

# VERTICAL CAPACITIVE SiBARS

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## ABSTRACT

This work introduces high frequency, vertical silicon bulk acoustic resonators (SiBAR). A combination of the new resonator structures with much larger transduction area and the HARPSS fabrication process is used to demonstrate high frequency capacitive resonators with significantly lower impedances compared to the previous capacitive resonators. Impedances as low as a few kilo-Ohms and quality factors in the range of 20,000 to 50,000 in the VHF range have been achieved for the first thickness mode of the fabricated resonators. Resonant frequencies as high as 983MHz are demonstrated for the third thickness modes of the capacitive SiBARS.

## I. INTRODUCTION

High frequency mechanical resonators such as surface acoustic wave (SAW) [1] and film bulk acoustic wave resonators (FBAR) and filters [2] are widely used in RF front-end duplexers as band-select filters. Recent developments in silicon micromachining technologies has paved the way for implementation of high frequency silicon capacitive resonators with close to one order of magnitude higher quality factors ( $Q$ ) compared to the SAW resonators and FBARs. Such devices are gradually entering the market opening up new opportunities for more advanced wireless communication systems. Due to their lithographically defined resonant frequencies, in-plane capacitive resonators with operating frequencies in a wide range from tens of kHz up to GHz can be implemented on the same substrate simultaneously. This can be a great progress towards implementation of multi-band wireless communication systems. In addition, due to their much larger  $Q$  values compared to piezoelectric resonators, capacitive resonators may enable direct channel selection right after the antenna resulting in dramatic simplification of the transceiver architectures. Low cost batch fabrication using conventional silicon processing techniques is another advantage for silicon resonators. However, despite resonant frequencies in the VHF and UHF range with quality factors as high as a few tens of thousands [3-6], high equivalent electrical impedance remains the major drawback for incorporation of such devices in electronic systems. Fabrication and mechanical design techniques [3,5,6] have been utilized to alleviate the impedance issue, but the demonstrated impedances in the VHF and UHF range are not yet promising.

This work introduces the concept of silicon bulk acoustic resonators (SiBAR) and presents preliminary fabrication and characterization results for such devices. SiBARS can combine the advantages of capacitive silicon resonators with the low impedances offered by the FBAR-like structures. Close to one order of magnitude lower impedances compared to the previously demonstrated SCS disk resonators have been obtained from for the SiBARS operating in the VHF band. It is demonstrated that SiBARS maintain quality factors as high as the capacitive bulk mode disk resonators [4-6].

## II. DEVICE CONCEPT AND OPERATION

Figure 1 shows the schematic view of a piezoelectric film bulk acoustic wave resonator (FBAR) (Figure 1a) as well as a capacitive silicon BAR (Figure 1b). SiBARS can be considered as vertically placed versions of FBARs with a bare silicon resonating membrane that is operated electrostatically in its horizontal thickness longitudinal mode.

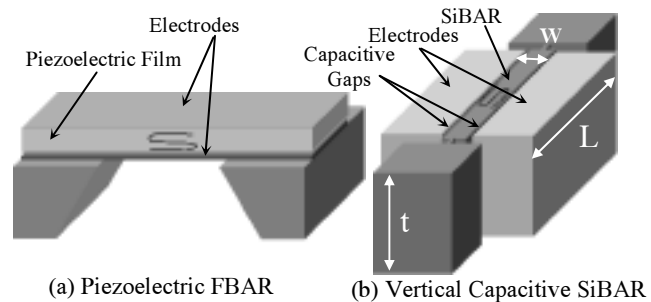


Figure 1. Schematic diagram of (a) a piezoelectric FBAR and (b) a vertical capacitive SiBAR.

As an example, Figure 2 shows the mode shape for the thickness longitudinal mode of a  $20\mu\text{m}$  wide,  $80\mu\text{m}$  long,  $50\mu\text{m}$  thick SiBAR (ANSYS modal analysis). As opposed to the FBARs where the resonant frequency is determined by the thickness of a deposited piezoelectric film, resonant frequency of the SiBARS is determined by their lithography defined horizontal thickness (width). Therefore resonators with different resonant frequencies can be fabricated on the same substrates simultaneously. In addition frequency tuning capability offered by capacitive transduction mechanism can be used for post-fabrication fine-tuning of the resonators.

