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State of the art of High Temperature Power Electronics

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Abstract

High temperature power electronics has become possible with the recent availability of silicon carbide devices. This material, as other wide-bandgap semiconductors, can operate at temperatures above 500°C, whereas silicon is limited to 150-200°C. Applications such as transportation or a deep oil and gas wells drilling can benefit. A few converters operating above 200°C have been demonstrated, but work is still ongoing to design and build a power system able to operate in harsh environment (high temperature and deep thermal cycling).

1 Introduction

The first part of this paper will describe some of the most prominent applications for high temperature power electronics. This is where high temperature-capable converters are enabler for new solutions, such as electrical actuators for jet engine.

The second part will give a short explanation on why wide-bandgap semiconductors are needed for high-temperature electronics, and why, among them, silicon carbide has been chosen.

Finally, we will see that a lot of work is still required to design a complete power converter (this include passive components, packaging, control circuits in addition to the active power devices).

2 Applications for high-temperature power electronics

“High temperature” means different things to different applications. In high voltage systems (such as power distribution), where silicon-based diodes or thyristors are limited to 125°C max-

imum junction temperature, an ambient of 100°C would be considered insanely high, whereas running in an environment as high as 150°C is already pretty common for some automotive systems.

Here, we list a few applications that all currently require power electronic systems operating at temperatures above 200°C (sometimes a lot more!), with some details on their environment. However, please note that this list is not exhaustive. For example, applications such as electricity distribution can also benefit from high temperature systems.

2.1 Aircrafts

In order to reduce the complexity of wiring and piping of commercial aircrafts (which make use of hydraulic, pneumatic and electric actuators), manufacturers are moving towards the so-called “more electric architecture”, which tends to use only electrical systems. For example, the MOET (More Open Electrical Technology) project, funded by the European research program FP6 [1], is focussed to “Validate scalable electrical networks up to 1MW considering new voltages and advanced concepts including system transformation of future air, actuation and electrical systems into all electrical solutions”

To achieve sufficient efficiency, electrical actuators should be driven through power electronics converters, in a distributed fashion [2]. Converters should be placed as close as possible to the actuator they control. This implies that some converters will be subject to harsh environment. For example, some of them will have to operate near the jet engine, with ambient temperature ranging from -55°C to 225°C [2].

Obviously very high reliability is expected from these systems, despite long operating life (10 - 30 years) and frequent deep thermal cycling (several takeoff-landing per day).

2.2 Automotive

Even when considering “classical” vehicles (as opposed to hybrid or full electric cars), the cost of the electrical system is more than that of the internal combustion engine (ICE) and its associated transmission [3]. Under the hood, temperatures can reach or exceed 140°C (for example, the rectifier diodes at the back of the alternator can operate above 160°C junction temperature [4]). At the opposite, temperatures can drop to -40°C in some places of the car.

In hybrid vehicles, it is possible to take advantage of the ICE cooling loop to extract heat from the power electronic systems, but the water can reach up to 120°C [3], so there is little headroom when working with 150 or 175°C-limited silicon devices.

2.3 Space exploration

Space exploration is obviously a “niche” market, but it sets some seriously challenging goals [5]: surface temperature on Venus can reach 460 to 480 °C. On Jupiter, temperature increases with depth (and pressure); and a few hundred kilometres down, the ambient temperature reaches 400°C and 100 bars, with a very aggressive atmosphere (winds around 200 m/s, hydrogen-rich chemical composition. . .).

Thermal cycling is also an issue as ambient temperatures can be as low as -140°C during the night.

	"Classical" semiconductors		wide-bandgap semiconductors				
	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
Bandgap Energy E_g (eV)	1,12	1,4	2,3	2,9	3,2	3,39	5,6
Elec. mobility μ_n ($\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$)	1450	8500	1000	415	950	2000	4000
Hole mobility μ_p ($\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$)	450	400	45	90	115	350	3800
Critical elec. field E_C ($\text{V} \cdot \text{cm}^{-1}$)	$3 \cdot 10^5$	$4 \cdot 10^5$	$2 \cdot 10^6$	$2,5 \cdot 10^6$	$3 \cdot 10^6$	$5 \cdot 10^6$	10^7
Saturation velocity v_{sat} ($\text{cm} \cdot \text{s}^{-1}$)	10^7	$2 \cdot 10^7$	$2,5 \cdot 10^7$	$2 \cdot 10^7$	$2 \cdot 10^7$	$2 \cdot 10^7$	$3 \cdot 10^7$
Thermal cond. λ ($\text{W} \cdot \text{cm}^{-1} \cdot \text{K}^{-1}$)	1,3	0,54	5	5	5	1,3	20
Dielectric constant ϵ_r	11,7	12,9	9,6	9,7	10	8,9	5,7

Table I: Physical properties of "classical" and wide-bandgap semiconductors. Note that some of these materials exhibit anisotropic behaviour, so the values given here should just be considered indicative.

