Pak. J. Engg. Appl. Sci. Vol. 25 July, 2019 (*p.* 43–51)

Modal Analysis of Micro-Electromechanical Systems

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Abstract

Dynamics of micro sensor has been studied in this research to check the sensitivity of 2 models having a difference in their substrate material. The sensitivity can be seen by calculating the natural frequencies, FRF curves, damping ratios and Quality factors. These parameters were derived using ANSYS simulation for both models and then results were compared to check the most sensitive model. Effects of ambient pressures on dynamics of two different micro cantilevers arrays were studied using ANSYS simulations. One array had substrate of N Type Silicon while other model was assigned Quartz as its substrate material, while the beams of both models had same material of polysilicon. Modal and Transient analyses were performed to obtain resonance frequencies and FRF curves of all beams. FRF curves were analyzed to obtain damping ratios and quality factors for each beam of both models. Comparison between resonance frequencies, damping ratios and Quality factors of two arrays were to see the effects of substrate material over sensitivity of array. One of the geometric parameters (Gap height) was also studied under ambient pressures to check the dependency of energy dissipation mechanism over gap height of micro beams form their substrate. Comparison of Natural Frequencies, FRF curves, damping ratios and Quality factor revealed that Quartz substrate model is good to be used in sensitive applications than N Type Silicon model.

Key Words: Resonance Frequencies, FRF Curves; Damping Ratio, Quality Factor, Micro Cantilever Arrays

1. Introduction

MEMS are the tiny machines which perform combined electrical and mechanical functions to complete a task. These devices get excited from some external agency like ambient pressure or electric actuation, by which they are deflected or start to oscillate [1]. Such type of mechanical movements make their connection to their substrate (which senses the motion, transforms the mechanical information to electrical signal and decides for the response to be carry out) as it is in the case of accelerometers, gyroscope and micro cantilevers [2]. Micro cantilevers are used as energy harvesters to convert ambient vibration in to electric power (in micro watts). Micro cantilevers are used at airports and cellular phones in the form of arrays to multiply its benefits.

Performance of these micro devices depends on their sensitivity, which varies with geometric parameters (length, width, thickness, and gap height), shape and substrate materials in case of sensitive applications. Sensitivity of micro systems can be evaluated experimentally as well as using simulation techniques by obtaining resonance frequencies, FRF curves, damping ratios and Quality factors.

Number of researches is made to see the variation of sensitivity with respect to length, width, gap height, thickness, shape and material of substrate. For example, Ozdoganlar studied the effects of gap height of the micro cantilevers form their substrate over their damping characteristics. It is found that gap height and damping are in inverse relation to each other, i.e higher the gap height lower will be the damping. He calculated the damping of micro cantilevers array at a range of ambient pressure and compared the effects of pressure over structural and air damping and concluded that air damping is dominant at higher pressures while structural damping is dominant at pressures near vacuum. [3]; [4]. Blom studied effects of pressures and geometric parameters over natural frequencies and damping of micro cantilevers and found that damping becomes dependent over thickness of the beams at critical pressures and independent of length while it relates to thickness in inverse at critical pressure [5]. Yasumura analyzed micro cantilever array by calculating its Quality factor and found that reduced thickness results in reduced Q factor [6]. Cheng performed static analysis of thin films at different thicknesses and used it to obtain young's modulus while dynamic analysis to get the natural frequencies [7]. Kahrobiyan studied that sensitivity of micro cantilevers is greatly affected by geometric parameters like when ratio of thickness to length becomes larger than 10 [8]. Borkar studied the effects of length, width, thickness over sensitivity of MC using modeling and simulation tools. It is observed that increased thickness requires higher actuation voltage while increased length requires less voltage for actuation [9]. Ansari studied sensitivity of MC with hole near its fixed end using FEM simulation and found thickness is directly related to sensitivity of MC of this design [10]. Hawari studied the effects of shape over sensitivity of MCs using ANSYS simulations he obtained maximum deflections and natural frequencies for 6 different shapes to study their sensitivity [11]. Paul studied the effects of substrate materials over sensitivity of MC and concluded that it should be necessarily accounted in sensitive applications [12].

In the study of nonlinear dynamics of MCs it is seen that main cause of these non-linearity are flexural rigidity especially these are occurring because of varying lengths of the beams [13-16].

