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Material selection for CMOS compatible high Q and high frequency MEMS disk resonator using Ashby approach

G. M. Sundaram[a], Mahesh Angira[a], Navneet Gupta[a], Kamaljit Rangra[b]
[a]*Department of Electrical and Electronics Engineering, Birla Institute of Technology and Science, Pilani, Rajasthan 333 031, India.*
[b]*Central Electronics Engineering Research Institute , Pilani, Rajasthan 333 031, India.*

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Abstract

In this paper, the most appropriate material for MEMS Disk resonator compatible with CMOS technology is selected using the Ashby approach. Materials indices are formulated based on three primary performance parameters, namely high Q, high resonant frequency, and low process temperature. The selection chart shows that for high Q and high frequency, poly$Si_{0.35}Ge_{0.65}$ is the best possible material for MEMS resonator. The close match between theoretical and experimental findings validates our proposed study.

Keywords: Material Selection; CMOS; MEMS.
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1. Introduction

Resonator is a key component in the transceiver system, which are often utilized for frequency selection in the radio-frequency (RF) and intermediate-frequency (IF) stages. Micro electromechanical (MEMS) resonators are the prime candidates for being used as frequency selection and generation components due to their ability to resonate at GHz frequencies and their exceptionally high–Q. Moreover these resonators provide frequency stability, thermal stability, and CMOS–compatibility [1-2]. Many approaches to obtain high frequency are being investigated to render MEMS resonators compatible with the CMOS circuitry. However, according to the best knowledge of the authors, the material selection approach is hardly used to enhance the performance of the MEMS resonators [3].

With the development of fabrication techniques, the numbers of materials that can be used for MEMS resonator have been increased. Three basic requirements for material selection in MEMS resonator are high Q, high resonant frequency, and low process temperature which in turn depends on suitable material to be used for the disk and supporting beam. Though several material selection strategies have been developed in the past, the methodology for selecting the material for disk and supporting beam in high Q-MEMS resonator had never been proposed. Ashby provides a comprehensive material selection strategy with less computation [4].For MEMS based design, the Ashby approach is widely accepted . So the Ashby approach is used to choose suitable material for a center-supported disk resonator. This paper present a detailed analysis of material selection for the high Q-disk MEMS resonator based on the electro-static actuation model compatible with Ashby approach.

This paper is organized as follows; Section 2 provides a brief explanation of MEMS resonator, Section 3 presents a brief description about the material for MEMS resonators, Section 4 explains the Ashby Approach and performance indices, Section 5 explains the results and discussion and finally section 6 gives the conclusion of the work reported in this paper.

2. MEMS DISK resonator structure and its operation.

Figure 1 shows a center-supported disk resonator of radius 'R' and thickness ’t’ supporting beam of diameter ' a' and height' h'.

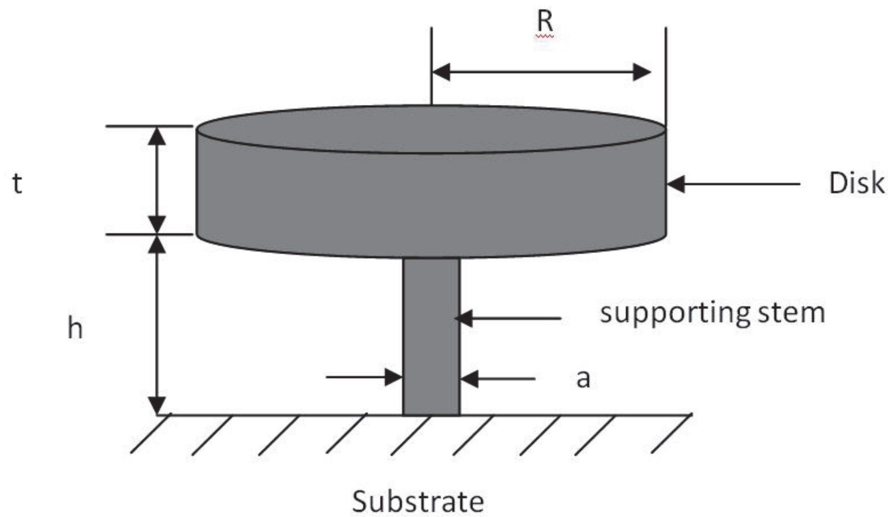

Fig.1: Schematic view of MEMS disk resonator

The electrodes are positioned around the circumference of the disk with a specific gap spacing, 'd'. This narrow air (or vacuum) gap defines the capacitive, electromechanical transducer of the device. To excite vibrations, a dc bias voltage 'V_P' is applied to the disk structure, and an ac input signal 'v_i' to oppositely located input electrodes. These voltages result in a force proportional to the product 'V_P 'and 'v_i ' that drives the resonator into its vibration. For radial-contour mode disk expands equally in all the lateral directions.

