SURVEY OF APPLICATIONS OF WBG DEVICES IN POWER ELECTRONICS

by

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Abstract

Wide bandgap devices have gained increasing attention in the market of power electronics for their ability to perform even in harsh environments. The high voltage blocking and high temperature withstanding capabilities make them outperform existing Silicon devices. They are expected to find places in future traction systems, electric vehicles, LED lightning and renewable energy engineering systems. In spite of several other advantages later mentioned in this paper, WBG devices also face a few challenges which need to be addressed before they can be applied in large scale in industries. Electromagnetic interference and new requirements in packaging methods are some of the challenges being faced by WBG devices. After the commercialization of these devices, many experiments are being carried out to understand and validate their abilities and drawbacks. This paper summarizes the experimental results of various applications of mainly Silicon Carbide (SiC) and Gallium Nitride (GaN) power devices and also includes a section explaining the current challenges for their employment and improvements being made to overcome them.

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Chapter 1 - Introduction

Silicon (Si) based switching devices have been predominantly used in application of power electronics for a long time. With the advancements in technology, there has been an increasing demand for more efficient and powerful switching devices which can withstand high temperatures and voltages. Wide bandgap (WBG) semiconductor devices are known to meet those demands with their special characteristics.

As the name indicates, WBG semiconductors have energy bandgaps significantly greater than that of the conventional silicon devices. This bandgap is the energy difference between the top of the valence band and bottom of conductance band in materials. Typically WBG devices have bandgaps greater than 3eV while silicon and GaAs have 1.12eV and 1.43eV respectively [1]. Insulators have even higher bandgaps, typically greater than 4eV. Conductors have almost no energy gap and the small energy gap present in the semiconductors allows it to partially conduct the current. It is this energy gap that enables the semiconductors to be used as switches (see fig.1). The higher energy bandgap in WBG devices adds some remarkable characteristics, making their operation superior compared to other semiconductors. Advantages of WBG devices include high breakdown field, low dielectric constant, good thermal conductance, higher carrier mobility and high saturated velocity. When compared to silicon devices, they can reduce energy losses significantly, can operate at higher temperatures and frequencies and can improve power quality [2].

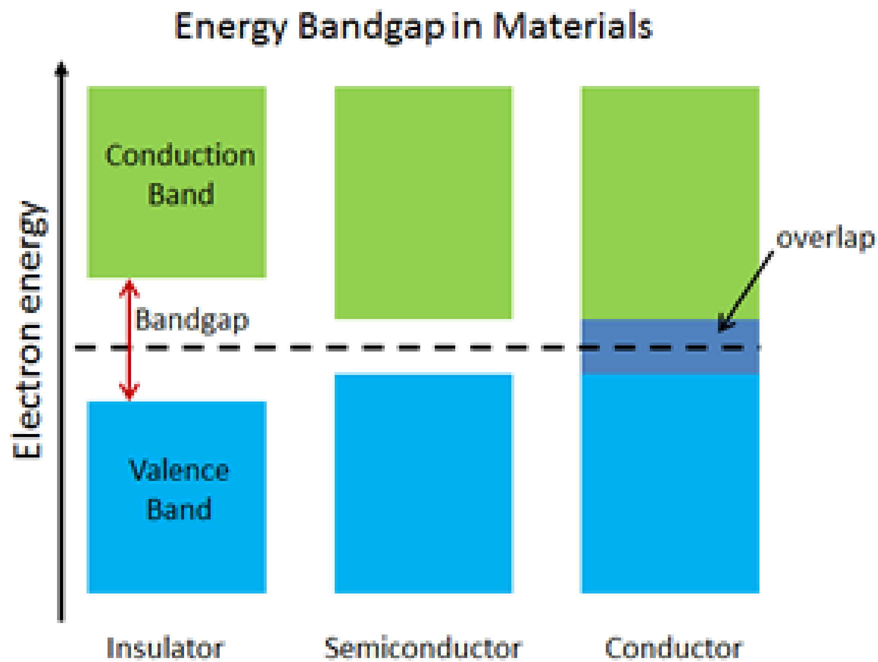

Fig. 1 Energy Bandgap in Materials [1]

Though it was known for over 40 years that WBG devices could be the best bit for many applications, due to material quality issues, a high performance device couldn't be produced for long time. However, the invention of Gallium Nitride based LEDs and commercialization of SiC substrates changed the scenario in the early 1990s. Most important WBG devices are Silicon Carbide (SiC) and Gallium Nitride (GaN) with SiC being more commonly used with its technology being more matured than that of GaN and the possibility of using SiC in producing MOSFETs [3]. The first SiC devices which came into market are Schottky diodes followed by Junction gate FETs and MOSFETs. A Major challenge in SiC commercialization was with elimination of several defects like edge dislocations, triangular defects and basal plane dislocations. The first commercial SiC JFETs and MOSFETs were rated at 1200v and got released in 2008 and 2011 respectively.

Dielectric breakdown field strength of SiC is approximately 10 times higher than that of Si. SiC devices can have thinner drift layers and/or higher doping concentrations which lead to a breakdown voltage of 600V and up. They have very low area specific resistance relative to silicon devices (see fig.2). IGBTs (Insulated Gate Bipolar Transistors) are known to operate in high-voltage and high-current applications. But they present low resistance only at the cost of switching performance. MOSFETs are majority carrier devices and when combined with advantages of SiC semiconductors like higher breakdown field and higher carrier concentration, SiC MOSFETs exhibit nearly ideal characteristics of a power switch i.e., high voltage, low on-resistance, and fast switching speed. Large bandgap of SiC devices enable them to operate at high temperatures (150°C - 175°C). Proper packing can even make them operate at 200°C and higher [4].

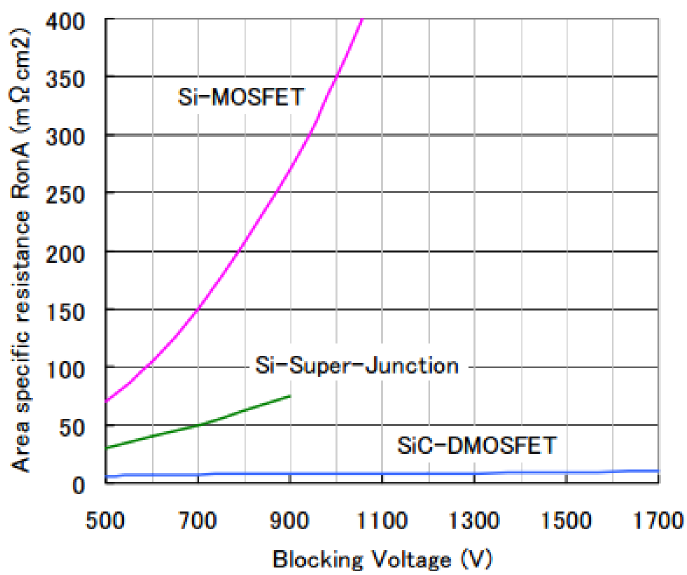

Fig. 2 SiC Specific On-Resistance Vs Blocking Voltage [2]

WBG devices find their applications in vast areas of power electronic applications. Power factor correction circuits, solar inverters and dc/dc converters are some of the common circuits where SiC devices can be used [4]. Motor drive inverter modules have been developed using SiC power devices and are known to run efficiently compared to the Si-based drives. Results also show the ability of SiC devices to reduce the size of motor drive inverters [5].

