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Impact of Wide Band-Gap Semiconductors on the Design in Power Electronics

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Objective – The paper is a review paper on the Wide Band-Gap semiconductors used in power semiconductor devices for power electronic applications. Beyond the presentation of the significant properties of these materials and the impact on the performance of power semiconductor devices, industrial development, reliability and design are the topics covered.

Findings & Originality – This is a review paper.

Keywords - Wide Band-Gap, Power Semiconductor Devices, Power Electronics, Reliability, Robustness, Design.

1. Introduction

Because of their superior properties with respect to silicon ones, Wide Band-Gap Semiconductors (WBG) enable a great reduction of power losses in power electronic converters even at high frequencies.

L. Lorenz had presented in 2019, his vision for power electronic applications (Table 1).

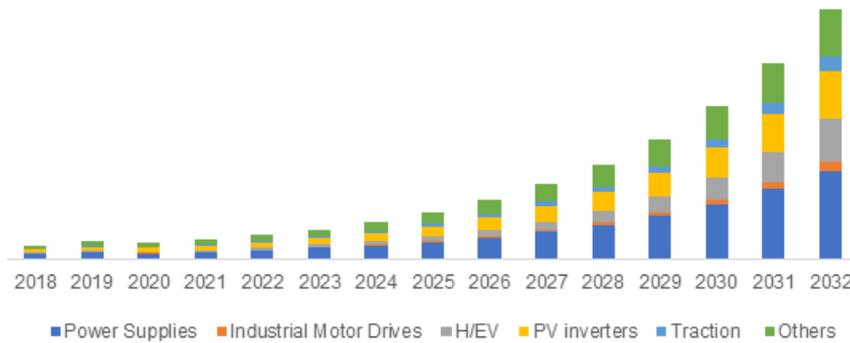
Table 1: Power Semiconductor Device Competitors vs. the targeted voltage rating (6,6,6)

600 V	1200 V	> 3 kV	> 10 kV 6,6
Si IGBT	Si IGBT	Si IGBT, Thyristor...	Bipolar SiC: IGBT, GTO ...
Si Superjunction	SiC MOSFET	SiC MOSFET	
GaN HEMT			
SiC MOSFET			

His vision shows a battle of technologies, particularly for the 600 V target, even the 1200 V target. For very high voltages, greater than 10 kV, only the SiC could reach the target, but only some research prototypes exist mainly based on bipolar devices.

However recently, N. Kaminski states that the winner is the SiC MOSFET. In 2022, the SiC power semiconductor market reaches USD 1 billion and will reach USD 15 billion by 2032 as shown in Figure 1. If the GaN market looks smaller today, analyses consider that it will take a significant market share by 2030. These promising markets allow substantial investment, particularly for SiC. Most production units are now using 6 inch wafers and 8 inches is being rolled out to some manufacturers. The increase of the wafer diameters enables drastic reduction of the manufacturing cost.

**GaN & SiC Power Semiconductor Market Size, By Application, 2018 & 2032
(USD Million)**



Source: www.gminsights.com

Figure 1: GaN & SiC Power Semiconductor Market Size 6 with a value projection of USD 15 billion in 2032.

2. WBG Semiconductor Properties

Concerning the semiconductor properties (Figure 2) 6, the main advantage of wide-band-gap semiconductors with respect to silicon, is a higher electric breakdown field. This enables to block the same voltage using thinner semiconductor layer with a higher doping concentration. That yields to a strong reduction of the on-resistance for MOSFET. So, SiC-MOSFETs are strong competitors of Si-IGBTs, while reduced size enable to reduce the switching energy. Moreover, the thermal properties of the SiC material enable high-power applications based on SiC MOSFET modules. In the same way, GaN High Electron Mobility Transistors (HEMTs) are further limited in power and voltage ratings (650 V is a standard). The lateral structure of GaN HEMT yields to very small devices but reduces the power capability of such devices.

