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MEMS Resonator for RF Applications

Vivek Harshey*, Amol Morankar, Dr. R.M. Patrikar
Visvesvaraya National Institute of Technology, Nagpur (INDIA)
*Corresponding author: National MEMS Design Centre
Electronics and Computer Science Engineering Department
VNIT Nagpur (India) PIN: 440010
harshey.vivek@gmail.com

Abstract: As the transistors are scaling so are the devices made using this technology apart from RF circuits. This paper presents use of a simple fixed-fixed beam as a RF resonator which can be scaled like transistor with improved performance. This resonator can then be used in the oscillator and filter part of RF transceiver, which can actually be fabricated on chip without losing its Q-factor. Paper also presents the simulation results of Comsol Multiphysics, which were used to evaluate pull in voltage, Q-factor, resonant frequency and thermo elastic damping of this resonator.

Keywords: RF transceiver, filter, fixed-fixed beam, High-Q on chip

1. Introduction

Vibrating mechanical tank components, such as quartz crystals and surface acoustic wave (SAW) resonators with Q's in the range of 10e3-10e6, are widely used to implement high-Q oscillators and band pass filters in the radio frequency (RF) and intermediate frequency (IF) stages of communication transceivers. Due to orders of magnitude higher quality factor Q, filters using such technologies greatly outperform comparable filters implemented using conventional transistor technologies in insertion loss, percent bandwidth, achievable rejection, and dynamic range. Oscillators also benefit substantially from high Q, as their phase noise at important offsets is often inversely proportional to the square of Q .Unfortunately, however, the crystal and SAW devices that provide beneficial high Q's are off-chip components that must interface with transistor electronics at the board level, posing a significant bottleneck against the ultimate miniaturization of wireless communicators, and trumpeting a need for on-chip replacements.

The rapid growth of IC-compatible micromachining technologies that yield micro-scale, high-*Q* tank components may now bring the first of the above strategies closer to reality. Specifically, the high-*Q* RF and IF filters, oscillators, and couplers, currently implemented via off-chip resonators and discrete passives may now potentially be realized on the micro-scale using micro-machined equivalents based on a variety of novel devices, including high-*Q* on-chip mechanical resonators, may now not only provide an attractive solution to the above, but might also enable a paradigm-shift in transceiver design where the advantages of high-Q (e.g., in filters and oscillators). This paper will discuss designing of resonator and effects of various parameters on the resonator behavior.

2. Principle

The principle of operation of a mechanical resonator is same as that of guitar string. A guitar string of 25” made from Ni and steel tuned to a note A vibrates at exactly 110 Hz this guitar string is actually mechanically selecting this frequency, and is doing so with a *Q* on the order of 350, which is ~50 times more frequency selective than a typical on-chip electrical *LC* tank. The RF and IF filters are also doing the same thing but at much higher frequencies. These frequencies can be achieved by scaling , similar to transistor technology. IC-compatible materials (such as polysilicon), supporting it at nodes rather than at its ends (to minimize anchor losses), and exciting it electro-statically rather than plucking it, one can achieve a free-free beam (FF-beam) resonator.

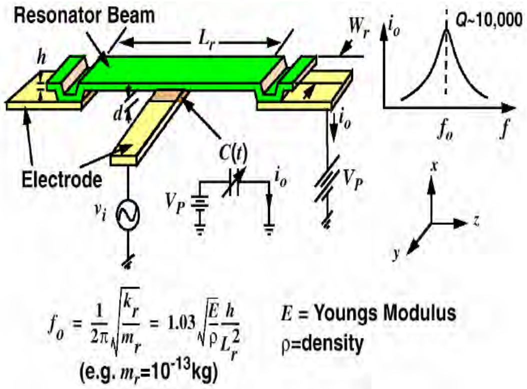


Figure 1: Fixed-Fixed beam resoanator

Consider a fixed-fixed beam as shown in figure 1. Here the moving and fixed part forms two electrodes of a capacitor. A dc actuation voltage is applied to the moving part of the beam and an ac signal is applied to the fixed. The dc voltage is needed to create the necessary electrostatic force for the movement of the beam. The electrostatic force will bend the beam but the beam will oscillate only if this force oscillates, which is done by applying an ac signal at the fixed electrode. The beam oscillates with maximum amplitude at its resonance frequency

