Wide Bandgap (WBG) Power Devices and Their Impacts On Power Delivery Systems

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***Abstract*—**Wide bandgap (WBG) power semiconductor devices have the capability to reach higher voltage, higher frequency and higher temperature compared with silicon based power devices. These capabilities have the potentials to revolutionize the way we deliver and manage power in the future. This paper reviews the WBG progress and their potential transformative impacts on low voltage, medium voltage and high voltage power delivery systems.

I. INTRODUCTION

Wide bandgap (WBG) power devices are developed on materials that have higher bandgap (Eg) than silicon material. The direct benefit is a significantly increased breakdown critical electric field (Ec) which can be utilized to design power devices with much lower conduction resistance Ron for a given chip area. Because of this, device structures based on unipolar majority carrier operation (MOSFET, JFET etc) are sufficient to cover a large array of power electronics applications. The needs for bipolar devices are much less than the silicon case where silicon power MOSFET could not be scaled economically to higher than 600V, even if the super junction (SJ) MOSFET concept is used. Therefore in high voltage applications where the current state-of-the-art device is silicon bipolar IGBT, WBG devices also have an upper hand in switching speed due to the unipolar current conduction mechanism. The switching speed is fundamentally determined by the parasitic capacitance in the device. Higher switching speed can be utilized to increase the system switching frequency without a major penalty in conversion efficiency. This can in higher power density. The large bandgap also results in much lower leakage currents in the WBG power devices hence the intrinsic capability of these device to operate at higher junction temperature Tj is excellent. On the other hand, silicon power devices have high leakage currents, which limits the device's ability to operate at higher than 125°C. However, due to the unipolar current conduction mechanism, the WBG power devices conduction resistance Ron increases with the temperature which will limit the extent of the high Tj benefit. Increasing Tj also have an impact on other supporting components in a WBG converter such as the gate driver circuit and packaging materials. Therefore the high temperature roadmap for WBG power device is not currently a high priority.

II. UNIPOLAR DEVICE FIGURE OF MERIT (FOM)

There are many materials that can be classified as WBG materials. However, currently only SiC and GaN power devices are commercially introduced after several decades of development. Devices based on these two materials will be discussed in this paper.

Numerous unipolar device FOMs have been proposed to provide a simple way of judging WBG material advantages. Several FOMs are developed in [1] that took into account the device capacitance and the switching losses. Due to the increased Ec in WBG materials, the specific capacitance is actually higher in WBG devices than silicon. However, due to a large reduction in specific Ron, the chip size for a given Ron is actually much smaller (die size reduction), resulting in lower overall capacitance hence much lower switching losses. Table I [1] summarizes the results for a few important materials, all normalized to Si material. The HMFOM represents the loss reduction potential in a hard switched converter while the HCAFOM represents the chip size reduction potential. It shows that SiC and GaN based power devices could potentially reduce the losses by 8 times while reducing the chip size by about 64 times. However, smaller die size will increase the thermal resistance as shown by the HTFOM.

TABLE I
COMPARISON OF VARIOUS SEMICONDUCTOR MATERIALS BASED ON THE NEW HMFOM, HCAFOM, AND HTFOM (NORMALIZED AGAINST SILICON)

Semiconductor Materials	Electron mobility μ (cm^2/V-s)	Relative dielectric constant ε	Critical field E_c (kV/cm)	Thermal conductivity σ_{th} (W/m-K)	$HMFOM = E_C\sqrt{\mu}$	$HCAFOM = \varepsilon E_C^2\sqrt{\mu}$	$HTFOM = \frac{\sigma_{th}}{\varepsilon E_C}$
GaAs	8,500	13.1	400	55	3.3	4.9	0.3
GaN	900	9	3,000	110	8.0	61.7	0.1
Ge	3,900	16	100	58	0.6	0.3	1.0
Si	1,400	11.7	300	130	1	1.0	1.0
GaP	250	11.1	1,000	110	1.4	4.5	0.3
SiC(6H,α)	330	9.66	2,400	700	3.9	25.7	0.8
SiC(4H,α)	700	9.7	3,180	700	7.5	65.9	0.6
Diamond	2200	5.7	5,700	2000	23.8	220.5	1.7

