Analysis and Study of Quality Factor for Simple Fixed Beam MEMS Resonator

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Abstract— This paper focus the study of Quality factor of MEMS resonators are analyzed by varying the material of cantilever beam. Modeling and simulation of Thermoelastic Damping (TED) is an important issue in the development of actuators, MEMS resonators, and filters. The energy dissipation mechanism by TED highly affects the Q factor. Here we uses material s Ge, GaAs, PolySi, Single Crystal Si. Out of these material Single crystal shows the better value of Qfactor at eigen frequency (6.304492e5). Modeling and simulation of TED effect on various resonators are done by using COMSOL Multiphysics software. Thus the effect of material properties on the Q factor is also studied in the case of simple fixed-fixed beam resonators.

Keyword— MEMS, NEMS, Eigen frequency analysis, Simple fixed beam resonators, COMSOL, Displacement.

II. INTRODUCTION

Thermoelastic damping has been identified as an important loss mechanism in MEMS resonators [l]-[4].With the advent of the microelectromechanical systems (MEMS) technology, MEMS resonators with low weight, small size, low consumption energy and high durability have been extensively utilised for various sensing and wireless communications applications such as accelerometers, gyroscopes , oscillators , and filters [1].

The main advantage of MEMS resonators lies in the possible integration onto the silicon based IC platforms. Silicon MEMS resonators are positioned as potential competitors to quartz crystal resonators [5] [6] . However, to compete with the mature, well-established quartz technology, silicon MEMS resonators must first provide the same or better performance characteristics. For all these applications, it is important to design and fabricate micro electromechanical resonators with very high quality factors (Q factors) or very little energy loss. Q factor is defined as the ratio of total system energy to dissipation that occurs due to various damping mechanisms. Thermoelastic damping is considered to be one of the most important factors to elicit energy dissipation due to the irreversible heat flow of oscillating structures in the micro scales. In this study, the Q-factor for thermo elastic damping is investigated in various RF MEMS resonators, because a high quality factor directly translates to high signal-to-noise ratio, high resolution, and low power consumption. A low value of Q implies greater dissipation of energy and results in reduced sensitivity, degraded spectral purity and increased power consumption [7]. It is therefore desirable to eliminate, or mitigate, as many mechanisms of dissipation as possible. Various energy dissipation mechanisms exist in microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) [6]. Several different mechanisms contribute to energy dissipation such as air-damping, squeezed-film damping, acoustic radiation from the supports of the beam (also called anchor or clamping losses), damping due to crystallographic defects (such as dislocations and grain boundaries) and thermo elastic damping [8]. Some of these sources of energy losses are considered extrinsic such that they can be altered by changing the design or operating conditions . For example, operating the device in vacuum and designing nonintrusive supports reduces air-damping and clamping losses, respectively. However, intrinsic sources of dissipation, such as thermo elastic damping, impose a strict upper limit on the attainable quality factors of a resonator

III. THERMOELASTIC DAMPING

Zener predicted that thermo elastic losses may be a limitation to the maximum Q factor of a resonator [9]. Basically, the principle of thermoelstic damping is the following: When a mechanical structure vibrates, there are regions where compressive stress occurs and others where tensile stress occurs, in a cyclic way given by the vibration frequency. Accordingly, compressed regions heat up and stretched regions cool down. Hence a temperature gradient is established between different regions of the system.

However, to set the mechanical system in vibration, energy must be provided, leading to a non-equilibrium state having an excess of energy. Disregarding thermo elastic damping, the vibration could persist indefinitely in an elastic body that is perfectly isolated from its environment. However, local temperature gradients lead to irreversible flow of heat, which is a dissipation mechanism that attenuates the vibration until complete rest is achieved. Heat flow through a thermal resistance will result in power dissipation, which is a Q limiting energy loss mechanism. This loss is the most prominent when the period of the resonator is of the same order as the thermal time constant across the beam. From a thermodynamic standpoint TED can be viewed as the initial flexing of the beam which causes the temperature profile of the beam to become more ordered. If the beam re-establishes equilibrium this order is lost, resulting in an irrecoverable increase in entropy, which is an energy loss[10]

