Benefits and advantages of silicon carbide power devices over their silicon counterparts

Giuseppe Vacca outlines the advantages of silicon carbide compared with traditional silicon and the benefits attainable for fabricating power devices.

Silicon carbide power devices allow us to leverage many important advantages over traditional silicon technology, which has already reached intrinsic limitations due to material characteristics: silicon's physical-electrical properties are precluding further performance improvement, while research activity requires such great effort that it is too expensive and uneconomic in terms of cost of investment.

To overcome these constraints from silicon performances limitation, major semiconductor companies have understood that it has become necessary to make use of new compound materials like silicon germanium (SiGe) and gallium arsenide (GaAs). For some applications it is even better to turn to wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN). Among these, 4H-type SiC is the most currently cited, and many researchers believe that it will play a very important role in the future of electronics because it shows great potential in power electronics devices.

Interest in silicon carbide has increased greatly over the last several years, since this novel semiconductor can boost power handling capability, and its behavior is achieved through the combination of higher power density together with better efficiency. These qualities are coupled with the possibility of handling operating temperature above 150°C (the maximum operating temperature for counterpart silicon-based devices).

Silicon carbide is now the semiconductor material used for manufacturing innovative power devices, accounting for the biggest share of investment in R&D, in both microelectronics design centers and foundries. SiC devices are opening up advanced applications in the most important fields of electronics, and its properties allow the performance of existing semiconductor technology to be extended.

As a binary compound containing equal amount of silicon and carbon atoms in a hexagonal crystal structure, there are two principal kinds of polytypes of silicon carbide: 6H-SiC and 4H-SiC. Before the introduction of 4H-SiC, the dominant polytype was 6H-SiC. Both types have been used for some years for manufacturing electronic devices, although recently 4H-SiC has become dominant. They have similar electrical properties, but 4H-SiC is preferred because its electron mobility is identical along both the horizontal and vertical planes of the crystal, whereas 6H has anisotropic behavior.

Introduction

As a result of silicon carbide's favorable features, SiC power devices and power integrated systems can handle much higher power density compared with traditional silicon counterparts.

This happens because SiC-based devices combine higher breakdown voltage with wider frequency bandwidth signals, allowing significant performance improvement in many applications such as radio-frequency, microwave and power electronics, with plenty of advantages offered by silicon carbide devices over silicon diodes, MOSFETs and other type of transistors currently on the market.

Silicon carbide's larger bandgap energy (3.2eV, about three times higher than silicon's 1.1eV) — in conjunction with the high breakdown voltage and a typical critical electric field at least one order of magnitude greater than silicon's — are properties that can be conveniently exploited to fabricate new power devices with very good performance.

The main advantage of a SiC MOSFET is the low drain-to-source ON-resistance (R_{DS-ON}) — about 300–400 times lower than that of silicon devices with a comparable breakdown voltage — presenting a key desirable feature for designing extraordinarily efficient power electronics equipment and related systems.

Based on these advantages and potential future development, silicon carbide technology is attracting the most important semiconductor players thanks to the possibility of providing higher power levels in an extremely effective and efficient way, minimizing power loss and hence improving average efficiency up to 10% while diminishing die size by about five-fold.

On the other hand, it means that silicon carbide can manage higher power levels than silicon devices utilizing the same active area. Fabricating devices with the same performance level yet reduced dimensions is then achievable (see Figure 1).

