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A Review: Properties of Silicon Carbide Materials in MEMS Application

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ABSTRACT

The paper presents the review properties of silicon carbide materials in the MEMS application. The study aims to explore silicon carbide in MEMS technology which considers the development of microscale and integrated devices that combine electronics, electrical and mechanical elements. MEMS has become a key area micro-device technology which incorporates materials, mechanical, electrical, chemical and optical disciplines as well as fluid engineering. The prevalence of MEMS technology in harsh environments has grown tremendously in recent years, especially at high temperatures up to 1240˚C, wider bandgap (2.3 – 3.4 eV), a higher breakdown field (30 × 105 V/cm), a higher thermal conductivity (3.2 – 4.9 W/cm- K), a higher saturation velocity (2.5 × 107 cm/s), higher oxidation, corrosive environments and higher radiation. Recent developments in robust MEMS for extreme environments such as MEMS pressure sensors have been widely used in ships, warships, gas turbine engines, cars and biomedical equipment. The growing demand for MEMS pressure sensors with high-temperature operating capabilities, mainly for automotive, gas turbine engine and aerospace applications was investigated from this study as alternative silicon carbide to silicon in the fabrication of these devices.

Keywords: MEMS; Silicon carbide; High temperature, Radiation, Sensor.

1. INTRODUCTION

MEM's most common material is silicon as the active component of most modern electronics devices using its electrical, optical, photo-electrical and thermos-electrical equipment [1]. Unfortunately, silicon-based power devices reach their materials properties limit, which has led to significant efforts to find alternatives to silicon-based power devices to improve performance. Today, with the continued demand for higher current and voltage handling capability and increased packing volume, these silicon-based systems tend to be approaching their theoretical efficiency limits. Therefore, it is necessary to consider other semi-conductive materials to achieve further improvements in device performance of the device to be used in harsh environments such as higher thermal conductivity, high voltage power, higher breakdown voltage and etc [2]. Draghici (2019) stated that silicon is generally limited in the quality of electronic devices for harsh environment applications due to its ease of oxidation, narrow bandage, corrosion and degradation, such as the operating temperature and radiation limit of silicon electronics. It is susceptible to being etched at high temperature by reactive media and decay of its mechanical strength. With rapid micro and nanotechnology advances driving advancements in the semiconductor industry, silicon carbide materials are beginning to become the streaming technology with the potential for next-generation power semiconductor devices to replace existing high-power silicon technology [3].

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In terms of its mechanical strength, chemical inertness, electrical stability, radiation tolerance, high temperature operating capability, high voltage and energy handling capacity, high power output. Silicon carbide has emerged as a prominent technological field due to its exceptional advantages over silicon-based semiconductors [4]. Even though silicon carbide devices price is still costly than their counterparts in silicon, silicon carbide materials are finding more applications where the benefits of silicon carbide technology can offer system benefits that are significant enough to offset the increased cost of the device. Therefore, harsh applications in the environment needs platform materials such as silicon carbide to be allowed. Mostly designed structures are emerging in the development of silicon carbide into micromachining and microfabrication related to thin-film technology. The use of silicon carbide into MEMS technology is encouraged by its good mechanical strength, resistance to corrosion, electrical and thermal efficiency, and bio-compatibility. Chen & Mehregany (2018) recommended that silicon carbide is extremely suitable for harsh environments inspired to develop this microsystem platform material and is particularly suitable for high-temperature pressure sensors [5]. New legislation has given MEMS industries and incentive to reduce emissions, pollutants and noise.

MEMS performance is recongnize by improving the sensor, which requires electronics made from durable materials from high-temperature platforms to improve MEMS performance. The instrumentation can provide reliable monitoring of operating parameters in and around applications such as pressure sensors. Pressure sensors used in applications such as aircraft propulsion, automotive engines, industrial gas turbines, geothermal and oil and gas exploration are typically exposed to harsh environments, mainly when high temperatures, high pressure and oxidation are present [6]. The production and efficiency of the large industrial gas turbine for electrical power generation have been steadily increasing the early 1970s. This rise was primarily due to the introduction of structural materials with high temperatures. The use of these advanced materials has led to an increase in gas turbine firing temperature over the past 30 years from 982°C to over 1427 °C [7]. Higher operating temperatures are historically the primary means of improving industrial power generation gas turbines. Higher operating temperatures require materials and related technology such as enhanced oxidation and harsh environments that require high-temperature capacity [8].

The firing temperature has a profound impact on the gas turbine's output. The MEMS demand for increased reliability and efficiency, pressure sensor designed to perform reliability in challenging environments [9]. The pressure sensor is one of the MEMS sensors based on silicon carbide actively developed and promoted by NASA Glenn Research Center with piezoresistive sensing using 4H and 6H SiC wafers, which can work up to 600 °C [10]. Nevertheless, the bulk SiC wafer's cost is the major obstacle to commercial production rolling out. The cheaper alternative is on silicon wafer single crystal (3C-SiC-on-Si) using cubic silicon carbide thin film. Researchers at Case Western Reserve University developed a single 3C-SiC-based pressure sensor. With a pressure range of 1100-1760 Torr (0.15-0.23 MPa) on ceramic packaging, this capacitive-based pressure sensor can withstand temperatures of up to 400 °C which the highest capacitive pressure sensor [11]. However, for commercial applications, this pressure range is insufficient, such as testing the internal combustion engine pressure. The point here is to address the deficiency in using silicon carbide materials in this work by modifying the manufacturing process and packaging.