In the present study, effects of ambient pressures, effects of this pressure over gap heights of a micro cantilevers array and effects of substrate materials are studied. Modal Analysis and Transient Analysis are performed in Ansys Workbench to obtain the natural frequencies of the MC Array and FRF curves for two models having difference in their substrate materials. These natural frequencies provided with a direct comparison of sensitivity of two models while FRF curves are analyzed to obtain damping ratios and quality factors of both models. A comparison of damping ratios and quality factor has been made between two models to check for the more sensitive model on these ambient pressures.

2. Methodology

2.1 Modeling

The comb like structure is modeled in Ansys Design modeler in micro units. Base of the structure (substrate) is modeled first so that other beams structures may be constructed over it. Base has dimensions as 1000*300µm while its thickness is kept as 30µm. 2 similar sets of sketches are constructed, each set consisting of 4 beams of lengths 800,700,600 and 300 µm. The sketches are extruded later to get two set of beams. All the beams are having same width of 20µm. These sketches are also used to print the faces under the beams to get the perfect mesh. The two sets are different in their gap heights from the substrate and the thickness of the beams which will be described later.

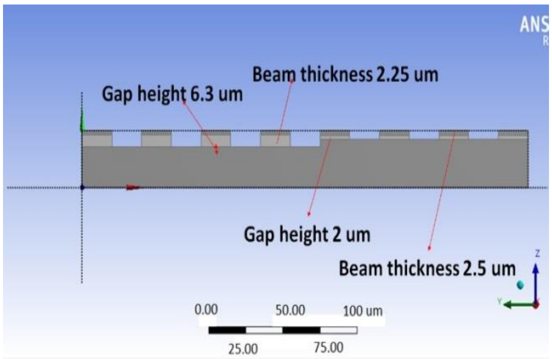

Fig. 1: 2 sets of beams showing difference of gap height from beam to substrate

Another 2 sets of sketches are again drawn and extruded to remove the materials between the beams to give them the shape of cantilever. At the end the sketches are drawn and extruded to get the different gap heights and thicknesses to make the beams set different. Upper set is given the thickness of 2.25 µm and gap height of 6.3 µm while lower set is given gap height of 2.5µm and thickness of beams is kept as 2.5µm as its cross-sectional view is shown in Fig.1 and an isometric view is also shown in Fig. 2, difference of thickness and gap heights is indicated by arrows.

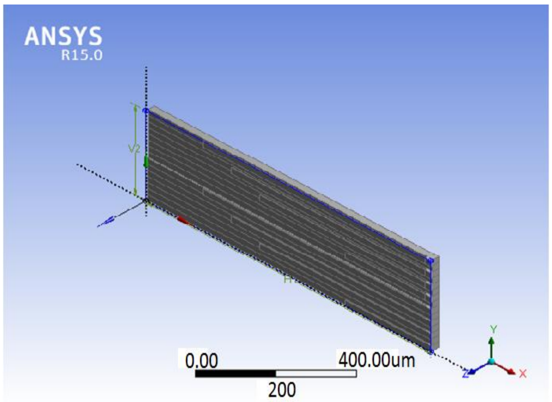

Fig. 2: MCs Array; upper set have thickness of 2.25µm and lower set has thickness of 2.5µm

2.2 Material Assignment

Simulations are done over 2 different models having different substrates while the beams material is same for both models. First model is assigned material of N Type silicon while 2nd is assigned as Quartz. Beams are made of polysilicon for both models. The materials properties are given in the table 1 below:

Table 1: Material properties for beams and substrates

Beam's Materials	Young's Modulus (Pa)	Poisson's Ratio	Density
Polysilicon	1.6e11	0.22	2329
Substrate	Young's Modulus Pa	Poisson's Ratio	Density
Silicon	1.68e11	0.23	2329
Quartz	7.6e10	0.17	2200

2.3 Mesh

A fine mapped mesh is generated over the array.

2.4 Boundary Conditions

Modal Analysis required fixed support to get the natural frequencies. Modal frequencies are obtained for both models. Fixed support is shown in blue color in Fig. 3.

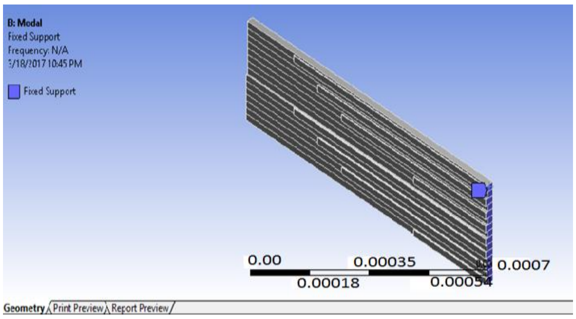

Fig. 3: Boundary condition for modal analysis

Transient Analysis required time varying load along with fixed support. A range of ambient pressures are applied to see the effects of pressures over the structure. Pressure is applied for 1ms and then removed to observe the structure behavior for next 10s. Pressure is varied from experiment to experiment from 10Pa to 10MPa. Red surface expresses the applied pressure in Fig. 4.