GaN devices have been gaining popularity in the applications requiring 600V or below. The enhancement mode gallium nitride on silicon (eGaN) field effect transistor (FET) was launched by Electric Power Conversion Corporation in 2009. GaN devices have superior characteristics like higher mobility of electrons and higher bandgap when compared to SiC devices. The on-resistance of GaN devices is smaller than SiC devices even at higher breakdown voltages (see Fig.3). These properties contribute to the smaller size of GaN devices. Also, due to the lateral structure of eGaN FET, capacitance of gate to drain remains low which enables the device to operate at very high switching frequencies. Low voltage GaN devices do not require the expensive and bulky packages which make it very cost effective. GaN devices dominate RF frequency applications [8]. GaN RF devices find applications in broadband amplifiers, radar, telecom base stations, military communications and satellite communications.

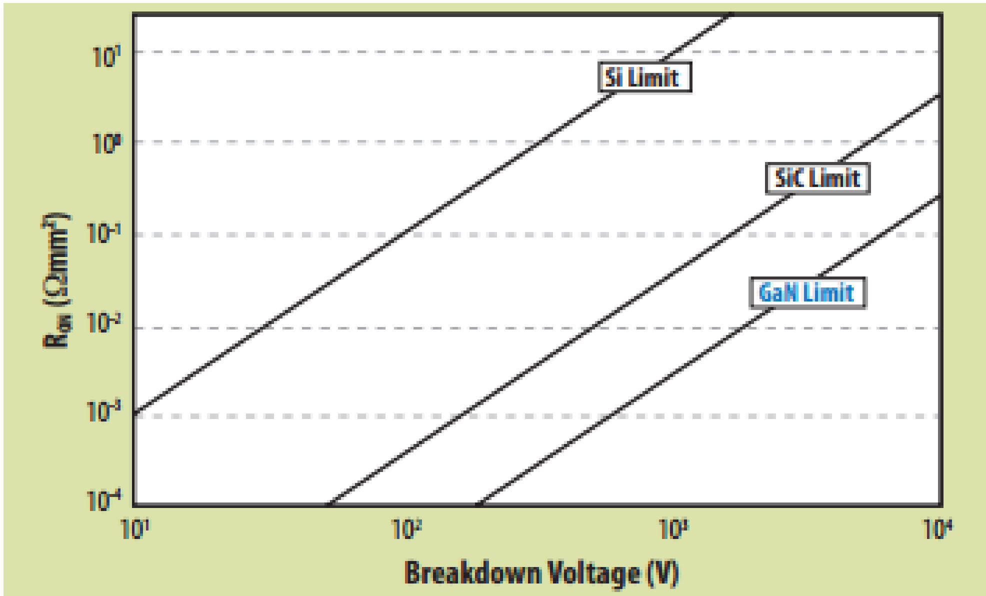

Fig. 3 Theoretical On-Resistance Vs Blocking Voltage Capability [3]

When it comes to thermal conductivity, SiC devices have higher values than GaN devices. This becomes a main challenge as they would need special packaging/ heat sinks to be used at higher temperatures. Lack of homogenous substrates at reasonable cost makes it unfeasible to develop vertical structure of GaN devices which can fetch many advantages like effective heat distribution, ability to handle high surge currents and transient voltages. All these reasons made GaN devices unfit for high temperatures [7]. Efficiency analysis done on a GaN based 1 kW inverter showed that the highest efficiency obtained is 99.41% which is 4.89% higher than that obtained for a Si based inverter [9]. GaN based dc-dc converter of 1.7kW also achieved very high efficiency of 98.7% [10]. Material properties of Si, SiC and GaN devices can be seen in Table 1 below.

Material Property	Si	SiC-4H	GaN
Band Gap (ev)	1.1	3.2	3.4
Critical field 10^6 V/cm	.3	3	3.5
Electron mobility (cm^2 /V-sec)	1450	900	2000
Electron saturation velocity (10^6 cm/sec)	10	22	25
Thermal Conductivity (Watts/cm^2 K)	1.5	5	1.3

Table.1 Material Properties Comparison of Semiconductors [4]

SiC devices perform with an increased efficiency of 2.3% when compared to Si devices, when used in an inverter of 12kVA operated at 20 kHz. Even at the high frequency of 100 kHz, the SiC inverter loss recorded is always less than 190 W, where as it is 348 W for Si IGBT inverter at 20kHz [11]. Less losses and high frequency operation will reduce the weight and volume of power converters. SiC switches outperform ultra-high speed CoolMOS semiconductor switches in Photovoltaic (PV) pre regulator DC-DC converter applications [12]. A new record in efficiency of inverter for PV application has been demonstrated by Fraunhofer Institute [13]. A single phase inverter with SiC JFETs has shown a maximum efficiency of 99% with a switching frequency of 16 kHz.

SiC diodes can be much more efficient than Si diodes with the reverse recovery current of the former being near to zero. In Si diodes, minority carriers get stored in a drift layer during the conduction phase and this causes transient current during external commutation. Reverse recovery time and reverse recovery current are directly proportional to the forward current and temperature of operation. SiC diodes are majority carrier devices and hence do not have a problem pertaining to minority carriers storage. Reverse recovery current in SiC diodes happens only to discharge the junction capacitance and is independent of forward current and temperature. This leads to fast recovery in diodes and also reduces noise emission caused due to the reverse recovery currents [4]

In terms of die area requirement for cooling, SiC diodes need a die area which is 15% smaller that of Si diodes at 10 kHz. At 40 kHz, the die area required for Si diodes is 40% more than that required for SiC diodes. For a given die area, higher frequency can be applied to SiC devices which reduces the size, weight and cost reduction of filters [14]. The SiC Schottky diodes being a majority carrier device with fast switching speed, ability to withstand high temperatures and with low forward voltage drop makes it ideal to use as a freewheeling diode in motor drive applications [5]. SiC diodes also eliminate the need for bigger heatsinks. Some of advantages of SiC Schottky diodes are reduced diode switching losses and positive temperature coefficient making it possible for parallel operation. Forward characteristics of a SiC diode are shown in Fig.4 below. G1 and G2 represent first and second generation diodes respectively from Rohm.

