Silicon Carbide (SiC)-Based Sensors for Harsh Environment Applications

By: Engr. Dr Cheong Kuan Yew, *M.I.E.M., P.Eng.*

Abstract

An overview of gas sensors fabricated on single-chip silicon carbide (SiC) used in harsh environments has been presented in this article. The definition of harsh environment and the potential applications of the sensors have been elaborated. The intrinsic material properties of this wide bandgap semiconductor, have also been highlighted. In addition to that the requirements of a sensor operating at this condition, sensing mechanisms, and types of sensor architectures have been briefly reviewed. Finally, challenges faced by the SiC-based sensors, in terms of fabrication and commercialisation, have been suggested.

1. INTRODUCTION

Emissions of uncontrolled hazardous gases from industries and automotives have contributed to numerous environmental issues globally. There is a need for us to control and monitor the emissions of such gases and to reduce the energy consumption of industries and automotives by using on-line gas sensors. A sensor is a device to transform physical quantities, such as pressure, chemical concentration and types, temperature and others into electrical signals, which can be processed and interpreted. An on-line gas sensor enables real-time emission data to be measured, extracted, and interpreted, so that in-situ adjustment and control can be performed immediately. In order to do so, the sensor has to respond very fast and effectively, as well as to be able to withstand severe and extreme environmental conditions surrounding the sensors. For examples, in turbine engines, in automotive engine control, in spacecraft and aircraft engine control, in oil and gas drilling parts, etc., whereby their operating temperatures are extremely high and surrounding conditions are very corrosive. Hence, a suitable material needs to be carefully selected to fabricate the sensors so that they could carry out their pre-determined functions without being affected by conditions in the vicinity . Of the many electronic materials available, wide-bandgap semiconductors, such as SiC, AlN, GaN and diamond, are the potential candidates for this application due to their superb intrinsic electrical, mechanical, and chemical properties [1]–[5], [8]. In comparison to SiC, the fabrication technology of other wide-bandgap semiconductors is still not as mature as what is available in SiC [1]–[5]. Therefore, SiC-based gas sensors have a better potential to be commercialised in the near future [1] if some of the challenges, highlighted in this article, can been circumvented.

Table 1: Semiconductor technologies for some selected high-temperature electronics [3]

High Temperature Electronics Application	Peak Ambient	Chip Power	Current Technology	Future Technology
Automotive				
Engine Control Electronics	150˚C	<1kW	BS & SOI	BS & SOI
On-cylinder and Exhaust Pipe	600˚C	<1kW	NA	WBG
Electric Suspension and Brakes	250˚C	<10kW	BS	WBG
Electric/ Hybrid Vechicle PMAD	150˚C	>10kW	BS	WBG
Turbine Engine				
Sensors, Telemetry, Control	300˚C	<1kW	BS & SOI	SOI & WBG
	600˚C	<1kW	NA	WBG
Electric Actuation	150˚C	>10kW	BS & SOI	WBG
	600˚C	>10kW	NA	WBG
Spacecraft				
Power Management	150˚C	>1kW	BS & SOI	WBG
	300˚C	>10kW	NA	WBG
Venus and Mercury Exploration	550˚C	~1kW	NA	WBG
Industrial				
High Temperature Processing	300˚C	<1kW	SOI	SOI
	600˚C	<1kW	NA	WBG
Deep-Well Drilling Telemetry				
Oil and Gas	300˚C	<1kW	SOI	SOI & WBG
Geothermal	600˚C	<1kW	NA	WBG

2.0 APPLICATIONS OF SENSORS IN HARSH ENVIRONMENTS

It has been increasingly recognised that gas sensors fabricated from wide-bandgap semiconductors are able to function at temperatures more than 300˚C without any addition of an external cooling system [3]–[5]. This characteristic enables it to benefit a variety of important applications such as in automotive, aerospace, oil and gas deep-well drilling, and energy production industries [1]–[5]. Besides withstanding high temperatures, corrosion and radiation resistance are other essential requirements for the sensors to operate at extreme conditions [3]–[7]. Tables 1 [3] and 2 [8] lists the general operating conditions for high temperature electronic applications ,compared between currently available technology and future technology. It is very obvious that wide-bandgap semiconductors, including SiC, may dominate most of the applications.

Since there are numerous applications of SiC-based sensors in harsh environments, in this article, only two examples will be shown and these examples are not limited to gas sensors.

