

**MAGNETOMOTIVE AND TENSION-BASED TUNING OF A
MICROMECHANICAL RESONATOR**

by

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and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
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ABSTRACT

The principle attribute of mechanical resonators is ruled by their resonance frequencies. As the main components of resonating Micro- and Nanoelectromechanical Systems (MEMS and NEMS), mechanical resonators determine the sensitivity, accuracy, and operation range. Therefore the tuning capability of such systems is crucial for design and development of NEMS and MEMS. In this study, a transversally and axially tunable microresonator is fabricated and studied.

Magnetomotive actuation and optical read-out techniques are employed to excite microresonator and measure the output. Two active tuning mechanisms, magnetomotive tuning and tension-based tuning, are used to tune the resonance frequency of the micromechanical resonator. A chip-bending method is introduced to realize tension-based tuning mechanism. The variation in the effective stiffness of the micromechanical resonator due to softening effect and hardening effect is investigated.

The resonance frequency is tuned in the range of -13% with the magnetomotive tuning mechanism and the resonator exhibits a resonance frequency shift from 789 kHz to 683 kHz. The resonance frequency tuning range for chip-bending method is found to be 8%, from 789 kHz to 854 kHz. Simultaneous use of both techniques results in minor deviations from the aforementioned values. The combination of both tuning mechanisms represents one of the few examples in the literature. The approach is especially promising for use in sensor and RF filter applications.

ÖZET

Mekanik çınlaçların temel özellikleri rezonans frekansları tarafından belirlenir. Rezone Mikro- ve Nano-elektromekanik sistemlerin (MEMS ve NEMS) ana elemanı olan, mekanik çınlaçlar hassasiyet, kesinlik ve çalışma aralığını tayin eder. Bu nedenle, bu sistemlerin akort edilebilme kabiliyeti NEMS ve MEMS'lerin tasarlanması ve geliştirilmesinde kritik rol oynar. Bu çalışmada, enine ve eksenel olarak akort edilebilen mikroçınlaç üretilmiş ve incelenmiştir.

Mikroçınlaç'ı harekete geçirmek ve çıktıları ölçmek için mıknatıslı devinim tahriki ve optik okuma metotları kullanılmıştır. Aktif iki akort mekanizması (mıknatıslı devinim ve gerilme bazlı) mikromekanik çınlaçın rezonans frekansını akort etmek için kullanılmıştır. Gerilme bazlı akort etme mekanizması olarak yonga bükme tekniği tercih edilmiştir. Yumuşatma ve sertleştirme etkilerinden dolayı mikromekanik çınlaçın efektif rijitliğindeki değişimler araştırılmıştır.

Rezonans frekansı, mıknatıslı devinim akort mekanizması ile -13% aralığında akort edilmiş ve çınlaç, 789 kHz'ten 683 kHz'e kadar rezonans frekansında kayma sergilemiştir. Yonga bükme metodu için rezonans frekansı akort etme aralığı 789 kHz'ten 854 kHz'e 8% olarak tespit edilmiştir. İki tekniğin eşzamanlı kullanılması sonucu, bahsi geçen değerlerde ufak sapmalar meydana gelmiştir. Her iki akort etme mekanizmasının kombinasyonu literatürde birkaç örnekten birini temsil eder. Bu yaklaşım özellikle RF filtre ve sensör uygulamalarında kullanım için umut vaat etmektedir.

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NOMENCLATURE

MEMS	Micro-electromechanical systems
NEMS	Nano-electromechanical systems
SEM	Scanning Electron Microscope
FIB	Focused Ion Beam
CNT	Carbon Nanotube
RF	Radio Frequency
VHF	Very –High Radio Frequency
UHF	Ultra-High Radio Frequency
LbL	Layer by Layer
FEM	Finite Element Model
FEA	Finite Element Analysis
LDV	Laser Doppler Vibrometer
NW	Nanowire
DC	Direct current
PECVD	Plasma-Enhanced Chemical Vapor Deposition
PVD	Physical Vapor Deposition
IPA	Isopropyl Alcohol
PR	Photoresist
RIE	Reactive ion etching
HF	Hydrofluoric acid
UV	Ultraviolet
ω_0	Nominal Frequency
ω_s	Softened Frequency
ω	Frequency
v	Velocity
ε_0	Permittivity of free space
V_{DC}	Bias Voltage
V_{tun}	Tuning voltage

t	Time
V_{pp}	Peak To Peak Actuation Voltage
E	Young's Modulus
I	Area Moment of Inertia
i	Current
i_{ac}	AC current
i_{dc}	DC current
V_{off}	Offset Voltage
ϵ	Longitudinal strain
N	Axial Tensile Force
ρ	Density
σ	Axial Stress
ϑ	Poisson ratio
x_d	Oscillation Amplitude
x_c	Critical Drive Oscillation Amplitude
R	Resistance
L	Inductance
C	Capacitance
R_{termin}	Terminal Resistor
A	Cross Section Area
l	Length
φ	Normalized length
m_{eff}	Effective Mass
m_{total}	Total Mass
k_{eff}	Effective Stiffness
k_{mech}	Mechanical Stiffness
k_0	Initial Mechanical Stiffness
C_{feed}	Parasitic Capacitance
Q	Quality Factor
k_e	Electrical stiffness
k_{ms}	Magnetomotive Stiffness
d_0	Initial Gap between electrode and resonator

B	Magnetic Field
L_r	Beam Length
W_r	Beam Width
H_r	Beam Height
F	Force
c_1, c_2, c_3, c_4	Mode Shape Constant
w	Mode Shape Function



Chapter 1

INTRODUCTION

The recent developments in micro- and nanofabrication technologies and techniques have empowered the advancement in micro- and nanoelectromechanical system (MEMS, NEMS) resonators. Being in nano and micro scales gives mechanical resonators advantage of compactness, high sensitivity, high resolution, low power consumption and low cost. Micro- and nanomechanical resonators are used for detection and sensing in many applications, such as mass and force sensing, biological sensing, radio frequency (RF) filtering, and even quantum measurement[1-5].

The resonance frequency is the main element that determines the sensitivity, accuracy and operation limit of MEMS and NEMS resonators. Therefore, the tuning capability of mechanical resonator is important and essential for future design and development of NEMS and MEMS resonators. Frequency tuning is crucial for applications which require controllable sensitivity and stability, such as oscillators, filters, and sensors. Moreover, frequency tuning can be used to compensate for resonance frequency shift that can occur in MEMS and NEMS resonators. The resonance frequency of a mechanical resonator depends on geometry, material properties, intrinsic stress, temperature, pressure, and many other environmental factors. Any change in these properties may cause a shift in resonance frequency which diminishes reliability and accuracy of the system. In that case, frequency tuning can be employed for correcting resonance frequency shift that occurs due to fabrication process or environmental effect [6-9]. Frequency tuning is usually categorized in two sections, Passive and Active Tuning methods.

1.1. Passive tuning

Passive tuning is a permanent tuning method that changes the structure or properties of the mechanical resonator. Unlike to active tuning, there is not any energy consumption once tuning is made which makes such method very attractive for low energy applications. The most commonly used passive tuning method is post-fabrication tuning.

1.1.1. Post-Fabrication

Generally, post-fabrication tuning methods are employed for compensating or repairing local imperfection and errors occur during fabrication, which cause variation in expected resonance frequency. Among the various techniques, focused ion beam (FIB) is the most suitable technique for post-fabrication process. FIB can be used for a material depositing and sputtering in nano-scale which gives it capability of a broadband frequency tuning. Syms *et al.* reported that by using FIB, they able to shift resonance frequency of an electrostatic comb-drive by 5%. Enderling *et al.* demonstrated a tuning method where FIB is used to deposit platinum on the tip of micromechanical resonator (Fig. 1.1). In this study, they changed the effective mass of the cantilever system which altered the resonance frequency. Liu et al. reported a new study which they achieved more than 20 MHz frequency shift with 1.4 % tuning range. In this study they made use of molecular layer by layer self-assembly approach to vary the resonance frequency of film bulk microresonator, shown in Fig. 1.2 [10-13].

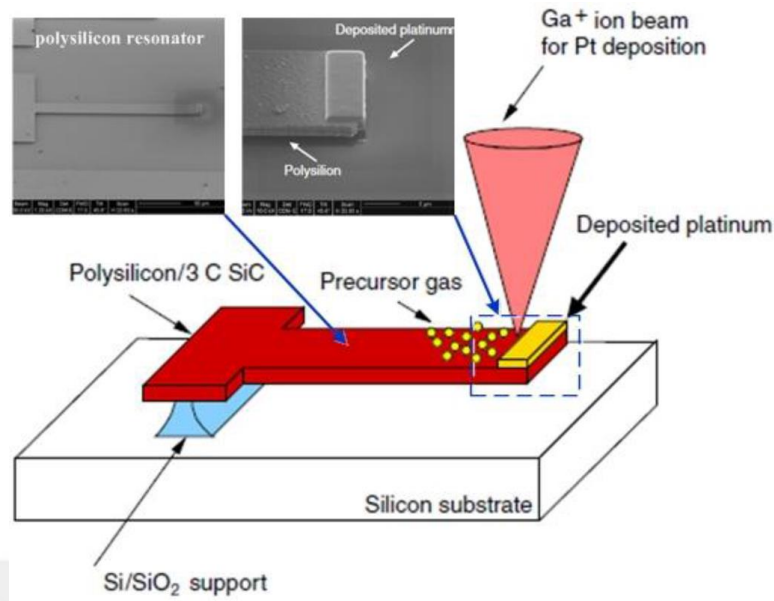


Figure 1. 1: Frequency tuning of resonators by FIB Pt deposition reported by Enderling et al. Adopted from [10]

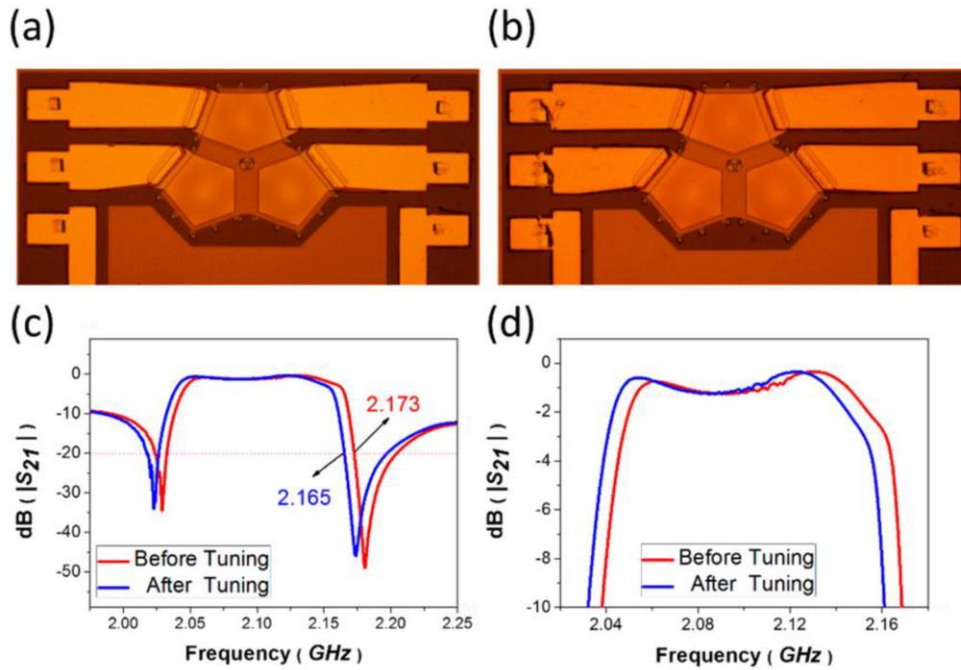


Figure 1. 2: Frequency tuning of microresonator using molecular LbL self-assembly approach reported by Liu et al. Microscope images (a) before and (b) after LbL assembly. Performance of (c) wide band and (d) pass band (red) before and (blue) after LbL assembly. Adopted from [13].

1.2. Active Tuning

Active tuning can be defined as real time tuning methods that temporally change the effective stiffness mechanical resonator and shift the resonance frequency while excitation force is present. Active frequency tuning most commonly is achieved by the excitation system

itself and they can be an on-chip mechanism or an external force. On-chip approached is generally applicable for systems that make use of voltage induced forces, such electrostatic, magnetomotive, and piezoelectrical systems. The latter method uses external force excitation systems such as photothermal. Table 1.1 compares actuation mechanism that used for frequency tuning [1, 13-19].

Actuation Type	Fabrication Process	Power consumption	Applied Voltage	Current	Nonlinear Effect
Electrostatic	Simple	Low	High	Low	High
Magnetomotive	Simple	Medium	Low	Medium	High
Electrothermal	Simple	High	Low	High	Medium
Piezoelectric	Complex	Low	Medium	Low	High
Photothermal	Complex	Medium	-	-	High

Table 1.1: Comparison of actuation mechanisms in MEMS and NEMS resonators. Adopted form [1, 15].

1.2.1. Electrostatic Tuning

Electrostatic actuation is an on-chip excitation method that is widely used due to its low power consumption and ability to generate large force at small size. The resonance frequency is controlled by DC voltage that applied on the resonator or on the electrodes for excitation purposes. In some cases, an extra voltage gate similar to electrode is introduced to the system for tuning resonance frequency via applying bias voltage.

1.2.1.1. Electrical Softening

As for all active tuning, actual idea in tuning frequency is controlling effective stiffness (k_{eff}) of the system by introducing an additional equivalent stiffness. In the electrostatic system, introduced additional stiffness is called electrical stiffness that causes an electrical softening [20-23].

For instance, Scheibner *et al.* employed an extra electrode system and applied DC voltage to tune the frequency range of the vibration detection system shown in Fig. 1.3. The effective stiffness of the system shown is calculated as following [22]:

$$k_{eff} = k_0 - \frac{V_{tun}}{2} \frac{d^2 C(x)}{dx^2} \quad (1)$$

Where k_0 is the mechanical stiffness, V_{tun} is the applied bias voltage on the electrodes for tuning frequency, and C is the total capacitance between electrode and seismic mass.

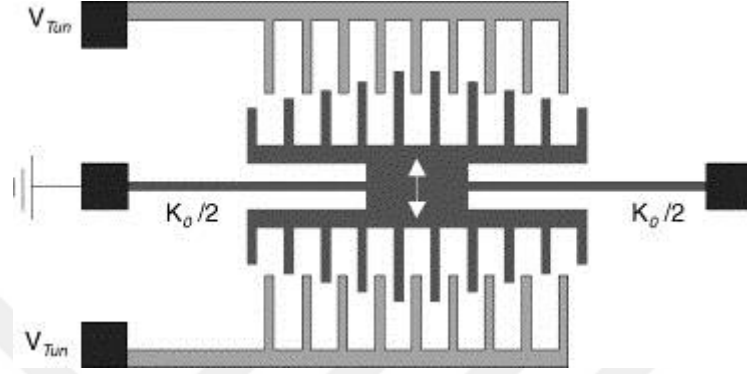


Figure 1.3: Frequency tuning by electrostatic tuning. Adopted from [22].

A 0.7% of frequency shift is reported for this system with tuning voltage of 35V. The resonance frequency is tuned from 1 to 10 kHz. Another study that reported by Pourkamali *et al.*, showed 10% tuning range in resonance frequency, from 505 kHz to 450 kHz [24]. Several nanowire (NW) and carbon nanotube (CNT) resonator studies that uses electrostatic actuation reported a decrease in resonance frequency due to electrical softening[25-27]

1.2.1.2 Elastic Hardening

Electrostatic tuning can also offer a distinct hardening effect which increases the resonance frequency. By making use of electrostatic attraction force, large elastic deformation can be realized. This elastic deformation causes an increase in the resonance frequency [28, 29].

Zhong *et al.* reported a dual-gate electrostatic mechanism which can make use of both elastic hardening and electrical softening to increase and decrease resonance frequency (Fig. 1.4). This study has similarity with our study which combines hardening and softening effect to tune the resonance frequency. Only difference is they used on type of tuning mechanism where we use two different tuning mechanism[30].

Ning *et al.* reported a new design of CNT resonator where the resonance frequency can be tuned transversally and axially. This study is one of the few studies where the frequency tuning is realized axially and transversally, by two different tuning mechanism

which is very similar to our study. However, the difference is Ning *et al.* used both tuning mechanisms to accomplish hardening effect (Fig. 1.5) [31].

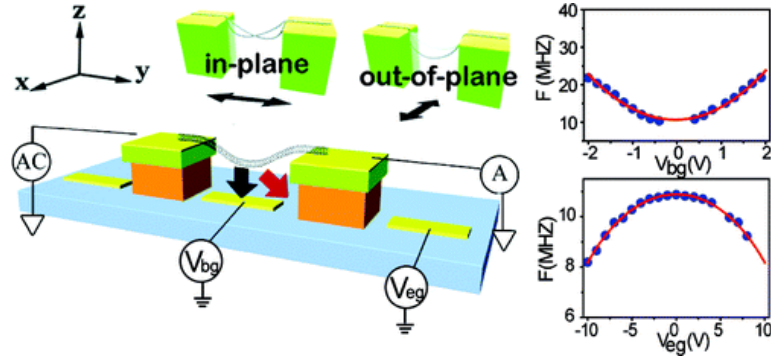


Figure 1.4: Zhong *et al.* Dual-gate tuning mechanism. Adopted from [30].

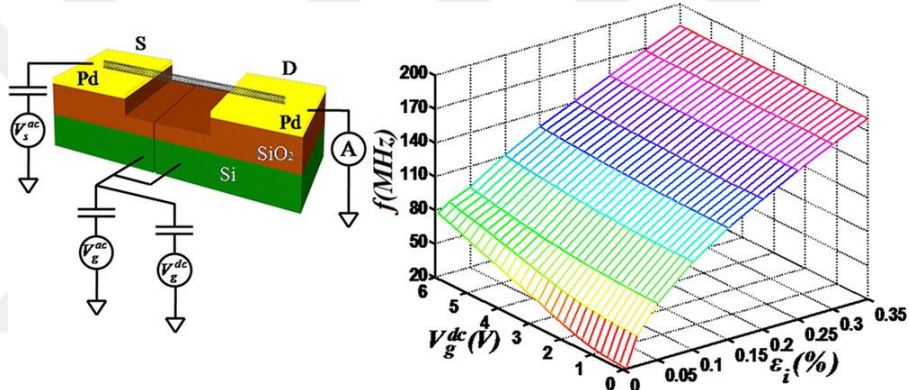


Figure 1.5: Ning *et al.* transversally and axially tuning. Adopted from [31].

1.2.2. Tension – Based Tuning / Hard Spring Effect

Resonance frequency and tensile stress have well known proportional relation. The presence of tensile stress increases the resonance frequency which is called “hard-spring effect”. The main idea in tension-based tuning mechanism is controlling the tensile stress induced on a mechanical resonator. This idea can be realized by applying axial tensile force to the mechanical resonator. Q factor of mechanical resonator is also increased with tensile stress [32-35]. Ning *et al.* claim to increase the resonance frequency of CNT resonator from 9.44 MHz to 21 MHz by employing axial strain as shown in Fig. 1.6 [31].

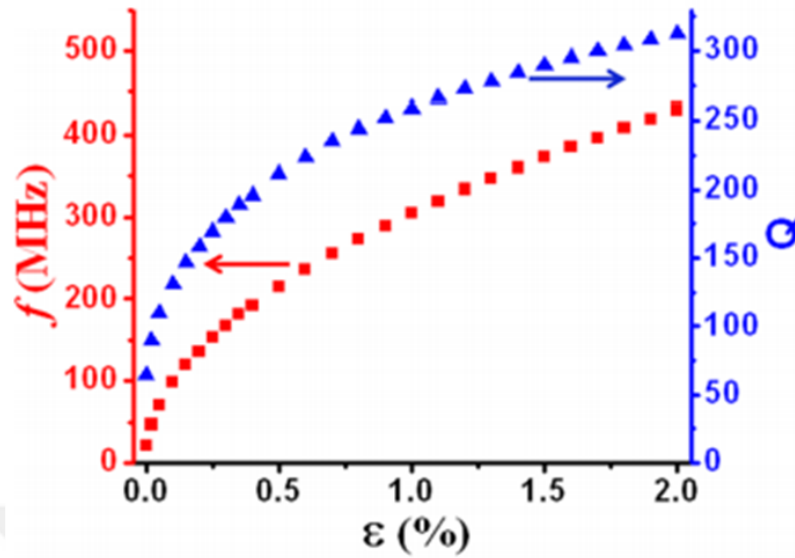


Figure 1.6: Frequency tuning by tension. Adopted from [31].

Verbridge *et al.* also reported an increase in both Q factor and resonance frequency of double clamped nanomechanical resonator with tensile stress. In their study, they induced tensile stress on mechanical resonator through controllable substrate bending which is similar to a method we employed for this study, and they claim to increase resonant frequency from 14.6 MHz to 35.5 MHz, shown in Fig. 1.7. They also stated that they achieved 390 000 Q factor at room temperature, Fig. 1.8. In addition, there are studies that reported an increase in torsional stiffness up to 26% [36-38].

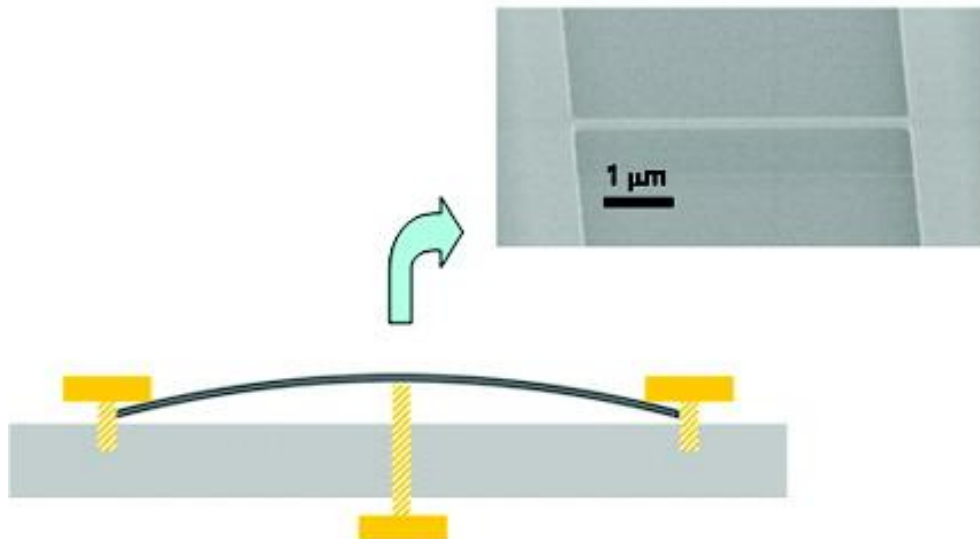


Figure 1.7: Substrate bending schematic. Adopted from [36].