3. Materials for MEMS Resonator

There is a wide variety of materials available for MEMS, however only few materials can be qualified as structural materials for MEMS devices due to difficulties in micro fabrication technologies. These materials are traditionally grouped under four classes: metals and alloys, glasses and ceramics, polymers and elastomers, and composites. The properties of materials commonly studied while designing are Young’s Modulus (E), Poisson’s ratio (σ), fracture strength (σ_F), yield strength, fracture toughness, coefficient of thermal expansion and residual stress (σ_R) [5]. Using Ashby approach, the designer considers all the materials and studies their properties to optimize the design performance and reliability. Certain other properties like electrical resistivity and conductivity are also considered while dealing with the electrical aspects. The properties of materials with different deposition techniques and length scale changes drastically from its bulk values however the properties whose physical origins lie at the atomic scale (size and weight of atoms, nature of bonding and bond density, etc.) are, expected to be the same in micromechanical and bulk structures [6]. Sharpe [6] has tabulated initial design values based on an extensive survey of such measurements whose values are listed in Table 1 along with the nominal bulk values tabulated by Ashby and Jones.

Table 1: Recommended initial design values of material properties

Property	Recommendation
Density , ρ (kg/ m^3)	$\rho_\mu \approx \rho_{bulk}$
Young's Modulus, E(GPa)	$0.8\ E_{bulk} \leq E_\mu \leq E_{bulk}$
Poisson's ratio σ	0.25
Fracture strength, σ_F (Mpa)	$\sigma_{F,\mu} \approx \sigma_{F,bulk}$
Linear expansion coefficient, α (K^{-1})	$\alpha_\mu \approx \alpha_{bulk}$
Specific heat, Cp (J $kg^{-1}K^{-1}$)	$C_{p,\mu} = C_{p,bulk}$
Intrinsic loss coefficient , η_i	$10^{-2} < \eta_i$ (Polymers)
	$10^{-5} < \eta_i < 10^{-2}$ (Metals)
	$10^{-7} < \eta_i < 10^{-4}$ (Ceramics)
Residual stress σ_R	$-1\ GPa \leq \sigma_R \leq 1\ GPa$

μ indicates microscales.

The following three properties identified by MacDonald et al [7] are of extreme importance for MEMS devices; Compatibility with semiconductor technology, good electrical and mechanical properties, intrinsic properties that retard development of high stress during processing. It is already known that 0.35 μm technology can withstand at 525°C for 90 min [8]. Therefore we are interested to find such materials that can be deposited at temperatures lower than **525°C** and exhibit mechanical properties suitable for vibrating micromechanical disk resonator. Through literature review [6-9] it has been observed that the possible materials used for MEMS disk resonator for CMOS technology are Nickel (Ni), poly$Si_{0.35}Ge_{0.65}$ .bulk metallic glass materials [11-14], which include $Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$, $Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$, and $Au_{49}Ag_{5.5}Pd_{2.3}Cu_{26.9}Si_{16.3}$.

Table 2: Material performance indices for high-Q resonators. [6-9]

Material	Modulus, E,(GPa)	Density ,ρ, (kg/m^3)	Process Temperature Tp[$_0$C]
Nickel	195	8900	380
poly$Si_{0.35}Ge_{0.65}$	146	4280	450
$Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$[8}	94.8	15300	250-280

$Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$	96.7	6100	380-450
$Au_{49}Ag_{5.5}Pd_{2.3}Cu_{26.9}Si_{16.3}$	66.38	11000	150-190

4. Material selection – the Ashby method

Ashby material selection strategy is used to characterize the appropriate material for desired performance depending upon its attributes (mechanical, electrical and thermal properties of the material). Once the need of the application is decided, the performance indices are discovered, all the materials are considered and their material properties are studied. After that material selection charts are plotted and analyzed. The materials that meet the need are then taken into consideration and thus subset of the originally considered materials is obtained [14].

Three things specify the design of structural elements: the functional requirements, the geometry, and the properties of the material. The performance of an element is described by an equation of the form as [14]

$$p=f(F,G,M) \quad (1)$$

Where p describes some performance aspects of the component: its mass or volume, or cost, or life for example. Optimal design is the selection of the material and geometry, maximizing or minimizing p according to its desirability. The optimization is subject to constraints, some of which are imposed by the material properties, M.

