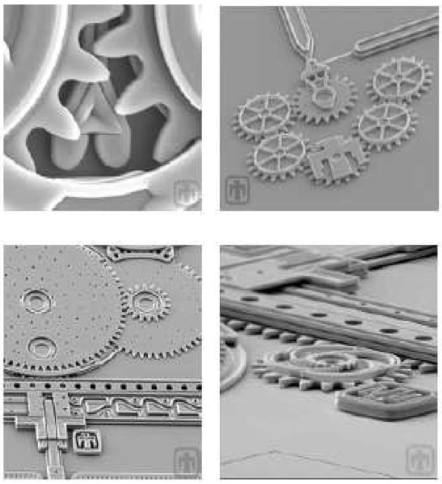


Figure 2.1: SEM pictures of Electrostatic micro engine systems

2.2 Application of MEMS

The major application of MEMS technology to date is in sensors. These include sensors for medical (blood pressure), automotive (pressure, accelerometer), and industrial (pressure, mass air flow) applications [13, 14]

MEMS systems will have applications in a variety of areas, including:

- Remote environmental monitoring and control. This can range from sampling, analyzing, and reporting to doing on-site control. The applications could range from building environmental control to dispensing nutrients to plants.
- Dispensing known amounts of materials in difficult-to-reach places on an as-needed basis. This could be applicable in robotic systems.
- Automotive applications will include intelligent vehicle highway systems and navigation applications.
- Mass data storage devices using magnetic and atomic scale patterning for storage densities of terabytes per square centimeter.
- Integrated micro-opto-mechanical components for low power optical communication, displays and fiber –optic switches/modulators
- RF and wireless application for relay and switching matrices, reconfigurable antennas, switched filter banks, electromechanical front-end RF filtering and demodulation.

2.3 MEMS Market and Industry Structure

The potential of MEMS technology promises to revolutionize our present-day life-styles as much as the computer has. In addition to completely new applications enabled by MEMS technology, existing applications will likely be replaced by miniaturized, low-cost, high-performance, "smart" MEMS technology. The potential for cost-effective and high-performance systems has attracted attention from both government and industry alike. The substantial up-front investment often required for successful, large-volume commercialization of MEMS is likely to limit the initial involvement to larger companies in the IC industry. These companies can leverage their existing capital investment in semiconductor processing equipment toward the development of MEMS components for large-volume applications.

Estimation shows that fort he near future MEMS products will have a fast increase on all over the world. Recent forecasts imply that growth of the market potential of

MEMS products reaches $6 billion by the year 2006 as it can be see in Figure 2.2 [15]. This extended growth of MEMS market can be explained as it does not have only one application area. Currently, the majority of MEMS products are sensors that are used in lots of systems. Thus, advantages of MEMS increase not only its market structure but also market of other sectors using it [15].

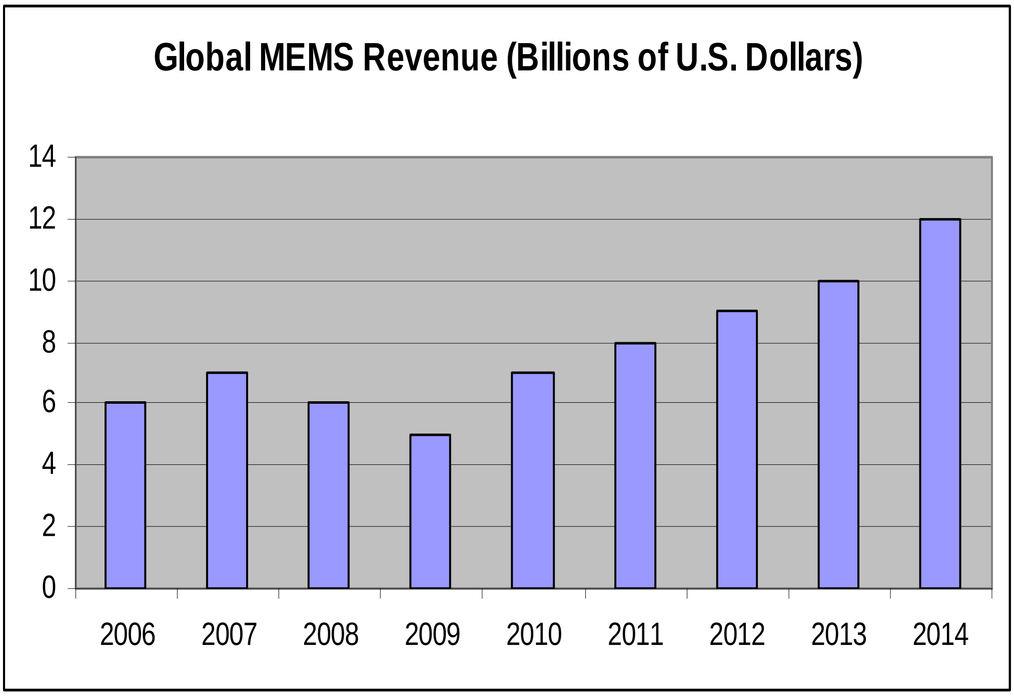


Figure 2.2: MEMS market revenue in the world

The MEMS market for sensors will continue to grow, particularly for sensors with integrated signal processing, self-calibration, and self-test. However, a substantial portion of the MEMS market will be in non-sensing, actuator-enabled applications, such as scanners, fuel-injection systems, and mass data storage devices.

A number of companies are already marketing MEMS devices and systems for commercial use. These companies include a broad range of manufacturers of sensors, industrial and residential control systems, electronic components, automotive and aerospace electronics, analytic instruments, and biomedical products. Examples of such companies include Goodyear, Honeywell, Lucas Novasensor, Motorola, Hewlett-Packard, Analog Devices, Texas Instruments, Siemens, and Hitachi. In addition, many small, emerging businesses have also been formed to commercialize MEMS components [15].

2.4 Trends in MEMS

MEMS technology is extending and increasing the ability to both perceive and control the environment by merging the capabilities of sensors and actuators with information systems. Future MEMS applications will be driven by processes that enable greater functionality through higher levels of electronic-mechanical integration and greater numbers of mechanical components working either alone or together to enable a complex action. These process developments, in turn, will be paced by investments in the development of new materials, device and systems design, fabrication techniques, packaging/assembly methods, and test and characterization tools [15].

3. PULL IN PHENOMENON

3.1 Introduction

Pull-in phenomenon is a discontinuity related to the interplay of the elastic and electrostatic forces. When a potential difference is applied between a conducting structure and a ground level the structure deforms due to electrostatic forces. The elastic forces grow about linearly with displacement whereas the electrostatic forces grow inversely proportional to the square of the distance. When the voltage is increased the displacement grows until at some points the growth rate of the electrostatic force exceeds that of the elastic force and the system cannot reach a force balance without a physical contact, thus pull-in occurs. The critical voltage is known as the pull-in voltage [16].

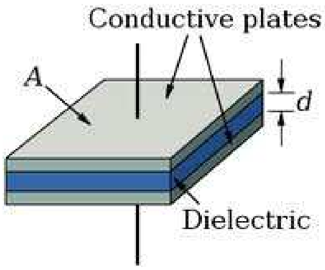


Figure 3.1: Schematic of a parallel plate capacitor

3.2 Pull-in voltage in electrostatic micro actuators

In figure 3.1 when voltage is applied over the capacitance, electrostatic force will work to reduce the plate separation d-x. At small voltages, the electrostatic voltage is countered by spring force $F_k = kx$ but as voltage increased the plates will eventually snap together. Estimating this pull-in voltage V_p and the plate distance x_p before pull-in effect is required for the successful design of electrostatic actuators, switches, varactors and sensors. [5] Also in figure 3.2, the plate is attached to a spring k. The capacitor capacitance C depends on the plate overlap area A, dielectric constant of the surrounding medium ε and gap d-x

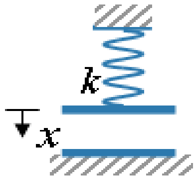


Figure 3.2: Schematic of an electrostatic actuator.

$$C = \varepsilon \frac{A}{d-x} \tag{3.1}$$

The simplest model is the single degree of freedom lumped mass model defined by second order differential equation with constant coefficients where m is the mass of the movable plate, b is the damping coefficient and k is the stiffness of the spring [4]

$$m\ddot{x} + b\ddot{x} + kx = f(t) \tag{3.2}$$

To derive the expression for pull-in, start by writing the total potential energy in the system [5]:

$$E = -\frac{1}{2}\frac{\varepsilon A}{d-x}V + \frac{1}{2}kx^2 \tag{3.3}$$

where the first term is the electrostatic potential of the deformable capacitor because of voltage source and second term is due to mechanical energy stored in the spring. The force acting on the movable plate is obtained by deriving equation (3.2)

$$F = -\frac{\partial E}{\partial x} = \frac{1}{2}\frac{\varepsilon A}{(d-x)^2}V^2 - kx \tag{3.4}$$

At equilibrium point $F = 0$, so the electrostatic force and spring force equals each other and equation (3.4) gives us:

$$kx = \frac{1}{2}\frac{\varepsilon A}{(d-x)^2}V^2 \tag{3.5}$$

Equation 3.4 can be solved for the equilibrium plate position x as a function of applied voltage V [5]

$$V_0 = \sqrt{\frac{2kx(d-x)^2}{\varepsilon A}} \tag{3.6}$$

In the domain $0 < x < d$, V has a maximum value for $x = d/3$. The equilibrium voltage associated with this point is called the pull-in voltage.

