SIC RESONANT DEVICES FOR HIGH Q AND HIGH TEMPERATURE APPLICATIONS

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ABSTRACT

Polycrystalline cubic silicon carbide (polySiC) lateral resonant devices have been fabricated by surface micromachining, packaged using ceramic-based materials and nickel wirebonding procedures, and successfully operated over $<10^{-5}$ -760 Torr and 22-950°C pressure and temperature ranges, respectively. Device Q 's of $>100,000$ at $<10^{-5}$ Torr and resonant frequency drifts of <18 ppm/hr under continuous operation have been determined using an electron microscope-based setup. Finite element analysis revealed that changes in resonant frequency with increasing temperature depend on the interplay between the decrease in Young's modulus of polySiC and induced stresses in the suspension beams of the lateral resonant device, which occur due to mismatch in thermal expansion coefficients of the polySiC film and the underlying substrate.

INTRODUCTION

Micromachined polysilicon resonators are emerging as potential on-chip replacements for discrete oscillators and filters in high performance communication transceivers [1]. The integrated microelectromechanical polysilicon devices exhibit frequency selectivity characteristics that are superior to integrated RC active filtering techniques based upon traditional electron devices. Micromachined resonator Q 's of $>80,000$ under vacuum conditions and resonant frequency coefficients of <10 ppm/°C have been reported [2]. In addition to high Q transceiver components, the utility of polysilicon resonators has also been demonstrated in a number of other applications including mechanical properties testing, pressure sensing, and inertial navigation systems [3-5]. However, the electrical and mechanical properties of polysilicon begin to rapidly degrade at elevated temperatures ($>350^\circ\text{C}$), making it increasingly unsuitable for high temperature applications [6-8]. In contrast, SiC is well known for its mechanical characteristics, chemical inertness, high thermal conductivity, and electrical stability at temperatures well above 600°C [8, 9]. Although the material properties and microfabrication compatibility of SiC make it an attractive structural material for fabrication of high Q and/or high temperature microelectromechanical devices, the development of SiC as a structural material has been limited by a combination of fabrication, packaging, and testing challenges.

This paper presents development of cubic polycrystalline SiC (polySiC) lateral resonant devices (subsequently called resonators) that are fabricated, packaged, and successfully operated over a

wide range of pressures and temperatures. First, the fabrication of polySiC resonators by a surface micromachining process using SiO_2 , polysilicon, and nickel (Ni) as the isolation, sacrificial, and contact metallization layers, respectively, is presented. Details of the resonator packaging scheme using ceramic-based materials and Ni wirebonding procedures are also outlined. Next, both optical and electron microscope-based experimental setups and protocols to investigate changes in resonator Q with pressure and resonant frequency with temperature are described. Finally, resonator testing results are presented and the behavior of resonant frequency with temperature is examined using finite element analysis.

FABRICATION

The starting substrate for polySiC film growth is prepared by depositing a $3.5\text{ }\mu\text{m}$ -thick polysilicon film by LPCVD on a $1.5\text{ }\mu\text{m}$ -thick SiO_2 layer grown thermally on 100-mm diameter, (100) Si wafers. A polySiC film with a nominal thickness of $2\text{ }\mu\text{m}$ is grown at 1280°C in a cold-wall, rf-induction-heated, vertical APCVD reactor [10]. The polySiC film is then mechanically polished using a SiC slurry to reduce the surface roughness (R_a) from $\sim 400\text{ }\text{\AA}$ on the as-grown film to $<40\text{ }\text{\AA}$. Figure 1 outlines the fabrication of

Figure 1. Schematic description of the polySiC resonator fabrication process showing cross-sections after: (a) Al deposition by sputtering; (b) definition of resonator pattern by plasma etching; (c) deposition of Ni by sputtering; (d) definition of Ni contact regions by photolithography and wet etching; and (e) release of polySiC resonators in KOH.

Figure 2. SEM micrograph of a released polySiC lateral resonant device. The suspension beam length and width are nominally 100 μm and 2.5 μm , respectively. Exposed polySiC shows up as dark gray, while the Ni metallization appears light gray.

polySiC resonators by surface micromachining. A 5000Å-thick aluminum (Al) film is deposited on the polySiC film by sputtering and subsequently patterned using photolithography and Al etchant to delineate the resonator geometry. Next, the resonator pattern is defined in the polySiC by dry etching in a $\text{CHF}_3/\text{O}_2/\text{He}$ plasma with Al acting as the etch mask [10]. Afterwards, the Al mask is stripped and a 7500Å-thick Ni film is sputter deposited, patterned by photolithography, and wet etched to define nickel contacts to the polySiC. Finally, the resonator is released by a timed etch of the sacrificial polysilicon in 40 wt.% KOH at 40°C and dried using a supercritical CO_2 drying process. Figure 2 presents a SEM micrograph of a released polySiC resonator.

