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SiC Devices: Current Trends and Applications in Power Electronics Circuits

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ABSTRACT

The advent of Wide Band Gap (WBG) materials, notably Silicon Carbide (SiC) and Gallium Nitride (GaN), has precipitated a paradigm shift in the realm of power semiconductor devices. These advanced materials have enabled the development of compact, high-density power converters that can operate at elevated power levels, temperatures, and frequencies, while maintaining exceptional efficiency, thereby surpassing the limitations of conventional Silicon (Si)-based power devices. This paper primarily focuses on SiC-based devices, with particular emphasis on SiC MOSFETs and SiC IGBTs.The inaugural section provides a concise introduction to SiC devices, highlighting their superior attributes vis-à-vis Si devices. The subsequent section delineates the prospective applications of SiC devices in power electronics circuits, while also addressing the attendant challenges. The third section presents an overview of the current trends and ongoing research in SiC-based power electronics circuits, encompassing a broad spectrum of applications.

Keywords—SiC, 4H-SiC, WBG, Energy gap, Efficiency, EV, MV, HV, HVDC, on-state resistance, HVDC, SiC Converters

I. INTRODUCTION

Silicon Carbide (SiC) is a Wide Band Gap (WBG) compound semiconductor made up of equal parts of Silicon (Si) and Carbon (C) via covalent bonding which leads to a highly ordered configuration [1]. It can be doped n-type by nitrogen or phosphorous and p-type by beryllium, boron, aluminum, or gallium similarly like Silicon. Semiconductor power devices (Diode, BJT, MOSFET, IGBT, SCR, GTO, etc.) can be manufactured using these n-type and p-type materials. SiC is extremely hard (9.5 on Mohs scale) and exists in a variety of polymorphic crystalline structures (polytypes) e.g. 3C-SiC, 6H-SiC, 4H-SiC; out of which 4H-SiC is generally the most preferred one in the manufacturing of practical power devices [2]. SiC power devices are emerging as high power high efficiency alternatives to Silicon (Si) based devices which is by far the most mature and commonly used semiconductor material for power devices.

Si based power devices are at the peak of their research and reaching their physical and material limits. The main drawback of SiC devices is its high cost which comes due to the fact that it has higher material cost, higher manufacturing cost, poor wafer yield and packaging cost as compared to Si devices [3]. SiC based device technology is an emerging field with lots of new devices being developed every day and lot of research going on to improve their reliability and stability in different applications and at various operating conditions.

Si based power devices currently are cascaded (high voltage) or paralleled (high current) for high power applications. Operating temperatures and frequencies of Si devices are also limited, thus limiting the overall performance of Si devices as compared to SiC devices. SiC devices can operate at high voltages (upto around 3kV) and high current density (2 to 3 times of Si) at high frequencies and temperatures (currently, the guaranteed operating temperatures for SiC devices are upto 150°C to 175°C, operation upto 400°C is possible, and maximum junction temperature is 600°C) with low on-state resistance (SiC devices have much lower drift-layer resistance than Si devices) as compared to Si devices. The main reason behind the high performance of SiC devices is the wide band gap (energy gap) of 2.36eV (3C-SiC) to 3.26eV (4H-SiC) in SiC as compared to 1.11 V in Si. Other reasons being the high dielectric breakdown field strength, approximately 10 times higher than that of Si. SiC devices can be made to have very high breakdown voltage (600V and up) with a very low on-state resistance compared to silicon devices. Theoretically, SiC can reduce the resistance per unit area of the drift layer to around 1/300 times as compared to Si for the same breakdown voltage.

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Other derived advantages include smaller size, smaller passives, smaller and less expensive cooling system.

Figure 1: Performance improvement of SiC over Si devices [4]

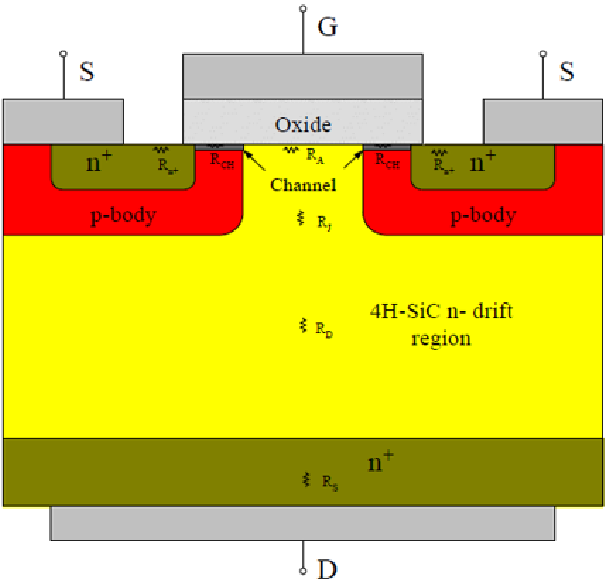

Figure 2: Structure of SiC DI-MOSFET [5]

