18µm THICK HIGH FREQUENCY CAPACITIVE HARPSS RESONATORS WITH REDUCED MOTIONAL RESISTANCE

Siavash Pourkamali and Farrokh Ayazi
School of Electrical and Computer Engineering, Georgia Institute of Technology
Atlanta, GA 30332-0250

ABSTRACT

This paper reports on implementation and high-Q operation of thick bulk mode VHF capacitive disk resonators with reduced motional resistance. Single crystal silicon (SCS) disk resonators as thick as 18µm with capacitive gap size of 160nm (aspect ratio>110) are fabricated on SOI substrates using a three-mask version of the HARPSS on SOI process. The new resonator design with increased number of electrodes as well as larger device thickness results in over 20X lower motional resistance and larger signal to noise ratio comparing to the previously demonstrated thin VHF HARPSS resonators. Quality factor as high as 25,900 is measured for an 18µm thick side-supported disk resonator in air at the frequency of 149.3MHz. The same resonator exhibits a quality factor of 45,700 in vacuum.

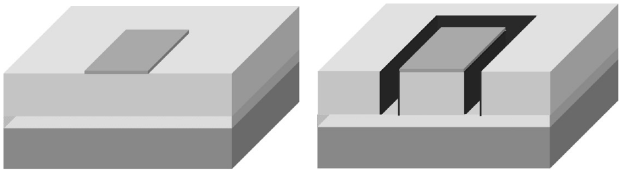
INTRODUCTION

A great amount of research is being conducted on silicon based micromechanical resonant devices as viable substitutes for currently off-chip frequency selective components in electronics. Despite recent demonstrations of operating frequencies in the UHF range with high quality factors (>10,000) [1], the major bottleneck for utilization of capacitive resonators as RF components is their extremely high equivalent impedances and low power handling capability. Several techniques have been incorporated in the design of microresonators in order to increase the electrostatic transduction area and reduce the motional resistance of such devices [1,2].

The first VHF SCS capacitive resonator was implemented using a HARPSS-based fabrication process on SOI substrate [3]. Comparing to the surface micromachined polysilicon resonators [1] with thickness limited to 2-3µm, HARPSS SCS resonators can potentially be as thick as a few tens of microns [4] providing much larger transduction area and consequently lower motional resistance and higher power handling. This work is the first demonstration of thick VHF HARPSS resonators using a simple three-mask process. It is shown practically that much lower motional impedances can be obtained from thicker resonators. The measured quality factors for the thick structures are even higher than that of their thin counterparts both in vacuum and air and the resonance frequency is not affected by the resonator thickness.

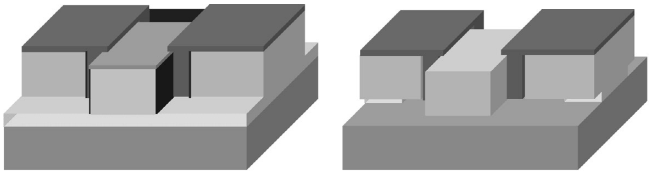
THREE-MASK HARPSS-ON-SOI PROCESS

A simple three-mask HARPSS on SOI process is developed in this work to fabricate thick SCS resonators with polysilicon sense and drive electrodes. The process flow is shown in Fig. 1. A 1µm thick thermal oxide layer is first grown on the low resistivity SOI substrate. The oxide is patterned and kept only on top of the resonating body of the resonators as well as the polarization voltage wirebonding pads (Fig. 1a) to protect them against the silicon etching plasma. Vertical trenches are then etched using the Bosch process all the way down to the SOI buried oxide to define the shape of the resonators. Therefore the thickness of the resonators is determined by the SOI device layer thickness and can be as large as a few tens of microns. Trench sidewalls are coated with a thin sacrificial LPCVD oxide layer. The thickness of the deposited sacrificial oxide layer determines the capacitive gap size in between the SCS resonators and their polysilicon electrodes and can be reduced to tens of nanometer independently from the lithography limits. Sacrificial oxide is etched back on the surface (Fig. 1b) and trenches are subsequently refilled with p-type doped polysilicon to form the electrodes. The silicon device layer is then patterned to provide electrical isolation between different devices as well as the input, output and body of individual resonators. At the same time the polysilicon inside the trenches is patterned and kept only in the electrode area (Fig. 1c). Structures are finally released and undercut in hydrofluoric acid by removing the sacrificial oxide layer and the underlying buried oxide (Fig. 1d).