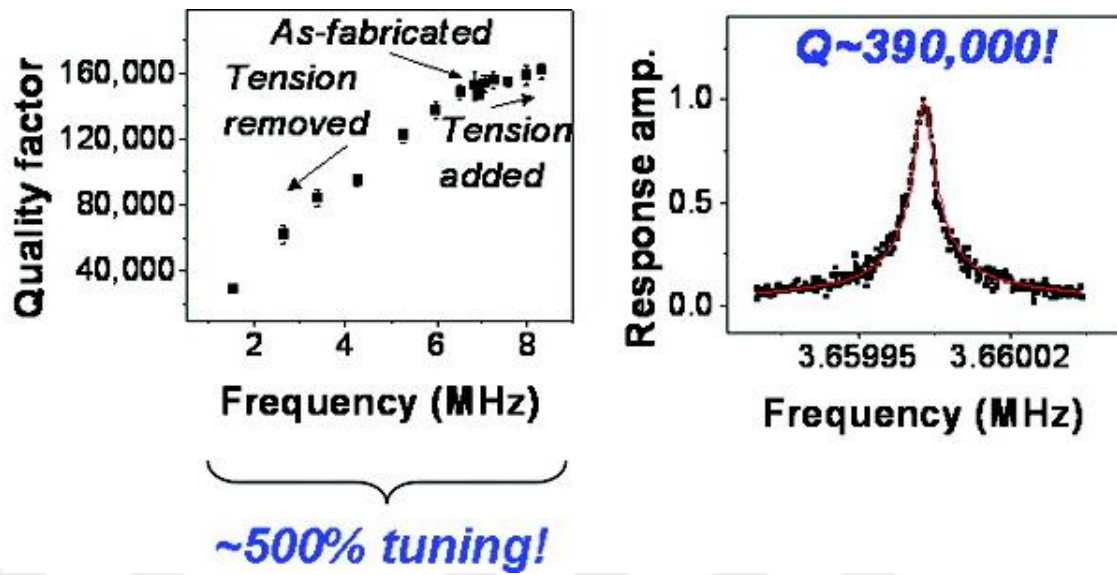


Figure 1.8: Frequency and Q factor change with tension. Adopted from [36].

1.2.3. Electrothermal Tuning

The main idea in electrothermal tuning is shifting resonance frequency by introducing thermal strain into system. The thermal strain is generated by an expansion or shrinkage of the mechanical resonator. Advantages of this tuning mechanism are easy to fabricate and low operating voltages. However, this technique suffers from high power consumption since electrothermal require high current [14, 39-41].

Jun *et al.* reported an electrothermal tuning method where a composite of Al-SiC double clamped nanomechanical resonator is actuated using magnetomotive technique. In addition to that a direct current is employed by 100 mV DC voltage to heat the resonator, shown in Fig. 1.9. Upon heating, the resonance frequency is abated. They also reported a 10% of frequency shift and 8% decrease in Q factor. Syms *et al.* reported that they achieved 6.5% resonance shift at 31 kHz. In another study, approximately 1.1% of frequency shift with 54mV is reported [40, 42-44].

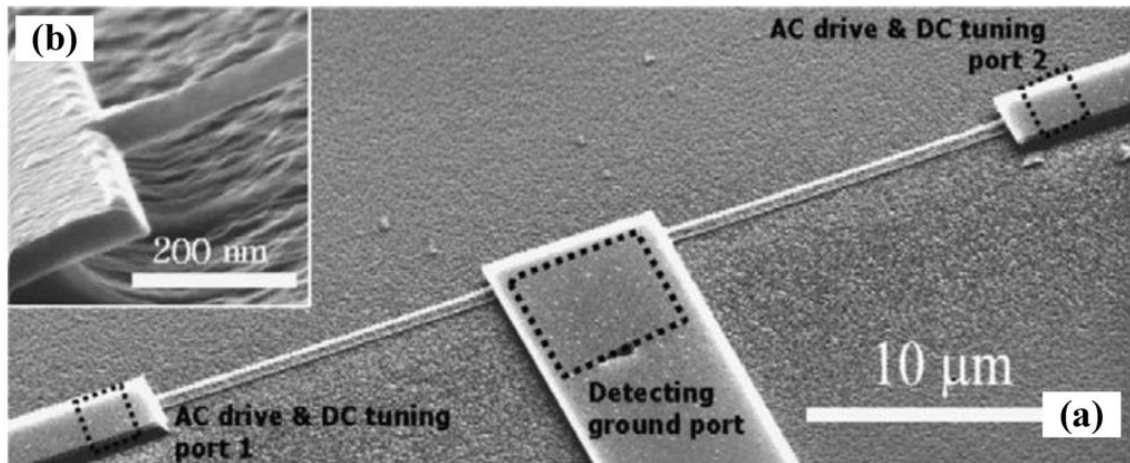


Figure 1. 9: a) SEM of a completed nano-mechanical resonator. The nanobeams with two AC driving and DC tuning ports and a detection port; (b) Close-up view of the suspended structure. Adopted from [1, 42]

1.2.4. Photothermal Tuning

Photothermal tuning is an optical technique where laser beam is used to induce thermal stress on mechanical resonator and shift the resonance frequency. Photothermal method can also be used to get information about resonator properties such mechanical and thermal. Being wireless and having high sensitivity makes photothermal tuning method suitable for measurement and tuning operation in liquid, gas, and vacuum[45-50].

There are several example studies reports a shift in resonance frequency as function laser power. Sampathkumar *et al.* reported a shift in resonance frequency as a function of laser power, shown in Fig. 1.10. Pini *et al.* claim to decrease the resonance frequency of bimetallic cantilever by %30 with laser beam that use for probing, shown in Fig. 1.11. They have also reported a non-linear behavior in resonance frequency shift. Kim *et al.* also reported an ample reduction in resonance frequency due to compressive stress that generated by the photothermal heat. As optical power is increased, a resonance frequency shift is observed due to thermal stress. Zhong *et al.* reported a resonance frequency shift by a tunable optical gradient force [19, 46, 51-53].

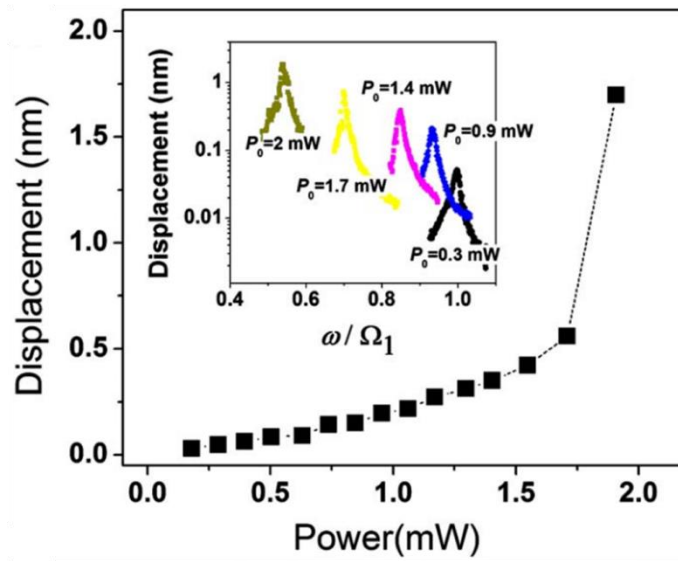


Figure 1.10: The frequency shift as functions of excitation power. Adopted from [19].

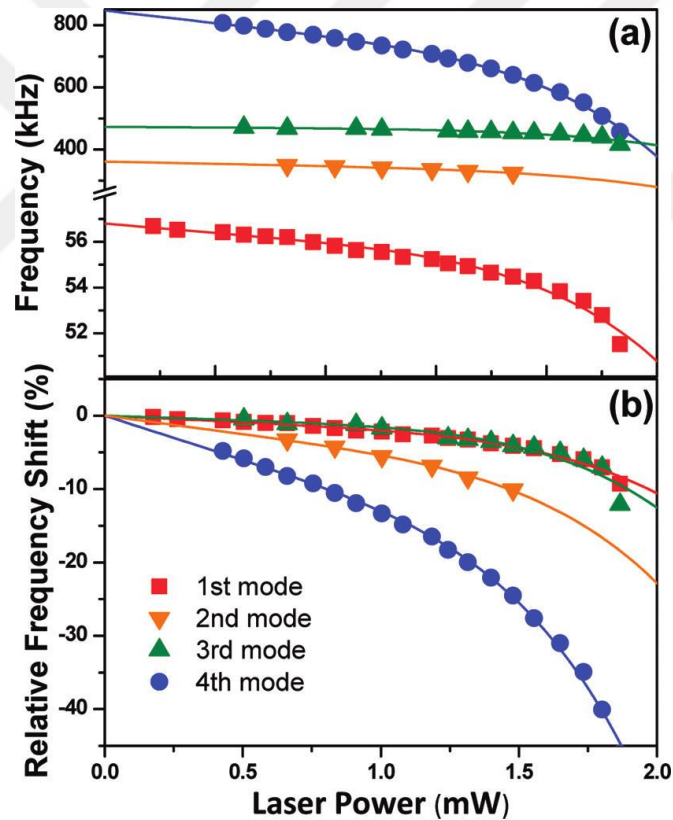


Figure 1.11: First four resonant frequencies of a microcantilever plate as a function of the laser power intensity; (a) the frequency values are shown, and (b) the relative frequency shifts are calculated with respect to the extrapolated frequency value at zero laser power intensity. Adopted from [46].

1.2.5. Magnetomotive Tuning

The magnetomotive technique is usually used as actuation and sensing purposes. However, it requires a strong magnetic field and subjected to eddy current damping. The principle behind the actuation is the varying current passing through conductive in magnetic field generates a Lorentz force, shown in Fig. 1.12. To realize this principle, there are many studies where the mechanical resonator made of dielectric materials are coated with conductive metals. There are very few examples where magnetomotive technique is directly used for a resonance frequency tuning. Generally the resonance frequency tuning is made by electrostatic scheme while the actuation is realized by a magnetomotive method [18, 54-57].

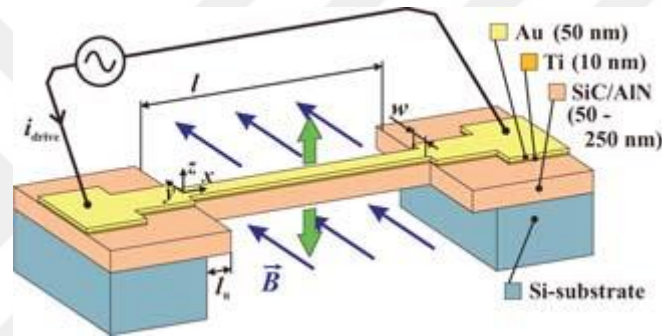


Figure 1.12: Scheme of a magnetomotively actuated beam resonator. The rf current through the top metallization of the beam generates an alternating Lorentz force. Adopted from [54].

Sunier *et al.* presented a cantilever resonator for magnetic field sensor. This sensor employs the Lorentz force and provides a shift in the resonance frequency. This mechanical sensor is embedded with current coil and by generating an electrical current through this coil, the Lorentz force is generated in presence of magnetic field. This Lorentz force acts as additional stiffness that similar to electrical stiffness that found in electrostatic scheme, and change effective stiffness of the system. Thus, causes a frequency shift in resonance frequency. They reported that they achieved 65 kHz/Tesla sensitivity with 0.025 Hz short term stability. Ohnishi *et al.* also reported a study where a cantilever resonator is tuned by using Lorentz force, shown in Fig.1.13. They claimed that they achieved 10-fold tunable spring constant which shifts the resonance frequency of the cantilever resonator from 1.1 kHz to 3.8 kHz [58, 59].

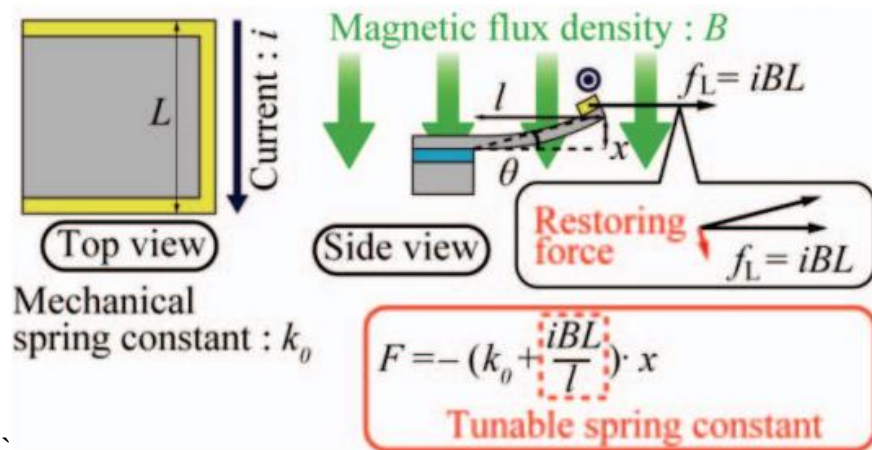


Figure 1.13: Concept of the spring constant tuning of a cantilever structure using Lorentz force. Adopted from [59].

Ekinci *et al.* demonstrated a magnetomotive tuning technique which is similar to our study in which we used magnetomotive technique for not only actuation but also for tuning purposes. In their study, they subjected a beam resonator to dc current and with additional varying force at resonance frequency. In the presence of magnetic field the beam resonator started to oscillate. Later, the dc force is increased by increasing dc current and resonance frequency shift is occurred, shown in Fig. 1.14 [60].

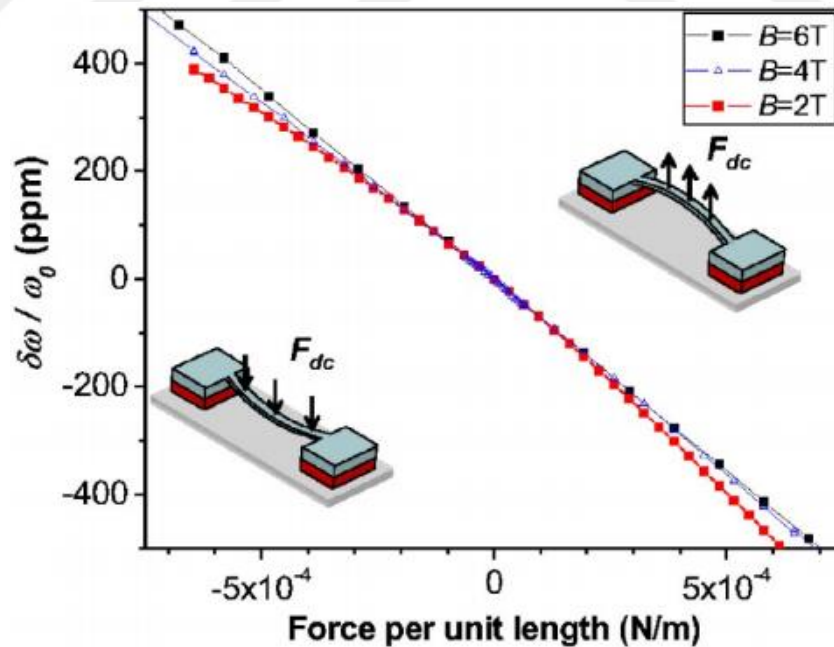


Figure 1.14: Frequency shift as a function of dc force. Adopted from [60].

1.3. Dissertation Outline

Having reviewed the literature of tuning mechanisms in this chapter, it is noted that there are very few example of a bi-directional resonance frequency tuning. In this study, a microfabricated mechanical resonator is bi-directionally tuned by, magnetomotive and tension-based, two active tuning mechanisms. The succeeding chapters are outlined as:

Chapter 2 describes Numerical and Finite Element Models that are used for calculation and verification in both magnetic and electrostatic actuation schemes. It also details and discusses case studies for electrostatic actuation and capacitive readout system.

Chapter 3 details the microfabrication process flow that used to fabricate micromechanical resonator, in steps. It also describes and provides solutions for problems that are faced in this fabrication process.

Chapter 4 explains the measurement setup, equipment, and the experiment parameters and procedure.

Chapter 5, the results of the experiment are presented and effects of the parameter are shown and discussed.

Chapter 6 concludes this thesis with the summary of the work that is accomplished and the findings of experiments and measurements.

Chapter 2

MODELING

2.1 Stress Modeling

The stress model is well establish in the literature since the stress can be found in micro and fabricated devices or it can be induced on the device by axial load for tuning purposes. For double clamped microbridges, the undamped vibration for small displacement can be described by the Euler-Bernoulli beam model:

$$EI \frac{\partial^4 w}{\partial x^4} - \sigma A \frac{\partial^2 w}{\partial x^2} = -\rho A \frac{\partial^2 w}{\partial t^2} \quad (2a)$$

with boundary conditions:

$$w|_{x=0,l} = 0 \text{ and } \frac{\partial w}{\partial x}|_{x=0,l} = 0 \quad (2a)$$

Where E : Modulus of elasticity; I : Moment of inertia; ρ Mass density; A : Cross sectional area; σ : Stress; w : resonator deflection profile; x : Coordinate along resonator such that $0 \leq x \leq l$, with l : resonator length; and t : Time.

Solution of the linear partial differential equation (2a) is the mode function of the resonator (3).

$$w(x) = c_1 \cosh(B\varphi) + c_2 \sinh(B\varphi) + c_3 \cos(D\varphi) + c_4 \sin(D\varphi) \quad (3)$$

where $\varphi: x/l$, ω : frequency; auxiliary functions B and D are given in Eqn. 4; c_1 , c_2 , c_3 and c_4 are mode shape constants.

$$B = \sqrt{\sqrt{\left(\frac{\sigma A l^2}{2EI}\right)^2 + \left(\omega l^2 \sqrt{\frac{\rho A}{EI}}\right)^2} + \frac{\sigma A l^2}{2EI}} \quad (4)$$

$$D = \sqrt{\sqrt{\left(\frac{\sigma A l^2}{2EI}\right)^2 + \left(\omega l^2 \sqrt{\frac{\rho A}{EI}}\right)^2} - \frac{\sigma A l^2}{2EI}}$$

The non-trivial solution of Eqn. 3 gives the transcendental equation (Eqn. 5). Solutions to Eqn. 5, ω are in turn modal frequencies under stress, for the first natural mode [9].

$$1 + \frac{\sigma A l^2 / 2EI}{\omega l^2 \sqrt{\rho A / EI}} \sinh(B) \sin(D) = \cosh(B) \cos(D) \quad (5)$$

S. Bouswtra *et al.* normalized this equation (Eqn. 5) as [61]:

$$\omega(\sigma) = \omega(0) \sqrt{1 + \gamma_n \left(\frac{\sigma A l^2}{12EI}\right)} \quad (6)$$

$$\omega(0) = \frac{4.73^2}{2\pi l^2} \sqrt{\left(\frac{EI}{\rho A}\right)} \quad (7)$$

where γ_n is the coefficient for contribution of stress to flexural rigidity and the value for γ_n is 0.2949 for the first natural mode.

2.2 Electrostatic Actuation – Capacitive Readout

The two-port resonator system is modeled with stress integrated (Fig. 2.1). A mechanical micro resonator is placed between two electrodes used as resonating structure under tensile stress. The Actuator electrode excites the DC biased resonator with electrostatic forces while the Readout electrode converts the displacement of the resonator into signal.

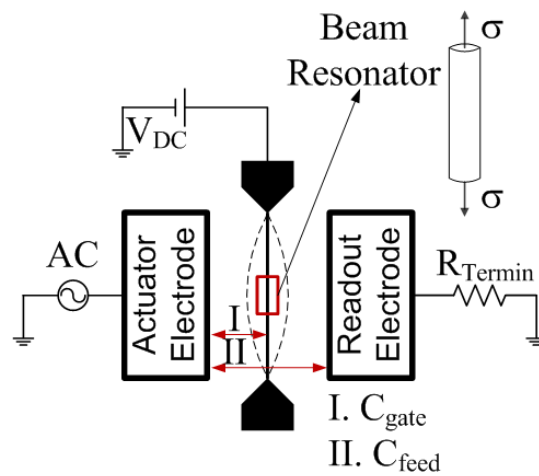


Figure 2.1: Schematic of Two port system. Adopted from [9].

The resonance frequency of the resonator under stress will differ from the natural resonance frequency. The resonance frequency as the following:

Firstly, constants of the mode function (Eq. 3) are determined by choosing c_2 as an arbitrary constant and rest are determined from the equations.

$$\begin{aligned} c_1 &= \frac{D \sinh(Bl) - B \sin(Dl)}{D \cosh(Bl) - D \cos(Dl)} & c_2 &= -1 \\ c_3 &= -c_1 & c_4 &= -\left(\frac{B}{D}\right) c_2 \end{aligned} \quad (8)$$

By numerical solution of the mode shape function (Eq. 3) natural resonance frequency of the resonator under axial load tensile load or stress is found. Instead of this another simplified equation (Eq. 6) can be used to find frequency of beam [61].

Secondly, the effective mass (m_{eff}) and the mechanical stiffness (k_{mech}) are determined with following equations [62]:

$$m_{eff}(x) = \frac{\rho A \int_0^l [w(x')]^2 dx'}{[w(x)]^2} \cong 0.396 m_{total} \quad (9)$$

$$k_{mech}(x) = \omega^2 m_{eff}(x) \quad (10)$$

m_{eff} and k_{mech} are calculated for $x=l/2$ since the maximum displacement would occur at the middle of the resonator. Note that due to presence of stress, k_{mech} is higher than the actual stiffness of the beam which comes from geometry and material properties.

Due to electrostatic attraction between actuation electrode and biased resonator, effective stiffness of the resonator (k_{eff}) of the system will be reduced. This is called “electrical softening” effect and the correlated electrical stiffness (k_e) is calculated as the following:

$$k_e = V_{DC}^2 \epsilon_0 W \int_0^l \frac{dx}{(d(x))^3} \quad (11)$$

$$d(x) = d_0 - \frac{1}{2} V_{DC}^2 \epsilon_0 W \int_0^l \frac{1}{k_{mech}(x') (d(x'))^2} \frac{w(x)}{w(x')} dx' \quad (12)$$

Where d_0 : Initial Gap between resonator and actuation electrode, W : Width of the resonator; V_{DC} : Bias Voltage applied on resonator; ϵ_0 : Permittivity of free space; and $d(x)$ is the gap between the resonator and electrode (Eq. 12) [62].

k_{eff} of the system will be sum of k_e and k_{mech} , and since k_e acts against k_{mech} , k_e will be deduced from k_{mech} as in the following equation (13) [62].

$$k_{eff} = k_{mech} - k_e \quad (13)$$

The new, softened frequency (ω_s) of the resonator due to reduction in k_{eff} can be calculated by substituting eq. (13) into eq. (10) as :

$$\omega_s = \sqrt{\frac{k_{eff}}{m_{eff}}} \quad (14)$$

2.2.1 Electromechanical Model

The two port system is modeled as equivalent circuit elements by using electromechanical analogy, including capacitance (C), inductance (L) and resistance (R) [62]. This equivalent circuit model is used for the determination of the resonance frequency of the system (Fig. 2.2).

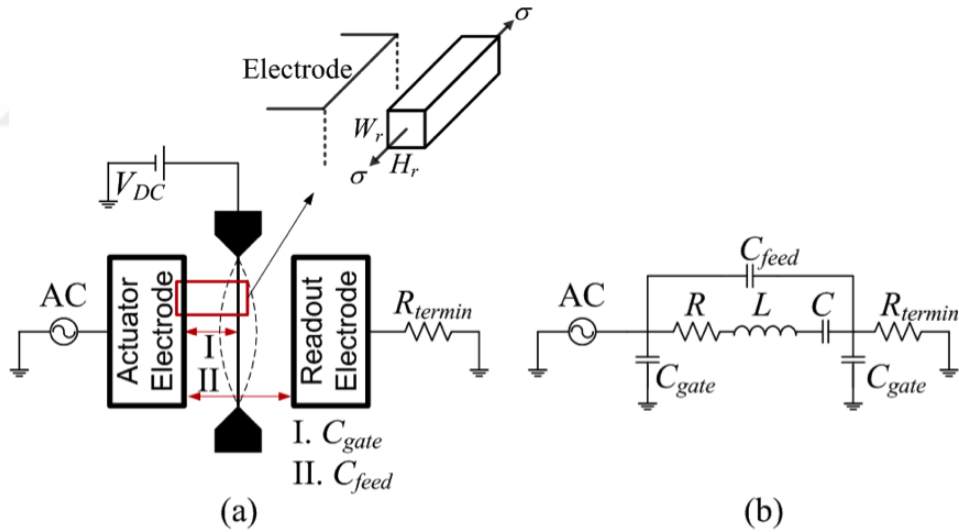


Figure 2.2: (a) Schematic of Two port system. (b) Equivalent circuit model of the system. Adopted from [9].