III. WBG IMPACT ON LOW VOLTAGE POWER DELIVERY SYSTEM

One of the most important impacts of power electronics in the last 50 years has been the elimination of the 60 Hz transformers and AC power, and the transformation of the low voltage power delivery systems for computers and consumer electronic products. Central to this achievement is the use of high switching frequency silicon power devices and pulse width modulation (PWM) techniques in delivering regulated DC powers to low voltage loads such as tablets/cell phones, LEDs and computers, while at the same time providing power factor correction (PFC). Figure 1 shows a typical low voltage power delivery architecture commonly found in today's computer supplies and data centers. The incoming universal AC grid power is converted by an unfolding (UF) bridge and a power factor correction (PFC) circuit to 400Vdc before it is stepped down to a lower voltage DC intermediate bus, such as 12V, and

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then it powers the digital loads at voltages as low as 1 V by a point-of-load (POL) converter. Silicon (Si) power MOSFETs from 20V to 700V are almost exclusively used in these converters with switching frequencies from tens of kilohertz on the PFC side to one megahertz on the POL side. In these applications, the major driving forces for innovations are higher power conversion efficiency and higher power density. A typical power conversion efficiency including all of these conversion stages is about 80% as shown in Fig.1 [3]. So 20% is lost in generated heat. Based on 2012 worldwide IT equipment's total power consumption, it is estimated that a worldwide 1% efficiency improvement in IT power supply alone would result in an annual electricity saving of more than 30 TWH! So there is an extremely high expectation for WBG power devices to improve the power conversion efficiency and the power density. The Google Little Box [2] is a great example of utilizing WBG (in this case GaN HFET) in achieving ultra-high power density and high efficiency.

SiC MOSFETs are typically constructed as a vertical power devices, similar to Si IGBT and MOSFET. For power supply applications, breakdown voltages lower than 700V are needed and their performance will have to compete with Si SJ MOSFETs. At this voltage level, the low channel mobility in SiC MOSFET inversion channel (most reported channel mobility are below 100cm^2/V-s and this remains one of the most important research areas for SiC) and the large substrate resistance prevent the SiC MOSFETs to reach their full potentials as suggested in Table I. For this reason GaN heterojunction FET (HFET) is a much more superior device in these voltage ranges and commercial GaN HFETs from 30V to 600V are currently available. GaN HFET are developed on GaN-on-Si wafer and the current conduction path is lateral through the 2DEG formed by the GaN/AlGaN heterojunction. Although the lateral structure is considered a disadvantage when compared to a vertical power device due to the ineffective utilization of the chip area, GaN HFET's Ron reduction is still very impressive, thanks to the high channel mobility (~2000cm^2/V-s) and the elimination of the substrate conduction resistance Rsub. Furthermore, the lateral HFET has even lower junction capacitance (Ciss, Coss) due to the lateral geometry, making them even more attractive in high frequency applications such as the ones shown in Fig.1.

Table II compares device performance currently achieved by 600V SiC MOSFET and GaN HFET and the best silicon SJ MOSFET. The important performance-dependent parameters are the three normalized FOMs which can be obtained from the datasheet. Smaller FOM1 represents the advantage of fast gate driving capability. Both SiC and GaN are superior to SJ MOSFET but the advantage of the GaN over SiC is also clear. FOM2 represents the reduction in switching losses in hard switched or soft switched converters. Again, both SiC and GaN are superior to Si while there is still a clear advantage for GaN. Finally, FOM3 represents the reverse recovery loss reduction in SiC and GaN. Dramatic improvement is possible in both SiC and GaN when operate as a rectifier in the third quadrant. As a matter of fact, the reverse recovery current and the associate loss, which has been a major headache for silicon power devices, can be considered eliminated in future WBG converters.