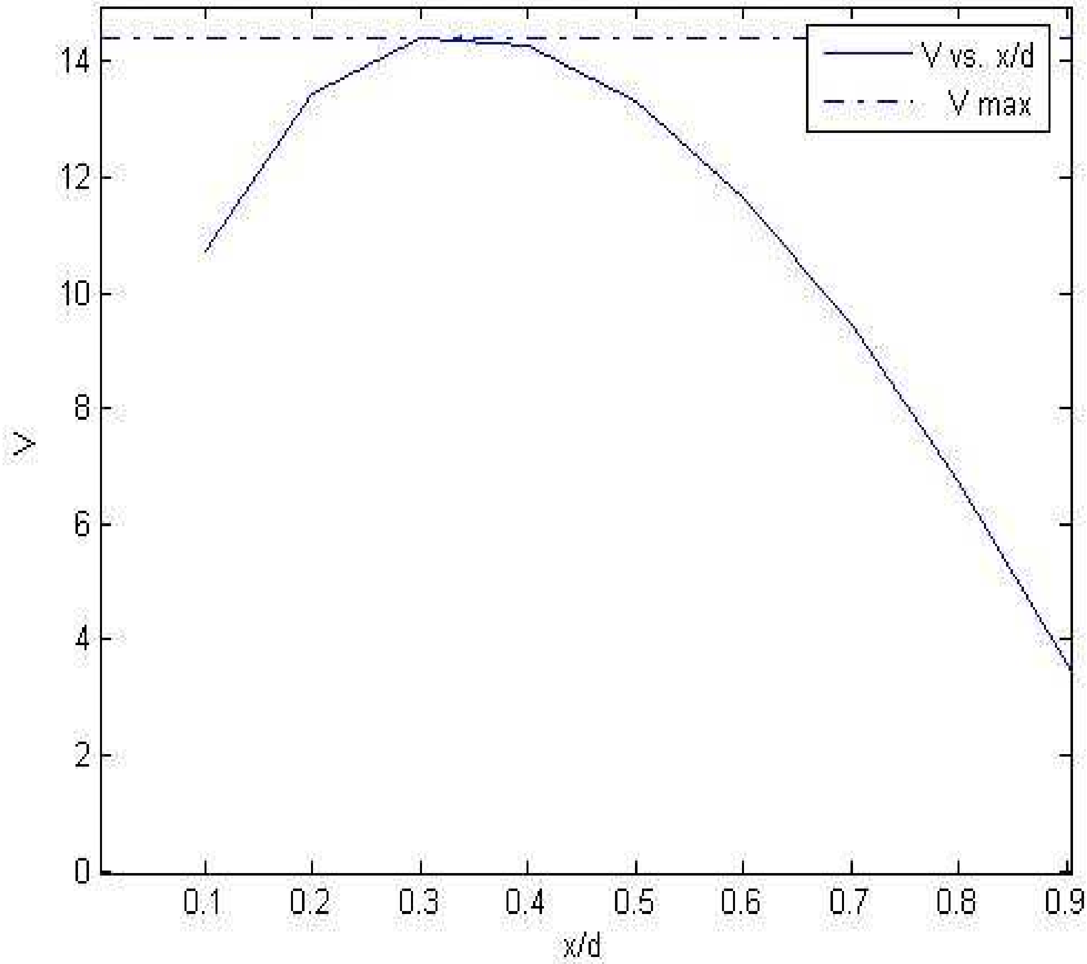


Figure 3.3: The equilibrium relationship between plate displacement x and voltage V

In the figure 3.2the equation 3.5 solved for "εA" is constant. So it can be easily seen that, V has a maximum value for $x = d/3$.

For $x = d/3$, maximum value of V can be calculated ,

$$V = \sqrt{\frac{8kd^3}{27\varepsilon A}} \tag{3.7}$$

3.3 RF MEMS Switch

Mobile technologies have relied on Radio frequency (RF) switches for a long time. Though the basic function of the switch has remained the same, the way they have been made has changed in the recent past. RF micro electro mechanical systems (MEMS) have been pursued for more than a decade as a solution of high-performance on-chip fixed, tunable and reconfigurable circuits for example they being used to switch power between the transmitter and the receiver or in antenna arrays to form configurable arrays of antennas. RF MEMS switch has many advantages such as low loss, high isolation, good linearity, broad band and low power consumption [1]

The drive for MEMS switches for RF application had been mainly due to the highly linear characteristics of the switch over a wide range of frequencies. MEMS RF switches come in two configurations, series and shunt.

Series switch is in series with the power line and either closes and opens the line to turn it ON or OFF position. Series switch can be seen in figure 3.4. In series switch the contacting surface is usually at the end of a singly supported cantilever beam with a control electrode under the beam. By applying a voltage to the control electrode the beam can be pulled down to complete the connection between two conductors [2].

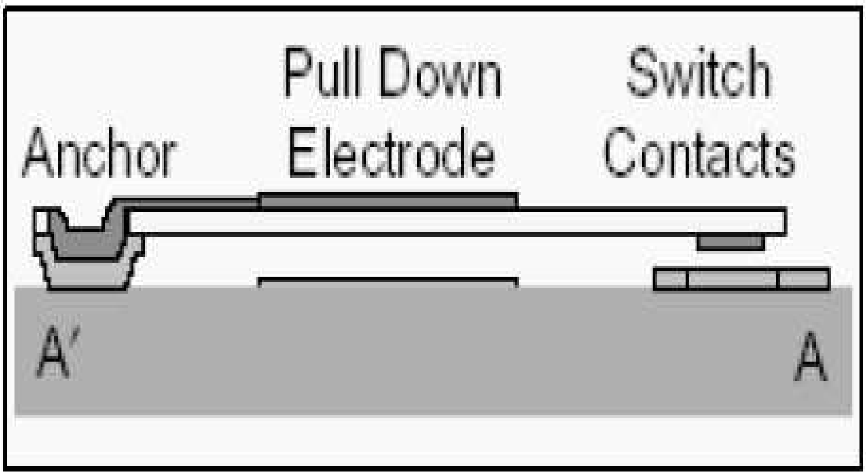


Figure 3.4: Series Switch

A shunt switch in figure 3.5 the power line is sandwiched between two ground lines and the switch turned on to short the power on the signal line to the ground thus preventing the power going past the switch [2]

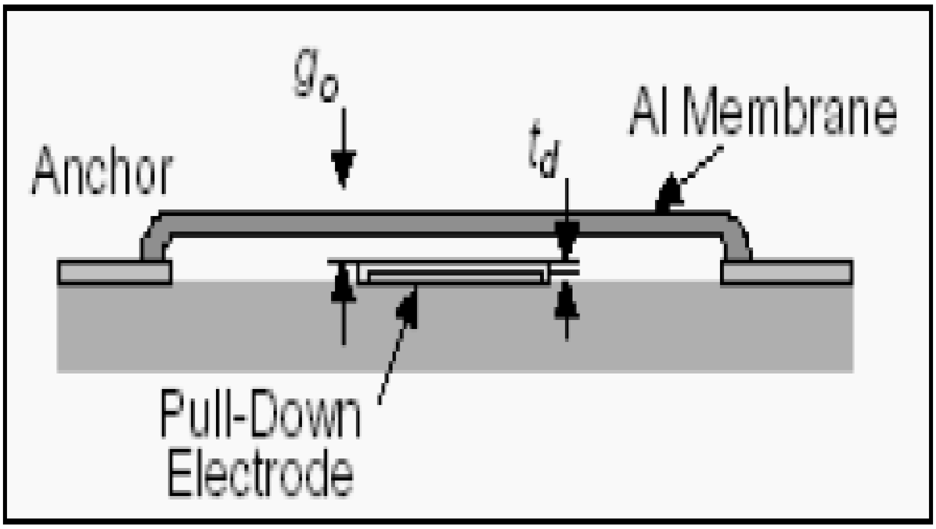


Figure 3.5: Shunt Switch.

This thesis organization is about series switch which has in line switch which is called cantilever beam switch. Cantilever beam switch actuation mechanism is electrostatic. Electrostatic methods rely on the basic columbic force of attraction between two oppositely charged plates. When electrostatic force is applied to the beam electrode, the contacts eventually snap down and completing the signal path circuit. [2]

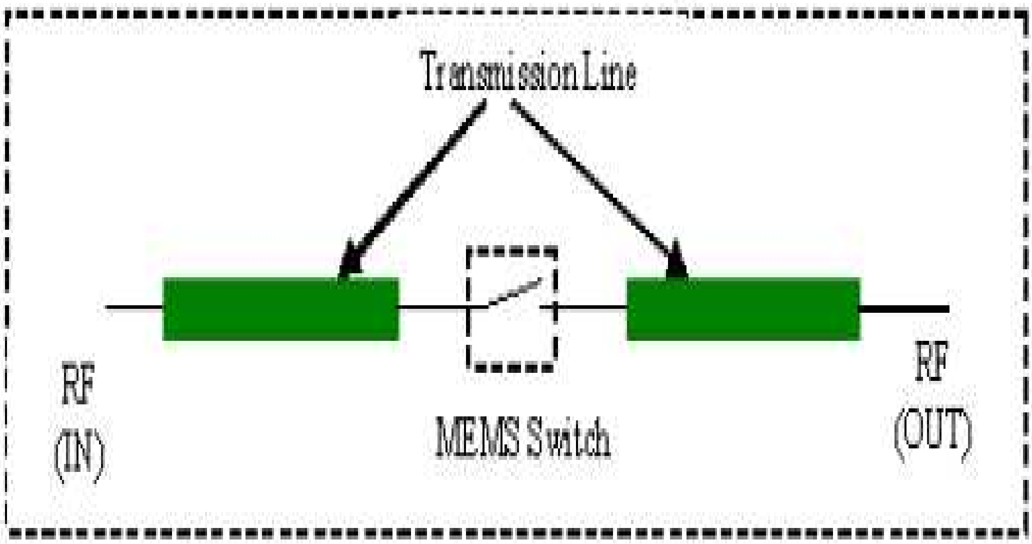


Figure 3.6: MEMS Switch between RF input and RF output

In figure 3.6 MEMS switch is used between RF input signal and RF output signal in transmission line for to reduce insertion loss. Because MEMS RF switch performances are better than PIN Diode and FET. Also power consumption of the RF MEMS switches are less than PIN Diode and FET.

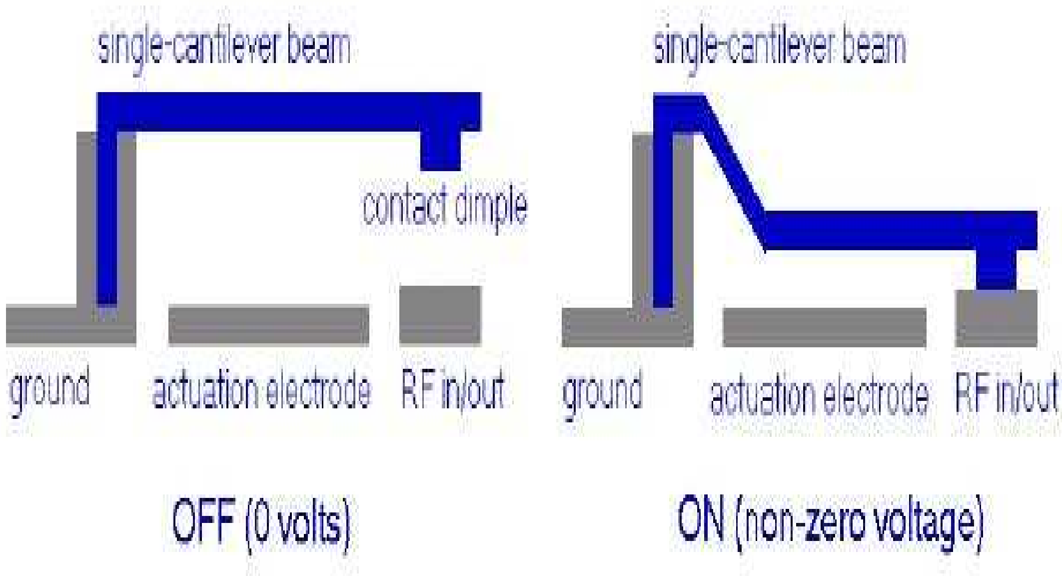


Figure 3.7: Cantilever Beam Resistive Switch

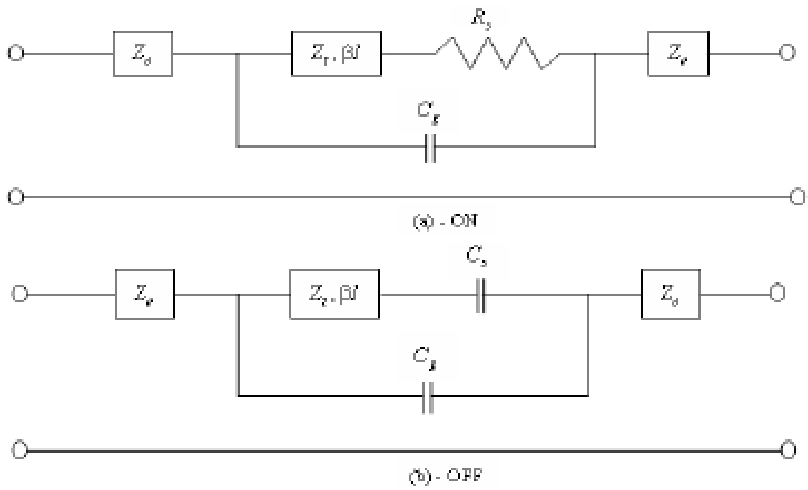


Figure 3.8: Series cantilever beam switch lumped circuit model a) ON state b) OFF state