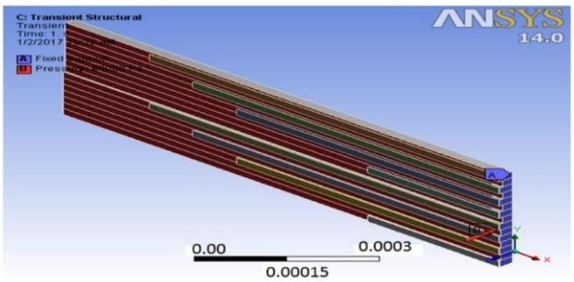

Fig. 4: Boundary conditions for transient analysis

Both models are solved and their FRF curves are obtained from time hits post processor to study the energy dissipation mechanism in the array.

FRF curves are analyzed using successive peaks method to calculate the log decrement curves for all beams individually using following relation (1):

$$\delta = \ln \frac{peak1}{peak2} \qquad (1)$$

This log decrement provided with damping ratio using following expression (2):

$$\zeta = \frac{\delta}{\sqrt{2\pi^2 + \delta^2}} \qquad (2)$$

Then Quality Factor is obtained using following relation (3):

$$Q = 0.5/\zeta \qquad (3)$$

3. Results and Discussions

3.1 Modal Analysis Based Results

Quartz substrate model demonstrated higher Natural frequencies than other model revealing its higher sensitivity than that of N Type silicon model.

Quartz natural frequency was found to be 4934.7 Hz while silicon model has first natural frequency of 4927.8. Comparison of their 6 natural frequencies is given in Table 2 below:

Table 2: Comparison of natural frequencies of 2 models

Mode	Frequency [Hz] Silicon	Frequency [Hz] Quartz
1	4927.8	4934.7
2	5470.1	5477.4
3	6478.9	6489.8
4	7190.5	7201.5
5	8897.5	8914.3
6	9874.2	9891.4

3.2 FRFs Based Results

Effect of Pressure—Oscillation amplitude are seen to be dissipated fastly at lower pressures because of high damping.

Effects of difference ambient pressures are shown in Figs. 5-8 below for both models: Effects of changing pressure from low to high pressures are shown for beams of different lengths to verify the results.

