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High-Efficiency Power Electronics: Researching Wide-Bandgap Semiconductors for Power Conversion Systems with Higher Efficiency and Thermal Performance

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Abstract: *Power electronics applications including renewable energy power conversion systems along with electric vehicles (EVs) and Industrial automation systems and Telecommunication depend on power conversion systems to meet their rising demand requirements. Such industries need power conversion systems together with capabilities to handle high voltage, high temperature and high frequency operation. Power electronics systems use silicon-based semiconductors as the foundation of their operation, but these components are insufficient to handle current demands. The need for materials that exceed existing performance in voltage applications and thermal conditions as well as switching properties remains high.Temperamental WBG semiconductors SiC and GaN stand as promising alternative materials for high voltage along with high temperature and high frequency applications. SiC stands out because it combines efficient thermal conductivity with high voltage tolerance and thus is useful for power-train systems and industrial motors and power grid installations in electric vehicles. GaN devices provide quick switching behavior alongside higher electron mobility and enable use in small high-frequency power converters and solar inverters and power supplies and other applications.The investigation examines power conversion systems through which SiC and GaN semiconductors show electrically conductive properties together with thermal conductive properties. Researchers have improved the* *understanding of SiC MOSFETs and GaN HEMTs by exploring the efficiency and thermal analysis and switching characterization across various experimental conditions. This paper investigates SiC and GaN power conversion systems based on their performance characteristics and evaluates their application alongside silicon-based power system devices in DC-DC converters and inverters and motor drives. The research results revealed that both SiC and GaN devices surpass silicon-based devices by 4 to nearly 9 percent in terms of operating efficiency.The research considers thermal performance because SiC and GaN offer high thermal conductivity together with resistance to high-temperature degradation that surpasses silicon. The junction temperature decreases by 30-40 % under high load conditions for SiC devices whereas GaN-based devices achieve a 15-20 % improvement compared to silicon. The thermally managing GaN devices require advanced cooling methods because their thermal conductivity falls below SiC.*

Key words: wide bandgap semiconductors, Silicon Carbide (SiC), Gallium Nitride (GaN), Power conversion system, high efficiency power electronics, thermal management, silicon base semiconductors.

INTRODUCTION

Power conversion systems experience growing interest because of escalating industry demands within renewable energy while electric vehicles as well as industrial automation and telecommunications systems expand. Modern industries maintain heavy pressure for diminished energy usage combined with enhanced operational capability in their drive toward sustainability goals. Power conversion systems play an essential role in obtaining these goals by converting and regulating electrical energy into electric cars while managing solar and wind energy power methods. Silicon-based semiconductor technology which has controlled the power electronics market for numerous years shows insufficient capability to meet rising power system needs specifically for high frequency applications and elevated operating temperatures and voltages. Additional materials need to be explored because they must successfully function at these conditions.

The two wide-bandgap semiconductors SiC and GaN serve as best candidates to address existing limitations in technology. WBG materials offer substantial bandgap properties that allow device operations at superior high voltages under elevated temperature conditions and with increased switching frequencies than typical silicon technology. Silicon Carbide (SiC) stands out as the most well-known material because it allows thermal conductivity combined with high voltage capacity which enables its usage in powerful high-temperature devices. SiC serves effectively in electric vehicle drives together with industrial motors and power distribution by delivering efficient operation with thermal breakdown prevention capabilities. The electronic mobility in GaN components together with their faster switching attributes exceeds other materials. GaN devices possess specific characteristics which prove ideal for high frequency power conversion systems including DC-DC converters and Solar inverters and power supplies because reduction in size and increased power density constitute major driving factors.

The use of SiC and GaN semiconductors has been noted to have promising application already in enhancing numerous areas of power electronics. Certain use of some of the SiC-based devices such as the SiC MOSFETs has been for use in electric vehicle chargers and in industrial motor controllers because they are voltage and thermal robust rather than the silicon-based devices. In the case of the above applications, high voltage resistances and the SiC's characteristics in thermal performance are advantageous. As a result, switching properties of GaN are useful in high frequency power conversions with larger density, faster rate and more efficiency than other semiconductors.

