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Comprehensive Analysis of a High-Q, Low Motional Resistance, Very High Frequency MEMS Resonator

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Abstract: In this study, design and simulation of an IC-compatible microelectromechanical resonator for use in VHF range of a wireless communication system as a base element in integrated micromechanical resonator based oscillators and front-end filters is reported. This resonator can be implemented using thick polysilicon technology. The resonator with new design and structure reduces vibrating micromechanical series motional resistance R_x by increasing electrode-to-resonator overlap area through use of scale up of the motionless dimension of the device; while maintaining the resonant frequency. Quarter-wavelength supporting and attaching to nodal points of the resonator is required to maximize quality factor of the device. Resonant frequencies around 71 MHz, quality factor of 9912 and motional resistances R_x on the order of 480 Ω were obtained by this design.

Key words: Microelectromechanical systems, mechanical resonator, motional impedance, quality factor

INTRODUCTION

Miniaturization of the constituent components of super-heterodyne wireless transceivers is a field of research that has received considerable attention recently. To date, several of these components can already be miniaturized using integrated circuit transistor technologies. Reduced size constitutes the most obvious incentive for replacing SAWs and crystals by equivalent devices. Typically, the front-end of a wireless transceiver contains a good number of off-chip high-Q components that are potentially replaceable by micromechanical versions. Among the components targeted for replacement are RF filters, including image reject filters (with center frequencies ranging from 800 MHz to 2.5 GHz), IF filters (with center frequencies ranging from 455 kHz to 254 MHz) and high-Q low phase-noise local oscillators with frequency requirements in the 10 MHz to 2.5 GHz range (Nguyen, 1998, 1999; De Los Santos, 2002). One of the challenging issues which has hindered deployment of the microelectromechanical resonators and filters is large motional resistance R_x of these devices with electrostatically and capacitively transduction.

Among methods for lowering the motional resistance R_x of electrostatically and capacitively transduced micromechanical resonators presented so far are: (1) decreasing the electrode-to-resonator gap (Bannon III *et al*., 2000), (2) increasing the dc-bias voltage V_P and (3) summing together the output currents of an array of identical resonators (Demirci *et al*., 2003). Unfortunately, each of these methods comes with some drawbacks. In particular, although the first two methods are very effective in lowering R_x (with fourth power and square law dependencies, respectively), they do so at the cost of linearity (Navid *et al*., 2001; Alastalo and Kaajakari, 2006). On the other hand, method (3) actually improves linearity while lowering R_x. However, this method is difficult to implement; since it requires resonators with precisely identical responses and consumes large area of silicon chip; since it uses an array of resonators instead of a single resonator.

This study presents a novel method for lowering motional resistance based on a technique which utilizes true potential of a single square frame resonator in three-dimensions and raises the linearity as well. Using this new technique, a simply-supported square frame microelectromechanical resonator (with an effective R_x of 478 kΩ) was designed and simulated at 71 MHz. This effective resistance is about 75X smaller than the 35.9 kΩ exhibited by a 72 MHz Clamed-Clamped beam resonator (Varadan and Vinoy, 2002), 73X smaller than the 34.8 kΩ

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demonstrated by a 71 MHz free-free beam resonator (Wang *et al*., 2000) and 8.4X smaller than the 4kΩ presented by a 68.1 MHz mechanically-coupled 11-resonators array (Demirci *et al*., 2003).

This R_x-reduction method is superior to methods based on scaling down of electrode-to-resonator gaps, dc-bias increases, or using an array of identical resonators; because it allows a reduction in R_x without sacrificing linearity and consuming large chip area.

MATERIALS AND METHODS

Resonator structure and operation: Figure 1 shows schematic top view of the proposed micromechanical resonator (along with appropriate bias, excitation and sensing circuitry). This resonator consists of a simply-supported square frame resonators, supported by four tethers and attached to substrate only at anchors, all suspended above the substrate.

To operate this resonator, a dc-bias V_P is applied to the suspended resonator structure and two complement ac input voltages v_i and $-v_i$ are applied to the input electrodes, which are placed by a 100 nm gap from the structures, as shown in Fig. 1. The application of input voltages v_i and $-v_i$ creates x- and y-directed electrostatic forces between input electrodes and the conductive resonator that induce x- and y-directed vibration of the input resonator when the frequency of the input voltage comes equal to the resonant frequency of the mechanical resonator. Vibration of the square frame resonator creates a dc-biased, time-varying capacitor between the conductive resonator and electrodes, which then sources an output current given by:

$$i_o = V_P\left(\frac{\partial C}{\partial x}\right)\left(\frac{\partial x}{\partial t}\right) \quad (1)$$

where, $\partial C/\partial x$ is the change in resonator-to-electrode capacitance per unit displacement at input ports. The output current i_o is then directed to resistor R_L, which converts the current to output voltage.

