Silicon Carbide for RF MEMS

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Abstract — **Silicon carbide (SiC) is an excellent candidate for use in next generation RF MEMS devices such as microfabricated switches, micromechanical resonators, and filters. SiC is characterized by a wide bandgap, high acoustic velocity, high thermal conductivity, high electrical breakdown strength, and low chemical reactivity. These material properties lead to potential improvements in operating frequency, power handling capability, and reliability for such devices relative to their silicon counterparts. Furthermore, film deposition and micromachining techniques for SiC have been developed which leverage established tools and processes found in silicon-based microfabrication facilities, thereby demonstrating SiC as a commercially viable microsystem material. This paper will present recent performance results from SiC-based RF MEMS components.**

I. Introduction

Driven by the explosive demand for wireless communication services and products, developers of RF MEMS are continuously looking for ways to extend the performance, operating capabilities, reliability, and ease of integration of these components. Early work focussed on lateral resonators that were typically fabricated using polysilicon surface micromachining and exhibited resonant frequencies on the order of a few 10's of kHz [1]. While recent efforts to improve silicon-based resonator fabrication and design have resulted in devices with vibration frequencies into the 100's of MHz, there has been growing interest in developing materials other than silicon for micromechanical devices as a means to further increase resonant frequency while maintaining high quality factors (Q). Currently, the two leading candidates under investigation are diamond and silicon carbide (SiC), due primarily to the high acoustic velocities of these materials [2,3]. Of the two, SiC is currently at the forefront due to more advanced deposition and patterning technologies that in most cases are quite similar to, and compatible with, silicon processing techniques.

This paper highlights the merits of using SiC for RF MEMS, beginning with a summary of its relevant material properties. Next, a review of the key processing techniques and recent demonstrations of SiC-based RF MEMS devices is presented. These examples illustrate not only the ability to fabricate SiC devices with a wide range of operating frequencies, but also the ability of SiC devices to operate in harsh environments, such as those characterized by high operating temperature, where silicon is not well suited. The paper also includes a description of recent developments in fabricating nanoscale SiC mechanical resonators that have fundamental frequencies in excess of 1 GHz, a first for micro- or nanoelectromechanical systems (NEMS) [4]. In addition to looking at device performance, challenges related to RF MEMS will be discussed.

II. The Silicon Carbide Advantage

SiC is an excellent addition to the MEMS toolbox based on its combination of mechanical, thermal, and electrical properties. SiC has an acoustic velocity that is approximately 50% higher than that of silicon, translating to higher resonant frequencies for oscillating structures with the same dimensions. Chemically, SiC is extremely inert and the oxidation rate of SiC is quite low even at elevated temperatures, which results in devices that are potentially less susceptible to deleterious changes that could result from surface modification of the structures. This is a particular advantage over other structural materials given that MEMS (and NEMS) devices have high surface-to-volume ratios compared to their macro-scale counterparts. The chemical inertness of SiC is also advantageous when it is used in conjunction with silicon substrates, in that structures such as the thin SiC membranes shown in Fig. 1 can be readily fabricated using conventional silicon micromachining. SiC is electrically and mechanically stable to higher temperatures than silicon as a result of its wide band gap (2.3 to 3.2 eV) and high sublimation temperature (>2000°C). In addition to thermal stability, the thermal conductivity of SiC is much greater than silicon. This ensemble of physical properties makes SiC very attractive for a wide variety of RF MEMS applications. Table I summarizes the key material properties of SiC.

Silicon carbide micro- and nanostructures have been fabricated using a variety of film deposition and pattern delineation techniques that are quite similar to processes used in silicon. Like silicon, SiC can be deposited in thin film form using conventional chemical vapor deposition (CVD) techniques. Atmospheric pressure CVD (APCVD) has been used to deposit single crystal 3C-SiC films on Si substrates using carbonization-based heteroepitaxy [5].

TABLE I

KEY MATERIAL PROPERTIES OF SIC AND SILICON

Property	3C-SiC	Polysilicon
Young's modulus (GPa)	448	150
Density (g/cm^3)	3.3	2.3
Acoustic velocity (m/sec)	11,652	8,075
Thermal conductivity (W/cm-°C)	5.0	1.5
Dielectric constant	9.7	11.9
Breakdown voltage (MV/cm)	4.0	0.3
Bandgap (eV)	2.3	1.12
Melting point (°C)	> 2000	1410

This capability gives 3C-SiC a distinct advantage over the other common SiC polytypes (6H-SiC and 4H-SiC) in that silicon micromachining techniques can be used in tandem with SiC micromachining to create complex structures and devices. For applications that do not require single crystal films, APCVD can also be used to deposit polycrystalline 3C-SiC (poly-SiC) [6]. Poly-SiC is more versatile than 3C-SiC from a micromachining perspective because it can be deposited on SiO_2 and polysilicon sacrificial layers and electrically insulating Si_3N_4 films, whereas 3C-SiC is restricted to single crystal silicon. In both cases, the deposition temperatures range from a low of 1050°C for poly-SiC to a high of ~1300°C for 3C-SiC.