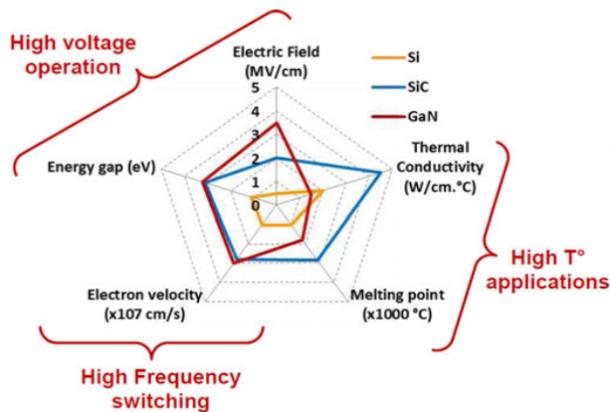


Figure 2: Comparison of material properties of Si, SiC and GaN 6

Furthermore, numerous defects in the bulk material or at the interfaces induce drain leakage currents that are not so low and limit the voltage rating of GaN HEMTs. For instance, the drain leakage current of a GaN HEMT is several decades higher than the equivalent (same current rating) SiC MOSFET.

WBG power semiconductors enable faster switching and consequently higher DC/DC frequency with a strong reduction of the size of the passive elements so a possible reduction of the weight and the size, even the cost of such converters.

However, a clear advantage of GaN HEMTs vs. SiC MOSFETs, is a faster switching, mainly because of the lateral structure of GaN HEMTs. That enable GaN HEMTs to operate at higher switching frequencies, higher than 500 kHz, such as DC/DC converters.

Concerning the maximal temperature rating, some SiC MOSFETs could operate at 200 °C and 150 °C for GaN HEMTs. This is a clear advantage for some applications as automotive ones.

3. Targeted Applications

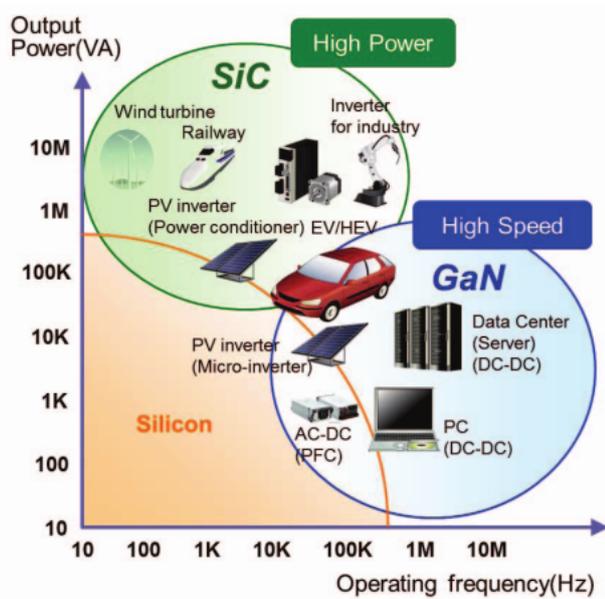


Figure 3: Potential applications of Si, GaN and SiC power semiconductor devices 6

Some studies show the potential applications of silicon, GaN and SiC power semiconductor devices as shown in Figure 3 6. The electric vehicle, EV, and hybrid electric vehicle, HEV, are clearly the applications which today drive the power electronics market, and which in particular enables the strong growth of the market for power components in SiC or even in GaN. However, the availability of such new power semiconductor devices with very good properties, enable to develop