The released polySiC resonator chip is packaged onto a ceramic plate with patterned gold pads and steel posts as shown in Fig. 3. The chip is attached to the ceramic plate using commercially available zirconia-based cement (AREMCO Ultra-Temp 516), which is thermally conductive, stable to 1760°C, and resistant to chemical attack. The gold pads on the ceramic plate enable electrical connection from the resonator chip to external circuitry through the stainless steel screws, nuts, and washers. Electrical connections from the Ni contact pads on the resonator chip to the gold pads on the ceramic plate are realized by 25 μm -diameter Ni wires. Attachment of Ni wires to the pads is achieved by a thermosonic wirebonding process optimized for maximum pull strength [11].

EXPERIMENTAL SETUPS

The packaged resonators are tested under different conditions of pressure and temperature. Figure 4 presents the experimental setup used to test devices at atmospheric pressure (760 Torr). The resonator package is placed on a heater capable of attaining temperatures as high as 1000°C. The heater is mounted on a thermally-insulating ceramic tile inside an aluminum chamber with openings for argon, electrical connections, and optical access. Probe tips are used to electrostatically actuate the resonator, while the microscope is used to monitor device motion. Argon is introduced at ~2 psi into the chamber during testing to minimize thermal oxidation effects on the probe tips and heater.

Figure 5 presents the experimental setup used to test devices under vacuum conditions. The resonator package is placed on a hot

Figure 3. Cross-sectional schematic view of the polySiC resonator package. External electrical connections to the resonator chip are enabled through the stainless steel screws, washers, hex nuts, gold pads, and nickel wirebonds.

stage mounted inside an environmental SEM (ESEM) and connected to external circuitry via electrical feedthroughs. The resonator motion is observed using an attached monitor. In addition to room-temperature imaging capabilities of a standard SEM under high vacuum ($<10^{-5}$ Torr) conditions, the ESEM can also perform

Figure 4. Test setup for atmospheric pressure (760 Torr) experiments. The optical microscope is used to observe resonator motion. Measurement uncertainty in resonant frequency is ± 50 Hz.

Figure 5. Schematic description of the environmental SEM setup used for experiments under vacuum conditions. Resonator motion is observed on an attached monitor. Measurement uncertainty in resonant frequency is ± 0.01 Hz.

imaging under low vacuum (0.1-20 Torr) and/or high temperature (1000°C) conditions.

Experiments are performed to determine the resonant frequency and Q of the resonator under different conditions of pressure and temperature. Resonant frequency is determined visually by adjusting the frequency of the excitation voltage to the resonator until maximum resonator amplitude is observed. Resonator Q is determined from knowledge of the resonant frequency and 3dB frequencies, which are defined as those frequencies at which resonator amplitude is ~70% of the maximum [12].

RESULTS

Table I presents a summary of resonator Q 's of three polySiC resonators measured at room temperature (22°C) under three different pressure regimes. The low-pressure tests are conducted inside the ESEM, while the atmospheric pressure tests are performed using the optical microscope setup. The nominal resonator frequencies are determined under high vacuum conditions. The resonator Q 's vary with pressure, with maxima and minima exhibited under high vacuum and atmospheric conditions, respectively. In general, resonator Q 's are below 150 for all devices at 760 Torr, between 2500 and 4000 at 0.1-0.2 Torr, and above 50000 at $<10^{-3}$ Torr. This increase in resonator Q with decreasing pressure is attributed to damping effects: at lower pressures, the damping is minimized and Q is increased. The effect of damping on resonators is dominant for pressures down to $\sim 10^{-3}$ Torr, and at extremely low pressures (high vacuum conditions), the Q is limited by the internal friction of polySiC [7, 13]. A 800 million cycle, 16 hr aging test performed at 22°C on a ~14 kHz resonator reveals that the resonant frequency drift is approximately 17.5 ppm/hr.