Since, center frequency of a given mechanical filter and oscillation frequency of a given oscillator are determined primarily by the resonance frequencies of its constituent resonators, careful mechanical resonator design is imperative for successful device implementation. The selected resonator design must not only be able to achieve the needed frequency but must also do so with adequate linearity and tunability and with sufficient Q.

As shown in Fig. 2, the microresonator is formed of four polysilicon beams which are attached to each other and organized in a square frame. Other polysilicon tethers

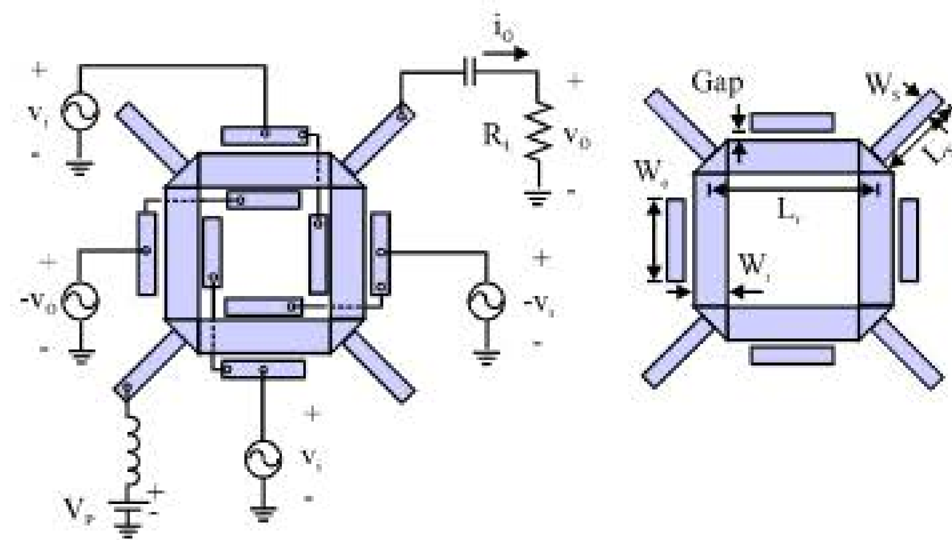

Fig. 1: Top view schematic of a square frame micromechanical resonator, along with the preferred bias, excitation and sensing circuitry

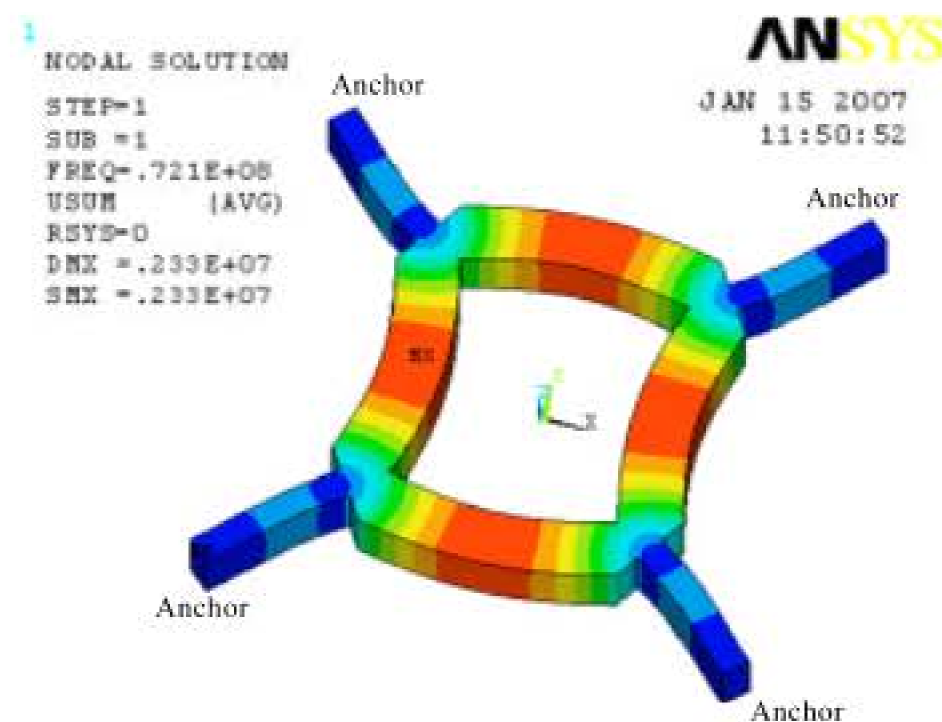

Fig. 2: Fundamental mode shape of the micromechanical resonator simulated by ANSYS

attach corners of this frame to anchors. The anchors are tightly placed on substrate and cause the whole structure to suspend above the substrate with a little space between them. This polysilicon square frame can freely move parallel to substrate in x and y orientations.