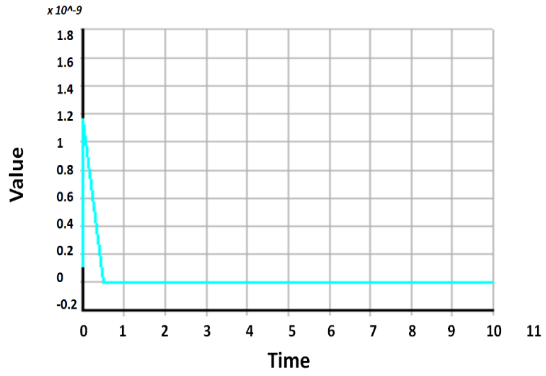

Fig. 5: Model with Quartz as substrate; FRF curves for beam with L=800µm

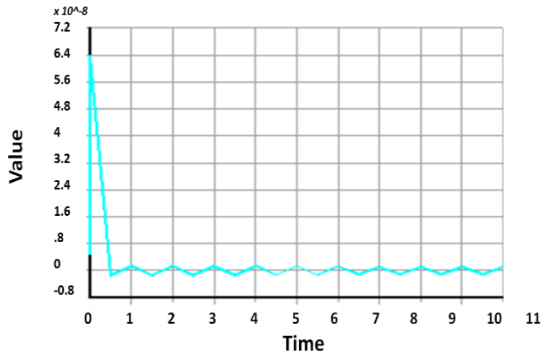

Fig. 6: Model with Quartz as substrate; FRF curves for beam with L=800µm

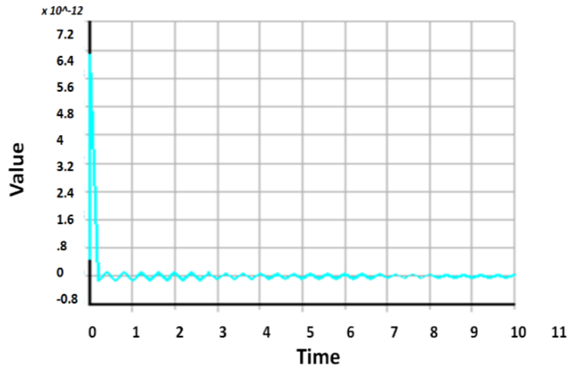

Fig. 7: Model with N Type Silicon as substrate; FRF curves for beam with L=700µm

Effect of Gap Height—Gap height and damping are observed to be inversely related to each other in such a way that higher gap height revealed low resistance to energy damping and Beams with lower gap height have higher damping thus the oscillations reduced faster**.**

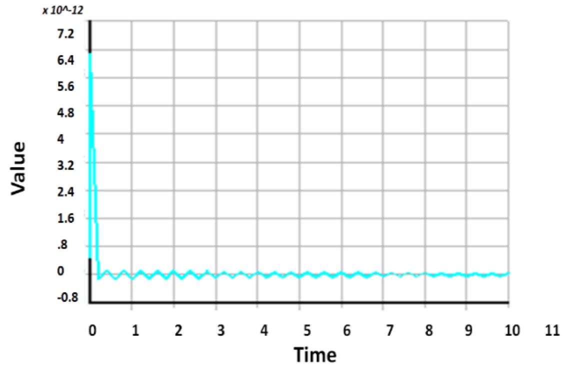

Fig. 8: Model with N Type Silicon as substrate; FRF curves for beam with L=700µm

Behaviors are same for effects of gap heights at different pressures these facts are reflected in the Fig.s 9-14 below:

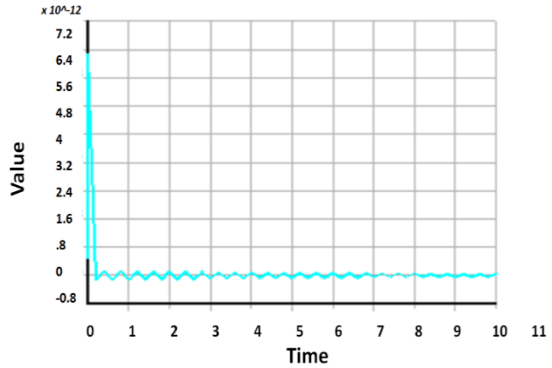

Fig. 9: Model 1: FRF Curves showing the effects of gap height h=6.3 µm on damping at P=10Pa, for beam with L=800 µm

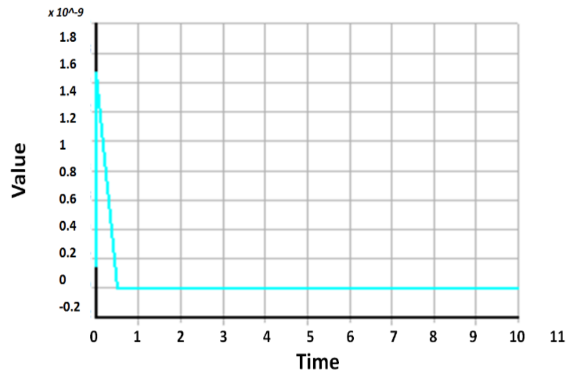

Fig. 10: Model 1: FRF Curves showing the effects of gap height h=2 µm on damping at P=10Pa, for beam with L=800 µm

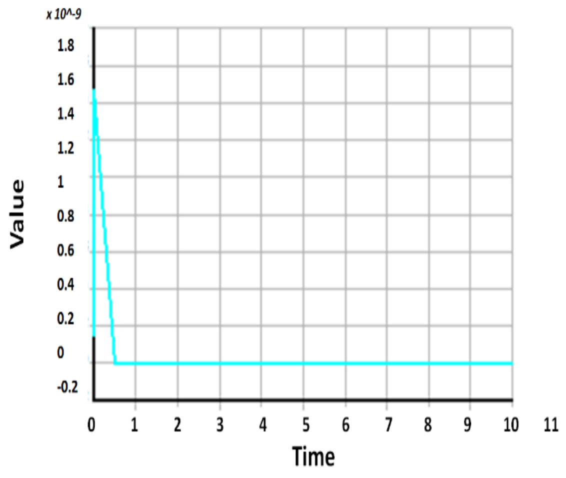

Fig. 11: Replication of results at higher pressure: P=1Mpa for beam with L=800 µm, h=6.3 µm