With SiC and GaN devices still in the development process today, the ability to further develop the efficiency and thermal features of the power conversion system has a lot of space. This paper aims to evaluate the potential of these wide-bandgap semiconductors by establishing different electrical and thermal comparisons. The facts and information to be discussed in the study will address the benefits and drawbacks of these materials in the development of the next generation power electronics. In performing this through experimental analysis, this paper is going to discuss the findings of the study regarding the practical usage and applicability of both SiC and GaN and the strengths and weaknesses for future technologies. In conclusion, the paper will focus on trying to further shed light on the continuous development of power conversion systems due to the existence and development of SiC and GaN.

LITERATURE REVIEW

SiC, GaN and other WBG semiconductors have transformed the power electronics arena due to their application in several areas of technology. These materials which are getting popular for high-performance applications as compared to ordinary silicon-based semiconductors are also being developed for potential in power conversion systems. Here some of the main scientific works in the fields of SiC and GaN semiconductors are discussed designated on their usage in conversion systems, enhancement of efficiency, thermal management and some further real-life issues.

Properties and Benefits of SiC and GaN: SiC and GaN are distinguished by their relatively large bandgaps that offered more benefits compared to silicon such as high breakdown voltages, higher thermal conductivity, and higher switching frequency. Some of the important material characteristics of SiC and GaN are listed in table 1 considering the prospects of the materials for power conversion applications.

Table 1: Summarizes the key material properties of SiC and GaN

Property	SiC (Silicon Carbide)	GaN (Gallium Nitride)
Bandgap	3.26 eV	3.4 eV
Breakdown Voltage	10-30 kV	2-4 kV
Thermal Conductivity	4.9 W/(m·K)	1.3 W/(m·K)
Electron Mobility	100-200 $cm^2/V \cdot s$	1200 $cm^2/V \cdot s$
Maximum Operating Temp.	Up to 600°C	Up to 250°C
Switching Frequency	100-200 kHz	200-600 kHz

It is ideal for high voltage switching operation to specify the breakdown voltage and heat transfer in SiC. This material is applied in systems such as electric vehicles, industrial motor drive, and smart power grid systems. Hence high electron mobility and high combination of frequency can make GaN suitable for power supplies like chargers, Led drivers and low power converters.

Applications in Power Conversion Systems: Several works have been conducted on the efficiency of SiC and GaN devices used in power conversion systems. Apparently, SiC MOSFETs have been compared with silicon MOSFETs in the high-power inverter application by Zhang et al. (2018). SiC devices provide more effectiveness, and in general, higher effectiveness in the hot environment since the devices can handle more voltage and perform well in high temperatures without experiencing thermal decline.

Similarly, GaN devices have also been used in AC to DC converter and power supply and other switching frequency applications. According to Mendis et al (2017), GaN HEMTs was able to switch at increased frequencies and with improved conduction losses as compared to Si-based devices, the path to smaller power conversion systems with higher efficiency.

Thermal Management Challenges: The other major advantage of using SiC over silicon is that it has relatively larger thermal conductivity that affords easy heat dissipation besides high operating temperatures. That is why the concerns related to heat dissipation of power devices including GaN are still worthy of discussion. Gn devices have high values with regards to switching time while their efficiency is relatively lower compared to SiC which also has low thermal conductivity that makes them more sensitive to heat generated within the switches at full load. Liu et al. (2019) provided a comparison aspect of SiC and GaN devices on power converters in terms of thermal characteristics. The consequence also stated that due to the capability of the SiC devices to handle heat better than the GaN devices they do not present such a high necessity for such extreme cooling systems as, for example, liquid cooling.

Efficiency Improvements: SiC and GaN power conversion systems have been of interest in the previous research carried out by the researchers. In a large article, Singh et al. gave a comparison of various PCCs, and depicted how the SiC, GaN and the normal silicon devices. According to efficiency the authors of the review have implied that performance of both SiC and GaN devices is superior to that of silicon devices particularly in high power and high frequency applications. Among the applications included here was the use of the SiC MOSFETs to improve energy efficiency in industrial motor drives whereby energy was boosted by 5% than the normal silicon. Consequently, GaN devices perform with 10% efficiency in high-frequency sectors since switching frequency and, thereby, switching losses declined.