Figure 6 presents a graph showing the variation of resonant frequency with temperature for a polySiC resonator actuated at 150Vpp under atmospheric conditions. The corresponding resonant frequency drops from 30400 Hz at 22°C to 30000 Hz at 410°C. The resonator does not operate above 500°C due to breakdown of the electrically isolating SiO_2 layer. Figure 7 presents a graph showing the variation of resonant frequency with temperature for a comparable polySiC resonator under low vacuum (0.1-0.2 Torr) conditions. The device is actuated at 3.5Vpp and operates over a 22-950°C temperature range. The resonant frequency of the vacuum-tested device drops steadily from 28930 Hz at 22°C to 28402 Hz at 700°C, followed by an increase to 28544 Hz at 900°C, and then a slight decrease to 28500 at 950°C.

Finite element analysis is performed to investigate changes in resonant frequency with increasing temperature. A preliminary finite element model is analyzed using ANSYS software to examine interactions between the polySiC resonator and silicon substrate [14]. The bottom of the silicon substrate is fixed in the direction normal to the surface and allowed free thermal expansion

Table I. Resonator Q determined at different pressure regimes.

Device #	f_r (Hz)	Q_1 ($\pm 5\%$)	Q_2 ($\pm 10\%$)	Q_3 ($\pm 15\%$)
1	10060	25	2875	62888
2	11360	34	3474	107926
3	28920	148	3616	57828

f_r : resonant frequency; Q_1 : 760 Torr; Q_2 : 0.1-0.2 Torr; and Q_3 : $<10^{-3}$ Torr.

Figure 6. Variation of resonant frequency with temperature for a polySiC resonator operated at atmospheric pressure at 150Vpp actuation. Device does not operate above 500°C due to breakdown of the insulating SiO_2 layer.

Figure 7. Variation of resonant frequency with temperature for a polySiC resonator (comparable to the one in Fig. 6) under vacuum conditions (0.1-0.2 Torr) at 3.5Vpp actuation.

in directions parallel to the surface. Figure 8 presents a graph showing the variation of thermal expansion coefficients with temperature for cubic SiC (assumed equivalent to polySiC) and silicon, while Table II lists the other material properties used in the finite element analysis [14-16].

Figures 9 and 10 present graphs of normalized resonant frequency versus temperature based on the results of the finite element analysis and the experimental data shown in Fig. 7, respectively. In both cases, there is an initial steady decrease in resonant frequency, followed by a slight increase, and another slight decrease. The differences between the finite element results and experimental data may due to variations between the actual material property parameters and those used in the model as well as the influence of intrinsic stresses in the various material layers.

Examination of the material properties used in the finite element model provides qualitative insight into the resonant frequency versus temperature behavior for the devices. The thermal expansion coefficient of polySiC is lower than that of silicon from 22°C to ~200°C, while at higher temperatures, the thermal expansion coefficient of polySiC is greater than that of silicon. Consequently, at temperatures below 200°C, the silicon substrate expands faster than the polySiC layer, which induces a resultant compressive thermal stress in the suspension beams of the

Figure 8. Variation of thermal expansion coefficient of SiC and silicon as a function of temperature [14-16].

Table II. Materials properties used in finite element analysis [14].

Material	ρ (kg/m ³)	E (GPa)	α_E (ppm/°C)
SiC	3230	400	46
Silicon	2320	160	80

ρ : density; E: Young's modulus; and α_E : temperature coefficient of Young's modulus.

resonator. The net effect of the induced compressive stress and decrease in Young's modulus of polySiC leads to a decrease in the resonant frequency. As temperatures increase above 200°C, the polySiC film begins to expand faster than the silicon substrate, which induces a resultant tensile stress in the resonator suspension beams. The lowering effect on the resonant frequency due to the decrease in Young's modulus is counteracted by the induced tensile stress, which tends to increase resonant frequency. The net effect of increasing tensile stress and decreasing Young's modulus with increasing temperature leads to a resonant frequency minimum, and then, an increase. However, as the temperature increases even further, the effect of the decrease in Young's modulus dominates leading to the eventual decrease in resonant frequency.

Figure 9. Predicted resonant frequency as a function of temperature obtained using finite element analysis.

Figure 10. Normalized experimental data of Fig. 7.

CONCLUSIONS

PolySiC resonators have been fabricated by surface micromachining and successfully packaged for operation in vacuum and high temperature environments. Resonator Q's above 100,000 under vacuum conditions have been observed. Changes in resonant frequency with increasing temperature are attributed to a decrease in Young's modulus as well as thermal expansion mismatch with the underlying substrate.

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