The resonance frequency of this simply-supported square frame depends upon many factors, including geometry, structural material properties, stress, the magnitude of the applied dc-bias voltage V_P and surface topography.

Accounting for these while neglecting finite width effects, an expression for resonance frequency can be written as (Timoshenko *et al*., 1974):

$$f_{nom} = \frac{\beta_n^2}{4\pi\sqrt{3}}\kappa\frac{W_r}{L_r^2}\sqrt{\frac{E}{\rho}} \quad (2)$$

where W_r and L_r are the width and effective length of the beam, respectively, E is the Young's modulus, ρ is the

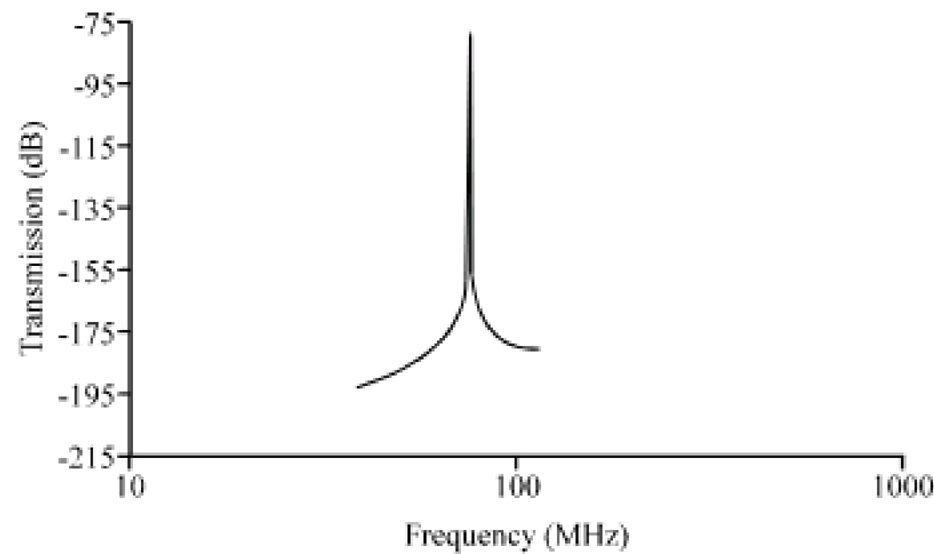

Fig. 3: Mechanical frequency response of the microresonator

density of the structural material, β_n = 3.1415, 6.2831, 9.4247 for the first three modes of a simply-supported beam, f_{nom} is the nominal mechanical resonance frequency of the resonator if there were no electrodes or applied voltages and κ is a scaling factor that models the effects of surface topography.

Mechanical frequency response of the designed resonator is shown in Fig. 3.

To properly excite this device, a voltage consisting of a dc-bias V_P and an ac excitation v_i is applied across one of the resonator-to-electrode capacitors (i.e., the input transducer). This creates a force component between the electrode and resonator proportional to the product $V_P v_i$ and at the frequency of v_i. When the frequency of v_i nears its resonance frequency, the microresonator begins to vibrate, creating a dc-biased time-varying capacitor $C_0(x,t)$ at the input transducer. A current is then generated through the output transducer and serves as the output of this device. When plotted against the frequency of the excitation signal v_i, the output current i_o traces out the bandpass biquad characteristic expected for a high-Q tank circuit.

It must be noted that from the discussion associated with Eq. 1, the effective input force ($\sim V_P v_i$) and output current can be nulled by setting V_P = 0. Thus, a micromechanical resonator (and oscillator or filter constructed of such resonators) can be switched in and out by the mere application and removal of the dc-bias voltage V_P. Such switchability can be used to great advantage in receiver architectures.

Design of the micromechanical resonator in form of Fig. 2, has some advantages as follows:

- The fully-differential electrode configuration cancels the second harmonic distortion term (HD_2); therefore, improves the power-handling capability and dynamic range of the resonator
- The present structure design, decreases input and output impedances significantly and in filter design case, matches the impedance of filter to the impedances of the stages before and after the filter, properly
- Since, the proposed resonator structure has four almost motionless node points, the quality factor due to energy loss mechanisms of support loss ($Q_{Support}$) is high and hence Q of the whole structure is high
- Since, the resonator vibrates in x and y directions, the electrodes are placed besides the structure instead of beneath it. So, the fabrication, mask defining, pattern generation and manufacturing of the device will be done more easily and inexpensively

Frequency tuning: Resonance frequency of the microresonator is a function of the dc-bias voltage V_P. Thus, frequency of this device is tunable via adjustment of V_P and this can be used advantageously to implement filters and oscillators with tunable center frequencies, or to correct for passband distortion caused by finite planar fabrication tolerances.