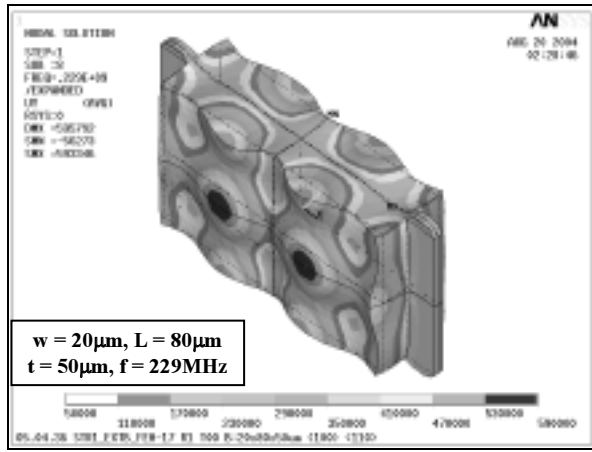


Figure 2. ANSYS modal analysis showing the thickness longitudinal mode shape for a 50µm thick, 80µm long, 20µm wide SiBAR.

Equation 1 gives the electrical equivalent resistance for a two-port vertical (in plane) capacitive microresonator in general:

$$R_{21} = \frac{\sqrt{KM}g^4}{Q\epsilon_0^2 L_{eff}^2 t^2 V_p^2} \propto \frac{g^4}{Q V_p^2 L_{eff}^2 t} \quad (1)$$

where  $K$  and  $M$  are the effective mechanical mass and stiffness of the resonator,  $g$  is the capacitive gap size,  $Q$  is the quality factor of the resonator,  $V_p$  is the applied polarization voltage,  $L_{eff}$  is the effective electrode length and  $t$  is the thickness (height) of the structure. Gap size ( $g$ ) has the most significant contribution in the equivalent resistance. However, excessive reduction of the gap size will eventually result in non-linearity and limit the dynamic range of the device. In addition the maximum applicable bias voltage reduces by decreasing the gap size and partially cancels the effect of gap reduction on the electrical impedance. Increasing the thickness of the resonators for lowering the equivalent resistance was demonstrated for HARPSS VHF disk resonators in [5,6]. It was shown theoretically that impedances in the sub-kilo-Ohm range can be achieved in VHF range for disk resonators by hardly pushing the fabrication limits to produce larger thickness and smaller capacitive gaps. However, for UHF disk resonators with diameters smaller than 10µm, the available area for sensing and actuation is extremely limited resulting in even higher impedances. SiBARs fabricated using the HARPSS process can be tens of microns thick. On the other hand, the length of the structure ( $L_{eff}$ ) can be tens to thousands of microns providing an extremely large capacitive transduction area. This sets the platform for implementation of low impedance VHF and UHF capacitive resonators without the need for aggressive reduction of the capacitive gap sizes. Furthermore, as opposed to the disk resonators, resonant frequency of the SiBARs can be scaled up by reducing their width (horizontal thickness) without decreasing the available transduction area.

It is worth mentioning that as shown in Figure 2, for resonators with thickness > width, the thickness longitudinal

mode will be distorted having different vibration amplitudes at different locations, which is also observed in FBARs [7]. To avoid charge cancellation and maximize the electromechanical coupling, precautions need to be taken in choosing the resonator dimensions.

### III. HARPSS-ON-SOI IMPLEMENTATION

The three-mask HARPSS-on-SOI fabrication process [6] is used in this work to implement vertical capacitive SiBARs. The process flow consists of only three lithography steps and a number of thin film deposition and etching steps. HARPSS-on-SOI fabrication process is capable of producing tens of microns tall SCS resonating elements separated from polysilicon sense and drive electrodes with deep sub-micron capacitive gaps. The capacitive gap size is determined in a self-aligned manner by the thickness of the deposited sacrificial oxide layer.

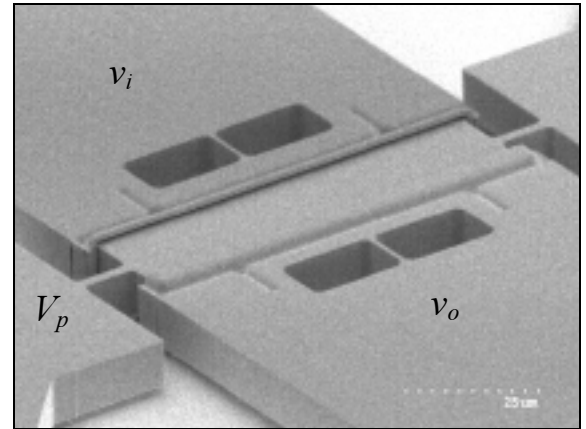


Figure 3. SEM view of a 20µm wide, 80µm long, 10µm thick SiBAR with 225nm capacitive gaps.