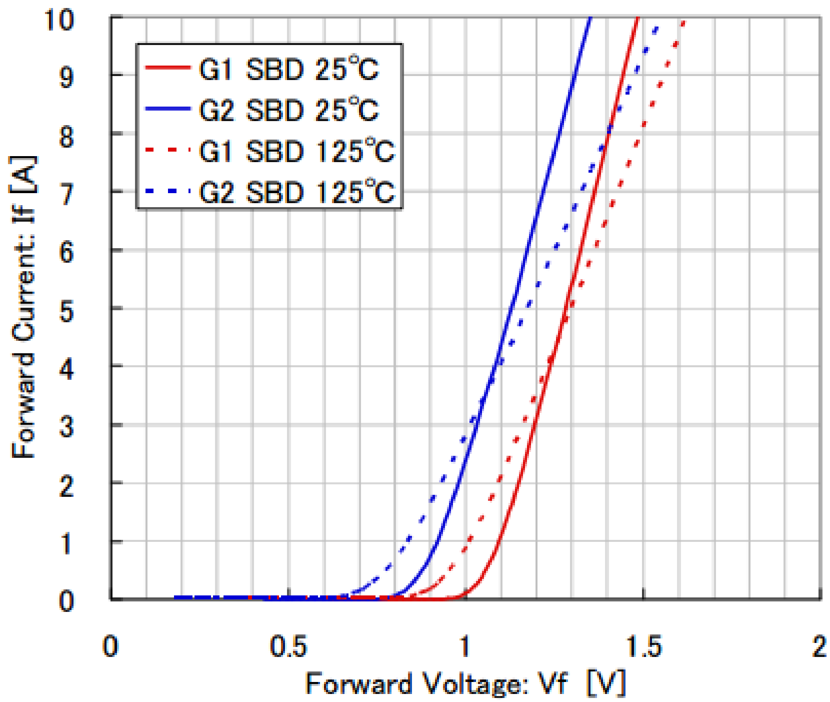

Fig. 4 Forward Characteristics of 600V 10A SiC-SBD [5]

Optically activated SiC power transistors which do not need electrical bias on the base but instead are triggered by the optical pulses can be of great use in high temperature and high power applications. They also provide improved long term reliability because of the absence of metal contact. If a SiC power transistor employs a bipolar device structure, it can amplify the photo generated current by its internal gain and thus can switch at high speeds even with low optical triggering power [15].

Chapter 2 - Application of WBG devices in Inverter

In this chapter, a brief explanation regarding different ways of application of WBG devices in inverters is discussed (ex: using hybrid devices instead of using WBG devices directly). Effects of deploying WBG devices in Inverters used for different applications are presented. Results of tests conducted on WBG based inverters are presented to corroborate the conclusions drawn.

2.1 Inverters in Renewable Energy Engineering

In the present scenario, Wide Bandgap (WBG) devices cannot be used in all converter applications due to cost constraints. They are high cost devices compared to Si devices. To overcome this constraint, one can take advantage of the special characteristics of SiC devices. A hybrid power module formed by paralleling major Si devices with minor SiC devices can be used in place of Si device [16]. Positive temperature coefficients of Si and SiC devices make this paralleling possible. These hybrid power modules can exhibit quasi soft-switching and can therefore improve the efficiency of converter greatly. Application of a hybrid device has been demonstrated with one SiC MOSFET (100A/1.2 kV) in parallel with three Si IGBTs (100A/1.2 kV). To achieve quasi zero-voltage switching, the SiC is turned on first and is turned off later than other Si IGBTs. This hybrid module and the switching pattern are shown in Fig.5 and Fig.6 below respectively. Time setting of the turn-on delay and turn-off delay should be less than dead time between complimentary switches. Since the total current flows through SiC MOSFET during turn-on and turn-off delay timings, it is recommended to use this module only in light load or medium load conditions. It has been reported that replacing all Si-devices with these hybrid modules in a three-phase three-level neutral-point-clamped (NPC) PV inverter of 250 kW showed that CEC efficiency can be improved by up to 2%.

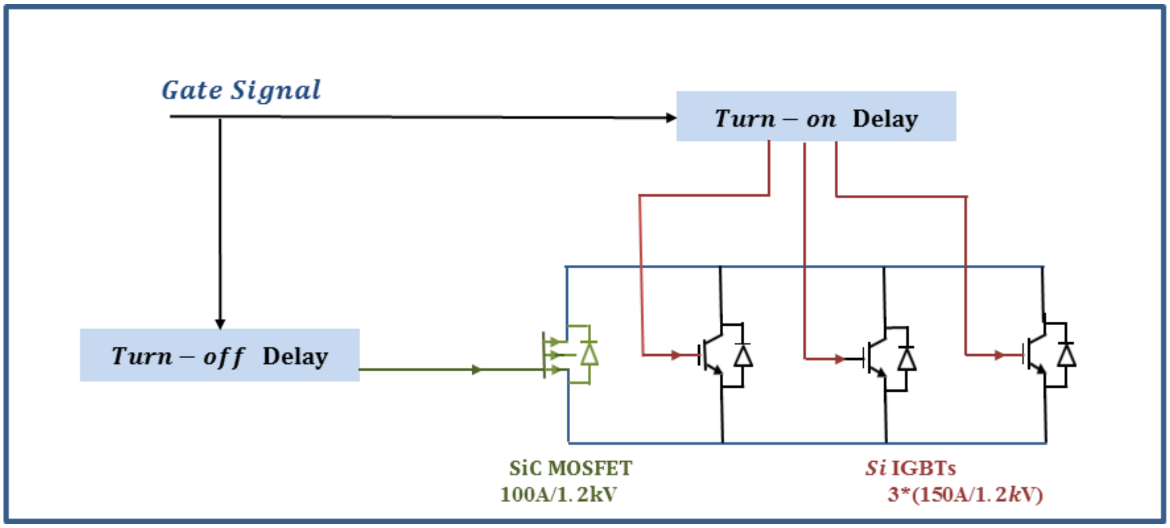

Fig. 5 Hybrid Power Module for PV Application [6]