The dc-bias dependence of resonance frequency arises from a V_P-dependent electrical spring constant k_e that subtracts from the mechanical spring constant of the system k_m, lowering the overall spring stiffness $k_r = k_m - k_e$, thus lowering the resonance frequency according to the expression:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_m - k_e}{m_r}} = \frac{1}{2\pi}\sqrt{\frac{k_m}{m_r}}\left[1-\left(\frac{k_e}{k_m}\right)\right]^{1/2} = \frac{\beta_n^2}{4\pi\sqrt{3}}\kappa\frac{W_r}{L_r^2}\sqrt{\frac{E}{\rho}}\left[1-\left(\frac{k_e}{k_m}\right)\right]^{1/2} \quad (3)$$

where, k_m and m_r denote values at a particular location (usually the beam center location) and the quantity k_e/k_m must be obtained via integration over the electrode width W_e due to the location dependence of k_m as follows (Nathanson *et al*., 1967):

$$\frac{k_e}{k_m} = \int_{L_{e1}}^{L_{e2}} \frac{V_P^2 \varepsilon_0 h_r}{d^3(x) k_m(x)} dx \quad (4)$$

where, range of integration is from $L_{e1} = 0.5(L_r - W_e)$ to $L_{e2} = 0.5(L_r + W_e)$ and h_r and d(x) are structure thickness and gap between electrode and vibrating beam, respectively.

It must be noted that Eq. 3 is only valid for a case in which four outer electrodes are used. If in addition of four outer electrodes, four inner electrodes are also used (in order to reduce R_x further), then the term k_e/k_m in Eq. 3 should be multiplied by a factor of 2. In that case, the frequency f_0 decreases further, with increasing V_P.

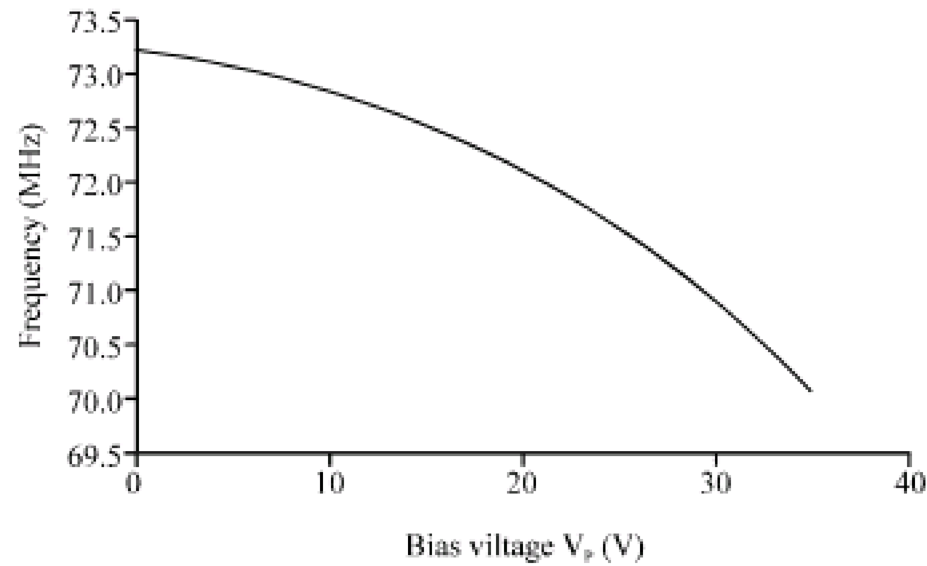

Fig. 4: Simulated frequency versus applied dc-bias V_P for the present microresonator

The dependence of the resonance frequency to dc-bias voltage V_P, is shown in Fig. 4.

MOTIONAL RESISTANCE CALCULATION

An electrical model with a core RLC circuit was defined for the microresonator based on mass-spring-damper system. Of the elements in the equivalent RLC circuit, the series motional resistance R_x is the most influential in both oscillator and filter circuits. In oscillators, R_x generally governs the gain needed to instigate and sustain oscillation; whereas in bandpass filters, it dictates the ease of matching the designed filter to low impedance stages before and after the filter (e.g., the antenna).

$$R_x = \frac{\sqrt{k_r m_r}}{Q\eta_e^2} = \frac{D_r}{\eta_e^2} \tag{5}$$

where, η_e is the transduction parameter for a capacitive transducer and is calculated theoretically as follows:

$$\eta_e = V_P\left(\frac{\partial C}{\partial x}\right) = \frac{V_P \varepsilon_0 W_r W_e}{d_0^2} \tag{6}$$

and D_r is the damping factor which is given by:

$$D_r = \frac{\sqrt{k_m m_r}}{Q_{nom}} \tag{7}$$

where k_m and m_r denote the mechanical spring constant value and the equivalent mass of the system at the beam center location on the resonator and Q_{nom} is the quality factor of the resonator without the influence of applied voltages and electrodes.