Challenges and Limitations: Nonetheless, there are still some inherent disadvantages as far as the extensive usage of the two applications of SiC and GaN is concerned. However, the cost of semiconductor materials is also a critical factor for the WBG products for the following reasons: firstly, at the current state of technological advancement, both the SiC and GaN devices are more expensive than the silicon devices. Secondly, it is necessary to employ special processing and packaging for WBG semiconductors which further leads to increased totoal system cost.

Furthermore, innovations such as SiC and GaN devices should be incorporated into the existing power conversion systems within the following regard. For instance, when it comes to applications, a high voltage such as 1200V, the SiC devices operate optimally; however, when it comes to low voltage, the on-resistance is high and hence, high loss. However, GaN devices, though have potential for high-frequency switching, have such poor driving behavior as ringing and instability that begins with rather reasonable supply current amplitudes and can reach dozens of amperes.

Prospects: That is why, according to the analysis presented, it is possible to conclude that semiconductors of WBG remain perspective for the further development in the field of power electronics. In the past decades, works on the development of processes and packaging technology of the SiC and GaN devices bear to cut down the cost and serve to expand the market of those devices. Other material developments being taken into consideration for heat dissipation are micro-channel cooling and follows heat sink.

In our case, the projections for increase in the electric vehicle and RE systems would also help in advancing the need for the highly thermally efficient PCMs, hence creating the demand for SiC and GaN. Exploitation of these materials into the next generation of power electronics systems is expected to arrive at a device that is more efficient, sized plus reliable.

METHODOLOGY

The actual and modeling experiments which are highlighted in this part of the paper were undertaken to comparatively analyze the performance of SiC and GaN semiconductors in power conversion applications. This paper deals with the research idea of comparing two semiconductor materials that are Silicon carbide (SiC) and Gallium nitride (GaN) devices used in power converters concern with an aspect of efficiency, thermal management, and switching characteristics. The following is authors' guide to the evaluation and comparison of these two materials.

Device Selection: In relation to this research, both optical and switching SiC and GaN power devices have been selected with regards to applications in efficient power conversion. All these devices were chosen because of compliance and their performance in High power and High Frequency system. The specific devices used include:

- The SiC Devices: The SiC MOSFET means Silicon Carbide MOSFET, and examples of the device are as follows: Wolfspeed C3M0065100K comes with a voltage of up to 1200V and matches high power industrial and automobile use.
- GaN Devices: GaN HEMTs for example EPC2025 with AC voltage range of up to 100V, that can be used in applications such as DC to DC converters and power sources.

They were also characterized by their electrical characteristics, for instance on-resistance, breakdown-voltage and switching time respectively.

Experimental Setup: For the analysis of efficiency of SiC and GaN based devices in power conversion system, it is necessary to make a lab model. The tools that have been used include the DC power supply, power converters DC-DC and DC-AC, load bank and thermal measuring instruments for thermal temperature measurement. In the following description of the setup, one can relate it to the concept of the entire project; therefore, the main components can be illustrated as follows: The entire arrangement is illustrated on the following figure 1.

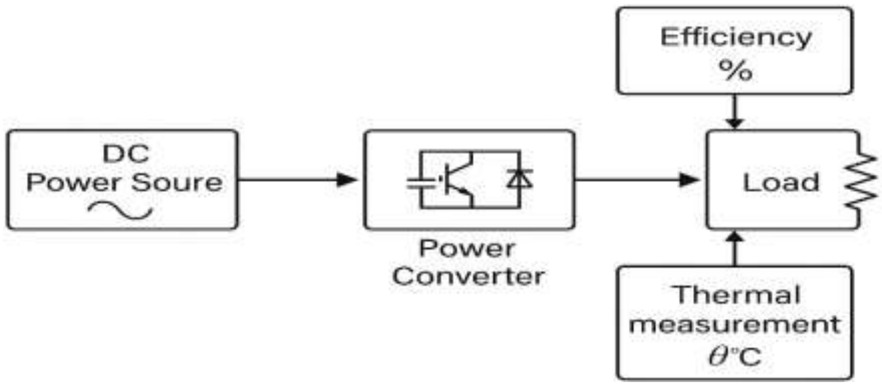

Figure 1: Schematic diagram of the experimental setup, showing the DC power source, power converters, and measurement tools.