In figure 3.8 the electrical model MEMS series switch are series capacitances C_S in the up-state position and small resistance R_S in the down state position. In this circuit, cantilever beam is represented by a transmission line with characteristic impedance of Z_t and electrical length of βl. The two lines around the beam at ports contribute to the two Z_0 transmission lines. Capacitive coupling between the two lines via the electrodes introduces C_g. There is one capacitor C_S adjacent to Z_t at off state or one resistor R_S at on state due to coupling capacitance and contact resistance respectively. The coupling resistance R_S is mainly affected by surface roughness of contact areas as well as applied force between contacts. If the contact surface is smooth enough and applied force is large, then R_S should be relatively small [2].

3.3.1 Cantilever Beam Switch and Equations

A cantilever is a beam supported on only one end. The beam carries the load to the support where it is resisted by moment and shear stress. MEMS cantilevers are commonly fabricated from silicon (Si), silicon nitride (Si_3N_4), or polymers [17,18]

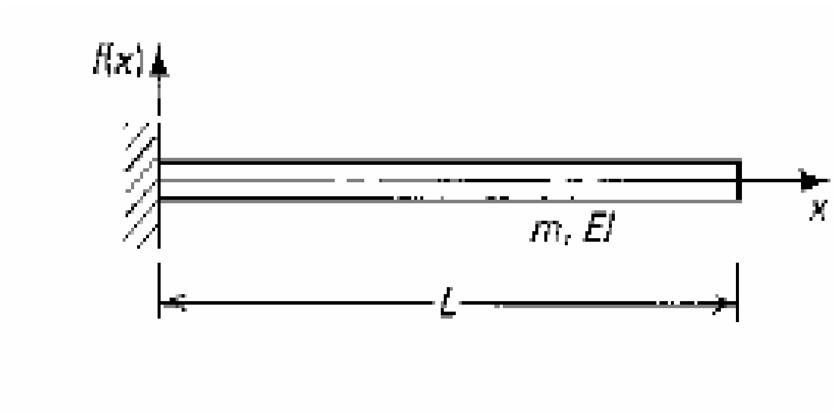


Figure 3.9: Basic structure of fixed end cantilever beam, Mass m, Young Modulus E and Inertial Moment I

This general geometry can be applied for MEMS switch.

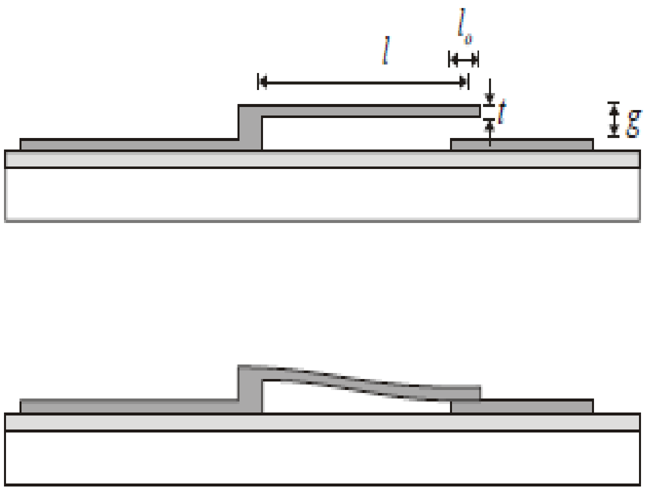


Figure 3.10: Cantilever beam switch

It can be easily seen that cantilever beam separated by a dielectric spacer from the fixed ground plane in Figure 3.10 [3] Electrostatic actuation is a very common design for MEMS design. Pull in voltage is one of the most important criteria for MEMS cantilever beam design. Accurate modeling of pull in voltage is very challenging due to high nonlinearities and instability. Effects such as fringing fields, residual stress, tip deflection, beam adhesion to the bottom plate have further complicated modeling. Numerical methods based modeling, such as the finite element method is often used for the modeling. There are various commercial MEMS simulation software such as Coventorware, Comsol, Intellisuite, Ansys, Femlab and Sugar.

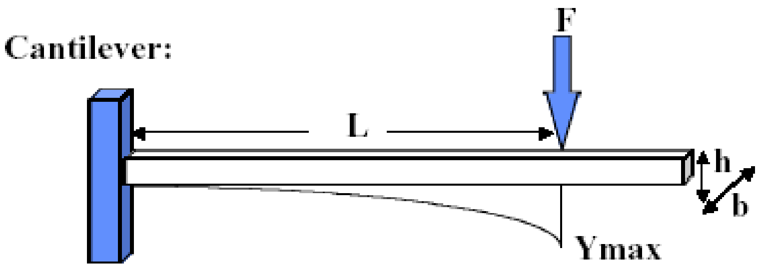


Figure 3.11: Cantilever Beam Switch Displacement when Electrostatic Force is applied

When electrostatic force is applied to the beam, electrostatic pressure will pull the cantilever beam towards the ground as Figure 3.11 [20]. This electrostatic force depends on actuation voltage. Typical actuation voltage of high power switches range anywhere between tens of volts to nearly hundred volts. This is an important parameter for designing switch. Because it effects compatibility of the switch with other circuitry on the same die [2]. In some cases, though the actuation voltage is too high because of that some extra interface circuitry for switch compatible can be needed in the board. So this consumes extra area on the wafer. The main factors influencing the magnitude of the actuation voltage are electrode spacing, area of actuation electrode and dielectric material in between the two electrodes. The switch operates linearly with in approximately the top $1/3$ of the gap. First the beam is pull down to this part then the electrostatic force overcomes the spring force and switch operation became nonlinear and snaps together. The applied voltage in this situation is called pull-in voltage. Pull in voltage calculated before in equation 3.7 $V = \sqrt{\frac{8kd}{27\varepsilon A}}$ where ε is dielectric constant, A are of beam, k spring constant, d dielectric gap. In cantilever beam, applying a voltage to the beam a electrostatic force is occurred. Then this force causes a tip deflection. The superposition principle is one of the most important tools for solving beam deflection problems allowing simplification of very complicated design problems.

For beams subjected to several loads of different types the resulting shear force, bending moment, slope and deflection can be found at any location by summing the effects due to each load acting separately to the other loads. Therefore maximum displacement of the beam can be calculated from the Figure 3.12

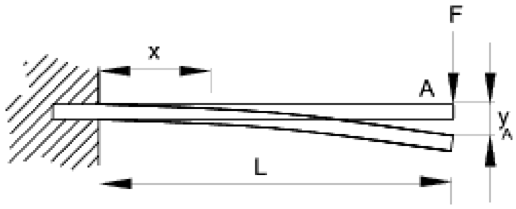


Figure 3.12: Cantilever beam (uniform section) with a single concentrated load at the end

At the fix end $x = 0$ $dy = 0$, $\frac{dx}{dy} = 0$ [19]

From the equilibrium point, at the support there is a resisting moment $-FL$ and vertical upwards force F. At the any point x, along the beam there is a moment

$$-F(L-x) = M_x = EI\frac{d^2y}{dx^2} \quad \textbf{(3.8)}$$

$$EI\frac{d^2y}{dx^2} = -F(L-x) \quad \textbf{(3.9)}$$

After integrating the equation (3.9), getting equation

$$EI\frac{dy}{dx} = -F(Lx - \frac{x^2}{2}) + C_1 \quad \textbf{(3.10)}$$

C_1=0, because $\frac{dy}{dx} = 0$ at $x = 0$. Integrating equation (3.10) again,

$$EIy = -F\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) + C_2 \quad \textbf{(3.11)}$$

Also $C_2 = 0$ because $y = 0$ at $x = 0$

At the end A, $x = L$ so

$$y_A = -\frac{F}{EI}(\frac{L^3}{2} - \frac{L^3}{6}) = -\frac{FL^3}{3EI} \quad \textbf{(3.12)}$$

$$Y_{\max} = \frac{FL^3}{3EI} \quad \textbf{(3.13)}$$

E is the young modules value for beam material, I moment of inertia, L is the length of beam [20].

$$I = \frac{bh^3}{12} \quad \textbf{(3.14)}$$

b is the width of the beam and h is the thickness of beam.

$$k = 3E\frac{I}{L} \quad \textbf{(3.15)}$$

Spring constant of the beam described in equations 3.15, where E is the young modulus of the beam material, L is the length of the beam and I moment of inertia [20].

In this thesis organization, polysilicon is chosen for making cantilever beam switch material. Young’s modulus E is important when choosing material for making MEMS cantilever beam switch. Because in solid mechanics, Young's modulus, also known as the tensile modulus, is a measure of the stiffness of an isotropic elastic material. It is defined as the ratio of the uniaxial stress over the uniaxial strain in the range of stress in which Hooke's Law holds. It can be experimentally determined from the slope of a stress-strain curve created during tensile tests conducted on a sample of the material. Tip deflection effects by material’s Young Modulus directly. Also spring constant is important parameter for deflection of the loaded part. The spring constant effects cantilever beam thickness. For example a 20 % increasing in the thickness of the beam causes 73% increasing in the spring constant. High spring constant causes more stress in the beam. More stress also effects working parameters of the cantilever beam switch such as isolation and switching time.

Go back to mathematical model of the parallel plate actuator again

$$m\ddot{x} + b\dot{x} + kx = \frac{\varepsilon AV^2}{2(d_0 - x)^2} \quad \textbf{(3.16)}$$

m is the mass of movable plate and $\ddot{x} = \frac{d^2x}{dt^2}$ means acceleration of the beam from the oscillation resonant frequency [20].