The three groups of parameters in Eq. (1) are said to be 'separable' when the equation can be written as

$$p=f_1(F).f_2(G).f_3(M) \quad (2)$$

The performance can be optimized by optimizing the appropriate material indices. This optimization can conveniently be performed using graphs with axes corresponding to different material properties [14].

4.1. Performance indices

4.1.1. Quality factor

The mechanical quality factor (Q) of a disk resonator is defined as

$$Q = 2\pi \frac{W}{\Delta W}$$

Where ΔW denotes the energy dissipated per cycle of vibration and W denotes the maximum vibration energy stored per cycle, which is expressed as [15]

$$W = \frac{1}{2}\frac{\boldsymbol{E_d}}{(\mathbf{1}-\sigma_d^2)}\pi t[\gamma_p B J_2\,(\gamma_p)]^2 \quad (3)$$

Where ρ is the density, E_d is the Young's modulus of the disk material **,** σis the Poisson's ratio of the disk material,J_2 is Bessel function, Bis the vibration amplitude, tis the thickness ,γ_p is frequency parameter for the p th mode which is given by

$$\gamma_p = \alpha k \tag{4}$$

Where k is a parameter dependent upon Poisson's ratio, and α is a mode-dependent scaling factor that accounts for higher order. The amount of energy loss per cycle through the enter support beam is further expressed as [15]

$$\Delta W = \pi\sigma_{zz}^2 \pi a^2 u_z \tag{5}$$

Where

σ_{zz} is the normal stress on the substrate ,u_z is the displacement in the substrate due to the normal stress which is given by [15]

$$u_z = \frac{\mathbf{8a}}{\boldsymbol{E_{sub}}} \frac{\mathbf{1-v_{sub}^2}}{\mathbf{1-2v_{sub}}} \boldsymbol{\psi}\sigma_{zz} \tag{6}$$

Where

$$\sigma_{zz} = \frac{\boldsymbol{E_s\sigma_s}}{\mathbf{1-\sigma_s}} \cdot \frac{2.B}{a.cos\left(\frac{2\pi}{\lambda}.h\right)} J_1\left(\gamma_p.\frac{a}{R}\right) \tag{7}$$

Where h is the height of the stem, R is the radius of the disk and *a* is the diameter of supporting beam. For increasing the Q-factor, the value of W should be high, and ΔWshould be low. Therefore, for high Q, the value of E_d should be high and Es should be as low as possible. Hence by using eq (3) and eq (7) we can say that material index related to the Quality factor is E_d. Therefore first material index is: $IM_1 = E_d$.

Therefore, the performance index related to quality factor in the disk is $PI_1 = f(E_d)$.

4.1.2. Resonant frequency

The mechanical resonant frequency for the radial contour mode of a disk is governed mainly by its material properties and its radius. Neglecting second order effects due to thickness and finite anchor dimensions, the resonant frequency may be determined by finding a numerical solution for the system of equations [16-17].

$$\frac{J_0\left(\frac{\varsigma}{\xi}\right)}{J_1\left(\frac{\varsigma}{\xi}\right)} = 1 - \sigma \tag{8}$$

Where

$$\varsigma = \omega_0 R\sqrt{\frac{\rho(2+2\sigma)}{E}} \quad \text{and } \xi = \sqrt{\frac{2}{1-\sigma}} \tag{9}$$

Where, Jα is Bessel function of the first kind of order α, ω_0 is the angular resonance frequency, R is the radius of the disk, andE , ρ and σ are the Young's modulus of elasticity, mass density and Poisson's ratio of the material of the disk respectively. Simplification of (8) and (9) can yield the following expression for the resonant frequency for the' i'th breathing mode:

$$\omega_0 = \frac{\lambda_i}{R}\sqrt{\frac{E}{\rho(1-\sigma^2)}} \tag{10}$$

Here, λ_i is the frequency parameter for the i th mode. (λ_1 = 1.99, λ_2 = 5.37, λ_3 = 8.42, λ_4 = 11.52). Therefore an infinite number of resonant frequencies are possible for a disk of a certain shape and material; however, the fundamental mode is typically the frequency of primary interest for this resonator. Both the resonator material and its dimensions have an effect on the natural frequency. Poisson's ratio for the most of the MEMS material is 0.25 so it is neglected.