Table II Comparison of 600V Si SJ MOSFET, SiC MOSFET and GaN HFET

600V FETs	Ron (mohm)	Ciss (nF)	FOM 1 (Ron*Ciss)	Coss (nF)@400V	FOM2 (Ron*Coss)	Qrr(uC)	FOM3 (Ron*Qrr)
Si SJ	37	7.24	267	0.38	14	36	1332
SiC MOS	120	1.2	144	0.09	10.8	0.053	6.3
GaN HFET	25	.52	13	0.13	3.25	0.113	2.8

Si SJ: Infineon IPW65R037C6. SiC MOSFET: Rohm SCT2120AF GaN HFET: GaNSystem GS66516T

The low Ron and fast switching capability of the GaN HFET could have a dramatic impact on future low voltage power delivery system. A simplification of the power delivery architecture can result in substantial energy savings. A possible roadmap is shown in Fig.2. At the front end, the Totem-Pole bridgeless PFC (Fig.3a) [4] could be utilized to replace the currently used CCM PFC, achieving 99% efficiency while reducing the footprint due to >1 MHz operating frequency. Figure 2b shows a design conducted by the author's team of a 3 kW GaN prototype using two phase Totem-pole PFC topology. The GaN devices operate with a variable frequency under ZVS condition, and >99% efficiency have been measured. In the Fig.2 power delivery system, a single isolated DC/DC stage based on soft switched converter topologies such as LLC [5] or phase-shift half bridge [6] topology can be used to replace the current two-stage solution by eliminating the intermediate bus. The high switching frequency can be used to provide fast regulation of the 48V (or 12V) bus. 98.3% efficiency was achieved in [5] while more than 98% efficiency was also achieved by the phase-shift half bridge as reported in [6]. The circuit topology and results from [6] are shown in Fig. 4. Finally, the 48V-to-1V POL converter can be achieved by using 80V-100V GaN HFET in a non-isolated Buck converter [7]. Thanks to the extremely fast switching speed, the ultra-low duty ratio and small dead time can be achieved. 92% peak efficiency has been reported in [7]. With these innovations, the efficiency of the low voltage power delivery system (universal AC input to POL) could be improved by 9%. This will be a substantial achievement if realized on a large scale.

IV. WBG IMPACT ON MEDIUM VOLTAGE POWER DELIVERY SYSTEM

The above discussion indicates that GaN HFETs could play a major role in low voltage power delivery system with substantial gain in energy efficiency. This is primarily due to GaN HFET's superior capability to switch at higher frequencies. However, the universal AC input is supplied by a medium voltage 60Hz distribution transformer. The distribution transformers, in existence for more than a century, have an efficiency from 97% at full load to 99% at partial loads [8]. Therefore, there are more losses in the power delivery system if the medium voltage grid is taking into account. The overall efficiency is lower than 86% from the medium voltage AC grid to the POL even if GaN is used.

One disruptive solution enabled by WBG devices is to replace the 60Hz medium voltage distribution transformer by a solid state transformer (SST) [9]. SST is a medium voltage AC-AC converter that also has a low voltage (380V) DC output. Future low voltage power delivery system in data centers, for example, can be directly powered by a SST from its 380Vdc terminal/bus, hence eliminating the low voltage PFC stage in Fig.2. Such a medium voltage to low voltage power delivery system, shown in Fig.5, can achieve 88% to 90% medium voltage AC to POL conversion efficiency, and only three conversion stages are needed. Considering data centers and IT equipment consume a substantial amount of energy (about 15% of the worldwide electricity) and is rapidly growing, such a power delivery architecture is critical for a sustainable society.

To develop a SST, there is a need to develop medium voltage power electronics technology. Core to this development is the development of medium voltage high frequency power switches. For many decades, medium voltage power switches are silicon bipolar devices (SCR, GTO, IGBT) and they are generally very slow. Therefore they are not suitable to implement medium voltage converters with high step down ratio needed in a SST. The development of WBG devices, in this case vertical high voltage SiC power devices, fundamentally changed this situation. The breakdown voltage of SiC power devices have exceeded 27 kV [10] and the switching frequency of more than 40 kHz has been demonstrated in a 15kV SiC MOSFET [11-12]. To summarize, the key enabling capability of high voltage SiC power devices for SST application is the 40X to 100X increase in the V*f capability, as shown in Fig.6. With this dramatically improved V*f capability, reliable medium voltage SSTs can be developed using simple topologies such as the one shown Fig. 7, even though the input voltage can be as high as 7200Vac[13]. AC to AC or AC to DC conversion efficiency higher than 98% have been demonstrated in the SiC based medium voltage SSTs.

