Wide Bandgap Power Switches (GaN HEMT and SiC Power MOSFETs) for Hard- and Soft-Switching Applications, a Long-Term Perspective

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Abstract

Gallium Nitride (GaN) and Silicon Carbide (SiC) are rapidly being adopted over traditional silicon MOSFETs in the realm of high-power applications. In this paper, we discuss both these emerging technologies, their use in hard- and soft-switching applications and advances in the coming years. We will discuss the properties of e-mode/d-mode GaN and SiC, explore their advantages in high-power applications, and compare efficiency and power losses in OBC applications.

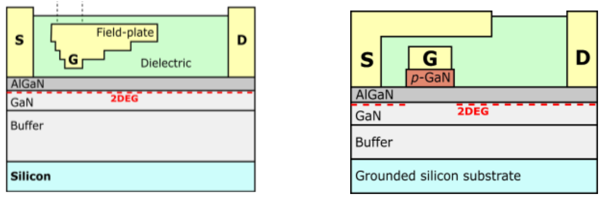
INTRODUCTION

Gallium Nitride (GaN) and Silicon Carbide (SiC) have emerged as leading technologies in the realm of high-power applications, increasing power delivery capabilities in data center, energy, and automotive industries [1-4]. These wide-bandgap semiconductors possess superior electrical properties, including higher breakdown voltages, superior thermal conductivity, and faster switching speeds compared to traditional silicon-based devices [5-6]. The unique attributes of GaN and SiC enable the design of power devices that are not only more efficient but also more compact and reliable, addressing critical demands in modern power systems. GaN HEMTs and SiC MOSFETs are fundamentally different devices and have their respective material advantages and disadvantages. As such, one is more suitable than the other in certain applications in the automotive and industrial space. Their overlap is at the 650V, often seen as a battleground area. In general, SiC MOSFETs are more suitable for high power 1200V, 100A+ type of applications, while GaN HEMTs are more suitable for low to mid-power applications especially at 650V node. Moreover, SiC MOSFETs are used in hard-switching applications while GaN HEMTs are more commonly used in soft-switching applications.

In this paper, we discuss both these technologies, their use in hard- and soft-switching applications and advances in the coming years. We will discuss the properties of e-mode/d-mode GaN and SiC, explore their advantages in high-power applications, and compare efficiency results in OBC applications.

DEVICE DIFFERENCES: GaN vs SiC MOSFET

GaN transistors benefit from a key natural phenomenon: the 2-dimensional electron gas (2DEG) channel. The 2DEG is a reservoir of charge that spontaneously forms at the interface between the GaN and a thin AIGaN layer [7-8]. Its electron density is amongst the highest naturally occurring in semiconductors. It also offers high mobility at 2000 $cm^2/V \cdot s$, which is twice that of state-of-the-art silicon (Si) and silicon carbide (SiC) devices [9]. As a result, the 2DEG enables a low resistance-versus-capacitance figure of merit (FOM). Figure 1 shows the archetypal form of a lateral GaN power transistor. The AlGaN/GaN layers are deposited on a substrate, typically silicon, and separated by an engineered buffer to achieve desired device characteristics. The channel is formed between the source and drain terminals to enable current to flow between the source and drain contacts. The gate terminal modulating the current is located between the source and drain terminals and is isolated with a dielectric stack. A field-plate structure is typically included for electric field spreading and to balance performance and reliability. The SiC MOSFET shown is a planar type. SiC MOSFET is also realized using trench technology to achieve lower Rds(on), a different approach to device design.

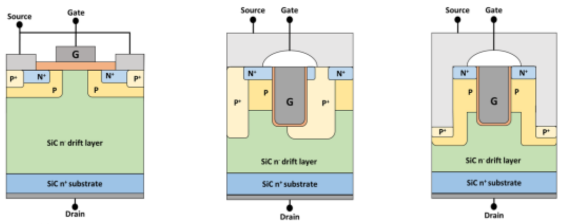


d-mode GaN HEMT e-mode GaN HEMT

Fig. 1 GaN Power Transistor d-mode HEMT and e-mode non-isolated p-GaN gate structure HEMT

Thanks to the material's properties, the 2DEG channel at the AlGaN/GaN interface forms spontaneously, with no need for external gate bias. Thus, the device as constructed is normally on and requires a negative gate bias to deplete the channel to turn off, rendering this embodiment a depletion mode (d-mode) device. But power electronic systems require normally off devices for fail-safe operations. In order to function as a normally-off device the GaN d-mode structure is connected in series normally-off Si MOSFET, typically achieving a positive threshold voltage of 2.5 V to 4.0 V depending on power level, topology, and system architecture [10].