Therefore, the second material index related to the resonant is defined as: $IM_2 = \sqrt{\frac{E}{\rho}}$

Therefore, the performance indices related to the resonant frequency is $PI_2 = f(E,\rho)$

5. Result and Discussion

Figure 2 shows the plot of density versus Young's modulus (E) for all possible disk resonator materials.

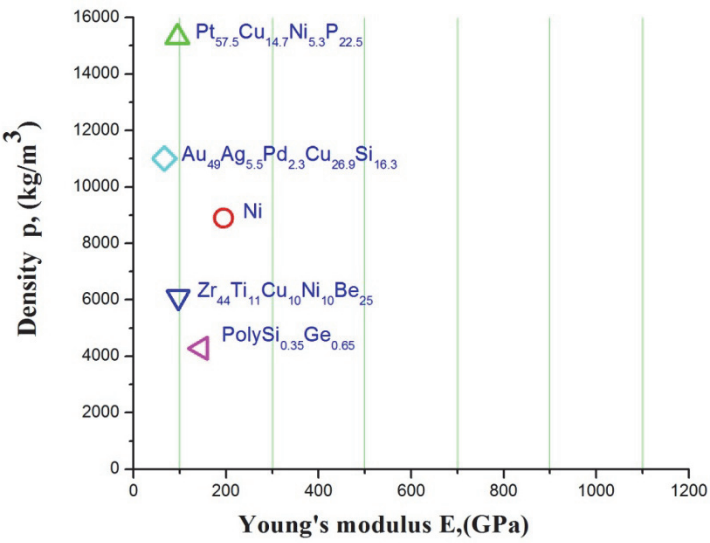

Fig. 2: shows the plot of density versus Young's modulus (E)

From eq (3), & (9) it is clear that material with a high value of Young's modulus (E) and low value of density provides high Q and high resonant frequency. It is observed from the plot that poly$Si_{0.35}Ge_{0.65}$followed by$Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$and Ni are the possible material that provide high Q and high resonant frequency.

However for the next generation CMOS technology, the requirements for the thermal budget are less than **525 ^{o} C** [5]. Figure 3 shows the plot of Young's modulus (E) versus process temperature for all possible disk materials that are compatible with CMOS technology.

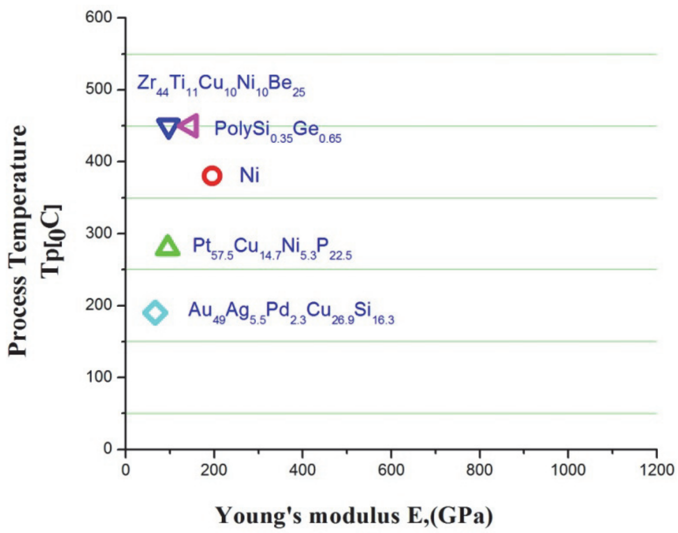

Fig. 3: Variation of Process Temperature versus Young's modulus

From eq(3), it is clear that the material should have high Young's modulus, therefore from fig. 3, it is clear that Ni followed bypoly$Si_{0.35}Ge_{0.65}$and$Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$ are the most suitable materials to be used as disk materials for MEMS resonators. Out of these three materials poly$Si_{0.35}Ge_{0.65}$ possess lowest value of density. Hence it is concluded that polySi$_{0.35}$Ge$_{0.65}$is the best possible material to be used for MEMS resonators. The outcome of this study is compared with the experimental founding's of Quevyeb [18]. According to them poly-SiGe disk resonator has been developed with Q's of 15,300 at frequency up to 425 MHz. This validates our proposed study.

6. Conclusion

Material selection for high Q disk MEMS resonator, using Ashby approach has been discussed in this paper. In this work we have developed the performance and material indices for High Q disk MEMS resonator. Using material selection chart it was observed that for High Q, high resonant frequency and CMOS compatible process temperature, polySi$_{0.35}$Ge$_{0.65}$ is the most suitable disk material.

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