The Equivalent circuit elements and electromechanical transduction parameter (η) can be calculated by using following equations (15), (16). [62]:

$$\eta = V_{DC} \epsilon_0 W \sqrt{\int_0^l \int_0^l \frac{k_{R,c}}{k_{eff}(x')} \frac{1}{[d(x')d(x)]^2} \frac{w(x)}{w(x')} dx' dx} \quad (15)$$

$$L = \frac{m_{r,c}}{\eta^2} \quad C = \frac{\eta^2}{k_{R,c}} \quad R = \frac{\sqrt{k_{R,c}m_{r,c}}}{Q\eta^2} \quad (16)$$

Where Q : Unloaded Quality factor, $k_{R,c}$: k_{eff} at $x=L/2$, $m_{r,c}$: m_{eff} at $x=l/2$. In Fig. 2.2b, R , L , and C values represent the resonator while C_{gate} represent the capacitance between electrodes and the resonator, C_{feed} is a parasitic capacitance that caused by the cross-talking between read-out and actuation electrodes which obtained via COMSOL Finite Element Model (FEM), and R_{termin} is a termination resistor[9]. This equivalent electrical circuit model is simulated in LTSpice circuit simulation program and the results are verified by FEM analysis.

2.2.2 Finite Element Model

COMSOL Multiphysics software is used for conducting an electromechanical finite element analysis to verify LTSpice circuit simulation output and to determine the C_{feed} component of the equivalent circuit model.

2.2.2.1 Fringe Capacitance

C_{feed} is the total parasitic capacitance that two-port system has. But since electrodes and resonator have the same heights, the system does not have any feed through capacitance between electrodes and only have fringe capacitance.

For determination of C_{feed} capacitance, Electrostatic physics module is used. Simplified version of the two-port system is constructed as geometry (Fig.2.3 (a), (b)). Later the materials are defined. The device layer is chosen as Si while the seed layer is chosen as SiO_2 . The structure is meshed by using COMSOL physics-controlled mesh generator for “extra fine” size and with free tetrahedral type mesh.

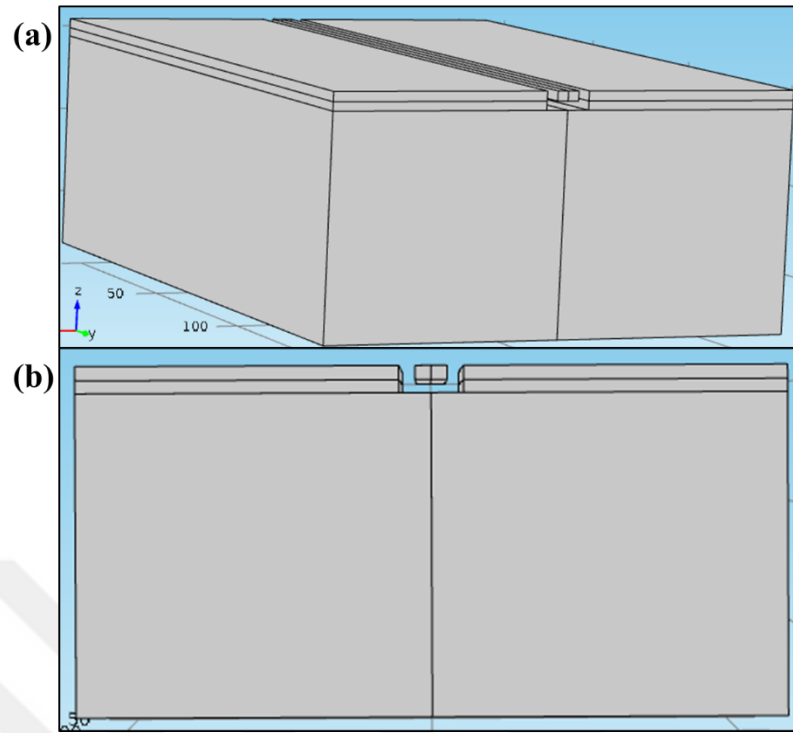


Figure 2. 3: Constructed geometry (a) Isometric view. (b) Front view.

Boundary conditions are Terminal, Ground, Floating Potential and Zero Charge. Electrodes and the substrate are selected as terminal boundary (Fig. 2.4) while the resonator and seed layer is selected as ground boundary.

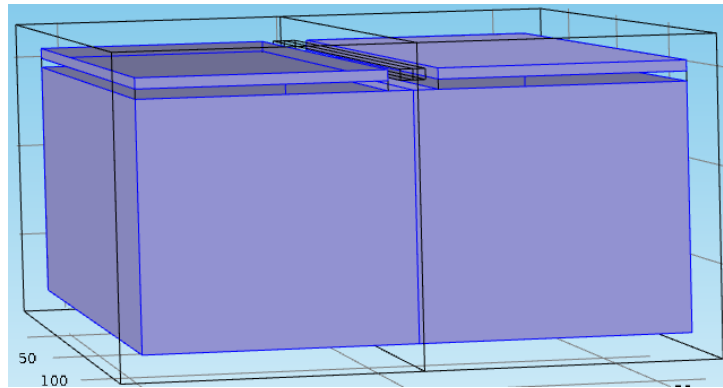


Figure 2.4: Terminal Boundary.

The air has two type boundaries which are zero charge and floating potential. The analysis is conducted for both boundaries. Because the zero charge boundary implies the electrical field line are tangential to boundary while the floating potential boundary implies the electrical field line are perpendicular to boundary. And both of these boundaries would converge to each other as the air field is increased. Therefore, the actual C_{feed} would be the half of the sum of the obtained values.

2.2.2.2 Electromechanical Model

The electromechanical model is established in COMSOL to verify the LTSpice output. For this simulation, Electromechanical Physics module is employed. The geometry is simplified to one electrode and resonator (Fig. 2.5). The mesh is construed by using COMSOL physics-controlled mesh generator for “extra fine” size and with free tetrahedral type mesh.

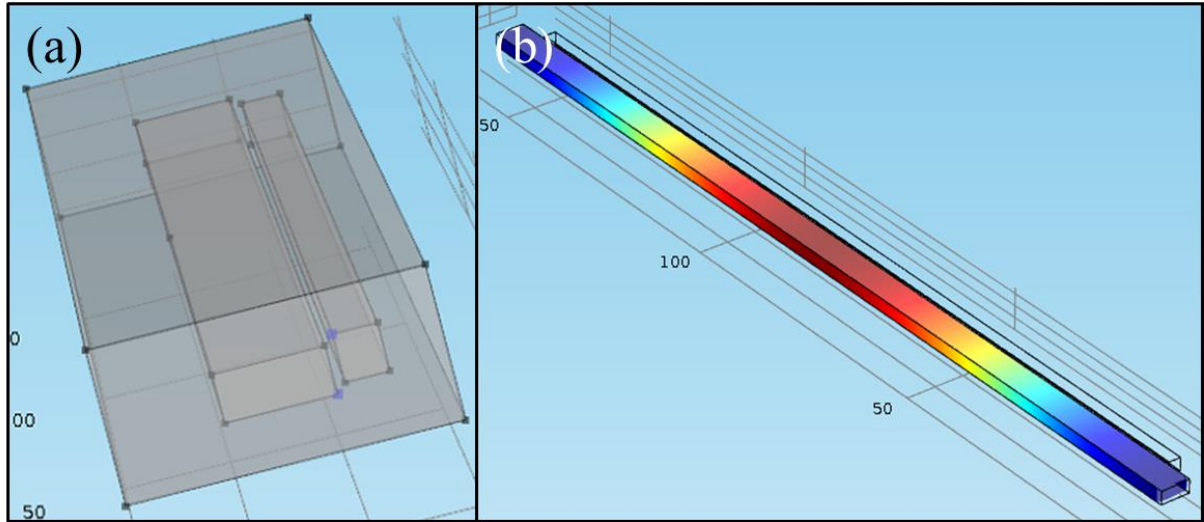


Figure 2.5: Constructed geometry (a) Isometric view (b) solution view.

The boundary conditions are Terminal boundary with sub boundary of Harmonic Perturbation, Ground, Fixed mesh, and sub domain boundary Initial Stress and Strain. As in the Fringe Capacitance analysis, electrodes are selected as terminal boundary with sub boundary of Harmonic Perturbation while the resonator is selected as ground. V_{DC} voltage is defined in terminal boundary while the V_{AC} is defined in Harmonic Perturbation boundary. The fixed mesh boundary used on electrode to reduce computational weight since there will not be any deformation on electrode. Lastly, the initial stress and strain domain boundary used on resonator and the stress is defined along the longitudinal direction of the resonator, only.

2.2.3 Case Studies and Verification

Some case studies are defined in Table 2.1. These case studies are simulated in order to determine the effects of the parameters on the output. Case Study #1 is a specific resonator system which is polysilicon double clamped resonator with two-port system, published in [63]. This system specification is used in this proposed equivalent circuit methodology and

obtained R, L, C values are implemented in LTSpice simulation (Fig. 2.6(b)) to determine the output of the system. Obtained results are plotted in (Fig. 2.6(c)) as a function of stress. Analytical and computational results agree with error less than 0.5% which verifies the accuracy of the proposed model.

Case Study #	1	2	3	4	5	6
Beam Length, L_r (μm)	40	50	40	40	40	40
Beam Width, W_r (μm)	2	2	2.5	2	2	2
Beam Height, H_r (μm)	8	8	8	10	8	8
Electrode-to-Beam Gap, d_0 (μm)	0.1	0.1	0.1	0.1	0.125	0.1
Bias Voltage, V_{DC} (V)	7	7	7	7	7	10
Unloaded Quality Factor, Q	3600					
Feed Through Capacitance, C_{feed} (fF)	88.3	1110	87.6	105	75.5	8.83

Table 2.1: Case Studies. Adopted from [9].

Case Study#1 is used as base design for the other case studies by changing one parameter at a time (Table 2.1). Each case is simulated with stress up to 1GPa which can assume to be reasonable limit for Si resonators. While Q is kept constant for all cases and C_{feed} values are determined by FEM as mention previous section. R, L, and C values are determined for all cases and simulated in LTSpice simulation program. The S_{21} parameter is obtained as output. These outputs are plotted in Fig. 2.7, where the progression of the resonance frequency and quality factor is observed as function of stress.

The effects of the parameter can be easily observed for the stress-free frequency. For instance, when the Case Studies #2 and #3 compared with Case Study #1, the change in k_{mech} of the resonator due to L_r and H_r can be observed by the variation of resonance frequency (Fig. 2.7 (b), (c)). As the length increases, k_{mech} decreases (Fig. 2.7(b)). On the other hand, increase in height increases the k_{mech} as well as the resonance frequency (Fig. 2.7(c)).

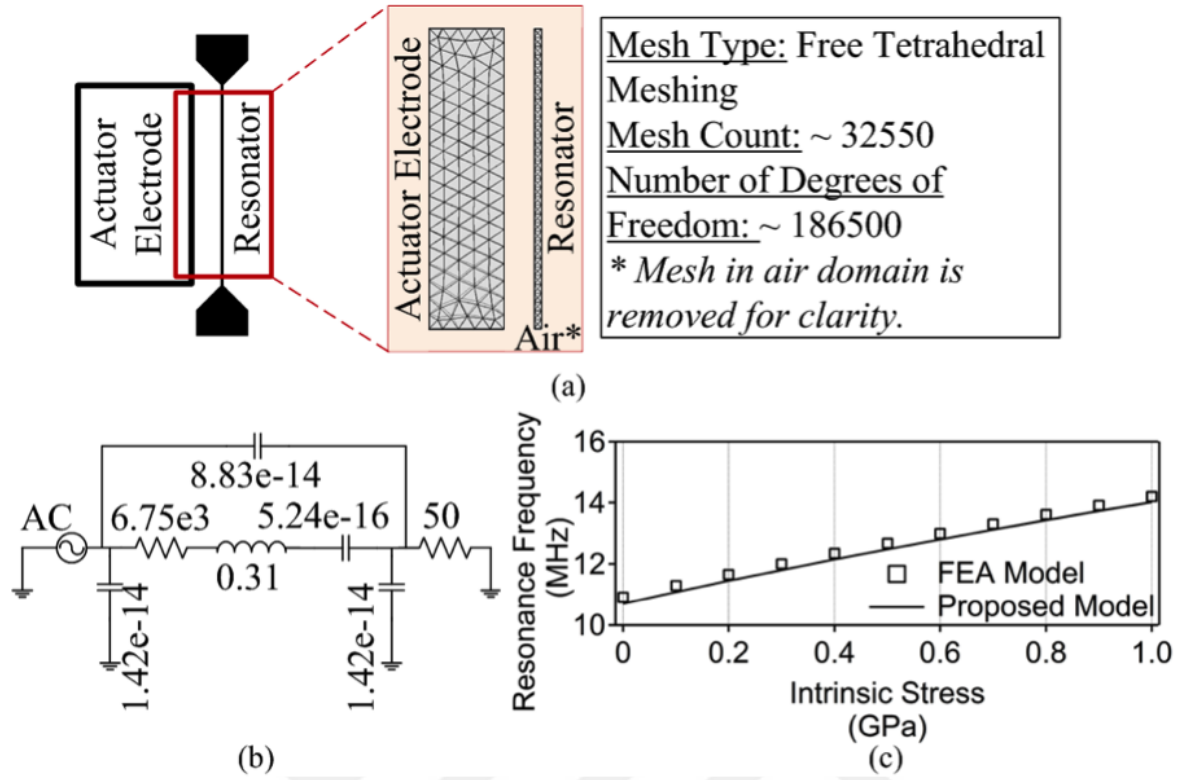


Figure 2.6: (a) COMSOL Multiphysics® model, (b) LTSpice IV model of the equivalent circuit as proposed in this work (Numerical values are given for 0.5 GPa. Respective units in Ω , H, F), (c) First-mode resonance frequencies as a function of intrinsic stresses obtained through finite element analysis (FEA) and the proposed model of this work . Adopted from [9].

Nevertheless, variation in width of resonator or gap between electrode and resonator, or bias voltage directly change k_e . For example, in Fig. 2.7(d) and (f), the resonance frequency decreases due to increase in width and bias voltage respectively which directly increases k_e and decreases k_{eff} of the system. On the other hand, increase in gap between electrode and resonator causes a decrease in k_e which increase k_{eff} and resonance frequency (Fig. 2.7(e)).

When the evolution of the resonance frequency is observed as function of stress, it can be seen that resonance frequency increases with stress. The reason is that the stress contributes the modal stiffness of the resonator. The escalation in resonance frequency is found to be 20% in Case Study #3 and 30% in Case Studies #1, 4 and 5, and 50% in Case Study #2 when stress-free and 1GPa stress situations are compared.

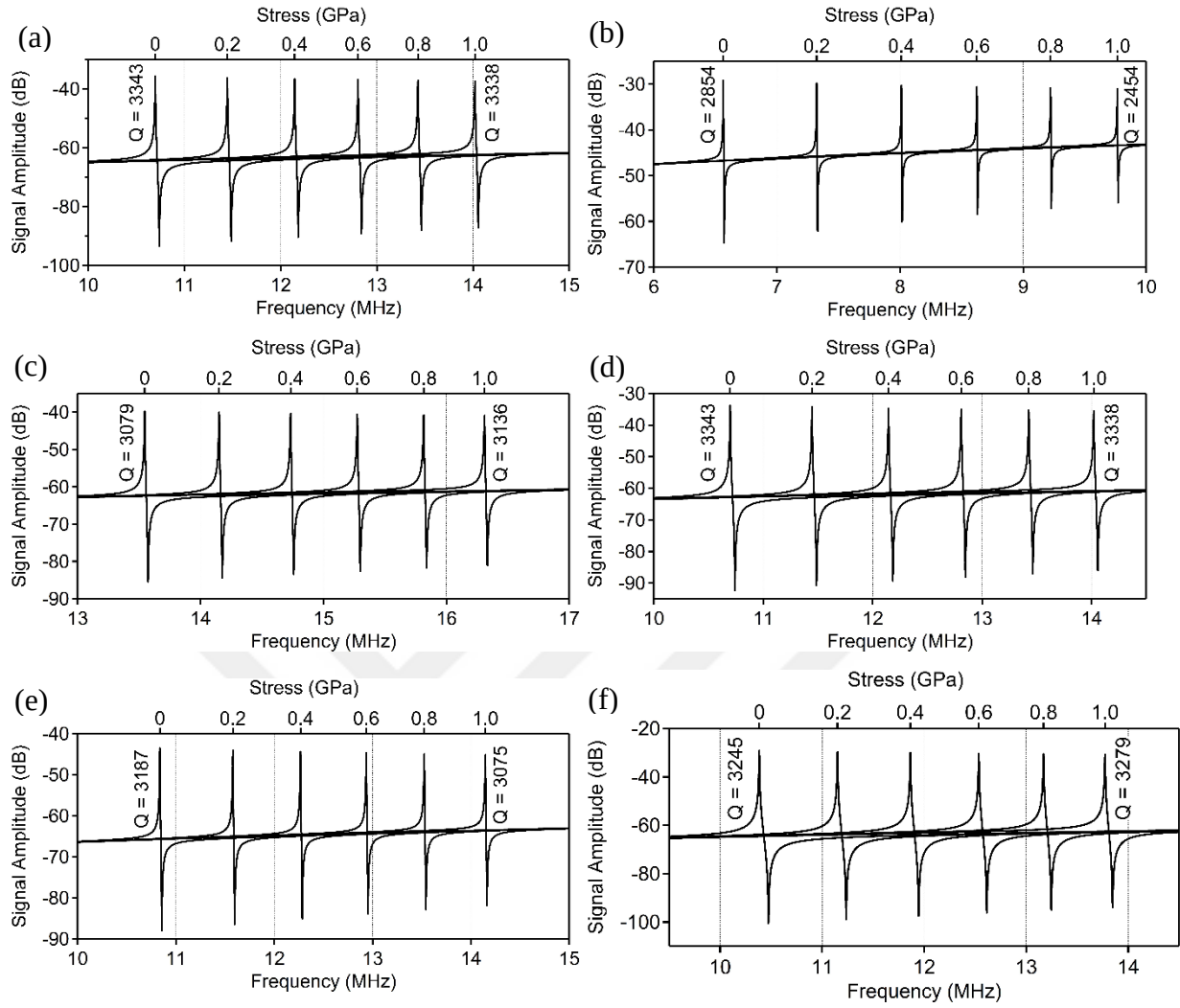


Figure 2.7: Signal response as a function of stress (a) Case Study #1, (b) Case Study #2, (c) Case Study #3, (d) Case Study #4, (e) Case Study #5, (f) Case Study #6 . Adopted from [9].

In addition, Q factor is reduced from the unloaded value of 3600 due to existence of anti-resonance peak. Although there is a reduction in Q factor, in overall situation Q factor does not change significantly with stress for any cases except for Case Study #2 (Fig. 2.8). In Case Study #2, Q factor shows a decreasing trend as the stress increases. This trend contradicts the reported studies in literature where increase in Q factor with the stress [36]. If one looks closely to case studies, one would see that the C_{feed} parameter stands out in Case Study #2, which is much higher than the rest of the C_{feed} in other studies. If Fig. 2.2(b) is reinvestigated, it can be seen that C_{feed} is in parallel to R, L, and C parameter of the resonator, and as C_{feed} increases, the impedance of this parasitic branch of the circuit decreases. Reduction in the impedance of the parasitic branch increases the power consumed on the parasitic branch while decreasing the output power of the resonator. Since the Q factor is the ratio of the Output Power and Total

Consumed Power, increase in C_{feed} decreases Q factor. However, this does not explain the decrease in Q factor as function of stress since C_{feed} is independent of stress.

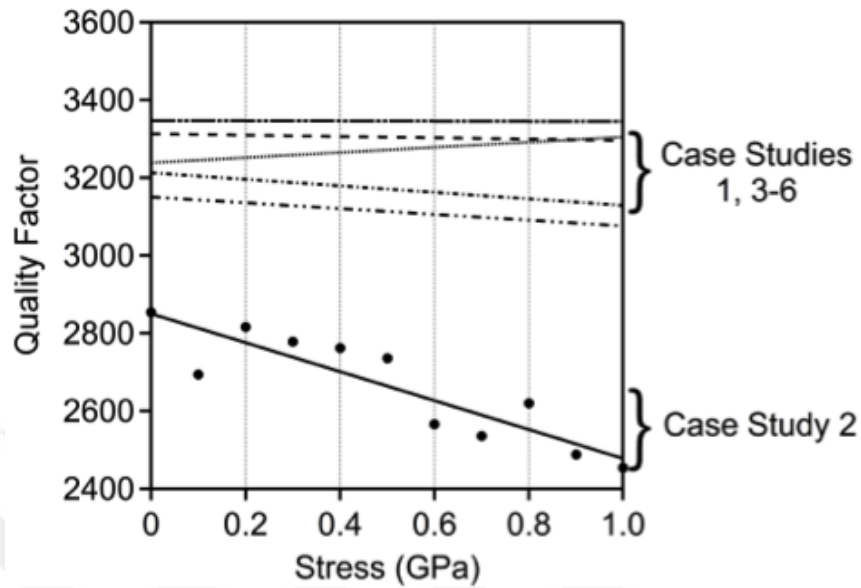


Figure 2.8: Q Factors of case studies. Adopted from [9].

The actual reason for reduction in Q factor along stress can be interpreted from Figure 2.9. Figure 2.9 demonstrate stress dependence of R, L, and C values for Case Study #2. As it is seen; R parameter increase with the stress and since R parameter is the dominator impedance of the Resonator branch, it increases the equivalent impedance of the resonator branch. This raise in the impedance causes the decrease in the power directed on the resonator branch.

If the C_{feed} value is increased for other case studies, the similar abate in Q factor can be observed. For instance, C_{feed} value of the Case Study #1 is increased from 88.3fF to 1.11pF and similar deterioration is observed in Q factor (Fig. 2.10).