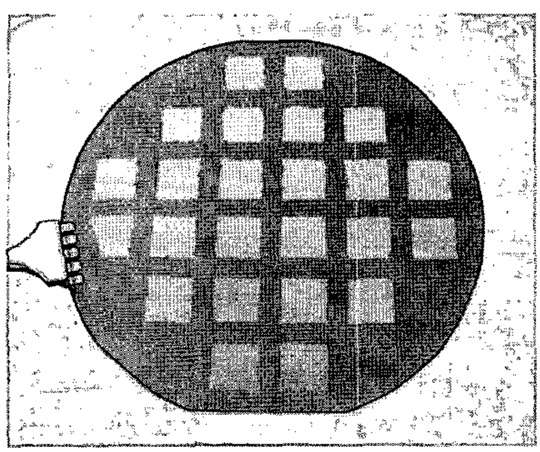

Fig. 1. SiC membranes measuring 1cm x 1cm, fabricated on a 100mm diameter silicon wafer. Bulk micromachining to remove the underlying silicon did not attack the SiC film.

Deposition processes for poly-SiC are not restricted to APCVD. In fact, several groups have developed low pressure CVD (LPCVD) processes for poly-SiC [7,8]. LPCVD has several distinct advantages over APCVD, including much higher throughput, improved film uniformity, and lower deposition temperatures. Approaches using dual precursors [7] and single precursors [8] are currently under development. Success in achieving both high throughput (50, 100mm-diameter wafers) [7] and low deposition temperature (800°C) [8] has recently been reported.

Patterning of SiC films can be performed using a variety of techniques, which include reactive ion etching (RIE), micromolding, and lift-off. RIE processes for SiC follow conventional approaches using fluorine-based chemistries often mixed with O_2. For bulk micromachining, DRIE of SiC has also been demonstrated [9]. The micromolding approach is of particular interest for complex structures because RIE etching typically suffers from poor selectivity to convenient sacrificial layers (polysilicon, SiO_2) and photoresist etch masks. The micromolding process bypasses this problem altogether by using prepatterned SiO_2 and polysilicon molds in conjunction with mechanical planarization, and thus is well suited for the fabrication of complex multilayer devices [10,11]. Lift-off patterning capitalizes on differences in nucleation and growth mechanisms for SiC on vertical silicon and SiO_2 surfaces, and is well suited for patterning thin (< 500 nm-thick) poly-SiC and 3C-SiC structures on very thin (~100 nm) sacrificial layers that might otherwise be severely damaged by RIE.

Using the aforementioned film growth and patterning techniques, a wide range of micromachined devices - many relevant to RF MEMS - have been fabricated from SiC. Lateral microresonators operating at kHz resonant frequencies have been made from highly textured poly-SiC thin films (~2μm thick) that were grown by APCVD on polysilicon sacrificial layers and patterned by RIE [3]. Single crystal, 3C-SiC lateral resonators have also been fabricated from epitaxial films that were transferred to SiO_2 sacrificial layers using wafer bonding techniques [12]. Clamped-clamped beam vertically actuated microresonators with MHz resonant frequencies have been fabricated from poly-SiC films grown by APCVD on polysilicon sacrificial layers and patterned by lift-off [13]. Clamped-clamped beam nanoresonators with GHz resonant frequencies (the highest reported to date) have recently been fabricated from ultrathin (~100Å) 3C-SiC films grown on single crystal silicon by APCVD and pattered by electron beam lithography [4]. Such a wide range of resonant frequencies could be achieved due to the combination of the versatile fabrication approaches and the outstanding material properties of SiC.

As researchers move toward advanced architectures for wireless communication, the ability to integrate micromechanical or nanomechanical elements with electronic circuitry will become more critical from the standpoints of cost, size, and performance [14]. While it is fair to say that a SiC integrated circuit technology is still limited (in comparison to silicon) in large measure by issues related to the quality of substrates, epitaxial films, insulating layers, and contacts, continued advancements in these areas should reach a point where an all-SiC microsystem is technically feasible. In fact, material compatibility issues should be less of a problem for an integrated SiC fabrication process than the same process in silicon due to its chemical inertness and temperature stability. For instance, fabrication of the mechanical components could be performed after the electronics have been made by exploiting the low diffusion coefficients of dopants in SiC. By incorporating relatively low SiC deposition temperatures (e.g., film deposition at 900°C or below) and the proper choice of sacrificial materials, the integration challenges faced by silicon-based devices, i.e., thermal budget and protection of electronics during release, could be minimized.