2.4 Deep oil/gas extraction

Requirements for these applications are quite different from the ones we have just seen: most systems here are expected to run continuously at high ambient temperature for 5 years or more, but without much thermal cycling. However, due to the high cost associated with stopping the exploitation (the power systems are located downhole, several kilometres deep), reliability must be excellent.

An example of use of power electronics is the electrical downhole gas compressor [6], designed to increase the production of gas wells by putting a compressor close to the gas reservoir. For this application, the ambient temperature is expected to reach 150°C ¹. For deep oil wells, temperature is expected to reach 225°C , with a system lifetime of 5 years [7].

3 Silicon carbide: the key enabler

3.1 Wide bandgap semiconductors for high temperature

Some of the physical properties of several semiconductor materials are listed in table I. Silicon is, by far, the most used material in power electronic devices. The properties of gallium arsenide (GaAs) are also given for reference, as this material is mainly used for very high-frequency applications. Power components made of silicon carbide (especially the 4H polytype) have become commercially available in recent years. Schottky-barrier diodes can be bought from many suppliers (Infineon, Cree, ST Microelectronics...) for a few euros, and controlled switches (JFET) are available as engineering samples. The advantages of this material, as well as of the other wide-bandgap materials in table I, are a higher critical field, a higher saturation velocity, and a lower intrinsic carrier density (due to the higher bandgap).

The advantages of wide-bandgap materials become clear in figure 1. It can be seen that silicon devices rated above a few hundred volts cannot operate higher than 200°C . Worse, high-voltage silicon components (such as 6.5 kV IGBTs) are limited to an even lower junction temperature (125°C in this case). With wide-bandgap semiconductors, the operating area is a lot bigger, allowing very high-voltage (up to a hundred kilovolts) devices, operating at temperatures above 400°C or more.

¹<http://ior.senergyltd.com/issue13/research-development/smes/corac/>

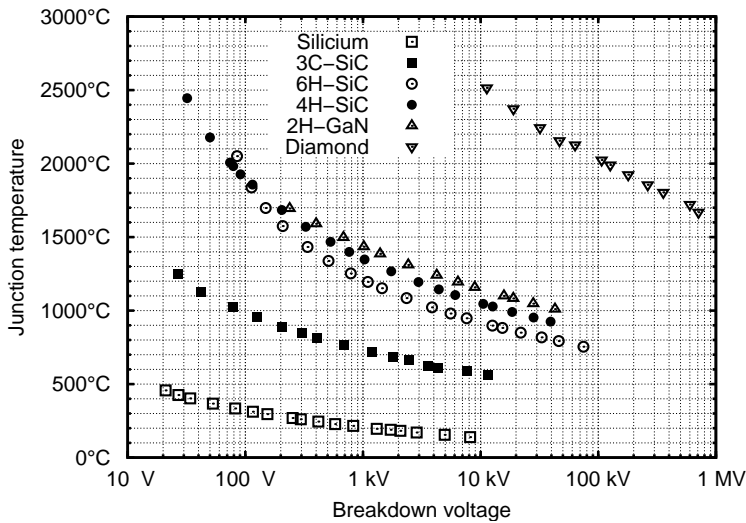


Figure 1: Thermal runaway limits for various semiconductors: This corresponds to the maximum operating temperature of an optimal structure (thickness, doping level) designed to sustain the voltage on the x-axis (results obtained by simulation).

However, all materials have not reached the same technological maturity. Silicon technology is, of course, very well known, with very low cost material and very high yield production. GaN is, at the moment, available only as heterostructures with a thin layer of GaN on top of other materials (sapphire, silicon or SiC). Therefore, it is not possible to build vertical devices, thus making this material less appealing for power applications. Diamond technology is currently at a very early stage, with no good quality wafers available, and a lot of process steps to be developed.

