PIEZOELECTRIC SINGLE CRYSTAL 6H SILICON CARBIDE MICROELECTROMECHANICAL RESONATORS

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ABSTRACT

Piezoelectrically driven and sensed single-crystalline 6H silicon carbide (SiC) microelectromechanical resonators were designed and fabricated on a novel 100 mm silicon carbide on insulator (SiCOI) process. The prototype resonators have frequencies in the UHF range (464 MHz) with quality factors (Qs) as high as 7,400 for an $f \cdot Q$ product of 3.4×10^{12} . Measurements at temperatures up to $+200^\circ\text{C}$ and RF drive levels of up to 30 Vac demonstrate that these resonators are robust for high temperature and high power applications.

INTRODUCTION

In this paper we demonstrate electrically-driven single-crystalline 6H silicon carbide (SiC) microelectromechanical (MEMS) resonators. In contrast to current state-of-the-art SiC resonators, the resonator presented herein is driven electrically by its own piezoelectric properties, not by an additional piezoelectric layer [1-2] or by alternate means [3]. SiC has been recognized as a potential leading MEMS material due to its high bandgap, high thermal conductivity, and ultra-low mechanical loss [4-6]. Yet the difficulty of fabricating silicon-on-insulator (SOI) like structures has held back the proliferation of SiC MEMS technology. In this paper we experimentally demonstrate a resonator fabricated from a SiC-on-insulator (SiCOI) substrate using standard 100 mm wafer bonding, thinning, and etching techniques with significant advantages over smart-cut technologies [3]. The resonator technology presented enables high voltage (> 30 Vac) reference oscillators to generate frequency sources at ultra-high frequencies (300 MHz to 3 GHz), a potential game changer for wireless communication.

6H SILICON CARBIDE RESONATOR DESIGN AND EXPERIMENTAL REALIZATION

A schematic cross section of the piezoelectric resonator is shown in Figure 1. Similar to a SOI process, the 6H SiC layer is bonded to a Si substrate with an intermediate sacrificial silicon dioxide dielectric layer to form the SiCOI wafer. RF electric field is exerted in the thickness-direction (Z) by a set of electrodes formed on top of the SiC layer with alternating polarity. A ground electrode is formed on the bottom of the SiC layer and accessed with metallized vias. Finally, the sacrificial oxide is removed via either vapor HF etching or liquid HF etching followed by critical point drying.

Figure 1. Schematic cross section of the single-crystalline 6H SiC piezoelectric MEMS resonator fabricated on a SiC-on-insulator (SiCOI) wafer.

Figure 2(a) shows a photograph of a typical custom bonded 100 mm SiCOI wafer after thinning of the SiC layer to final target thickness. Only two voids were observed after bonding. Since the SiC to oxide bond is very strong and uniform across wafer, the voids remained the same size after annealing, and the SiC layer only delaminated at the void regions after grind and polish, as shown in the two dark regions in the photograph. Figure 2(b) maps the resulting SiC layer thickness after grind and polish. A median SiC thickness of $3.5 \mu\text{m}$ was achieved. A thin SiC layer is desirable to exploit the intrinsic piezoelectric properties of 6H SiC, since a greater electric field strength can be imparted across the thickness of the resonator for the same RF drive voltage.

Figure 2. (a) 100 mm SiCOI wafer after grind and polish down to target median thickness of $3.5 \mu\text{m}$, (b) wafer map of SiC layer thickness.

Finite element method (FEM) simulation of the expected mode profile of the designed resonator structure is shown in Figure 3. Since the 6H SiC in this work has its crystalline c-axis oriented parallel to the thickness of the device, a high-order in-plane extensional mode is excited via the lateral field piezoelectric coefficient e_{31} . Figure 3(a) shows the total displacement field, while Figure 3(b) and 3(c) show the along length (Y) and along thickness (Z) displacements, respectively. The Z displacement pattern is needed for comparison with laser doppler vibrometer (LDV) measurements presented later. From these figures, it is seen that the alternating electric field polarity induces an alternating polarity extensional strain region centered at each electrode finger. While the Y displacement pattern shows a clean vibration mode, it

was found that asymmetries in the thickness direction induced from having a solid blanket metal on the backside of the SiC layer caused the Z displacement to have additional perturbations of the mode pattern in addition to the expected alternating polarity from the in-plane extensional mode. However, the perturbing motion is much smaller than the desired Y displacement pattern and can be ignored for practical purposes. Figure 3(d) plots the result of a coupled piezoelectric frequency domain analysis of the resonator when an RF drive voltage is applied to one of the interleaved electrode plates and the piezoelectrically-generated charge is collected on the other electrode plate. For this particular resonator design, a simulated resonance frequency of 463.7 MHz is obtained, which matches with experimental results from electrical and optical testing (464.5 and 464.2 MHz, respectively).