$$f_0 = 1.03\sqrt{\frac{E}{\rho}}\,\frac{h}{Lr^2} \qquad (1)$$

where E is the Young's modulus of the material and ρ is the mass density of the material , h is the height or thickness of the beam and L_r is the beam length. According to the equation for resonance frequency the frequency increases as the length decreases. This oscillation of the beam changes the gap between the electrodes also changing the capacitance between the two electrodes. The variation in capacitance produces an ac current given by

$$i_0 = Vp\frac{dC}{dt} \qquad (2)$$

The variation in capacitance is maximum at f_0 and hence the current. Practically a mechanical transducer in the form of $\lambda/4$ length is used to connect two such beams, the ac input signal is applied to moving electrode of first beam and the output current is measured at the moving electrode of the second beam. This current can then be amplified by normal transistor circuit, thus giving a very high Q filter on chip (fig 2).

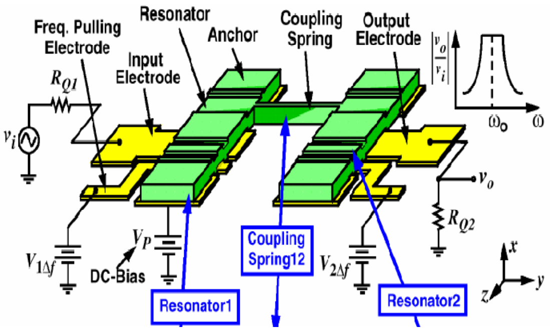


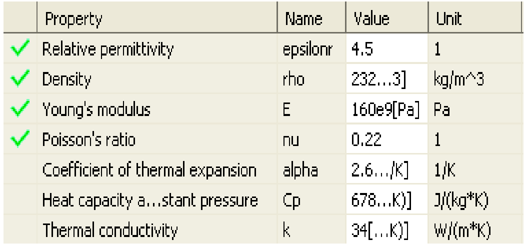
Figure 2: MEMS filer using fixed-fixed beam

3. Analysis using COMSOL Multiphysics

The structure was built in 3D builder of the Comsol Multiphysics (ver. 4.1)
The resonator has following dimensions for a 10 MHz frequency

(Length) Lr = 40 µm
(Width) Wr = 8 µm
(Thickness) h = 2 µm
(Gap spacing) d = 0.1 µm

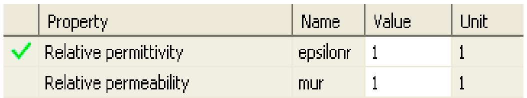
The material chosen for the resonator is poly-silicon having following material properties



	Property	Name	Value	Unit
✓	Relative permittivity	epsilonr	4.5	1
✓	Density	rho	232...3]	kg/m^3
✓	Young's modulus	E	160e9[Pa]	Pa
✓	Poisson's ratio	nu	0.22	1
	Coefficient of thermal expansion	alpha	2.6.../K]	1/K
	Heat capacity a...stant pressure	Cp	678...K)]	J/(kg*K)
	Thermal conductivity	k	34[...K)]	W/(m*K)

Table 1: Material properties of poly-silicon

Then resonator was set in an environment of air having dimension 100µm×100µm×100µm. The material properties are



	Property	Name	Value	Unit
✓	Relative permittivity	epsilonr	1	1
	Relative permeability	mur	1	1