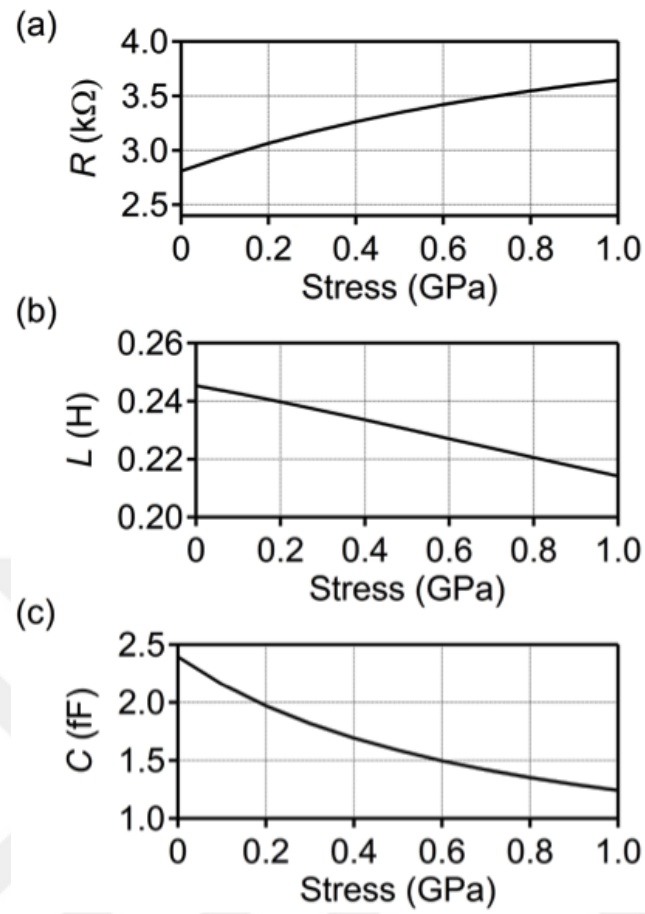


Figure 2.9: Stress dependence of R , L , and C parameters for Case Study #2. Adopted from [9]

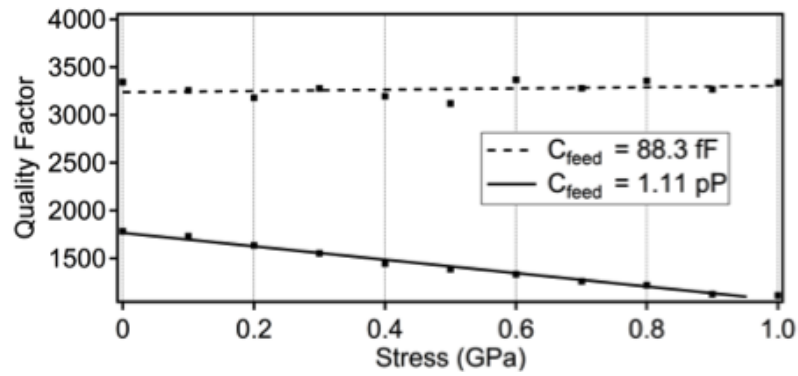


Figure 2.10: Q factor behavior of Case Study #1 with regular and increased C_{feed} . Adopted from [9].

2.3 Magnetic Actuation – Optical Readout

A MEMS chip that contains a released beam resonator is placed in magnetic field (B). A small sinusoidal current flow (i_{ac}) and (i_{dc}) are introduced to resonator in order to resonate the resonator and tune with a magnetomotive force (Fig. 2.11). MEMS chip is also bent with help of screw to induce a stress on the resonator (Fig. 2.12). And a Laser Doppler Vibrometer is used to measure the resonance.

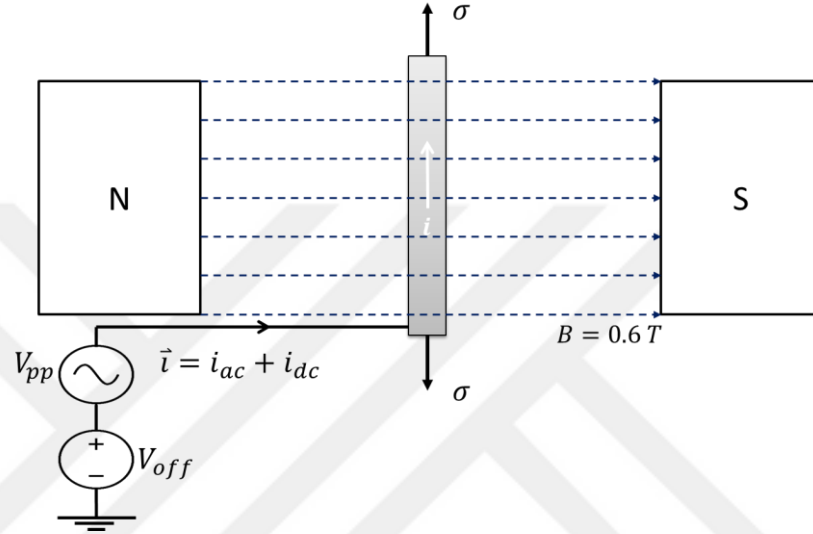


Figure 2.11: Schematic of the actuation system

Stress induce on resonator through bending is obtained by the following Eqn. (17) which is driven from Equation (6). Since the nominal natural frequency ($\omega(0)$) is known and $\omega(\sigma)$ is measured, the stress introduced into system and strain applied on resonator is found by using Eq. (17).

$$\sigma = \frac{12EI \left(\left(\frac{\omega(\sigma)}{\omega(0)} \right)^2 - 1 \right)}{\gamma_n A l^2} \quad (17)$$

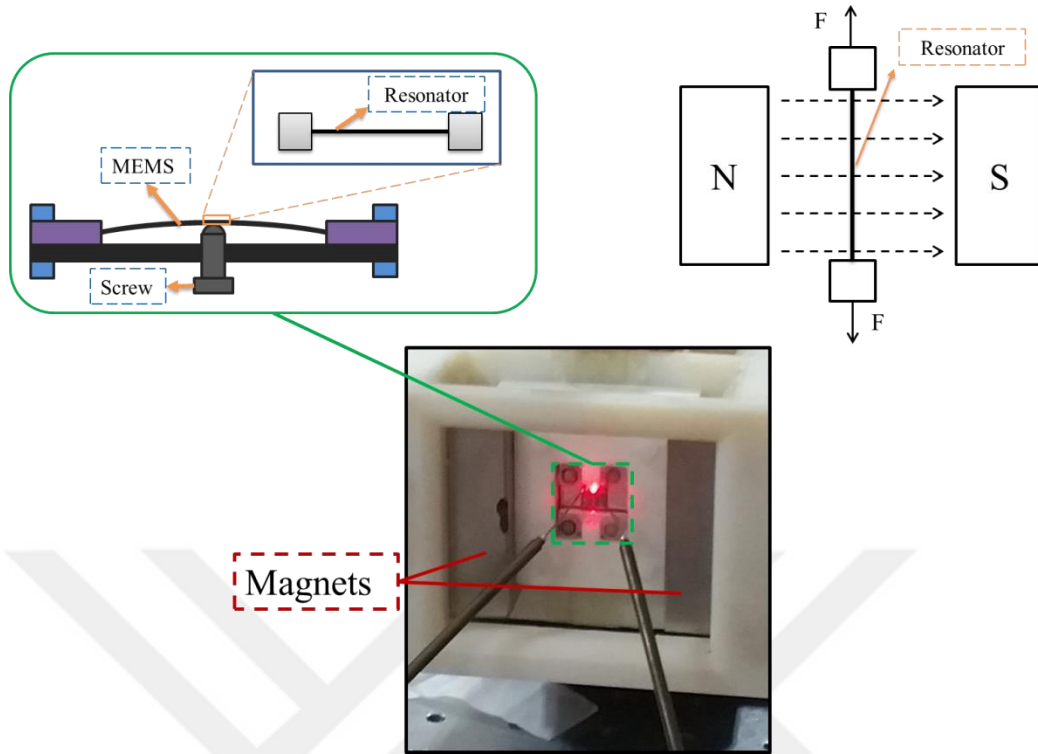


Figure 2.12: Schematic of bending and actuation.

When i_{dc} component is introduced into the system with i_{ac} component the resonance frequency decreases due to softening effect that is similar to electrical softening mentioned in Electrostatic Actuation section. The reason of this reduction is known to be decrease in k_{eff} of the system. For known resonance frequency k_{eff} can be calculated as the following:

$$k_{eff} = \omega_s^2 m_{eff} \quad (18)$$

$$m_{eff} = 0.396 m_{total} \quad (19)$$

The magnetic softening stiffness (k_{ms}) that is occurred due to presence of i_{dc} component is calculated by Eq. (20):

$$k_{ms} = k_{mech} - k_{eff} \quad (20)$$

Where k_{mech} can be obtained for zero or more stress and strain values from the measured frequency of experiments which only actuated by a small i_{ac} current without i_{dc} component. In that case k_{mech} would be equal to k_{eff} and they can be calculated by using Eq. (18).

Oscillation amplitude (x_d) is very critical to establish a linear response. The oscillation amplitude must be smaller than the critical drive amplitude (x_c). x_c amplitude for double clamped beam can be calculated with the following Eqn. (21).

$$x_c = \sqrt{\left[\frac{2}{0.528Q(1 - \vartheta^2)} \right]} t \quad (21)$$

Where Q is the Q factor, ϑ is the passion's ratio, and t is the thickness of the resonator. x_d can be calculated from the measured data with the following equation.

$$x_d = \frac{v}{2\pi\omega} \quad (22)$$

Where v the velocity is measured, and ω is the resonance frequency of the resonator.

2.3.1 FEM Analysis

Two different FEM analyses are conducted. One of them for verification of stress induced resonance frequencies. While other one is used for observing the modal frequency of whole chip and the stress variation on the resonator.

2.3.1.1 Stress and Strain Resonance Frequency Analysis

In this model, a basic 3D bulk beam is constructed (Fig. 2.13) and Solid mechanic module physics is used. The study type is chosen as “eigenfrequency”. Boundary conditions are Fixed Constrain and Prescribed Displacement. One end of the beam is selected as fixed constrain boundary while other end selected as prescribed displacement boundary.

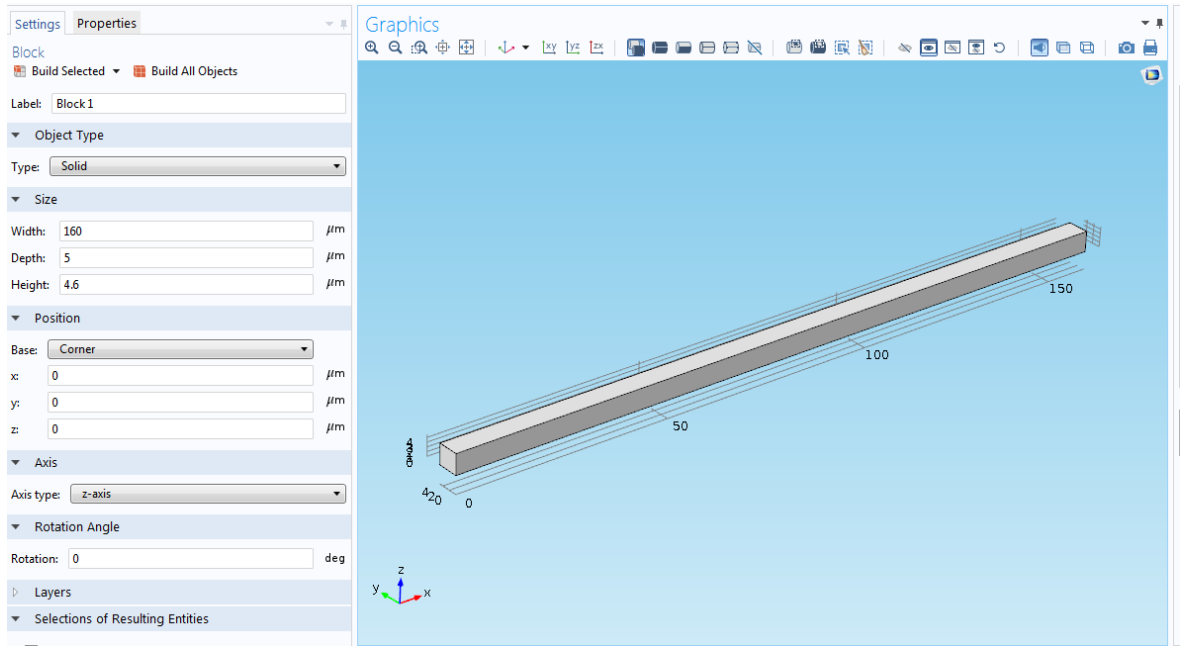


Figure 2.13: Isometric view of constructed geometry

Later, prescribed boundary defined as parameter in direction of longitudinal of the beam. Note that, in prescribed displacement boundary, rest of the other direction displacements must set to “0”. Then Analysis is simulated with parametric sweep and the results are obtained for series of strain values (Fig. 2.14).

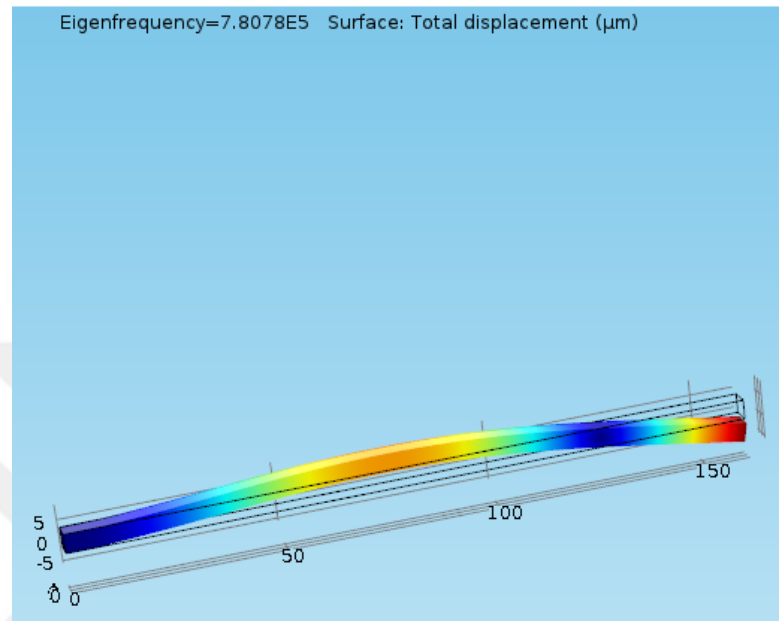


Figure 2.14: Solution of the analysis

2.3.1.2 Modal Analysis and Bending Simulation

In this model, whole MEMS chip is constructed in COMSOL (Fig. 2.15). In this simulation, two studies are computed. The first one was conducted to see the stress gradient on the resonator while the second one was conducted to observe modal frequencies of the whole MEMS chip. Both simulations are computed in the same model with two different studies. Both simulations have same boundary conditions expect the first simulation has an extra Prescribed Displacement boundary condition to simulate screw (Fig. 2.17).

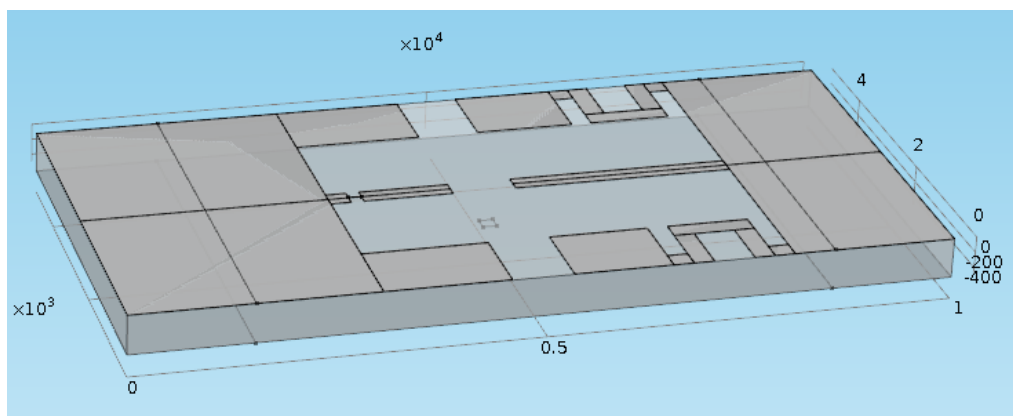


Figure 2.15: Isometric view of constructed geometry

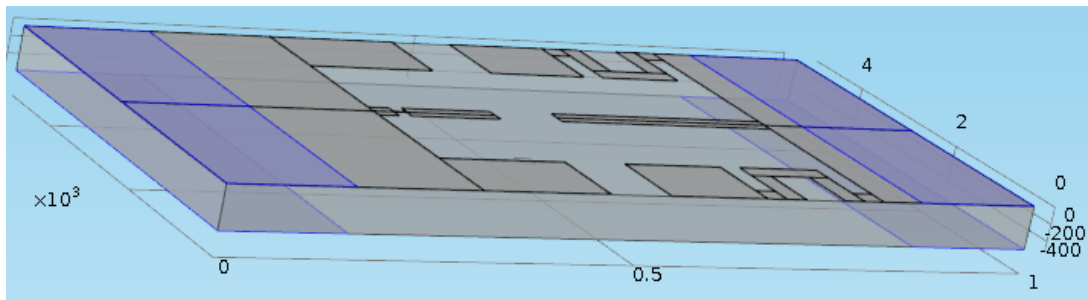


Figure 2.16: Fixed Constrain Boundaries

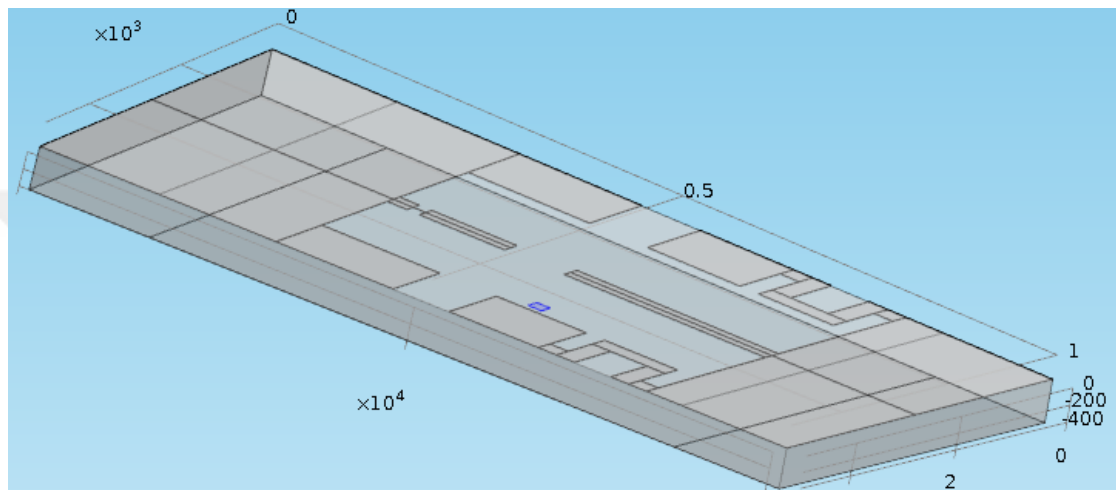


Figure 2.17: Prescribed Displacement Boundary

The first study is computed with stationary step. Results show that there is not any significant stress gradient along the resonator (Fig. 2.18). If we look closely to cross section of the resonator at different location, it can be seen the von mises stress value does not differ too much (Fig. 2.19-21).

The second study is computed with Eigen frequency step. The results show that there are a few whole structure modes where the resonator also resonates with the structure which may cause error in measurement (Fig. 2.22-24).

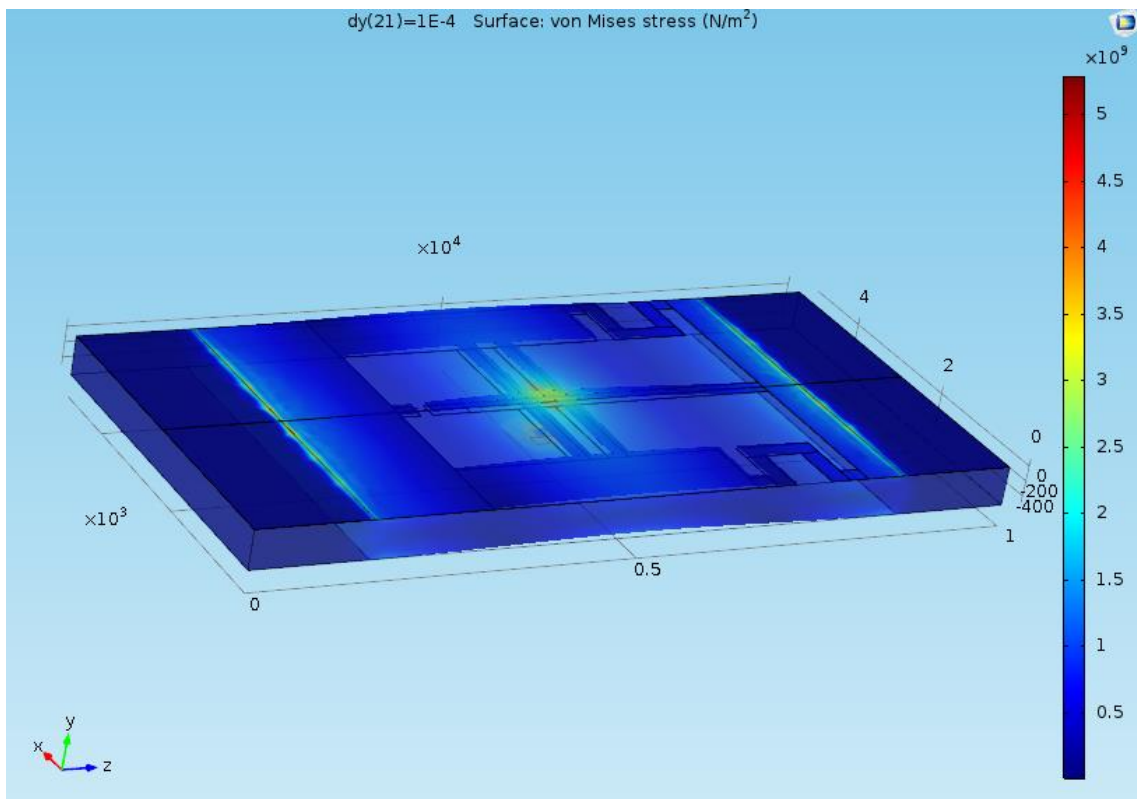


Figure 2. 18: Von Mises Stress of the bended structure.

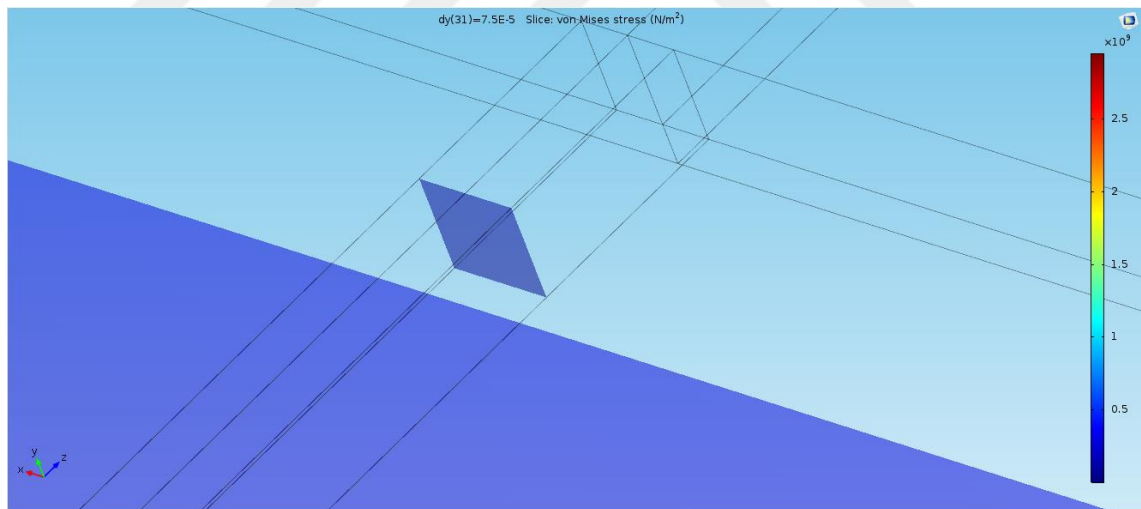


Figure 2.19: Von Mises Stress of the cross-section of the beam.

