Single-Crystal Silicon HARPSS Capacitive Resonators with Submicron Gap-Spacing

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ABSTRACT

This paper reports on the fabrication and characterization of single crystal silicon (SCS) in-plane capacitive resonators with submicron gap spacing using the HARPSS process. The resonating element is made out of single crystal silicon and the drive and sense electrodes are made out of trench-refilled polysilicon, hence yielding an all-silicon microresonator with potentially better temperature and long-term stability. The capacitive gap is defined by a sacrificial oxide layer, which can be potentially reduced to the ten's of nanometer range (700nm reported in this paper). Quality factor as high as 67,000 was measured in 1mTorr vacuum for the 40kHz fundamental resonance frequency of a clamped-clamped beam SCS HARPSS resonator. A 510 μ m long, 5.5 μ m wide, 20 μ m thick clamped-clamped beam resonator was operated in its third resonance mode at 1MHz and demonstrated a Q of 11,000 under vacuum. Electrostatic tuning characteristics of the resonators have been measured and reported.

1. INTRODUCTION

MEMS resonators are a potential candidate to replace current off-chip frequency selective mechanical components such as crystal, ceramic and SAW devices in wireless communication systems. High quality factors, small size and compatibility with IC integration are the major advantages of the silicon MEMS resonators over their counterparts. Extension of the frequency range of capacitive MEMS resonators into the low GHz range requires process technologies that can yield 10-100 nanometer capacitive gap spacings in between the high quality factor (Q) resonating structure and the drive and sense electrodes [1].

A number of poly and single crystalline silicon resonators have been reported in literature [2-7]. Polysilicon capacitive resonators with submicron gap spacing have been demonstrated with metal electrodes that result in a thermal mismatch [2]. Single crystal silicon (SCS) is a more attractive structural material for microresonators compared to polysilicon due to its inherent high mechanical quality factor and independence from various process parameters. However, single crystal silicon resonators reported previously in literature had either complex non-capacitive sense and drive mechanisms [4], large capacitive gaps [5], or low quality factor [6]; such issues may compromise design flexibility and limit the high frequency applications of the microresonators.

This paper reports, for the first time, the implementation of high-Q single crystal silicon resonators with submicron gap spacing using an enhanced and modified version of the HARPSS process. The in-plane resonating element is made out of single crystal silicon and the drive and sense electrodes are made out of trench-refilled polysilicon, hence yielding an all-silicon microresonator. Measurement results on the Q and tuning characteristics of the fabricated beam resonators in the fundamental and third order modes are presented.

2. RESONATOR FABRICATION

The HARPSS process [7] has been previously used to make thick polysilicon resonators [7,8]. In this paper, the HARPSS

process is modified to implement single crystal silicon resonating structures with trench-refilled poly electrodes. The schematic diagram of an in-plane clamped-clamped beam resonator fabricated through the HARPSS process is shown in Fig. 1.

Figure 1. HARPSS clamped-clamped beam SCS resonator

The fabrication process flow is shown in Fig. 2. The SCS resonating beam is defined by two adjacent high aspect-ratio trenches that are 2 to 5 μ m wide and up to 100 μ m deep. The trenches are etched in an inductively-coupled plasma (ICP) deep reactive ion etching (DRIE) system using the Bosch process. The height of the trenches determines the height of the resonator. A thin conformal layer of sacrificial LPCVD high-temperature oxide is then deposited and trenches are consequently refilled with doped LPCVD poly to form the vertical electrodes. The lateral gap spacing is defined by the thickness of the deposited oxide layer, and thus can be scaled down to the ten's of nanometer range [1].

Figure 2. Process flow for HARPSS single crystal silicon beam resonators.