To having better insight into what parameters governs R_x, a closed form expression can be obtained by substituting Eq. 6 into 5 and using lumped terms for integrated parameters, which yields:

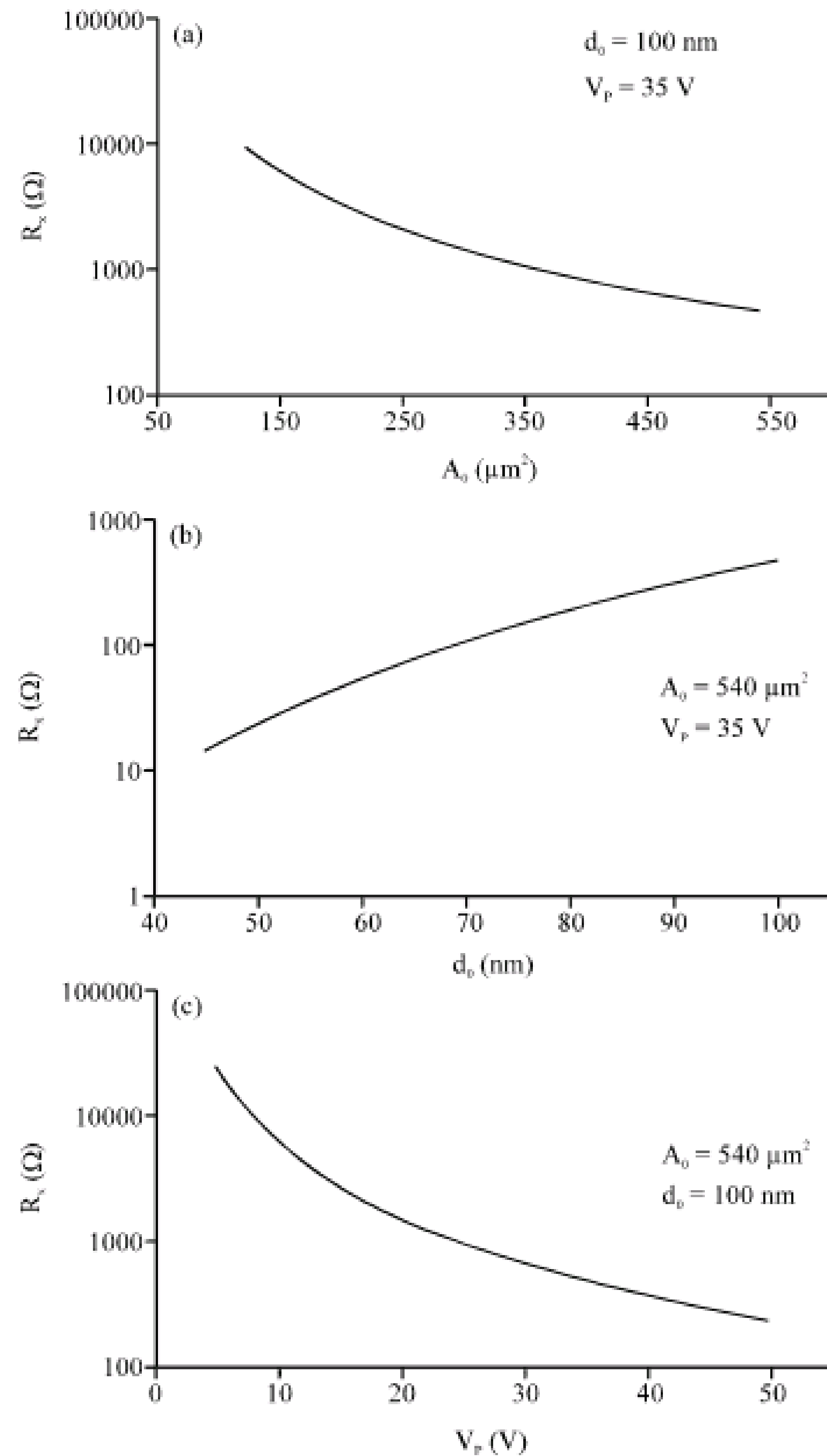

Fig. 5: Simulated plots presenting R_x values obtained via., Eq. 8. (a) R_x versus electrode-to-resonator overlap area A_0. (b) R_x versus electrode-to-resonator gap spacing d_0. (c) R_x versus dc-bias V_P

$$R_x = \frac{D_r d_0^4}{\varepsilon_0 A_0^2 V_P^2} \tag{8}$$

where, A_0 is the effective electrode-to-resonator overlap area of the resonator.