Alternatively, a GaN e-mode approach opts to control the 2DEG channel inside the HEMT itself. As depicted in figure 1, a p-type doped GaN layer is added under the gate metal to achieve normally off operation. The p-GaN layer serves as a built-in negative battery (approximately -3.2 V) that turns the 2DEG channel off and yields a positive threshold voltage between 1-2V [11]. Both GaN devices d-mode and e-mode are lateral devices making it possible to make monolithic integration possible. Today's GaN transistors are available from 40V, 100V, 200V and 650V in production. GaN FETs at 1200V have been demonstrated, but still only in research mode.



(a) Planar gate (b) Trench gate (c) Double trench

Fig. 2. SiC MOSFET. Planar and Trench structures

Fig. 2 shows two approaches to realizing a SiC MOSFET. Planar and Trench. The planar structure includes an N+ substrate, N- drift region, P+ base region, N+ region, gate oxide layer, source, drain and gate electrodes and uses a double diffusion process. In the conduction mode, when a positive gate bias is applied, the oxide layer forms an electric field gradient, and the carrier electrons move to the junction between the P+ base region and the oxide layer to form a conductive channel. Conductive channels are formed on the right and left sides to enhance the current carrying capability, increasing the drain current. In the cut-off mode, Vg = 0V, the P+ base and N- drift region between the drain and the source can form a PN junction and the device turns off.[12]. SiC MOSFET is a vertical device with a drain node at the bottom of the device, so a purely discrete device.

Monolithic integration is not possible in SiC technology. Today, SiC MOSFETs portfolio of products are available in breakdown voltages of 650V, 1200V, 1700V, 3300V, 6500V and 10kV.

HARD AND SOFT SWITCHING APPLICATIONS

Even though GaN and SiC transistors are fundamentally different structures, at 650V and beyond, they both find applications in high power applications. The primary reason to use these WBG devices over silicon MOSFETs is to achieve higher efficiency through lower switching and conduction losses. Since these devices switch at a much higher frequency (hundreds of kHz) than for silicon MOSFETs, they also help shrink the total size of the system due to smaller magnetics and lower cooling requirements.

HARD SWITCHING VS SOFT SWITCHING

By definition, hard switching uses the device's own ability to switch leading to sharp voltage and current transitions during the on/off operation in the absence of any additional control circuit. This results in higher switching losses, higher electromagnetic interference (EMI) and lower efficiency. Applications using hard-switching entail high power motor drive inverters and switched-mode power supplies. In contrast, soft switching employs resonant circuits to smooth out these transitions in a more controlled manner to minimize overlap of voltage and current waveforms resulting in lower losses and higher efficiency. It also contributes to reducing the losses of the inductance, transformer, and diode. The method involves switching in ZVS and ZCS conditions, i.e., transistors turn on or off at or near zero voltage or current. Soft Switching techniques require more complex control circuits because the various waveforms need to be coordinated exactly. Resonant type Half-bridge converters and especially full-bridge converters are suitable for higher power designs [13]. Examples of soft-switching applications are high-frequency power converters and resonant converters.

EXAMPLE OF HARD SWITCHED TTMPFC CIRCUIT:

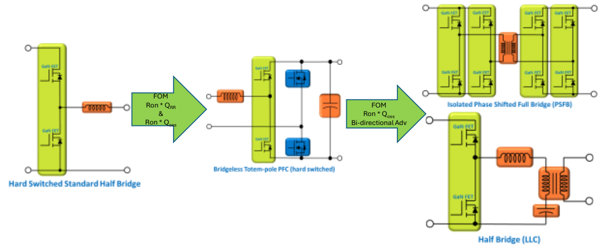


Fig. 3. GaN HB in a bridgeless PFC application

Let us consider a Totem-pole PFC (Power Factor Correction) Topology implemented in a hard-switched configuration in Continuous Conduction Mode (CCM). It uses four active switches to replace the traditional bridge rectifier and a boost PFC stage. These switches can be SiC MOSFETs or GaN cascodes or e-mode GaN HEMTs. In the CCM operation, inductor current is always flowing, and the switches experience rapid and uncontrolled hard-switching transitions leading to power losses. The totem pole bridgeless topology is an effective way to achieve the highest efficiency and reduce component count. This is done by replacing a diode full-bridge rectification stage by a half-bridge rectification and using GaN switches (or SiC MOSFETs) for the high frequency boost leg. The hard-switching loss confines the operating frequency of WBG devices to <100kHz, which results in high volt-seconds product being applied across the inductor. This limits the advantage of WBG-based totem-pole PFC design to reduce size of the magnetics. However, the savings in switching losses alone clearly outweigh this limitation.

