# Silicon Carbide Micro/Nano Systems for Harsh Environment and Demanding Applications

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## ABSTRACT

Micro/nano systems enable the development of smart products and systems by augmenting the computational ability of microelectronics with the perception and control capabilities of sensors and actuators. Micro/nano systems are also known as micro- and nano-electromechanical systems (MEMS and NEMS), and have been commercialized in a wide range of applications including crash sensing, blood pressure measurement, optical projection, fluid flow control to name a few. Silicon, in single- and polycrystalline form, has traditionally been the platform semiconductor material underpinning the fabrication of the mechanical and electronic elements of micro/nano systems. However, the material properties of silicon impose limitations on its use in harsh environment and demanding applications. Such applications involve operation in the presence of high temperatures, corrosive media, high shock loads, erosive flows, and/or high radiation, or involve performance requirements for the mechanical elements that are beyond silicon's capabilities. Silicon carbide (SiC) is an alternative platform semiconductor material that enables such applications because of its wider bandgap and higher melting/sublimation temperature, elastic modulus, fracture toughness, hardness, chemical inertness, and thermal conductivity. This overview highlights recent material, process, and device advances in the context of the effort to establish a SiC micro/nano systems technology. This technology enables sensing and actuation in propulsion, power generation, resource exploration, nuclear reactor instrumentation, deep space exploration, and communications to name a few.

***Keywords***: silicon carbide, harsh environment, MEMS, NEMS

## 1 SIC AS A MEMS AND NEMS MATERIAL

SiC has proven to be an excellent semiconductor material for high power, high frequency, and high temperature electronics because of its outstanding electrical and thermal properties including a wide bandgap, a high breakdown voltage, and a high thermal conductivity coefficient. It is becoming an important MEMS and NEMS platform material for harsh environment applications due to its combination of excellent mechanical and chemical properties, which include high Young's modulus and fracture toughness, resistance to oxidation, and chemical inertness in alkaline and acidic solutions. MEMS and NEMS are viable enabling technologies with significant potential for economic impact in areas that would benefit from miniaturized systems manufactured using batch processing techniques. Current dominance of single crystal silicon and polysilicon (poly-Si) in micro/nano systems has resulted from their favorable electrical and mechanical properties coupled with the mature infrastructure of silicon integrated circuits (IC) industry. The development of SiC bases micro/nano systems has received far less attention and investment. However, recent advances in SiC processing has made it a leading material for MEMS and NEMS for harsh environment applications [1-2]. Interest in SiC micro/nano systems with performance characteristics that cannot be achieved using silicon has provided substantial impetus for developing SiC MEMS and NEMS technologies that are analogous to those for silicon.

## 2 DEPOSITION OF SIC FILMS FOR MICRO/NANO SYSTEMS

Because of its chemical inertness, it is difficult and slow to bulk micromachine a SiC wafer. Furthermore, crystal-plane selective etching analogous to silicon has not been demonstrated. As a result, most of the attention and progress in SiC micro/nano systems has been based on deposited films of SiC. Formation of SiC requires reactions between Si and C atoms under suitable thermal and chemical conditions. Formation of amorphous stoichiometric SiC films generally requires temperatures above 700°C, with polycrystalline SiC (poly-SiC) requiring higher substrate temperatures (>800°C), and single-crystalline still higher temperatures (>1150°C).

SiC thin films have been deposited by several approaches, most notably atmospheric pressure chemical vapor deposition (APCVD) [3], Plasma enhanced chemical vapor deposition (PECVD) [4], and low pressure chemical vapor deposition (LPCVD) [5-6]. Throughout 1990's, APCVD was the dominant method used to grow epitaxial SiC films (3C- and 6H-SiC) for electronic and MEMS device applications [1]. APCVD systems can easily be maintained at very high substrate temperatures (>1300°C).

This feature is particularly advantageous for SiC epitaxy, where temperatures typically range from ~1150°C to ~1300°C for 3C-SiC grown on Si wafers. A common process for growing epitaxial 3C-SiC on Si largely follows processes first detailed by Nishino, et al.[7] and Powell, et al [8]. These processes are based on the conversion of a clean Si surface to 3C-SiC in a hydrocarbon gas, followed by 3C-SiC film growth using Si- and C-containing precursors. Single-crystalline 3C-SiC films has been heteroepitaxially grown using this method despite the nearly 20% lattice mismatch between 3C-SiC and Si.