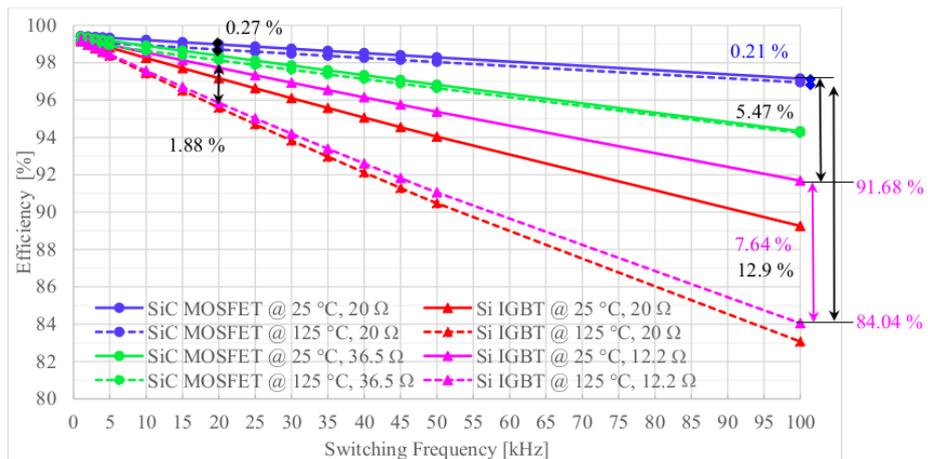


Figure 4: Comparison of a 1.2 kV SiC MOSFET and 1.2 kV Si IGBT efficiencies in a three-phase inverter

numerous other studies for new applications of such devices. For instance, photovoltaic (PV) inverters, electric traction as railway applications even other stationary applications (wind power, data centers, industry...) 6.

In comparison to Si-based component, for the same level of on conduction losses, SiC power components, enables a clear reduction of the switching losses as shown in Figure 4. That enables a possible reduction of total losses or for embedded applications a clear reduction of the size and mass of the converters.

For high-voltage devices, bipolar devices enable a reduced voltage drop as shown in Figure 5.

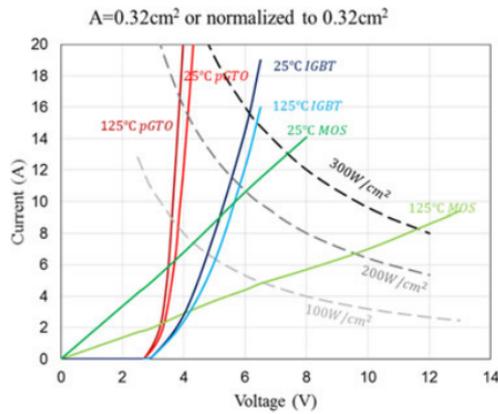


Figure 5: I-V curve comparison of 15 kV SiC P-GTO, IGBT, and MOSFET at 25 °C and 125 °C

The blocking voltage could be very high as 27 kV for a SiC IGBT 6 but the cost of fabrication of such a device is too high for commercialization. However, power SiC modules 3.3 kV, 750 A are available 6 with the target of railway applications 6.

Another advantage of bipolar power devices is the capability to be optically driven 7 which could simplify the serial association for high-voltage applications.

4. Reliability and Design

Most of the above discussed properties yield a clear advantage for SiC and GaN versus silicon power devices. However, the reliability of SiC and GaN power devices are reduced with respect to silicon ones 7, 7,7,7.

4.1 SiC MOSFETs

The key issue of the design of SiC MOSFET is the gate oxide channel, because of a reduced electron mobility in the channel. However, manufacturers have optimized the gate oxide fabrication process and reach nowadays good on-resistance. Several SiC MOSFET structures have been developed and commercialized as shown in Figure 6 (a:Planar, b:Trench) and Figure 7 (a: Asymmetric Trench, b: Double Trench). The trench structure enables to decrease the specific on-resistance but the robustness in short-circuits and avalanche modes 6 are addressed (reduced with respect to planar topology ?).

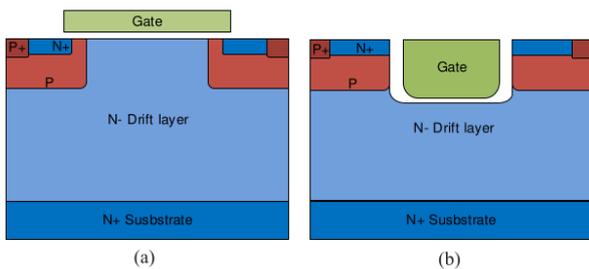


Figure 6: (a) Planar and (b) trench SiC MOSFET 6.

