MEMS Disk Resonator for 5G Application: An Analytical Case Study

Varad C. Joshi¹, Mandar M. Pimparkar² and Prasanna P. Deshpande³

¹Student, Department of Electronics and Comm. Engg; RCOEM, Nagpur (India)

²Student, Department of Electronics and Comm. Engg; RCOEM, Nagpur (India)

³Assistant Professor, Department of Electronics and Comm. Engg; RCOEM, Nagpur (India)

ABSTRACT

RF-MEMS resonators are being considered as a reliable solution, required by the high-performance passive components in the present 5G communication. 5G protocols demand ultra-high frequency (UHF) ranging from 3 GHz to 30 GHz with reduced time and less power consumption. In this paper, an attempt is being made to show the dynamics of MEMS disk resonator in 5G communication range of frequency using polydiamond material. MEMS technology is preferred due to its high-quality factor and its efficient compatibility to CMOS. The analytical result of 24.2 GHz and of 33.2 GHz in third and fourth mode respectively show the efficient operation of the disk resonator in the UHF range.

KEY WORDS: MEMS RESONATOR, RF MEMS, 5G COMMUNICATION, DISK RESONATOR, QUALITY FACTOR, MEMS TECHNOLOGY, UHF.

INTRODUCTION

Wi-Comm technology e.g. GSM, 3G, 4G etc. has made significant advances since the late 1980s (Basu and Bhattacharya 2011; Deshpande et al. 2018; Deshpande and Pande 2019; Deshpande et al. 2020). Compared with these technologies, 5G communication protocols require very high frequency for operation and transmission so as to have more advancement with minimum hardware and low power consumption (Iannacci 2019). 5G network can accommodate a wide range of connections with respect to the current mobile networks as well as supporting machine-to-machine (M2M) networking, and high communicating capacity approximately 1000 times more than that of the 4G (Iannacci 2019). The generation

of high frequency along with high quality factor is still a challenge to fulfil the present constraints in the high speed 4G technology.

The design and developments in RF- MEMS resonator have been proven by the different researchers (Basu and Bhattacharya 2011; Deshpande et al. 2018; Deshpande and Pande 2019; Deshpande et al. 2020; Chorsi and Chorsi 2018). One of the prominent designs is a disk structure. The disk design has a potential to achieve very high frequency with high quality factor (Q) and low power consumption. The fabrication process of such design is a bit complex but cost effective (Chorsi and Chorsi 2018). Resonating disk has infinitely many eigen frequencies depending on the mode of operations. Some theoretical investigations of disk resonators have been made in these articles (Basu and Bhattacharya 2011; Chorsi and Chorsi 2018; Chaudhari and Bhattacharyya 2013; Hao et al. 2004).

However, capacitively transduced bulk acoustic wave (BAW) resonator, also known as contour mode resonator (CMR) is a good option to operate in high frequency range with high Q than flexural mode (Hao et al. 2004). This is due to its larger structural stiffness and

ARTICLE INFORMATION

*Corresponding Author: joshivc@rknc.edu

Received 18th Oct 2020 Accepted after revision 24th Dec 2020

Print ISSN: 0974-6455 Online ISSN: 2321-4007 CODEN: BBRCBA

Thomson Reuters ISI Web of Science Clarivate Analytics USA and Crossref Indexed Journal

NAAS Journal Score 2020 (4.31)

A Society of Science and Nature Publication,
Bhopal India 2020. All rights reserved.

Online Contents Available at: <http://www.bbrc.in/>

Doi: <http://dx.doi.org/10.21786/bbrc/13.14/110>

lesser surface to volume ratio (Deshpande et al. 2018; Deshpande and Pande 2019; Deshpande et al. 2020). In radial disk CMR, the frequency of resonance is directly proportional to the acoustic velocity ($\sqrt{E_y/D}$), where E_y and D are the elasticity modulus and density of the material respectively. The diamond material helps to reduce energy loss through anchors (Chorsi and Chorsi 2018). A systematic account of disk geometry, its modes of vibration, fabricating material, electrical equivalent model, and method for analysis of radial-contour mode resonator is presented in this paper.