SiC, in the other hand, has showed very good progress in recent years, with very good quality, up to 4 inches wafers now available from different manufacturers. This is why we will focus on this material in the remaining of this paper

3.2 power devices for high temperature

3.2.1 Unipolar devices

In silicon, unipolar devices (mainly Schottky Barrier Diodes and MOSFET) are not considered for operating voltage above a few hundred volts, because of their increase in resistivity. Silicon carbide, however, offers a much lower resistivity (respectively 100 and 2000 times lower for 6H an 4H-polytypes [8] than a layer of silicon designed to sustain the same breakdown voltage), making unipolar devices a sensible choice up to around 10 kV. For high temperature applications, however, pure SBDs should be replaced by Junction Barrier Schottkies (JBS) to take advantage of a lower leakage current.

One of the advantages of unipolar devices is their speed, offering very low commutation losses due to the lack of recovery phenomenon [9]. Their conduction losses, however, are somewhat higher than that of their bipolar counterparts. The high temperature reliability of unipolar SiC devices has been found to be as good as that of Si-diodes [10].

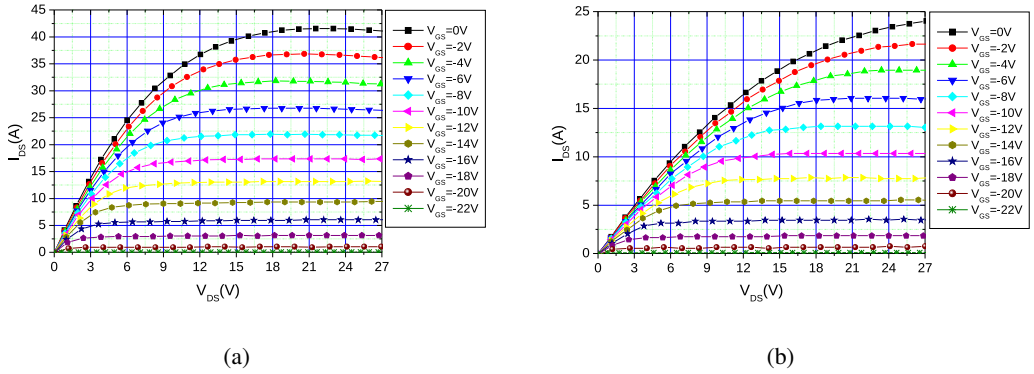


Figure 2: Static characteristic of a 1200V – 15A – 200 mΩ JFET (third generation) from SiCeD, for two ambient temperatures: (a) 25°C and (b) 225°C. Curves were acquired using a Tektronix 371 curve tracer in pulse mode. Please note that both curves have a different y-scale for the sake of readability.

Regarding controlled switches, MOSFET have not reached yet maturity: their oxide layer has poor reliability under high temperature and high voltage; the carrier mobility in their channel is low, and charge trapping in the gate oxide causes threshold voltage instability [11]. Apparently, some of these limitations have been overcome recently, as SiC MOSFETs operating above 200°C have been demonstrated [12], but without any information about reliability and ageing.

Currently, JFETs are considered good candidates as the “general purpose” SiC controlled switch. They are available as engineering samples (for example from SiCeD, see figure 2), and should be commercially available soon. Their main drawback is that they are “normally on”, i.e. they conduct current when no voltage is applied between their gate and source terminals. This requires special care when designing a converter to ensure that a fault in the control circuit won’t result in a short-circuit in the power side. Furthermore, it can be seen in figure 2 that JFETs require a negative voltage on the gate, whereas Si MOSFET require a positive voltage to turn on.

A SiC JFET/Low-voltage Si MOSFET hybrid has been presented to create a “normally-off” switch. This component is called a Baliga-pair [8] or a cascode. The presence of a Si-MOSFET, however, makes it ill-suited to high temperature.

3.2.2 Bipolar devices

As unipolar devices have quite good performances up to a few kilovolts, most of the work on bipolar devices is towards very high voltage (tens of kilovolts), for energy distribution applications (PiN diodes, BJT, thyristors). However, bipolar devices can be interesting for high temperature, even at low voltage, as their losses tend to reduce as temperature increases [13]. Furthermore, Bipolar Junction Transistors (BJTs) are normally-off devices, which could make designing a converter easier (although they require fairly high current to drive them). Transic² is an example of a company which sells BJTs for 600 V applications

Bipolar devices have long been crippled by defects in the base material (stacking faults).