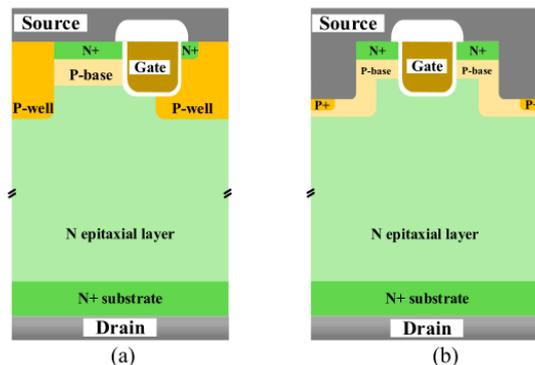


Figure 7: (a) Asymmetric trench and Double trench SiC MOSFETs

The more studied degradation phenomenon in SiC MOSFETs is the threshold voltage shift due to bias temperature instability (BTI) 7,7. Such phenomena are clearly related to trapping/de-trapping near the SiC/SiO₂ interface of the MOSFET channel. This phenomenon is very complex and numerous studies are under progress. Some studies show that it is possible to analyze, even to predict the role of the traps in the MOSFET characteristic drifts 7.

Several standards have been published on the topics as JEDEC-183 (SiC), JEDEC-184 (SiC), but an abundant literature on the subject greatly complicates the analysis or even the prediction of the characteristics of such components.

Short-circuits robustness is another reliability issue. While Si-IGBT datasheets specified the withstand for 10 μs duration, most SiC-MOSFETs have a lower withstand duration, mainly because the dies are smaller, so the power density to be dissipated during a SiC-MOSFET short-circuit is very high 7. Some TCAD (technology computer-aided design) simulations

7 have shown that high temperatures are reached during a short-circuit, which could explain most of the failure mechanisms: Interlayer dielectric (ILD) even gate oxide cracks, thermal runaway, metallization melting...

Another interesting reliability issue is the avalanche mode robustness. It had been shown that the cell structure could have a real impact on such robustness 6.

Finally, for high-voltage applications, the impact of cosmic radiation needs a classical trade-off 7, and a breakdown voltage derating depending on the irradiation dose fluence and energy ?.

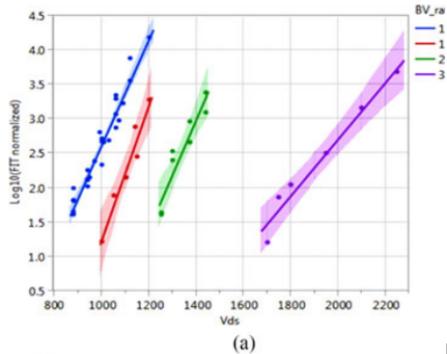


Figure 8: SiC MOSFET with total active area of 7.2 cm², room temperature, and sea level. (a) Failure caused by terrestrial cosmic radiation (manque signification legend 1,2,3) 7.

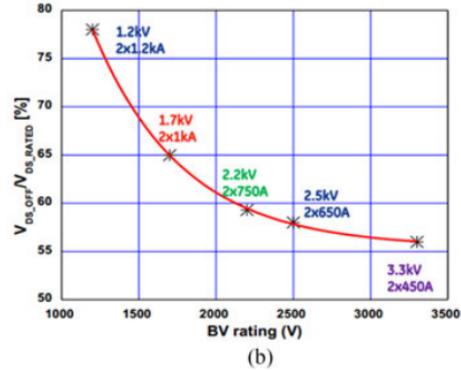


Figure 9: SiC MOSFET with total active area of 7.2 cm², room temperature, and sea level. (b) voltage derating guideline for failure rate of 100 7.