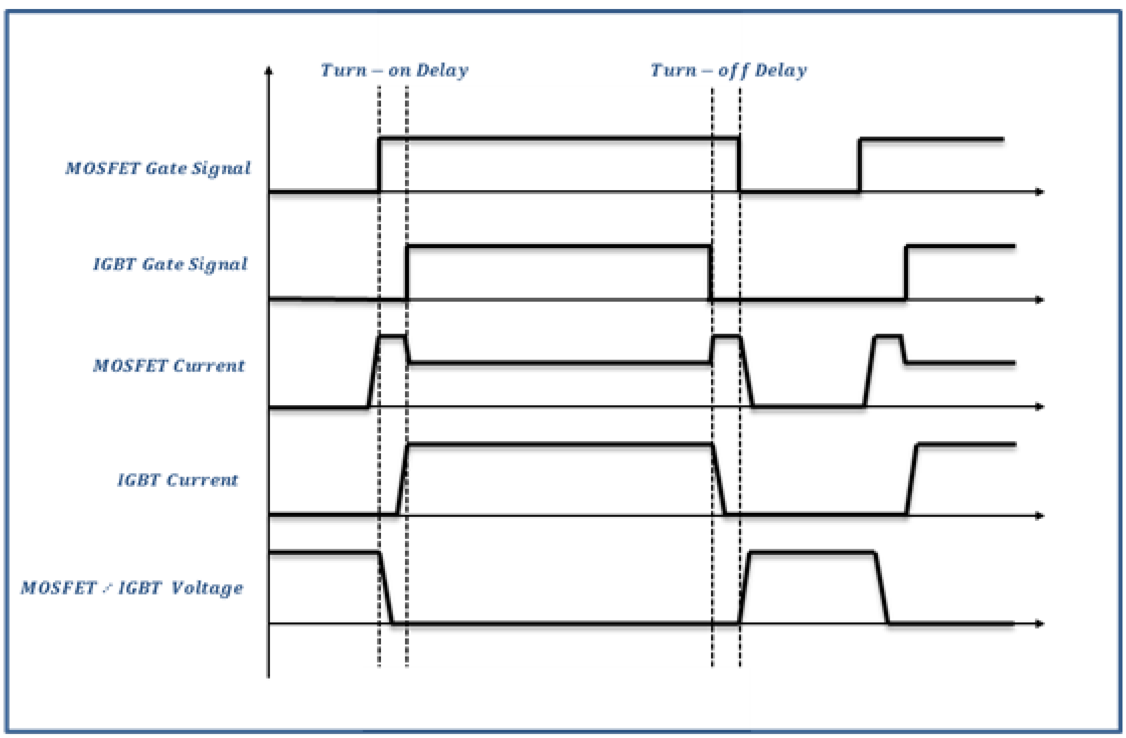

Fig. 6 Switching Pattern of Hybrid Module [6]

Another type of hybrid device can be formed by paralleling Si IGBT and SiC diode. It is surprising to notice that the overall losses (switching + conduction losses) in this hybrid device are encountered to be less than that of SiC devices itself, when employed in AC-AC converters. It is observed that though the switching losses remain low in the SiC devices, for the given AC/AC converter application, conduction losses decrease in the hybrid device [17]. A Similar case has been observed when a hybrid switch formed by Si IGBT operated in parallel with SiC MOSFET is deployed in 100kW converter operated at 2 kHz [18]. Conduction losses are registered to be higher in SiC at higher current densities. These hybrid devices exhibit better conduction properties and also lower switching losses compared to Si devices. Cost analysis also shows a very moderate increase in cost for a significant loss reduction compared. Higher Si/SiC current ratio leads to lower cost increment.

Similar hybrid power modules implemented in Wind turbine Power Converters showed improvement in efficiency. A module with one SiC MOSFET paralleled with five Si IGBTs was deployed in grid side converter and a module with one SiC MOSFET paralleled with one Si IGBT was deployed in generator side converter. Simulated results of a back to back power converter in a 250 kW DFIG system (see Fig.7) showed the efficiency improvement of 12.2% at 10 kHz switching frequency (see Fig.8) and 3.9% efficiency improvement at 2 kHz switching frequency when compared to efficiency of a back to back converter formed with Si devices only.

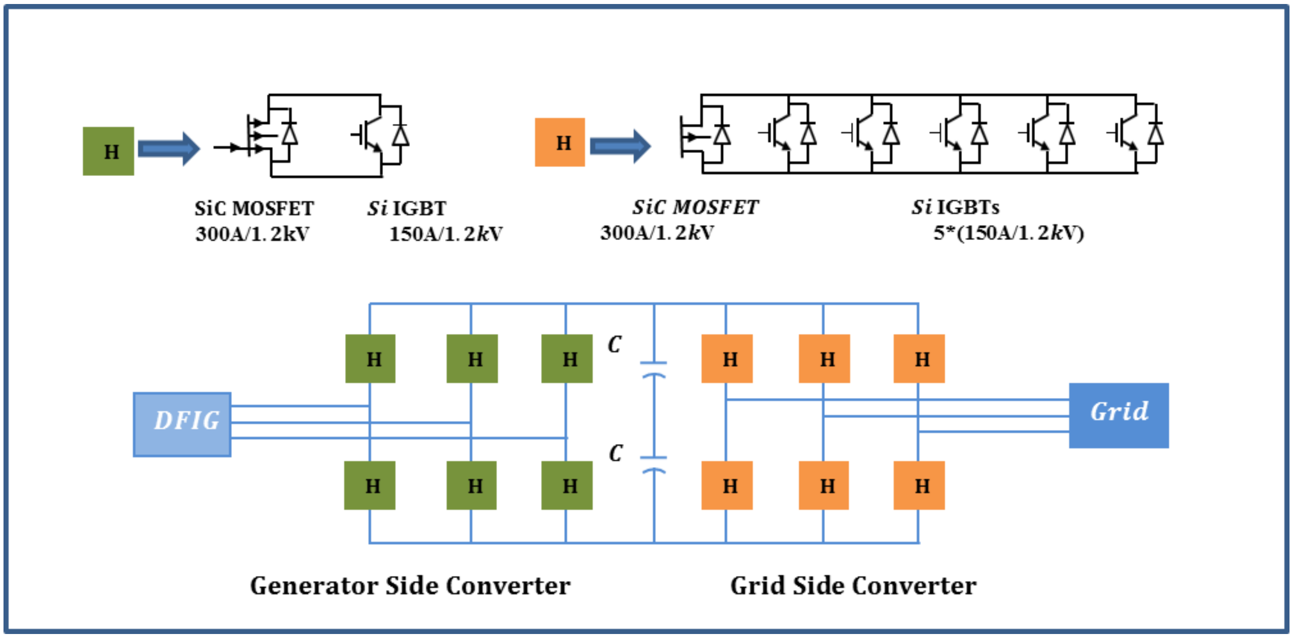

Fig. 7 Back to Back Converter [6]