Fig. 4 the power loss comparison of hard-switched 240V to 400V Half Bridge at 50kHz and 100kHz using Renesas SuperGaN© 650V, 35mΩ GaN cascode switches vs the same configuration using 650V, 33mΩ SiC MOSFETs. It shows that GaN cascodes achieve 15% decrease in power loss over SiC MOSFETs at 50kHz and 27% decrease at 100kHz. Fig. 5 shows the Efficiency vs Output Power curve.

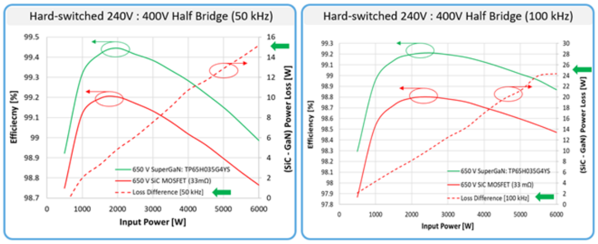


Fig. 4. Power loss comparison of hard-switched 240V to 400V HB at 50kHz and 100kHz using Renesas (Renesas) 650V, 33mΩ GaN cacodes and an equivalent 650V, 30mΩ SiC MOSFET

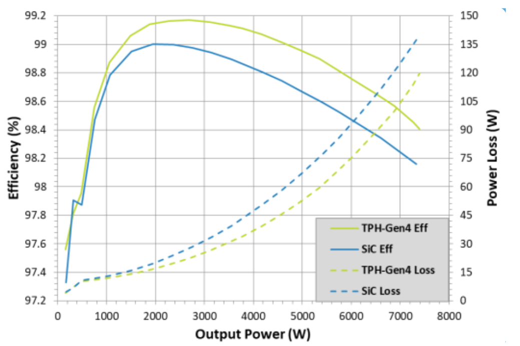
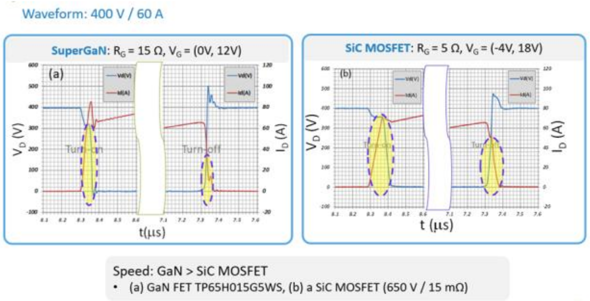


Fig. 5. Efficiency vs Output Power

Even at higher power 7kW HB synchronous boost converter stage (240V to 400V), Renesas SuperGaN© device outperforms an equivalent SiC MOSFET achieving up to 40% reduction in power loss at a moderately low frequency of 70kHz. While GaN devices are capable of switching at much higher frequencies, 70kHz is chosen for a fair comparison given the technological differences between the two devices.

The superior performance of GaN devices over SiC devices, even at higher power levels, is attributed primarily to lower turn-on and turn-off losses as shown in Fig. 6.



Speed: GaN > SiC MOSFET
- (a) GaN FET TP65H015G5WS, (b) a SiC MOSFET (650 V / 15 mΩ)

Fig. 6. Turn-on and Turn-off losses of a Renesas GaN cascode vs SiC MOSFET

LONG-TERM PERSPECTIVE

Both WBG technologies are rapidly advancing towards higher BV and lower specific resistance (Rsp) targets. While SiC dominates at 1200V today, GaN HEMTs have already been demonstrated at 1200V and can compete in certain applications in future. State-of-the art SiC MOSFETs will achieve Ron*AA < 2mΩ.cm^2 FOM soon. GaN technology is targeting Ron*AA = 2.3mΩ.cm^2, higher breakdown voltage >1200V and higher current to compete with SiC MOSFETs but it will take several years to catch up. It remains a strong contender at the 650V node. Renesas has demonstrated its 900V SuperGaN© capabilities outperform an equivalent 900V SiC MOSFET in a 6.6kW CLLLC converter [14]. It is important to note that Ron*AA is just one of the FOMs for comparison. It should be considered alongside conduction hard-switching FOM Ron*Coss, Ron*gm and conduction soft-switching FOMs for overall power loss and efficiency calculations. This is what tilts the balance towards GaN devices because of their high switching speed and extremely low Qg. Long-term prospects for both these technologies indicate co-existence at mid-power levels (650V node, < 8kW) and SiC will keep its edge for higher power applications at 1200V. At high power levels, higher thermal conductivity of SiC devices provides a major advantage over GaN devices. 1200V GaN HEMT has been demonstrated in academic research but is several years away from industrialization. Advances in monolithic GaN bidirectional switch (BDS) technology will enable new topologies which otherwise would not be possible with silicon, or SiC. We will also see the emergence of hybrid system solutions utilizing both GaN and SiC devices. For 800V bus applications in high-end EVs, multi-level converter topologies using only 650V GaN switches have also been demonstrated.