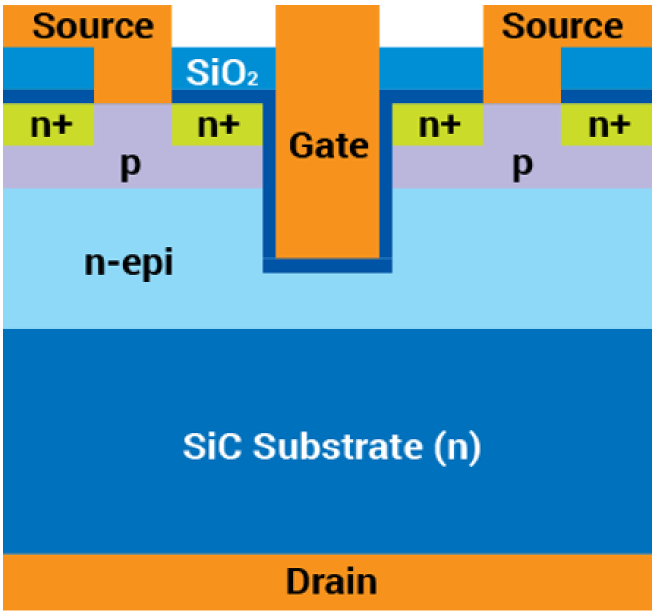

Figure 3: Basic structure of a trench gate SiC MOSFET [6]

shows the significant increase in performance improvement of SiC devices over Si devices at higher operating voltages [4]. Figure 2 shows the basic structure of a SiC Double Implanted Metal Oxide Semiconductor Field Effect Transistor (DI-MOSFET). Figure 3: Basic structure of a trench gate SiC MOSFET [6] shows the basic structure of a trench gate MOSFET.

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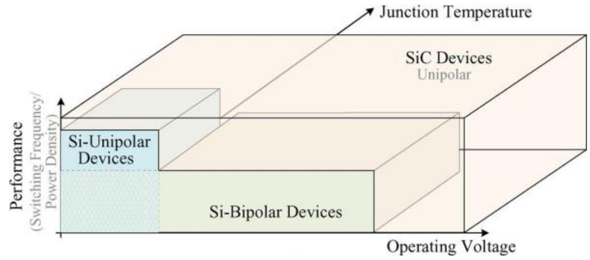

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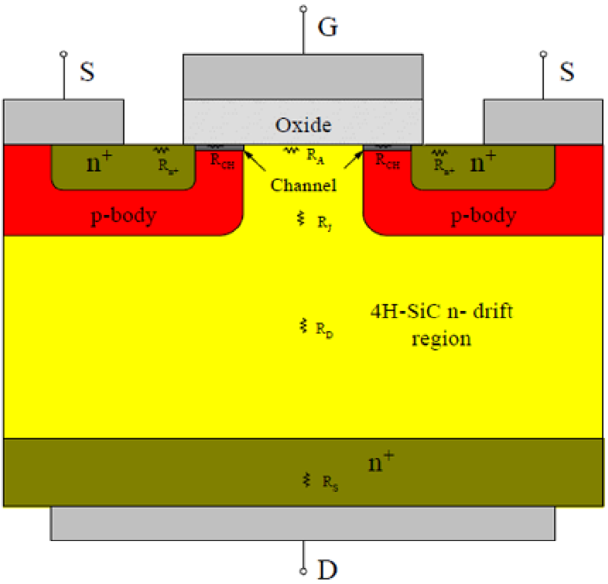

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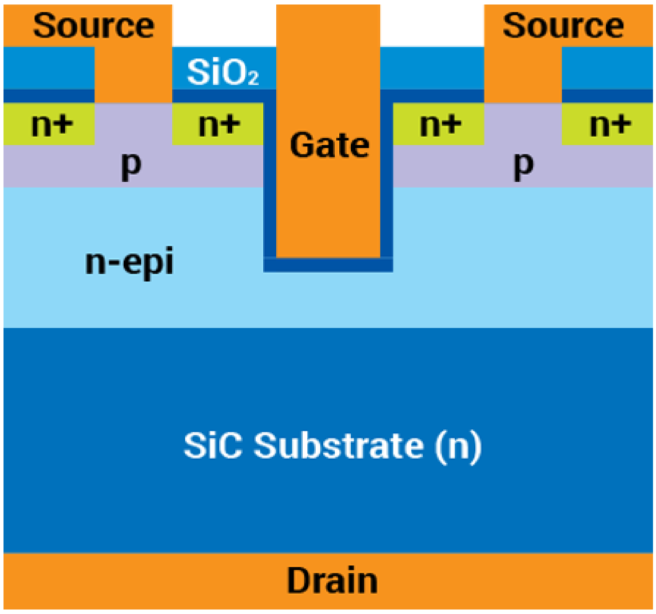

Figure 3: Basic structure of a trench gate SiC MOSFET [6]

The comparison of band gaps of some materials is given in Table 1. The wider bandgap, higher thermal conductivity, and larger critical electric field allow SiC devices to operate at higher temperatures, higher current density, and higher blocking voltages than Si power devices.

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Table 1: Band gap in eV of different materials

Material	Symbol	Band gap (eV)
Silicon	Si	1.1
Germanium	Ge	0.67
Gallium Nitride	GaN	3.4
Gallium Phosphide	GaP	2.26
Gallium Arsenide	GaAs	1.43
Silicon Carbide	4H-SiC	3.26
Silicon Carbide	6H-SiC	3.05
Silicon Carbide	3C-SiC	2.36

Figure 3 shows the comparison of bandgap, breakdown field, thermal conductivity, and saturation drift velocity for Si, SiC and GaAs. It can be seen that the bandgap of SiC is much higher than other materials enabling the devices to operate at high temperatures. Thermal conductivity of SiC is also higher than Si and GaAs which enables high current density devices to be fabricated. High breakdown field of SiC (almost 10 times that of Si) enables it to have higher blocking voltage as compared to other materials. A 6 W efficient Phi-2 boost converter is presented by Kassakian in [7] which operates at a very high frequency of 75 MHz with an efficiency of 73%.