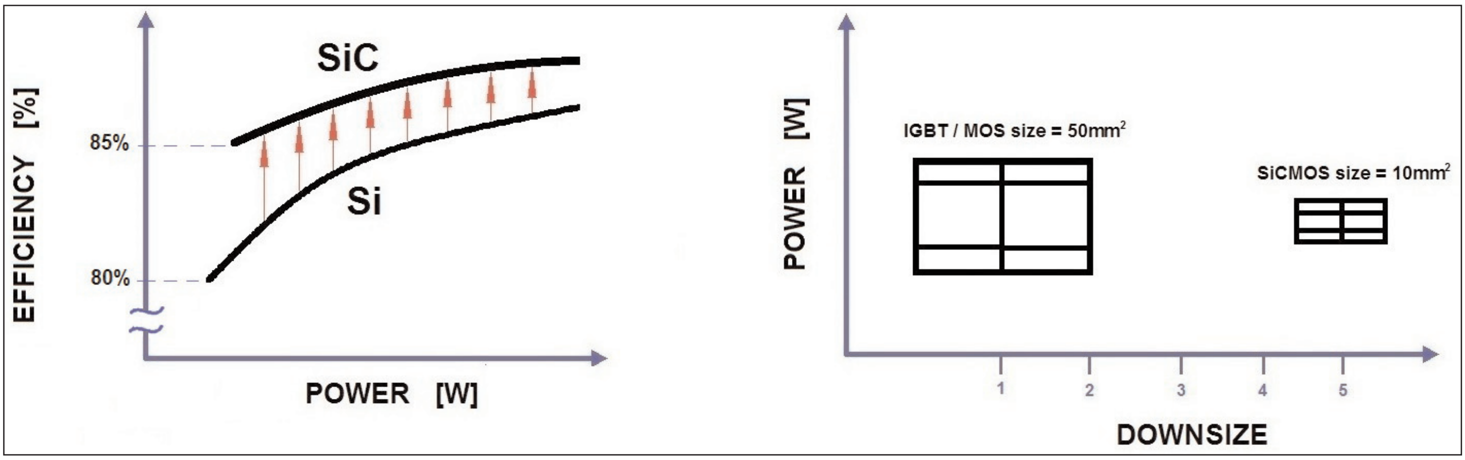

Figure 1. Estimated efficiency improvement and downsizing for SiC versus silicon devices.

Electro-thermal characteristics

Silicon carbide devices can exhibit simultaneously high electro-thermal conductivity and extremely fast switching.

Indeed, the lower output capacitance and $R_{DS\text{-}ON}$ make SiC MOS suitable for switching designs such as digital power supplies, three-phase inverters and many kinds of electronic converters (AC to DC and DC to DC).

This happens because SiC components are capable of handling high energy levels while operating at much higher switching frequencies.

Using SiC devices hence enables significant cost saving and downsizing of magnetic parts (transformers, chokes, inductors) used in all switching mode design systems.

Note that achievable $R_{DS\text{-}ON}$ values for SiC MOS are much lower than for silicon MOSFETs with a comparable drain-to-source voltage, so SiC MOS devices can reduce conduction loss and frequency-switching loss at the same time.

Thermal conductivity is a key additional feature because it represents how easy it is to remove heat caused by power loss, avoiding any temperature rise in the device.

Note that electron mobility and breakdown electric field are dependent on the dopant concentration — nitrogen is used as an n-type dopant and aluminium as a p-type dopant.

It is quite difficult to cool down devices made from semiconductor material characterized by low thermal conductivity. In this case, a de-rating factor arises, causing partial performance degradation when devices are operating at high temperatures. In contrast, high thermal conductivity means that power devices can be cooled in the best way without any performance degradation.

Additionally, silicon carbide exhibits an operating temperature of at least 200°C, i.e. 50°C higher than the absolute maximum rating of silicon MOS devices. Sometimes this temperature can go up to 400°C or more.

Properties @ 300K		Si	SiC (4H)
Band Gap Energy [eV]		1.1	3.2
Electronic Mobility [$cm^2/V \cdot s$]		1400	900
Breakdown electric field [KV / cm]		300	2400
Thermal conductivity [W / cm·K]		1.5	4

Figure 2. SiC versus silicon properties.

This advantage allows SiC power devices to work well in hot and hostile environments, avoiding performance de-rating and related problems regarding reductions in mean time to failure (MTTF) and life time, and enabling appreciable gains in quality and reliability.

As a summary of the benefits obtainable by using SiC devices and systems already on the market, a simple comparison between different technologies can be seen from the Johnson figure of merit (see Figure 3).