Of course the replacement of the millions of distribution transformers by smart SST will have a far reaching impact on the whole electric power grid, particularly the distribution grid. It will transform the grid to an actively controlled, smart and resilient grid because the SST provides advanced power management capabilities such as reactive power injection, harmonic mitigation, low voltage ride through. The DC and AC interfaces are ideal for integrating distributed renewable generations and energy storage devices [14].

V. WBG IMPACT ON HIGH VOLATEG POWER DELIVERY SYSTEM

Currently there is no known commercial applications of WBG power devices in high voltage transmission applications. High voltage applications such as in FACTS and HVDC are currently served by high power silicon thyristors (SCR, <8kV) and Si IGBTs (<6.5 kV). However, due to WBG such as SiC's extreme capability to support high blocking voltages, transmission applications such as HVDC could benefit tremendously from ultra-high voltage SiC technology. SiC IGBT, GTO and ETO [15] with a blocking voltage from 22 to 27 kV have been developed and demonstrated. In HVDC applications, the switching frequency does not need to be high but the current and voltage ratings are generally very high. In this case, SiC based GTO/ETO thyristor technology offers the best capability when designed for 15 kV or higher. Theoretical analysis indicates that SiC GTO/ETO designed with blocking voltages up to 50 kV will still have a substantial current conducting capability. These devices are ideal for HVDC applications where the DC bus voltage can be as high as 1 million volts!. The number of cells needed in a HVDC converter can be substantially reduced. If successfully developed and implemented, SiC HVDC converter could be drastically simpler and more efficient. Ultra high voltage SiC power switch also have very large RBSOA hence they can interrupt large amount of currents. Therefore they are also ideal device for ultra-fast solid state or hybrid circuit breakers which is a key technology for much faster protections in DC and meshed AC grids.

VI. WBG IMPACT ON RENEWABLE EBERGY SYSTEMS AND CLEAN TRANSPORTATION

WBG devices are also expected to have a major impact in other major industry and energy applications such as PV and wind power converters, electric vehicle traction inverters and industry motor drives. Devices needed are in the range of 1200V to 6500V and the current ratings needed are high. Currently a number of SiC power modules are being developed for these markets. The salient features that make SiC power modules attractive are the high reliability including avalanche capability, and the linear resistive conduction characteristic verses the non-linear I-V characteristic of the IGBT. The resistive behavior has the advantage of lower losses in light load conditions. The same linear conduction capability also exists in the third quadrant, allowing the SiC inverters to be implemented without additional freewheeling diodes. By parallel sufficient MOSFETs, very low Rdson devices can be obtained which can easily outperform the IGBT in terms of efficiency even if the switching frequency is low. Recently a 900V/1.25 mOhm module was announced by Wolfspeed [16]. In an EV traction inverter study [17], the 900V SiC MOSFET based EV's EPA metro-highway cycle fuel economy could potentially improve up to 5% by replacing silicon with SiC.

REFERENCES

[1] Alex Q. Huang, "New Unipolar Switching Power Device Figures of Merit", IEEE Electron Device Letter. Vol. 25, No.5, pp.298

[2] https://www.littleboxchallenge.com/

[3] Y. Hayashi, H. Iso, D. Hara and A. Matsumoto, "Current-fed GaN front-end converter for ISOP-IPOS converter-based high power density dc distribution system," *EPE'15 ECCE-Europe), 2015 17th European Conference on*, Geneva, 2015, pp. 1-10.

[4] Z. Liu, X. Huang, M. Mu, Y. Yang, F. C. Lee and Q. Li, "Design and evaluation of GaN-based dual-phase interleaved MHz critical mode PFC converter," *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Pittsburgh, PA, 2014, pp. 611-616.

[5] M. Domb,"High power density, high efficiency 380v to 52v LLC converter utilizing E-Mode GaN switches," *PCIM Europe 2016;* pp.1-7.