PECVD is an attractive deposition technique for amorphous SiC films from a MEMS/NEMS fabrication point-of-view because it enables SiC films to be deposited on a variety of substrate materials at temperatures much lower than APCVD and LPCVD, often between 200 and 400°C. However, hydrogen is often incorporated in the films. The residual stress in PECVD SiC films is dependent on various deposition parameters and can be significantly reduced after film deposition by annealing [4, 9]. The amorphous SiC films deposited by PECVD are resistant to KOH, HF, and TMAH and are often used as an etch masking material in Si bulk micromachining [9].

Low temperature LPCVD processes for poly-SiC has been developed independently by a number of research groups [10-12]. These efforts have explored a wide range of precursor combinations, ranging from single sources like tetramethylsilane (TMS), 1,3 disilabutane ($H_3Si\text{-}CH_2\text{-}SiH_2\text{-}CH_3$ or DSB) to dual sources such as acetylene and dichlorosilane. The reported deposition temperatures range from 650°C to 1150°C. Our deposition technology is based on a high throughput LPCVD furnace specifically designed to deposit poly-SiC films at substrate temperature lower than 900$^{o}$C [12]. The furnace is a horizontal, resistively-heated, hot-wall reactor and is capable of holding up to 100, 150 mm-diameter wafers, making it the largest furnace for poly-SiC films to date. Stoichometric (111) oriented nitrogen-doped poly-SiC are deposited routinely in this furnace. The residual stress and thickness uniformity of the films have been optimized by adjusting the precursor flow rates and the deposition pressure. Figure 1 shows a 150 mm-diameter Si wafer coated with a 1 μm-thick poly-SiC film.

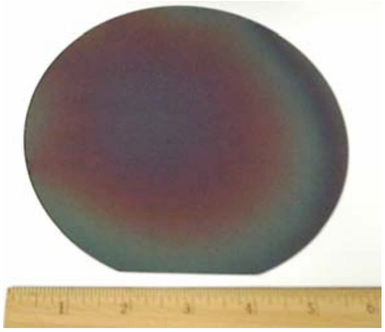

Figure 1. Poly-SiC film, 1 μm-thick, deposited on a 150 mm-diameter Si wafer by LPCVD.

## 3 SIC MICRO- AND NANO-MACHINING

Most of the silicon IC standard processing tools and methods can generally be used with SiC. Surface micromachining is a fabrication process where a device structural layer is deposited onto a sacrificial layer that is selectively etched to release the designed free standing device components. SiC surface micromachining involves the deposition of a structural poly-SiC layer, patterning of the SiC layer by reactive ion etching (RIE), and releasing of the structural components of the device by etching the sacrificial layer [1]. Both $SiO_2$ and poly-Si have been used as sacrificial layers due to the chemical inertness of SiC to $SiO_2$ and silicon etchants. Figure 2 shows a lateral resonant device fabricated by surface micromachining using poly-Si as the sacrificial layer. This type of resonator exhibited a mechanical quality factor of 150,000 when tested under vacuum conditions and was operated successfully at a temperature 1000$^{o}$C [13]. The very high quality factor and the high operating temperature demonstrate the outstanding mechanical and thermal properties of poly-SiC.

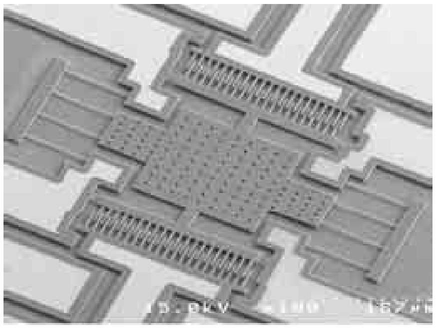

Figure 2. Lateral resonator fabricated from a 2 μm-thick poly-SiC film by SiC surface micromachining.

Because of the challenges with wet chemical etching of SiC noted above, inductively coupled plasma–reactive ion etching (ICP–RIE) is commonly used bulk micromachining of SiC substrates and thick films (i.e., several microns and more) [14]. F-based plasma chemistries, for instance, CF4, CHF3, and SF6, mixed with O2, are the common gases used in RIE patterning SiC. Figure 3 shows a micro turbine rotor etched in single-crystal 6H-SiC using optimized, time-multiplexed etch/passivation ICP deep-RIE process.