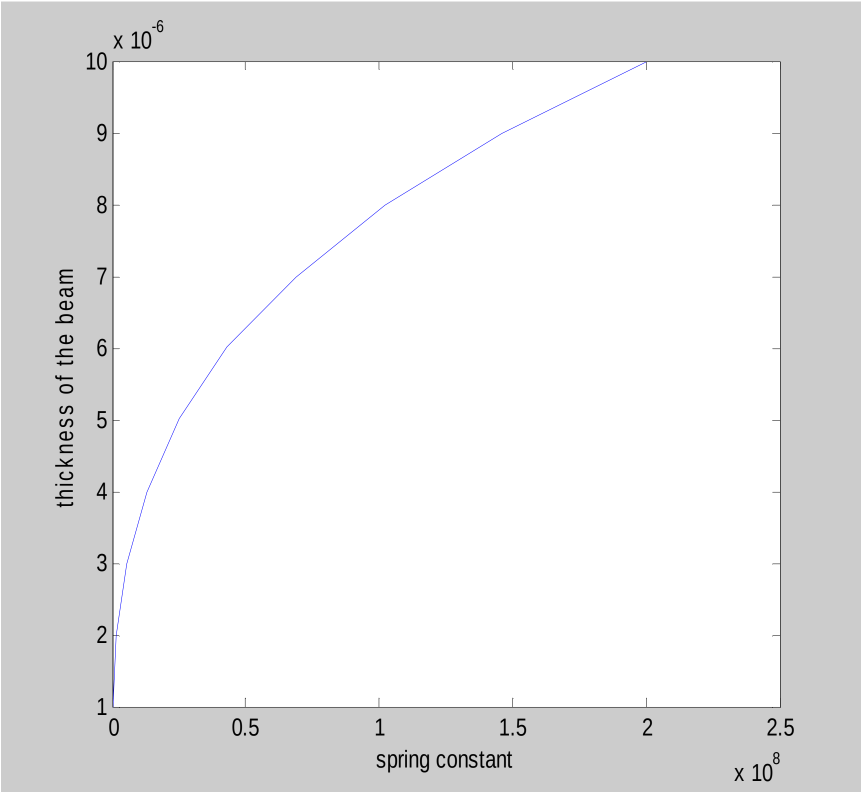


Figure 3.13: Spring constant variation with respect to the thickness of the beam

$$f_0 = \frac{1}{2\pi}\left\{\frac{3EI}{L^3 m}\right\}0.5 \qquad \textbf{(3.17)}$$

Neglecting the damping,

$$x = Y\cos(2\pi f_0 t) \qquad \textbf{(3.18)}$$

Y is the initial displacement from the equilibrium point. So,

$$\ddot{x} = \frac{d^2x}{dt^2} = Y(2\pi f_0)^2\cos(2\pi f_0 t) \qquad \textbf{(3.19)}$$

The maximum force due to proof mass where the mass of the beam is calculated from the mass=volume*density [20].

$$Volume = L * h * b \qquad \textbf{(3.20)}$$

L is the length of the cantilever beam, h is the height of the beam and b is the width of the beam. Micro cantilever beams have higher frequencies. For example, the polysilicon cantilever beam which's dimensions are $L = 100\mu m$, $W = 60\mu m$ $do = 2\mu m$ and $h = 2\mu m$ has nearly 2 KHz resonant frequency.

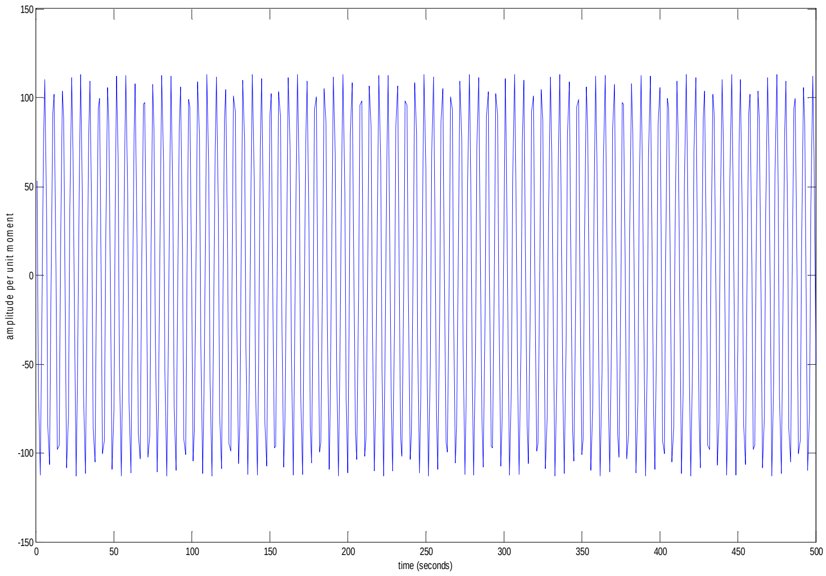


Figure 3.14: Open loop step response for cantilever beam without damping.

In figure 3.14, structural damping is zero. The zeros of the system are in the imaginary axis and the dynamics only marginally stable. Since the effects of damping on micro-cantilever beam in MEMS can not be ignored under micro-scale system and keep the system stable [21]. Stabilization is important issue for RF MEMS switches. Because RF MEMS switches is working very high frequencies.

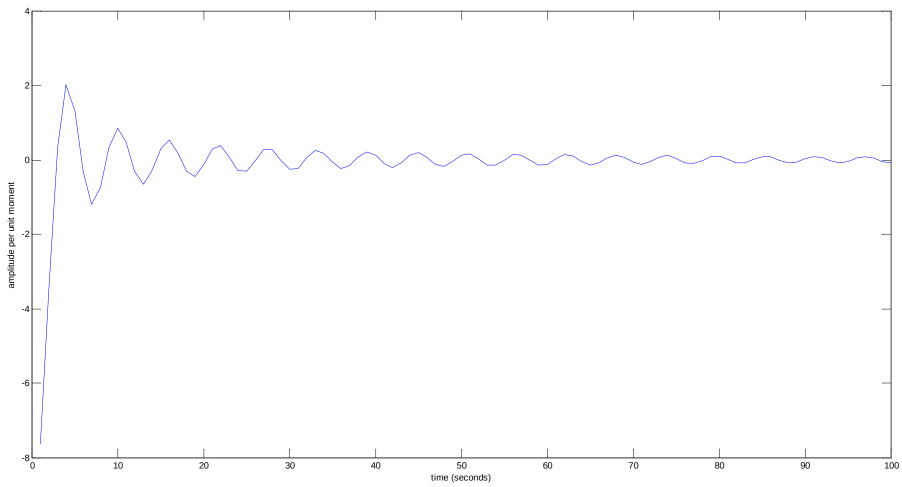


Figure 3.15: Open loop step response for cantilever beam with damping

If damping is to low for cantilever beam, the severe degree of resonance of beam impact from the external force which causes large signals to overload the control circuitry resulting system failure [8]. Generally high damping ratio is preferred for cantilever beam switch. Therefore in designing MEMS switches or devices damping factor take into considerations on the early stages [21].

3.3.2 Cantilever Beam Stress

Beams structure characterized by their ability to support bending and they can provide linear degree of freedom. Moment and transverse loads applied to the beam so it becomes curved [8]. Axial loads make beams longer or shorter. As the loaded beam takes on a curved shape, one side of the beam became longer while opposite side is shortened. Therefore, shortened side of the beam becomes compressive and the longer side of it becomes tensional. Neutral axis of the beam which is a plane through the geometric center of the beam does not change in length at all and unstressed as a result of bending. For simple cases in beam bending, the maximum stress is in at beam surface also it is independent at the material composing of cantilever beam. The magnitude of the stress of the beam bent into a curved shaped by either a moment or a transverse load

$$\sigma = \frac{Mc}{I} \qquad \textbf{(3.21)}$$

$$M = P.L \qquad \textbf{(3.22)}$$

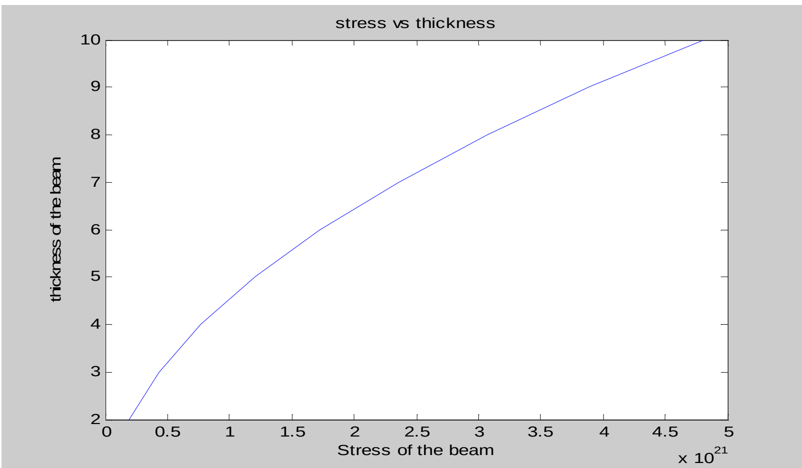


Figure 3.16: Air gap thickness vs. stress of the beam

M is the moment which causes beam curvature, c is the distance from the neutral axis (usually half of the thickness of gap but in this thesis organization $c = \frac{2d}{3}$ can be acceptable, because of maximum pull in voltage value) and I is the area moment inertia of the beam. P is referred pressure also equals to electrostatic force [8].

For example the figure 3.16 above is showing, when thickness of the air gap increases stress in the beam also increases. Because pull in voltage value increase with thickness of the between beam and bottom plate so needing to apply more electrostatic force to cantilever beam switch. Therefore it causes more stress in the beam. Another important parameter for stress is material properties of the cantilever beam. In figure 3.15, it can be easily seen that stress is increasing when young modulus of the beam is increased. When young modulus is getting bigger, applied voltage value for electrostatic force is also increasing. So it will cause more stress in the beam.