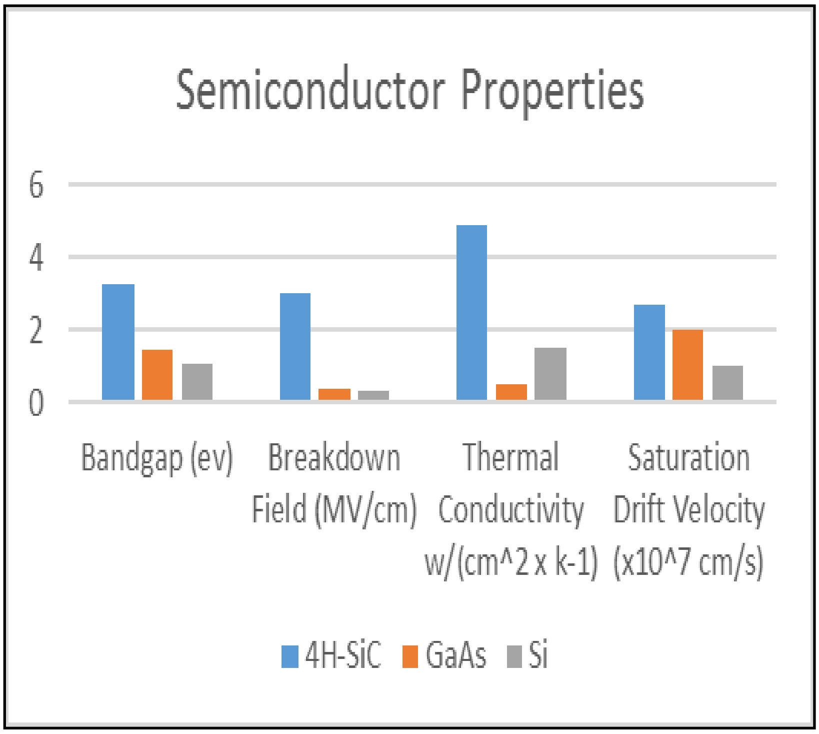

Figure 3: Graph showing superiority of SiC over Si and GaAs

This paper focuses on the current trends of use of SiC devices in various power electronics circuits and applications, highlights the major advantages, limitations and introduces some of the challenges faced while replacing conventional Si devices with SiC or other WBG devices in various applications, and future scope for these devices. It also enlists some of the commercially available SiC discrete devices and power modules.

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II. APPLICATIONS IN POWER ELECRONICS CIRCUITS

As discussed, WBG and SiC technology is continuously evolving day by day with new research going on in the physics of the devices. Devices are becoming better by having increased blocking voltage, higher power ratings, high temperature ratings, lower on-state resistance and many other features. Based on their features, these devices are implemented and tested in various power eletronics coverters. Based on the current ratings of WBG devices, they are being tested mostly in medium voltage (MV) converters for various applications, although there is a wide scope of applications as further improved devices are being made. This section gives an bird's eye overview on applications of SiC devices and other WBG devices in various power electronics converters.

The broad areas of applications of power electronics in which SiC devices can be applied are Medium Voltage (MV) and Low Voltage (LV) applications, Electric Vehicles (EV) and Automotive Industry, Photo-Voltaic (PV) applications and high power (utility) applications. These main application areas are discussed in this section. Table 2 enlists various applications of power electronics circuits and the desired features of corresponding semiconductor switches for the application. It also lists the redundant features of the devices for the applications. Then the use of SiC devices in various applications are discussed showing the advantages and limitations of using SiC devices in these applications.

Table 2: Importance of device features in various PE applications

Application	Most Important	Less Important	Other
MV & LV applications	Efficiency (low on-state resistance R_{ON}), Size	High temperature, High frequency, High blocking voltage	Cost
Electric Vehicles (EV) & Automotive Industry	Efficiency, Size, Reliability, High temperature, Power density	High blocking voltage, High frequency	Cost and Weight
PV applications	Efficiency, High temperature, High frequency	High blocking voltage	Payback cost
Utility (HVDC, Wind Turbines)	High blocking voltage, High current, Efficiency	High frequency, Power density	Reliability

A. Medium Voltage Applications

The main requirements of MV converters are high power density, higher efficiency, reliability and small size. Other parameters like high temperature and high frequency operation are also useful in such applications.

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Results in [4] shows that better conductivity of SiC devices results in smaller chip area compared to Si devices. Figure 4 shows the mean efficiency and power density of a 12kW 450 V DC-DC converter operating at 100kHz and >95% efficiency with Si and SiC devices when used in a DC-DC converter in kW/dm3.