(a) Grow and pattern initial oxide

(b) Etch trenches, deposit LPCVD sacrificial oxide etch back oxide



(c) Pattern silicon substrate and polysilicon inside the trenches

(d) HF release

Figure 1. *Fabrication process flow for thick SCS bulk mode resonators on SOI.*

SCS disk resonators designed for operation in their elliptical resonance modes with frequencies in the VHF range were fabricated using the described processing technique. Figure 2 shows the close-up view of a fabricated 18µm thick, 29.2 in diameter side supported disk resonator and its electrodes. To maximize the quality factor, the disk is supported at only one resonance node with a 1.2µm wide, 4.0µm long support beam.

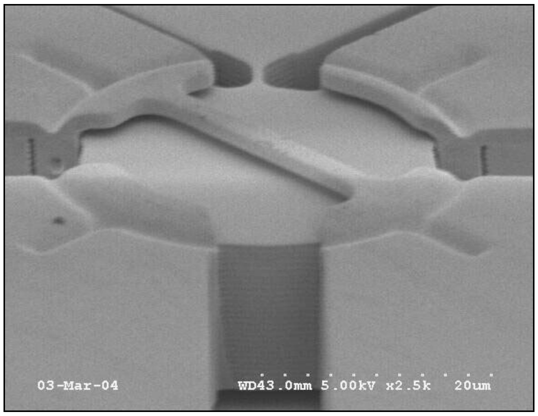


Figure 2. *SEM of a 29.2µm diameter, 18µm thick, SCS disk resonator supported at one resonance node. Gap Size = 160nm.*

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The new design for disk resonators in this work incorporates four electrodes all around the periphery of the disk for maximum signal transduction. Figure 3 is the overall SEM view of the same disk resonator showing all the electrode interconnections. Each pair of confronting electrodes of the resonator is electrically connected. The polysilicon beam bridging over the resonator (Fig. 2) provides electrical connection between two of the electrodes, while the other pair of electrodes are connected by a silicon trace extending around the device (Fig. 3).

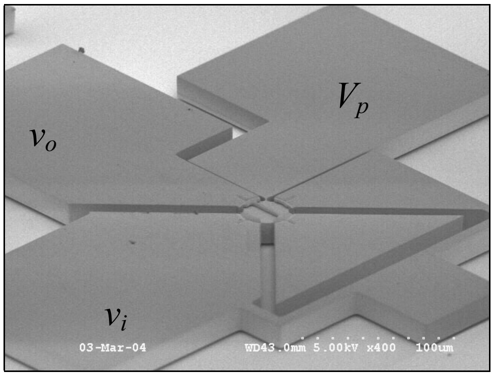


Figure 3. *Overall SEM view of the SCS disk resonator of Fig. 2, showing the electrode interconnections.*

MEASUREMENT AND DISCUSSION

The fabricated resonators were tested in a two-port configuration both in vacuum and atmospheric pressure. Figure 4 shows the frequency response of the 18μm thick disk resonator of Fig. 2, operating in its elliptical bulk mode at 149.3MHz while Fig. 5 is the frequency response of a 3μm thick resonator of the same type. Quality factor of 25,900 was measured for the 18μm thick resonator in air (Fig. 4a), which is over 3X larger than that of the 3μm thick resonator (Fig. 5a) and is the highest reported quality factor in air for VHF capacitive resonators. The measured quality factor for the 18μm thick resonator in vacuum is 45,700 (Fig 4b), slightly larger than that of the 3μm thick resonator (Fig. 5b). Comparing the frequency plots in Figs. 4 and 5, improved signal to noise ratio for the thicker resonator is apparent.