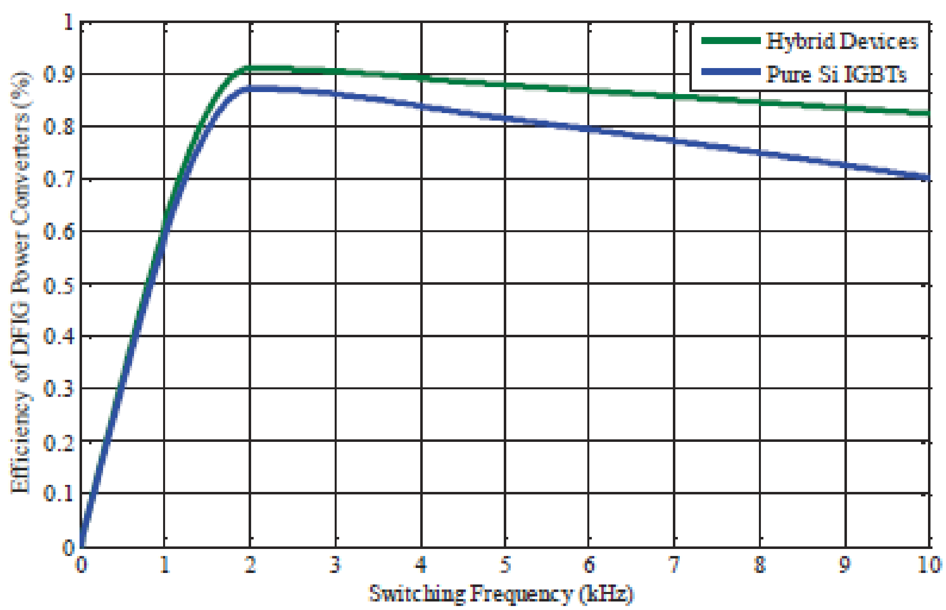

Fig. 8 Efficiency Comparision at different Switching Frequencies [6]

In order to achieve increased efficiencies in Photovoltaic systems, inverters with three-level (3L) structures are being used. But these complex 3L inverters can be replaced with two-level (2L) inverters, if SiC MOSFETSs are employed instead of Si IGBTs or MOSFETs. 3L inverters are capable of achieving efficiencies up to 98%, but they have disadvantages like the need for more switches leading to complex drive and protection circuitry, double voltage requirement in the dc link, along with the need for voltage balancing loop. 3L inverters show problems such as unequal loss distribution among the switching devices and this causes unequal temperature distribution between switches. This problem aggravates with increase in frequency and causes a concern in the reliability point of view [19]. It has been shown that 2L topology employing SiC devices can show better efficiency along with eliminating the above discussed problems. Table 2 shows the comparison of different PV inverter topologies. The main challenge for using SiC modules being high cost, this problem can be overcome in 2L inverters by the positive impact of reduced complexity and higher switching frequency operation. 40% lower inductance, 70% lower dc-link capacitance, half number of gate drivers and smaller PCB account for the overall cost reduction. Efficiency measurements have shown that 2L inverter operated at 50 kHz is more efficient than 3L-Diode Neutral Point Clamped inverter operated at 16 kHz for injected power higher than 9 kW.

	Three phase PV-Inverter topologies	
	3-level NPC Si	2L- Full bridge SiC
Switches	12+6 diodes	6
Gate Drivers	12	6
PWM algorithm	Complex	Simple
PCB Size	Higher	Lower
Output filter size	Decreased	Decreased
THD	Decreased	Increased
Efficiency	Moderate	Higher
Size and weight	Higher	Lower
switch stress	Uneven	Even
DC link balancing	Needed	Not needed
Operating temperature	Low	Higher
DC link capacitor bank	Bigger	Smaller
Protection	Complex	Simple

Table.2 Comparison between 3-Phase PV-Inverter Topologies using Si and SiC Technologies [7]

Efficiency and cost of Photovoltaic systems (PV) have become the hot topic in energy industry. It has been seen that PV systems perform well when one uses micro-inverters rather than string or central inverters. WBG devices can be used in building micro-inverters so as to reduce size and cost since the cost of micro-inverters depend more on the heat removal requirements rather than on the semiconductor devices. It is seen that a dual stage micro-inverter comprised of an interleaved fly-back converter using GaN devices in the low-voltage side performs better than the one used with Si devices. GaN devices reduce the voltage spikes. Also, GaN devices show an efficiency improvement of 3% in the dc-dc converter and 1% in the inverter stage [20-21]. From the above references, it can be seen that SiC devices show a great potential for application in PV inverter systems. A PV inverter system generally requires high efficiency at high voltages. Typically, a PV inverter system consists of a DC-DC converter and a

DC-AC inverter. A DC-DC converter is placed in between PV panels and inverter, which also operates as Maximum Power Point Tracker. An experiment conducted on SiC switching cell (SiC MOSFET + SiC diode) based dc-dc interleaved boost converter showed a considerable improvement in efficiency. Overall efficiency can be further increased when SiC devices are deployed in the DC-AC inverter too [22].

2.2 Inverters for Mitigating Frequency Transient Issues

With the increasing growth of wind and solar energy systems, the need for energy storage systems to mitigate frequency transient issues is also increasing. In this scenario, SiC inverters can play a better role over Si inverters in supporting the grid to mitigate the frequency transient issues. A surge of power is provided from the energy storage system through an inverter to control the frequency. Devices used in such an inverter have to withstand high currents and temperatures for a short period of time. SiC devices investigated for this application, in which 62.5kW active power flow is allowed through a 30.6kVA inverter using three different cooling methods to cool the inverter module, showed positive results. Two different cooling methods namely Liquid-cooled aluminum heat sink with water-ethylene glycol (WEG) coolant, direct-cooled module base plate (WEG coolant) have shown better results where the steady state module temperature is below the rated peak junction temperature of 150^{o} C. A Cooling method using an Air-cooled aluminum heat sink would need additional design optimization to mitigate the worst-case frequency event, if the process takes more than 10sec [23].

2.3 Inverters for High Speed Machines and Motor Drives

High speed in electric machines can be obtained by varying poles and frequency. The traditional high-speed machines are mostly of two pole type because of the frequency requirement being low. Achieving high frequency of 2 kHz using IGBT devices, whose switching frequency is typically 20 to 30 kHz, was a challenge. The insufficient switching frequency may lead to improper voltage and current waveforms. Going for a machine with high number of poles reduces the stator yoke thickness, thus making the machine smaller and cheaper. With the outstanding characteristics of SiC devices, we can achieve high fundamental frequencies as required by higher pole machines. Comparing machines of different number of poles, keeping the number of turns per coil constant, shows that there is a 25% weight reduction from a 2 pole machine to a 4 pole machine and accordingly a 4 pole machine has 33% more power density. Comparing machines with different number of turns per coil but similar stator inductance shows that the efficiency of 2 pole machines is higher than that of 4 pole and 8 pole machines. But there is a considerable amount of reduction in copper loss and weight when a high pole machine is considered. Inverter efficiencies and THD in machine currents are compared and are as shown in graphs Fig. 9 and Fig. 10 [24].