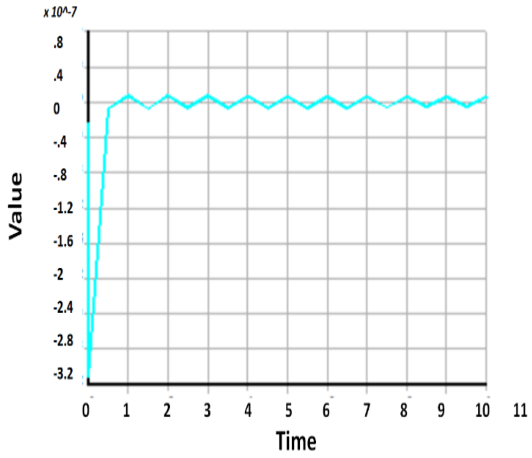

Fig. 12: Replication of results at higher pressure: P=1Mpa for beam with L=800 µm, h=2 µm

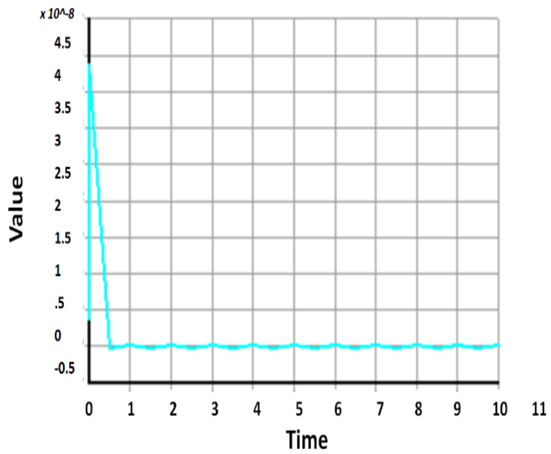

Fig. 13: FRF for beam with L=300µm and h= 6.3µm

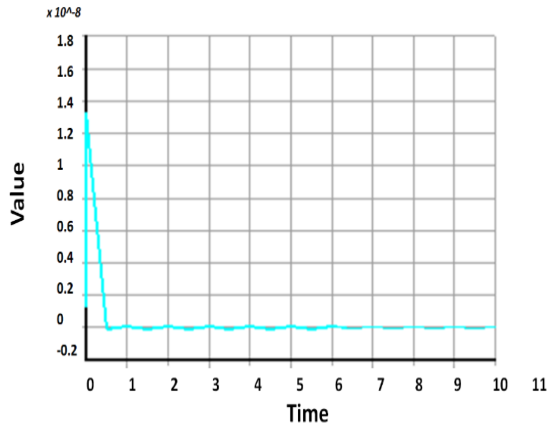

Fig. 14: FRF for beam with L=300µm and h= 2µm

3.2.1 Damping ratios and Quality factor

It is observed in all beams that damping is highest at lower pressures which indicate that the structural damping is higher at lower pressures or at pressure near vacuum, it decreases at higher pressures. Damping Ratios and Quality Factor express the nonlinear behavior because dynamics of each beam is being affected by neighboring beams oscillations.

Model with Quartz Substrate

Beams with identical thickness and gap heights indicate the same behavior at lower and higher pressures. Other variances in behavior and non linarites are due to different lengths and interactions of neighboring beams in the oscillations of each beam.

This fact is demonstrated in Fig.s 15 and 16 for one set of beams at same height and thickness so called the set of h=6.3 µm and the replication of results is again demonstrated in Fig.s 17 and 18 for the beam set with h=2µm.

In both models it is revealed that at lower pressure damping is higher and at higher pressure it gets lowered. While non linarites in the mid of each graph have been seen are because of the nonlinear dynamics of the structure and interruptions of the neighboring beams oscillations.