The resonator is released from the silicon substrate using a dry silicon etch in SF_6 plasma, consisting of an anisotropic etch followed by an isotropic etch to undercut the structures. Finally, the sacrificial oxide is removed in a $\text{HF}:\text{H}_2\text{O}$ (1:1) solution. Fig. 3 shows the SEM picture of a fabricated clamped-clamped beam resonator with a length of $510\mu\text{m}$, width of $6.5\mu\text{m}$, height of $20\mu\text{m}$, and a capacitive gap of 700nm . Figures 4 and 5 are the SEM pictures of the beam electrodes area, showing the single crystal beam, the polysilicon electrodes and the submicron gap.

Figure 3. A $510\mu\text{m}$ long, $6.5\mu\text{m}$ wide, $20\mu\text{m}$ tall clamped-clamped beam HARPSS SCS resonator with a gap spacing of 700nm .

Figure 4. SEM of the electrode area showing the polysilicon electrodes as tall as the beam separated by submicron gaps.

Figure 5. Close-up view of the electrode area showing the 700nm gap spacing.

Disk resonators have also been fabricated using the above process to obtain higher resonance frequency. The SEM picture of a $20\mu\text{m}$ diameter SCS disk resonator fabricated using the HARPSS process is shown in Fig. 6. Characterization and measurement results for the disk resonators will be reported in the future.

Figure 6. SEM picture of a $20\mu\text{m}$ in diameter SCS disk resonator with polysilicon electrodes.

In this process, the trenches define: 1) the boundary of the resonating structure, and 2) the polysilicon electrodes. At the end of the process, all the polysilicon inside the trenches should be removed, except for the electrode area. Two methods were investigated, as shown in Fig. 7(a) and (b), to separate the polysilicon in the electrode area from the areas that only define the boundary of the resonator. The first method is to physically disconnect the polysilicon electrode by using discontinuous trenches and etch away the polysilicon inside the trenches that define the boundary of the resonator. However, this method creates “stubs” on the sides of the beam as shown in the SEM of Fig. 7(a), introducing residual extra mass. FEM simulations using ANSYS have shown that these stubs do not alter the resonance frequency significantly. The size of these stubs can be controlled by characterizing the isotropic release etch. The alternative method is to use a continuous trench to define the boundary of the resonator and reduce the width of the trench in certain areas. As shown in Fig. 7(b), the narrow trench (located in between the regular size trenches) is primarily filled by the sacrificial oxide.

Figure 7. Diagram and SEM of the separation methods using a) disconnected trenches, b) narrow trenches.

Due to the presence of voids in the middle of oxide-filled narrow trenches, a thin residual poly line may be formed, connecting the electrode trench-refilled poly to the boundary poly. This parasitic poly will be subsequently etched away during the isotropic etch step of the release process.

3. MEASUREMENT RESULTS

Prototypes of the fabricated SCS beam resonators were tested under vacuum in a two-port configuration using an Agilent 4395A network analyzer. A low noise JFET source-follower with a gain stage was used to interface with the resonators. The sensing interface circuit was built on a printed circuit board (PCB) using surface mount components and the MEMS resonator chip was mounted on the board and wire-bonded. The PCB was placed in a custom vacuum system, which kept the pressure less than 1mTorr.

Fig. 8 shows the plot of a typical frequency response taken from the network analyzer, showing a Q of 62,000 at 49 kHz for a 1100 μm long, 7.5 μm wide and 20 μm tall SCS clamped-clamped beam resonator under 1mTorr vacuum. The summary of the measured Q values for the beam resonators with fundamental frequencies ranging from 41.5kHz to 530 kHz is given in Fig. 9. A Q of ~20,000 was measured for the 0.5MHz beam resonator.

Figure 8. Response of a 1100 μm long, 7.5 μm wide, 20 μm tall HARPSS SCS beam resonator, showing a Q of ~62000 at 49kHz.

Figure 9. Plot of measured Q vs. measured fundamental resonance frequencies of SCS beams. Q decreases with increasing frequency.