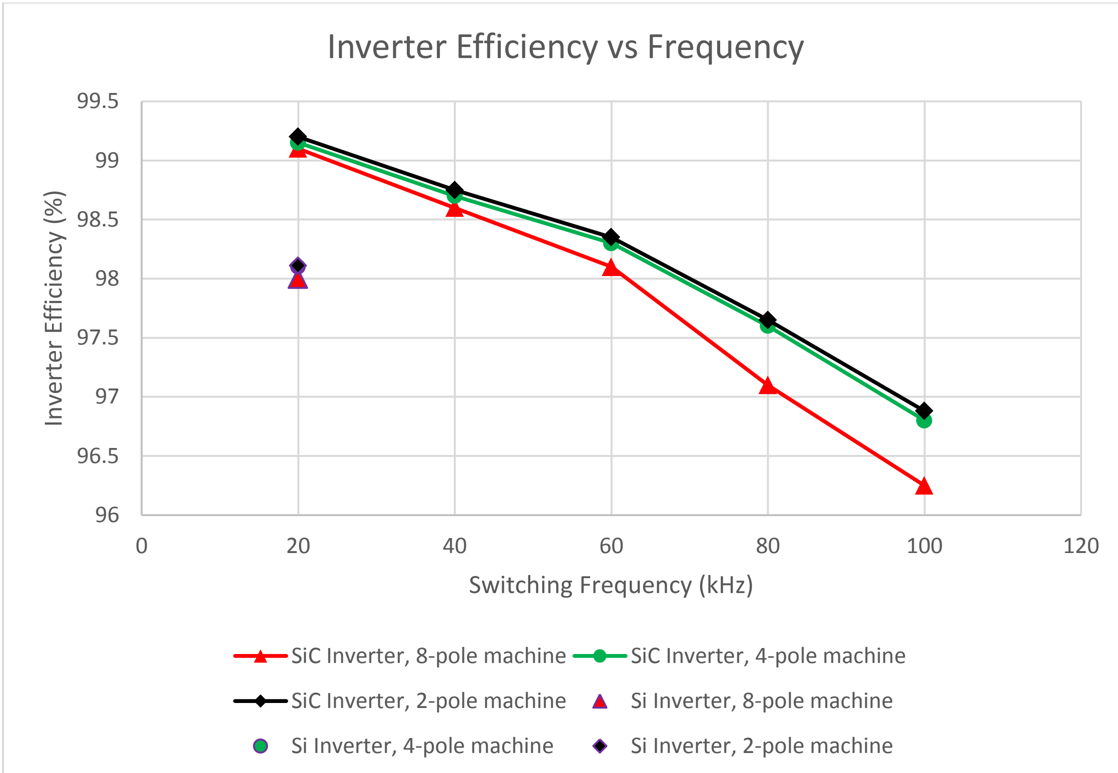

Fig. 9 Comparison of Inverter Efficiency of different Pole Machines [8]

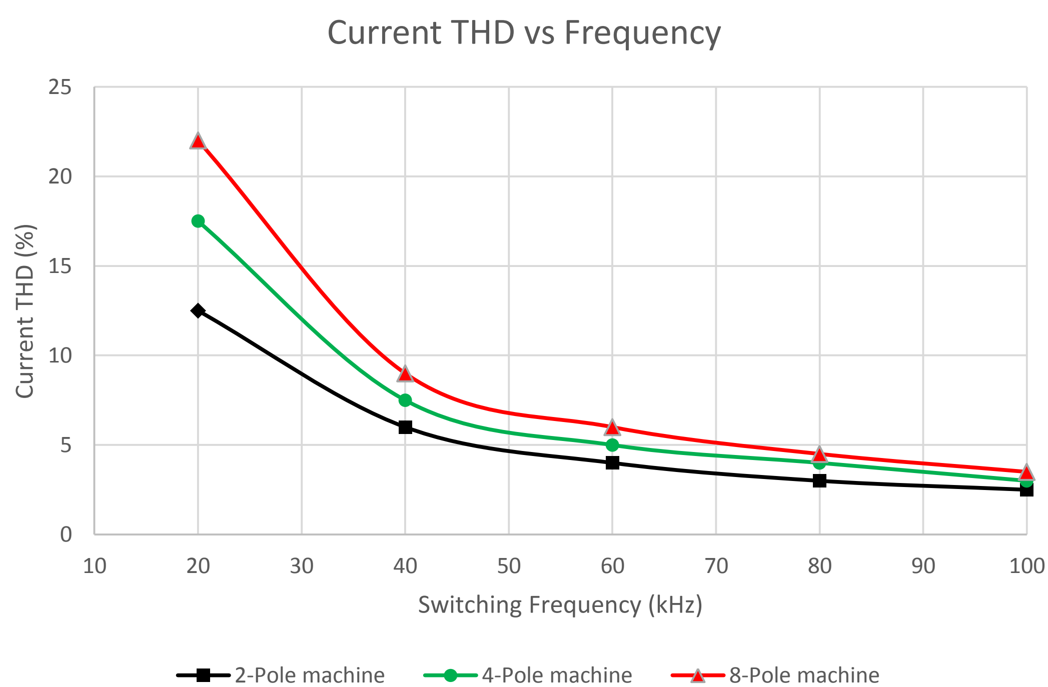

Fig. 10 Comparison of Machine Current THD of different Pole Machines [8]

Combination of SiC MOS–enhanced JFET and a Schottky diode has been proven to reduce the size and losses of motor drive's inverter. Current/voltage overshoots are seen to be considerably reduced using this combination. Comparisons done between a Si IGBT and a SiC MOSFET in a 60kW motor drive system showed that SiC devices exhibit lower losses, lower junction temperature and lower package size when a similar heat sink is used for both applications. When junction temperatures of both inverter modules are kept same, it is observed that weight and size of heatsink required for SiC inverter module is almost one third of the one required for Si inverter module [25-26].

Chapter 3 - Application of WBG devices in DC-DC converters

The current chapter discusses about the potential of WBG devices for application in dc-dc converters. DC-DC converters find application in many important areas like Photovoltaic systems, hybrid vehicles, data centers etc., and results presented in this chapter show that WBG devices improve system efficiencies.