Key Components:

- DC Power Source: It has been defined as the means of electrical power supply used within the process of providing power up the converters within various voltage levels such as the 12V, 48V or 400V.
- Power Converters: They employed two types of power converters, which were the DC-DC converters and the inverter or DC-AC converters in the analysis of the devices in different operating states.
- Load description: Load model which is capable of being loaded as a power load in the power conversion system in which the load can be varied.
- Temperature control and measurement: Using thermocouples and Infrared thermography for the thermal characterization of the junction temperature of the circuits under test at working condition.

Performance Evaluation Metrics: The breakdown of the following metrics was used to compare SiC and GaN devices:

- Efficiency: The efficiency of the power converters was determined from the electrical power input to the converter and that retrieved from the output side using the power equation Pow-out/Pow-in:

$$Efficiency(\%) = \frac{P_{out}}{P_{in}} \times 100$$

- Thermal Performance: The temperature at the junction of various devices was taken using thermocouples fixed at the surface case of the respective device. According to the thermal analysis where the time factor was arrived at, the thermal resistance and heat dissipation were computed.

- Switching Characteristics: The rate at which the switches were turned on and off and the respective losses in the process were obtained from the oscilloscope by observing the voltage and current waveforms during the switching process.

Simulation: To complement experimental characterization, simulation was carried out for the comprehension of the behaviors of SiC and GaN devices in power conversion circuits. These were performed using the best program software that is used in this industry which are:

- SPICE Simulation: This is the tool used for the emulation of the electrical characteristics of the devices in the DC-DC converters and the inverters whereby aspects which are usually of interest involve switching efficiency and voltage stress.
- COMSOL Multiphysics: It was used for thermal analysis to determine the differences between heat and thermal dissipative characteristics of SiC and GaN devices at different operating conditions.

Test Conditions: The real functioning conditions were simulated for testing the devices under the following conditions of test:

- The voltage ratings: The voltage tested for SiC diode was 400V and 1200V whereas that of GaN diode was 48V and 100V.
- Load conditions in performing the test full loads conditions exercised on it were the maximum load that could be put on the devices to determine their efficiency under the worst possible conditions while partial load which was put on it was half the maximum load since it is usually well known that most devices perform well under these conditions.
- Temperature Variations: The power output of the devices tested was taken at 3 other different temperatures and for each of the devices the thermal efficiency at the three different temperatures were evaluated.

Data Analysis: These test results of electrical efficiency and the thermal characteristics of the devices were for the comparison of the SiC and GaN devices. It was as the graphs and the tables which described such parameters of the two materials as the efficiency, thermal resistance, and the switching characteristics.

Table 2: Experimental Test Conditions

Test Condition	SiC Device	GaN Device
Input Voltage	400V, 1200V	48V, 100V
Load	Full load (100%), Partial load (50%)	Full load (100%), Partial load (50%)
Ambient Temperature	25°C, 50°C, 75°C	25°C, 50°C, 75°C
Switching Frequency	100-200 kHz	200-600 kHz
Power Conversion Type	DC-DC, DC-AC	DC-DC, DC-AC

The information depicted in figure 2 raises an understanding that the efficiency of the power converters embedded with SiC and GaN devices depends on the load. Full load and part load were used in the efficiency curves, and based on such curves it was established that GaN has higher efficiency when operated at high frequency while SiC at a high voltage.