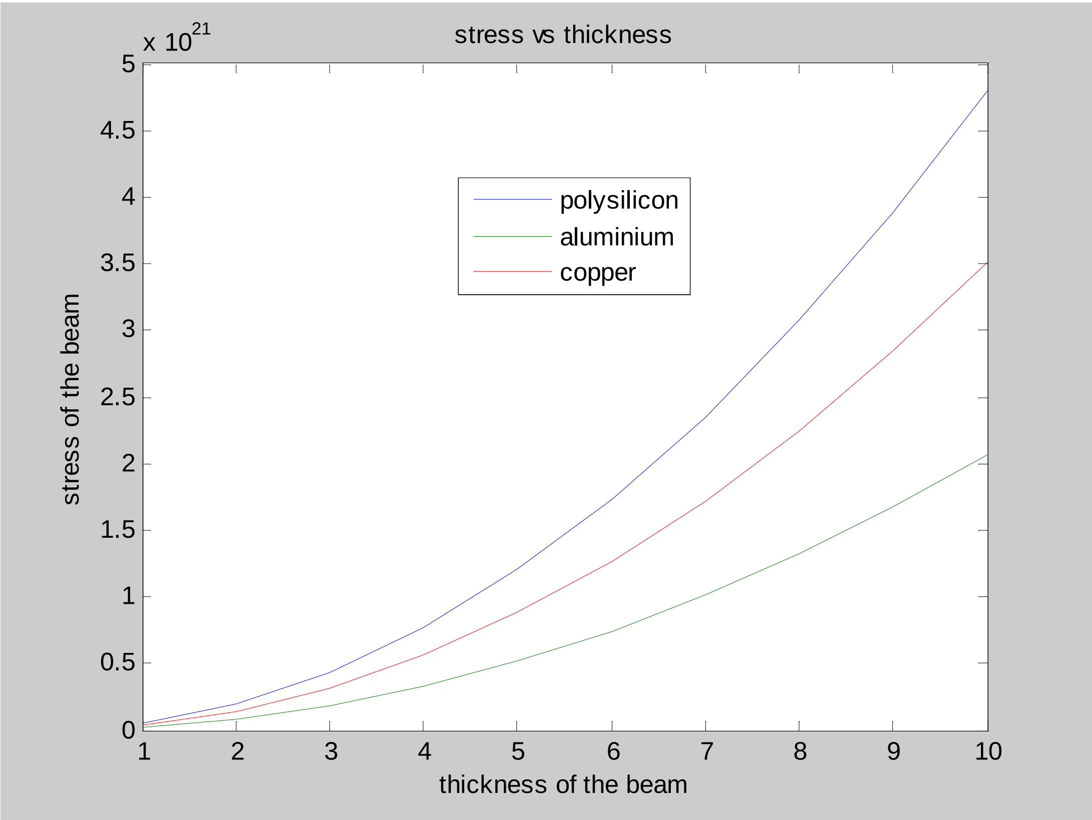


Figure 3.17: Stress and thickness relationship for different material

4. FABRICATION OF POLYSILICON CANTILEVER BEAM SWITCH

Some of the MEMS switches that have been proposed have excellent characteristic but can not be integrated into typical CMOS process flow. Process compatibility has become major concern as more and more MEMS technology is being integrated into the system [2]. In this thesis organization, electrostatically actuated polysilicon cantilever beam switch is being fabricated in YITAL (Semiconductor Technologies Design and Process Research Laboratory) at TUBITAK UEKAE's clean room. It also shows that CMOS process compatibility to the MEMS process. For example in MEMS technology, gold is suitable for parallel plate capacitive bottom electrode. But it affects CMOS chip's conductivity so in YITAL gold deposition is not used. Because of this effect, doped polysilicon is used for bottom electrode. The material parameters that determine the threshold voltage, the resonance frequency, and the maximum deflectable distance are the elastic modulus, the yield strength, and the dielectric constant. In table 4.1, lists these properties for different class of materials [22].

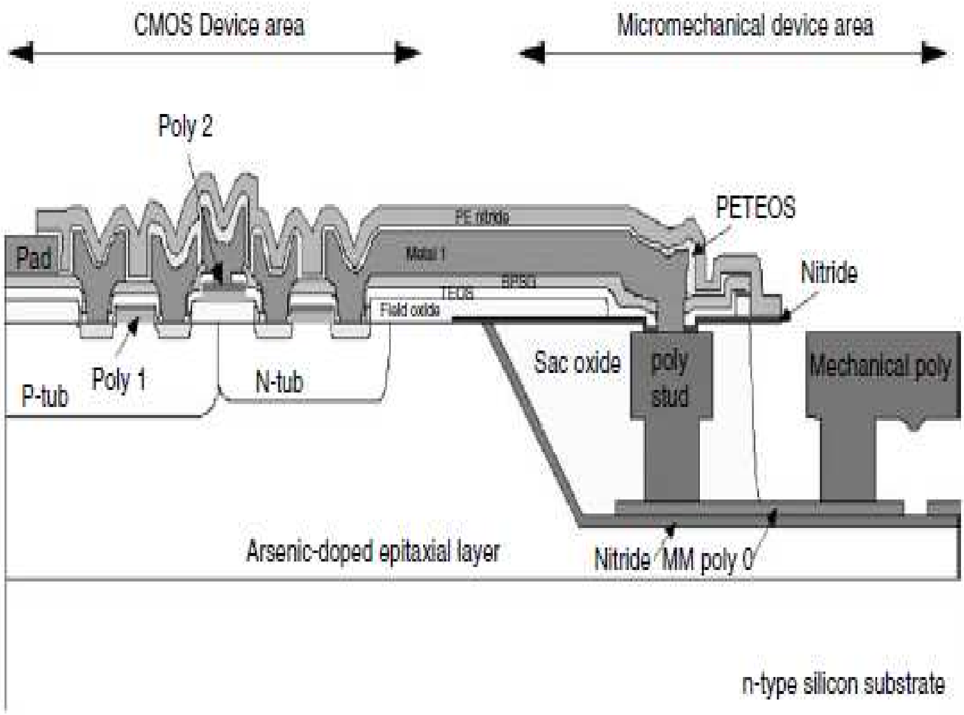


Figure 4.1: Schematic illustration of Cantilever Beam Switch with traditional CMOS process

Table 4-1: Elastic Modulus, Yield Strengths, Dielectric Constants of Various Materials

Class	Material	Elastic Modulus $E(N/m^2)$	Yield Strength $\sigma_y(N/m^2)$	Dielectric Constant ε_r
Ceramics	Ta_2O_5	$6.0x10^{10}$	----	25
	SiO_2	$7.17x10^{10}$	$8.4x10^{9}$	3.94
	Si_3N_4	$1.3x10^{11}$	$1.4x10^{10}$	7
	Al_2O_3	$5.3x10^{11}$	$1.54 x10^{10}$	10
Metals	Au	$6.13x10^{10}$	$3.24 x10^{8}$	----
	Al	$7x10^{10}$	$1.7 x10^{8}$	----
	Cr	$1.8x10^{11}$	$3.62 x10^{8}$	----
	Ni	$2.07x10^{11}$	$5.9x10^{8}$	----
Semiconductor	Si	$1.90x10^{11}$	$7.0 x10^{9}$	13.5
Diamond	C	$1.04x10^{12}$	$5.3 x10^{10}$	5.68

The mechanical and electrical properties of the materials depend on microstructure, such as whether the material is single or polycristal (grain size and grain orientation), amorphous, as-deposited, or annealed.

Si (1,0,0) p- type (CZ), 15-25 Ω/cm wafers used for this project. Their doping concentration nearly $5*10^{15}\, eV/cm$. For processing cantilever beam switch we need conductor and dielectric materials. For cantilever beam design we need two parallel plates. These plates are conductor so they can be actuated by electrostatically. Also for this switch, we need capacitive effect. Then the dielectric layer between to conductor plates is used.

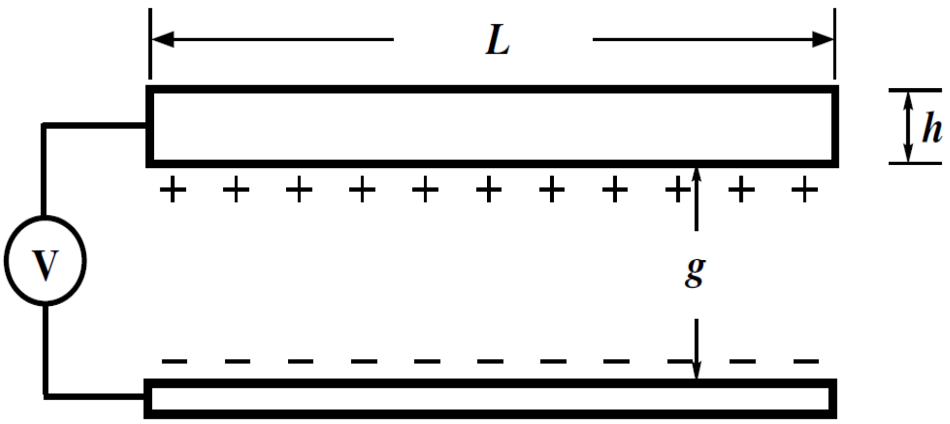
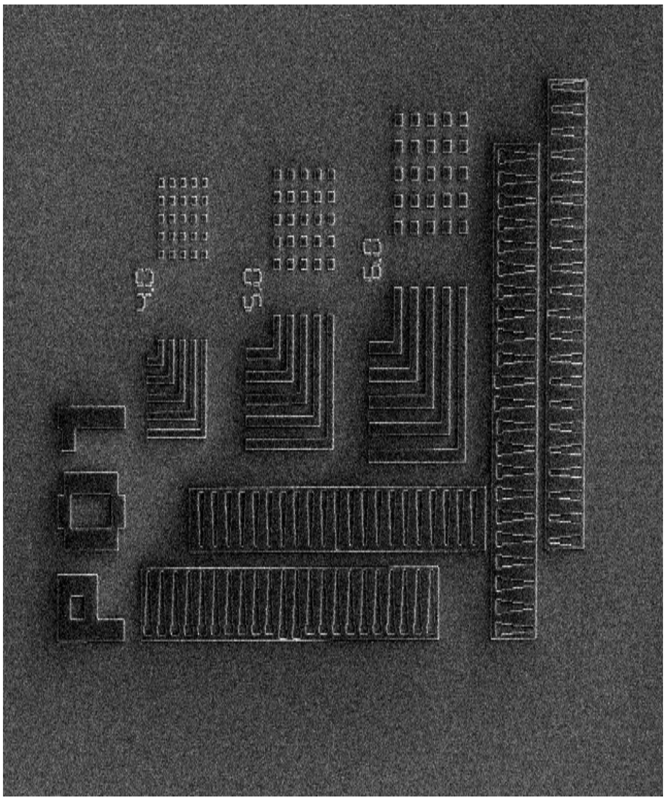
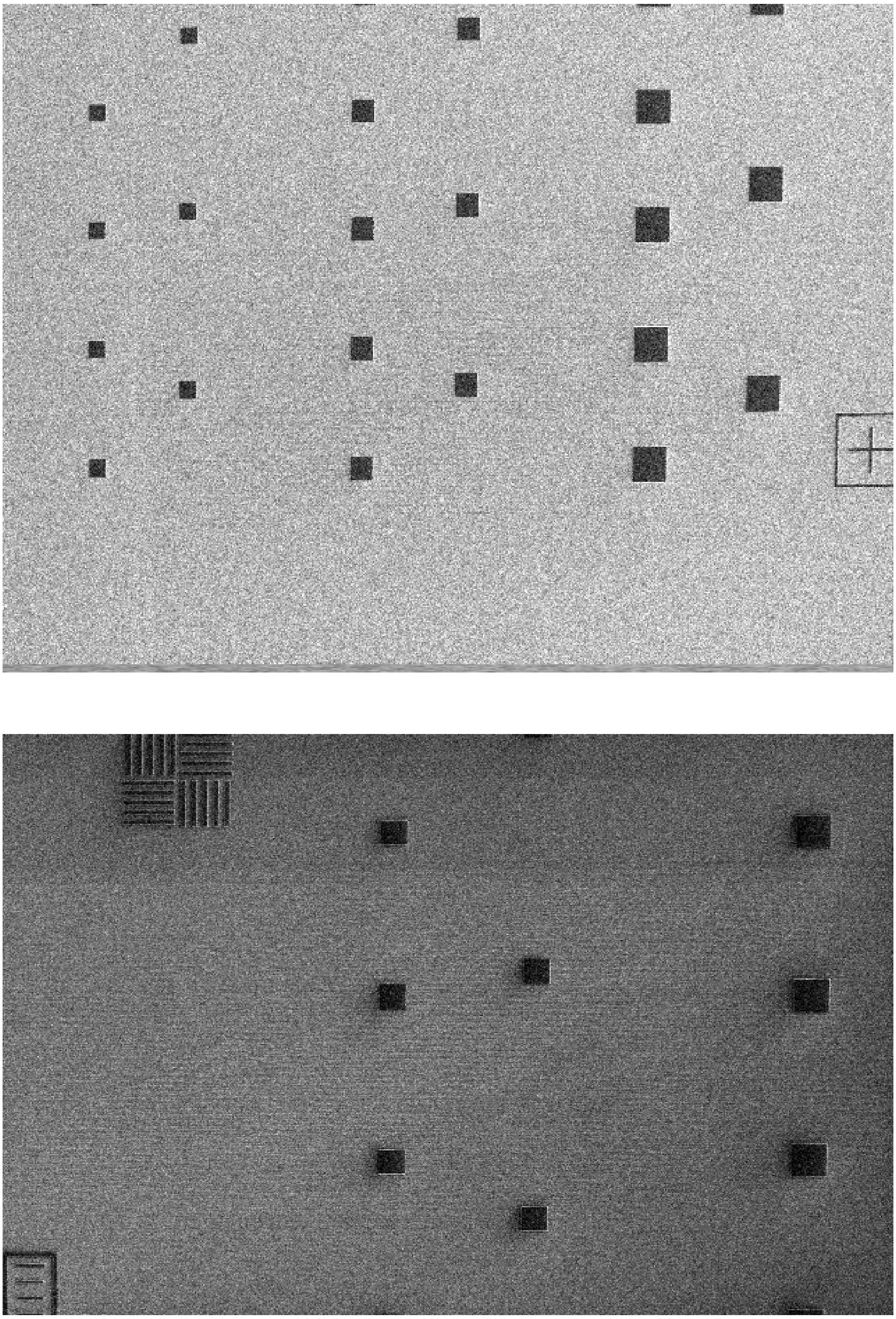