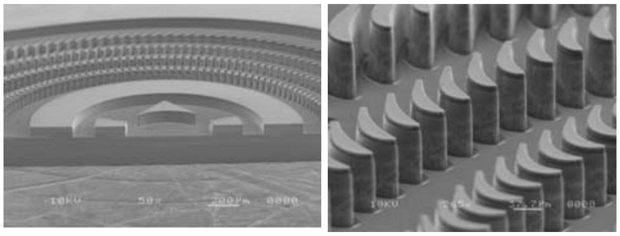

Figure 3. Global (left) and magnified (right) views of a micro turbine rotor etched in single-crystal 6H-SiC using a deep-RIE process. [Courtesy of G. Beheim and L. Evans, NASA Glenn Research Center (beheim@grc.nasa.gov)]

Again, due to its chemical inertness, RIE etching of SiC poses problems such as relatively slow etch rate, poor selectivity to poly-Si and silicon dioxide sacrificial layers, and micro-masking of the etch field. We developed several micro-molding processing techniques for SiC that avoid the RIE etching problems [1]. For example, we fabricated the fuel atomizer in Fig. 4 by deep-RIE etching of the mold pattern into a silicon wafer and then depositing SiC into the mold. The silicon mold was then dissolved in KOH to release the SiC part. This micro-molding technique avoids direct etching of SiC, while taking advantage of etching technology in silicon. Laser direct writing is another novel patterning method for SiC micro- and nano-machining. It has the advantages of fast removal rates, independence from etch masks (i.e., direct writing), and insensitivity to crystallographic orientation [15].

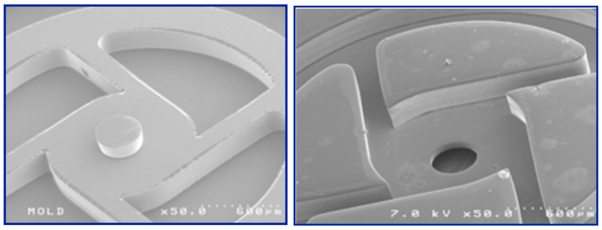

Figure 4. SiC fuel atomizer (right) fabricated by SiC deposition into a silicon mold (left). The SiC atomizer is ~400 μm-thick, with the top features ~275 μm deep.

## 4 SIC MICROMECHANICAL DEVICES

The advancement of processing technologies have made possible SiC based MEMS devices for harsh environment applications, including for example temperature, pressure, acceleration, and gas sensors.

### 4.1 Pressure sensors

The earlier SiC pressure sensors were developed based on piezoresistive sensing approach. Kulite Semiconductor Products (Leonia, NJ) has developed a 6H-SiC-based pressure sensor that exhibited stable operation at 500°C [16]. Another approach developed by Daimler Benz, AG, and the Technical University of Berlin for fabricating SiC-based pressure sensors utilizes 3C-SiC films grown on silicon-on-insulator (SOI) substrates and silicon bulk micromachining to produce dielectrically isolated 3C-SiC piezoresistors on a thick silicon membrane [17]. The thin oxide in the SOI substrate inhibits leakage current between the 3C-SiC piezoresistors and the silicon substrate, a problem that is magnified at high temperatures.

Researchers in our university developed a SiC-based pressure sensor using the capacitive sensing approach and our APCVD single-crystalline SiC epitaxial films [18]. The fabricated sensor demonstrates a high-temperature sensing capability up to 400°C. A similar sensor is being commercialized by FLX Micro, Inc. (Cleveland, OH). More recently, we have developed an all-SiC capacitive pressure sensor (using surface micromachining techniques) for high-temperature, harsh environment applications. The sensor was built on SiC wafer substrate, utilizing our LPCVD poly-SiC film process technology. The 200 nm-thin bottom electrode and the 3 μm-thick pressure-sensing top diaphragm/electrode were made of LPCVD poly-SiC. Figure 5 shows a plan-view optical micrograph of the all-SiC pressure sensor.

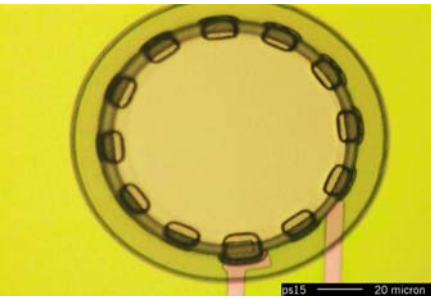

Figure 5. Plan-view optical micrograph of an all-SiC absolute pressure sensor fabricated by surface micromachining techniques on a SiC substrate. Vacuum sealing of the reference cavity is performed during the fabrication process at the wafer level.