Figure 3. Simulated resonator mode shape at resonance for 2.7 μm SiC thickness (a) total displacement, (b) Y displacement (along length of resonator, L), (c) Z displacement (out-of-plane displacement), (d) simulated resonance response from frequency sweep.

Figure 4 shows several scanning electron microscope (SEM) images of typical fabricated SiC resonators. An overview of the entire device including the ground-signal-ground (GSG) RF pads is captured in Figure 4(a). To facilitate testing of several different resonator geometries without repositioning probes, a common GSG spacing was chosen and 50 Ω coplanar stripline waveguides were designed to bring the RF signal into the device. The resonator plate is etched from a single layer of 6H SiC and has length L and width W as indicated by the yellow arrows in the SEM image in Figure 4(b). The final freestanding SiC resonator is defined by etching of narrow trenches around the resonator except at the tether regions, as shown in the dark black "U" shaped areas in the SEM

image, followed by removal of the sacrificial layer. The expected frequency of this device is given by

$$f \approx N/(2L) * v_{\text{acoustic}}, \quad (1)$$

where L is the resonator plate length, N is the number of interleaved electrodes, and v_{acoustic} is the speed of sound. For our prototype devices, we have selected $N = 17$ to maximize both the strain generated by the voltage applied to the piezoelectric transducers as well as the motional current collected on the output side of the device. The centerline-to-centerline electrode spacing is denoted as the electrode pitch in Figure 4(c), and is determined by

$$P_{\text{electrode}} \approx L / N. \quad (2)$$

For the resonator shown in Figure 4(b,c), $P_{\text{electrode}} = 12.35 \mu\text{m}$, $L = 211 \mu\text{m}$, and $W = 22 \mu\text{m}$. The SiC thickness was 2.7 μm for this device. Also visible are the four via holes which pass the ground planes through to the bottom surface of the SiC layer, after which they are routed across the tethers connecting the resonator body to the surrounding SiC frame. In a similar manner, the RF signal lines bridge the tethers on the top surface of the SiC.

Figure 4. (a) Scanning Electron Microscope (SEM) micrograph of fabricated 6H single-crystalline SiC resonator with input and output RF ports, (b) zoom-in view of SEM micrograph of a full resonator, (c) close-in SEM micrograph of resonator central region and tethers.

ELECTRICAL CHARACTERIZATION OF PIEZOELECTRIC 6H SiC RESONATORS

A set of resonators with varying lengths and two different thicknesses were systematically measured using a vector network analyzer. Figure 5(a) presents a plan view schematic of a 1 cm by 1

cm die containing 30 resonators and 8 de-embedding structures. The 30 resonators are divided into 3 designs, resulting in 10 resonators of each design which occupy two rows of the die. The resonator pitches within a design are varied from 10.53 μm to 12.87 μm in steps of 0.26 μm , resulting in frequency steps between 8 and 13 MHz. Figure 5(b) is a photograph of a corresponding fabricated SiC resonator die. Figure 6 shows the electrical testing setup on a wafer probe station. GSG probes are positioned on the device pads with the aid of the microscope and connected to the vector network analyzer via coaxial cables. An impedance standard substrate is used to bring the calibration plane to the probe tips prior to measurement.

Figure 5. (a) Schematic plan view of a 1 cm by 1 cm resonator die with 30 resonator design variations and 8 de-embedding structures. Electrode pitch (μm) and measured frequency (MHz) is given for each design; (b) Top view photograph of a released die.

Figure 6. Wafer probe station equipped with vector network analyzer (VNA), microscope, sample stage, and GSG probes. The die under test (DUT) is placed on the sample stage and the GSG probes are positioned under the microscope for each device.