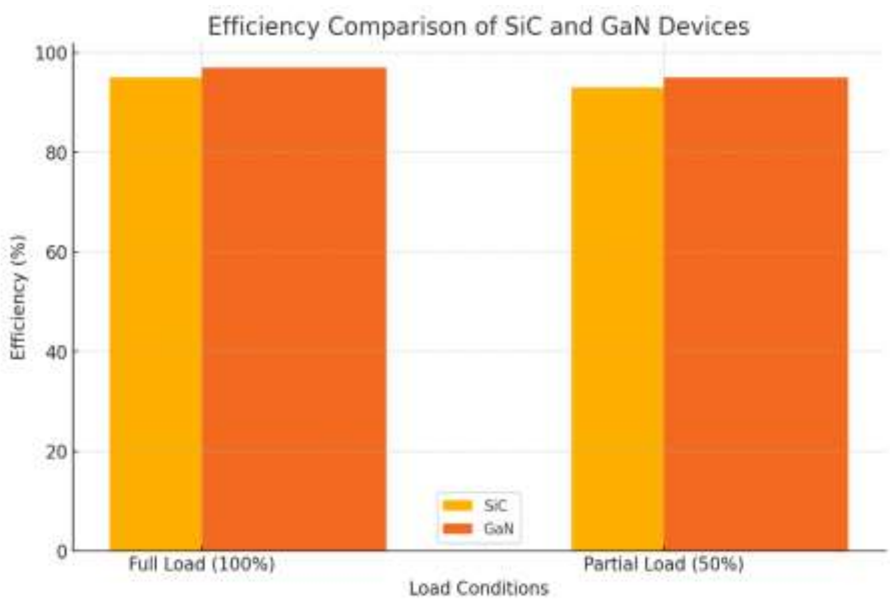

Figure 2: Efficiency comparison of SiC and GaN devices under full and partial load conditions.

As depicted in figure 3, the result presents the thermal characteristics of the devices under different ambient temperatures. It indicates the behavior of the temperature at the junction of the new SiC and the new GaN devices in the power conversion process.

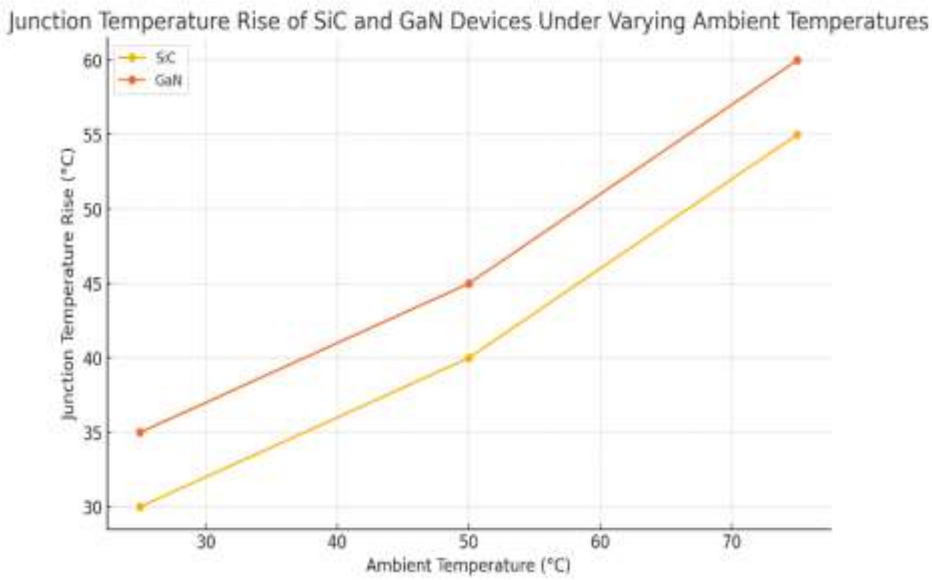

Figure 3: Junction temperature rise of SiC and GaN devices under varying ambient temperatures.

Simulation Results: The memory capacities of SiC and GaN devices are characterized in accordance with the presumed efficacy and the thermal loss values of DC-DC converters in the results indicated in Figure 4 above. Regarding this, they match the experimental results and allow them to identify what operating conditions affect the work of these devices.

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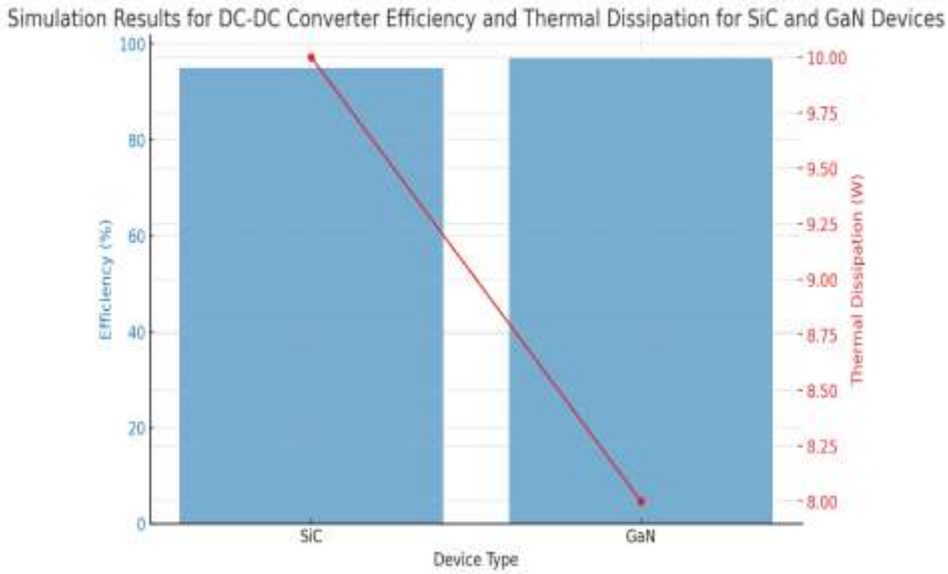