2. LITERATURE REVIEW

Since it can withstand mechanical and electrical perspectives at high temperatures, silicon carbide has been selected for manufacturing in MEMS sensor technology. In high-temperature applications, silicon carbide is potentially useful in semiconductor applications and its properties do not degrade at high temperatures. Marsi (2013) indicated that silicon carbide is considerated the leading alternative materials to silicon for harsh environments applications due to silicon carbide being a material capable of developing high-temperature solid-state electronics and transducers due to its outstanding electrical, thermal, mechanical and chemical properties [12].

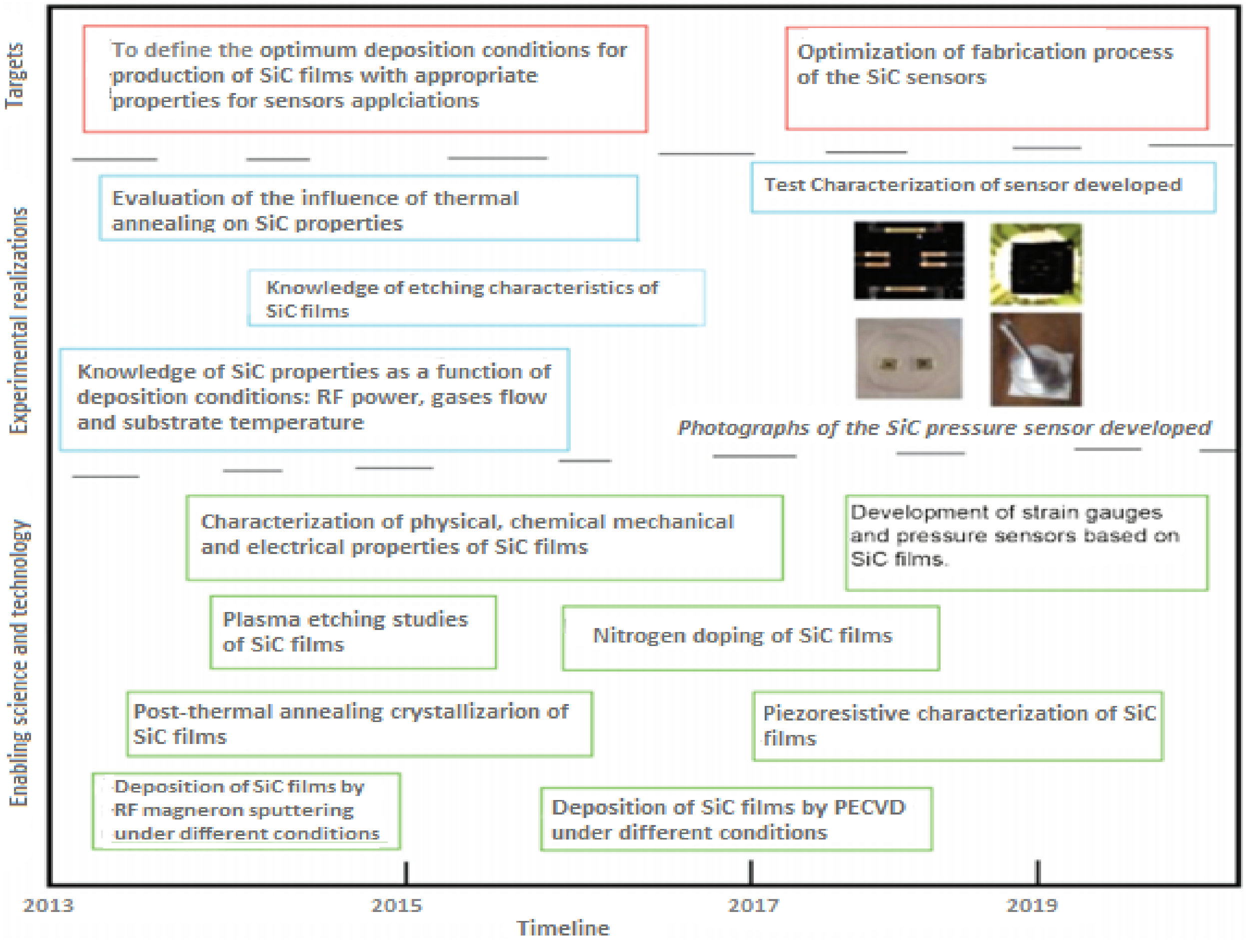

Figure 1. Evolution of research and development activities of SiC 2013-2019 (Balavalad, 2019).