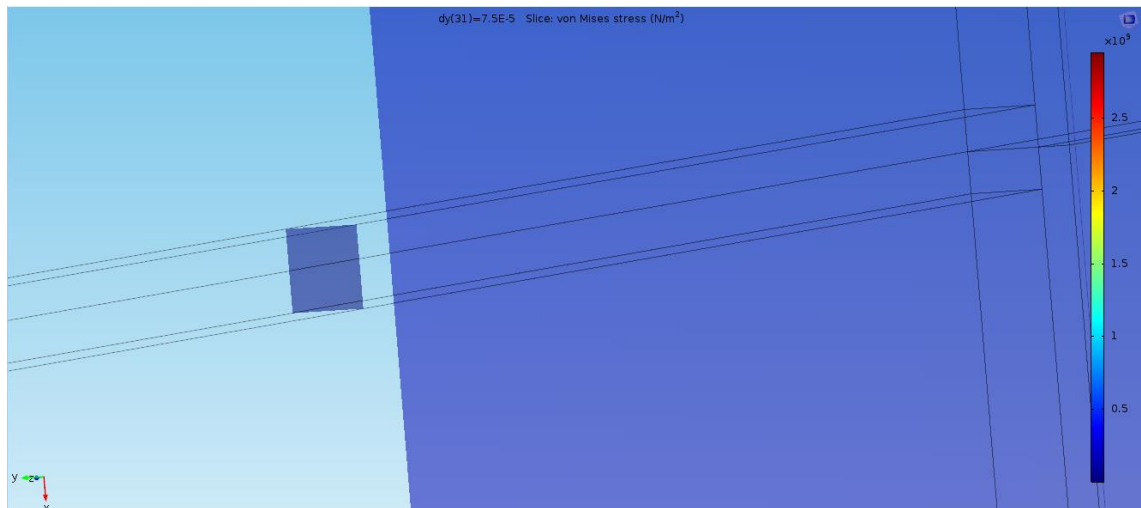


Figure 2.20: Von Mises Stress of the cross-section of the beam.

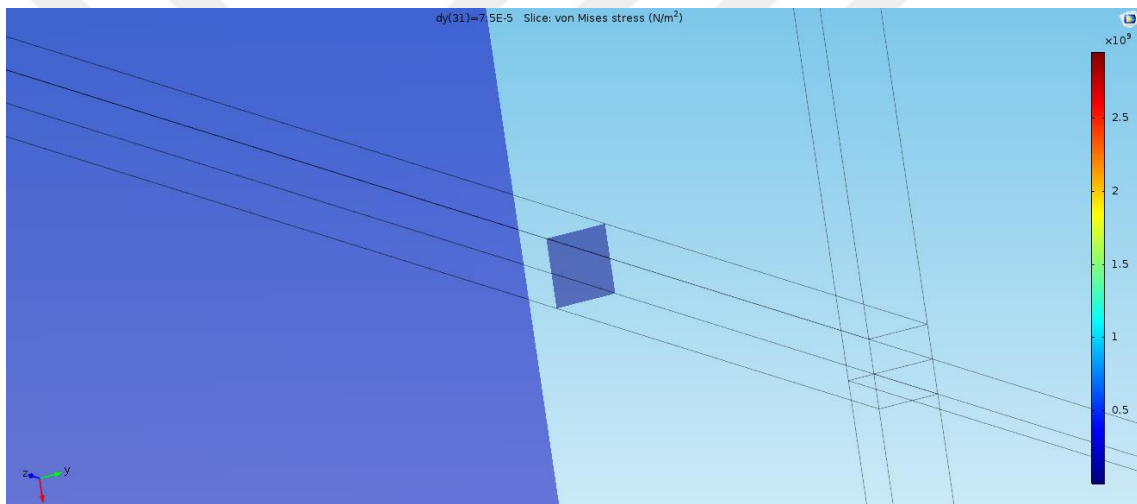


Figure 2.21: Von Mises Stress of the cross-section of the beam.

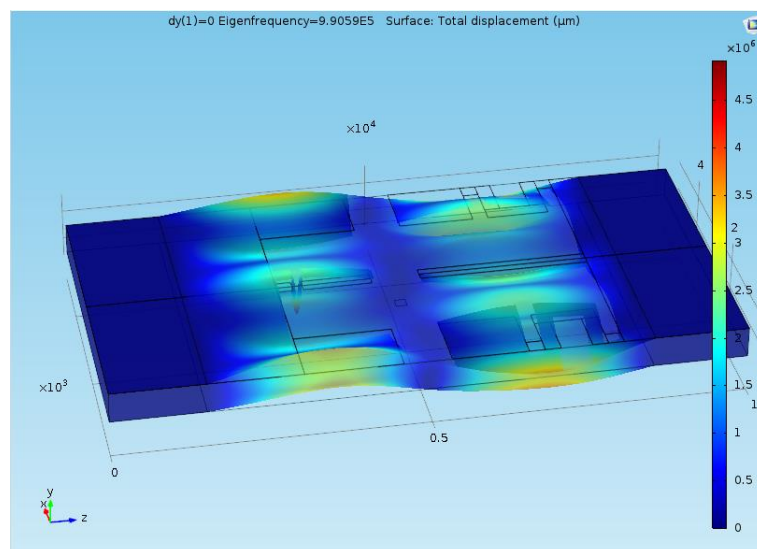


Figure 2.22: Eigen Mode of MEMS Chip

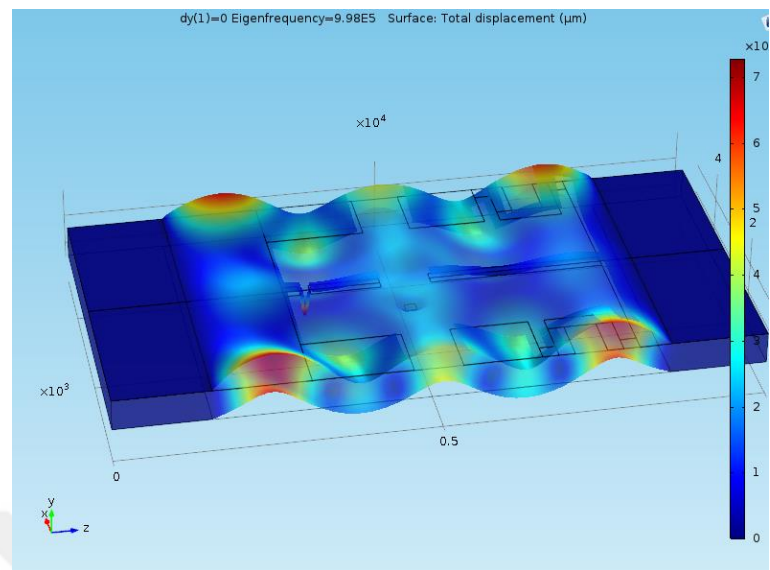


Figure 2.23: Eigen Mode of MEMS Chip

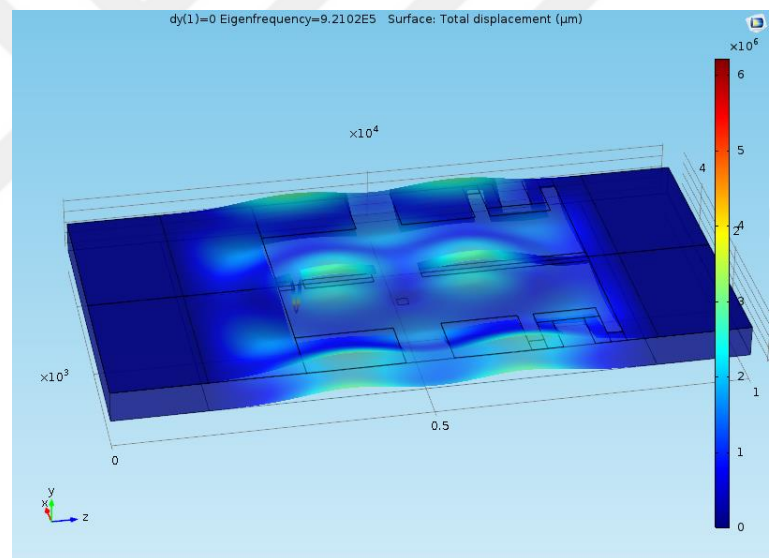


Figure 2.24: Eigen Mode of MEMS Chip

Chapter 3

FABRICATION

3.1 Fabrication Process Flow

Fabrication process flow is designed accordingly to infrastructure and material that our Clean Room contains. Fabrication process flow is initially design for the MEMS with Electrostatic Actuation – Capacitive Readout. Unfortunately, due to alignment problem we faced in the process we could not accomplish our goal and have to switch Magnetic Actuation – Optical Readout. For this system the fabrication process flow is simplified by removing alignment and some other steps. Fabrication process flows are demonstrated in Figure 3. 1-2. both fabrication flows contain similar steps, expect fabrication process flow Electrostatic Actuation has more steps and contain RIE and alignment steps. There may be some difference in the material used in both Fabrication process flows. These differences will be detailed in the step description. The specifications of the Silicon (SI) wafers used in the fabrication process are listed in Table 3.1.

Diameter	100 mm
Orientation	(100)
Doping type	P-type (Boron)
Resistivity	0 – 300 Ωcm
Handle layer thickness	500 $\pm$ 25 μm
Surface	SSP (Single Sided Polished)

Table 3.1: Specifications of the SI wafers are used in fabrication.

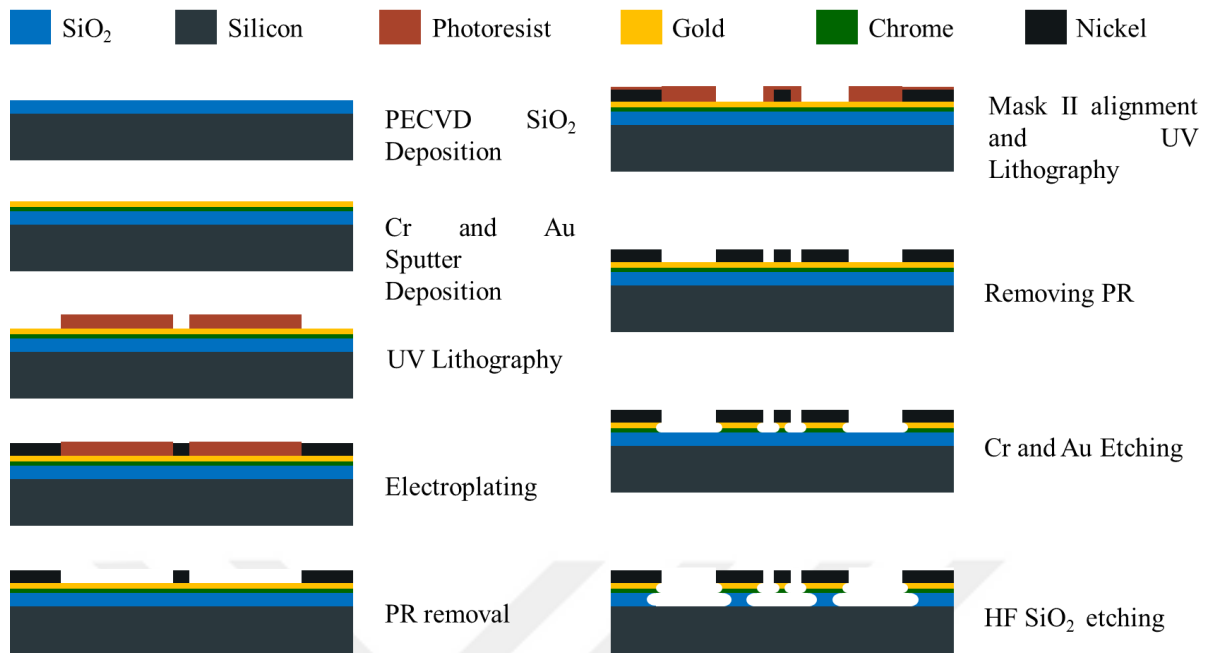


Figure 3.1: Fabrication Process Flow for Electrostatic Actuation and Capacitive Readout.

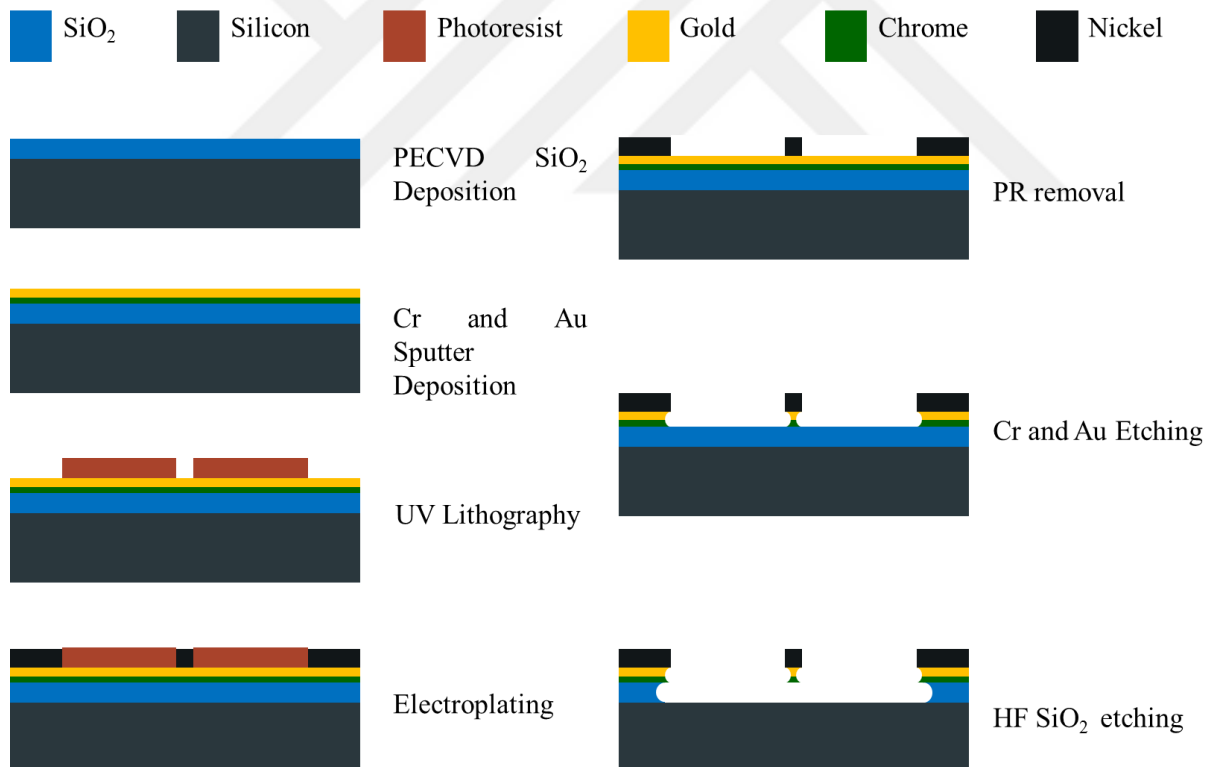


Figure 3.2: Fabrication Process Flow for Magnetic Actuation and Optical Readout.

3.1.1 Seed Layers Deposition

The first step of the process is coating SI wafer with silicon dioxide layer (SiO_2). This step is executed in Sabanci University Nanotechnology Research and Application Center (SUNUM) by using Plasma-enhanced chemical vapor deposition (PECVD) technique. The

coated SiO_2 layer has thickness of $2\mu\text{m}$ and the deposition rate was 75nm/min and total process took approximately 30 min. This step is required for releasing beam resonator. In contrast to cantilevers, beam structures could not be released with KOH etching due to directional etching of SI substrate. Therefore, an additional Seed layer is required to release the beam structure and that layer is SiO_2 . Moreover, SiO_2 employed as insulator for the electrodes in the Electrostatic actuation system.

The second step of the process sputter deposition of Chrome (Cr) and Gold (Au) layers. This step is executed in Koc University Clean Room by using Physical vapor deposition (PVD) technique. The deposition process was executed in room temperature. Cr and Au layers are required seed layers for Electroplating of Nickel (Ni). In this case, Cr layer has thickness of $\sim 20\text{nm}$ and it is required for bonding between Au and SiO_2 layers. It enhances the adhesion of the Au layer. On the other hand, Au layer has thickness of $\sim 120\text{nm}$ and it is required for conducting electrical current that is essential for electroplating deposition of the nickel.

3.1.2 Photolithography

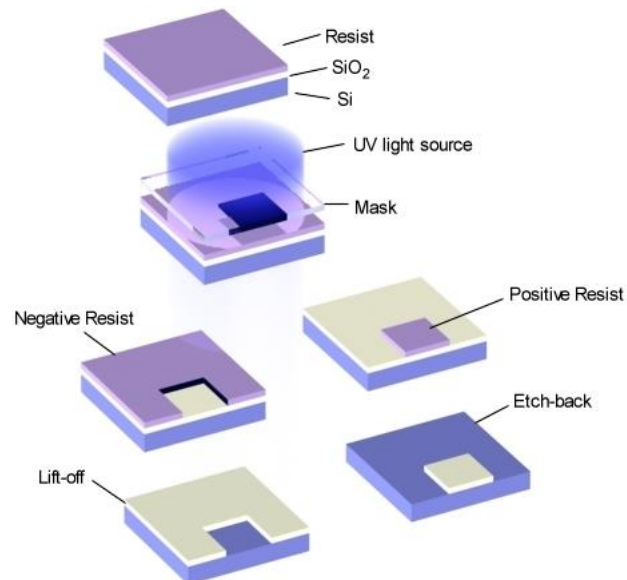


Figure 3.3: The demonstration of patterns formed using positive and negative photoresists .
Adopted from [64]

The third step of the process (Figure 3.3 [64]) is UV lithography step where MEMS structure is mold-patterned by using photoresist (PR). This patterned PR on SI wafer acts as mask and led the nickel to be deposited into shape of the desired structure shape. In this step there is variation in the PR material used for two fabrication flow. For electrostatic actuation system SU-8 negative PR was used. SU-8 is used for high ratio structure. The information and experience about SU-8 PR and its patterning process is detailed in the SU-8 Section. For magnetic actuation system AZ5214E image reversal photoresist is used.

AZ5214E PR is coated on SI wafer with spin coating. Then coated SI wafer is prebaked on the hotplate with 110°C for 50 second to enhance adhesion and remove excess solvent. Afterward, SI wafer is exposed to UV light for 6s through the mask that is drawn using Layout Editor. Later on, patterned SI wafer directly put on the hotplate (120°C) and baked for 2 min, this step is needed for the reversal of the PR and it is called Reversal bake step. After reversal bake step, flood exposure step took place where SI wafer was exposed to UV light without any mask or pattern for 15s. Finally, SI wafer is developed in petradish by using AZ 726 developer for ~15s.

Note that the quality of the pattern depends on the thickness of the photoresist, exposure and development time. All of these parameters are optimized values that are obtained for the desired thickness through multiple trial and error experiments. Results of these experiments can be found in Appendix section. As the results of this process $2.4\mu\text{m}$ thick pattern are obtained.

3.1.3 Electroplating

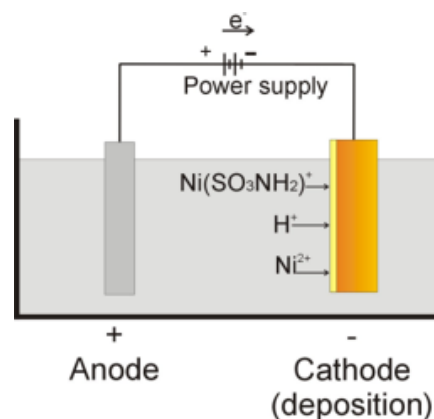


Figure 3.4: Schematic representation of electroplating process. Adopted from [64]

After Lithography patterning of PR, Si wafer is sliced into dice and MEMS structure is formed via Ni electroplating. The exposed surface of the Au surface is deposited via Ni. Ni is

specially used as MEMS structural material because of its high resistance over oxidative and corrosive agent that would be used in Reactive Ion Etching process, and ferromagnetic behavior that can be used in magnetic actuation. Note that, in Electrostatic Actuation fabrication wafer would be sliced after the second UV lithography patterning. Therefore, the first electroplating deposition would be applied to whole wafer for the alignment.

For electroplating procedure is an electrochemical deposition. It is used for growing metal on conducting metal. In our case, we make use this application to deposit Ni into cavity that produced by PR. There are many different type of bath used for this process. In this case, Ni sulfamate solution is used since it is known to cause very low residual stress in the Ni deposited structure and it is commonly used in engineering application. The bath composition consists of 40 g/l H_3BO_3 , 600 g/l $\text{Ni}(\text{SO}_3\text{NH}_2)_2 \cdot 4\text{H}_2\text{O}$ and 10g/l $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$. Nickel chloride in the solution increases the conductivity of the analyte and Boric Acid preserve the pH of the solution [64]. Nickel Sulfamate solution is employed as conductive electrolyte to carry nickel ions form anode to cathode and the anode is bulk of pure Ni (Fig. 3.4).

The essential parameters that decide the quality of the structure are current density [mA/cm^2], temperature [$^\circ\text{C}$] and pH. These parameters determine the deposition rate, surface roughness, internal stress, and adhesion. In our electroplating process, temperature was held at 45°C , current density was $10\text{mA}/\text{cm}^2$, and pH was 3.5 – 4 for stress–gradient-free structure [65]. Electro deposition took 20 min to fill $2.4\mu\text{m}$ thickness of the PR pattern and another 10 min additional deposition continued to increase the height of the structure to $4.6\mu\text{m}$.

3.1.4 Wet-etching

3.1.4.1 Removal of PR

In this step PR is removed after the deposition of Ni for further etching of Au, Cr and SiO_2 layer as well as releasing the beam resonator or for the new lithography patterning. Acetone is used for the removal of the AZ5214E PR. After acetone bath the chip is submersed in to Isopropyl Alcohol (IPA) and then it is dried with Nitrogen air. The SU-8 PR is removed with RIE and detailed explanation for SU-8 removal can be found in SU-8 section.

3.1.4.2 Wet etching of Seed Layers

The wet etching of the seed layer is executed to release the beam resonator at end of both fabrication processes. This step takes place at end of the first electroplating for the

magnetic actuation fabrication flow, and at end of the second electroplating for the electrostatic actuation fabrication flow.

After removal of the PR exposes the Au layer and to etch layers beneath it first Au layer must be etched. Au etchant-water solution with 5:1 ratio is used to etch the Au layer. This etching process generally takes 2-5 min depends on the structure if there is narrow gaps it takes longer. After Au layer etching, chip is submersed into water to stop etching and to remove Au etchant from the chip.

Next, the Cr layer would be etched with Cr etchant-water solution which has 5:1 ratio. This process similar to Au etching takes 2-5 min. After etching process, chip is submersed into water.