Table 2: Specification of current temperature ranges encountered in harsh environments [8]

Application	Temperature (˚C) Operating range	Maximum
Civil	-55 to +85	+150
Military	-65 to +125	+175
Instrumentation	0 to +40	+60
Automotive	-45 to +85	+280
Well logging	-45 to +300	+400
Aerospace	-65 to +125	+175

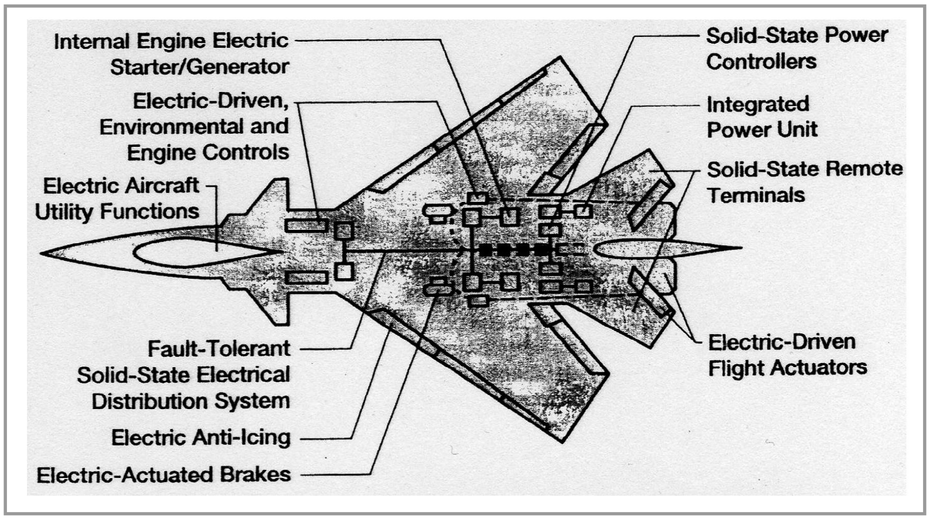

Figure 1: Schematic diagram of a fighter aircraft, which illustrates electronic subsystems potentially improved by the insertion of SiC electronic materials [9]

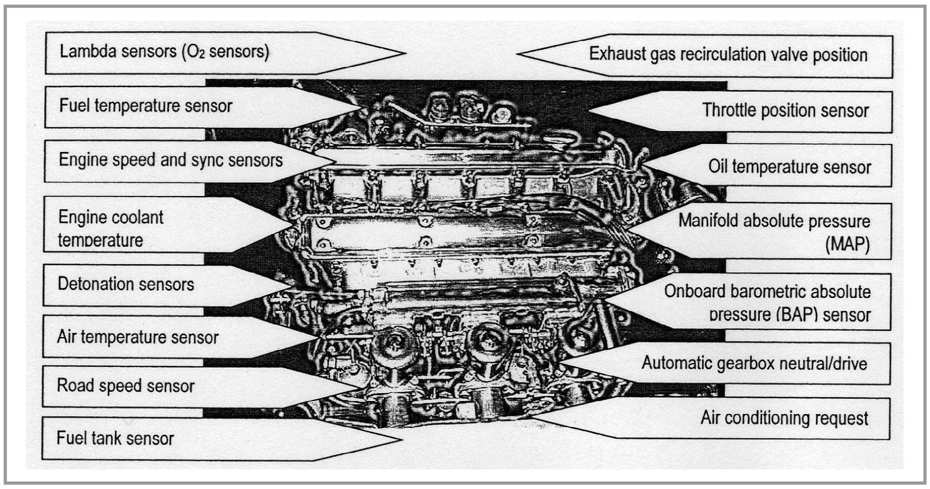

Figure 2: Input signals for various types of sensors in an ECU [10]

They are applied in (1) aircraft and (2) electronic engine control units (EUCs) of an electrical vehicle. Figure 1 illustrates a fighter aircraft with electronic subsystems that are able to improve their performance by using SiC-based sensors [9].

Figure 2 shows an ECU with various types of sensors [10]. These sensors operate in an environment consisting of fuel, oil, water, salt spray, ozone, dust and sand, or cleaning materials. They need to withstand vibration and shock of up 100 times gravitational acceleration [11].

3.0 REQUIREMENTS OF SENSORS OPERATING IN HARSH ENVIRONMENTS

In order for a sensor to function effectively in a harsh environment, there are four (4) basic requirements that need to be fulfilled [1], [3], [5], [6]. (1) High sensitivity – a very minute amount of gases need to be effectively detected. For example, in a car exhaust, the sensor must respond to a change between oxidising and reducing atmospheres within 10 ms. (2) High selectivity – capable of differentiating and distinguishing between various types of gases. This is important because emission gases usually consists of a combination of gases (various classes of hydrocarbon gases (C_xH_y), ammonia, oxygen, NO_x, hydrogen, etc.) and they need to be detected independently. (3) High stability – suitable materials need to be selected to prevent degradation. In addition, electrical fluctuation and interference due to thermal energy have to be kept to a minimum level. (4) High reliability – sensors must withstand a pre-determined number of operation cycles before failure occurs.