METHODOLOGY

The quality of a device depends upon its materialistic properties that are its physical and mechanical

parameters. After certain trial of experimentations, the best suitable design parameters were decided according to (Deshpande et al. 2020). The physical design decides the performance parameters like resonance frequency (f_{res}), quality factor (Q) and motional resistance (R_e) etc. The low motional resistance transmits the more power (Basu and Bhattacharya 2011; Deshpande et al. 2018; Deshpande and Pande 2019; Deshpande et al. 2020; Clark et al. 2005). To improve these performance parameters, the device geometry such as diameter of a disk and width of the disk must be investigated properly. Also, the proper selection of electrode parameter reduces the anchor loss improving the quality factor further. Table 1 below shows some well-known materials along with their properties.

Table 1. Properties of some structural materials (Huang 2008)

Material	Polysilicon	Single crystal Silicon	Polydiamond	Silicon carbide
Density D (kg m^{-3})	2,300	2,330	3,500	3,200
Elasticity modulus E_y (GPa)	150	130	1,144	415
Temperature of deposition ($^{\circ}\text{C}$)	588	1000	800	800
Poisson's ratio (σ)	0.226	0.28	0.069	0.192
Electricity conductivity ($10^7 \Omega^{-1} \text{m}^{-1}$)	0.001	0.00023	0.001	0.00083

Our study involves the radial-contour mode disk resonators, with a polydiamond disk of radius R_d , thickness t , and a polysilicon stem at its centre is shown in Fig. 1 (a). Fig. 1 (b) and (c) represents its cross-sectional view and Butterworth van-dyke (BVD) model respectively. The stationary electrode surrounding the disk is made up of polysilicon with a lateral capacitive actuation gap (Chorsi and Chorsi 2018). A structure using polydiamond material has high acoustic velocity and is able to achieve the desired resonance frequency easily. Electrostatic force shows quadratic dependence on voltage/charge and further behaves non-linearly (Chaudhari and Bhattacharyya 2013). The linearity of the system improves by applying a very small dc bias voltage which exerts a force on the plate and due to which the plate undergoes in plane vibration around its equilibrium position (Basu and Bhattacharya 2011; Chorsi and Chorsi 2018).

By applying V_{ac} sinusoidal voltage, resonator is forcefully vibrated at the resonance frequency f_{res} and a dc-bias voltage V is applied to the stem which in turn produces a time-varying field F_2 . This field generates symmetrical contraction and expansion of the disk around its perimeter. A time dependent motional current i_m is generated with frequency ω at the load. The applied dc bias voltage V charges the disk-to-electrode capacitor, the generated electrostatic force F' having both constant and time varying components F_1 and F_2 in radial direction is explained in (Hao et al. 2004; Clark et al. 2005).

$$F' = \frac{1}{2} \left(\frac{\partial C_1}{\partial r} \right) (V - V_{ac})^2 = F_1 + F_2 \quad (1)$$

Figure 1: Contour mode disk resonator with surrounding electrode (a) perspective view (b) cross-section view (c) BVD equivalent circuit (Basu and Bhattacharya 2011; Deshpande et al. 2018; Deshpande and Pande 2019; Deshpande et al. 2020)

The time varying field F_2 is given by

$$F_2 \cong -V \left(\frac{\partial C_1}{\partial r} \right) V_{ac} \quad (\text{for } V \gg V_{ac}) \quad (2)$$

Where, $\partial C_1 / \partial r$ is the change in the electrode to resonator overlap capacitance per unit radial displacement at input (Basu and Bhattacharya 2011).

$$C_1(r) = C' \left(1 - \frac{r}{d_g} \right)^{-1} \Rightarrow \frac{\partial C_1}{\partial r} = \frac{C'}{d_g} \left(1 - \frac{r}{d_g} \right)^{-2} \quad (3)$$

$C' = C_0$ is static electrode to disk capacitance i.e.

$$C' \cong \frac{\epsilon_0 \theta R_d t}{d_g} \quad (4)$$

R_d is a radius and t is the thickness of the disk, ϵ_0 is the permittivity in vacuum, d_e is the static electrode to disk gap and θ is angle of the input edges of the electrode. Now the following approximate expression can be obtained,

$$\frac{\partial C_1}{\partial r} = \frac{\epsilon_0 \theta R_d t}{d_e^2} \quad (5)$$