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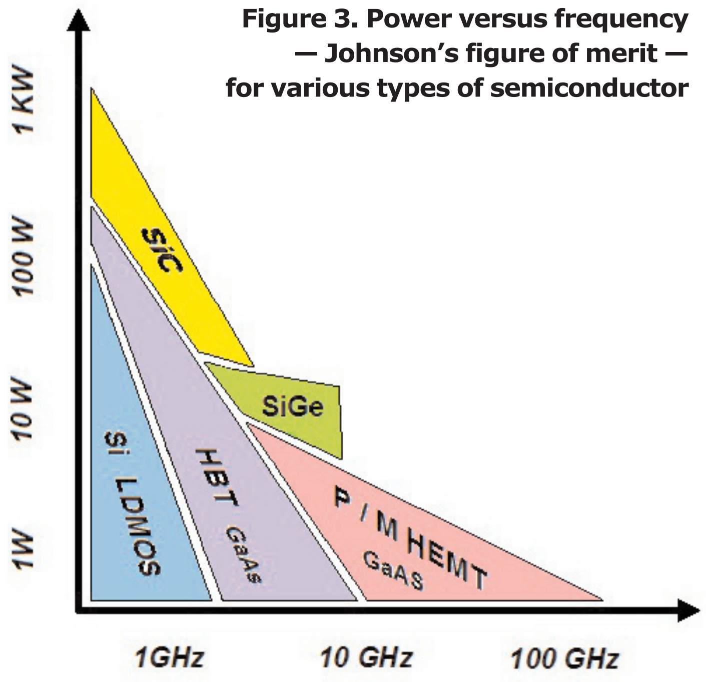

Figure 3. Power versus frequency — Johnson's figure of merit — for various types of semiconductor

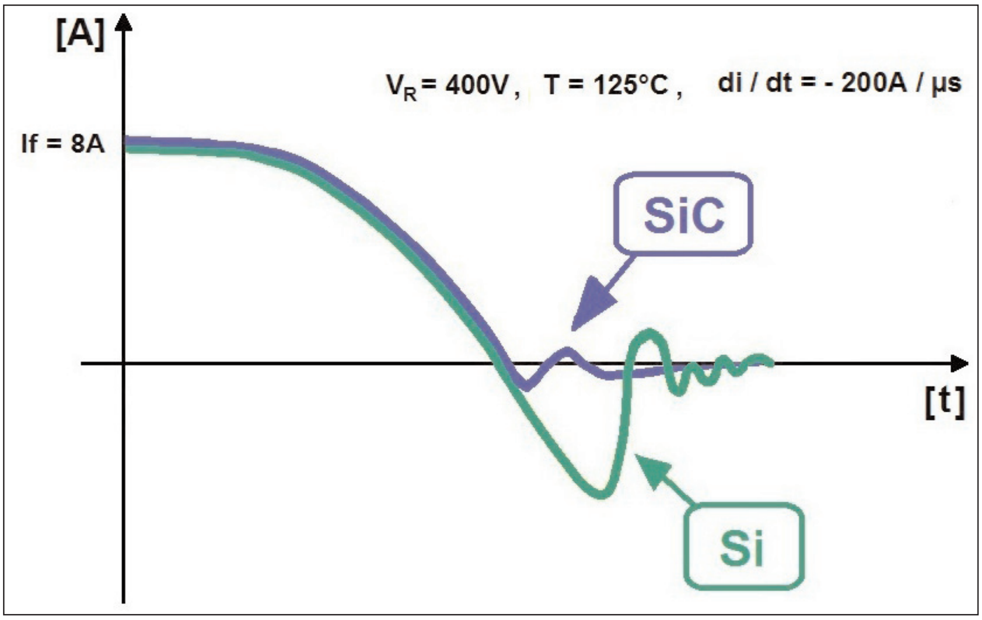

Figure 4. Reverse recovery time comparison of SiC Schottky diode versus silicon fast recovery diode.

Available devices

Silicon carbide power electronic devices can be classified in two main categories:
(1) power devices grown on semiconducting substrates, e.g. SiC Schottky barrier power rectifiers (diodes) and power switches (SiC MOSFETs);
(2) devices grown on semi-insulating substrates, i.e. high-power, high-frequency metal-semiconductor field-effect transistors (MESFETs).

Using homoepitaxial growth on SiC makes it possible to fabricate both kinds of devices with lateral and vertical structures.

Lateral devices — basically SiC MESFETs — are popular in high-frequency applications because they are utilized in RF and microwave amplifiers working in the S-band (up to 4GHz), and they can also be used for satellite applications. These devices can work at a maximum operating temperature of 250°C.