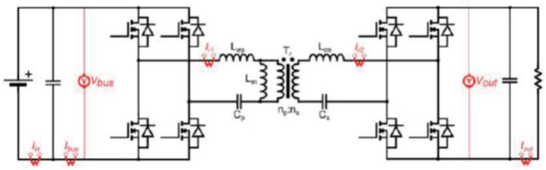


Fig. 7. CLLLC Converter topology

CONCLUSION

Similarities and differences between GaN transistors and SiC MOSFETs were presented along with their operating principles. Each of these technologies finds its place in various applications in industrial and automotive space. Comparison of power loss using GaN and SiC devices in a 7kW hard-switched 240V to 400V half-bridge boost converter shows a clear advantage in the efficiency vs output power plot. SiC devices with 1200V breakdown voltage and 100A+ current capability are dominant in the 11kW to 22kW power applications such as traction inverters in electric vehicles (EVs). GaN devices are suitable for low to mid-power soft-switched applications such as LLC resonant converters. Long-term prospects of both technologies were also discussed.

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REFERENCES

[1] M. Buffolo *et al.*, "Review and Outlook on GaN and SiC Power Devices: Industrial State-of-the-Art, Applications, and Perspectives," in *IEEE Transactions on Electron Devices*, vol. 71, no. 3, pp. 1344-1355, March 2024

[2] R. S. Pengelly, S. M. Wood, J. W. Milligan, S. T. Sheppard and W. L. Pribble, "A Review of GaN on SiC High Electron-Mobility Power Transistors and MMICs," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 6, pp. 1764-1783, June 2012

[3] G. Iannaccone, C. Sbrana, I. Morelli and S. Strangio, "Power Electronics Based on Wide-Bandgap Semiconductors: Opportunities and Challenges", *IEEE Access*, vol. 9, pp. 139446-139456, 2021

[4] M. J. Kasper, J. A. Anderson, G. Deboy, Y. Li, M. Haider and J. W. Kolar, "Next Generation GaN-based Architectures: From 240W USB-C Adapters to 11kW EV On-Board Chargers with Ultra-high Power Density and Wide Output Voltage Range", *PCIM Europe 2022; International Exhibition and Conference for Power Electronics Intelligent Motion Renewable Energy and Energy Management*, pp. 1-10, 2022

[5] Rashid, M.H. Power Electronics Handbook; Butterworth-Heinemann: Oxford, UK, 2017

[6] Chen, K.J.; Häberlen, O.; Lidow, A.; Lin Tsai, C.; Ueda, T.; Uemoto, Y.; Wu, Y. GaN-on-Si power technology: Devices and applications. IEEE Trans. Electron Devices **2017**, 64, 779–795

[7] T. R. Lenka, G. N. Dash and A. K. Panda, "2DEG transport characteristics by self-consistent subband calculations of Schrödinger and poisson equations in InAlN/GaN HEMT," *2014 IEEE 9th Nanotechnology Materials and Devices Conference (NMDC)*, Aci Castello, Italy, 2014, pp. 124-127.

[8] T. N. Upal, M. A. Uddin, M. Hossain, F. Jahan and Z. H. Mahmood, "Study of charge density at InxGa1-xN/GaN heterostructure interface," *2009 2nd International Workshop on Electron Devices and Semiconductor Technology*, Mumbai, India, 2009, pp. 1-4.

[9] W. Adepoju, I. Bhattacharya, M. E. Bima and T. Banik, "Modeling and Performance Comparison of GaN HEMT and SiC MOSFET for Onboard Charging Application," *2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring)*, Helsinki, Finland, 2021, pp. 1-7.

[10] T. Zhu, F. Zhuo, F. Wang, H. Wang, X. He and S. Shi, "A Novel Cascode GaN Switch Integrating Paralleled GaN DHEMTs for High-Power Applications," *2018 1st Workshop on Wide Bandgap Power Devices and Applications in Asia (WiPDA Asia)*, Xi'an, China, 2018, pp. 332-336.

[11] I. Hwang *et al.*, "Source-Connected p-GaN Gate HEMTs for Increased Threshold Voltage," in *IEEE Electron Device Letters*, vol. 34, no. 5, pp. 605-607, May 2013.

[12] J. Yao, J. Yao “Working principle and characteristic analysis of SiC MOSFET, J. Phys.: Conf. Ser. 2435 012022, 2023.

[13] “Power Supply Design Notes: Hard switching and Soft switching to reduce losses” Power Electronics News Dec. 13, 2020

[14] “A comparison among wide bandgap devices using a CLLLC bi-directional resonant converter”, A. Llop et al., PCIM Europe 2022