III. RESONATOR EXAMPLES

To demonstrate the ability of SiC to extend microsystem technology to a wide variety of operating environments, polySiC microresonators have been fabricated and successfully operated over a broad range of pressures (~10^{-5} to 760 Torr) and temperatures (25 to 950°C) [3]. Finite element analysis correlates well with experimental results, which indicate that a decrease in resonant frequency at elevated temperature is due to two main factors: reduction in Young's modulus and thermally induced stress resulting from differences in thermal expansion coefficients between the structural material and the substrate, in this case polySiC and silicon, respectively. An SEM micrograph of a released polySiC resonator is shown in Fig. 2.

Resonant frequency was measured as a function of temperature over the range from room temperature to 950°C, and quality factor was determined as a function of pressure over the range from 760 Torr to high vacuum. As expected, the resonator Q values were low (generally below 150) at atmospheric pressure due to squeeze film damping being a dominant phenomenon in this regime. High drive voltages ($150V_{pp}$) were therefore required to drive the resonators under these conditions; as a result, the devices would now operate beyond 500°C due to

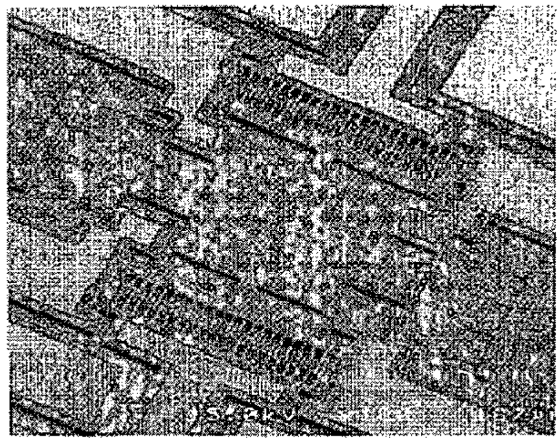

Fig. 2. SEM micrograph of a released poly-SiC lateral resonant device [3].

electrical breakdown of the insulating oxide film. Q values increased as the operating pressure was decreased, exhibiting a maximum of greater than 100,000 in high vacuum. By contrast, only $3.5V_{pp}$ was required to actuate the resonators in vacuum, eliminating the oxide failure and enabling the SiC resonators to operate up to a temperature of 950°C.

In another device example, vertically actuated clamped-clamped beam resonators were fabricated from poly-SiC on thin polysilicon release layers, and shown to operate in the MHz frequency range [13,15]. A sample device is shown is Fig. 3. Resonator characterization was performed in vacuum at room temperature. The devices suffered from low Q values (<150) that were attributed to high parasitic series resistance in the beams. Scaling of

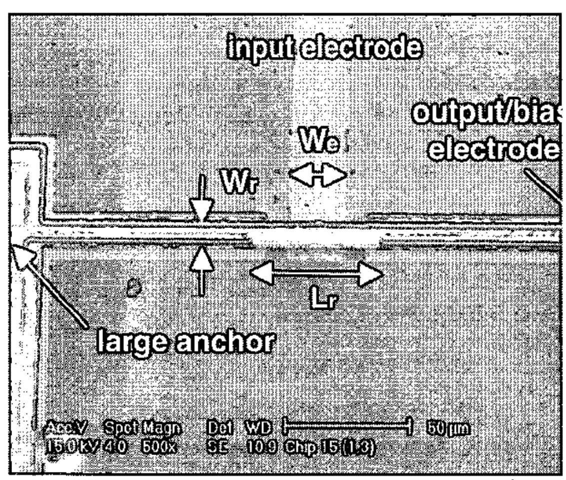

Fig. 3. SEM micrograph of a released poly-SiC vertically actuated resonant device [15].

the SiC C-C beam resonator design to the nano regime, however, has demonstrated the feasibility of resonator structures to vibrate at microwave frequencies [4].

IV. Conclusions

SiC is an attractive candidate for use in RF MEMS applications, based on its ensemble of material properties which include high acoustic velocity, stability at elevated temperatures, and chemical inertness. Furthermore, a variety of microfabrication techniques – similar to, and compatible with, those used for silicon - have been demonstrated for SiC. The combination of material properties and fabrication techniques has been used to produce SiC mechanical resonators that exhibit a wide range of resonant frequencies (kHz to GHz), some of which are capable of operating in harsh environments, e.g., temperatures as high as 950°C. One challenge limiting the growth of SiC for RF MEMS is integration with electronic circuitry.

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