The peak radial displacement is a function of (r, ϕ) and is given by (Hao et al. 2004).

$$D(r, \phi) = Ah J_1(h_r) \quad (6)$$

Table 2. Values for λ_i for the various vibrating modes (Chaudhari and Bhattacharyya 2013)

Mode (ith)	Frequency parameter (λ_i)
1st	1.99
2nd	5.37
3rd	8.42
4th	11.52
5th	14.89

at the perimeter $r = R_d$. Now, equation becomes

$$D(R_d, \phi) = \frac{Q E_2}{j k_{eff}} \quad (7)$$

The constant h mentioned in (6) is given by

$$h = \sqrt{(\omega^2 D) / \left[\frac{E_y}{1+\sigma} + \frac{E_y \sigma}{1-\sigma^2} \right]} \quad (8)$$

A time varying capacitance is generated due to the input voltage between the output electrode and the disk causing the generation of a motional current i_m at the output electrode which is expressed as:

$$i_m = V \frac{\partial C''}{\partial t} \quad (9)$$

$$i_m = - \frac{Q \omega}{k_{eff}} \left(\frac{\partial C_1}{\partial r} \right) \left(\frac{\partial C''}{\partial r} \right) V^2 V_{ac} \quad (10)$$

At frequency ω , the output current is same as the input current. Thus, for in phase displacement towards the drive electrode, the current is 1800 out of phase w.r.t input voltage. In cylindrical co-ordinate system the design is described and the resonance frequency for radial contour bulk vibrations can be derived in terms of Bessel functions as given in (Clark et al. 2005).

Table 3. Parameters of polydiamond material

Class	Parameter	Symbol	Values	Units
The disk (polydiamond) (Huang 2008)	Modulus of elasticity	E_y	1144	GPa
	Poisson's Ratio	σ	0.0691	-
	Density	D	3500	Kg/m ³
	Acoustic Velocity	v_p	18500	m/s
Constants (Akgul 2014)	Haymaker Constant of polydiamond	A	2.2×10^{-19}	J
	Plank's constant divided by 2π	η	1.055×10^{-34}	J.s
	Speed of light	c	2.988×10^8	m/s
	Permittivity of Vacuum	ϵ_0	8.85×10^{-12}	C ² .N ⁻¹ .m ⁻²
Electrodes (Chorsi and Chorsi 2018) Gap (Chorsi and Chorsi 2018)	Static Electrode to Disk Capacitance	C'	35.324	fF
	Span Angle of electrode	θ	360	°
	Disk to Electrode Gap	d_e	40.0	nm

$$\frac{J_0(\xi)}{J_1(\xi)} = (1 - \sigma)$$

$$\text{where, } \zeta = \omega R_d \sqrt{\frac{D(2+2\sigma)}{E_y}}, \xi = \sqrt{\frac{2}{1-\sigma}} \quad (11)$$

On simplifying the above eqn. (11) and obtaining the relation for resonant frequency for i th breathing mode is (Chorsi and Chorsi 2018).

$$f_{reso} = \frac{\omega}{2\pi} = \frac{\lambda_i}{2\pi R_d} \sqrt{\frac{E_y}{D(1-\sigma^2)}} \quad (12)$$

Where λ_i is the frequency parameter for any particular mode, the values for which are provided in Table 2.

RESULTS AND DISCUSSION

The dynamics of the UHF vibrating contour mode disk resonator in various modes of resonance are presented and discussed. All physical constants required for numerical calculations are presented below in Table 3.

Considering these parameters, the two different materials i.e. polysilicon and polydiamond have been used to design radial disk resonator, whose resonance frequencies

has been calculated for different modes including fundamental mode is presented in Table 4.

From Table 4, it can be predicted that, the polydiamond is more prominent and suitable than polysilicon in UHF range. Table 4 also reads that, higher the mode of

vibration, higher is the resonance frequency (Chorsi and Chorsi 2018). For further investigation of the quality factor, Q which is one of the important parameters for RF communication, the resonance will be helpful (Basu and Bhattacharya 2011; Deshpande et al. 2018; Deshpande and Pande 2019; Deshpande et al. 2020).