²<http://www.transic.com/>



Figure 3: A JFET-based, 540 V, 15 A, 3-phase inverter (6 JFETs) in a single package with an external DC capacitor. This system has been successfully tested at 200°C.

Their performances used to drop rapidly during operation. This is apparently getting better, and some bipolar devices have been found to be stable for long periods (although the quality of the base material still has a lot of influence) [14]

3.3 High temperature converters

Now that some SiC components have become available, some of the research work has shifted to high-temperature converters. As we will see below, active devices are just one of the many parts required to build a converter (high temperature passive, packaging, control circuits are also required).

As long as the ambient temperature remains under 150°C, classical silicon control circuits can be used. This is the case with inverters designed for automotive hybrids, which make use of the ICE cooling loop (120°C) [15]. In this case, it is possible to use Si IGBTs together with SiC SBDs, providing the thermal resistance of the package is low enough to keep the junction temperature of the IGBT below 175°C.

In [16], an inverter operating at 150°C ambient temperature is presented. Here, the idea is to take advantage of SiC devices to allow the junction temperature to reach 250°C. The 100°C temperature gradient allows to use a less efficient (and therefore much smaller) heatsink

At a even higher temperature (200°C), a SiC MOSFET-based, 2-kW boost converter is demonstrated [12]. In [17], authors have designed all the basic building blocks for a JFET driver, to be built in SOI. These blocks (in discrete form) have been used to drive a JFET-based inverter operating at 200°C ambient temperature [18]. A picture of the inverter can be seen in figure 3

Finally, in [19], a buck converter (SiC JFET and SBD) is tested at 400°C. However, due to the very high leakage current in the SBD at high temperature, the converter is derated to 200 V instead of 600V. Moreover, the saturation current in the JFET drops from 3.5 A to 0.7 A at high temperature. Also, some components, such as the control circuits and the input capacitor are kept at ambient.

4 Remaining issues

As we have seen, some of the basic building block for high temperature power converters have become available in recent years. Although the first demonstrators have been presented, re-

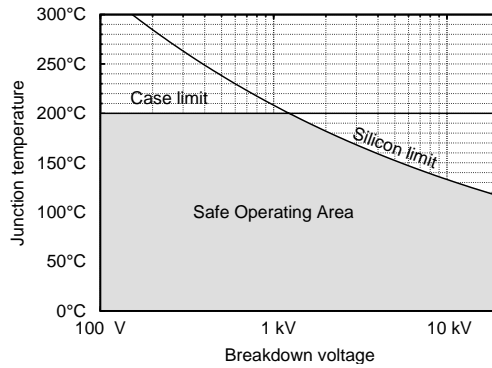


Figure 4: For low-voltage silicon devices, the maximum operating temperature is limited by the materials of the case. For higher voltage devices, the limit is the silicon.

search is still ongoing to provide systems with better performances, and more important yet, better reliability.

4.1 Better SiC devices

At the moment, only SiC SBD have reached maturity.

MOSFETs have only been demonstrated by a few research laboratory, with little information about their reliability.

JFETs are getting better, but some of their parameters (such as the threshold voltage) are not fully controlled yet. Because of this, drivers must be individually matched to the transistors (the gate breakdown voltage is only a few volts away from the threshold voltage). This should improve soon.

The gain of BJTs is still relatively low (in the order of 30). This puts a lot of constraints on the driver, which has a lot of current to source. Darlington pairs or more advanced combination should improve this issue.

4.2 high temperature/reliability packaging

As can be seen in figure 4, even for silicon devices, the maximum operating temperature is sometimes limited by the packaging. Most packaging solutions have indeed been developed for mild ambient [20], and require a complete redesign to cope with high temperature environments.

An example of this is the die-attach solution: in classical power modules, it is made using the so-called “high temperature” lead-rich solder alloy [20], which melts at 312°C, or with other alloys which have an even lower melting point [21]. Although the melting point is higher than most high temperature environments, a wide safety margin must be ensured between the maximum operating temperature and the melting point: the closer you are to the melting point, the worse the mechanical properties of the solder alloy. In most cases, the homologous temperature (ratio of the melting point over the operating temperature, both expressed in Kelvin) should not exceed 0.67 (although values as high as 0.85 are not uncommon in electronics).