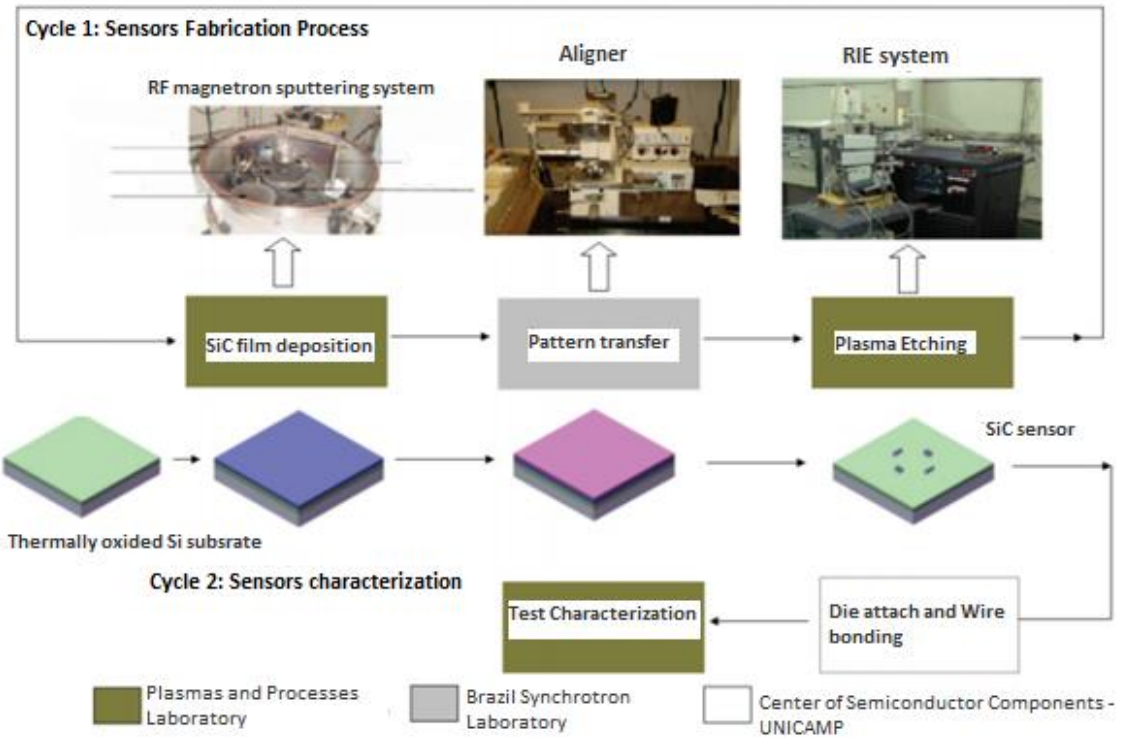

Figure 2. Silicon carbide sensor growth cycles (Balavalad, 2019).

The evolution of research and development (R&D) activities from 2013 to 2019 are summarized in Figure 1 to implement a technology roadmap for silicon carbide thin film production. The silicon carbide thin film is tested at different stages to develop SiC thin film. There are three important technologies, including silicon carbide deposition techniques, SiC sensor fabrication techniques and silicon carbide sensor characterization. This is early-stage development to make reasonable small-scale requirements to achieve high productivity, high quality and fabricating in the next phase [13].

The growth cycles for the silicon carbide are shown in Figure 2. As it can be observed, the first phase of two phases in silicon carbide is the fabrication process of sensors involving the transfer of patterns through photolithography. The second step is to character of sensors such as die connection and wire bonding. This step is to collect and place MEMS die into the package. This process phase is to use a mechanical assembly to connect electrically to the MEMS sensor. These phase cycles are designed to improve performance the films performance and usability by using the power sources pulsed. The MEMS sensor output will impact each cycle. Figure 3 shows the types of sensors being built and the development of technology pursued by the researcher until 2015. Implementation of the silicon carbide deposition process, silicon carbide processing, silicon carbide sensor microfabrication and silicon carbide sensor packaging are the leading technologies involved. Such developments will incorporate silicon carbide devices for various high-power system such as propulsion systems, aerospace systems, aeronautical systems, inertial systems, gas turbine and others. Researcher's goals will focus on improving the quality of the silicon carbide pressure sensors built over the next few years [14].