### 4.2 Accelerometers

In military and space applications the need for improved system performance in extreme impact (>100,000 g), high electromagnetic (EM) field (>18T in some rail guns), and high temperature (>500°C) environments has generated strong demands for rugged sensors and instrumentation. Preliminary tests of bulk-micromachined 6H-SiC high-g piezoresistive accelerometers were successfully performed to 40,000 g [19]. Sensitivities ranging from 50 to 343 nV/g were measured for differing sensing elements.

### 4.3 Gas sensors based on micro-hotplate

Boston MicroSystems (Boston, MA) is developing SiC micro-hotplate-based conductometric gas sensors for monitoring air pollutants and toxins such as CO, $NO_x$, and volatile organic compounds [20]. Metal oxide semiconductors (MOS) such as tin oxide and tungsten trioxide are favored conductometric materials given their excellent durability and sensitivity, but require elevated operating temperatures between 200°C and 500°C. By integrating MOS films onto SiC micro-hotplate arrays, such conductometric gas sensors can be miniaturized, resulting in operation at miliwatt power levels and response times of less than a millisecond. Since the micro-hotplates provide localized heating, the rest of the sensor chip remains at ambient temperatures.

## 5 SIC NANOMECANICAL DEVICES

### 5.1 Nano-beam resonator

SiC is an excellent material for high-frequency NEMS mechanical resonators because the ratio of its Young's modulus to mass density is significantly higher than silicon. The characteristic resonant frequency of NEMS devices scales up with decreasing device size. One recent advance has been crucial to breaking the 1-GHz barrier [21]: the use of SiC epitaxial films to fabricate nano-beams such as that in Fig. 6. One application of such nano-beam resonators is in communication and signal processing as reference oscillators and filters. Another application is in ultra-sensitive mass detection. A modulated flux of atoms can be adsorbed on the surface of a SiC NEMS resonator within an ultrahigh vacuum environment, the mass-induced resonance frequency shifts as a result.

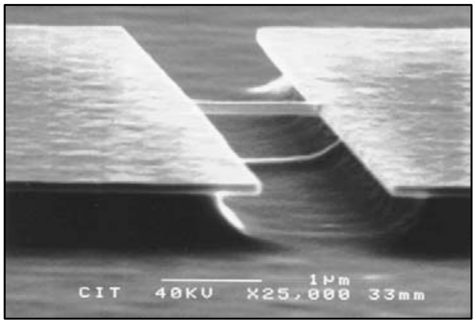

Figure 6. A 3C-SiC doubly-clamped nano-beam with a fundamental resonance frequency in excess of 1 GHz [21].

## 5.2 Nano-porous membrane/shell

Porous materials have found wide applications in the biomedical field thanks to their selective permeability. SiC has attracted attention in this area because of its good bio-compatibility. Direct electrochemical etching is a conventional way to create nano-scale pore sizes. In our group, a selective chemical vapor deposition process has been developed to deposit porous polycrystalline SiC thin films containing a high density of through-pores measuring 50 to 70 nm in diameter [22] (see Fig. 7). A mechanically-durable, chemically-stable, and well anchored porous structure can be fabricated after releasing the underlying sacrificial material through the pores.

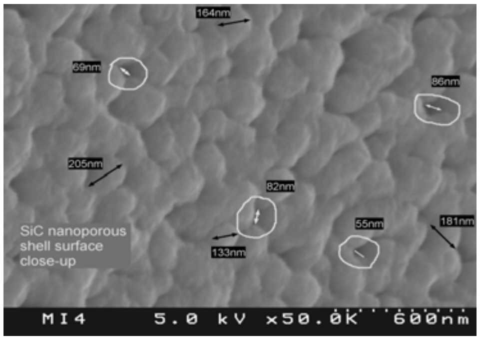

Figure 7. SEM micrograph of a nano-porous poly-SiC film fabricated by APCVD SiC deposition.

## 6 CONCLUSION

SiC is an excellent semiconductor platform for development of micro/nano systems for harsh environment and demanding applications that cannot be served by silicon because of silicon’s inherent material limitations. Much progress has been made in developing SiC as a micro- and nano-mechanical material and fabrication techniques have been developed. SiC MEMS and NEMS devices targeted for specific applications are emerging and at early stages of commercialization. Though not described here, we and others are developing a SiC IC technology to provide electronic signal amplification and processing in connection with the MEMS/NEMS devices for harsh environment (high temperature/radiation) applications.

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