DC-DC converters with SiC JFETs and SiC MOSFETs show efficiencies of 96% and 95.5% respectively [27]. Also, these efficiencies have weak frequency dependence unlike the coolMOS/SiC JBS diode combination. When SiC devices are used in matrix converters, the converters efficiencies exceeded 94% at 100 kHz, where when implemented with Si devices, they showed 90% efficiency. Also, much shorter turn on and turn off times can be achieved using SiC devices [28].

In a Photovoltaic Application, GaN HEMT switches have been chosen for a Quasi-Switched-Capacitor circuit, which forms the secondary side of a full-bridge current source isolated DC-DC converter [29]. Peak efficiency of 92.7% is achieved with a switching frequency of 500 kHz and 89.0% at 1 MHz which are relatively high efficiencies at such frequencies.

SiC devices can be used as a utility interface for battery systems. Similar to the results discussed above, analysis has shown good justification of increment in cost of system due to usage of SiC devices as the losses, weight and volume of converter came down considerably. This type of system works perfectly for solar systems where efficiency and reliability are important factors. An SiC converter showed high efficiency, both in charging and discharging modes when compared to Si converter [30]. It is surprising to see that the cascode configuration of Si MOSFET and SiC JFET perform better than SiC JFET itself. Cascode configuration, when implemented in a dc-dc boost converter showed an efficiency of almost 98% for 400 kHz and almost remained same for 1 MHz. The reason behind this high efficiency is that the SiC JFET operates in common-gate configuration and hence, no miller effect will be seen, leading to lower switching losses. An added advantage is that the commercial common driver can be used for this configuration needing no special driver design. An SiC MOSFET gave lower efficiencies than SiC JFET due to the higher on-resistance and higher parasitic capacitances [31].

Zero Voltage Switching (ZVS) converters find applications in high voltage DC system, inductive heating and electric chargers. SiC devices are proven to perform efficiently in these converters. One can use two level converters instead of a 3 level ones by deploying SiC devices. The superior benefits of using SiC devices in ZVS converters being low parasitic capacitances which allow fast switching with lower turn-off losses, low body diode recovery turn off time and low body diode charge which reduces losses and electrical noise. Also short turn on and turn off delay time of SiC devices will reduce dead time, which in turn reduces conduction losses and winding losses [32]. With possible high resonant frequencies, magnetizing and resonant inductances can be greatly reduced.

Application of WBG power devices in data centers has been investigated in [33]. For application in data centers, HVDC power distribution architecture is seen to be more efficient than AC power distribution architecture [34]. The former architecture includes a front end rectifier, intermediate bus converter and a load converter. SiC devices are deployed in a 480VAC to 400

VDC front end rectifier, and the full load efficiency obtained was 98.54%. GaN devices are deployed in a 400 VDC to 12 VDC intermediate bus converter which employs unregulated LLC resonant converter as the topology. It is important that the dead time of switches needs to be low to achieve effective energy transfer. Since dead time of switches is directly linked to the output capacitance of switching device, GaN devices exhibit lower conduction losses because of its low output capacitance. It is seen that transformer winding loss also depends on the dead time of switches (not directly proportional) and it was investigated that optimal dead time point for GaN devices is 120ns where as it is 150ns for Si devices [33]. The GaN based converter exhibits efficiency of 96.1% at full load, which is 0.6% higher than Si based converter.

Hybrid electric vehicles (HEV) gained the attention of the market in the recent years. To do their best in overcoming the present problems of global warming, automobile industries are investing huge amounts in research on electric vehicles and hybrid electric vehicles. In this scenario, it is being proved that SiC devices can give best solutions to tackle efficiency issues. A typical hybrid electric vehicle consists of a battery, inverter, dc-dc converter and a motor. The dc-dc converter works as a bidirectional converter charging the battery during regenerative breaking and delivering power to motor through the inverter [35]. The Motor is coupled to the Internal Combustion engine transmission and hence drives the car in electric vehicle mode. Experiments conducted on a bidirectional converter using SiC MOSFETs and SiC SBDs showed an average efficiency above 99% [36]. A Converter with SiC modules are seen to operate with 0.14% higher efficiency at 150 kHz switching frequency than a converter with Si modules operating with 20 kHz switching frequency. This is remarkable since it maintains efficiency and also reduces system volume, weight and cost at same time. In this case it is seen to reduce the weight by 4.60 kg and volume by 4.72 L. In other words, the SiC module gives the best platform for HEV since they can operate at high temperatures with relatively less cooling requirements, and provides extremely valuable energy savings, weight and volume. Thermal stress is the main concern in the inverters operated in electric vehicles. SiC device based inverters can overcome this challenge since the average junction temperature and junction temperature fluctuation is low, when compared to Si devices.

Chapter 4 - Other Applications of WBG devices

Apart from applications in Inverters and DC-DC converters, WBG devices find application in surge protection circuits which has been discussed in this chapter. Also a special nature exhibited by SiC JFET has been discussed in this chapter which enables it to function as a switch and also as an antiparallel diode with a few constraints.

Silicon carbide provides a solution to the problem of protection of electronics from over voltages due to transient events. Surge protection is a serious issue especially at higher temperatures because currently existing silicon devices become highly leaky at temperatures over 150^0C. SiC devices have a low instrinsic carrier concentration and this leads to only low leakage currents. Transient voltage suppressors fabricated in SiC are seen to withstand high temperatures up to 300^0C with leakage currents 6 times lower than that in Si devices [37]. Heat generated in die during surge events gets dissipated fast due to high thermal conductivity of SiC devices. Since the surge events last for only nearly 100s of microseconds, SiC devices are seen to withstand multiple back to back hits of surges. SiC devices can carry higher current densities and this results in smaller dies for a given current rating compared to Si devices. This in turn reduces the capacitance of the device and reduces the loading on downstream electronics. The weight and volume which can be saved gives a great advantage particularly when these devices are used in applications like aerospace, defence,etc. Analog and digital ICs, when fabricated in SiC showed reliable operation at high temperatures of 300^0C. A Special packaging process like Aluminum Nitride (AlN) thin film packaging process, was found to be a good match for protecting SiC based integrated circuits with coefficient of thermal expansion of AlN close to that of SiC [38]. Also, ceramic based electronic packaging technologies proved to be a reliable platform.