Table 2: Material properties of air

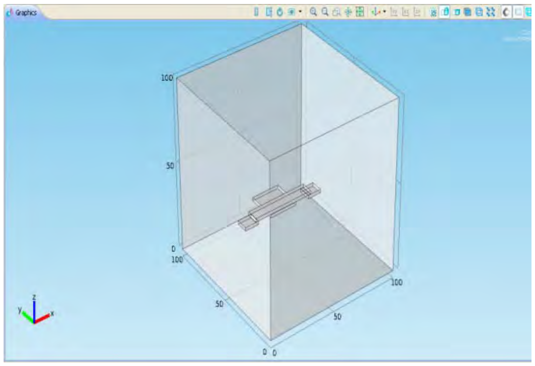


Figure 3: Poly-Si Resonator beam in air as di-electric

3.1 Electrostatic Analysis

The electrostatic analysis is done to get various electrical parameters for resonator beam like static capacitance as a function of voltage, pull in voltage etc. The physics included for the analysis were Electrostatic (es), Solid Mechanics (solid) and Moving Mesh (ale). The electrostatics part was applied to all the domains, the solid to resonator beam and fixed electrode and ale part was applied to the beam only. Now to apply a variable voltage a parameter Vin was taken as a parameter and applied to terminal of moving electrode; the ground electrode is selected as the fixed electrode. As the voltage is applied the electric field $\mathcal{E}$ is generated which puts a force on the moving part. This force is calculated by adding Force Calculation in electrostatics (es) physics and the force variable Fes $(Fes.ex + Fes.ey + Fes.ez)$. The boundary conditions for mechanics are that the anchors don't move and also the fixed electrode so they are defined as fixed constraint. The moving mesh evaluates the displacement of the beam as a function of applied potential. In the Study the parameter Vin was varied from 0V to 8V. The equations defining the problem are the standard Maxwell equation and Newton's equation

$$\nabla . D = \rho_v \qquad (3)$$

$$E = -\nabla V \qquad (4)$$

When solved in Comsol the following results were obtained

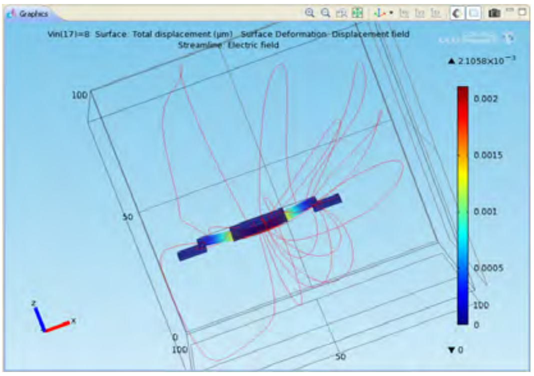


Figure 4: Electric field lines in red along with the electrostatic displacement of the beam.

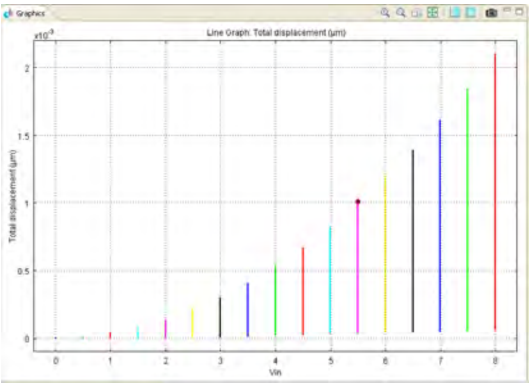


Figure 5: Displacement as function of input static voltage, note the pull-in voltage denoted by red dot

The pull in voltage is given by

$$V_{\text{pull-in}} = \sqrt{\frac{8kd^3}{27\varepsilon A}} \qquad (5)$$

This comes about 5.4V. The pull in voltage obtained from **Figure 5** exactly 5.5V.

3.2 Eigen frequency analysis

The stationary waves on a fixed-fixed structure are quantized meaning the frequencies corresponding to form stationary waves are quantized. The lowest frequency for which these stationary waves are formed is called fundamental harmonic. The modes of oscillation have different shapes for different frequencies. These eigen frequencies are obtained by solving the eigen value equation of the form

$$Av = \lambda Bv \qquad (6)$$

The eigen value results and corresponding modes of the beam oscillation are shown in simulation results for first three modes.