Figure 4.2: Schematic illustration of Cantilever Beam Switch

Firstly, silicon wafers cleaned with standard RCA cleaning at chemical wet bath. Immediately wafer oxidized at 900 C° with O_2 atmosphere. Oxidation is not necessary but it reduces stress between nitride and silicon layer interface. After oxidation Silicon Nitride (Si_3N_4) layer deposited with LPCVD furnace. This layer works like dielectric isolation between the substrate and the device. The thickness of the Silicon Nitride layer is 1500 $\overset{0}{A}$. On the top of this layer $0.3\mu m$ thick Polysilicon named Doped Polysilicon I deposited in LPCVD (Low Pressure Chemical Vapor Deposition) furnace. Then the wafers were doped with phosphorus ($POCl_3$) source. So polysilicon's grain sizes changed then its slice resistance value decrease nearly 25 Ω / cm^2. The Doped Polysilicon I layer patterned with first mask (wavelength 436 nm) set using photolithography for bottom electrode. Then polysilicon layer etched using Reactive Ion Etch chamber. After etching, the photoresist was stripped in a chemical solvent bath. For the switch design the Doped Polysilicon I patterns remained after etched makes electrodes, the signal line and the polysilicon layer of the electrical pads.

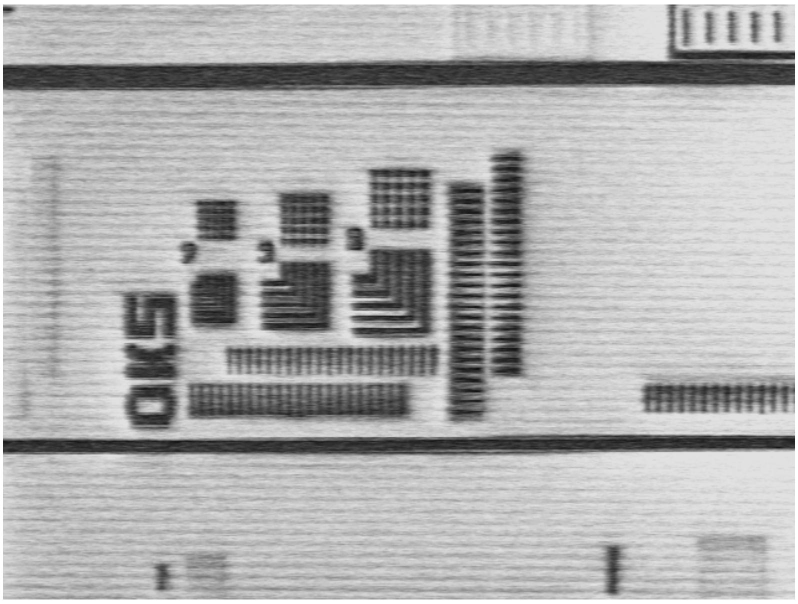


Picture 4.3: SEM image of Doped Polysilicon I layer mask pattern

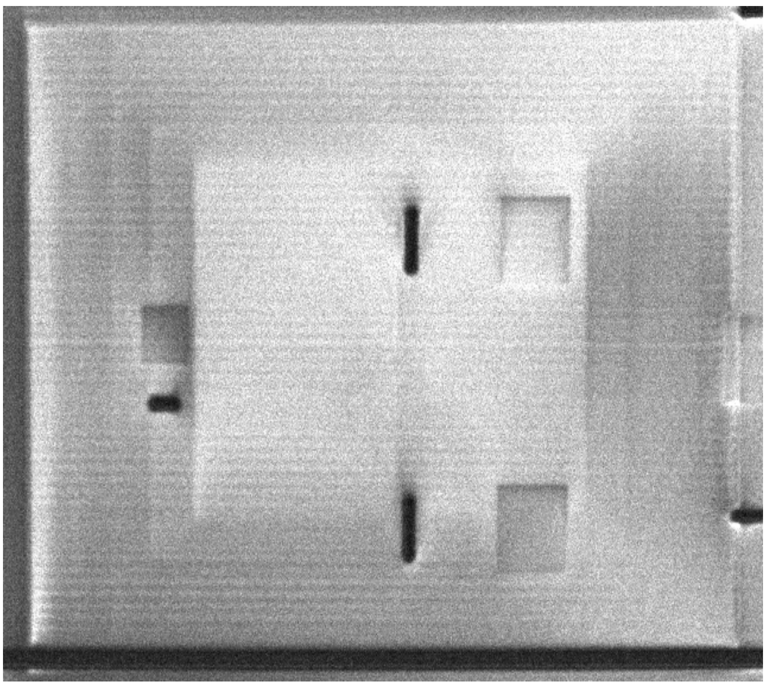


Picture 4.4 SEM images of Doped Polysilicon I different size of bottom electrode pattern

After Doped Polysilicon layer, $2\mu m$ thick BPSG oxide layer was deposited in the LPCVD furnace. This layer would provide anchor part of the beam because BPSG oxide layer is sacrificial. At the end of the all the process step, this layer all etched with wet etching chemicals so it become air gap between beam and bottom electrode layer. Again after deposition, BPSG oxide layer was patterned and etched with mask named OKS. This time wavelength of the photolithography was 365 nm. Then photoresist was removed by chemical solution.



Picture 4.5 SEM image of BPSG layer mask pattern



Picture 4.6 SEM image of different size of after etching BPSG Oxide layer pattern

Table 4.2: Polysilicon Cantilever Beam Switch Process Layers

Material	**Thickness**	**Type of Layer**	**Function**
Si	$500\mu m$	p-type semiconductor	Substrate
SiO_2	$120\ \overset{0}{A}$	Dielectric	Decreasing stress between Si_3N_4 and Si layers
Si_3N_4	$1500\ \overset{0}{A}$	Dielectric	Dielectric layer between beam and bottom electrode
Doped Polysilicon I	$3000\,\overset{0}{A}$	Conductor (n-type)	Bottom electrode
BPSG	$2\mu m$	Dielectric (doped SiO_2)	Sacrificial Layer for gap between beam and bottom electrode
Doped Polysilicon II	$2\mu m$	Conductor (n-type)	Beam
Aluminum	$2\mu m$	Conductor	Contact Pads

Figure 4.7: Oxide growth

Figure 4.8: Silicon Nitride (S_3N_4) deposition

After silicon dioxide is deposited, silicon nitride is deposited on silicon dioxide layer. Because this layer satisfies dielectric material between bottom electrode and silicon wafer for isolation.

Figure 4.9: Polysilicon I deposition (bottom electrode)

In this thesis organization doped polysilicon used for top and bottom electrode. Firstly bottom electrode is deposited after lithography process, bottom electrode is etched according to first mask.

Figure 4.10: After Polysilicon I etch (bottom electrode)

Figure 4.11: BPSG oxide deposition (anchor-sacrificial)

In figure 4.11, BPSG oxide is deposit conformal on bottom electrode. Then this layer etched for OKS mask.

Figure 4.12: BPSG oxide etch (anchor-sacrificial)

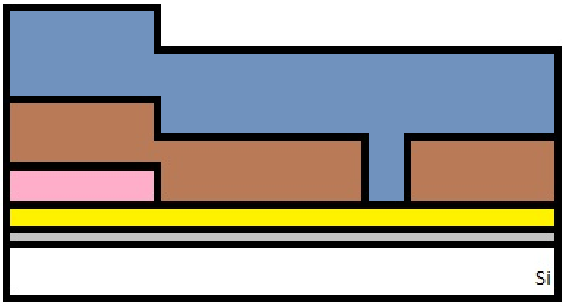


Figure 4.13: Polysilicon II deposition (beam)

In figure 4.13, after BPSG oxide is etched, polsilicon II deposited on the surface for stop electrode.

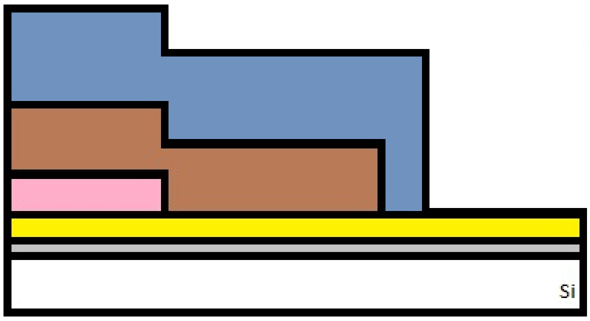


Figure 4.14: Polysilicon II etch (beam)

In Figure 4.14 second doped polisilicon layer is etched according the mask set. So bottom electrode also means cantilever beam is occurred. After BPSG oxide which is used for sacrificial layer is etched in HF chemical solution, air gap is satisfied. In figure 4.15 polysilicon cantilever beam switch can be easily seen.

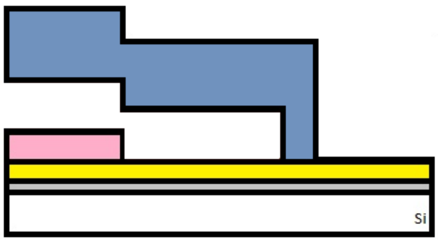


Figure 4.15: Sacrificial BPSG Oxide etch (air gap)

After all layers are defined, ConventorWare simulation program can be used. Firstly, fabrication steps are entered to process recipe system with thickness of layer. Then mask of the MEMS switch is designed. Mask defines active regions in the layer. Because deposition occurs all surface. But some part of the deposition layer is has to etched. So masking design is also important parameter for cantilever beam switch.