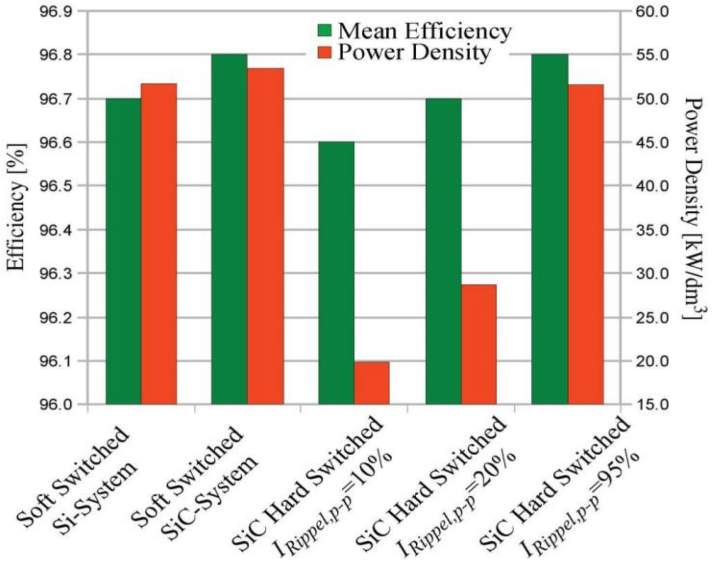

Figure 4: Mean efficiency and power density of 12kW DC-DC converter when operated using Si & SiC at 100kHz and >95% efficiency [4]

Experimental analysis in [8] show that 15kV 20A SiC IGBT can be switched at 6.2 kHz with liquid cooling with 10kV operating voltage and 5A current due to high dv/dt and di/dt generated noises known as Electro-Magnetic Interference (EMI). The comparative loss analysis of SiC MOSFET and SiC IGBT was done at 5kHz for a 100 kW and 1MW converter and it was shown that 15kV SiC IGBT is the best suited for high power and high temperature applications as compared to Si device. SiC IGBT gave an efficiency of 99.35 and 99.27 while SiC MOSFET gave an efficiency of 99.07 and 98.99 for 100kW and 1MW converters respectively. It also refers to the increasing on-state resistance of SiC devices with increase in operating temperatures. The issue of EMI at higher frequencies along with phase-leg shoot-through (crosstalk) is addressed in [9].

MV converters used for grid connected applications find series and parallel connected Si devices. But this increases the number of devices to be handled and henceforth reduces the reliability of system. SiC devices with their high voltage and high current capacity prove to be promising candidates for such applications by enabling the design of non-cascaded converters for grid applications with comparatively simple control circuits. But these converters have an issue of low power quality at low currents. Madhusoodhanan et al. had proposed a control scheme to mitigate this issue while analyzing the harmonic performance and current distortion of a grid connected 3 level Neutral Point Clamped (NPC) multilevel converter in [10].

Colmenares, Sadik, Hilber, and Nee in [11] carried out the reliability analysis of a high efficiency 312kVA three phase voltage source inverter using parallel connected SiC modules. The results show that increasing the number of devices (parallel or series) reduces reliability of the system and an undesired tradeoff needs to be made between efficiency and reliability. V_{GS} and V_{DS} stress were studied and a solution to increase reliability by decreasing the positive gate source voltage and adding redundancy was proposed.

Crosstalk effect due to high dv/dt and EMI are major concern while using SiC devices in conventional circuits at high frequency. This necessitates the decoupling of high and low side SiC MOSFET of a same leg. Yan, Yuan, and Wu in [9] proposed a 100kHz split output converter to mitigate these issues in SiC based converters at high frequency. The proposed converter achieved an efficiency of 95.91% at a switching frequency of 100kHz with significant EMI reduction. It was able to reduce the high turn-on current overshoot, low frequency ringing during turn-on transient and reduced current and voltage distortion at the turn-off. Some disadvantages were also reported like current freewheeling, current pulses and voltage spikes of split inductors and the absence of synchronous rectification.

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Piasecki and Rabkowski in [12] tested a grid connected 10kVA SiC MOSFET (CREE C2M0025120D) and diode (CREE C4D20120D) based bidirectional converter. It had improved dynamic performance due to the excellent dynamic behavior of SiC devices as well as harmonic and reactive power compensation using the applied control algorithm. It was able to control the bidirectional power flow more dynamically even between change in operation from inversion to rectification and vice-versa.

B. Photo-Voltaic (PV) Applications

Ho et al. in [13] presented an interleaved boost converter for PV applications containing SiC Schottky diode (Cree C2D20120D 22A 1200V 175°C) in conjunction with a CoolMOS switch (Infineon IPW90R120C3). Due to the use of Schottky diode, the reverse recovery losses were found to be low as well as the turn on transient loss of the switch was also reduced. This paper elaborates the benefits of high breakdown voltage and small reverse recovery current of SiC diodes in bringing higher efficiency and power density in PV applications.

Use of appropriate SiC MOSFET/IGBT switches in place of CoolMOS switches can yield better results. Higher switching frequency can further reduce losses given that it is outside human audible frequency range and does not interfere with other circuits (EMI/EMC).

Breazeale and Ayyanar in [14] demonstrated the use of SiC MOSFETs (Cree CMF10120D) for making a transformer-less PV inverter with efficiency more than 97%. The efficiency was found maximum at 40kHz frequency. Any further increase in frequency led to decrease in efficiency due to semiconductor switching losses. This drawback in the proposed converter will be overcome as new WBG based transistors having low switching losses at higher switching frequencies become available. Mouli, Schijffelen, Bauer, and Zeman compared the performance of Interleaved Boost Converter using SiC MOSFETs and diodes with that of Si [15]. The results showed that the use of SiC devices instead of Si devices reduced switching losses and recovery losses to a great extent, thus increasing the overall efficiency of the converter. High switching frequency due to SiC switches in conjunction with powdered iron core contributed in overall size reduction of the circuit. Increasing the switching frequency helps in improving the efficiency as well as power density, which has been possible quite to an extent due to SiC switches. This also reduces the size of heat sink required. 1.2kV Si MOSFETs were not available with high currents, whereas 1.2kV SiC MOSFETs at high currents are now available thus opening new scope for single phase and three phase high power applications. Figure 5 shows the schematic of IBC used to study the impact of Si and SiC devices for PV application.