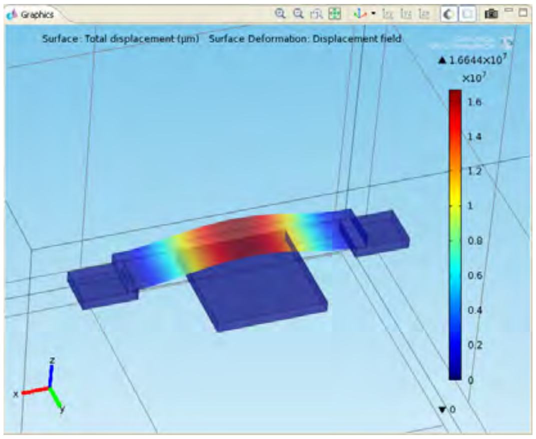


Figure 6: Mode 1 f_0 = 9.097 MHz

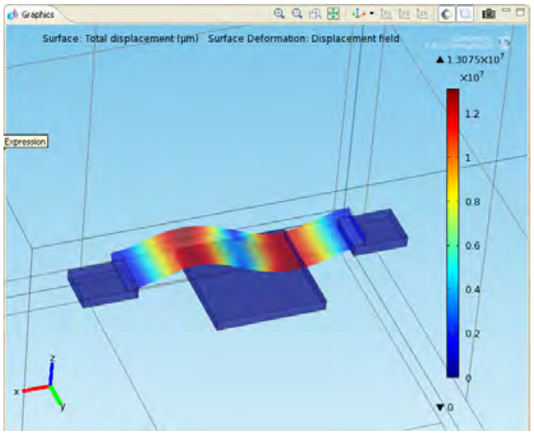


Figure 7: Mode 2 f_0 = 24.3 MHz

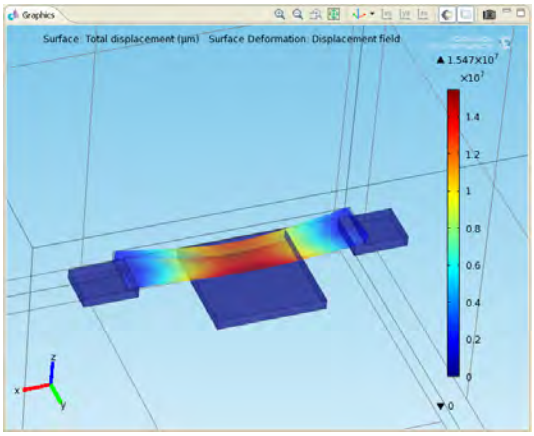


Figure 8: Mode 3 f_0 = 26.5 MHz

The calculated value of the resonance frequency is

$$f_0 = 10.69 \text{ MHz}$$

But the simulated frequency is 9.09 MHz for mode 1. This is because some of the energy is lost in damping at the anchors.

3.2 Thermo-Elastic damping at the anchors

When the beam oscillates the amount of displacement is maximum at the center of the beam (for mode 0) and decreases as one traverse towards the anchors. This is shown in **Figure 9.** Thus the energy conservation from potential to kinetic is followed at other nodes except at the anchors. At the anchors the energy is transferred from anchors to substrate in the form of heat. This causes anchors to heat and also decreases the Q of the beam. The mechanism of thermo-elastic damping is one of the reasons why the power handling capacity of the beam is less than what is expected. Thermo-elastic damping also limits the power handling capacity of the beam. The source of this heat can be modeled by equation

$$-2\pi f o(\rho C p T + T o \times solid\_entropy)\ W/m^3$$

Where Cp is the specific heat of the material, T is the temperature of the material, To is reference temperature and taken as 0K. The simulated results in comsol (**Figure 10)** shows that the temperature of anchors is much more than that of the rest of the beam.