IV. SIMPLE FIXED-FIXED TYPE BEAM RESONATORS

The resonator is a beam of silicon with length 400 µm, height 12 µm, and width 20 µm as shown in Fig.1. The beam is fixed at both ends, and it vibrates in a flexural mode in the *z* direction (that is, along the smallest dimension). The model assumes that the vibration takes place in vacuum. Thus there is no transfer of heat from the free boundaries. The model also assumes that he contact boundaries are thermally insulated [8].

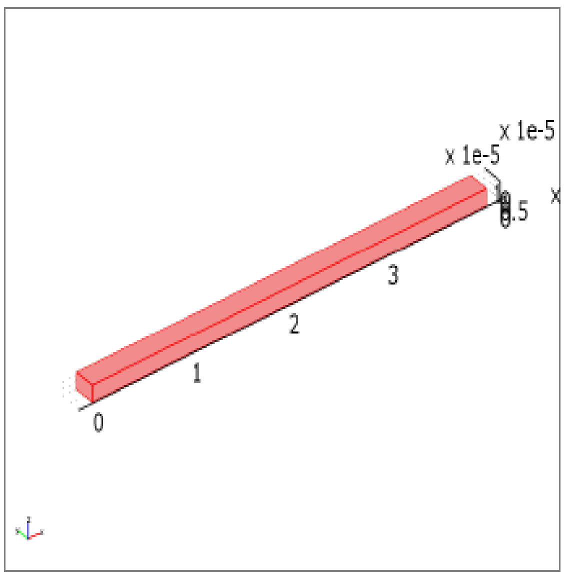

Figure 1: Geometry of a simple fixed-fixed type beam resonator.

A high Q value is a key factor of a MEMS resonator. It it essential that the resonator vibrates consistently at the desired frequency and that it requires as little energy as possible to maintain its vibration. These features can be characterized by the resonator's Q value, which is a measure of the sharpness of its spectrum's peak. There are several ways to define the Q value, for example:

$$Q = \frac{2\pi W_0}{\Delta W} = \frac{\omega_0}{2\delta} = \frac{\omega_0}{\Delta\omega}$$

where W_0 is the total stored vibrational energy, ΔW is the energy lost per cycle, ω_0 is the natural angular frequency, δ is the damping factor (vibration decays exponentially with δt), and $\Delta\omega$ is the half power width of the spectrum.

In order to improve the resonator, the designer needs to consider all aspect that produce damping and noise to the system. For example, resonators are usually run in vacuum to minimize effects of air and squeeze-film damping.

For simple structures, researchers have developed analytical expressions to estimate thermoelastic damping. According to Zener [11] and [12], you can calculate the Q value for a resonator with a single thermal mode by:

$$\frac{1}{Q} = \left(\frac{E\alpha^2 T_0}{\rho C_p}\right)\left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)$$

where E is the Young's modulus, α is the thermal expansion coefficient, T_0 is the resonator temperature at rest, ρ is the density, C_p is the heat capacity of the material, ω is the vibration angular frequency, and τ is the thermal relaxation time of the system. Thus it is easy to see that in order to have good Q value, the system needs to be designed so that ω is as far from $1/\tau$ as possible.

The natural frequency of a beam clamped at both ends can be calculated as [1]

$$\omega_0 = a_0^2 \frac{h}{L^2}\sqrt{\frac{E}{12\rho}}$$

where a_0 equals 4.730; h and L are the thickness and length of the beam, respectively; and E and ρ are material parameters as above.

The thermal relaxation time of the beam is given by

$$\tau = \frac{\rho C_p h^2}{\pi^2 \kappa}$$

where κ is the thermal conductivity and other parameters are as above.