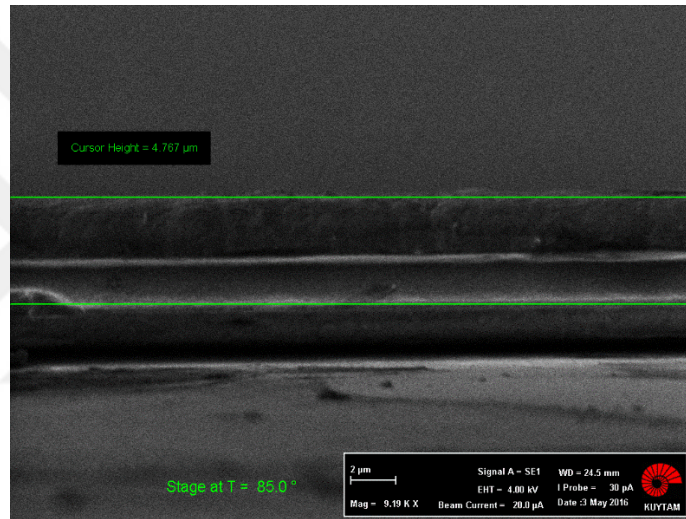
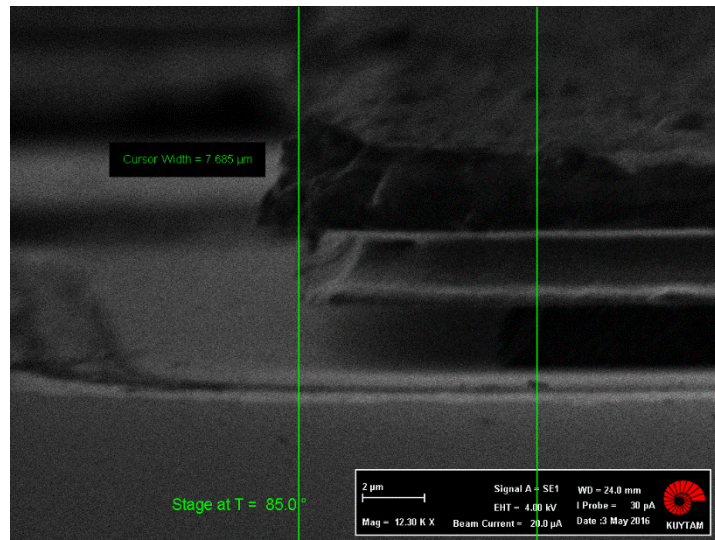


Figure 3.5: SEM image of the released resonator

Final step for the release of the beam resonator is Hydrofluoric (HF) Acid etching of the SiO_2 layer. For this step, HF-water solution with 5:1 ratio is prepared. And multiple chips are immersed into the solution for different duration time and most optimum time is found to be 3.5 min to etch SiO_2 layer of $2\mu\text{m}$ thickness. In addition, the obtained etching rate is approximately $500\text{nm}/\text{min}$ which logical value for 5:1 ratio of HF-Water solution, and it is also very consistent with literature [HF- 5:1 etching rate Ref]. Afterward, chips are immersed into water for removal of the HF. Then they are immersed into acetone and IPA bath, respectively. Final they are kept in clean room to dry in room temperature in order to prevent the sticking of the beam resonator. SEM image of the resonator is demonstrated in Fig. 3.5-6, from these images the over etch of the SiO_2 is found to be $\sim 7.5\mu\text{m}$.

Figure 3.6: SEM image of the over etch of the SiO₂ Layer

3.1.5 Alignment and UV Lithography

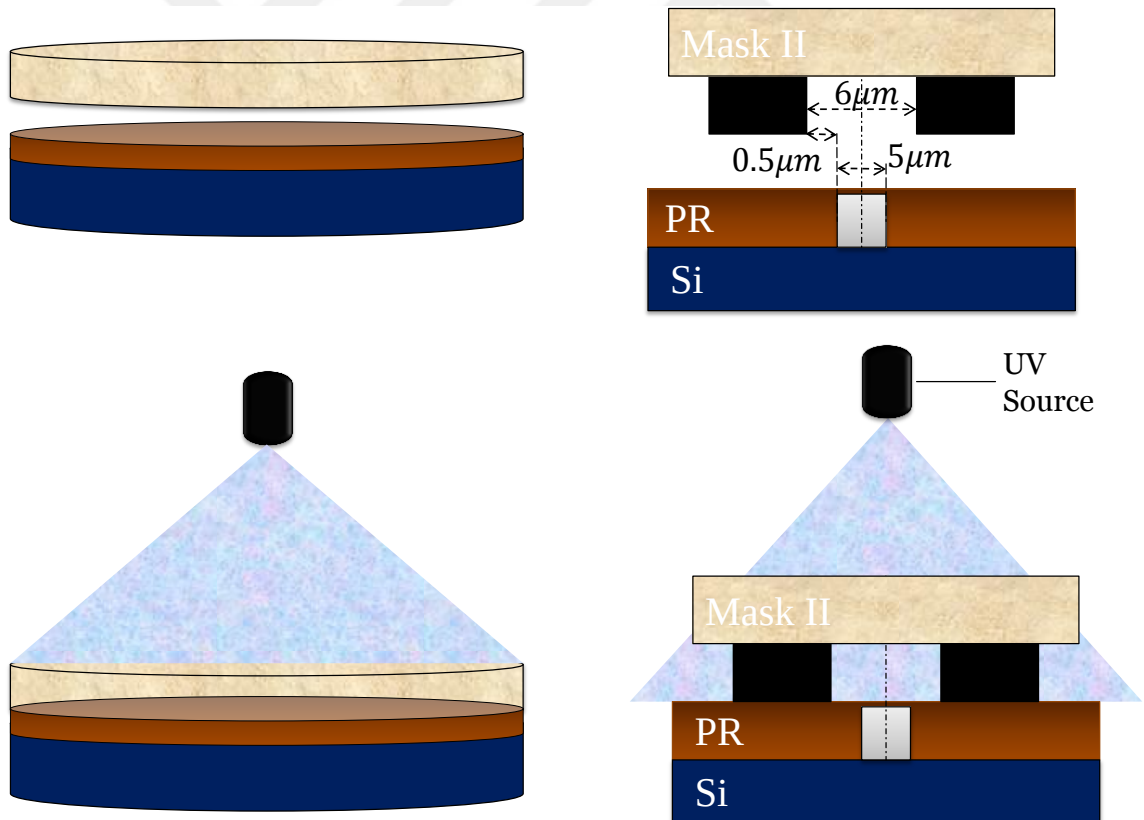


Figure 3.7: The demonstration of Alignment procedure.

This step is only applicable for the electrostatic actuation fabrication flow. This process is used to form another mold-pattern for electrodes by using second mask (Mask II). In the proposed electrostatic model, we have two electrodes at the both side of the beam

resonator with gap of $0.5\mu\text{m}$. Since our UV lithography has resolution of $2\mu\text{m}$, we could not pattern the electrodes on the first mask. So we proposed a two mask fabrication flow in order to obtain $0.5\mu\text{m}$ gap between electrodes and the beam resonator. Fig. 3.7. demonstrates the alignment procedure. The Mask II is aligned of the wafer by the help of the alignment structure (Fig. 3.8) that designed and printed on both mask. These alignment structures on both masks would complement each other when they are aligned on top of each other. Once they complement each other whole wafer and structure would be aligned. In this step the alignment process is supposed to occur with $0.5\mu\text{m}$ resolution. However, this resolution was not achieved and alignment process could not be completed. Therefore, Fabrication Process is simplified for magnetic actuation and optical readout.

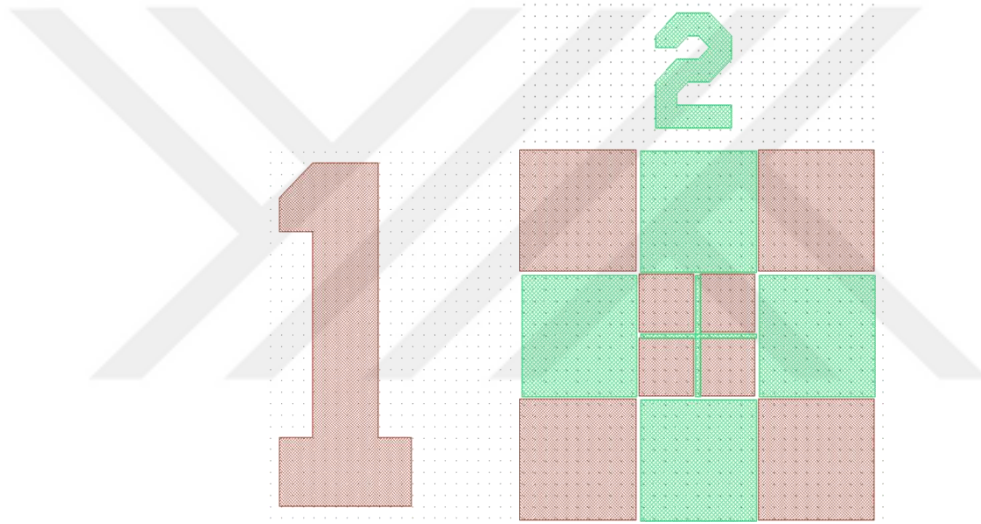


Figure 3.8: The demonstration of Alignment Structure on both masks.

3.1.6 Conclusion

Upon inspection with Surface profiler and SEM imaging after HF etching, dimensions of the resonator and the MEMS were obtained. The results showed that the nickel structure has $4.6\mu\text{m}$ of a thickness and an under etch of $7.6\mu\text{m}$. Dimension of the resonator were found to be as thickness (t) $4.6\mu\text{m}$, width (w) $5\mu\text{m}$ and length (l) $160\mu\text{m}$. The young's module of the nickel structure is the determined, by the nominal resonance frequency of the resonator, to be 162.6 GPa . SEM image of the Ni structure and the resonator are shown in Fig. 3.9.

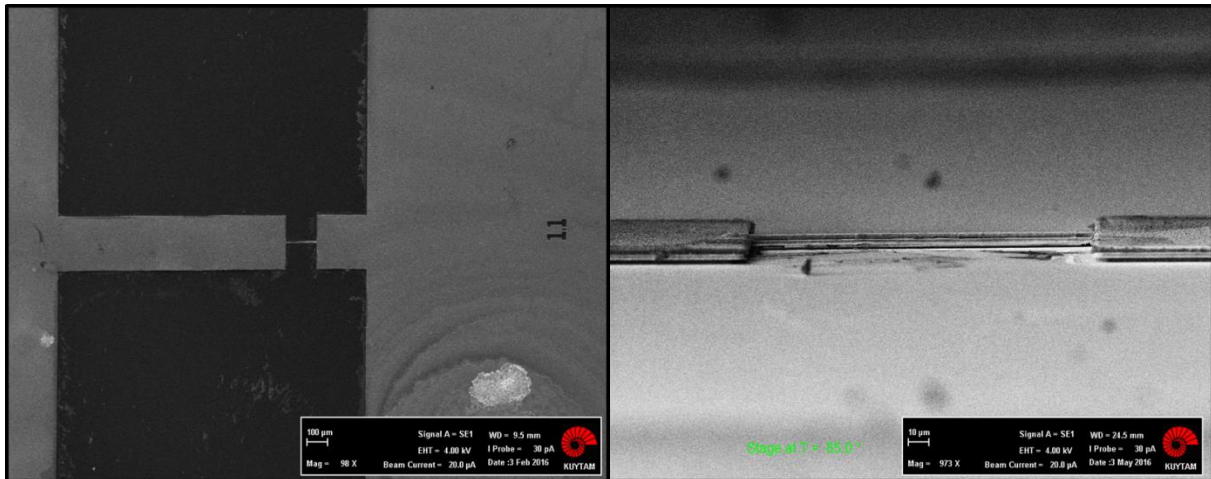


Figure 3.9: SEM Image of the Ni structure and the resonator.

The initial measured resonance frequency of the resonator is 822 KHz. After one set of experiment, the resonance frequency decrease to nominal frequency of 789 KHz. Abatement in resonance frequency is induced by relaxation of the residual stress that formed in electroplating stage. The residual stress is obtained from the difference between nominal resonance frequency and initial resonance frequency of the resonator and it is found to be 38MPa which is quite fit the literature for Nickel Sulfamate Bath Solution [66].

3.2 SU-8

SU-8 is epoxy based negative PR. This PR can produce structure with aspect ratio of 40:1 and thickness of 2mm. It is very sensitive to 365nm and smaller wavelength. Moreover it is used in photonics as a device layer after it hard baked due to its transparency and high aspect ratio. This PR is selected to obtain 20:1 aspect ratio for electrostatic actuation.

3.2.1 Coating

SU-8 is coated on wafer via spin coating. Coating requires 2 step spin coating procedure. Spin Coating procedure is as:

- Spin at 500rpm for 10s with 100rpm/s acceleration
- Spin at 2000rpm for 60s with 100rpm/s acceleration
- Keep the wafer in spinner without vacuum for 1min
- Bead removal with acetone soaked swap

Due to the viscosity of SU-8, at the end of the spin coating bead of PR accumulates at the edge of the wafer [67]. The edge bead prevents the mask from fully contacting with PR coated

wafer and causes a gap which eventually leads to diffraction in the UV Lithography [68]. In order to remove this bead, Acetone soaked swap is used to remove the bead at edges.

3.2.2 Patterning

After spin coating, SU-8 coated wafer must be soft-baked at 65°C and 95°C for 3min and 6min respectively in order to remove excessive solvent and prevent sticking. If the sticking problem continues, the soft-bake duration can be increased or the coated wafer can be dried with nitrogen air after it cools down the room temperature. As results of many experiments, we came to conclusion that the soft-bake is important for improving the adhesion. Increasing the soft-bake duration time, increases the amount of solvent that is removed and enhance the adhesion. However, there is a trade-off an increase in development time.

In the exposure step, Optimum exposure time found to be 40s. Because when the exposure time is lower than 40s, an adhesion and contrast problems are occurred, and for higher exposure time over development problem is occurred. All pictures that are taken for different exposure time can be found in Appendix section.

Post-bake step is a critical step for the patterning of the SU-8 PR. The actual pattern is formed in this step. In the post-bake, the wafer is baked at 65°C and 95°C for 1min and 6min similar to soft-bake. Post bake duration time has similar effect on adhesion and development time as the soft-bake step.

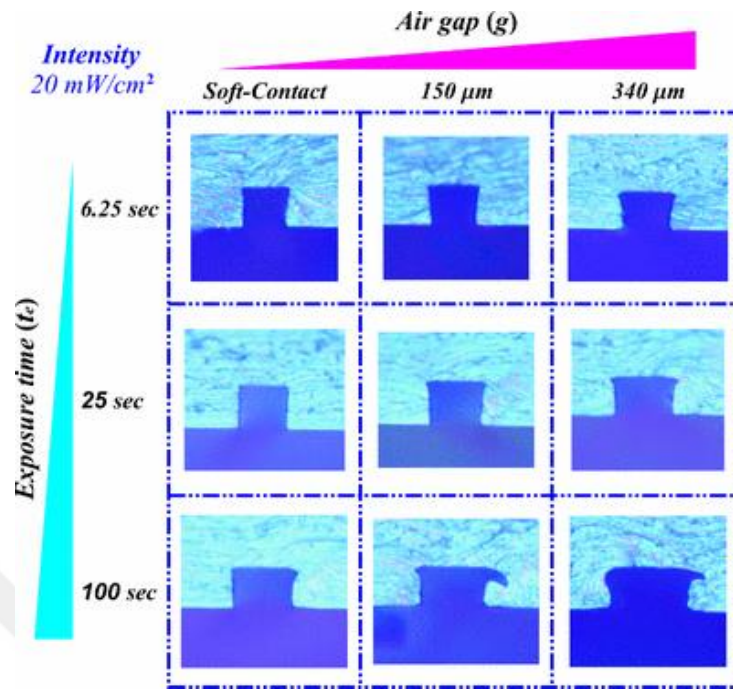


Figure 3.10: The effect of air gaps between mask and resist during exposure. Adopted from [69].

We faced many problems in patterning of SU-8. Major problem was T-profile and t-topping issues. These problems have decreased the contrast and the resolution. Due to these problems, 5 μm wide cavity for the beam resonator could not be achieved. T-profile problem occurs when there is air gap between the mask and the wafer (Fig. 3.10). The air gap between them leads to diffraction in the UV light and exposes the edge of the supposed vertical wall to UV light. Thus, an unwanted cure of PR is occurred. In order to solve this problem, edge bead that accumulated with spin coating is removed and a soft cushion is designed and manufactured from acetate paper (Fig. 3.11). The Soft cushion is placed beneath the wafer in order to bend the wafer and closed the air gap (Fig. 3.12) [67, 70].

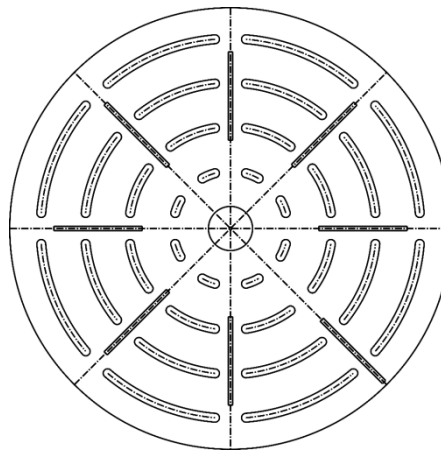


Figure 3.11: Designed the soft cushion during exposure

An improvement is observed in the resolution and quality of the pattern after edge bead was removed and the soft cushion was used (Fig. 3.12). However, as it is seen in Fig. 3.13, the beam resonator cavity was not achieved. After some SEM images were taken (Fig. 3.14), and bridges like structures were formed and blocked the cavity.

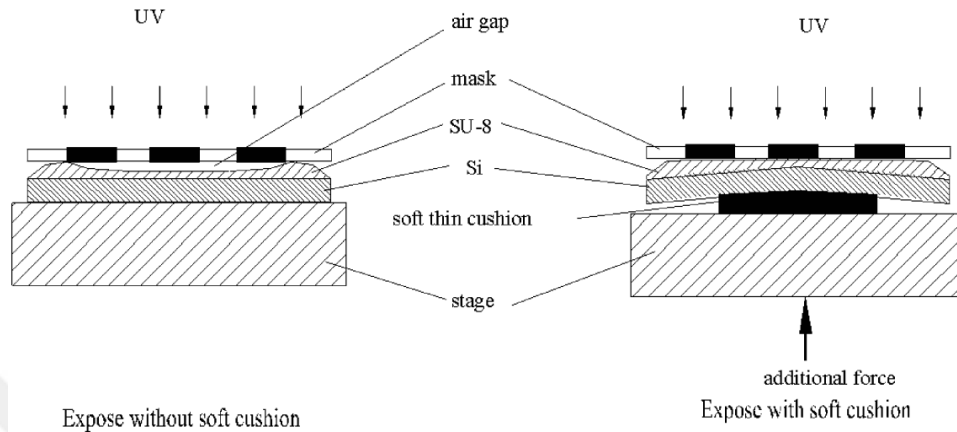


Figure 3.12: Effect of the soft cushion during exposure. Adopted from [70].

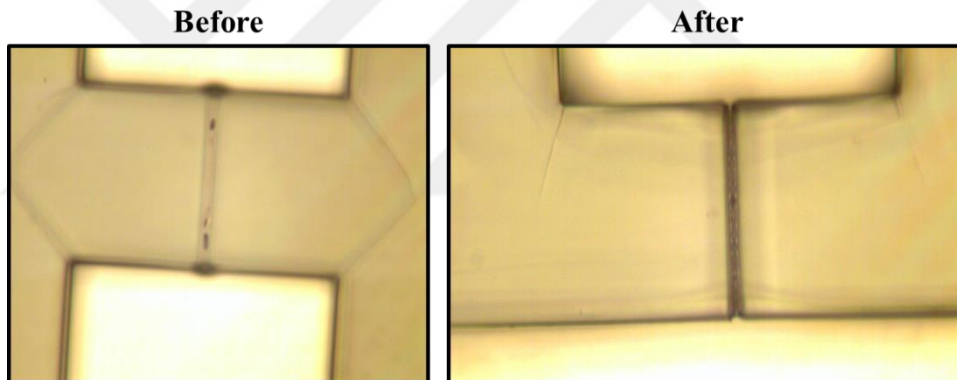


Figure 3.13: Optical Image of the sample before and after using soft cushion

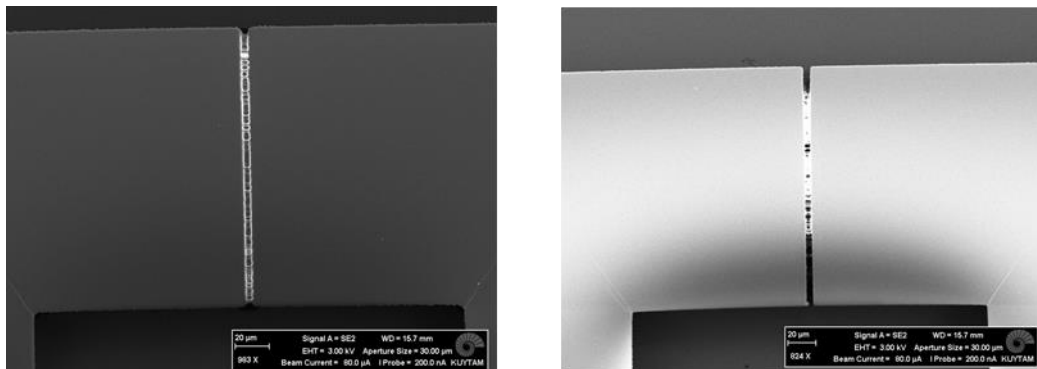


Figure 3.14: SEM images of the beam resonator cavity

After some literature search, another similar problem is found and it is called T-topping which is quite similar to T-profile case. However, the actual cause is the small wavelength component in the UV light. Since the SU-8 PR is very sensitive to 365nm and

smaller wavelength. When it is exposed to wavelength smaller than 365nm, the PR surface tends to cure rapidly and obstruct the curing process from diffusion toward wafer and instead the curing process starts to move parallel to surface which causes this kind of bridges. In order to solve this problem a custom filter that filter out wavelength smaller than 360nm. As a results T- topping problem is solved (Fig. 3.15). However, the resonator cavity still could not be achieved due to isotropic diffusion of the curing process. The cavity contained a cured SU-8 PR close to substrate (Fig. 3.16). Moreover, the failure in the alignment procedure makes the further improvement unnecessary.

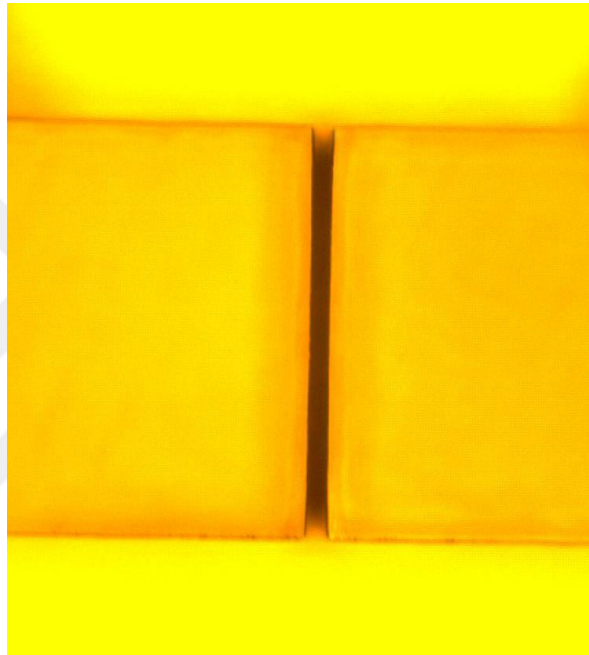


Figure 3.15: Optical images of the beam resonator cavity after using filter

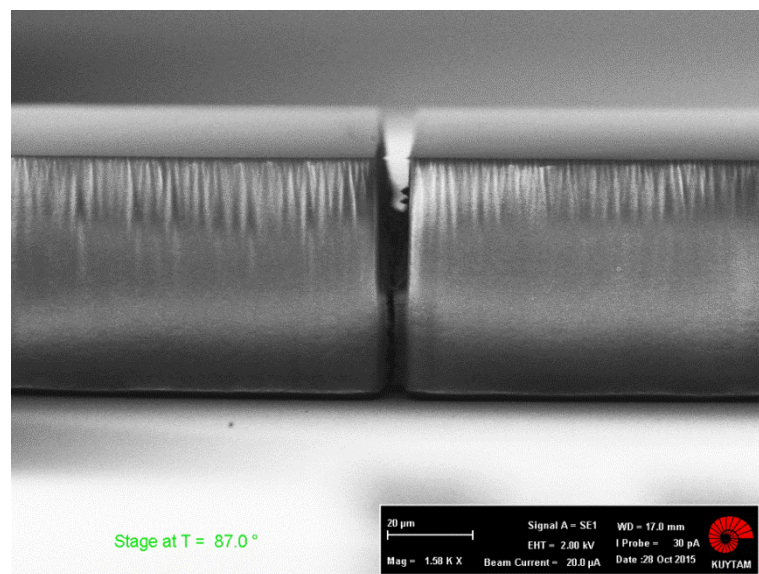


Figure 3.16: SEM images of the beam resonator cavity after using filter

3.2.3 Removal

Removal of SU-8 has been a research subject for decade due to highly cross-linked epoxy it contains after development has made it hard to remove. There have been many proposal and attempts for the removal technique. These include solvent removal, chemical removal, molten salt bath, burning [71, 72]. While some of these ideas have been successful, some of them have not been successful. Even the some of the successful techniques are not suitable due to damage caused on the metal part of the device such molten salt bath and burning. The most suitable and available solution we found was a chemical removal which is RIE.

