Material Selection for High Temperature Electronic Devices and Its Potential Applications

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PREAMBLE

This article briefly reviews the properties of semiconductor materials that can be applied as the substrate for high temperature electronic (HTE). The definition of high temperature and HTE will be explained. In addition, the reasons for using HTE in recent years will also be provided. Finally, the criteria for material selection for these applications will be discussed.

INTRODUCTION

The effects of temperature on materials and devices have been of great interest throughout the history of semiconductor research. High temperature electronics (HTE) can be defined as electronics that can sustain their operating temperature above 125°C. It affects the electronic function for the majority of commercially available silicon (Si)-based devices [1]. The developments of electronics that can be operated at high temperatures have been a critical technology for the 21st Century.

Within the last decade, engineers have attempted to find a new semiconductor material that is able to operate in a harsh environments with the aim of enhancing the performance of high temperature semiconductor devices [2]. Table 1 compares the standard operating condition for electronic appliances. The usage of these components beyond their intended range is not specified or recommended by the respective manufacturers as the reliability of the device degrades significantly.

There are many areas that require HTE devices and systems beyond this range. Aircraft, spacecraft, automotive industries and well logging are some of the areas. Electronic components and systems used in these areas must be able to operate at temperatures beyond 250°C. An overview for the applications mentioned as a function of temperature is show in Figure 1.

APPLICATIONS AND BENEFITS OF HTE

The principle driver for the development of HTE systems in the aerospace and spacecraft sector is for weight reduction and efficiency improvement. This can be achieved by eliminating cooling systems in jet engines or turbine controls. The traditional thermal management approaches introduce an additional overhead in the form of longer wires, more connectors and plumbing for the cooling system. All of this can add undesired size and weight to the system. It increases the complexity which corresponds to an increased potential for failure. The use of a HTE semiconductor is considered as the best solution to address this issue [2].

In the automobile industries, the driving force for using HTE is for the reduction of engine exhaust emissions and improved fuel efficiency.

Table 1: Comparison of standard temperature range for electronic devices. [3]

Component Classification	Temperature Operating Range (°C)
Commercial (TV, Computer, etc)	0 to + 70
Industrial/automotive	-25 to + 85
Extended Industrial	- 40 to +125
Military	- 55 to +125
Aerospace	-65 to +125

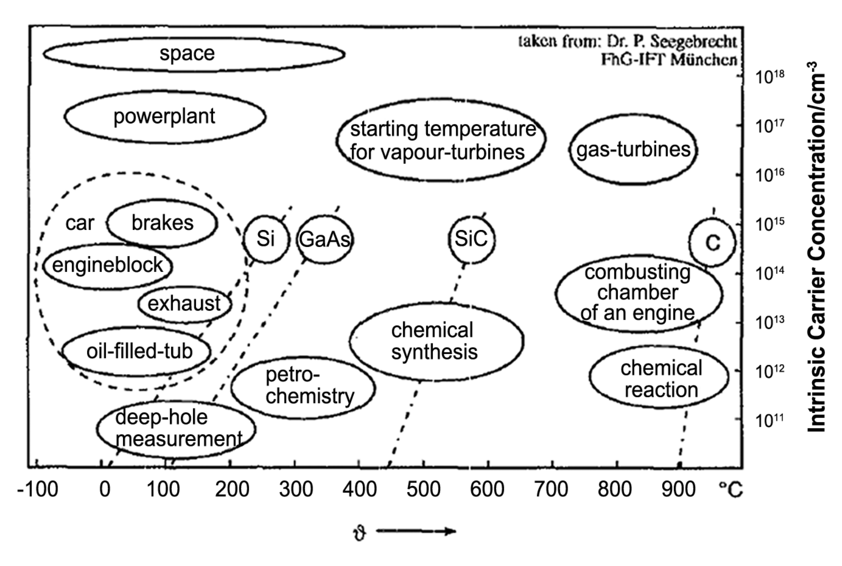

Figure 1: Temperature ranges for typical applications [4]

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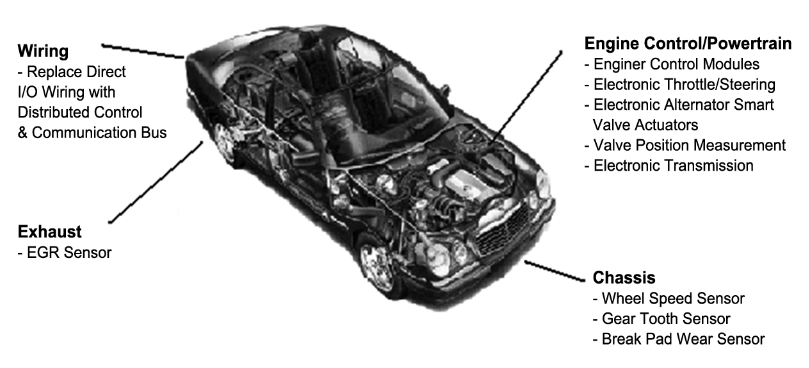

Figure 2: High temperature electronic devices and systems used in an automotive [4]

Reducing emissions, for example, depends on more precise and local control of the valve timing. It also depends on the primary sensing of cylindrical pressure and the camshaft position. Therefore, more sensors and signal conditioning electronics have been placed on vehicles to improve the precision of the measurements.