Vertical geometry devices comprise mainly high-voltage Schottky barriers and SiC MOSFETs. Both are already present in the portfolios of most key semiconductor players. The first devices demonstrate the remarkable advantages for Schottky diodes compared with silicon fast recovery diodes because SiC devices exhibit smaller reverse recovery current together with a shorter recovery time. These factors allow a significant reduction in switching loss accompanied by a low level of radiated emission. Furthermore, these positive effects deteriorate very little when temperature rises.

In contrast, traditional silicon diodes suffer performance degradation when the ambient temperature rises. This is due to switching loss, and the main effect is that electromagnetic interference increases.

PN junction silicon diodes exhibit a long transient and high current spikes when the junction polarization changes from forward voltage to reverse voltage. SiC Schottky barrier diodes (SBDs) have good behavior because they are unipolar devices, so they employ only majority carriers (and no minority carriers) to fulfill the conduction state. Based on this fact, the reverse recovery time of SiC SBDs is smaller and shorter than silicon fast recovery devices.

Thanks to these better characteristics, the deployment of SiC diodes is going ahead and they are replacing silicon counterparts, particularly in critical application operating at 600–1200V with current rating up to 50A, such us active PFC (power factor correction) and other kinds of boost converters, UPS (uninterruptible power supplies), motor drives, solar inverters, DC-to-DC primary stages, electronic welding machines, etc.

Automotive applications benefit from these new devices because they can be inserted into hybrid solutions and fast battery recharging equipment at charging stations for electric cars and industrial vehicles. Also, devices with a 1700V maximum voltage are already available.

The typical forward voltage of silicon carbide power Schottky diodes is around 1V, with the feature that V_f has a positive temperature coefficient (increasing with a rise in temperature), avoiding any thermal runway and facilitating easy parallel connection of more SiC diodes. So, they can perform automatic current sharing due to self-regulation, ensuring more stable operation compared with conventional silicon diodes (which have a negative temperature coefficient).

The most popular silicon power devices for switching applications are insulated-gate bipolar transistors (IGBTs). MOSFETs are used if the switching frequency overcomes 20MHz.

To achieve low $R_{CE\text{-}ON}$ (IGBT resistance in the conduction state) minority carrier injection is required, but their presence requires a longer switch-off time since they need to recombine. This kind of process is accompanied by power loss, because minority carriers cause a current tail and this effect has to be dissipated.

MOSFETs are unipolar devices, so they don't produce any current tails. Furthermore, if they are fabricated using silicon carbide, they can exhibit good performance in switching applications, adding to their great potential for withstanding high-temperature operating conditions.

The elimination of the tail current of silicon IGBTs is a considerable benefit in SiC MOS. But be aware that an additional ringing with overshoot can be observed when replacing IGBTs with SiC-based devices.