To avoid the use of very high-melting point solder alloys, which would put a lot of stress on semiconductor dice during assembly, different die-attach solutions have been explored. Sintering of micrometre-sized silver powder has been developed by Semikron [22]. With this

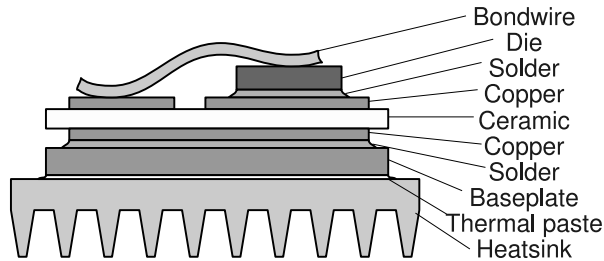


Figure 5: Cross section of a power module (with its associated heatsink), which shows the many layers and interfaces it contains. When this structure is submitted to power cycling, heavy mechanical stresses are generated and can eventually yield to fatigue and failure of the assembly.

technique, a joint is obtained by applying pressure (40 MPa) and temperature (about 250°C). As the die-attach material is pure silver, its melting point is expected to be 961°C, and therefore will operate at very low homologous temperature. To avoid the use of pressure (which requires dedicated tooling), researchers at the Virginia Tech. have presented a silver sintering solution using nanometre-sized powder [23],[24]. This solution gives good results compared to Epoxy-based die attach or Au-Ge solders [25].

Another approach is the Transient Liquid Phase Bonding (TLP)[26]. With this technique, a low-melting point metal (or alloy) will diffuse into a solid phase. Once it is completely diluted into the solid phase, the melting point of the newly formed alloy will be much higher than the process temperature. Such techniques have been applied to Au/Sn alloys [27], In/Ag [28], among others. Finally, more exotic solutions have been explored to create a very localised heating (hence avoiding stressing the dice) by using “explosive” reactive die attach [29].

In addition to the temperature-limitation of many parts of a classical packaging such as depicted in figure 5 (solders, wirebonds, silicone encapsulant, thermal paste...), it must be noted that power modules are very sensitive to thermal cycling. As we can see in figure 5, a power module is a stack of many materials, creating many interfaces. When such stack is submitted to thermal cycling, all parts tends to expand differently (as they all have different coefficients of thermal expansion), creating stresses at the interfaces. During the life of the power module, part of these stresses accumulates, creating fatigue and eventually failure. This phenomenon is already present with standard, silicon-based components, but becomes even more visible with high-temperature applications.

4.3 High temperature control circuits

Most high temperature converter use control circuits made with Silicon-On-Insulator (SOI) substrate. Many circuits have been developed by Honeywell for oil well applications [7]. In Europe, the company Cissoïd³ also designs SOI circuits for high temperature, including MOS-FET drivers [30].

Recently, the first SiC-based integrated circuit has been announced [11]. It should eventually allow very high temperature drivers, or monolithic integration of drivers and power. However, a lot of work is still needed to produce a driver complete with power supply and device

³<http://www.cissoïd.com/>

protections.

4.4 High temperature passives

Magnetic material can be found for ambient temperature up to 450°C [19]. Capacitors are much of an issue, as most dielectric material cannot be used above 200 to 250°C. For example, mica can be used up to 260°C, TFE up to 200°C [31]. A common dielectric in ceramic capacitors (X7R) can also be used at 200 °C, but at the expense of a strongly reduced capacitance (around 50%). For all these technologies, the dissipation factor is high (1%), as well as the cost for capacitors rated at a few hundred volts.

5 Conclusion

Silicon carbide allows power devices operating at very high temperature (in theory more than 1000°C). As we have seen, research is still needed to take fully advantage of this material. Packaging, passive components and control circuits are currently restricted to much lower temperatures. Research is also needed to produce better power devices, eventually using alternative wide-bandgap semiconductors, such as GaN or diamond.

The first demonstrators of high temperature converters have been presented recently. They prove the feasibility and the advantages of systems that can operate in harsh environments.

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