In this process, a recipe that found from literature is used. The recipe is as; $O_2 = 60$ sccm, $SF_6 = 3$ sccm, $Ar = 0$ sccm, and chamber pressure = 150 mT [72]. According to G. Hong et. al, they able to achieve 1.5-2 $\mu\text{m}/\text{min}$ etch rate. However, due to limitation of the RIE machine and failure in achieving the plasma, the recipe is modified. The modified recipe is as $O_2 = 40$ sccm, $SF_6 = 3$ sccm, $Ar = 10$ sccm, and chamber pressure = 100 mT. 0.5 $\mu\text{m}/\text{min}$ etch rate was achieved by using these recipe.

Chapter 4

MEASUREMENT SETUP AND PROCEDURE

4.1 Measurement Setup

The measurements are performed in Micro and Nano Characterization Lab, Bogazici University. The resonance frequency of the beam resonator is measured using Laser Doppler Vibrometer (LDV, Polytec OFV-2500). LDV is an interferometry-based velocity and displacement measuring technique used to detect vibrations by making use of the Doppler Effect to measure vibrations. When a light beam is shot on a vibrating object, the light's frequency would shift. And the interferometer in LDV would detect the shift of the backscattered light. In order to sense the shift, LDV divides the laser light into two parts; one would be used as reference beam and second part would be used as measurement beam. By comparing reference beam with the scattered beam light, LDV would measure the Doppler shift in the frequency. And from the Doppler shift of the frequency, velocity and displacement of the vibrating object would be obtained. The principle is shown in Fig. 4,1.

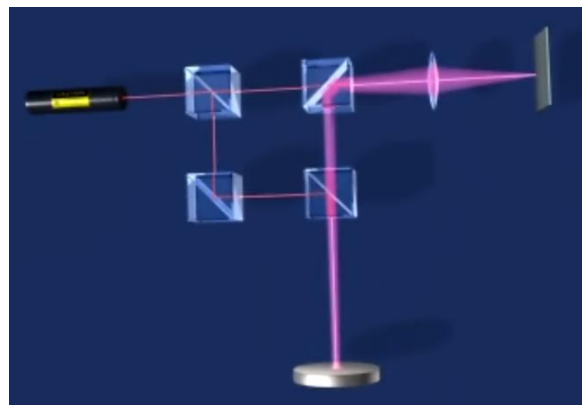


Figure 4.1: LDV interferometry. Adopted from [73]

As it is seen the schematic description (Fig. 4.2) whole measurement setup is controlled by the MatLab Software. MatLab Code uses GPIB interface to connect and control the oscilloscope and the function generator (Fig. 4.3). Basically, the code controls function

generator to create a sinusoidal signal and sweep the frequency of this signal and at the same time collects the data from the oscilloscope. The signal created by the function generator is split into two parts; one of them directly goes to oscilloscope as a reference signal and other one is connect to the resonator for actuation.

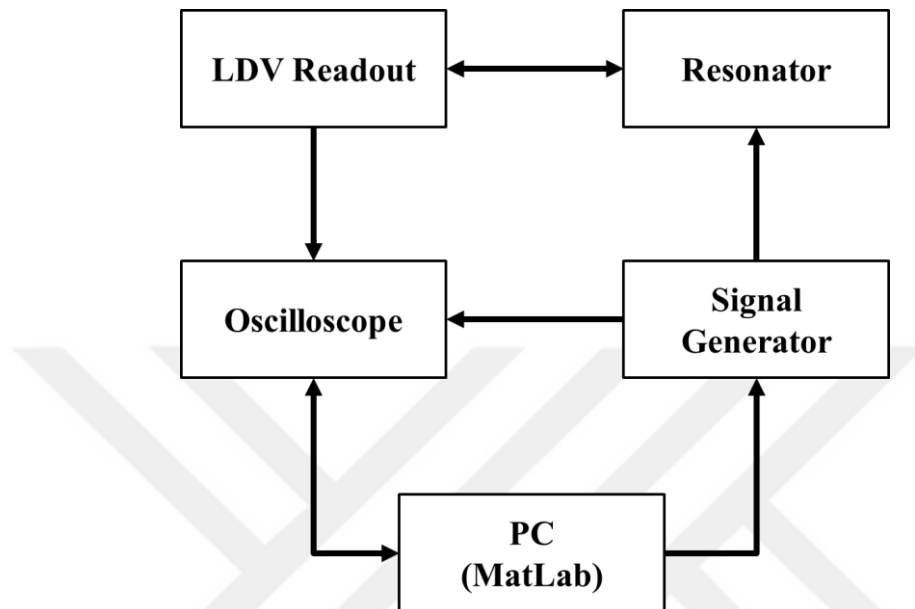


Figure 4.2: The schematic description of the measurement setup

The LDV is stationed right across of the experiment stage (Fig. 4.4). It takes the vibration data and provided is to the oscilloscope. Afterward, the MatLab code takes the data of the reference signal and the measured signal from oscilloscope and compares their phase and amplitude to determine the output of the resonator. These processes are repeated for the whole frequency sweep.

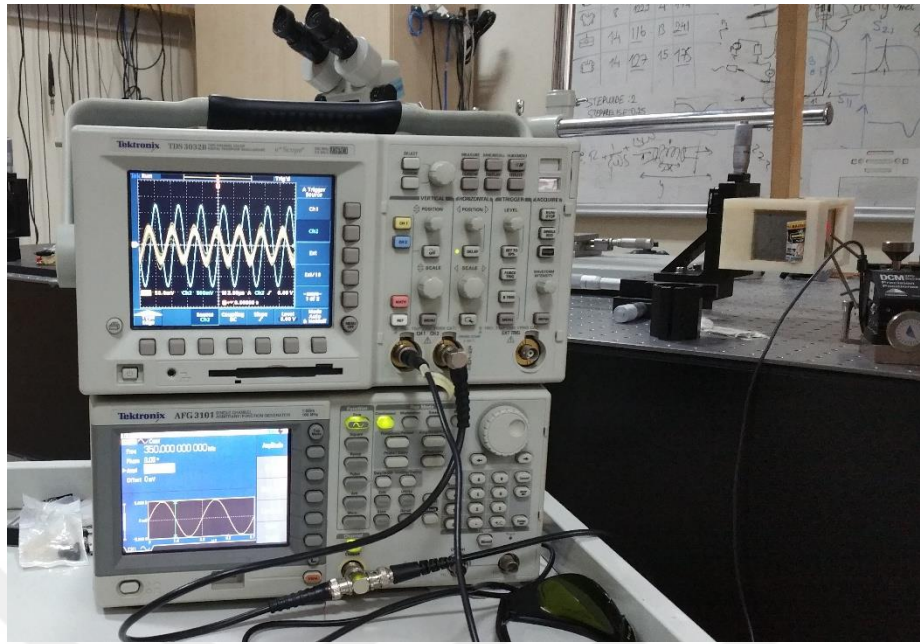


Figure 4.3: Oscilloscope (on-top) and Function Generator

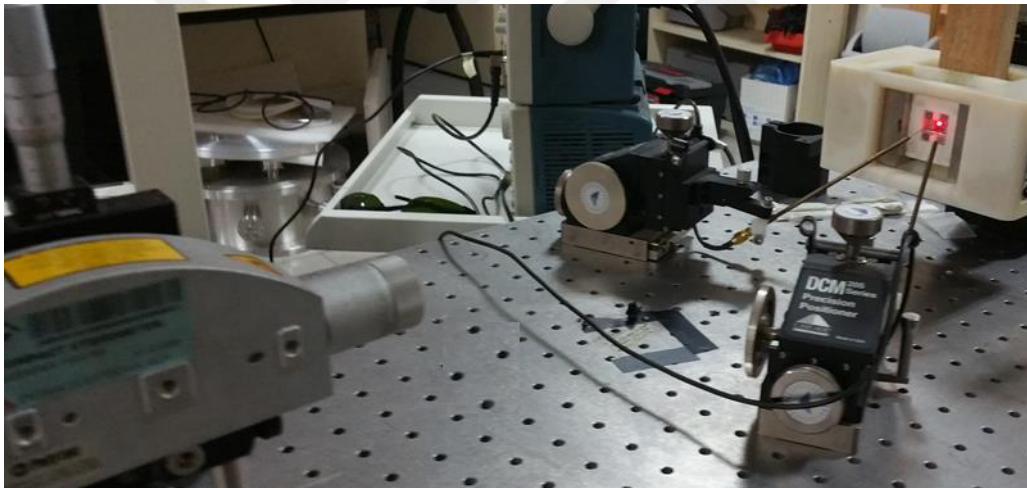


Figure 4.4: LDV and Experiment setup

4.2 Experiment Procedure

Initially, MEMS chip is placed on the bending platform (Fig. 4.5) which is made from aluminum to constrain the MEMS chip and bending it with screw, and constrained by the side of the chip. Then, the bending platform is placed in the holding platform which is made of ABS with the 3D printer and it is used to hold the bending platform and the MEMS chip in the middle of the magnets (Fig. 4.6).

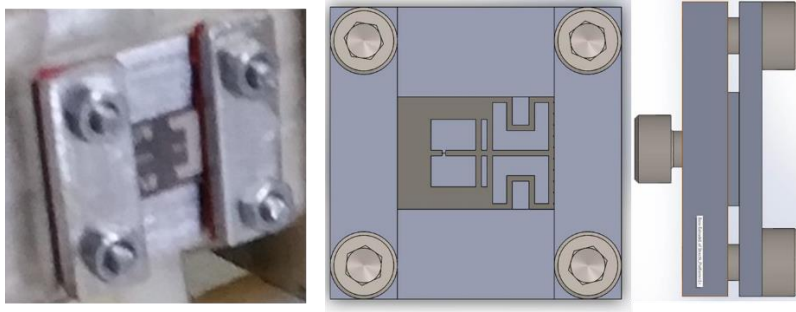


Figure 4.5: Bending platform

After holding platform is placed between the magnets, LDV focus point and reflection angle would be calibrated. Then, probes are stationed near the stage and the connections of the probes are established with the MEMS structure for actuation of the resonator (Fig 4.7). Finally, the experiment would be started by giving the input parameter into the MatLab code.

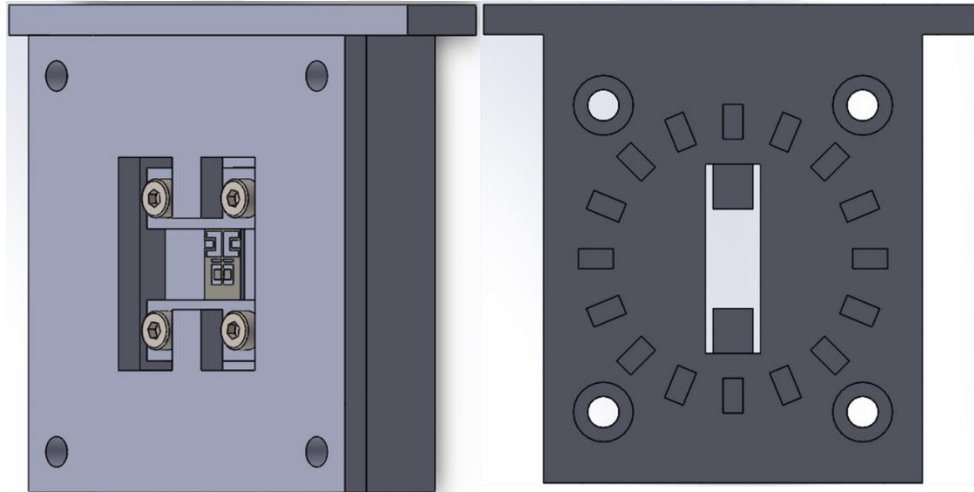


Figure 4.6: Holding platform

The code's input parameters are peak to peak actuation voltage (V_{pp}), offset voltage (V_{off}), frequency sweep range and step size. Generally, the frequency sweep parameter does not have any effect on the output. On the other hand, V_{pp} and V_{off} have effect on the results so the experiment is conduct each time for different parameter. Since these parameters are controlled by the code and there is no need for re-calibration of focus and reflection angle of the LDV since there is not any mechanical change on the stage.

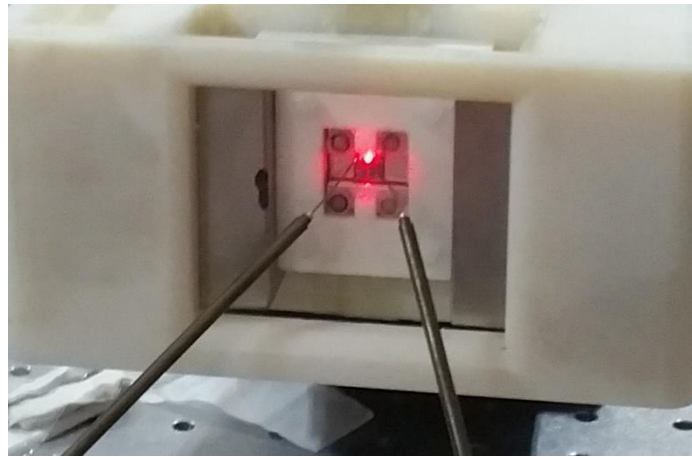


Figure 4.7: Experiment Stage

The last parameter for the experiment is the bending of the resonator. The bending is performed by tightening the screw on back. The degree of tightening is not certainly known but with help of sign engraved into back of the holding platform, the tightening degree is controlled. Each square engraved on back corresponds to 22.5° turn of a screw. The screw tightening process is done after all experiments for V_{pp} and V_{off} values are measured. After tightening of the screw focus and reflection angle of the LDV is recalibrated and the experiments are performed all over again for V_{pp} and V_{off} values.

Chapter 5

RESULTS AND DISCUSSION

In this section, results of the experiments are presented. Effects of stress, Lorentz force, and amplitude are shown and discussed.

5.1 Axial Stress / Strain Effect

Stress induced on micromechanical resonator ship-bending method. Increase in the bending raises the tensile axial force acted on resonator which leads to a shift of the resonance frequency of the resonator. Strain caused on the resonator by the tensile force is obtained by employing Rayleigh's energy method [61]. The measured resonance frequencies, strain values that are obtained via analytical model are shown in the Table 5.1 for two sets of experiments. Effective Stiffness of the resonator is also included in table for different strain values. Resonance frequencies versus strain values are verified by using FEM Analysis (Fig. 5.1).

Experiment-1			Experiment-2		
Resonance Frequency (KHz)	Strain (ϵ)	Effective Stiffness (k_{eff})	Resonance Frequency (KHz)	Strain (ϵ)	Effective Stiffness (k_{eff})
822.0	0.000E+00	4.372E+02	789.0	0.000E+00	4.028E+02
867.5	3.548E-04	4.870E+02	817.0	1.964E-04	4.319E+02
880.5	4.462E-04	5.017E+02	840.5	3.666E-04	4.571E+02
			854.5	4.702E-04	4.725E+02

Table 5.1: Resonance Frequencies, strain values and Effective Stiffness of resonator

Fig. 5.1 shows plots obtained from experimental data and FEM analysis. Both plots show linear increase and the error between two plots vary from 0.17% to 0.22%.

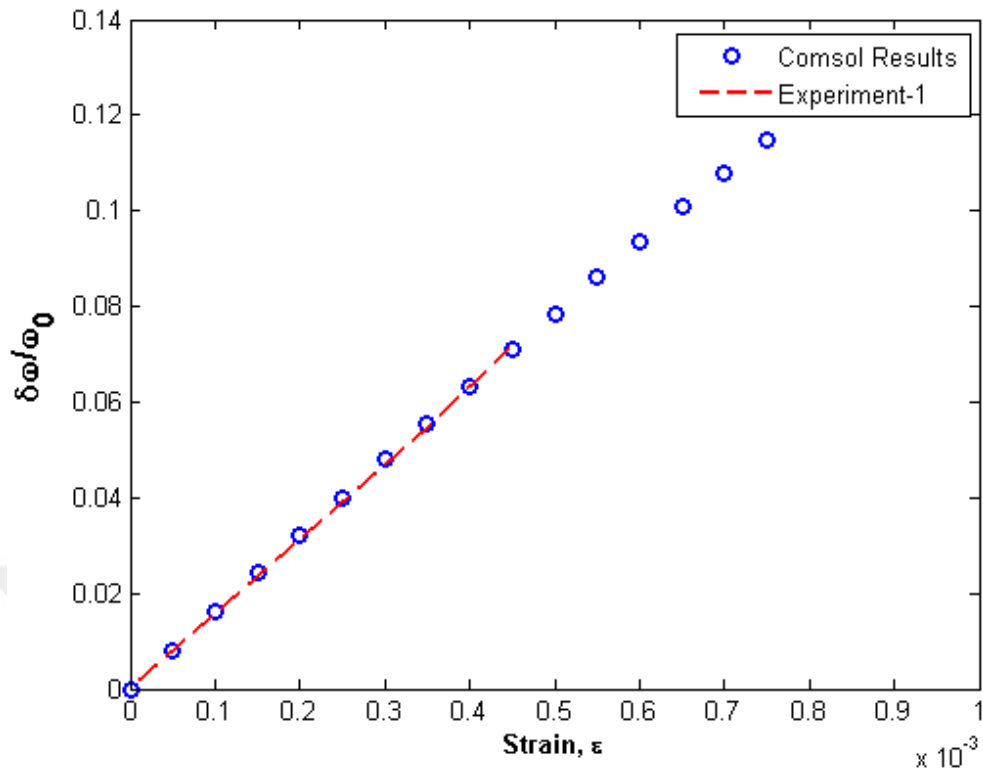


Figure 5.1: Normalized $\delta\omega$ vs Strain, experiment-1 data and FEM Analysis Results with initial 38MPa

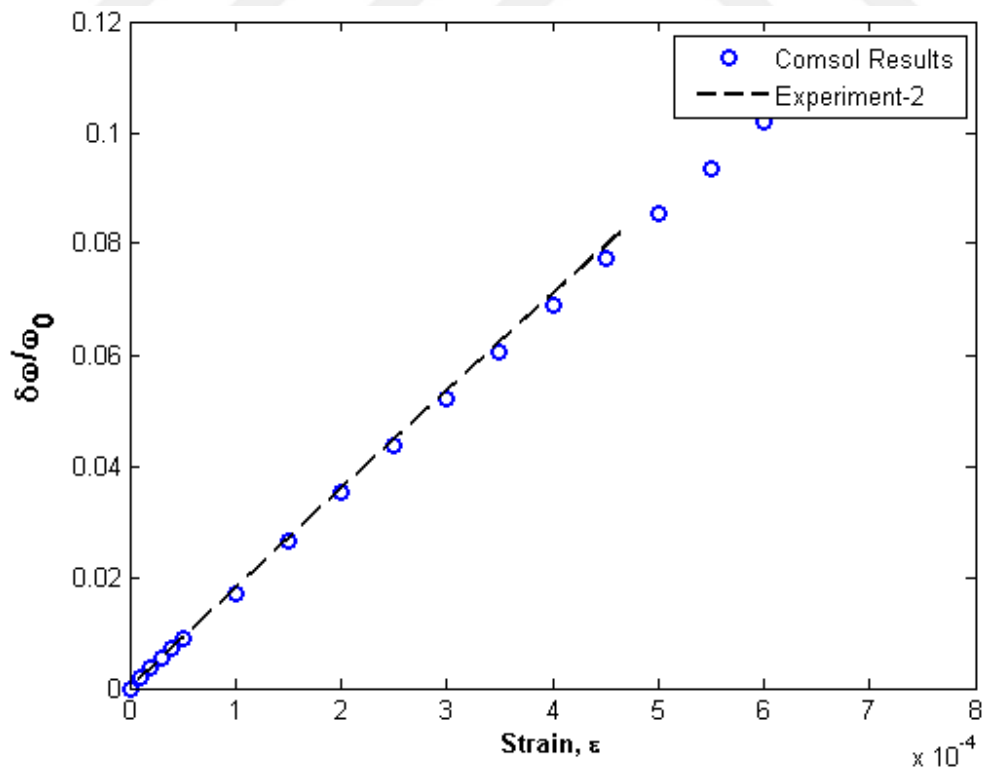


Figure 5.2: Normalized $\delta\omega$ vs Strain, experiment-2 data and FEM Analysis Results for stress free situation.

Fig. 5.2 shows plots obtained from the second experimental data and FEM analysis. In this set the initial stress is removed. As in the Fig. 5.1, plots show linear increase and the error between two plots varies from 0.07% to 0.35%. For both figures (Fig. 5.1-2), the sensitivity of the resonator $\left(\frac{\delta\omega}{\delta\epsilon}\right)$ varies approximately 1.2×10^8 . Although both figures shows a linear increase, the actual trend can be formulized as:

$$\omega(\epsilon) = \omega_o \sqrt{1 + \epsilon}$$

Where, ω_o is the nominal frequency and ϵ is the strain. However since the strain that applied is very small the trend in the graphs is much closed to linear.

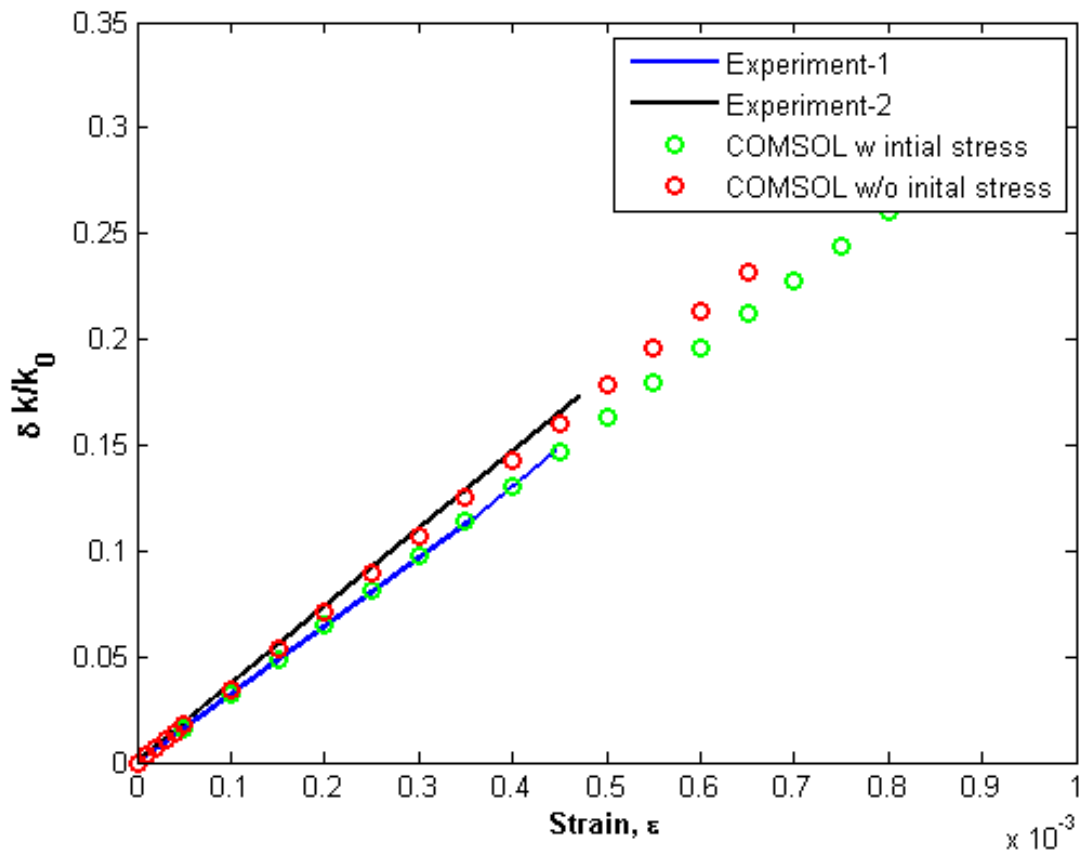


Figure 5.3: Normalized effective stiffness of the resonator vs the strain

The increase in resonance frequency due to strain is known as the “hard-spring effect” [33]. As the name implies, strain causes an increase in the stiffness of the resonator which leads to an increase in the resonance frequency. Fig. 5.3 shows the change in the effective stiffness of the resonator. The presence of the residual stress contributes to effective stiffness in the first experiment. Therefore, the effective stiffness in first experiment is higher than second experiment.