Around 100 sensors, including sensors for engine speed and angular position, automatic brake system (ABS), power steering and engine condition monitoring, are placed in cars. Figure 2 shows a few sensors that are usually included in cars. Smart sensors and related electronics which operate up to 250°C will form an important part of new developments to meet these aims [4, 5].

Another area that utilises HTE devices is the well-logging sector. This sector is one of the largest users of HTE and systems. The temperature requirements are generally less than 172°C (222°C for gas wells), but can range up to 312°C for several hours during logging. In order to maximise the product flow in this sector, sensors and data acquisition systems are extensively used to record the environments around drilling heads in oil, gas and geothermal fields. The parameters being monitored include temperature, pressure, flow rate, density and chemical composition.

The control of these parameters enables the productivity of the well to be optimised and, in extreme cases, prevents complete blocking of the well. Therefore, the development of HTE for the well logging sector is driven by the need for improved accuracy and resolution, improved reliability, reduced cooling requirement and increasing operating temperature [3].

HIGH TEMPERATURE ELECTRONIC SUBSTRATE SELECTION CRITERIA

The electronic revolution is mainly based on Si and is regarded as the first generation of semiconductor in the past century [2]. Enormous progress in Si-based devices is evident in every segment of the industry and society. More than 98% of the current electronic devices are using Si as the substrate [3]. Domination of Si comes from its material properties which are well understood. However, the operating temperature for devices made from this material is not more than 150°C.

Beyond this temperature, Si-based semiconductor devices are incapable of operating efficiently, especially when the high temperature is combined with a high power, high frequency and high radiation environment [7]. This is attributed to its properties in narrow band gap (1.12 eV) and low

Table 2: Comparison of some WBG semiconductor properties with Si for HTE. Data compiled from [7, 9-13]

Property	Si	GaAs	SiC			GaN	Diamond
			3C-SiC	4H-SiC	6H-SiC		
Bandgap, E_g (eV)	1.1	1.4	2.40	3.26	3.02	3.4	5.5
Dielectric Constant, ε_r	11.8	12.8	9.72	9.66	9.66	9	5.5
Thermal conductivity, λ (W/cm K)	1.5	0.5	3.2	3.7	4.9	1.3	20
Electron mobility μ_n (cm^2/V-s)	1400	8500	800	1000	400	900	2200
Hole mobility,μ_p (cm^2/V-s)	600	400	40	115	101	150	1600
Breakdown voltage (MV/cm)	0.3	0.4	1.5	3.2	3.0	5	10
Electronic maximum operating temperature (°C)	150	350	700	700	700	>750	1000
Melting point (K)	1690	1510	3100	3100	3100	2070	>2500
Physical stability	Good	Fair	Excellent	Excellent	Excellent	Good	Very good
Process maturity	Very high	High	Medium	Medium	Medium	Very low	Very low

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thermal conductivity [8]. Band gap is a property of semiconductors that determines the amount of energy required for current to flow in the material.

To overcome this problem, a semiconductor with a wider band gap is a better choice to produce devices for high temperature applications. Wide band gap (WBG) semiconductor offers various advantages, namely, higher temperature stability, higher chemical stability, higher thermal conductivity and higher breakdown field. Examples of WBG semiconductors are silicon carbide (SiC), gallium nitride (GaN) and diamond, with their superior electrical properties making them likely candidates to replace Si in the near future for HTE applications. Table 2 summarises some of the physical and electronic properties of these materials.

Among the candidates, SiC has emerged as a very promising candidate to replace Si in special applications, especially in HTE devices. A large amount of attention has been given to SiC, which is considered as the most mature WBG semiconductor. Due to the large band gap of SiC compared to Si, the former enables HTE devices to function efficiently at temperatures beyond 600^{o}C [2]. SiC has several advantages compared to other WBG materials, including the commercial availability of substrates, known device processing techniques, and the ability to grow thermal oxides. SiC has demonstrated large values of the following:

- band gap: enabling lower leakage current from temperature induced intrinsic conduction,
- breakdown electric field: sustaining an eight-fold larger voltage gradient, enabling thinner active regions, lower resistance and higher voltage operation,
- thermal conductivity: sustaining four-fold higher power densities than GaAs or Si,
- saturated electrons drift velocity, twice that of silicon, suitable for faster operating speeds,
- bonding energy (between Si and C), giving high mechanical strength, chemical inertness, and radiation resistance.