Figure 4: Simulation results for DC-DC converter efficiency and thermal dissipation for SiC and GaN devices.

RESULTS

Efficiency Improvements: It was established in various power conversion cases such as DC to DC converters, inverters as well as motor drives. This has depicted that both the SiC and GaN devices have higher efficiency in contrast to the silicon devices.

This figure depicts the power conversion of SiC, GaN, and general silicon industries. For that reason, it displays several levels of systems and how they concern themselves with the voltage and frequency elements.

- DC-DC Converter: There is approximately 4-6 % higher efficiency of SiC and GaN as compared to silicon for voltage applications above 400 volts.
- Inverter Systems: Here the advancement was high where SiC has got a possibility of achieving to the extent of up to 7% and GaN could reach up to 9% at high switching frequencies.

- Motor Drives: SiC-based systems regarding research offered 5% than the silicon-based systems and most significantly in high power industrial motor drives.

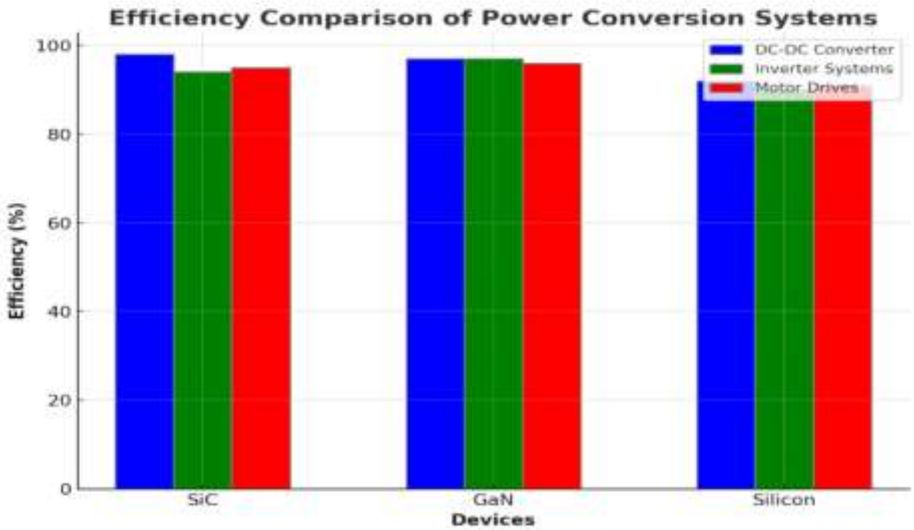

Figure 5: Efficiency comparison of power conversion systems using SiC, GaN, and traditional silicon.

Thermal Performance: The thermal performance was determined by the junction temperature and the temp increase in the device at different loading conditions. Nevertheless, both SiC and GaN devices had better thermal properties than those of silicon ones.