To sum up, with help of chip-bending technique, the resonance frequency of micromechanical resonator is increased 7.1% and 8.3%, and k_{eff} is increased 14.7% and 17.3% for the first and second experiments respectively. When these result compared with the study of Verbridge *et al.* which they tuned nanomechanical resonator frequency from 14.6 to 35.5 MHz, our result may seems negligible [36]. However, it must be noted that, nanomechanical resonators are much more sensitive than the micro resonator. In addition to that higher stress with smaller force can be induced on nanomechanical resonator due to their small cross-section. Moreover, there is slightly increase in Q factor, from 230 to ~275.

5.2 Lorentz Force Effect

The presence of the i_{dc} component in the excitation current introduces a constant Lorentz force that acts on resonator throughout excitation. The existence of such force reduce the effective stiffness of the system thus causes a shift in the resonance frequency of the resonator. This shift in frequency is called “softening effect”. In the second experiment, i_{dc} is introduced to system by applying an offset voltage with excitation voltage. Data are obtained for offset voltages of 1V- 4V for every strain values that applied on the resonator. Results are shown in the Fig. 5.4.

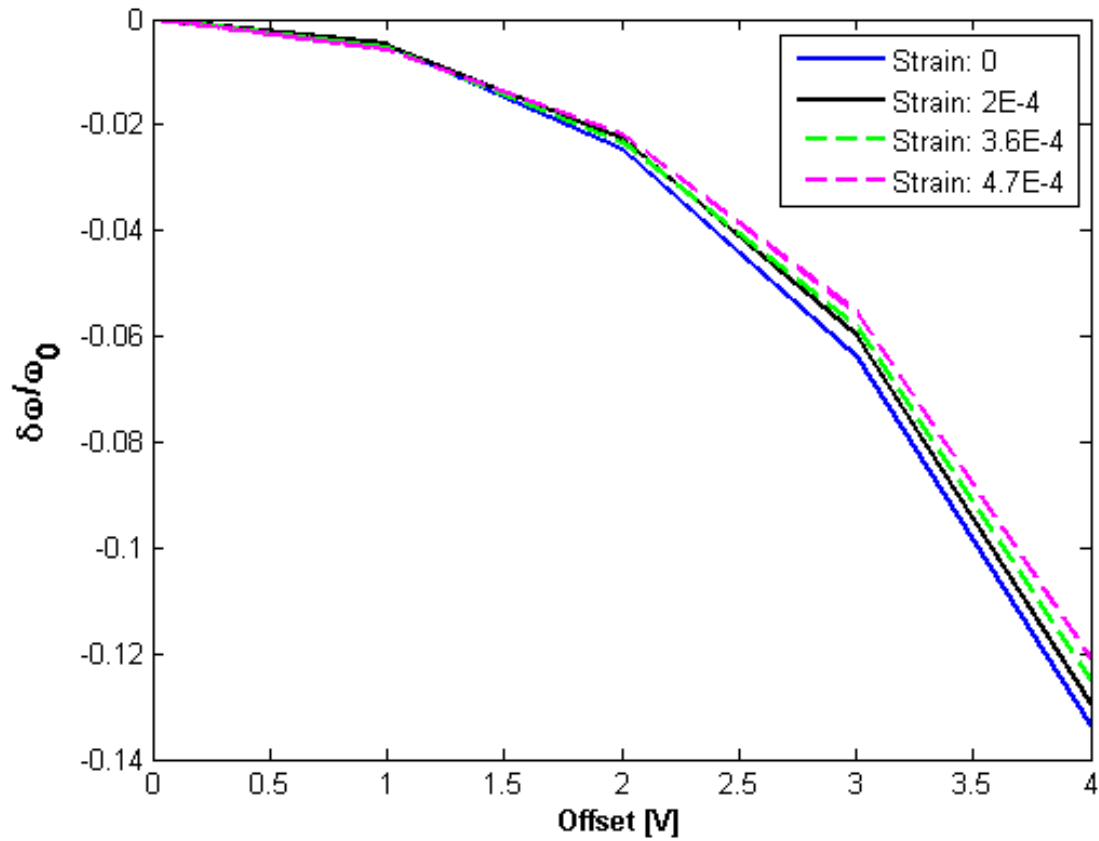


Figure 5.4: Normalized $\delta\omega$ vs Offset Voltage

Results show a dramatic decrease in resonance frequency as the offset voltage introduced into the system increases. These changes are occurs due to initial bending of the resonator that caused by the constant Lorentz force that acts on the resonator. As consequence of changes in offset voltage as well as the i_{dc} component in the system, the initial bending of the resonator varies and causes a shift in the resonance frequency. A similar phenomenon is also true for capacitive actuation system where the dc voltage that applied into the system cause a shift in the resonance frequency due to initial bending. The logic behind the variation of the resonance frequency is the same as in the stress effect. The initial bending of the resonator is caused by a force that acts against the mechanical stiffness (k_{mech}) of the resonator and alters the effective stiffness (k_{eff}) of the system. Fig. 5.5 demonstrates the variation in the effective stiffness of the system caused by the offset voltage.

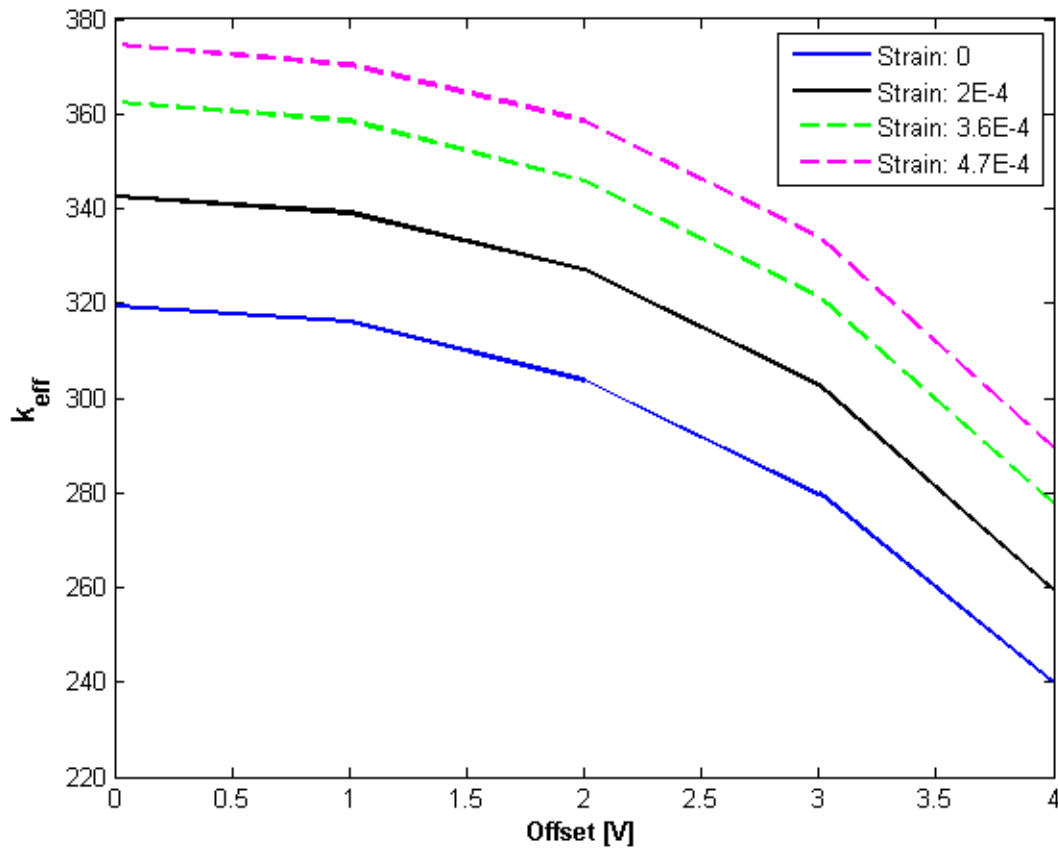


Figure 5.5: The change in the effective stiffness of the resonator with Offset Voltage

The results show that the effective stiffness is decreasing as the offset voltage is increased. Initial effective stiffness can be said to equal to mechanical stiffness of the resonator beam if there is not any load or force act on it. However, as the offset voltage is introduced to system, the effective stiffness (k_{eff}) will be resultant of the mechanical stiffness (k_{mech}) and the softening stiffness (k_{ms}). Since the mechanical stiffness comes from the material properties and dimensions of the structure, it can be said to be constant. Therefore, the softening stiffness can be obtained as the following:

$$k_{ms} = |k_{mech} - k_{eff}| \quad (23)$$

When the axial force applied on the resonator, k_{eff} for “0” offset voltage will be the equivalent stiffness of the system for that strain value. And by subtracting it from new k_{eff} that obtained after the offset voltage applied, will give k_{ms} .

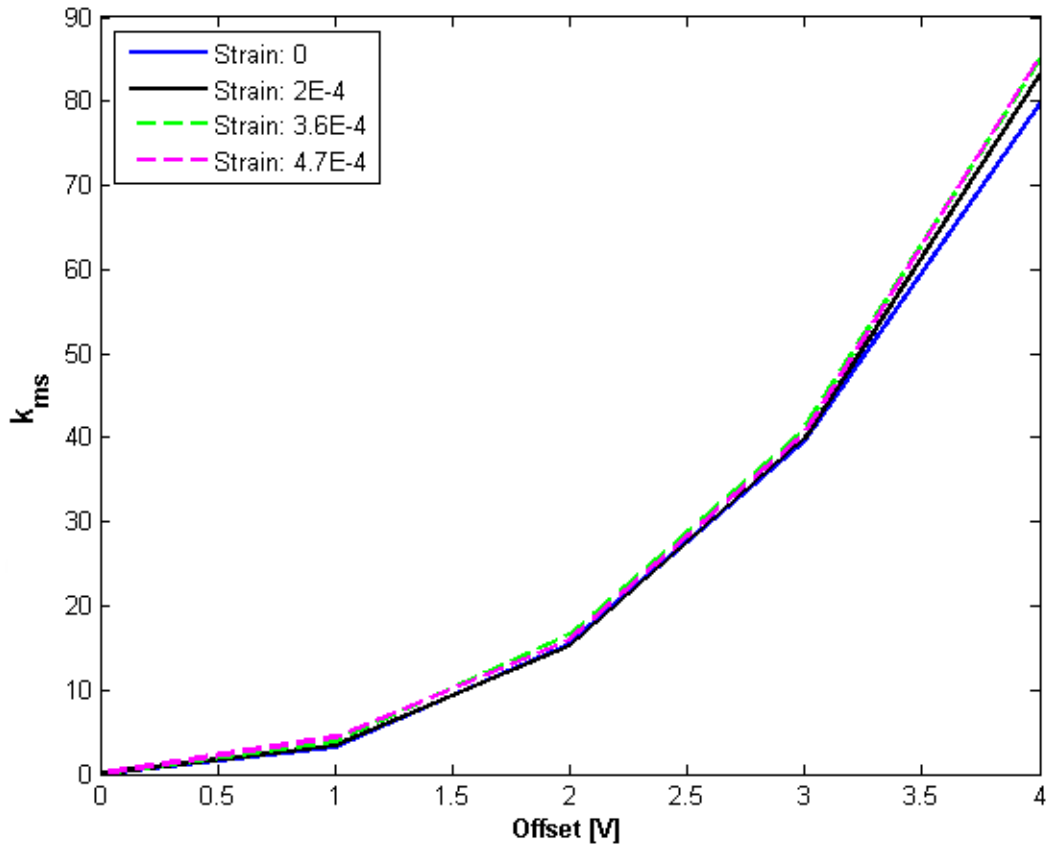


Figure 5.6: The change in the softening stiffness with Offset Voltage

Figure 5.6 displays k_{ms} change with the offset voltage for different strain values. The change in k_{sf} is almost the same for every strain values except for “4V” of offset voltage. This can be caused by environmental effect of the non-linearity in the system. Because as the voltage is increased, the amplitude is increased. Thus, the system might be forced into non- linear regime. As for the lower offset voltage the deviation between k_{ms} values is between 0.45-0.56 (Table 5.1.)

Ultimately, results show that k_{eff} is decreased 25% for all strain values and the resonance frequency is decreased 13% which very good for micromechanical beam resonator. Similar mechanism where Lorentz force used for tuning is reported by Ohnishi *et al.* have 10-fold tunable spring constant. In their study, they used a cantilever resonator which has small resonance frequency and small spring constant compare to beam resonator [59].

In the presence of the magnetomotive tuning force, chip-bending method’s tuning range is increased to %9 while the frequency tuning range of the magnetomotive tuning is decreased to -12%, in the presence maximum tension provided by chip-bending mechanism.

5.3 Amplitude Effect

In the experiments, the resonator is excited with peak to peak voltage of 500mV_{pp} for the sake of consistence. However, different values of excitation voltage are also used for observing amplitude effect on the response. The results showed that as the excitation voltage is increased, an unexpected response occurred. The response of the resonator is started to shift and show multiple resonance peaks (Fig. 5.7,8). Initially, the resonator is assumed to be reached its critical oscillation amplitude (x_c) but after some calculation is made, the maximum oscillation amplitude (x_{max}) and the critical oscillation amplitude (x_c) are found to be around 3.6 nm and 567 nm , respectively. As result, this possibility is eliminated since the difference between x_c and x_{max} is very large.

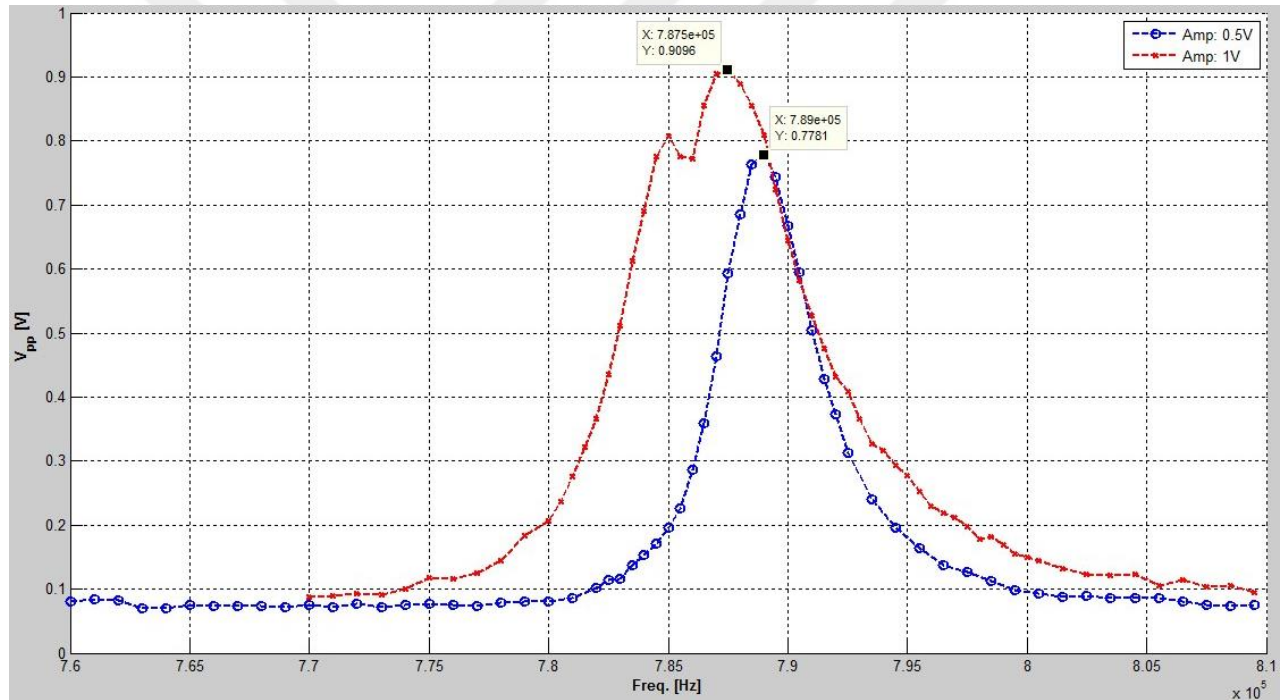


Figure 5. 7: The resonator response with amplitude

For further confirmation, the smaller resonance peaks are observed in different excitation amplitude. And it is seen that as the excitation amplitude is decreased the peaks starts to vanish. One of the reasons might be the separation of the modes where the recessive whole structure modes of the chip start to active due to high excitation force that caused by high amplitude. Modal Analysis conducted on FEM is also showed that there are a few whole body modes where the resonator is in oscillation and is close to actual resonance frequency

(chapter 2). Another reason for this phenomenon can be the high non-linear response of the magnetic actuation since it is known to have high non-linear effect[15].

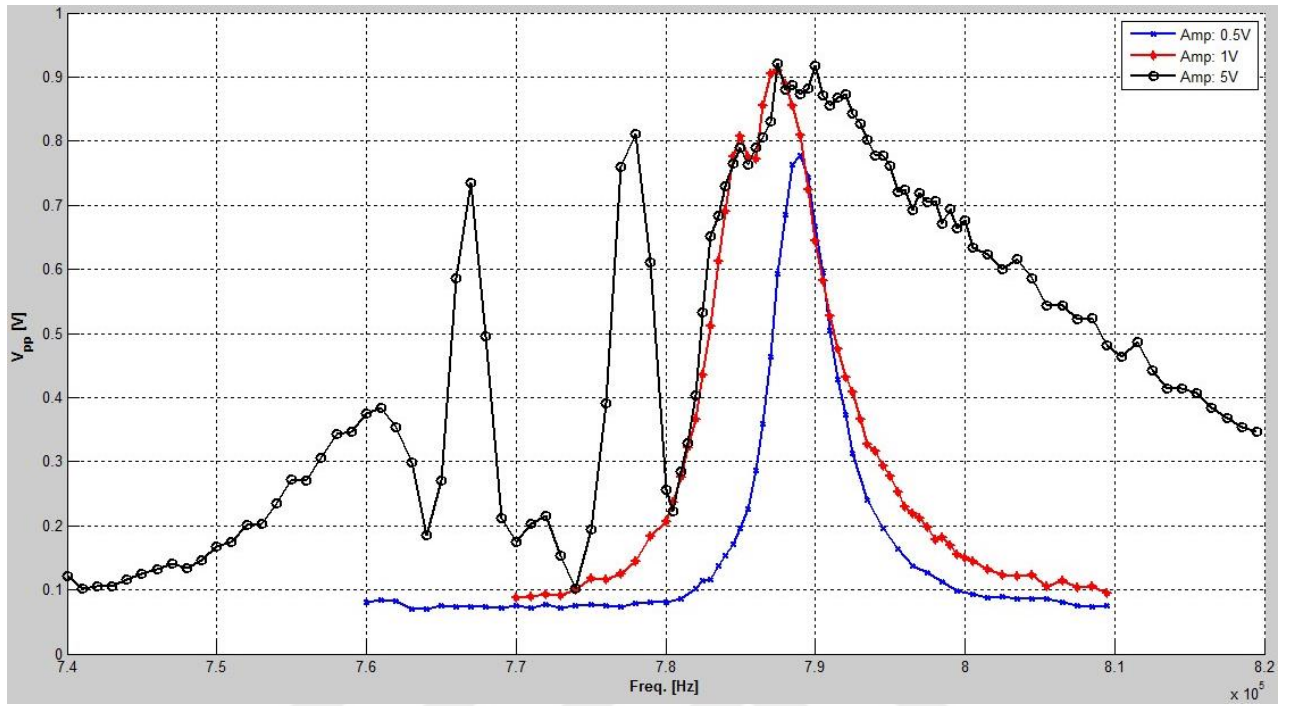


Figure 5.8: The resonator response with amplitude

Chapter 6

CONCLUSION

Two actuation and readout methods, magnetic actuation – optical readout and electrostatic actuation – capacitive readout, are proposed to accomplish the idea of a bi-directional frequency tuning of a microfabricated mechanical resonator. Stress effect is numerically modeled and verified by FEM analysis for both actuation and readout systems. In addition, some case studies are presented for electrostatic actuation and capacitive readout systems. Two fabrication flow processes are designed for two actuation and readout systems. Two mask and alignment procedures are proposed to achieve a higher resolution in fabrication of electrodes. However, this procedure could not be achieved due to lack of alignment resolution. Therefore, instead of electrostatic actuation and capacitive readout system, Magnetic actuation and optical readout is selected and the fabrication is proceeded without alignment procedure. As a result of fabrication process a micromechanical resonator is fabricated with a thickness of $4.6\mu m$, a width of $5\mu m$, and a length of $160\mu m$.

Experiments and measurements are carried out for magnetic actuation and optical readout methods in order to observe and verify two tuning methods. The first method, magnetomotive tuning, is used not only for softening the resonance frequency but also for exciting the micromechanical resonator. Actuation and frequency tunings are executed simultaneously by an AC voltage (V_{pp}) and a dc offset voltage is applied on the micromechanical resonator respectively, in presence of uniform magnetic field. Experiments are conducted by varying aforementioned voltages. An increase in softening effect is observed as the offset voltage is increased. The resonance frequency is shifted from 789 kHz to 683 kHz and k_{eff} is decreased 25% for the maximum offset voltage of 4V. The frequency tuning range is calculated to be -13% for magnetomotive tuning method.

The second frequency tuning method is the chip-bending technique. To investigate the outcomes of this technique on frequency tuning, a MEMS chip is placed on an aluminum platform and fixed at two sides. The screw placed beneath the MEMS chip is tightened to bend the chip. The bending of the chip stretches the micromechanical resonator which is located at the center of it. This stretch induces strain in the resonator, which generates a shift in the resonance frequency of the resonator due to the hardening effect. As a consequence of this technique, k_{eff} is increased by 14.7% and the resonance frequency is shifted by 8%, from 789 kHz to 854 kHz.

Simultaneous use of two mechanisms explained above arises a variation in tuning range of those methods. When the strain is maximized using the chip-bending method, the frequency tuning range of the magnetomotive technique is decreased by -12%. On the other hand, the frequency tuning range of the chip-bending method is increased in the presence of magnetomotive tuning force.

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