[6] F. Xue, R. Yu, W. Yu and A. Q. Huang, "Distributed energy storage device based on a novel bidirectional Dc-Dc converter with 650V GaN transistors," *2015 IEEE PEDG*, Aachen, 2015, pp. 1-6.

[7] Texas Instrument, SNVU520–May 2016 "Using the LMG5200POLEVM-10 48V to Point of Load EVM"

[8] Fuji Electric Review, Vol. 61, No.4, 2015. Pp. 285

[9] Huang, A. Q., et. Al, "The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet." Proceedings of the IEEE 99, no.1: 133–148.

[10] E.Van Brunt et. al, "27 kV, 20 A 4H-SiC n-IGBTs", Mat. Sci. Forum, Vol. 821-823, pp. 847-850, 2015

[11] Li Wang et.al. "A medium voltage bidirectional DC-DC converter combining resonant and dual active bridge converters," 2015 APEC, vol., no., pp.1104,1111, 15-19 March 2015

[12] Wang, Gangyao et. al, "Static and dynamic performance characterization and comparison of 15 kV SiC MOSFET and 15 kV SiC n-IGBTs," ISPSD 2015, vol., no., pp.229,232, 10-14 May 2015

[13] Wang, Fei; Wang, Gangyao; Huang, Alex; Yu, Wensong; Ni, Xijun, "Design and operation of A 3.6kV high performance solid state transformer based on 13kV SiC MOSFET and JBS diode," Energy Conversion Congress and Exposition (ECCE), 2014 IEEE , vol., no., pp.4553,4560, 14-18 Sept. 2014

[14] She, X.; Yu, X.; Wang, F.; Huang, A.Q., "Design and Demonstration of a 3.6KV-120V/10KVA Solid State Transformer for Smart Grid Application," Power Electronics, IEEE Transactions on , vol.29, no.8, pp.3982

[15] X. Song et al., "22 kV SiC Emitter turn-off (ETO) thyristor and its dynamic performance including SOA," Power Semiconductor Devices & IC's (ISPSD), 2015 IEEE 27th International Symposium on, Hong Kong, 2015, pp. 277-280.

[16] J. Casady *et al.*, "Ultra-low (1.25mΩ) On-Resistance 900V SiC 62mm Half- Bridge Power Modules Using New 10mΩ SiC MOSFETs," *PCIM Europe 2016*, pp. 1-8.

[17] M. Su, C. Chen, S. Sharma and J. Kikuchi, "Performance and cost considerations for SiC-based HEV traction inverter systems," WiPDA, 2015 IEEE 3rd Workshop on, Blacksburg, VA, 2015, pp. 347-350.

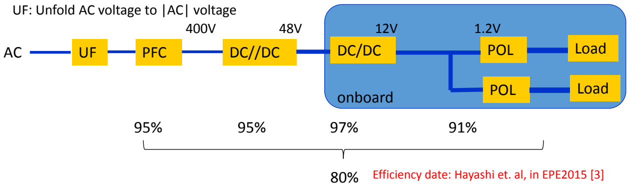

Fig. 1. Today's low voltage power delivery system using Si

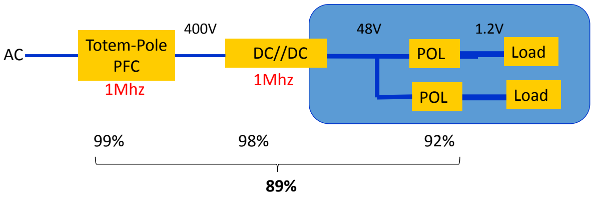

Fig. 2. Simplified power deliver system with GaN.