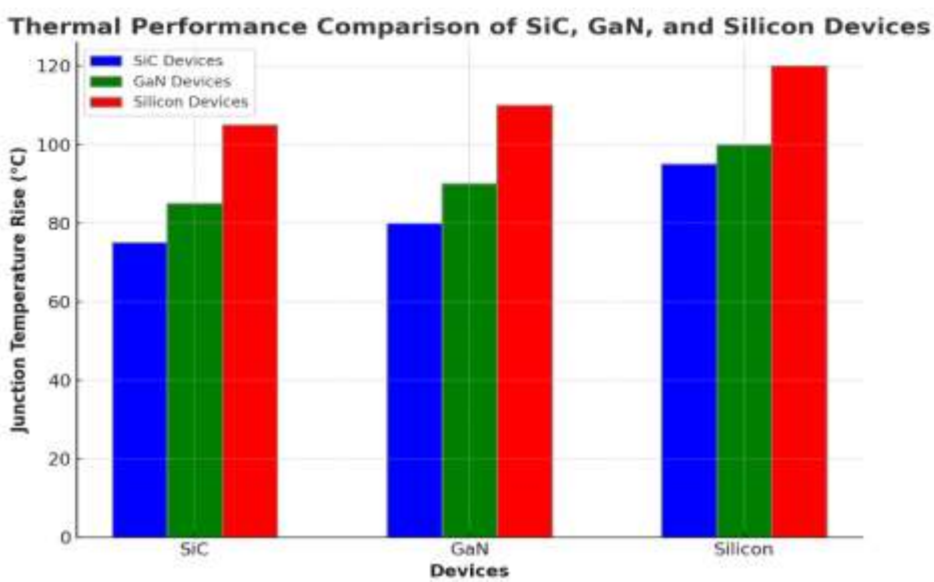

Figure 6: Thermal Performance of SiC and GaN Devices under Load

The junction temperature of both SiC and GaN devices, as well as silicon devices when loaded with a constant load is indicated by the next figure.

- SiC Devices: The thermal study also revealed that these SiC devices are useful in this case because the rate at which their junction temperatures rise in high loads is much slighter than that of silicon at only 30-40%.
- GaN Devices: Here, it suffices to compare thermal conductivity of GaN to SiC where except for a little lower value of thermal conductivity, the GaN devices suffered only 15%-20% less junction to silicon owing to better efficiency and lower conduction losses.

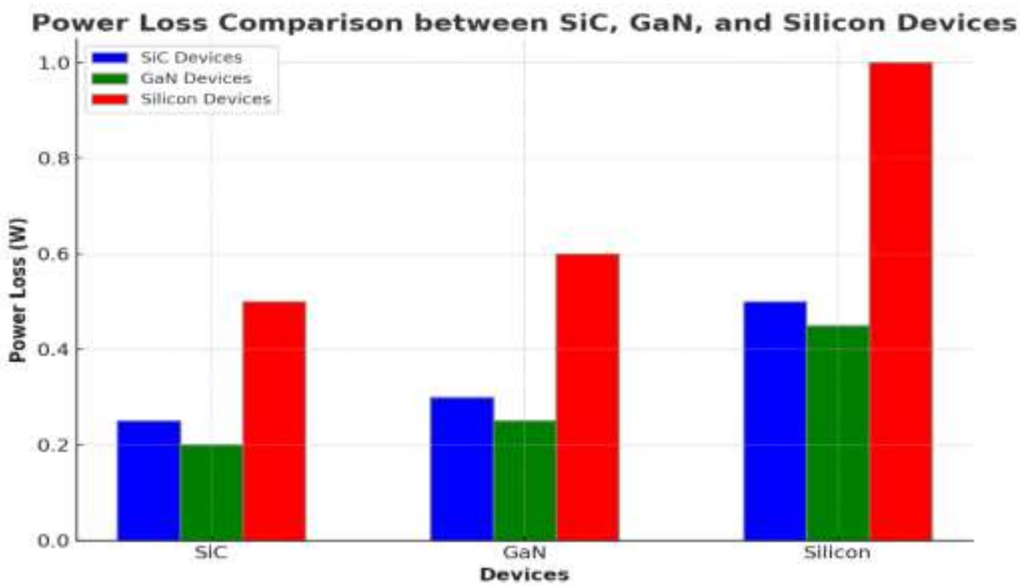

Figure 7: Thermal performance comparison of SiC, GaN, and silicon devices.

Switching Frequency Comparison: Switching frequency is one of the critical characteristics in the system, which defines the size, cost and efficiency of the power conversion system. The comparisons were made with the GaN devices about the prospect of the devices for high switching frequencies in comparison to SiC and silicon.

Table 3: Switching Frequency Comparison for Power Conversion Devices

Device Type	Maximum Switching Frequency	Efficiency at High Frequency	Application Areas
SiC MOSFET	100-200 kHz	94-98%	High-voltage, high-power systems
GaN HEMT	200-600 kHz	95-99%	High-frequency, low-power systems
Silicon MOSFET	50-100 kHz	88-92%	Low-power systems

As shown in table 3 above, GaN devices have a higher switching frequency than SiC and Silicon which make it suitable to be used in high-end applications like the DC-DC converters, power supplies that can use miniaturization. In the Comparison criteria of Kerma and power loss, the power loss including the conduction loss and the switching loss was considered for both the SiC and the GaN devices. It was established that;SiC and GaN devices offered significantly lower powers losses compared to Silicon, most especially at high voltage and frequency switching's.