To gain information about the quality of the resonator, it is of interest to know its natural frequency and Q value. To do this, run an eigenfrequency analysis to find the eigenvalues for this system. For a system with damping, the eigenvalue λ contains information about the natural frequency and Q value [6]. Fig.2 shows the variation of TED factor with eigen frequency. From the analysis it is clear that at some particular frequency internal friction (TED factor) is maximum and this corresponds to the maximum dissipation of the resonator

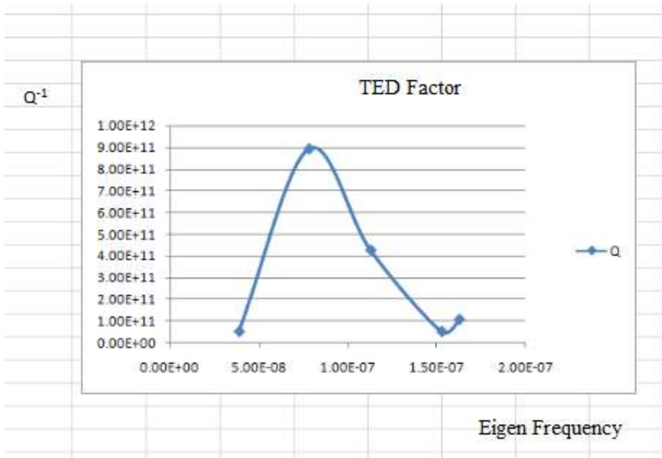

Figure. 2: TED Factor versus Eigen Frequency of a Simple fixed-fixed beam resonator.

Q factor of a simple fixed-fixed type resonator is highly material dependent. It depends on the parameters such as Young's Modulus (E), Thermal expansion Coefficient (α), Density of the material (ρ) and Poisson's ratio (υ). The variation of Q factor with thermoelastic damping (TED) is summarized in Table I.

Properties	Ge	GaAs	PolySi	Single Crystal Si
E	1.03E+11	8.59E+10	1.60E+11	1.57E+02
v	0.26	0.31	0.22	0.3
α	5.90E-06	5.70E-06	2.60E-06	2.60E-06
ρ	5323	5316	2.32E+03	2330
Eigen Freq	3.32E+03	8.45E+05	6.39E+05	6.30E+05
QwithTED	9.25E+05	4116.153	1.01E+04	10169.89

Table I: shows the variation of Q factor (with TED effect) with materials.

It is seen that compared to Ge, GaAs, PolySi, Single Crystal Si provides better Q value and less thermoelastic damping. The performance of Single Crystal Si based resonator in terms of Q factor with TED show better result than others.

V. SIMULATION RESULTS

There are various material which shows the variation in eigenfrequency by varying temperature so the quality of the material must be need to analysed for proper designing of MEMS resonator. Thus the following simulation is done as below given:-

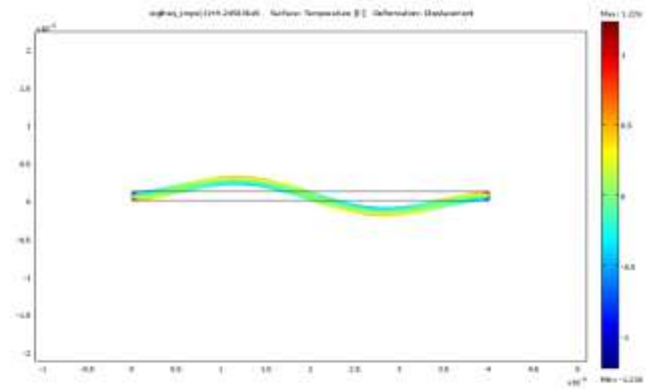

Figure 3: First eigenmode and temperature distribution of Ge material.