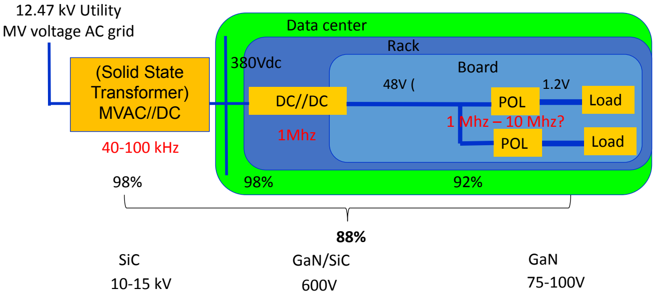

Fig. 5. Medium voltage to POL power delivery system for future data centers

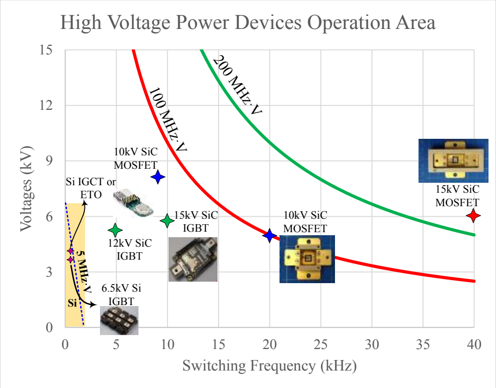

Fig. 6. Voltage*frequency capability of SiC high voltage power switches.

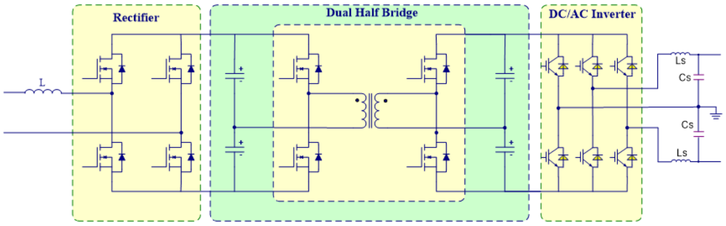

Fig. 7. Solid State Transformer (7.2 kVac to 240Vac power conversion). 15 kV SiC MOSFETs are used on the high voltage side

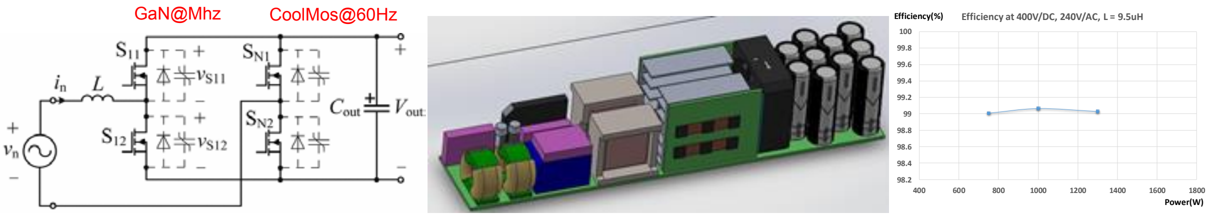

Fig. 3. a) Totem-pole bridgeless PFC circuit where 600V GaN switches at high frequency with ZVS condition. b) A prototype design of a 2.3 kW GaN Totem-Pole PFC. c) Measured efficiency exceeds 99%

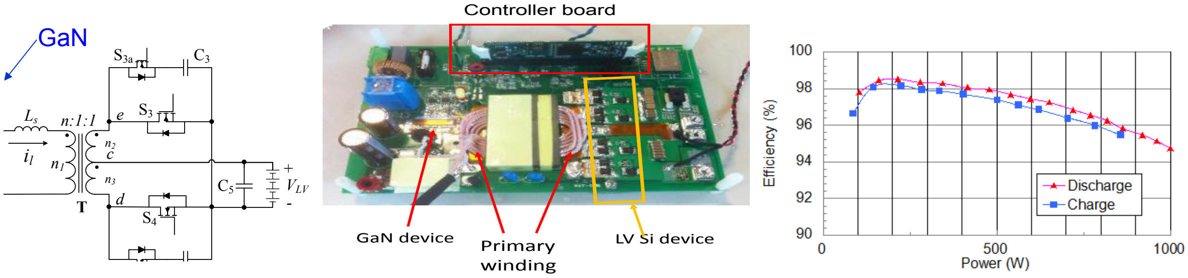

Fig. 4. a) Phase shift half bridge push-pull topology with active clamp. b) A 1 kW prototype. c) Measured efficiency exceeds 98%