Table 4. Comparison in resonance frequency in various modes for two different materials

Material	Disk radius (R)	Fundamental resonance mode	2nd resonance mode	3rd resonance mode	4th resonance mode
Polysilicon $E_y=150\text{GPa}$, $D=2300\text{Kg/m}^3$, $\sigma=0.226$	16.7 μm (Clark et al. 2005)	157.22MHz	424.27MHz	665.24MHz	910.16MHz
	10 μm	262.5MHz	708.53MHz	1.11GHz	1.51GHz
	1 μm	2.62GHz	7.08GHz	11.1GHz	15.1GHz
Polydiamond $E_y=1144\text{GPa}$, $D=3500\text{Kg/m}^3$, $\sigma=0.069$	16.7 μm	343.69MHz	936.09MHz	1.45GHz	1.98GHz
	10 μm	573.96MHz	1.54GHz	2.42GHz	3.32GHz
	1 μm	5.73GHz	15.4GHz	24.2GHz	33.2GHz

$$Q = \frac{f_{\text{reso}}}{\text{half power bandwidth}} \quad (13)$$

CONCLUSION

In this article, an electrostatically actuated radial contour mode MEMS disk resonator has been analysed with polydiamond material. The analytical derivation of the system involving electrostatic force is systematically done to derive the output current equation and also the resonance frequency. Capable of operating in UHF range the model has a high-quality factor, low actuation voltage and is power efficient than most of the MEMS resonators. The result shows that the polydiamond is more prominent material suitable to achieve high resonance frequency in third (24.2GHz) and fourth (33.2GHz) modes of operation. The theoretical analysis presented in the paper showcase the influence of various design parameters, which are advantageous for future research and optimization of MEMS disk resonators.

REFERENCES

- Akgul M (2014) A micromechanical RF channelizer. University of California, Berkeley
- Basu J, Bhattacharya T (2011) Microelectromechanical resonators for radio frequency communication applications. *Microsystem Technologies* (10–11):1557–1580.
- Chaudhuri R, Bhattacharyya T (2013) “Electroplated nickel based micro-machined disk resonators for high frequency applications”. *Microsystem Technologies* 19:525–535
- Chorsi Meysam and Chorsi Hamid (2018) “Modelling and analysis of MEMS disk resonators”. *Microsystem Technologies* 24(6):2517–2528. <https://doi.org/10.1007/s00542-017-3645-9>.
- Clark JR, Hsu WT, Abdelmoneum MA, and Nguyen CT. “High-Q UHF Micromechanical Radial-Contour Mode Disk Resonators”. *Journal of microelectromechanical systems*, vol. 14, no. 6, December 2005
- Deshpande PP, Pande RS and Patrikar RM “Fabrication and characterization of zinc oxide piezoelectric MEMS resonator”. *Microsystem Technology* 26, 415–423 (2020). <https://doi.org/10.1007/s00542-019-04509-w>.
- Deshpande PP and Pande RS, “Low motional resistance lateral field extensional UHF MEMS resonator”, *International Journal of Engineering and Advanced Technology (IJEAT)*, Volume 8, Issue 5, June 2019, pp. 2194–2198
- Deshpande PP, Talekar PM, Khushalani DG and Pande RS, “Piezoelectric Aluminum Nitride Micro Electromechanical System Resonator for RF Application”, *International Journal of Applied Engineering Research (IJAER)*, Volume 13, Number 6 (2018) pp. 4263–4267
- Hao Z, Pourkamali S, Ayazi F (2004) “VHF single-crystal silicon elliptic bulk-mode capacitive disk resonators–part I: design and modelling”. *Journal of Microelectromechanical Systems* 13(6):1043–1053
- Huang WL (2008) “Fully monolithic CMOS nickel micromechanical resonator oscillator for wireless communications”. Ph.D. thesis, Electrical Engineering, University of Michigan.
- Iannacci J. (2019) RF-MEMS for 5G applications: a reconfigurable 8-bit power attenuator working up to 110 GHz. Part 1 – design concept, technology and working principles. *Microsystem Technologies* (2020) 26:675–687. <https://doi.org/10.1007/s00542-019-04591-0>.