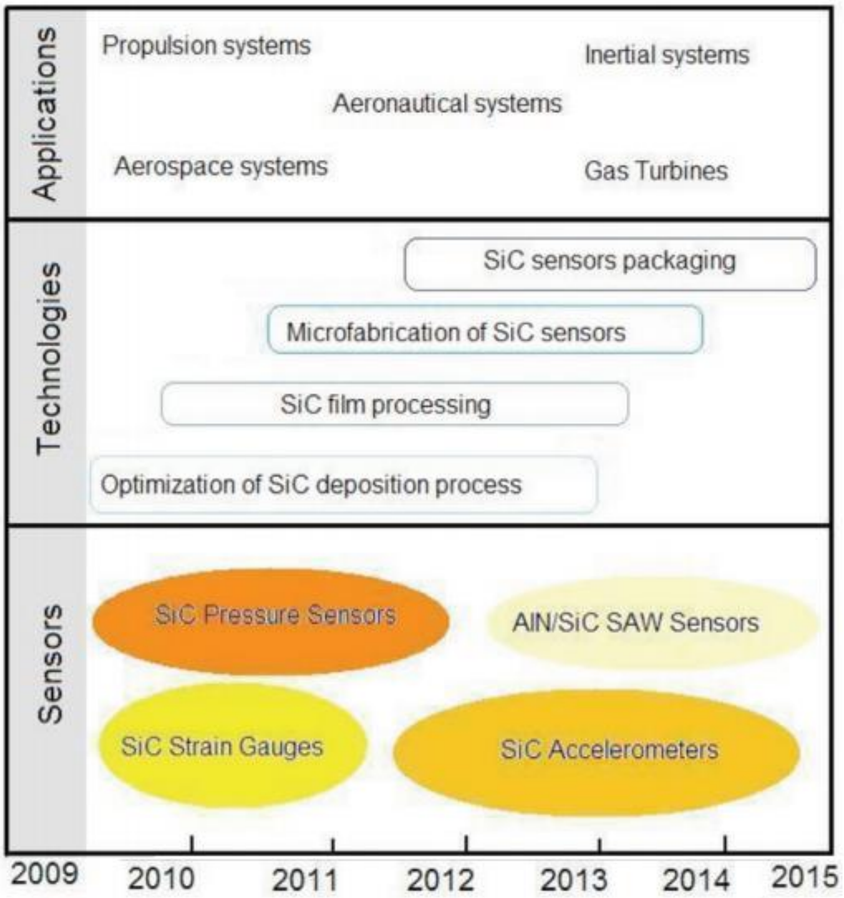

Figure 3. The types of sensors being built and the development of technology (Vasiliauskas 2012).

2.1 Polytypes of Silicon Carbide

Silicon carbide (SiC) is a compound of silicon and carbon that bonds together to form tough ceramics commonly used in high-endurance applications [15]. Grains silicon carbide can be bonded together by sintering to form tough ceramics that are commonly used in applications requiring high endurance in high-temperature resistance and high voltage in semiconductor electronics and sensors [16]. The decomposition temperature for silicon carbide is as high as 2400 ºC [17]. The structural component of silicon carbide is due to the combination of Si-C compounds as shown in Figure 4 [18]. This is correlated with solid covalent bonds that appear to have superior high melting and boiling points. It requires a lot of energy that is usable only at extreme temperatures throughout the entire structure. As a substrate microdevices, silicon carbide includes polymorphism called polytypism. All silicon carbide polytypes have the same planar arrangement of Si and C atoms recognized by changes in the stacking sequence of the identical planes [18].

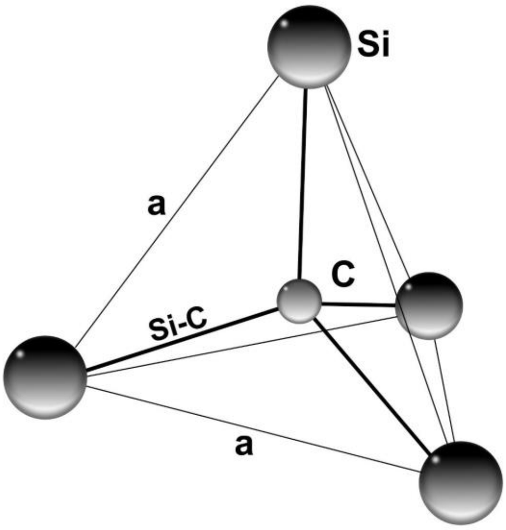

Figure 4. The SiC-tetrahedron building block of the C atom was bonded to four Si atoms (Vasiliauskas 2012).

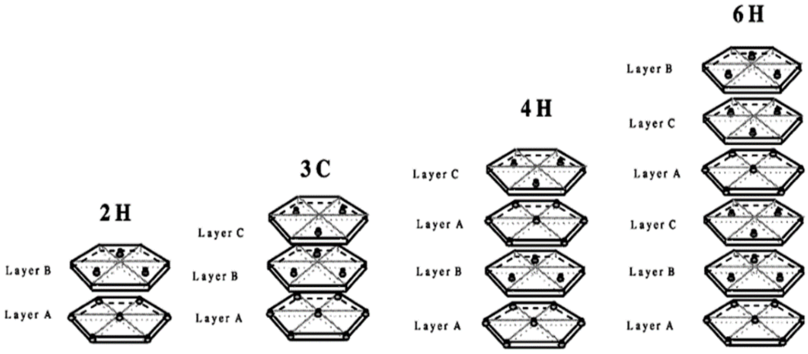

Figure 5. Illustration of the stacking of successive Si and C layers to show silicon carbide polytypes (Marcio *et al.* 2011).