4.0 ADVANTAGES OF SIC AS A HARSH ENVIRONMENT ELECTRONIC MATERIAL

There are a number of factors, both inside and outside of a semiconductor, that limit it to operate at high temperatures. Of the many wide-bandgap semiconductors, SiC is the preferable choice due to several reasons. Intrinsically, SiC demonstrates excellent material properties (Table 3) [13]. For example, its extremely low intrinsic carrier density (n_i) (approximately two orders of magnitude lower than GaN) enables low p-n junction and thermionic leakage current [3], [8], [14] in a device. In addition to that, its high melting point and thermal conductivity also

Table 3: Comparison of the properties for selected important semiconductors at 300K [13]

ELECTRICAL & PHYSICAL PROPERTY	Si	GaN	GaAs	SiC		
				4H	6H	3C
Bandgap (eV)	1.12	3.39	1.42	3.26	3.02	2.39
Relative dielectric constant	11.9	9.0	13.1	9.7	9.7	9.7
Intrinsic carrier concentration (cm^{-3})	10^{10}	$\sim10^{-5}$	$1.8x10^{6}$	$\sim10^{-7}$	$\sim10^{-5}$	$\sim10^{-1}$
Breakdown field (MV/cm) @ $N_D = 10^{17}$ cm^{-3}	0.6	5	0.6	3.0	3.2	>1.5
Saturated electron velocity (10^7cm/s)	1.0	2.7	1.2	2.0	2.0	2.5
Electron mobility (cm^2/V-s) @ $N_D = 10^{16}$ cm^{-3}	1200	900	6500	800^A 800^B	60^A 400^B	750^A
Hole mobility (cm^2/V-s) @ $N_A = 10^{16}$ cm^{-3}	420	150	320	115	90	40
Thermal conductivity (W/cm-K)	1.5	1.3	0.5	3 – 5	3 – 5	3 – 5
Melting Point (K)	1690	2773	1510	~3100	~3100	~3100
TECHNOLOGICAL PROPERTY						
Native oxide	Yes	No	No	←	Yes	→
Complementary device	Yes	No	No	←	Possible	→

^{A}: parallel to c-axis
^{B}: perpendicular to c-axis

makes this material suitable for high-temperature applications [3], [8]. Similarly, the relatively mature fabrication technology of SiC devices compared with other wide-bandgap semiconductor based devices further promote SiC for such applications [1], [12], [15].

5.0 TYPES OF SENSING MECHANISMS

There have been a few sensing mechanisms reported, such as catalytic decomposition by catalytic materials and electrochemical dissociation. The former mechanism has been widely reported and employed in SiC-based sensors. Therefore, in this article, this mechanism will be briefly described (Figure 3) as follows [1]. Gas molecules (H_2, C_xH_y, CO, O_2, etc.) are adsorbed, dissociated, and reacted on a catalytic material (Pt, Pd, NiCr, etc. [1], [16]) available on the sensor, forming detectable gas species (H^+, O^{2-}, etc.) These gas species are diffused from the catalytic metal onto an insulator or a semiconductor (located at the bottom of the catalytic metal,) by adsorption, to form complex compounds. A polarised layer at the metal-insulator interface will be formed and an electric field will be created. As a result, the concentration of mobile carriers in the semiconductor will be changed and the changes can be detected as electronic signals, such as changes in resistance, capacitance, or voltage (Figure 4). The sensing mechanism is extremely sensitive to the types of catalytic material used, device architecture, and surrounding operating temperature [1], [17]–[19].