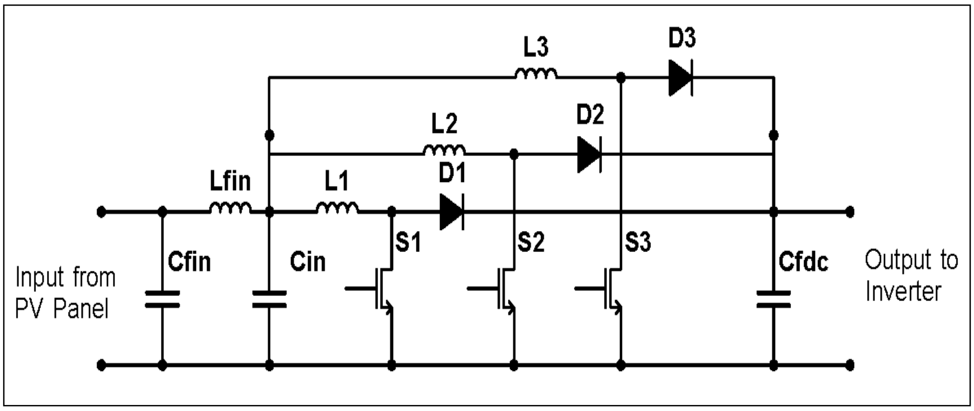

Figure 5: Schematic of IBC used in PV applications

The Si based converter was implemented using Si IXYS 1kV fast recovery diode DSEI30 and a 900V IGBT APT25GP90BDQ1. SiC based converter was implemented using SiC CREE Schottky diode C4D15120A and SiC CREE MOSFET C2M0080120D. Loss comparison of converters is shown in

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Table 3.

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Table 3: Comparison of Si and SiC based converter implementation

Type	Optimal Frequency	Inductor Core	Power Density & Efficiency (η)	Overall Losses
Si	19kHz	Ferrite Epcos N87 E65	Maximum η at 19kHz	200W
SiC	47kHz	KoolMμ powdered iron core E65 26μ, 40μ, 60μ	2.5 times with around 1% reduction in η compared to Si	150W

Frequency of more than 19kHz was not possible as switching losses increased drastically in Si based converter. In SiC based converter, operation above 47kHz may be possible, but the frequency was chosen purposely so as to reduce third order harmonic injection in the grid. Islam and Mekhilef had also proposed in [16] a transformer-less grid tied inverter for PV system with 98.32% using MOSFETs and SiC diodes having almost zero reverse recovery.

C. Electric Vehicles and Automative Industry

With the advent of electric vehicles, various electric motors (DC & AC) are being used to drive the vehicles. This involves power conversion from DC to AC (EV) and AC to DC/AC (Hybrid vehicles) to drive these motors. Efficiency plays a very important role here and hence this field of application involves the use of power devices mainly for efficient motor control using available DC power and/or IC engine-based generators as seen in hybrid vehicles these days. They include main driving motors as well as subsidiary motors used to control other systems in automobiles.

Efficiency, high temperature operation, reliability, power density, and size of a PE converter are the main requirements in the field of automobiles. Si based devices failed to meet all the requirements, and had limitations in their use in automobiles. They were required to be overrated to ensure a safety margin to avoid failure under worse operating conditions like high temperature, vibrations, noise, dust, etc. Efficiency is the most important parameter in case of battery-operated EV. SiC devices being able to work at high temperatures due to high bandgap of SiC, are preferred in EV to increase efficiency and enable reliable operation at high temperatures.

D. High Voltage (HV) Applications:

Conventional Si based devices is a mature technology and with research of more than 40 years, there arises a fundamental limitation on the design of Si devices above certain limits. Si devices have a maximum voltage rating of around 6-7kV while SiC devices can easily go above 10kV rating. Song et al. in [17] tested and demonstrated a 22kV SiC p-ETO with very low forward voltage drop, ultra-low leakage current, and high current turn-off. This device can be used in high voltage, high power, low frequency applications. Turn-off loses are expected to be reduced in near future developments of SiC n-type ETO thus increasing the switching frequencies to several kilo-hertz. M. Takasaki et al. in [18] developed a high efficiency D-STATCOM using SiC that can be directly connected to grid without a transformer. This becomes possible due to the use of SiC devices having high breakdown voltage. Table 4 shows basic details of the STATCOM.

Table 4: D-STATCOM using 1.2kV 30A SiC J-FET

Parameter	Value
System Voltage	2.2kV
System Frequency	50 Hz
Reactive Power Output	±33.3kVA (8.8A)
Switching Device	1.2kV 30 A SiC J-FET @ 4kHz 1.2kV-7.5A SiC SBD
Equivalent Switching Frequency	20.4kHz (above human audible level)
Converter Capacitor V_{ripple}	±5%
Current Distortion Factor	2.4% (maximum)

A compact prototype D-STATCOM using SiC switches was possible at such high switching frequency with a total loss of 0.95% in which converter loss was only 0.4%. Jun Wang et al. in [19] has presented a comparative analysis of Si and SiC based HVDC system by calibrated simulations. It is shown that a 30kV SiC thyristor based HVDC converter results in less number of series connected switches, lower forward voltage drop and conduction loss, simpler control circuit and improvement in efficiency compared to Si switch based systems.