Disorder in the stacking periodicity of similar planes results in a material with multiple crystal structures (polytypes) with the same atomic composition. The magnitude of the condition has been established for more than 250 silicon carbide. Although there are three crystalline structures, there are many number of polytypes: cubic, hexagonal and rhomboedral. There are two groups of polytypes of silicon carbide polytypes, β-SiC, 3C-SiC is the only cubic polytype and α-SiC is the hexagonal and rhombohedral forms. The most common polytypes of α-SiC have hexagonal symmetries called 6H-SiC, 4H-SiC and 2H-SiC shown in Figure 5 [19]. The processing of single-crystalline substrates and epitaxial thin films has three technically relevant factors. Several of there are hexagonal polytypes such as 4H-SiC and 6H-SiC, a nomenclature that stacks Si and C atom sequences. Both these polytypes are accessible as single-crystalline wafers, and substrates epitaxial films of the same polytype can be grown [20]. The third technically feasible polytype is a cubic polytype known as 3C-SiC, the only known cubic structure in SiC. 3C-SiC has a diamond lattice structure similar to Si that enables 3C-SiC films to grow epitaxially on Si wafers [21]. The advantages of coupled 3C-SiC films on Si wafer can be complemented to make them an attractive addition to Si for harsh MEMS setting at high temperatures.

A comparative silicon properties included the analysing of electronic semiconductor characteristics of the various SiC polytypes. In basic material, the major SiC polytypes have advantages and disadvantages over Si. In Table 1, SiC is most valuable product advantages compared with silicon [22]. Silicon carbide polytypes have a low electrical breakdown, a high carrier saturation frequency, wide bandgap power and high thermal conductivity that benefit significantly electrically. The efficiency of the electrical device is also improved the material chosen, like 3C-SiC in MEMS systems.

Table 1 Comparison of electronic semiconductor properties of different SiC polytypes (Okojie, 2019)

Property	**4H-SiC**	**6H-SiC**	**3C-SiC**	**Si**
Bandgap (eV)	3.2	3.0	2.3	1.1
Electron mobility μn (cm^2/V-s)	800	400	750	1200
Relative dielectric constant	9.7	9.7	9.7	11.9
Intrinsic carrier concentration (cm10^{-3})	~10^{-7}	~10^{-5}	10	10^{10}
Saturated drift velocity (×10^7 cm/s)	2.5	2.0	2.0	1.0
Thermal conductivity (W/cm-K)	5.0	5.0	5.0	1.5
Thermal expansion @ 300 K @ 1500-1600 K (10^7 K^{-1})	3.8 5.5	NA	4.3⊥c-axis	2.6 4.56
In plane lattice spacing [Å] Hexagonal structure [Å]	4.36 3.0813	3.08051	3.08129	5.43
Electron mobility at N_D= 10^{16} (cm^2/V-s)	|| c-axis:800 ⊥c-axis: 800	|| c-axis:60 ⊥c-axis: 400	750	300
Hole Mobility at N_D= 10^{16} (cm^2/V-s)	115	90	40	420
Acceptor dopants and shallowest ionization energy (meV)	200	200	270	45
Donor (nitrogen) dopant ionization energy (MeV)	45	85	50	45

2.2 Silicon Carbide Thin Film Deposition

Various techniques for producing cubic silicon carbide (3C-SiC) have been reported (Hens *et al.* , 2012). There are two stages for homoepitaxial 3C-SiC growth by sublimating and chemical vapor deposition (CVD), a process used for depositing thin films with the reaction of high purity gas-phase precursors in a solid surface [23].

2.2.1 Sublimation Technique

The most growing SiC substrate process is based on vapor phase growth with SiC sublimation products. SiC reaches 1800 °C to 2600 °C at temperatures containing complex elemental and molecular species (Forsberg 2001). The sublimation generates not only SiC (gas) but forms specific elementary and molecular species as a result of SiC separation as shown in the chemical equations (1), (2) and (3) [24].

$$SiC(s) \rightarrow Si(g) + C(s) \quad (1)$$
$$2SiC(s) \rightarrow SiC_2(g) + Si(g) \quad (2)$$
$$2SiC(s) \rightarrow C(s) + Si_2C(g) \quad (3)$$

Lely method in 1995 invented the growth process of highly pure SiC crystal using techniques of sublimation growth. The initial Lely method used a thin-walled internal porous graphite and a graphite cylinder (Jiang 2009). The SiC powder is heated between the internal and external tubes to 2550-2600° in argon atmosphere. However, the Lely method does an inadequate effect on the growth of SiC crystals. The modification in crystal size, doping, and polytype is disturbed because the growth rate, growth direction and initial nucleation are not controlled [25]. However, due to the self-terminating of the growth process of the inner cylinder which is blocked by rising crystal, the Lely procedure can create SiC crystals only up to 10 mm in diameter [26].

In 1978, Tairov and Tsvetkov developed the seeded sublimation method also known as Lely's system for transformation and physical vapor (PVT). Wijesundara, et al (2011) has growth in sublimation, emphasizing a better understanding of polytype stability concerning growth conditions such as supersaturation and Si/C ratio. With rising temperature supersaturation the growth of 3C-SiC is further enhanced. Cubic 3C-SiC is growth that prevails at 1800ºC. Figure 7(a) shows the growth rate with supersaturation intensification. In Figure 7(b) shows the surface cover temperature distribution [27].