Number	Step Name	Action	Layer Name	Material Name	Thickness	Mask Name	Photoresist	Etch Depth	Mask Offset
0	Substrate	Substrate	Substrate	SILICON_100	5	SubstrateMask			
1	Planar Fill	Planar Fill	anti_stress	OXIDE	0.05				
2	Planar Fill	Planar Fill	dielektrik	SI3N4	0.15				
3	Planar Fill	Planar Fill	doped_poly	POLYSILICON	0.4				
4	Straight Cut	Straight Cut				poly1	+		0
5	Conformal Shell	Conformal Shell	sacrificial_oxide	PSG	2				
6	Straight Cut	Straight Cut				oksit	-		0
7	Conformal Shell	Conformal Shell	poly2_doped	POLYSILICON	2				
8	Straight Cut	Straight Cut				beam	+		0
9	Delete	Delete		PSG					

Figure 4.16: Process steps table in CoventorWare simulation program

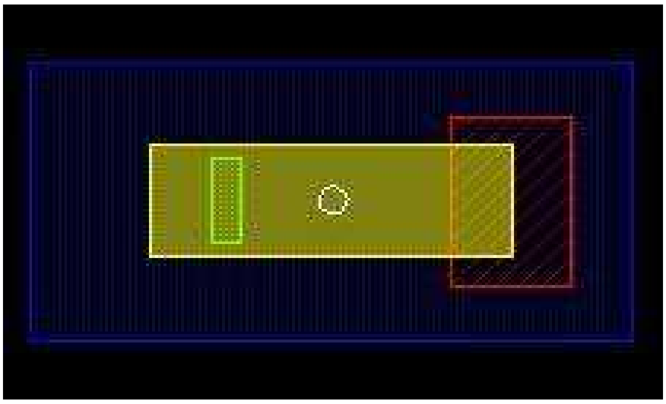


Figure 4.17: Mask of MEMS cantilever beam switch in CoventorWare simulation program

After one layer is deposited, photoresist applied as a thin film on a layer and subsequently exposed though the mask. The photoresist material is exposed to ultraviolet (UV) light, the exposed areas become soluble so that they are no longer resistant to etching solvents. After developing, the wafer is etched and all parts not covered by photoresist are removed. For figure 4.17 first mask is polysilicon mask, after deposition of polysilicon red area of the mask remains the other polysilicon area is removed by etchants. The other mask is processed respectively.

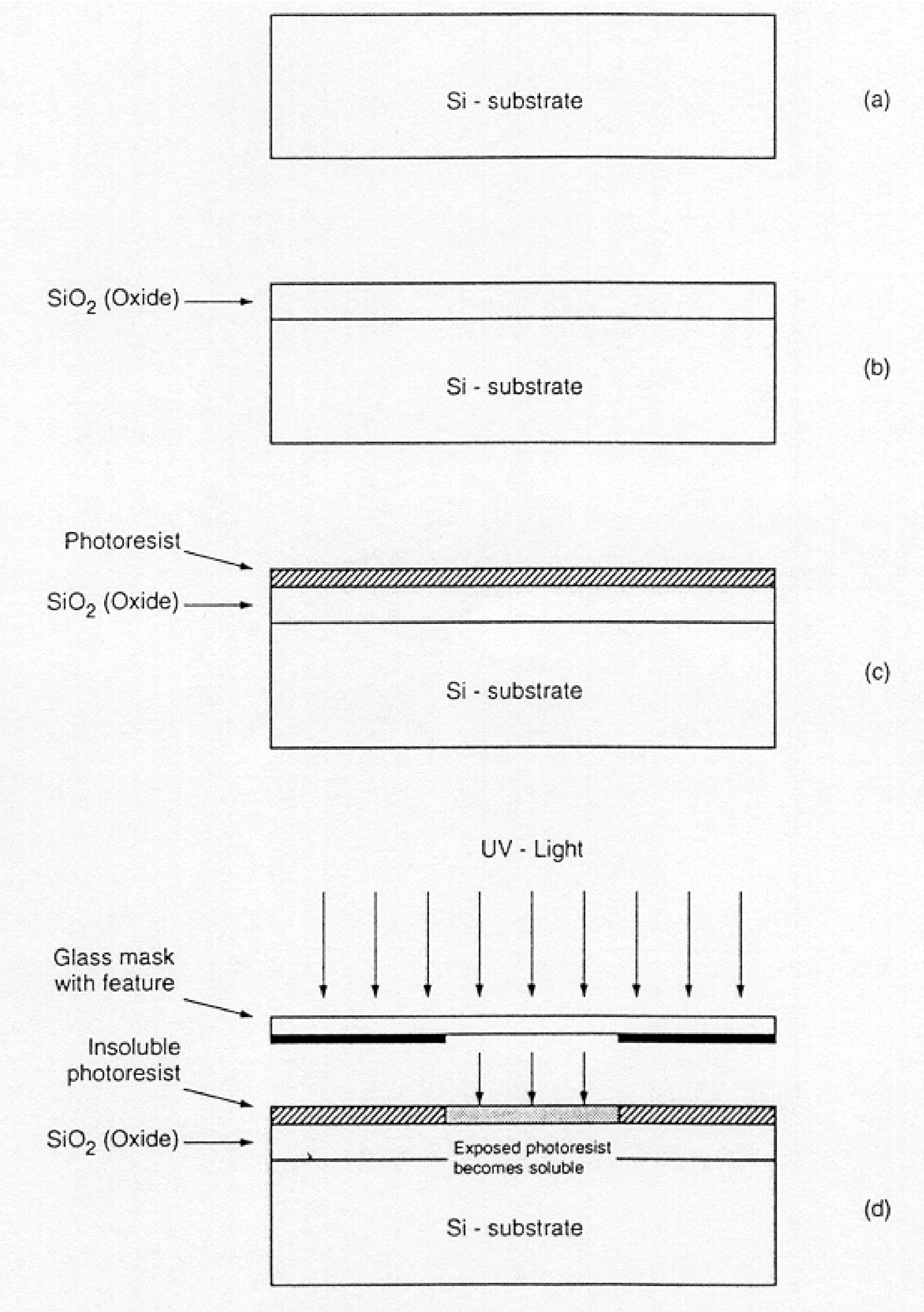


Figure 4.18: Photolithograph process

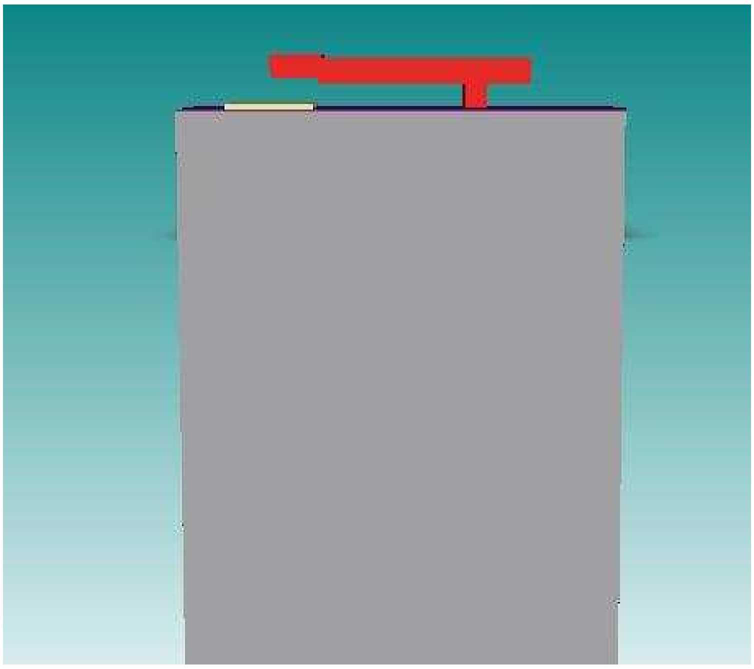


Figure 4.19: Images of cantilever beam switch simulation in CoventorWare

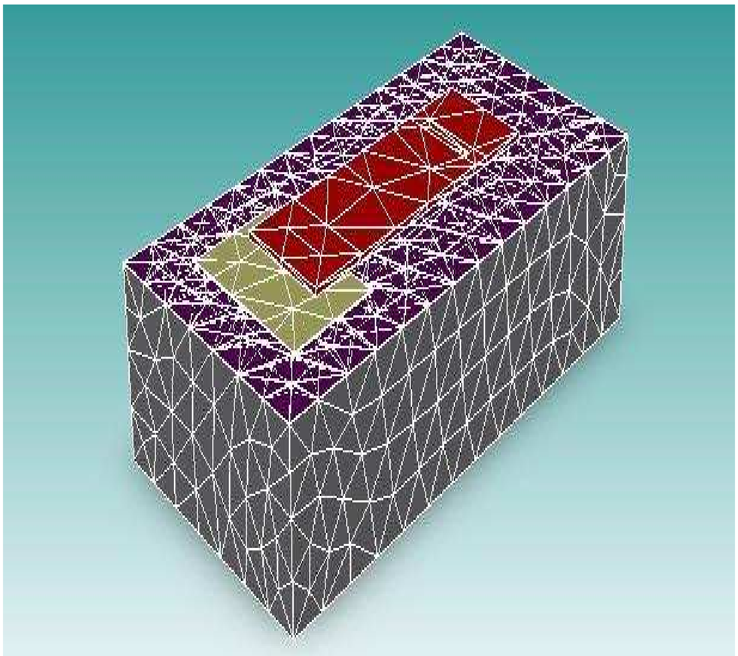


Figure 4.20: Meshing for cantilever beam switch in CoventorWare

In figure 4.19 yellow part is bottom electrode and it is used for measurement capacitance value between top and bottom part. Red part is cantilever beam part where voltage is applied during measurement. In figure 4.20 different size of mesh can be seen because of the stress effect is different for every layers.

