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One and two port piezoelectric higher order contour-mode MEMS resonators for mechanical signal processing

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Abstract

This paper reports on the design, fabrication and testing of novel one and two port piezoelectric higher order contour-mode MEMS resonators that can be employed in RF wireless communications as frequency reference elements or arranged in arrays to form banks of multi-frequency filters. The paper offers a comparison of one and two port resonant devices exhibiting frequencies approximately ranging from 200 to 800 MHz, quality factor of few thousands (1000–2500) and motional resistances ranging from 25 to 1000 Ω. Fundamental advantages and limitations of each solution are discussed. The reported experimental results focus on the response of a higher order one port resonator under different environmental conditions and a new class of two port contour resonators for narrow band filtering applications. Furthermore, an overview of novel frequency synthesis schemes that can be enabled by these contour-mode resonators is briefly presented.

Keywords: RF MEMS; Piezoelectric resonator; Contour-mode resonators; Aluminum nitride

1. Introduction

Recent advances in surface micromachining techniques have enabled the realization of miniaturized and high quality factor bulk acoustic resonators that can be integrated with state-of-the-art CMOS electronics [1–8]. Amongst these MEMS devices, a new class of resonators, dubbed contour mode because of their in-plane mode of vibration, has received large attention due to its ability to provide multiple frequency devices on the same silicon substrate. These laterally vibrating microstructures not only provide the advantages of compact size, low power consumption and compatibility with high yield mass producible components, but can also enable paradigm-shifting solutions for simpler frequency synthesizers and transceivers. For example, direct frequency synthesis without the need of complicated phase locked loops will be possible in spread spectrum communication systems via multi-frequency narrowband filter banks or high Q resonators.

Electrostatic and piezoelectric transduction mechanisms have emerged [3,4] as the preeminent techniques for driving and sensing resonant vibrations in micromechanical structures. Electrostatically-transduced resonators have demonstrated extremely high quality factors and high frequencies (up to GHz by employing overtones), but suffer from large motional impedances that make their interface with 50 Ω RF systems troublesome. Recent research activities [9,10] have demonstrated that lower impedances (100 Ω–10 kΩ) can be obtained via dielectric transduction by filling the actuation gap with solid high-k dielectrics. Although very promising, this technology is still unproven and fundamentally suffers from large intrinsic capacitances that mask the

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resonator response at high frequencies or complicate their interface with standard circuitry.

Piezoelectric actuation in aluminum nitride contour-mode resonators has been proven as a superior technology [6,11–14], capable of intrinsically providing low motional resistance (25–1000 Ω) while maintaining high quality factors (1000–2500) and reasonable reactance values that ease their interface with state-of-the-art circuitry. This paper reports on the design and experimental results of one and two port implementations of piezoelectric contour-mode resonators and describes advantages and disadvantages of each solution. Furthermore, experimental results for a novel one port higher order contour-mode solution employed to reach frequencies as high as 803 MHz and a new class of two port resonators for the implementation of narrowband filter banks are presented.

2. Resonator design

Contour mode of vibrations can be excited in c-axis oriented aluminum nitride films via the d_{31} piezoelectric coefficient. By applying an electric field across the film sandwiched between a top and bottom electrode, the MEMS structure tends to expand laterally and can be excited in resonant vibrations whose frequency is set by the in-plane dimensions of the device [6]. The most promising structures to obtain high Q and high frequency of operations are rings and rectangular plates as shown in Fig. 1. The frequency of vibration is generally set by the width of the structure, whereas the second dimension can be employed to control the equivalent motional resistance and static capacitance of the device. This is an additional degree of freedom that a disk structure does not offer. As shown in Fig. 1 and according to experimental results, manufacturing considerations and theoretical observations (structural rigidity):

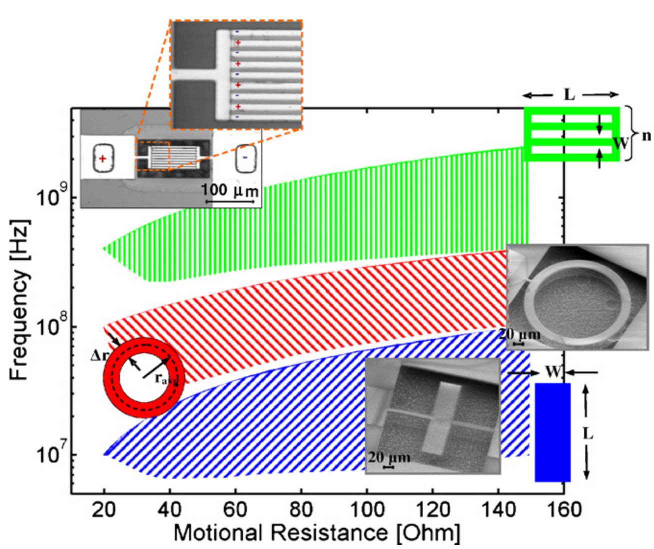

Fig. 1. Design space (frequency versus equivalent motional resistance) for contour-mode AlN resonators.

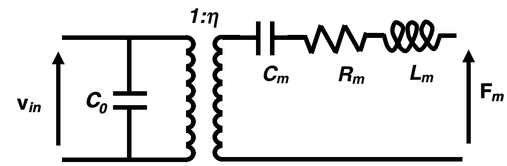

Fig. 2. Conventional Mason lumped circuit model for a piezoelectric transducer.

– the rectangular plate geometry [6] can be effectively employed from 10 to approximately 200 MHz;
– the ring geometry [12] can be adopted between 100 and 450 MHz;
– the higher order contour-mode rectangular geometry [15] can be used between 200 and 2000 MHz.

Although based on preliminary results and subject to improvements through future research, these guidelines offer a good prospective of the status and range of applicability of the AlN contour-mode technology.

The equivalent circuit representation for a piezoelectric transducer is a simplified version of the Mason's model as shown in Fig. 2 [16].

This model will be employed in the following sections to describe one and two port devices and analyze their fundamental characteristics. As shown in Fig. 2, the transducer can be modeled by an intrinsic capacitance, C_0, representing the physical capacitance of the electroded part of the piezoelectric device; a transformer, whose turn ratio, η, represents the conversion between electrical and mechanical variables at a specific location of the device (generally the point of maximum displacement); and motional capacitance, C_m, resistance, R_m, and inductance, L_m, representing the mechanical variables of the MEMS resonators, and being associated with compliance ($1/k_\mathrm{eq}$), damping (c_eq) and mass ($\mathrm{m_{eq}}$), respectively (see Table 1). More specifically

$$C_0 = \varepsilon_\mathrm{P}\frac{\text{Electroded area}}{\text{Thickness of electroded area}} \quad \eta = \frac{F}{V} = \frac{I}{v}$$
$$C_\mathrm{m} = \frac{1}{k_\mathrm{eq}} \quad R_\mathrm{m} = c_\mathrm{eq} \quad L_\mathrm{m} = m_\mathrm{eq} \tag{1}$$

Table 1
Mapping between mechanical and electrical variable used to derive the equivalent electrical circuit of Fig. 2

Mechanical variable	Electrical analogue
Force (F)	Voltage (V)
Velocity (v)	Current (I)
Compliance ($1/k_{eq}$)	Capacitance (C_m)
Damping (c_{eq})	Resistance (R_m)
Mass (m_{eq})	Inductance (L_m)

The arrow emphasizes the fact that it is a mapping process and proportionality factors are not explicitly indicated.