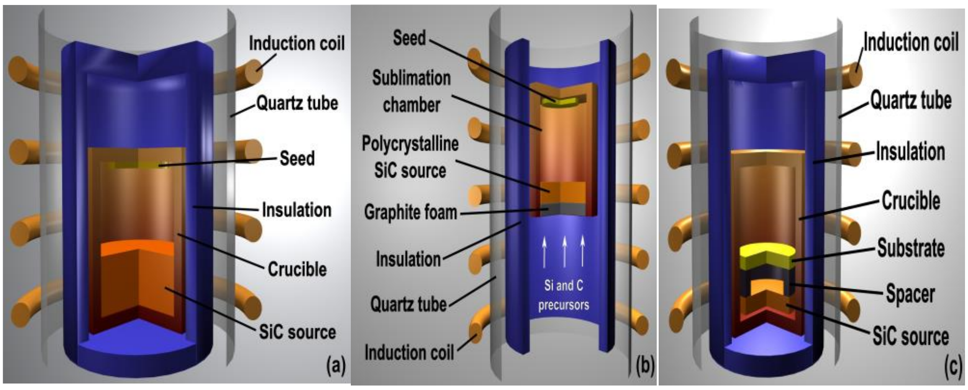

Figure 6. Growth geometry of: (a) seeded sublimation, (b) CF-PVT, (c) sublimation epitaxy (Herrera-Celis *et al.* 2019).

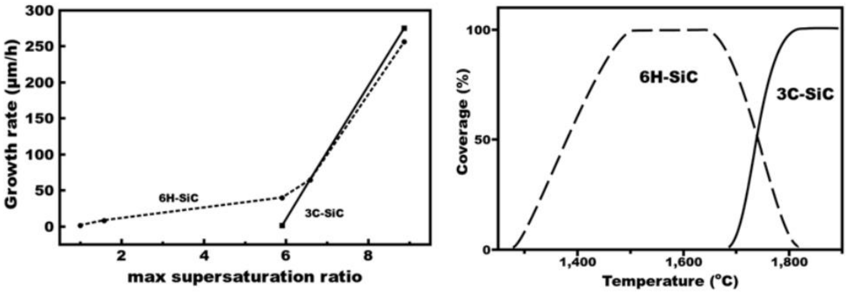

Figure 7. (a) Growth rate of 6H (dotted line) and 3C polytypes vs. supersaturation (b) 3C coverage vs. Process temperature (Meneses *et al.* 2019).

2.2.2 *Chemical Vapor Deposition (CVD)*

One of the techniques is to raise the semi-bulk by continuous flow of physical vapour mass transit materials based on SiC. This technique is considered for various applications involving gas chemical inertness and low activation. SiC thin films deposits at low pressure by chemical vapor deposition (LPCVD), atmospheric pressure chemical vapor deposition (APCVD), and plasma-etched chemical vapor deposition (PECVD). Depending on the parameter of the deposition considerations, the 3C-SiC thin films may be monocrystalline, polycrystalline or amorphous. APCVD and LPCVD are normally used to deposit poly-SiC at high temperatures up to 800 ºC [28], while sputtering and PECVD form amorphous SiC at low temperatures below 700 ºC. PECVD SiC films are used for film coating, pressure sensors and resonators [29].

The 3C-SiC is formed at lower temperatures and has a crystalline, silicon-like crystalline structure that allows 3C-SiC films on Si substrates to grow heteroepitaxially. The emblematic process involves altering Si through carbonization in a hydrocarbon gas, accompanied by 3C-SiC film development. Carbonized coating thickness 10 to 20 nm. Homoepitaxy then uses precursors containing carbon and silicon to grow the bulk of the film. This method was first developed for digital applications in hopes of a low cost, wider area alternative to the 6H-SiC and Si substrate

[30]. Many developments have been driven to replace SiC electronics with 3C-SiC, and recent advances are beginning to show the promise.

The CVD technique is based on the decomposition of precursor gas at a substrate heated to a reactor. Precursors are broken during growth process, resulting in Si and C producing chemical reactions, which are then deposited on a substrate to synthesize SiC. Typical temperature ranges from 1300 to 1600 ºC for growth. The strength of growth in the CVD is a good regulation of the growth cycle. Additionally, precursors of high purity may subsequently be produced in high purity. However, the SiC growth rate using conventional CVD is quite small, with a low reate of Si at 900°C with low rate at (4~5 µm/h). 3C-SiC CVD growth on silicon can be achieved at 1410 ºC below melting point of silicon. The growth method is employed at high temperature growth technique using silicon as the initial substrate for 3C-SiC growth is shown in Figure 8 [32].

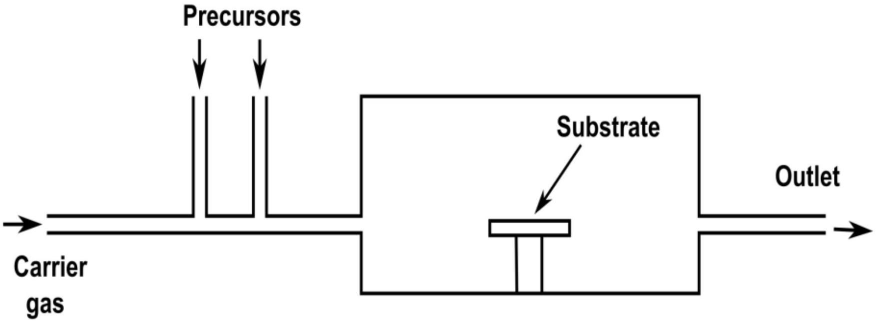

Figure 8. Principle configuration of a CVD reactor (Semenov, 2020).