It has been proposed in [39-40] that a SiC JFET can be used without an antiparallel diode for the majority of applications. It has been seen that an enhanced mode SiC JFET with a vertical channel conducts well in reverse direction when gate and source are short circuited. This choice of operating switch in absence of anti-parallel diode is not seen with Si MOSFETs. The reverse recovery time of a SiC JFET was found to be lower than that of a Si MOSFET. It is also observed that under proper driving conditions, reverse recovery speed of a JFET is nearly equal to that of a SiC SBD. This makes SiC JFET, a good choice for high speed synchronous rectification and bi-directional switching applications. In addition, the SiC JFET was seen to operate well as a diode in reverse direction both at room temperatures and also at high temperatures of 150^0C thus not interfering with actual advantages of SiC switches. Even though operating a SiC JFET without an external diode may increase losses during the dead time period, experiments showed that the overall dynamic loss doesn't exceed 10%. So, making minor changes to the gate driver circuit and a little compromise on performance can reduce the number of components in a system along with reduction in cost.

Chapter 5 - Challenges in Application of WBG devices

The current chapter briefly discusses about the present challenges in application of WBG devices. Also, a few proposed solutions to overcome these challenges have been presented.

Increased electromagnetic interference (EMI) caused by fast voltage and current switching transients poses challenges to Electro Magnetic Compliance. An SiC MOSFET combined with Si diode reduces the radiated and conducted EMI generated by a converter. Also, separate heat sinks for each switch in a given circuit can considerably decrease the EMI magnitudes [41]. A high rate of change of current generates high voltages while the parasitic inductances in the power circuits are high. So, higher voltage rating SiC devices must be used which will increase the equipment cost. Low parasitic designs in packaging of WBG modules and external power circuits should be considered to avoid radiated emission. LC filters are used to control the high di/dt in converters [16].

Also, SiC devices have high output capacitance when compared to Si devices. Large dv/dt can occur in medium and high voltage power converters which will generate high current density in addition to high displacement currents through the parasitic capacitance of the module and the converter load. This makes it hard to achieve fast switching. Moreover dv/dt capability of SiC devices is much limited due to the high density of crystal defects that are present in the drift region of the device. In fact, GaN devices undergo more stress due to higher dv/dt values. These dv/dt values increase greatly with frequency and slightly decrease with temperature but this poses a serious problem of long term reliability [42-43].

Large voltage spikes can occur in motor drive systems with long feeder cables if high speed switching is employed. The cable behaves like a transmission line when used with high speed switches and causes voltage spikes. This phenomenon is called reflected wave phenomenon. Owing to this, maximum cable length allowed decreases with increase in switching speed. Cable dielectric failures and motor insulation degradation are some of the consequences of voltage spikes. WBG devices can stand as a potential cause for this phenomenon since they operate at high switching speeds, and hence shorter feeder cables should be used [44-45].

In addition to this, there are a few challenges to be faced during the packaging. Reduced chip area of WBG devices lead to a need of improved heat spreading strategy. New packaging methodologies should be followed to handle the high temperatures. In order to take advantage of high temperature handling capacity of WBG devices, one needs to have other devices in circuit like the passive devices and gate drives which can withstand such high temperatures. In short, the converter as a whole should be able to work in a high temperature environment. Cost of system would greatly increase if it totally relied on WBG devices [46-47]. Also, reliability of SiC devices need to be further investigated. In one way, hybrid devices can be a good solution for cost problem.

An SiC power module with an advanced structure has been proposed in [48] which greatly increases efficiency of a solar inverter along with reduction of equipment volume by nearly 75%. The proposed module structure consists of a PCB with copper pins in place of aluminum wires to connect power devices [Fig. 11]. To give a rugged performance, ceramic substrate with Silicon Nitride is used for better thermal conductivity and also epoxy resin is used to withstand high temperatures. Low internal inductance (see Fig.12) and lower switching losses were registered using advanced structure. All these factors make the device reliable and resulted in an 80% reduction in losses as compared to Si devices. When deployed in a solar inverter of advanced 3 level type, efficiency was improved to 99.0%.

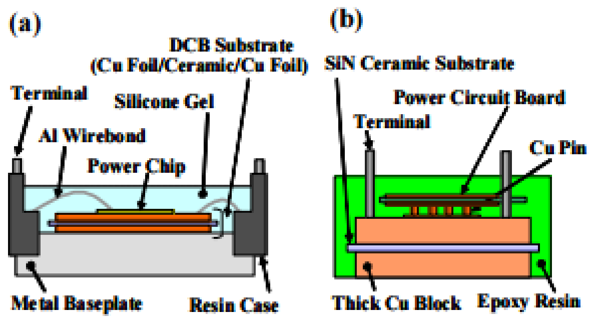

Fig. 11 Old and Advanced Structure [9]

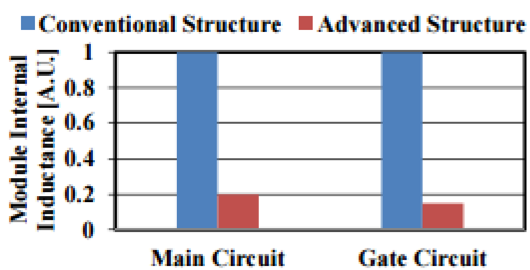

Fig. 12 Internal Inductance Comparison [9]

Chapter 6 - Conclusion

A brief survey of applications of wide bandgap power devices has been done and presented. Results obtained from the various experiments show that these devices have the potential to replace the existing Si devices especially in critical applications of aerospace, defense and upcoming electric vehicle systems.

GaN devices face challenges working in high temperature environments due to their low thermal conductivity, and with the current technology, they are not expected to perform well at voltages greater than 600V. However, GaN devices already have an advantage over using existing silicon substrates for their manufacturing and are proven to be very effective with operations involving high switching frequencies. They are highly potential candidates in RF frequency applications.

As seen in several sections above, SiC devices play a critical role in applications involving high temperatures and high voltages. They have the ability to greatly simplify systems by reducing the number of components, size and weight of systems. Higher pole machines can be used if SiC devices are used for drive control, which greatly reduces the size and weight of machine. The fact that SiC MOSFETs can operate without an external diode pave path calls for more research in that area. With further improvement in technology in this area, the cost of diodes can be totally eliminated in a system. SiC devices can be used for mitigation of frequency transients in grid because of their high switching frequencies. Hybrid SiC devices act as a smart solution to the problem of high cost. In many cases they are proven to be more efficient than Si devices. According to the Department of Energy, USA, billions of dollars can be saved in the form of energy savings if the cost of technology for production of semiconductors can be driven down [49]. Voltage transients can be mitigated by employing SiC devices, and so they can act as protection for downstream electronics in a system.

Various challenges being faced by SiC devices and possible solutions proposed by various authors are discussed. Relatively high cost, EMI issues, packaging requirements, displacement currents due to high di/dt are some challenges currently faced by WBG devices. Reliability tests are being performed, and all the challenges are expected to be overcome in the near future.

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