Despite having larger capacitive gap size comparing to the 3μm thick resonators, over 20X lower motional resistances (43.3kΩ in vacuum and 91.2kΩ in air) was measured for the 18μm thick resonator. Lower motional resistance is partly due to increased number of electrodes in the design and partly due to much larger device thickness. Motional resistance of a capacitive elliptical mode disk resonator is given by Eq. 1:

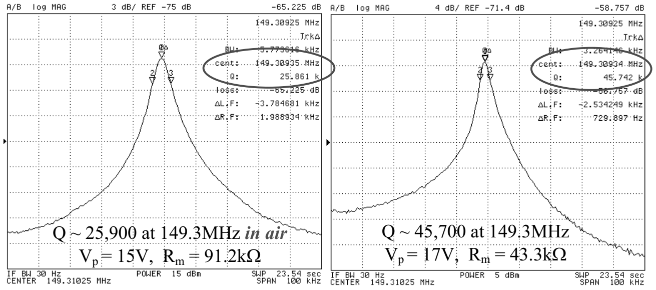
$$R_m = \frac{\sqrt{KM}\,d^4}{Q\varepsilon_0{}^2 L_{eff}{}^2 h^2 V_p{}^2} \propto \frac{d^4}{h.L_{eff}{}^2} \tag{1}$$

where K and M are the effective stiffness and mass of the resonators, d is the capacitive gap size, ε_0 is the permitivity of the surrounding environment, h is the device thickness, V_p is the applied polarization voltage and L_{eff} is the effective electrode length and is given by Eq. 2:

$$L_{eff} = R.\sin(\theta_e) \tag{2}$$

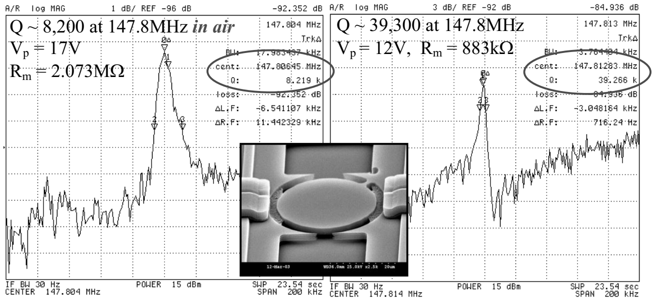
where θ_e is the span angle of the electrode and R is the disk radius. Therefore by increasing the number of electrodes from 2 to 4 in the new design, 2X larger effective electrode length and consequently 4X lower motional resistance is obtained. On the other hand 6 times larger device thickness results in an additional 6X lower motional resistance.

Further reduction of the capacitive gap size to 50nm for the same resonator will result in motional resistance values as low as 400Ω that is a reasonable value for RF applications.



(a) (b)

Figure 4. *Frequency response of the 18μm thick, 29.2μm diameter disk resonator: (a) in air, (b) in vacuum.*



(a) (b)

Figure 5. *Frequency response of a 3μm thick, 29.4μm diameter disk resonator with 120nm capacitive gaps:(a) in air,(b)in vacuum.*

CONCLUSION

Thick SCS bulk mode capacitive disk resonators with operating frequencies in the VHF range were fabricated using a three-mask version of the HARPSS on SOI process. The possibility of operation of thick bulk mode resonators without quality factor or resonance frequency degradation was demonstrated for the first time. The fabricated disk resonators exhibited high quality factors of 45,700, and 25,900 in vacuum and atmospheric pressure respectively. Over 20X lower motional resistance and larger signal to noise ratio was obtained for the 18μm thick disk resonators with the new design comparing to the 3μm thick resonator of the same type. Reasonable motional resistances for RF applications can be obtained from the thick resonators by reducing the capacitive size to sub-100nm levels.

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