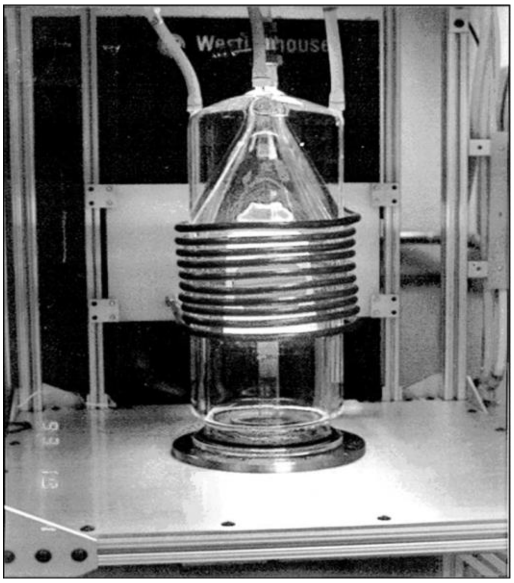

Figure 9. APCVD SiC reactor (Sun *et al.,* 2018).

Choyke *et al.* (2004) was among the first to report 3C-SiC heteroepitaxy for MEMS applications using propane, silane and hydrogen to grow 3C-SiC at 100 mm-diameter (100) Si wafers by APCVD at temperatures of 1360 ºC. They also identified 3C-SiC films growth on large area substrates where interfacial voids were not present [33]. The 3C-SiC thin film's characterization is crucial for MEMS structures used with small anchor pads on the substrate [34]. Growth of 3C-SiC heteroepitaxial films on Si substrates is not limited to APCVD and LPCVD processes using both single and dual source precursors [35,36]. Single source precursors are more increasingly becoming commercially available as Si- and C-containing compounds that decompose at low temperatures. LPCVD offers several advantages over APCVD, containing improved film thickness uniformity over large areas, potentially lower levels impurity due to improved vacuum systems and lower processing temperatures [37]. Zimbone *et al.* (2019) demonstrated the 3C-SiC thin films were grown at a diameter of 100-mm diameter, (100) silicon wafers in a cold wall, RF-induction heated reactor as depicted in Figure 9 [38,39].

3. RESULTS AND DISCUSSION

Usually, the high operating temperature inside the gas turbine engine is more significant than 300 ºC (38). However, the MEMS pressure sensor based on silicon could only operate below this point because of the restriction of its material properties. The excellent physical and electronic properties of silicon carbide allow the manufacture of high-speed, high-powered devices used in extreme environments at high temperatures and high radiation rates need other materials with broader bandages than silicon [40,41]. However, under extreme temperatures applications, strength information on the more progressive mechanical properties evolution of the microstructure. The characteristics of silicon carbide make it one of the best prospects for expanding the current technology's capabilities and operating system for semiconductor devices [42].

In addition, due to its chemical inertness and corrosion resistance, SiC has more advantages in this setting, and an extremely low thermal expansion coefficient and high Young's modulus. Because SiC is more resistant to stress distribution, corrosion effects from thermal shock resistance and fatigue mitigation from deflection applications, SiC is an excellent mechanical advantage [43-44]. SiC is the best material to replace Si in such an extreme environment because it can work up to 1000 ºC. Since its excellent mechanical, electrical and chemical properties, SiC is recognized. SiC is also a top product for microfabricated sensors and actuators designed to replace Si-based devices in harsh environments [45-46].

The crucial electrical doping fields (10 times higher than Si) and thinner drift layers in SiC can reduce the MEMS system's resistance compared to Si. Additional benefits, including higher thermal conductivity and heat transfer efficiency (3 times higher than), approximately 10 times higher electrical field strength than Si and higher drift velocity, will have significant impacts on the size, efficiency, and applications of power electronics in the years future. SiC devices will have a profound impact on our world's "Greening" [47-48].