Figure 5 present plots of R_x versus various parameters in Eq. 8, showing that small values of R_x are feasible if small values of electrode-to-resonator gap spacing d_0 and large values of dc-bias V_P and sufficiently large electrode-to-resonator overlap area are used. However, the use of such values should not sacrifice linearity.

As indicated in Fig. 5a, by choosing $d_0 = 100$ nm, $V_P = 35$ V and using eight electrodes (four outer electrodes and four inner electrodes), motional impedance of R_x is reduced to 478 Ω; which is a desirable value for a micromechanical resonator. Furthermore, as it was explained before, use of special design for the support beams prevents lowering quality factor of the flexural mode beam resonators. Hence, there will not be any decrease in Q and increase in R_x as a result.

It must be noted that in Fig. 5b and c, total electrode-to-resonator overlap area is equal to 540 μm² and overlap area for each electrode-resonator pair is only 75 μm², which leads to a large pull-in voltage (~180 V).

SUPPORT STRUCTURE DESIGN

The designed square frame mechanical resonator is supported by four flexural beams attached at its fundamental-mode node points (Fig. 2). Since, these beams are attached at node points, the support springs sustain no translational movement during resonator vibration (ideally) and thus, support (i.e., anchor) losses due to translational movements are greatly alleviated. Furthermore, with the recognition that the supporting flexural beams actually behave like acoustic transmission lines at the VHF frequencies of interest, flexural loss mechanisms can also be negated by strategically choosing support dimensions so that they present virtually no impedance to the simply supported beam. In particular, by choosing the dimensions of a flexural support beam such that they correspond to an effective quarter-wavelength of the resonator operating frequency, the solid anchor condition on one side of the support beam is transformed to a free-end condition on the other side, which connects to the resonator. In terms of impedance, the infinite acoustic impedance at the anchors is transformed to zero impedance at the resonator attachment points. As a result, the resonator effectively sees no supports at all and operates as if levitated above the substrate, devoid of anchors and their associated loss mechanisms.

Through appropriate acoustical network analysis, the dimensions of a flexural beam are found to correspond to a quarter-wavelength of the operating frequency when they satisfy the following expression:

$$L_s^2 = \frac{1}{4f_0}\frac{\beta_n^2}{4\pi\sqrt{3}}W_s\sqrt{\frac{E}{\rho}} \tag{9}$$

where, W_s and L_s are the width and length of the support beams, respectively, $\beta_n = 4.730$, 7.853, 10.996 for the first three modes of a clamped-clamped beam and f_0 is the resonance frequency of the microresonator.

Estimating quality factor: The mechanical quality factor (Q) of a resonator is:

$$Q = 2\pi\frac{W}{\Delta W} \tag{10}$$

where, ΔW denotes the energy dissipated per cycle of vibration and W denotes the maximum vibration energy stored per cycle.

Many dissipation mechanisms exist in microelectromechanical resonators, such as air damping, thermoelastic damping (TED), surface loss and support loss. Unloaded Q of a microresonator is mainly the combination of these dissipation mechanisms, expressed as (Bannon III *et al*., 2000):

$$\frac{1}{Q} = \frac{1}{Q_{air}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{Surface}} + \frac{1}{Q_{Support}} \tag{11}$$

Thus, to determine Q of the designed resonator, it was necessary to calculate Q of each dissipation mechanisms as following:

Q_{air} denotes the quality factor due to energy loss mechanisms of air damping and is determined as follows (Blom *et al*., 1992; Cho *et al*., 1993):

$$Q_{air} = \frac{k}{\omega_0 b} \tag{12}$$

where, k is stiffness of vibrating spring and b is damping coefficient of a rectangular parallel-plate geometries and has been derived from a linearized form of the compressible Reynolds gas-film equation as follows (Rebeiz, 2003; Cheng *et al*., 2002):

$$b = \frac{3}{2\pi}\mu\frac{A^2}{d_0^3} \tag{13}$$

where $\mu = 1.78\times10^{-5}$ kg m^{-1} sec^{-1} (for air in standard temperature and pressure (STP) conditions) is coefficient of viscosity and proportional to gas pressure and consequently mean free path of gas molecules (Abdelmoneum *et al*., 2003). A and d_0 are area of the device and gap between the two plates, respectively.