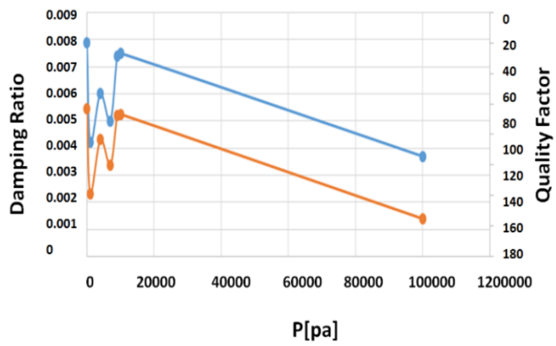

Fig. 15: L=700µm & h=6.3µm Thickness=2.25µm

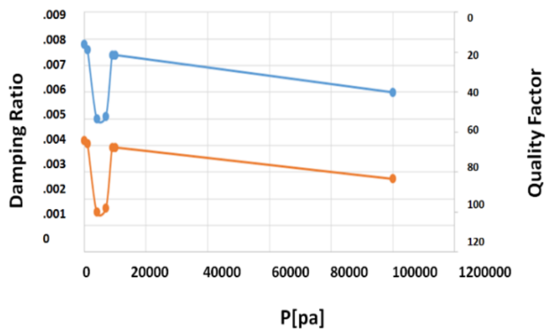

Fig. 16: L=300µm & h=6.3µm Thickness=2.25µm

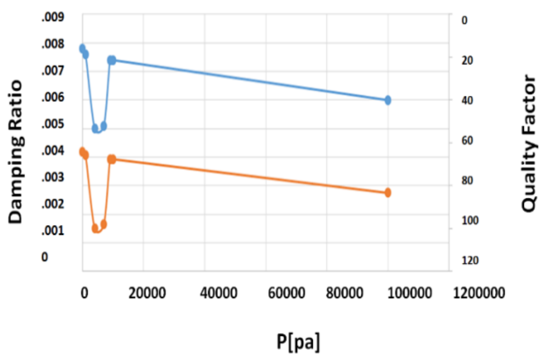

Fig. 17: Replication of results

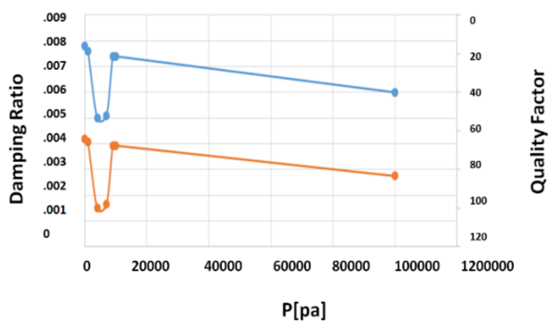

Fig.18: Replication of results

Model with N Type Silicon Substrate

The trend of high damping at lower pressure and vice versa was seen in this case but with some different type of non-linearity affects because of different material model.

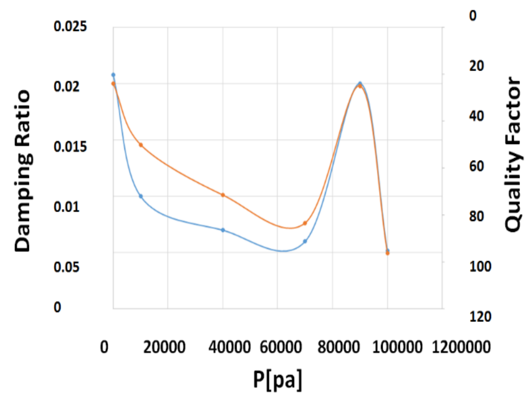

Fig. 19: L=700µm & h=6.3µm Thickness=2.25µm

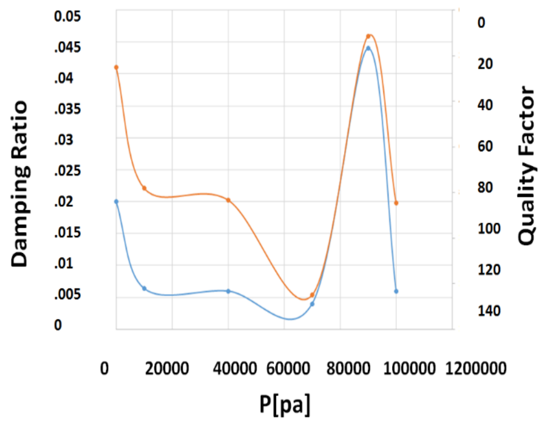

Fig. 20: L= 300µm & h= 6.3µm, Thickness= 2.25µm

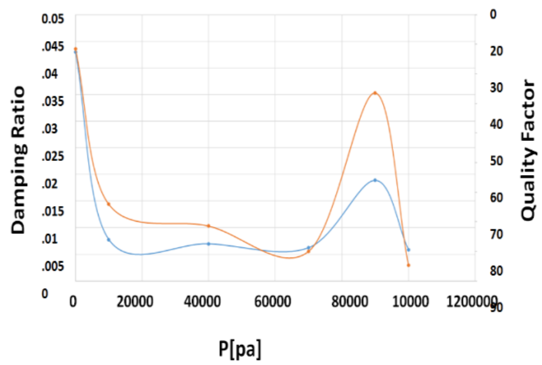

Fig. 21: Replication of results

Fig. 15 and 16 show the relation of pressure against damping ratios and quality factors for the beam set with h h=6.3 µm while in Fig.s 19-22, repeated experimental results are shown for other beam set with h=2 µm. non linarites are because of neighboring beams oscillations as well as difference in length.