Table 5 compares the performance of the two systems briefly with one single 30kV SiC thyristor and four series connected 8.5kV Si thyristors. An estimated yearly savings of 25 crore kWhr energy equivalent to ₹1.25 billion was calculated based on the losses in Si based devices.

Table 5: Comparison of Si & SiC based HVDC system

Parameter (*per 4 Si & 1 SiC switch)	Si System	SiC System
*Forward Voltage Drop	11.2V	4.6V
*Reverse Recovery Charge (Q_{rr})	44µC	32000µC
*Peak Reverse Recovery Current (I_{RM})	7.5A	125A
Total Switches used to make the system	5400	1350

Total Conduction Loss of Thyristors	49.2MW	20.3MW

Modular Multilevel Converter (MMC) HVDC systems are widely used these days. The auxiliary power supply required to supply driver and control circuits of the MMC-HVDC system takes input as ultrahigh voltage DC in kilovolts range and gives low voltage DC output. Yaqiang Han et al. in [20] has proposed a 4kV input auxiliary power supply for MMC based HVDC systems with an output 60W at 400V. This was made using series connected Cree C2M1000170D MOSFETs switched at 10kHz. Similar flyback topology based power supply was proposed and tested for common mode voltages for series connected SiC MOSFETs by Xiliang Chen et al. in [21]. It was shown that the common mode interference increases with increase in number of series connected SiC MOSFETs. Tamotsu Ninomiya et al. in [22] presented a 5kW high power-density (8.6W/cm3, almost 8 times of conventional power density) isolated DC-DC converter for HVDC power supply with a hybrid pair of Si-MOSFET and SiC-SBD and a compact SiC-SIT based static circuit breaker.

Shipboard and aircraft also critical field of applications for power electronics technology. The main requirements of power supplies here are high efficiency, compact size and high reliability. Apart from these, high temperature operation may also be a required parameter for defence applications. Wang et al. in [23] has discussed some advances in SiC that has made advances in motor drives and integrated power systems possible for optimised shipboard power supply systems.

III. CURRENT STATUS OF SIC DEVICES

SiC technology is developing at a rapid rate. New devices with better performance and higher ratings are becoming commercially available. But apart from the availability of the devices, cost needs to be traded off against system level benefits like increase in efficiency and reduction in size [3]. With continuous research going on around the world, it can be said that the cost is, and will be an ignorable parameter when compared to the overall system level benefits obtained with SiC devices replaced by Si devices.

Until recently, only high voltage high power discrete SiC devices were available, but now SiC MOSFETs are also available in low current ratings making it possible for the qualities of SiC to be exploited for low power applications at high frequencies, thus achieving high efficiency. CREE Power and RF (now Wolfspeed) is a leading manufacturer of SiC devices in the world. Other manufacturers include ROHM semiconductor, Infineon, ST Microelectronics, GeneSiC semiconductor, IXYS, Toshiba, etc. Some of the current commercially available SiC MOSFET modules and discrete MOSFETs by Wolfspeed are listed in Table 6 and

Table 7 respectively while discrete MOSFETs by ROHM are listed in Table 8. SiC Schottky Diodes by Wolfspeed and Infineon are listed in

Table 9: Commercially available SiC Schottky Diodes from Wolfspeed

Part Number	Blocking Voltage (V)	Current (A)	Package
C4D10120A	1200	10	TO-220-2
C4D10120D	1200	10	TO-247-3
C4D10120E	1200	10	TO-252-2
C4D15120A	1200	15	TO-220-2
C4D15120D	1200	15	TO-247-3
C4D20120A	1200	20	TO-220-2
C4D20120D	1200	20	TO-247-3
C4D30120D	1200	30	TO-247-3

C4D40120D	1200	40	TO-247-3
C3D10170H	1700	10	TO-247-2
C3D25170H	1700	25	TO-247-2
CPW4-1200-S010B	1200	10	Bare Die
CPW4-1200-S015B	1200	15	Bare Die
CPW4-1200-S020B	1200	20	Bare Die
CPW2-1200-S050B	1200	50	Bare Die
CPW5-1200-Z050B	1200	50	Bare Die
CPW3-1700-S010B	1700	10	Bare Die
CPW3-1700-S025B	1700	25	Bare Die
CPW5-1700-Z050B	1700	50	Bare Die

Table 10: Commercially available SiC Schottky Diodes from Infineon

Product (xx=Ampere)	Blocking Voltage (V)	Current (A)	Forward Voltage (V)	Package
IDKxxG65C5	650	2-6, 8-10, 12	1.5	D2PAK real 2pin
IDMxxG120C5	1200	2, 5, 8, 10	1.4-1.65	
IDLxxG65C5	650	2, 4, 6, 8, 10, 12	1.5	ThinPAK
IDHxxG65C5	650	2-6, 8-10, 12, 16, 20	1.5	TO-220 real 2pin
IDHxxG120C5	1200	2, 5, 8, 10, 16, 20	1.4 - 1.65	
IDWxxG65C5	650	10, 12, 16, 20, 30, 40	1.5	TO-247

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IDWxxG120C5B	1200	10, 15, 20, 30, 40	1.4	

and Table 10 respectively.