4.2 GaN HEMTs

The standard AlGaIn-GaN hetero-junction HEMT structure yields to a normally-On device 7 (Figure 11). Commercial devices are based on a cascode based on a low-voltage Si-MOSFET and a GaN-HEMT as shown in Figure 10.

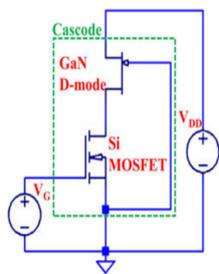


Figure 10: HEMT Cascode 7

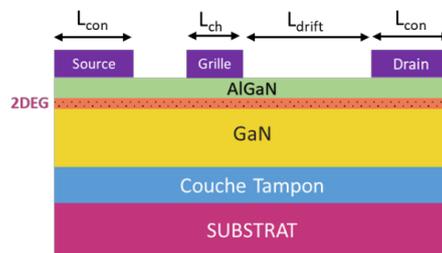


Figure 11: Normally-ON HEMT

Another way to obtain a normally-off HEMT, is to use a Gate Injection Transistor (GIT) 7, based on AlGaIn gate even a GaN gate with an ohmic contact. An alternative is the use of a Schottky based GaN gate, i.e. the P-GaN HEMT 7.

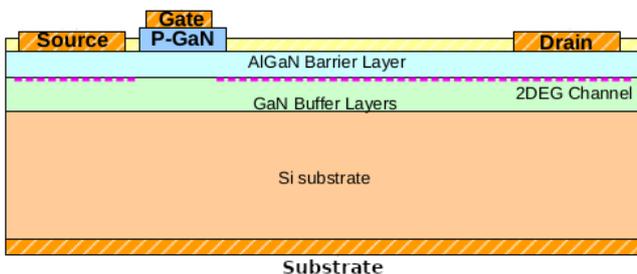


Figure 12: P-GaN HEMT Structure 7

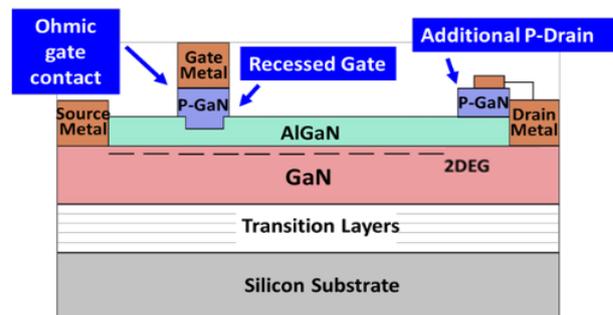


Figure 13: HD-GIT HEMT Structure 7.

Concerning GaN-HEMTs, the most studied degradation phenomena are the current collapse and the degradation of the dynamic on-resistance [7]. The analysis of the trapping/de-trapping near the 2-DEG channel, even in GaN or AlGaN layers may explain such complex phenomena. Some TCAD simulations have shown that the analysis event the prediction of the associated reliability issues could be achieved [7] and [7].

JEDEC-180 had been published for GaN devices, providing guidelines for evaluating the switching reliability of planar enhancement-mode, depletion-mode, integrated power solutions and cascode power switches.

Furthermore, other reliability issues are less studied as the short-circuit or maximal voltage robustness, even the degradation due to soft and hard switching [7].

Short-Circuits robustness had been also studied, but it had been shown that it depends strongly on the selected technology [7] even the generation of the dies. Moreover, the withstand in short-circuit had shown to be limited. Breakdown voltage robustness is very low and the critical energy is very small because of some dielectric breakdown [7].

5. Conclusion

Reliability is the main challenge for the massive implementation of WBGs power devices in application. However, most of this reliability issues could be managed at the design level [6], while the positive impact of SiC and GaN power devices on the world energy reduction is very high, particularly for electric vehicles. This is why the massive use of wide-bandgap power devices will inexorably continue its race towards the future of electrification technologies. One main research target remains the analysis and predictions of the WBG reliability issues based on models.

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