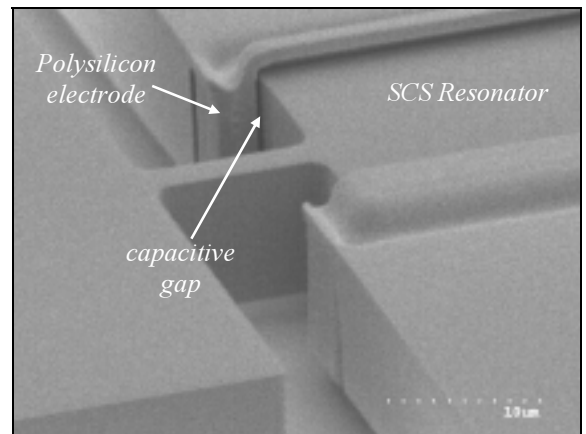


Figure 4. Close up of the support area of the SiBAR of Figure 3 showing the 225nm capacitive gap between the polysilicon electrode and SCS resonating body (electrodes cover the edges of the SiBAR).

SiBARs with different dimensions and capacitive gap sizes were fabricated on low resistivity SOI substrates. Figure 3 shows a fabricated 10µm thick, 20µm wide, and

80 $\mu\text{m}$  long clamped-clamped SiBAR. The resonator has 225nm capacitive gaps and is supported at two sides by 3 $\mu\text{m}$  wide, 10 $\mu\text{m}$  long support beams. Support beams are placed in the midpoint of the resonator width, which has zero vibration amplitude along the width. In addition, the length of the supports is chosen to be equal to the quarter wavelength at the operating frequency (half of the BAR thickness) to minimize flow of energy to the substrate and maximize the quality factor of the resonator. Figure 4 shows the close-up view of the support area for the same resonator and its capacitive gap.

#### IV. MEASUREMENT AND CHARACTERIZATION

Fabricated resonators were tested in a two-port configuration by direct connection to the network analyzer [5]. Figure 5 shows the measured frequency response for the 80 $\mu\text{m}$  long, 20 $\mu\text{m}$  wide resonator of Figure 3. Quality factors of 28,700 in vacuum and 20,200 in air were measured for the first horizontal thickness longitudinal mode of this resonator at 213.4MHz (Figure 5). The measured quality factors are in the range of values measured for the side supported SCS disk resonators with similar operating frequency [6]. Electrical equivalent resistance as low as 6.3k $\Omega$  was measured for this resonator which is more than an order of magnitude lower than that of the previously reported SCS disk resonators [5,6] and to date is the lowest reported value for a capacitive resonator at such a high frequency. The same resonator was also operated in its third thickness longitudinal mode at 693MHz with a Q of 6,000. Due to the location and size of the support beams, in the even thickness modes the supports will be subject to large vibration amplitude imposed by the resonator and introduce excessive loss. Consequently the quality factor will be too small to be able to detect the resonance peak. However for higher order odd thickness modes the midpoint of the device width is still the resonance node and high quality factors can be obtained.

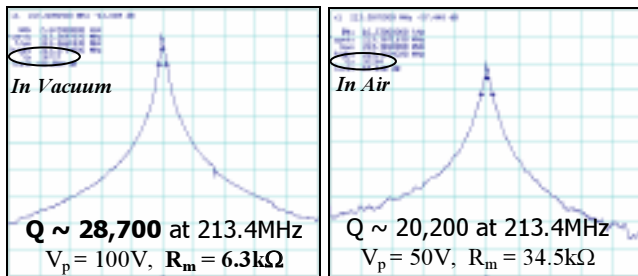


Figure 5. Frequency response of the SiBAR of Figure 4 in its first thickness longitudinal mode.

Figure 6 is the ANSYS modal analysis showing the mode shapes for the first and third thickness longitudinal modes of the same resonator. There is a good agreement between the measured resonance frequencies and the values given by the simulations. Electrostatic tuning range of 25kHz was achieved for this resonator (first mode) by changing the polarization voltage from 10V to 100V (Figure 7).