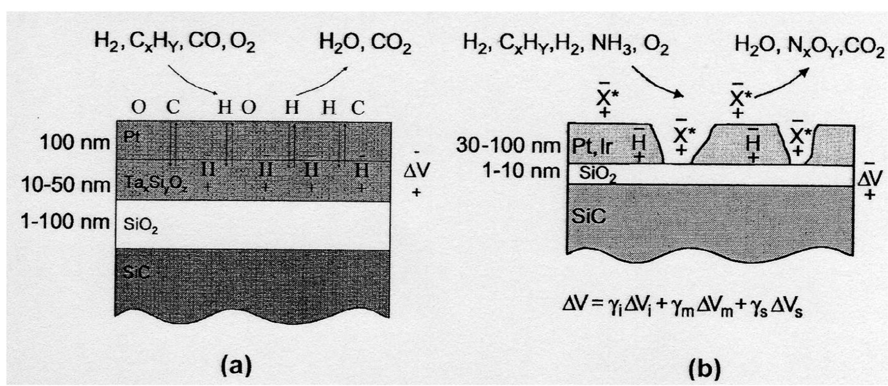

Figure 3: (a) Schematic diagram of a SiC-based metal-oxide-semiconductor device with a dense catalytic metal contact and (b) a porous catalytic metal contact. The total gas response is a combination of response at metal-insulator interface (i), metal in contact with insulator (m) and exposed insulator surface (s). The constant γ is a function of e.g. metal coverage and temperature [1]

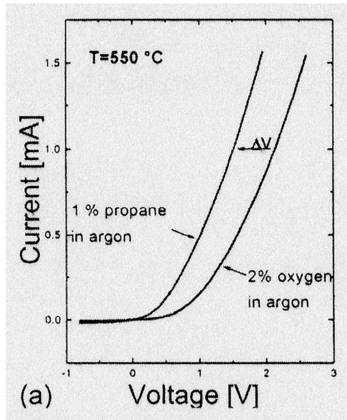

Figure 4: Typical I-V curve for a Schottky diode at 550˚C. The sensor response is indicated by an arrow. Composition of the device: Pt (150 nm); $TaSi_x$ (15 nm) and 6H SiC [1]

Table 4: Impact of temperature on electrical behavior of selected sensor structures [4]

DEVICE	EFFECT OF HIGH TEMPERATURE
Schottky diode	• Forward voltage drop decreases • Reverse current increases with T^2
p-n diode	• Voltage drop in forward direction decreases • Leakage current increases exponentially
Bipolar transistor	• Base-emitter voltage decreases at collector current • Current amplification increases with T^x ($1 < x < 2$)
JFET	• Channel mobility decrease with $T^{-3/2}$ • Pinch-off voltage increases
MESFET	• Similar to JFET
MOSFET	• Channel mobility decreases with $T^{-3/2}$ • Leakage current of p-n junctions increases exponentially • Threshold voltage decreases

6.0 AN OVERVIEW OF SIC-BASED SENSOR ARCHITECTURES

There are various types of device structures that can be used as a SiC-based sensor. In general, it can be grouped into three broad categories: (1) diode (such as p-n diode, Schottky diode), (2) transistor (such as MOSFET, MESFET, JFET, bipolar transistor), and (3) capacitor (such as MOS capacitor) (Figure 5) [1]. In order to improve sensor selectivity, sensitivity, and stability, modifications of device structures have been performed, such as replacing the bulk SiC substrate by a porous SiC substrate or incorporation of certain nanoparticles into the gate oxide [18], [19].

There are several high-temperature issues that need to be considered for each of the structures mentioned above (Table 4) [4].

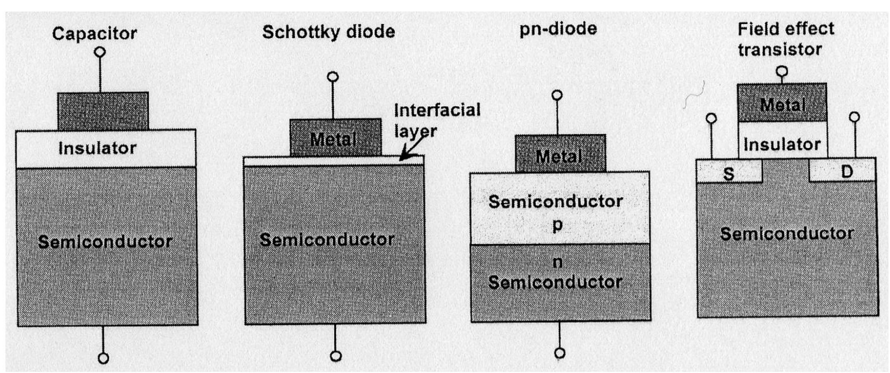

Figure 5: Schematic diagrams of different types of sensor architectures [1]

7.0 CHALLENGES IN FABRICATION AND COMMERCIALISATION OF SIC-BASED SENSORS

Even though the fabrication of SiC-based sensor is relatively mature compared to other wide-bandgap semiconductors, its technology has yet to be fully understood and developed. This challenge has to be overcome before a fully functional and reliable sensor could be commercialised. Of the many technological challenges, the following are the most essential and critical issues waiting to be solved:

1. Improvement of bulk SiC substrate quality,
2. Improvement of SiC-insulator interface quality,
3. Reduction of contact resistance on metal-semiconductor system,
4. Improvement of bulk insulator quality,
5. Improvement of SiC etch rate,
6. Development of a better technology to form opposite type of conductivity on SiC, and
7. Development of a better mounting and packaging technology of the sensor.