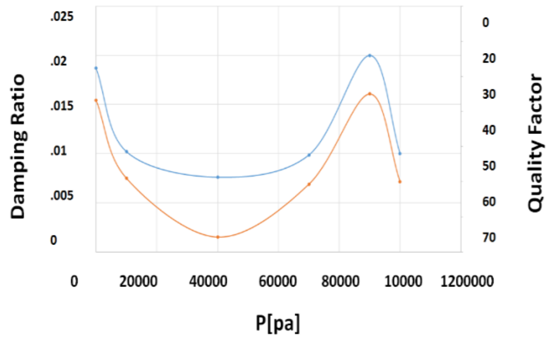

Fig. 22: Replication of results

3.2.2 Comparison of damping ratios between 2 Models

The model with Quartz substrate shows relatively less nonlinear behavior than silicon model.

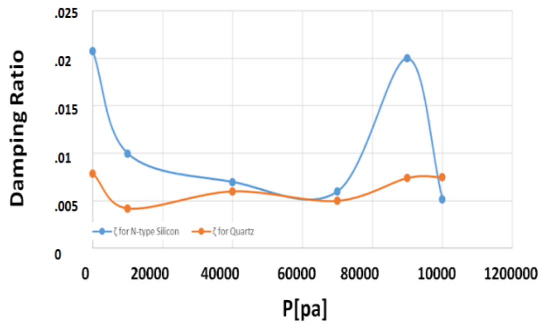

Fig. 23: Comparison of damping ratios for beam with L=700µm and h=6.3µm

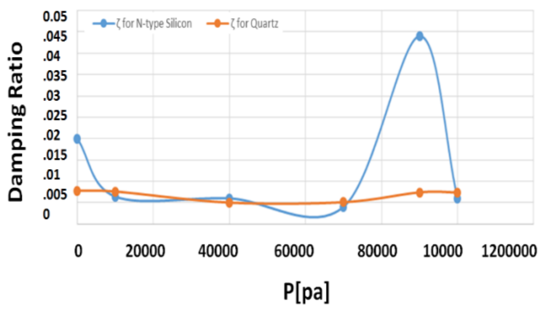

Fig. 24: Comparison of damping ratios for beam with L=300µm and h=6.3µm

The Quartz substrate model demonstrates less damping (low energy dissipation) and hence it's more sensitive than model 2 with substrate material of silicon, as revealed in Fig.s (23-26).

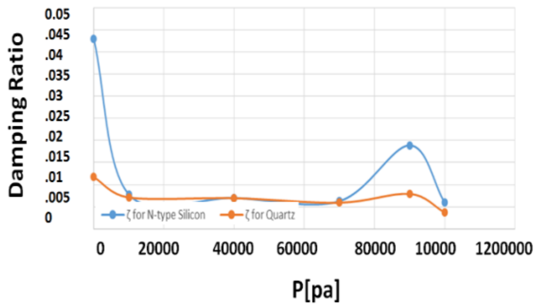

Fig. 25: Comparison of damping ratios for beam with L=700µm and h=2µm

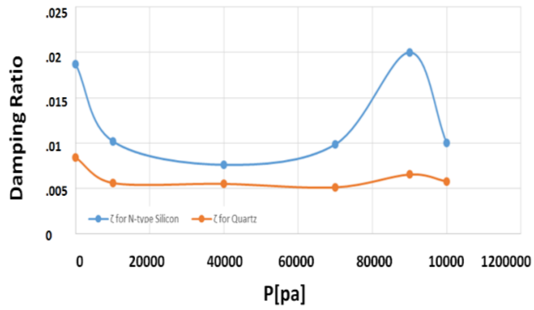

Fig. 26: Comparison of damping ratios for beam with L=300µm and h=2µm

3.2.3 Comparisons of Quality factor between 2 Model

The Quartz model shows higher Quality of vibrations and less resistance to motion decaying. Since Quality Factor is an inverse relation of damping and same relations must be seen in terms of Quality factor, so it is revealed again for both beams having different gap heights and demonstrated in Fig.s (27-30).