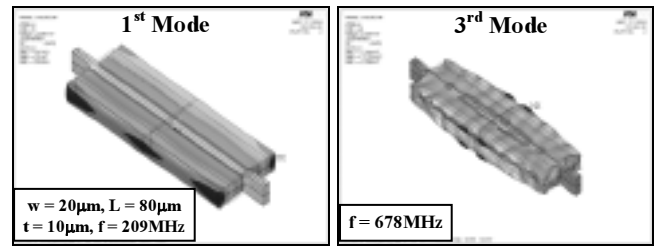


Figure 6. ANSYS finite element analysis showing the mode shapes for the first and third horizontal thickness longitudinal modes of the SiBAR of Figure 3.

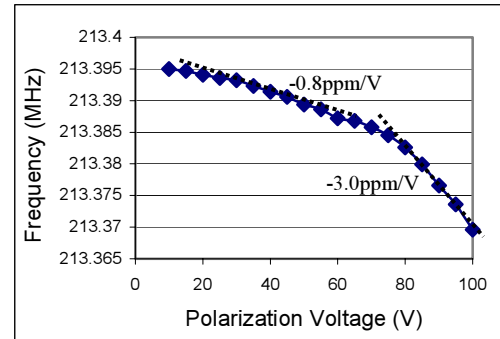


Figure 7. Measured electrostatic frequency tuning characteristic of the SiBAR of Figure 3 showing 25kHz of frequency tuning by changing the polarization voltage.

Figure 8 shows the measured frequency response and SEM of a 20 $\mu\text{m}$  thick, 30 $\mu\text{m}$  wide, 300 $\mu\text{m}$  long clamped-clamped SiBAR. Quality factor of 39,800 and electrical resistance of 5.5k $\Omega$  was measured for the first mode of this resonator at 137.2MHz under vacuum.

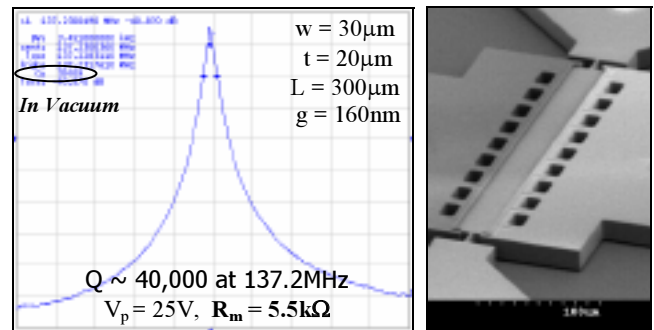


Figure 8. Frequency response and SEM view of a 20 $\mu\text{m}$  thick, 30 $\mu\text{m}$  wide, and 300 $\mu\text{m}$  long clamped-clamped SiBARs.

Figure 9 shows the measured temperature dependency of resonant frequency for a 142MHz SiBAR over the temperature range of 24 to 200 $^{\circ}\text{C}$ . The measured temperature coefficient of frequency (TCF) for this device is -26.6ppm/ $^{\circ}\text{C}$ , which is very close the measured values for SCS disk resonators [5] and the FBARs [8]. Frequency response as well as the SEM view of a 10 $\mu\text{m}$  thick, 15 $\mu\text{m}$  wide, and 300 $\mu\text{m}$  long SiBAR is shown in Figure 10 showing a quality factor of 24,200 at 281MHz for its first mode.

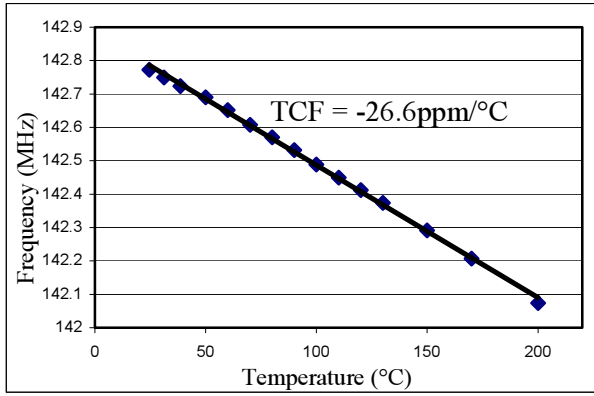


Figure 9. Temperature dependence of frequency of a 142.7MHz SiBAR showing a TCF of  $-26.6\text{ppm}/^\circ\text{C}$ .