Q_{TED} denotes the quality factor due to energy loss mechanisms of thermoelastic damping and is expressed as (Hao *et al*., 2003; Braginsky *et al*., 1985; Lifshitz and Roukes, 2000):

$$Q_{TED}^{-1} = \frac{E\alpha_T^2 T_0}{C_p}\frac{\omega\tau}{1+(\omega\tau)^2}, \tau = \frac{C_p W_r^2}{C_T \pi^2} \quad (14)$$

where α_T and C_p denote thermal expansion coefficient and specific heat at constant pressure of the material used for the beam, respectively; T_0 is the environmental temperature and where C_T denotes thermal conductivity of the beam material and ω denotes the angular frequency of the beam resonator.

$Q_{Surface}$ denotes the quality factor due to energy loss mechanisms of surface loss and the following expression it has been suggested for it (Hao *et al*., 2003; Braginsky *et al*., 1985):

$$Q_{Surface} = \frac{W_r h_r}{3W_r + h_r}\frac{E}{2E_{ds}\delta} \quad (15)$$

where, δ denotes the characterized thickness of the surface layer and E_{ds} is a constant related to the surface stress (Yasumura *et al*., 2000).

$Q_{Support}$ denotes the quality factor due to energy loss mechanisms of support loss and it can be calculated as follows (Mihailovich and MacDonald, 1995):

$$Q_{Support} = 2\pi\frac{KE_{tot}}{E_{loss}} \quad (16)$$

where, KE_{tot} is the stored flexural vibration energy for each resonant mode of a beam resonator can be expressed as (Cross and Lifshitz, 2001):

$$KE_{tot} = \frac{1}{2}mv^2 = \frac{1}{2}\rho h W_r L_r \omega_0^2 U_0^2 \quad (17)$$

where, ω_0 and U_0 denote the fundamental angular frequency of the vibration and the vibration amplitude, respectively and E_{loss} is the energy dissipated per cycle of vibration through supports via., anchors to substrate and for a clamped-free beam is calculated as follows (Hao *et al*., 2003; Hao and Ayazi, 2005):

$$E_{loss} = \frac{1.344}{Eh}\frac{1+\upsilon}{1-\upsilon}\Gamma_0^2 \quad (18)$$

where, υ is Poisson ratio of the support material and Γ_0 is a fundamental vibrating shear force on support where attached to substrate, which can be achievable by finite element analysis.

Plots of quality factor of the proposed microresonator versus electrode-to-resonator gap and versus ambient pressure are shown in Fig. 6 and 7, respectively.