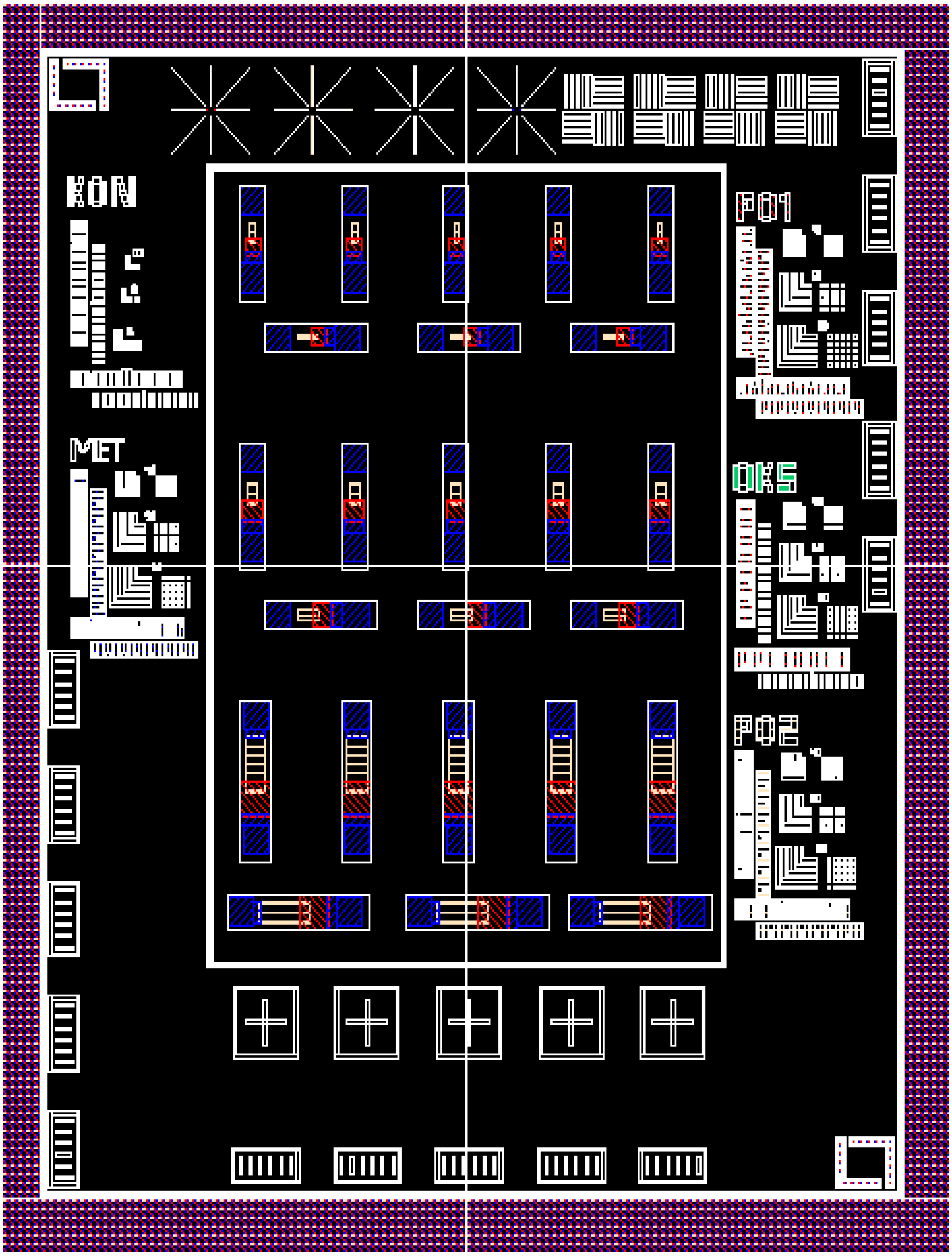


Figure 4.21: Mask of all layers with different size in L-edit program

In figure 4.21 all layers are drawn in L-edit program. Different size of pattern are used for test to find optimum dimensions of the cantilever beam switches. Also in the right and left hand side, some signs are used for alignment all mask sets in one way for lithography machine.

5. CONCLUSION AND FUTURE WORK

The main goal of that thesis is design and fabrication of MEMS cantilever beam switch. MEMS cantilever beam switch's isolation, insertion loss and compatibility with other circuitry in RF device is better than FET and PIN Diodes. Therefore design parameter is very important for fabrication for MEMS switch with RF device in the same die.

Pull-in voltage is very important for cantilever beam switch. Maximum voltage value calculated from the electrostatic force on the system. Therefore it can be reached when air gap is the third of initial condition. For dimension of the cantilever beam is $L = 100\mu m$, $w = 40\mu m$, $h = 2\mu m$ and $d = 2\mu m$, maximum value of pull-in voltage is 14 V. Also observing the result of resonant frequency of the beam is nearly 2 MHz range. But for fabrication case, three different dimensional cantilever beams are designed to see real time measurement. First one is $L = 100\mu m$, $w = 40\mu m$, $h = 2\mu m$, $d = 2\mu m$, second one is $L = 60\mu m$, $w = 20\mu m$, $h = 2\mu m$, $d = 2\mu m$ and third one is much more smaller than the other ones $L = 40\mu m$, $w = 10\mu m$, $h = 2\mu m$, $d = 2\mu m$.

Natural frequency and the effective masses of a cantilever beam are calculated from the mathematical equations. Simulations showed that resonant frequency of the beam is in the KHz values. Also comparing different material properties for fabrication cantilever beam switch showed that there is no more difference between Polysilicon and Aluminum. But stress gradient is depends on young modulus of the beam material. When young modulus of the beam material is increased stress gradient at the tip is also increasing. Another important issue is damping factor. For open loop system response damping factor is keeping the system stable.

In this thesis organization, compatibility of the traditional semiconductor fabrication step with MEMS switch is also investigated. Polysilicon is used for cantilever beam which is also used for CMOS gate region. In cantilever beam design phosphorus doped polysilicon also used for ground electrode. Finite element analysis in CoventorWare shows that, there will be an adhesion in between cantilever beam and ground electrode because there are made in a same material. After fabrication, capacitance versus voltage value will be measured. Resistance value of cantilever beam is not measurable in this design. For contacting, ground and cantilever beam is deposited by aluminum. Measurement contact pads dimension are $60\mu m X 60\mu m$ aluminum. Therefore contact resistance of aluminum pad is much bigger than cantilever beam resistance. So cantilever beam's resistance is neglected in the measurement. It will not give the solution when measuring the resistance in this design.

The future work includes testing the cantilever beam switch which is fabricated in TUBITAK BILGEM YITAL. After that, to understanding parameter variation, compare the result for different size of cantilever beam switches. Real time measurement is showed effective parameters in design MEMS cantilever beam switch.

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APPENDICES

APPENDIX A

%% The equilibrium relationship between plate displacement and voltage%%

```
d=10
n=10;
for i=1:n              % mathematical equations for calculate pull-in voltage, Area and the
                        epsilon is constant
   x(i)=i;
   m(i)=d-(x(i));
   k(i)=(x(i))/d;       %k= x/d ratio
   y(i)=sqrt(x(i));
   U(i)=(y(i))*(m(i))    %pull-in voltage
   end
   plot (k(1:10),U(1:10))
```

%%Spring constant variation with respect to the thickness of the beam%%

```
w=40e-6;  %width of beam
L=2e-6;   %length of beam
E=160e9;  % young modulus of polysilicon
for i=1:1:10
     h(i)=(i)/1000000;
     I(i)=(w*(h(i)^3))/12;  %inertia
     k(i)=(3*E*(I(i)))/(L^3); %spring constant
```

```
end

plot(k(1:10),h(1:10))

xlabel('spring constant')

ylabel('thickness of the beam')
```

%%%Open loop step response for cantilever beam without damping.%%%

```
b=60e-6;  %width

L=100e-6; %  lenght

h=2e-6;  %thickness

Ymax=6.6e-7; %maximum deflection point

dens=2.331; % density of polysilicon

m=2.8e-8;  % mass of this beam b*L*h*dens

E=160e9; %young modulus of polysilicon

I=((b*(h^3))/12); %inertia

g=sqrt(((3)*E*I)/((L^3)*m));

f0=(1/(2*pi))*(g)*(0.5);

for i=1:1:50

  t(i)=i;

             a(i)=((Ymax)*(((2)*(pi)*(f0))^2)*(cos(2*pi*f0*(t(i))))) %  acceleration

            end

plot (t(1:500),a(1:500))
```

%%% Open loop step response for cantilever beam with damping.%%%

```
b=60e-6;

L=100e-6;

h=2e-6;
```

```
Ymax=6.6e-7; %d/3 maximum displacement
dens=2.331;  %density of the polysilicon
m=2.8e-8;    % mass
E=160e9;     % young modulus of the polysilicon
I=((b*(h^3))/12);  %inertia of polysilicon beam
g=sqrt(((3)*E*I)/((L^3)*m));
f0=(1/(2*pi))*(g)*(0.5);
damp=1000; %damping
for i=1:1:100
     t(i)=i; %time (seconds)
     m(i)=(Ymax)*(((2)*(pi)*(f0))^2)*(cos(2*pi*f0*(t(i))));
    f(i)=(Ymax)*((2)*(pi)*(f0))*(sin(2*pi*f0*(t(i))));   % resonant frequency
     j(i)=(damp*f(i)*(1/i));
a(i)=m(i)-j(i);
end
plot (t(1:100),j(1:100))
```

%%% Air gap thickness vs. stress of the beam%%

```
L=100e-6; %Lenght of the beam constant
w=40e-6;  %width of the beam constant
E=160e+9; %young modulus of polysilicon
for i=1:1:10 % thickness of the beam
     h(i)=i;
    c(i)=i;  % distance from the neutral axis
    I(i)=(w*(h(i)^3))/12;
     F(i)=(3*E*(I(i))*(i))/(L^3);
```

```
    Sigma(i)=((F(i)*(L)*(i))/I(i));  %stress of the beam
end
plot(Sigma (2:10),h(2:10))
title('stress vs thickness')
xlabel('Stress of the beam')
ylabel('thickness of the beam')
```

%%% Stress and thickness relationship for different material %%%

```
L=100e-6; %Lenght of the beam constant

w=40e-6;  %width of the beam constant

E1=160e+9; %young modulus of polysilicon

E2=69e+9; %young modulus of aluminum

E3= 117e+9; %young modulus of copper

for i=1:1:10 % thickness of the beam

    h(i)=i;

    c(i)=i;  % distance from the neutral axis

    I(i)=(w*(h(i)^3))/12;

    F1(i)=(3*E1*(I(i))*(i))/(L^3);    %electrostatic force of polysilicon

    F2(i)=(3*E2*(I(i))*(i))/(L^3);      %electrostatic force of aluminum

    F3(i)=(3*E3*(I(i))*(i))/(L^3);        %electrostatic force of copper
```

```
    Sigma1(i)=((F1(i)*(L)*(i))/I(i));

    Sigma2(i)=((F2(i)*(L)*(i))/I(i));

    Sigma3(i)=((F3(i)*(L)*(i))/I(i));
end

plot(h(1:10),Sigma1(1:10),h(1:10),Sigma2(1:10),h(1:10),Sigma3(1:10))

legend('polysilicon','aluminum','copper')
title('stress vs thickness')
xlabel('thickness of the beam')
ylabel('stress of the beam')
```

APPENDIX B

YITAL (Cleanroom which MEMS is fabricated)

Figure B.1: Cleanroom 100 class

In the right hand side: oxidation and LPCVD (Low Pressure Chemical Vapor Deposition) furnaces for depositing silicondioxide and polysilicon layer. Also RIE is in this are which is using for layer etching.

In the left hand side: Scanning electron microscope for imaging pictures of the layers And Nanometrics which is used for measuring the thickness of depositing layer.

Figure B.2: SEM (Scanning Electron Microscopy)

Figure B.3: Chemical Bath for cleaning and wet etching wafers

Figure B.4: Yellow room for photolithograph wafers, 10 class

CURRICULUM VITAE

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