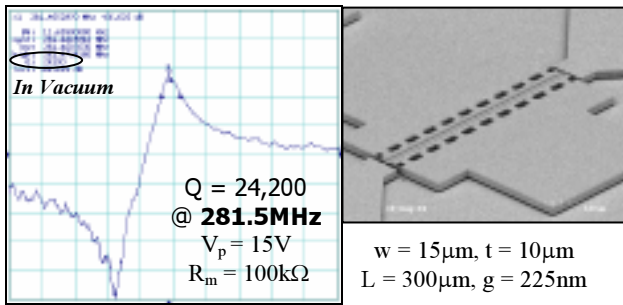


Figure 10. Frequency response of a  $10\mu\text{m}$  thick,  $15\mu\text{m}$  wide, and  $300\mu\text{m}$  long clamped-clamped SiBAR in vacuum.

Figure 11 shows some of the frequency responses in the UHF range measured for the third thickness modes of SiBARs with different dimensions. The measured quality factors are 3,100 and 3,700 at resonant frequencies of 502MHz and 983MHz corresponding to  $30\mu\text{m}$  and  $15\mu\text{m}$  wide resonators respectively.

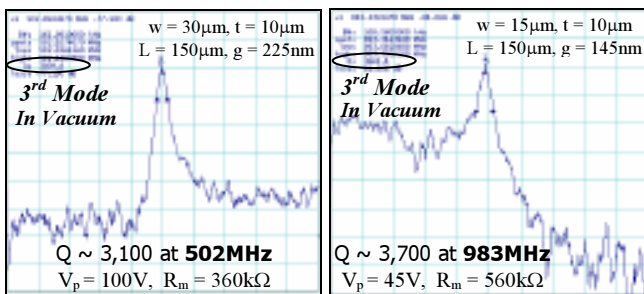


Figure 11. Frequency response of the SiBARs operating in their third thickness modes.

Table 1 summarizes the measured quality factors for SiBARs of different dimensions. It can be concluded from the data presented in Table 1 that increasing the length and thickness of the resonators with equal frequencies and support size, does not degrade their quality factor. This confirms the possibility of reduction of the equivalent resistances to any required level by further increasing the resonator length without sacrificing the quality factor.

Table 1. Measured quality factor and resonance frequencies for SiBARs with different dimensions.

Width & Thickness ( $\mu\text{m}$ )	length ( $\mu\text{m}$ )	Support Width ( $\mu\text{m}$ )	Support Length ( $\mu\text{m}$ )	Freq. 1 <sup>st</sup> Mode	Q (Vac)	Q (Air)	Freq. 3 <sup>rd</sup> Mode	3 <sup>rd</sup> mode Q (Vac)
w=30, t=10	150	3	15	142.9	45,700	24,600	-	-
w=30, t=10	150	5	15	143.3	37,700	-	502.1	3,100
w=20, t=10	150	3	10	213.6	30,800	20,600	-	-
w=20, t=10	80	3	10	213.4	28,700	20,200	690.3	6,000
w=15, t=10	300	3	7.5	281.5	24,300	-	-	-
w=15, t=10	150	3	7.5	279.6	10,600	-	983	3,700
w=30, t=20	300	3	15	137.2	39,800	-	-	-

#### IV. CONCLUSION AND FUTURE WORK

The new category of resonator structures referred to as “SiBAR” was presented as a viable approach towards implementation of high Q, low impedance high frequency capacitive resonators. Preliminary measurement results for the capacitive SiBARs in the VHF range shows motional resistances as low as a few kilo-Ohms with quality factors as high as side supported disk resonators (20,000-50,000). Resonant frequencies in the UHF range were demonstrated for third thickness modes of the SiBARs.

Using the potentially unlimited capacitive transduction area provided through the combination of the HARPSS fabrication process and the SiBAR structures, impedances well in the required RF range can be achieved for VHF and UHF capacitive resonators. As an example for a  $30\mu\text{m}$  wide,  $20\mu\text{m}$  thick,  $1500\mu\text{m}$  long SiBAR with a Q of 45,000, capacitive gap size of 100nm, and polarization voltage of 15V, equivalent electrical resistance will be close to  $300\Omega$ . Future work includes further enlargement of device length as well as reduction of the capacitive gap size to achieve sub-kilo-Ohm impedances. Very long SiBAR structures with different shapes are currently under investigation.

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