Materials Science and Engineering B 176 (2011) 283–288

Contents lists available at ScienceDirect

Materials Science and Engineering B

journal homepage: www.elsevier.com/locate/mseb

Review

State of the art of high temperature power electronics

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ARTICLE INFO

Article history:
Received 24 September 2009
Received in revised form
16 September 2010
Accepted 21 October 2010

Keywords:
High-temperature electronics
Power electronics
Silicon carbide
Semiconductor devices

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).

Contents

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.

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doi:10.1016/j.mseb.2010.10.003

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 maximum 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 1 MW 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 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 °C 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 460–480 °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).

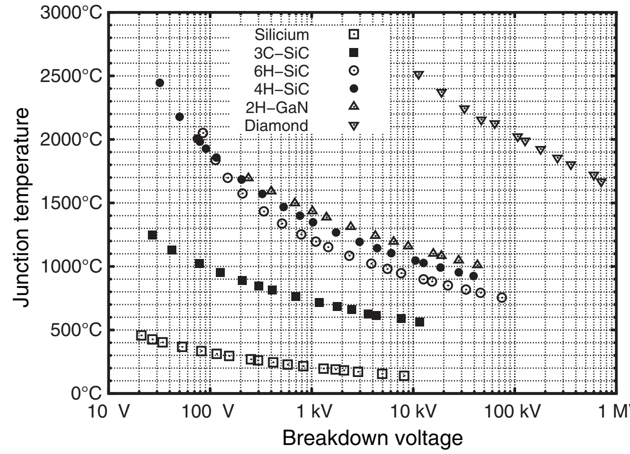

Fig. 1. Thermal runaway limits for various semiconductors: This corresponds to the maximum operating temperature of an optimal structure (thickness, doping level) designed to sustain the voltage on the *x*-axis (results obtained by simulation).

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

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 1. Silicon is, by far, the most used material in power electronic devices. The properties of galium 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 1, 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 Fig. 1. In this figure, explained in details in [8], the run-away temperature (*y*-axis) is defined as the temperature above which the

[1] http://ior.senergyltd.com/issue13/research-development/smes/corac/.