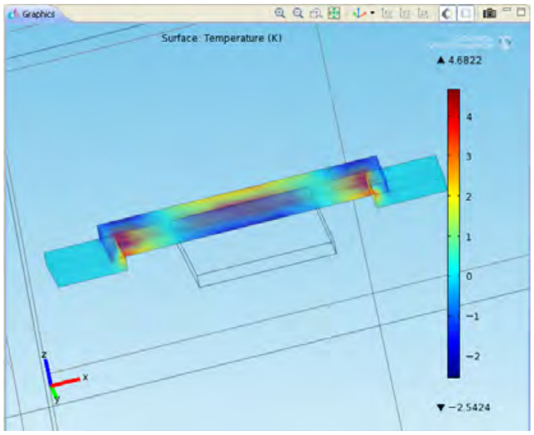


Figure 9: Thermo-elastic damping at anchors

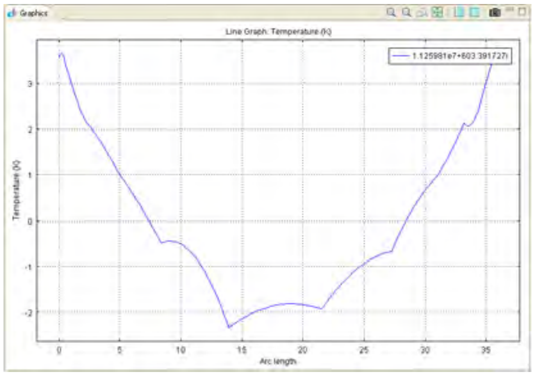


Figure 10: Temperature variation along the length

3.3 Frequency domain analysis

The frequency over which this resonator operates as a very High Q oscillator and the roll off at the other frequencies is obtained by applying an ac signal source at one of the electrode and sweeping the frequency of this ac source. Also the resonance curve or the frequency is observed to be a function of the static voltage. As the static voltage increases the internal stress of the beam also increases leading to an increase in electrical stiffness and decrease in resonance frequency. The resonance curve shifts as this static voltage is changed. This variation is given by

$$f_o = 1.03 \cdot \kappa \cdot \sqrt{\frac{E}{\rho}} \cdot \frac{h}{L_r^2} \cdot \left[1 - \left(\frac{k_e}{k_m}\right)\right]^{\frac{1}{2}}$$

Where ke is the electrical stiffness and km the mechanical stiffness. The resonance curve of **Figure 11** is obtained for a static voltage of 2V and hence the decrease in f_0 from 9.06 MHz to 8.5MHz.

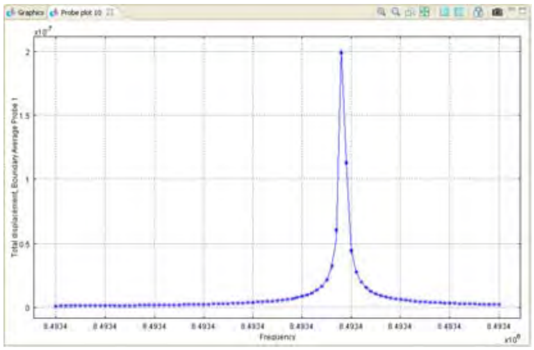


Figure 11: Maximum displacement as function of frequency (the resonance curve)

The Q of this resonator from **Figure 11** can be estimated as

$$Q = \frac{fo}{BW}$$

This comes out to ~ 10,000 in vacuum, which is very high as compared to a standard filter fabricated using transistors.

4 Conclusion

The fixed-fixed beam was found to have a Q of 10,000 and a resonance frequency of 8.5 MHz which can be scaled to higher values. The fixed-fixed beam resonator was built using poly-silicon which can be easily fabricated by the standard C-MOS process and hence can be used in on chip RF circuit. Also the pull-in voltage of this resonator is 5.5 V and this also is C-MOS compatible.

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