This figure 3 shows variation in temperature of Ge according to the eigenfrequency analyzed Quality factor 9.245036e5 by using TED

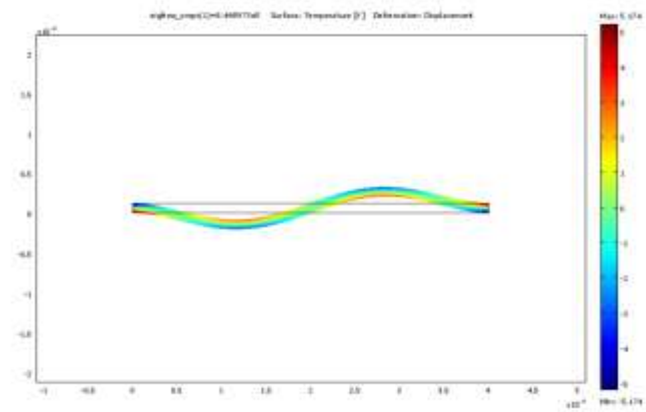

Figure 4: First eigenmode and temperature distribution of the GaAs material.

This figure 4 shows variation in temperature of GaAs according to the eigenfrequency analyzed Quality factor 4116.152562 by using TED.

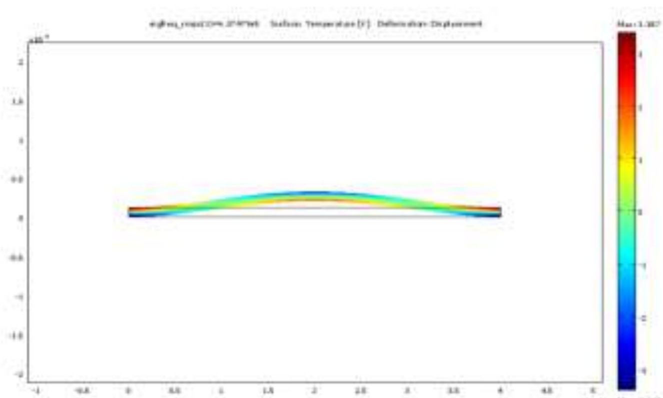

Figure 5: First eigenmode and temperature distribution of the PolySi

This figure 5 shows variation in temperature of PolySi according to the eigenfrequency analyzed Quality factor 10076.460279 by using TED.

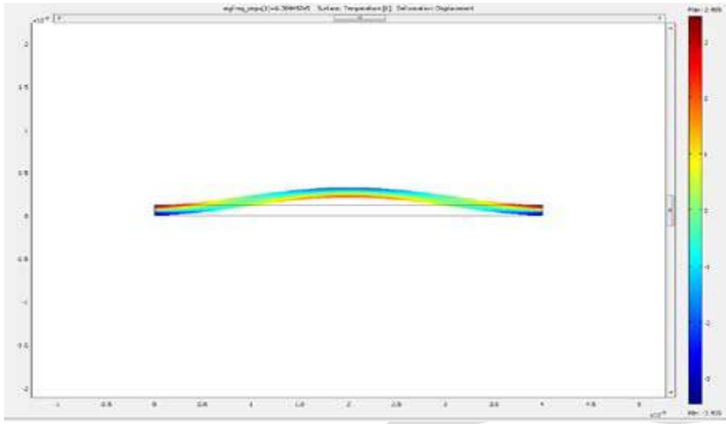

Figure 6: Simulated output of a Simple fixed-fixed beam resonator-2D showing the first eigen mode and temperature distribution (Eigen frequency=630.449KHz).

This figure 6 shows variation in temperature of PolySi according to the eigenfrequency analyzed Quality factor 10169.891942 by using TED.

V. CONCLUSION

Here we concluded that all the material i.e.Ge, GaAs, Poly Si, Single Crystal Si shows various changes in Quality factor when eigen frequency changes respectively. By using the TED factor ,Quality of various material analysed. Single Crystal Si intresting material of its high Q factor i.e 10170. Also PolySi shows the better Q value than when compare with GaAs, Ge but it nevertheless gives better result than Single Crystal Si. So due to high quality factor of Single Crystal Si , it is used in Tunnable piezoelectric Actutaor The analysis is done by using a high end software COMSOL Multiphysics. One important parameter is to able to predict the Q factor of the structure and have accurate design guidelines to reduces the energy losses.

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