Table 6: Commercially available SiC MOSFET modules by Wolfspeed

Part Number	Blocking Voltage (V)	$R_{ds(on)}$ (mΩ)	Current (A)	Package
CAS325M12HM2	1200	3.6	325	High-Performance 62mm
CAS300M12BM2	1200	5	300	Industry-Standard 62mm
CAS120M12BM2	1200	13	120	Industry-Standard 62mm
CCS050M12CM2	1200	25	50	Industry-Standard 62mm
CCS020M12CM2	1200	80	20	Industry-Standard 62mm
CAS300M17BM2	1700	8	225	Industry-Standard 62mm

Table 7: Commercially available discrete SiC MOSFETs by Wolfspeed

Part Number	Blocking Voltage (V)	$R_{ds(on)}$ (mΩ)	Current at 100°C (A)	Package
C2M0025120D	1200	25	60	TO-247-3
C2M0040120D	1200	40	40	TO-247-3
C2M0080120D	1200	80	20	TO-247-3
C2M0160120D	1200	160	11	TO-247-3
C2M0280120D	1200	280	6	TO-247-3
C2M0045170D	1700	45	48	TO-247-3
C2M1000170D	1700	1000	2.6	TO-247-3
C2M1000170J	1700	1000	3.6	7LD2PAK

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C2M002512 0D	1200	25	60	TO-247-3
C2M004012 0D	1200	40	40	TO-247-3
C2M008012 0D	1200	80	20	TO-247-3
CPM212000 025B	1200	25	71	Bare Die
CPM212000 040B	1200	40	40	Bare Die
CPM212000 080B	1200	80	20	Bare Die
CPM2120001 60B	1200	160	11	Bare Die
CPM217000 045B	1700	45	48	Bare Die

Table 8: Commercially available discrete SiC MOSFETs by ROHM

Part Number	V_{ds} (V)	Id (A)	$R_{ds(on)}$ (mΩ)	Package
SCT3022ALGC11	650	93	22	TO-247-3
SCT3030ALGC11	650	70	30	TO-247-3
SCT3120ALGC11	650	21	120	TO-247-3
SCT3060ALGC11	650	39	60	TO-247-3
SCT3030KLGC11	1200	72	30	TO-247-3
SCT3080KLGC11	1200	31	80	TO-247-3
SCT3160KLGC11	1200	17	160	TO-247-3

Table 9: Commercially available SiC Schottky Diodes from Wolfspeed

Part Number	Blocking Voltage (V)	Current (A)	Package
C4D10120A	1200	10	TO-220-2
C4D10120D	1200	10	TO-247-3
C4D10120E	1200	10	TO-252-2

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C4D15120A	1200	15	TO-220-2
C4D15120D	1200	15	TO-247-3
C4D20120A	1200	20	TO-220-2
C4D20120D	1200	20	TO-247-3
C4D30120D	1200	30	TO-247-3
C4D40120D	1200	40	TO-247-3
C3D10170H	1700	10	TO-247-2
C3D25170H	1700	25	TO-247-2
CPW4-1200-S010B	1200	10	Bare Die
CPW4-1200-S015B	1200	15	Bare Die
CPW4-1200-S020B	1200	20	Bare Die
CPW2-1200-S050B	1200	50	Bare Die
CPW5-1200-Z050B	1200	50	Bare Die
CPW3-1700-S010B	1700	10	Bare Die
CPW3-1700-S025B	1700	25	Bare Die
CPW5-1700-Z050B	1700	50	Bare Die

Table 10: Commercially available SiC Schottky Diodes from Infineon

Product (xx=Ampere)	Blocking Voltage (V)	Current (A)	Forward Voltage (V)	Package
IDKxxG65C5	650	2-6, 8-10, 12	1.5	D2PAK real 2pin
IDMxxG120C5	1200	2, 5, 8, 10	1.4-1.65	
IDLxxG65C5	650	2, 4, 6, 8, 10, 12	1.5	ThinPAK
IDHxxG65C5	650	2-6, 8-10, 12, 16, 20	1.5	TO-220 real 2pin

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IDHxxG120C5	1200	2, 5, 8, 10, 16, 20	1.4 - 1.65	
IDWxxG65C5	650	10, 12, 16, 20, 30, 40	1.5	TO-247
IDWxxG120C5B	1200	10, 15, 20, 30, 40	1.4	

Kadavelugu et al. in [24] has presented the frequency limit analysis of a 15kV N-IGBT using FEM analysis which shows that with liquid cooling, the IGBT can be operated at a maximum frequency of 6.2kHz at 10kV 5A with a maximum junction temperature of 150°C. This decreases to 3.9kHz at 10A. The limits corresponding to air cooled IGBT are 5.1kHz and 3.2kHz respectively. These frequency limits can be increased further but at a cost of increase in on-state resistance.

SiC devices are better over Si devices mainly due to properties like high temperature operation, high voltage & high-power ratings and high operating frequency (di/dt & dv/dt). But operation at high power and high frequency invites issues like increased EMI, crosstalk and detrimental effects on inverter fed motors [8], [9], [25]. It is shown in [25] that utilizing full switching speed capability of SiC devices leads to about 70% decrease in switching losses as compared to Si devices for same dv/dt at a significant cost of increased EMI.

Presently, all the properties of SiC cannot be utilised due to various problems like dramatic increase in on-state resistance and conduction drop with increase in temperature, current, etc. There needs to be a trade-off between simultaneous maximum voltage, current, temperature, and frequency that can be utilized out of the maximum available capacity of SiC devices.