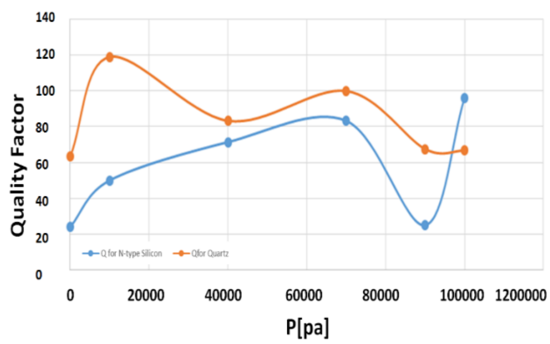

Fig. 27: Comparison of Quality Factors for beam with L=700µm & h=6.3µm

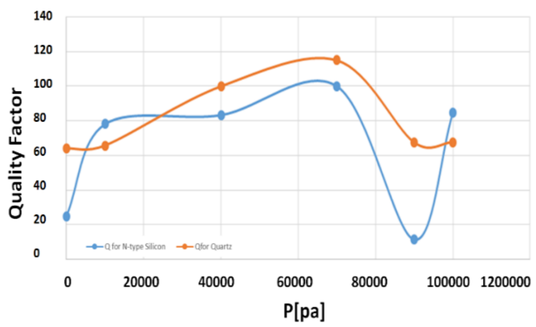

Fig. 28: Comparison of Quality Factors for beam with L=300μm & h=6.3μm

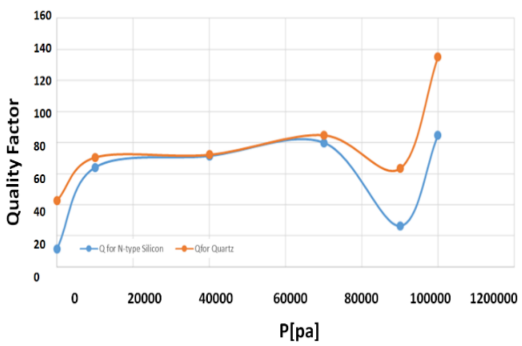

Fig. 29: Comparison of Quality Factors for beam with L=700μm & h=2μm

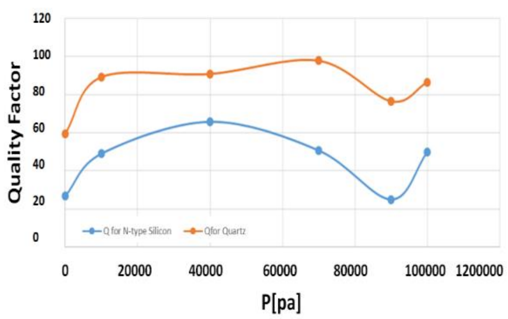

Fig. 30: Comparison of Quality Factors for beam with L=300μm & h=2μm

4. Conclusions

- Resonance Frequencies of 2 models are compared and found that Quartz models has higher frequencies than those of N Type Silicon model showing its higher sensitivity to the ambient pressures.
- FRFs curves attained at lower pressure have low oscillation amplitude, dissipated faster than the curves achieved at higher pressures verifying the fact that structural damping at higher pressures is lower than damping at vacuum or near vacuum pressures.
- FRF curves revealed lower oscillation amplitude and decayed faster for the beams with low gap height from the substrate. The case has been found to be conflicting for the beam with less thickness and larger gap height. But the effect of gap height is same over all lengths of beams validating this fact.
- Quartz model has been assessed against Damping Ratios and Q factor and it is perceived that the beams having same thickness and gap heights demonstrate almost the same behavior, specifically at lowest and highest applied pressures. The non linearities seen in the middle are because of differences in length and interruptions in oscillations from neighboring beams as all the beams vibrate at the same time and influence each other behavior
- N Type silicon model also demonstrates the aforementioned behavior at lower pressure but non linearities are seen to be more than that of Quartz model
- Comparisons of charts of damping ratios and quality factor revealed the fact obtained from modal analysis that Quartz model has higher sensitivity than N Type silicon model. Hence it can be deduced that Quartz model has higher capability to be useful for more sensitive applications because of its less resistance to vibration and less nonlinear behavior.

5. Future Research Recommendations

Nonlinear dynamics arising due to length differences, thickness and interfering effects of neighboring beams on each beam oscillations can be considered for future research.

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