A typical measurement using this setup is shown in Figure 7(a) for the resonator of Figure 4(b,c). The resonance frequency of this particular device is 464.5 MHz, indicated by the sharp peak in the transmission (S21) at that frequency and the corresponding dip in the reflection (S11). The electrical transmission response demonstrates the characteristic anti-resonance indicative of capacitive feedthrough in piezoelectric devices. Measurements of the resonance frequencies as function of resonator pitch are shown in Figure 7(b). Also plotted are finite element method (FEM) predicted frequencies, exhibiting excellent correspondence. As expected from the frequency law above (Eq. 1), an increase in the electrode pitch of the device causes a decrease in the frequency (this is because L increases with electrode pitch for a fixed number of electrodes N). The red and green experimental trend lines (linear fit) are seen to be good agreement with the FEM predicted frequencies, indicating that the resonances observed correspond with the expected vibration modes. This is strong evidence that the observed resonances are the designed piezoelectrically-transduced vibration modes.

OPTICAL CHARACTERIZATION OF PIEZOELECTRIC 6H SiC RESONATORS

Figure 8 shows the experimental configuration of the resonator die and several 2D Laser Doppler Vibrometer (LDV) scans of the same 6H SiC resonator from Figure 4(b,c). To facilitate the LDV measurement, which could not be done on the wafer probe station due to the requirement of a scanning XY stage, the resonator die was mounted and wirebonded in a ceramic leadless chip carrier (LCC) as shown. A socketed breakout board was used to bring in the RF drive signal.

Since the LDV measures motion perpendicular to the wafer, only the Z component of the resonator displacement pattern can be measured. The Z component of displacement is induced through Poisson's ratio in the extensional mode, thus providing a good measure of the extensional strain pattern of the resonator. Clearly visible in Figure 8 are the 17 regions of alternating strain polarity corresponding with the alternating polarity voltage applied to the top electrodes (compare with the Z displacement pattern of Figure 3). Also shown in the figure is the acoustic radiation leaking into the substrate through the support tethers. An AC voltage amplitude of 30 V was used in this experiment, which resulted in a max Z displacement of approximately 50 nm. This demonstrates the potential of MEMS SiC resonators to generate high voltage in ultra-high frequency applications when operated in oscillator configurations.

Figure 7. Experimental test results with vector network analyzer: (a) frequency sweep of one resonator design, (b) simulation and experimental data for frequency trend as a function of electrode pitch and device thickness. Frequency decreases when electrode pitch increases, and frequency decreases when electrode thickness decreases.

As shown in Figure 9, the resonance frequency for the 17th order longitudinal extensional mode was found from the LDV to be 464.2 MHz and the measured quality factor (Q) was 7,400 in air, resulting in an $f \cdot Q$ product of 3.4×10^{12} . This is a very high frequency-quality factor product approaching that of crystalline quartz. With further improvements to the resonator design to eliminate anchor loss from the tethers (see Figure 8 inset), we expect that an $f \cdot Q$ product of 6×10^{14} can be achieved [6], surpassing that of quartz and making these resonators the highest performing resonators to date in terms of phase noise and oscillator stability.

Figure 8. Laser Doppler Vibrometer (LDV) measurement of the Z component of the 6H SiC resonator extensional mode displacement pattern. (Inset) Circular radiation pattern emanating from tether.

Figure 9. LDV measurement of quality factor (Q) of 7,400 in air at a frequency of 464.2 MHz.

TEMPERATURE CHARACTERIZATION OF PIEZOELECTRIC 6H SiC RESONATORS

Single-crystalline SiC is expected to be a temperature robust MEMS material. To this end, we have measured the device from Figure 2 across temperature on a wafer probe station. The device was tested from +25°C to +200°C and back to +25°C in steps of 10°C with soak time of 10 min per temperature (limited by the wafer probe station maximum temperature). The results of this measurement are plotted in Figure 10. The frequency retrace of the

6H SiC resonator is excellent, exhibiting little hysteresis to within the temperature control ability of the wafer probe station. A linear fit to these results produces a temperature coefficient of frequency (TCF) of -18 ppm/°C for the 6H SiC device.

Figure 10. Measurements of the resonance frequency change in PPM of the resonator of Figure 4(b,c) from +25°C to +200°C and back to +25°C.

DISCUSSION AND CONCLUSIONS

The presented 6H SiC resonators were found to be robust to drive voltages up to 30 V_{ac} as well as temperatures at least +200°C, limited by the probe station. A moderate TCF of -18 ppm/°C was obtained for the particular resonator configuration. The piezoelectric response was measurable on a network analyzer up to 200°C, providing evidence that the piezoelectric effect can be maintained in SiC up to even higher temperatures. The relatively weak piezoelectric coupling coefficient of SiC makes it amenable to thin layer thicknesses, wherein the electric field strength can be more concentrated for the same applied drive voltage.

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