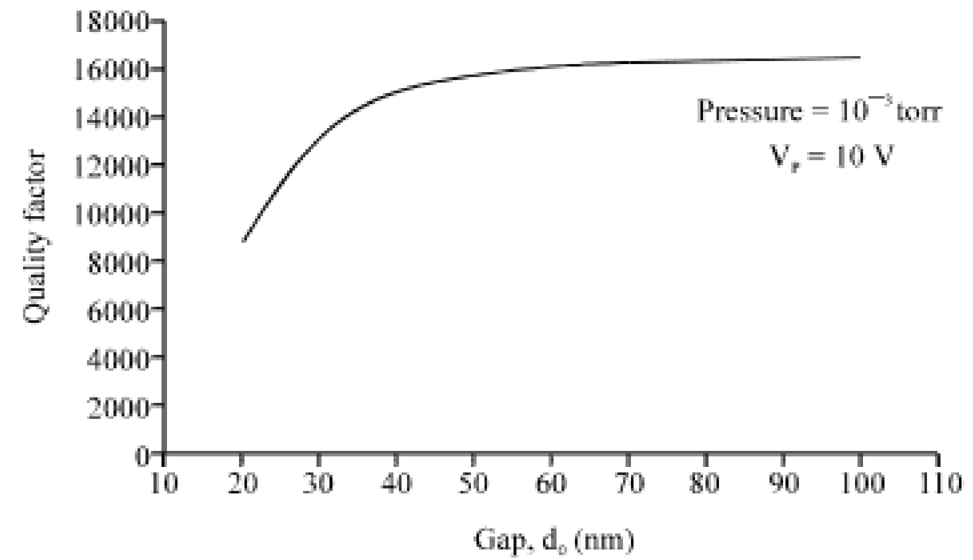

Fig. 6: Plot of Q versus electrode-to-resonator gap

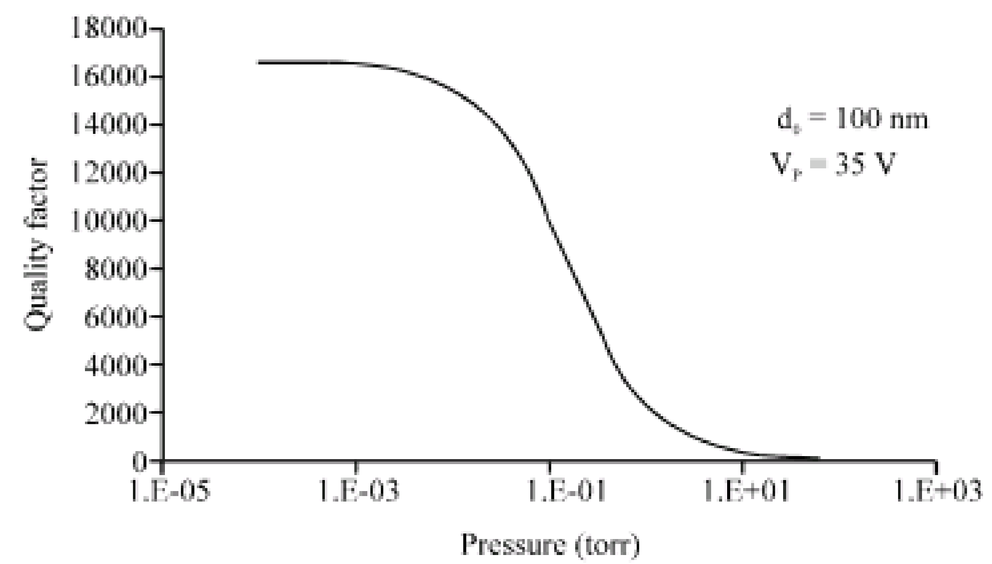

Fig. 7: Plot of Q versus ambient pressure of the microresonator

MICROMECHANICAL RESONATOR CHARACTERISTICS

It must be noted that the simulated spectrum for the 71 MHz micromechanical resonator shown in Fig. 3 was related to the not properly terminated resonator and the transmission gain at the peak of the simulated frequency characteristic was determined from an impedance-mismatched single resonator circuit. So, the simulated transmission gain was not the same as insertion loss. Indeed, the transmission gain was calculated via., the following formula:

$$\text{Transmission Gain} = 20\log\left(\frac{R_x + R_p}{R_L}\right) \quad (19)$$

where, R_p is the polysilicon interconnect series resistance.

The material properties used in this study and surrounding conditions of the resonator are shown in Table 1 (Hao *et al*., 2003; Abdolvand *et al*., 2006). Table 2 shown the simulated micromechanical resonator

Table 1: Material properties and surrounding conditions of the resonator

Parameters	Explanation	Value	Units
E	Young's modulus for polysilicon	150	GPa
ρ	Density of polysilicon	2,300	kg m^{-3}
υ	Poisson's ratio	0.28	-
α_T	Thermal expansion coefficient	2.6×10^{-6}	K
C_p	Specific heat	1.63×10^{6}	J K^{-1} m^{-3}
C_T	Thermal conductivity	90	W $m^{-1}K^{-1}$
T_0	Environmental temperature	300	K
μ	Absolute viscosity of air	1.78×10^{-5}	kg m^{-1} sec^{-1}
P_a	Ambient pressure	0.1	torr

Table 2: VHF micromechanical resonator summary

Parameters	Explanation	Value	Unit
f_{nom}	Mechanical resonance frequency	71.7	MHz
f_0	Center frequency	71	MHz
κ	Frequency modification factor	0.99274	-
L_r	Average beam length	10	μm
W_r	Beam width	2	μm
h_r	Structural thickness	15	μm
W_e(out)	Outer electrode width	5	μm
W_e(in)	Inner electrode width	4	μm
d_0	Electrode to resonator gap	100	nm
L_s	Support beam length	5.3	μm
W_s	Support beam width	1	μm
h_s	Support beam thickness	15	μm
Q	Quality factor	9,912	-
m_r	Resonator mass at middle of each beam	3.45×10^{-13}	kg
k_m	Resonator stiffness at middle of each beam	72,000	N m^{-1}
k_e	Electrical spring constant	-676	N m^{-1}
η_e	Transduction parameter	2.228×10^{-6}	C m^{-1}
V_P	DC-bias voltage	35	V
R_x	Motional resistance	478	Ω

Table 3: Calculated Q of each dissipation mechanisms and total Q of the resonator

Q_{Air}	Q_{TED}	$Q_{Surface}$	$Q_{Support}$	Q_{Total}
24,955	19,500	126,050	625,572	9,912

characteristics and finally, the calculated quality factor of the resonator and each of dissipation mechanisms are presented in Table 3.

CONCLUSION

Design and simulation of a VHF micromechanical resonator based on the new structure square frame suitable for operating around 71 MHz is reported. The proposed microresonator exhibits series motional resistances considerably smaller than that of other beam resonators by a factor equal to the number of electrodes used in each resonator. The present method for R_x-reduction does not degrade linearity of the resonator and in contrast to arrayed microresonators does not consume chip area anymore. This technique alleviates some of remaining challenges that slow the advancement in integration resonators, filters and oscillators into communication systems and helps realization of a single-chip, fully integrated communication system based on RF MEMS technology.

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