Apart from the issues addressed above, driving SiC MOSFETs of same leg, especially high side also require adequate care due to the repetitive high voltage applied at the gate of the high side switch and output of driver circuit. Wolski, Grzejszczak, and Barlik in [26] has presented a gate driver with ultra-low input to output stray capacitance (5pF) and capable of operating at a high voltage of 5kV while switching 10kV SiC MOSFET at 20 kHz. Zhang et al. presented yet another gate drive for a 15kV SiC MOSFET with fibre optic isolation (20kV) and immunity from high common mode noise (CM transient rejection of more than 200kV/µs) in [27]. It also had adequate protections like overcurrent protection, over & under voltage lockout, active miller clamping, soft turnoff, and fault reporting.

GaN is also a promising upcoming WBG material. Research is also going on for exploring the potentials of GaN based devices. Some of the reported papers on GaN devices and their applications are discussed here. Gurpinar, Yang, Iannuzzo, Castellazzi, and Blaabjerg in [28] compared GaN High Electron Mobility Transistor (HEMT) with Si IGBT for PV inverters focusing on thermal performance and reliability while concluding that GaN HEMT can lead to significant savings in system costs as compared to Si IGBT. Liu, Lee, Li and Yang in [29] has presented a two phase interleaved MHz totem-pole Power Factor Correction (PFC) rectifier.

IV. IMPORTANT CHALLENGES

She, Huang, Lucía and Ozpineci in [30] observed that SiC devices operating at high power has several benefits in terms of efficiency, switching speed, power density, and high-temperature operation, but on the contrary, there are several technical and other challenges which still are hindering the full scale development of these devices. Reliability of the devices has yet to be fully validated through long-term field performance under diverse operating conditions in sensitive areas like medical engineering and aerospace. The higher current handling capability and high temperature operation of SiC devices result in increased thermal cycling and thereby impose stringent requirements on packaging materials, packaging size and overall system reliability. The manufacturing processes also require continued improvement to increase the production yields and thereby further reduce device costs. Although using larger wafer sizes and potential utilization of existing silicon fabrication facilities may lower costs, but process compatibility and manufacturing flexibility are still some of the important concerns.

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The fast-switching characteristics of SiC devices also lead to major challenges for gate driver design, reduction in EMI, PCB layout optimization, and thermal management. As mentioned earlier also, high dv/dt and di/dt transients increase susceptibility to false gate triggering, insulation stress, fault protection complexity, and EMI emissions, which can be solved using advanced gate drivers, and customized innovative filtering techniques designed to mitigate these issues. Further, minimizing parasitic inductances through optimized packaging techniques is necessary to reduce voltage overshoot and fully utilize the current-carrying capability of the SiC converters. The high-power density in small SiC chips also demand advanced cooling solutions and improved thermal management strategies to ensure optimum performance of the devices. Moreover, the high-temperature capability of SiC devices creates a need for other high-temperature components in the converters like capacitors, sensors, gate drivers, and other control electronics components. Finally, widespread adoption of these devices is also limited by the significant non-recurring engineering effort required to design customized SiC-based systems and non-direct replacement of Si devices by SiC devices in conventional converters, highlighting the importance of standardized power electronic building blocks that can reduce development complexity, cost, and time-to-market.

Lee, Smet and Tummala [33] identifies Silicon Carbide (SiC) power devices as a key enabling technology for next-generation power electronic systems due to their superior switching speed, high-temperature capability, reduced conduction and switching losses, and increased power density. The primary contribution of the work is a comprehensive review of SiC power module packaging technologies, highlighting the limitations of conventional silicon-based packaging approaches and presenting recent advances in packaging structures, interconnection methods, thermal management solutions, and high-voltage insulation techniques required to fully exploit SiC device capabilities. The study concludes that packaging, rather than the semiconductor device itself, has become a critical bottleneck in modern days limiting the realization of the full performance potential of SiC-based power converters. These challenges collectively define the major research directions for future SiC device packaging and system integration.

V. CONCLUSION

The high energy band gap, high dielectric breakdown field strength, and better thermal conductivity makes WBG material-based devices like SiC and GaN better than Si based devices, which are dominating the semiconductor industry from a long time. But still the SiC technology is not mature yet for Si to be replaced by it at large scale. The above said properties provide high temperature operation, high voltage & high-power ratings and high operating frequency (di/dt & dv/dt) operation to SiC based devices thus making them better than Si devices.

SiC technology developing rapidly in recent days is opening up new scope of applications for low, medium and high-power areas in the field of power electronics. Extensive research is going on to test the feasibility and reliability of SiC devices in various power electronics applications. A general overview of the current applications of SiC devices and their availability is presented in this paper aiming to help researchers in the field get knowhow of the current status of SiC technology. Some major challenges arising due to various properties of these devices are also presented which can be a potential area of research.

Apart from the benefits listed, many factors like high dv/dt and high di/dt generated noises (EMI) at high frequency operation, phase shoot through problems (crosstalk) have limited the high power and voltage operation of SiC devices. Operating the devices at audible range switching frequencies is also a prone issue. Extensive research is going on to operate the devices at higher than 20kHz frequency and mitigate the EMI/EMC issues due to operation at high frequency along with addressing novel packaging techniques to address these issues. Owing to these facts, cost and efficiency are an undesirable tradeoff to be done while using SiC devices in existing converters. High frequency operation of SiC devices results in reduction of overall losses compared to Si devices. Moreover, the actual benefits of SiC devices are observed in applications rated above 10kW. Below this, they are no better than Si devices if operated at comparable switching frequencies. But with the availability of low current SiC devices, there is a scope of increase in efficiency by using the high switching speed of SiC devices in low power applications. Looking to the current scenario, the benefits of SiC devices outperforms its cost.

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