An almost infinite number of SiC polytypes are possible and approximately 200 polytypes have already been discovered. These polytypes are differentiated by the stacking sequence of the biatomic closed pack layers. The most common polytypes are hexagonal 6H-SiC and 4H-SiC, cubic 3C-SiC and rhombohedral 15R-SiC. However, not all types are easy to produce. Only 4H and 6H polytypes are available as substrate material in the market [2].

GaAs is the next most commonly used semiconductor after Si. Its bandgap is 1.4 eV, which makes it a suitable candidate for HTE application. However, due to the physical properties and difficulties in device fabrication using this material, it is not widely used for HTE application [14].

Among the WBG semiconductor, diamond has the most superior properties, unmatched by any other material. Obviously, diamond is the material of choice for many applications especially those which require a high operating temperature [2]. Diamond melts at approximately

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3827°C. It is stable at elevated temperatures, but its stability depends on the ambient. However, diamond is regarded as one of the most difficult semiconductors to build a functional device with.

CONCLUSION

The development of HTE has emerged as a critical technology in recent years. The aerospace, spacecraft, well logging and automobile industries require devices that can operate at high temperatures. Si-based semiconductor has been extensively used since the last century and is approaching its limits. New materials with WBG characteristics are being explored with the aim of replacing Si. ■

REFERENCES

[1] McCluskey, F.P., Grzybowski, R. and Podlesak, T. (1997) High Temperature Electronics. CRC Press, p.322.

[2] M. Willander, Friesel, M., Wahab, Q. and Straumal, B. (2006) Review silicon carbide (SiC) and diamond for high temperature device applications. Journal of Material Science : Material in Electronic 17: 1-25.

[3] Sharp, R. (1999): High temperature electronics-possibilities and prospects. In Advances in Semiconductor Devices (Ref. No. 1999/025), IEE Colloquium on, pp. 1/1-1/4.

[4] Klein, J.W. (1995): Silicon and gallium arsenide in high temperature electronics applications. In Signals, Systems, and Electronics, 1995. ISSSE '95, Proceedings., 1995 URSI International Symposium on, pp. 157-162.

[5] Johnson, R.W., Evans, J.L., Jacobsen, P., Thompson, J.R. and Christopher, M. (2004) The changing automotive environment: high-temperature electronics. Electronics Packaging Manufacturing, IEEE Transactions on 27: 164-176.

[6] Hornbeger, J., Lostetter, A.B., Olejniczak, K.J., T.Mcnutt, Lal, S.M. and Mantooth, M. (2004) Silicon carbide (SiC) semiconductor power electronics for extreme high temperature environment. IEEE Aerospace Conference Proceeding: 2538-2555.

[7] Casady, J.B. and Johnson, R.W. (1996) Status of silicon carbide (SiC) as a wide-bandgap semiconductor for high-temperature applications: A review. Solid-State Electronics 39: 1409-1422.

[8] Werner, M.R. and Fahrner, W.R. (2001) Review on materials, microsensors, systems and devices for high-temperature and harsh-environment applications. Industrial Electronics, IEEE Transactions on 48: 249-257.

[9] Mehregany, M., Zorman, C.A., Rajan, N. and Wu, C.H. (1998) Silicon carbide MEMS for harsh environments. Proceedings of the IEEE 86: 1594-1609.

[10] Driver, M.C., Hopkins, R.H., Brandt, C.D., Barret, D.L., Burk, A.A., Clarke, R.C., Eldridge, G.W., Hobgood, H.M., McHugh, J.P., McMullin, P.G., Siergiej, R.R. and Sriram, S. (1993) Advances in silicon carbide (SiC) device processing and substrate fabrication for high power microwave and high temperature electronics. GaAs IC Symposium: 19-21.

[11] Zolper, J.C. (1998) A review of junction field effect transistors for high-temperature and high-power electronics. Solid-State Electronics 42: 2153-2156.

[12] Chelnokov, V.E. and Syrkin, A.L. (1997) High temperature electronics using SiC: actual situation and unsolved problems. Materials Science and Engineering B 46: 248-253.

[13] Camassel, J., Contreras, S. and Robert, J.-L. (2000) SiC materials: a semiconductor family for the next century. Comptes Rendus de l'Acade´mie des Sciences - Series IV - Physics 1: 5-21.

[14] Dreike, P.L., M.Fleetwood, D., King, D.B., Sprauer, D.C. and Zipperian, T.E. (1994) An overview of high-temperature electronic device technologies and potential applications. Components, Packaging, and Manufacturing Technology, Part A, IEEE Transactions on 17: 594-609.