Fig. 10 shows the comparison between the measured and theoretical frequency tuning characteristics for a 300 μm long, 6.5 μm wide resonator by changing the DC polarization voltage (V_p). The mismatch is mainly due to fabrication uncertainties in defining the dimensions of the structure, which alter the overall stiffness. The resonance frequency changed from 505kHz to 450kHz by changing the polarization voltage by more than 40V (the calculated pull-in voltage was 56V), providing a large electrostatic tuning range (~10%).

Figure 10. Plot of the resonance frequency vs. polarization voltage for a 300 μm long, 6.5 μm wide beam resonator.

3.1 Third flexural resonance mode

In order to achieve higher operating frequencies, a few of the clamped-clamped beam resonators were actuated in their third flexural mode and the quality factors were measured. The second mode could not be actuated due to the midway position of the drive electrode. A Q of 10,700 was measured at 1.03MHz for the third resonance mode of a 510 μm long, 5.5 μm wide SCS beam resonator (the 1st mode is at 165kHz). Figure 11 shows the measured resonance peak for this mode (the anti-resonance peak is due to the parasitic feedthrough capacitance), and provides a summary of the Q measurement results for the 3rd mode of the beam resonators with other dimensions.

Figure 11. Plot of Q (~10,700) for a clamped-clamped SCS beam resonator operating in its 3rd flexural mode at 1 MHz.

3.2 Loss Mechanisms

Several possible loss mechanisms have been investigated by researchers including the thermoelastic damping (TED), support, and surface related loss mechanisms [5,9-11]. Using the TED relationships for beam resonators reported in references [9] and [10], a minimum Q of 11,000 occurs at frequencies of 4.8, 3.3 and 2.1MHz for SCS beam widths of 5.5, 6.5, and 7.5 μm , respectively. Figure 12 shows the plots of calculated Q_{TED} along with the Q measurement results for 5.5 μm and 7.5 μm wide SCS beam resonators. Although the measured Q values for each beam-width seem to follow the trend predicted by the TED loss (Q decreases with increasing frequency), there is a substantial offset associated with the measured Q values (a factor of 2-3 less than Q_{TED}).

Figure 12. Q vs. frequency showing the measured quality factor and calculated Q_{TED} for beam-widths of 5.5 μm and 7.5 μm .

The observed offset cannot be due to excessive support loss. For the beam resonators, the support loss is proportional to the third power of the length to width ratio (l/w)³ [11]. The length to width ratios are greater than 40 ($l/w > 40$) for all the beam resonators studied in this paper, suggesting much larger Q_{support} values than what was measured. However, the surface loss could very well be a major source of dissipation for the resonators reported here. Figure 13 shows the sidewall of a prototype beam resonator, showing significant surface roughness that is indeed present in all of the beam resonators due to the un-optimized DRIE process used in fabrication. The DRIE process can be easily optimized to eliminate the striation on the sidewall and increase the Q . As reported in reference [5], the losses associated with surface roughness can be significantly reduced by growing a thin oxide and subsequently removing it.

Figure 13. SEM of the sidewall of a SCS resonator. The vertical "striation" is caused by unoptimized DRIE etch conditions.

4. CONCLUSIONS

All-silicon high- Q capacitive micromechanical resonators with submicron gap-spacing utilizing single crystal silicon as the resonating element and polysilicon as the electrodes have been reported. The resonators were fabricated using the HARPSS process and uniform capacitive gaps of 0.7 μm are demonstrated. Quality factors as high as 67,000 for the 1st mode at 40kHz, and 11,000 for the 3rd mode at 1MHz have been measured for clamped-clamped SCS beam resonators. Investigation of various loss mechanisms revealed that the measured quality factor follows the behavior predicted by the TED loss mechanism with an offset. The reason for the offset is believed to be due to the excessive surface roughness of the SCS beam. Optimization of the DRIE process is expected to reduce the surface roughness and increase the Q . Future work will report on confirmation of the above as well as characterization of the UHF SCS HARPSS resonators.

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