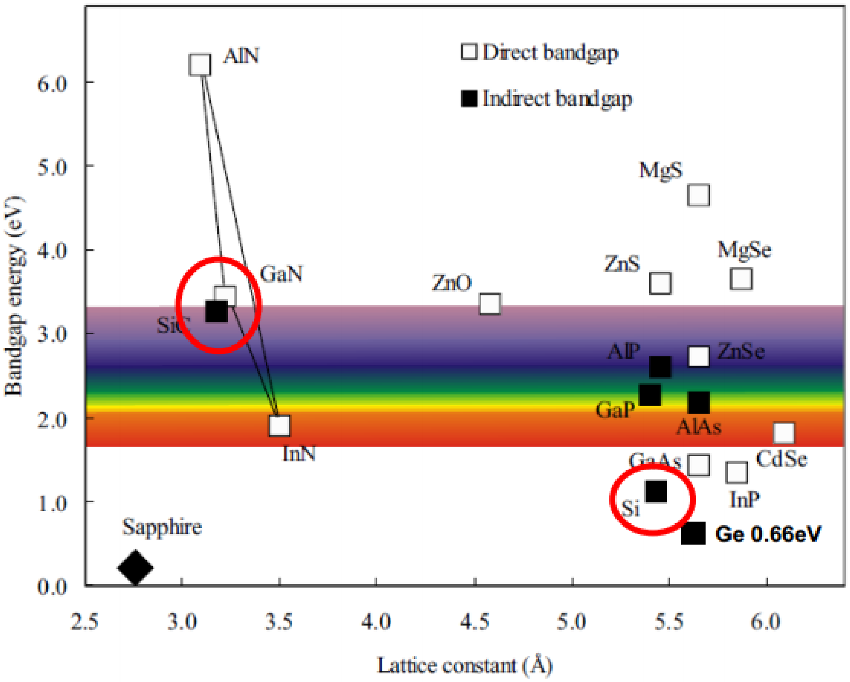

Figure 10. SiC widebandgap, highly efficient in areas where Si is leaky (Tu *et al,* 2019).

SiC also has outstanding electrical properties compared to Si, such as a wider bandgap (2.3 – 3.4 eV), a higher breakdown field (30 × 105 V/cm), a higher thermal conductivity (3.2 – 4.9 W/cm-K) and a higher saturation velocity (2.5 × 107 cm/s). Electrically stable, applied correctly in a high temperature, harsh environment and output of high-power semiconductor devices. Figure 10 shows SiC wideband gap is highly efficient in areas where Si is leaky [49]. In this work, we are not supposed to replace SiC with Si, but to supplement Si for a range of harsh environment MEM sensor applications to be used in MEMS phones. An exceptional mechanical and chemical property compared to silicon makes silicon carbide a more prominent material for MEMS fabrication is highly erosive environments. Table 2 the comparison characteristics of silicon carbide to other important semiconductor materials [50,51]. Vacca (2017) stated that the silicon carbide electrical properties extend beyond 300 ° C to the temperature regime, the theoretical upper limit of the silicon-based devices operating regime [52].

From Table 2, large bandage materials are less prone to thermal problems and have high electrical fields that allow for an improved insulation between devices and higher maximum packaging density of devices [53]. Higher thermal conductivity also increases the work cycle and maximizes the packaging capacity [54-55]. Since it has peak operating frequencies, silicon carbide has an advantage dependent on saturated drift speed [56-57]. Therefore, the lower dielectric constant for silicon carbide increases its price for operations with high-frequency devices. This ensures that MEMS-based SiC devices can operate efficiently and preserve the efficiency of their reliability [58]. Naumenko et al (2019) revealed that silicon carbide has excellent electrical characteristics such as wide band gap (9.3 eV) [59], high electrical breakdown (10 times higher than Si) [60], high electron density drift velocity low intrinsic carrier concentration allowing stable electronic properties in harsh environments making it a superior candidate for high temperature electronic applications [61]. In terms of mechanical properties, silicon carbide has higher rigidity and fracture strength and is more resistant to wear, oxidation and corrosion than silicon [62].

Table 2 Comparison of basic material properties of semiconductor materials Si, GaAs, GaN, SiC and Diamond (Marsi *et al,* 2016)

Property	Si	GaAs	GaN	ß-SiC (α-SiC)	Diamond
Bandgap (cV) 1000 K	1.1	1.4	3.5	2.3 (>2.9)	5.5
Maximum operating temperature (°C)	300	460	500	873 (1240)	1100
Melting point (°C)	1420	1238	1700 (600 – dissociates)	Sublimes >1800	Phase change
Physical stability	Good	Fair	Good	Excellent	Very good
Electron mobility (cm^2/V-s)	1400	8500	>440	1000 (600)	2200
Hole mobility (cm^2/V-s)	600	400	Not available	40	1600
Breakdown field , Eb (10^6 V/cm)	0.3	0.4		4	10
Thermal conductivity, σ_T (W/cm-°C)	1.5	0.5	1.3	5	20
Saturated electron drift velocity, Vsat (10^7 cm/s)	1	2		2.5	2.7
Dielectric constant, ε	11.8	12.8	12.1	9.7	5.5

4. CONCLUSION

In conclusion, a review of silicon carbide materials in MEMS application is to transform the new materials of single-crystal silicon carbide thin film into a MEMS capacitive pressure sensor as a sensing diaphragm. This is due to SiC also has outstanding electrical properties, wider bandgap (2.3 – 3.4 eV), a higher breakdown field (30×10^5 V/cm), a higher thermal conductivity (3.2 – 4.9 W/cm- K) and a higher saturation velocity (2.5×10^7 cm/s), electrically stable, applied correctly in a high temperature, harsh environment and output of high-power semiconductor devices. This hoped this Silicon Carbide (3C-SiC) could be developed as in other device types of MEMS. In the future, to achieve this goal as a more compact MEMS sensor established lower packaging costs, our layout is inherent simplicity and robustness of this physical configuration. It is hoped that this future work would improve understanding of Silicon Carbide materials and incorporate MEMS capacitive pressure sensor quality such as the innovation of the manufacturing process using ProTEK PSB as a polymer protection layer newly photosensitive. It also hoped that this work as a simple assembly approach to reduce manufacturing cost, smart interface featured and easy cleaning service for MEMS packaging.

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