8.0 CONCLUSION

In this article, an overview of SiC-based gas sensors used in harsh environments is briefly presented. The benefit of using SiC as base material and other pertinent matters related to this topic have been highlighted. It has been suggested by the author that, in order to commercialise SiC-based sensors, seven challenges have to be circumvented. ■

REFERENCES

[1] A.L. Spetz and S. Savage, "Advances in SiC field effect gas sensors," in *Silicon Carbide – Recent Major Advances*, W.J. Choyke, H. Matsunami, and G. Pensl Eds., Springer: Berlin, pp. 869-892, 2004.

[2] ___, "Advances in silicon carbide electronics," MRS Bull., vol. 30, April 2005.

[3] P.G. Neudeck, R.S. Okojie, and L.-Y. Chen, "High temperature electronics – A role for wide bandgap semiconductors?" Proc. IEEE, vol. 90, pp. 1065-1076, 2002.

[4] M.R. Werner and W.R. Fahrner, "Review on materials, microsensors, systems, and devices for high-temperature and harsh-environment applications," IEEE Trans. Industrial Electron., vol. 48, pp. 249-257, 2001.

[5] R. W. Bogue, "The role of materials in advanced sensor technology," Sensor Review, vol. 22, pp. 289-299, 2002.

[6] W.C. Nieberding and J.A. Powell, “High-temperature electronic requirements in aeropropulsion systems,” IEEE Trans. Industrial Electron., vol. IE-29, pp. 103-106, 1982.

[7] R.F. Jurgens, “High-temperature electronics applications in space exploration,” IEEE Trans. Industrial Electron., vol. IE-29, pp. 107-111, 1982.

[8] M. Werner, P. Gluche, M. Adamschik, C. Johnston, and P.R. Chalker, “High-temperature sensors based on SiC and diamond technology,” (unpublished).

[9] M.A. Capano and R.J. Trew, “Silicon carbide electronic materials and devices,” MRS Bull., March 1997, p. 19, 1997.

[10] [10] T. Köhler, S. Mietke, J. Ilgner, and M. Werner, “Markets for Microsystems and electronics in automotive applications,” (unpublished).

[11] K.F. Reinhart and M. Illing, “Automotive sensor market,” (unpublished).

[12] K.Y. Cheong, S. Dimitrijev, J. Han, H.B. Harrison, “Electrical and physical characterization of gate oxides on 4H-SiC grown in diluted N2O,” J. Appl. Phys., vol. 93, pp. 5682-5686, 2003.

[13] K.Y Cheong, “Silicon carbide (SiC) as non-volatile random access memory (NVRAM) material,” JURUTERA, August 2005, p.11.

[14] K.Y. Cheong, S. Dimitrijev, and J. Han, “Investigation of electron-hole generation in MOS capacitors on 4H SiC,” IEEE Trans. Electron Dev., vol. 50, pp. 1433-1438, 2003.

[15] K.Y. Cheong, W. Bahng, and N.-K. Kim, “Characteristics of post-nitridation rapid-thermal annealed gate oxide grown on 4H SiC,” Mater. Sci. Forum, vols. 483-485, pp. 689-692, 2005.

[16] T.J. Fawcett, J.T Wolan, R.L. Myers, J Walker, and S.E Saddow, “Wide-range (0.33%-100%) 3C-SiC resistive hydrogen gas sensor development,” Appl. Phys. Lett., vol. 85, pp. 416-419, 2004.

[17] J.P. Xu, P.T. Lai, D.G. Zhong, and C.L. Chan, “Improved hydrogen-sensitive properties of MISiC Schottky sensor with thin NO-grown oxynitride as gate insulator,” IEEE Electron Dev. Lett., vol. 24, pp. 13-15, 2003.

[18] E.J. Connolly, B. Timmer, H.T.M. Pham, J. Groeneweg, P.M. Sarro, W. Olthuis, and P.J. French, “A new ammonia sensor based on a porous SiC membrane,” Proc. 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, June 5-9, 2005, p. 3E4.134.

[19] A. Salomonsson, S. Roy, C. Aulin, J. Cerdà, P.-O. Käll, L. Orjamäe, M. Strand, M. Sanati and A.L. Spetz, “Nanoparticles for long-term stable, more selective MISiCFET gas sensors,” Sensors & Actuators B, vol. 107, pp. 831-838, 2005.