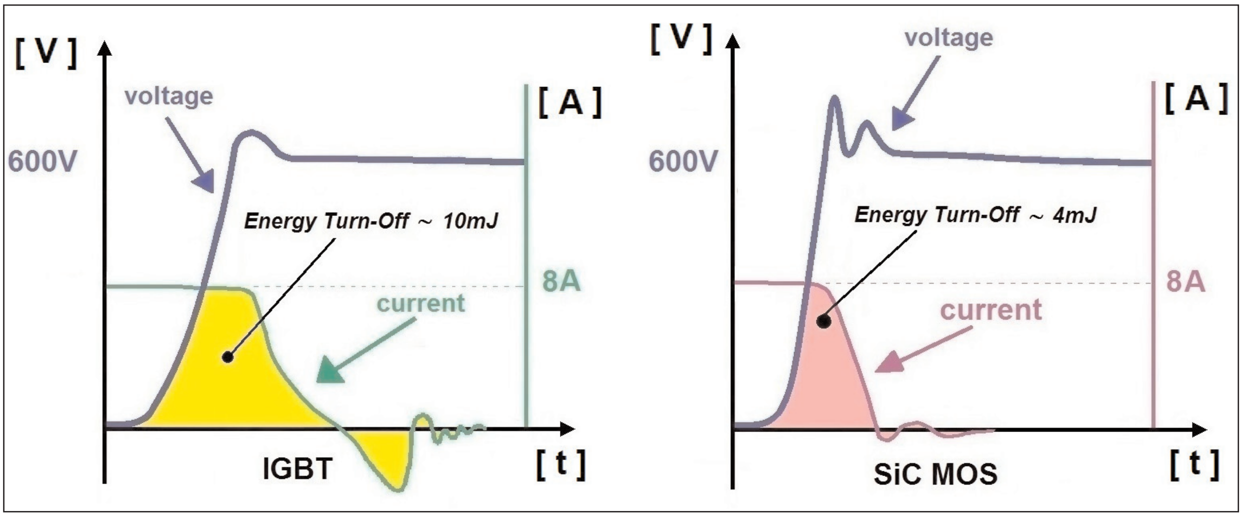

Figure 5. Comparison of energy loss during turn-off.

Three-phase inverters for high-power motor control intelligent power modules (IPM) represent an emerging market. These modules incorporate a gate driver, current monitor and overcurrent protection circuit, temperature feedback and other features. In this kind of power module, the six power devices are made using SiC MOS, replacing conventional IGBT or MOS.

This important evolution allows the handling of very high current values (up to 150A at 1200V and 250°C) in small packages. An appropriate study of power packaging and heat-sinks is required.

The particular application will define the standard of performance, size, power density and weight, especially for sensitive application such as electric aircraft.

Although many advantages are offered by SiC in terms of electrical and thermal properties, there are some aspects that are currently still limiting development and mass production because there are remaining material processing problems such as micropipes and screw dislocations, which have the effect of limiting die size. However, these problems have not halted the deployment of SiC power devices for some years now.

SiC wafer production for the microelectronic and optoelectronic industries is increasing greatly because demand is rising. Using chemical vapor deposition (CVD), it is possible to grow and produce epitaxial wafers with diameters of 3-inches (76.2mm), 4-inches (100mm) and 6-inches (150mm) for manufacturing vertically integrated structures.

An increase in wafer diameter helps to improve productivity and to reduce the production costs for power device manufacturers.

CVD equipment can be applied to SiC wafers of all sizes, and this tool contributes to reducing device production costs because, by using CVD, SiC epiwafers have fewer surface defects. Consequently, an improvement in yield is achieved. ■

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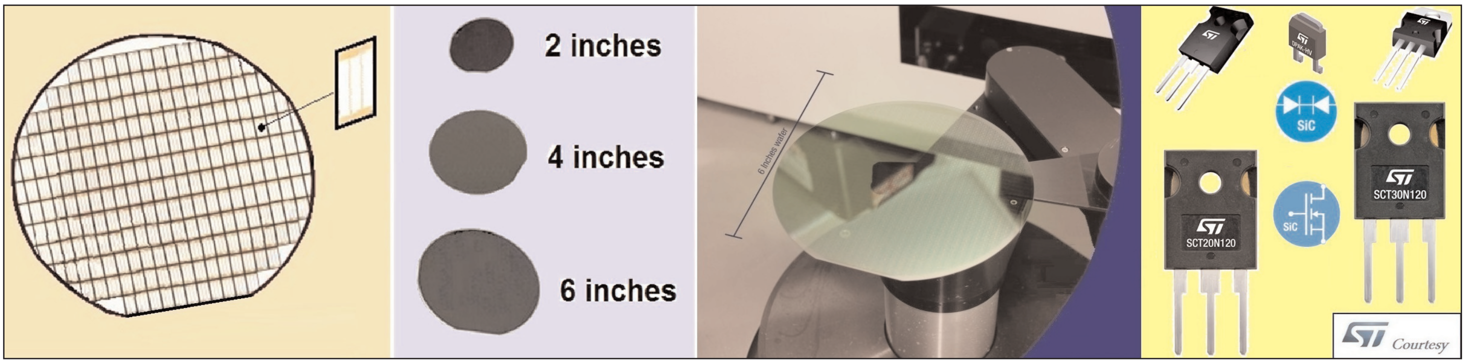

Figure 6. Examples of 2-, 4- and 6-inch 4H-SiC wafers and devices.