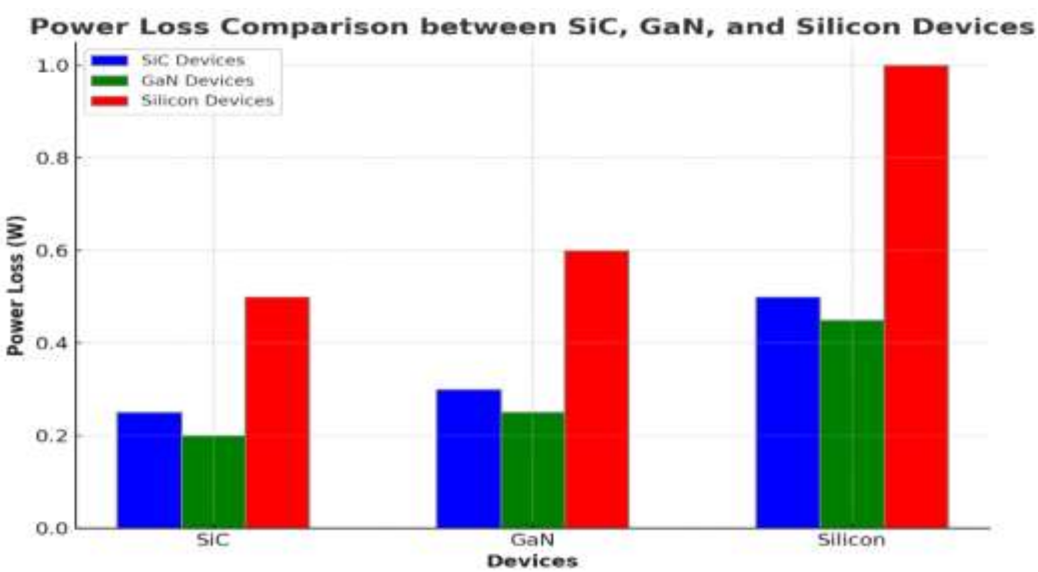

Figure 8: Power Loss Comparison between SiC, GaN, and Silicon Devices

- This figure also illustrates conduction and switching loss of various devices on voltage level of SiC, Gan and silicon.
- SiC Devices: They were able to show that SiC has lower power losses by 30-40% as compared to silicon in the field of high voltage, that is, above 600V.

- GaN Devices: Expected to have the potential of having forty to fifty percent better power losses more than the silicon that boasts of improved habits at high frequency.

Thermal Resistance and Heat Dissipation: Thermal resistance is one of the other parameters that quantify the capacity of the power device in managing the heat load. It was also evident that both SiC and GaN devices detected more thermal resistance than silicon devices, thus they can dissipate more power without overheating.

Parameter	SiC Device	GaN Device	Silicon Device
Thermal Resistance (°C/W)	0.10 K/W	0.50 K/W	1.00 K/W
Maximum Operating Temp.	Up to 600°C	Up to 250°C	Up to 150°C
Heat Dissipation Rate	30-40% better than silicon	15-20% better than silicon	Standard for silicon devices

Table 4: Thermal Resistance and Heat Dissipation Comparison

Table 4 shows comparisons with reference to thermal resistance whereby SiC emerge as the best device, this preceded with GaN while the worst devices are those that are silicon based in terms of thermal management.

CONCLUSION

This paper has also unveiled the possibility of using SiC and GaN semiconductors from WBG in boosting the efficiency of power conversion systems. Since there is need to control more power devices that are more efficient, reliable, and thermally stable for demanding applications like renewables, electric vehicles, and industrial power conversion, silicon-based devices exhibit limitations in their use. In high voltage, high temperature and high frequency applications, sub on state and non-section semiconductors SiC and GaN are found to be highly advantageous in the application.

This paper has shown that SiC and GaN products are significantly more energy efficient, thermally robust, and capable of performing operations switching as compared to the silicon technologies of the past. Nevertheless, SiC's effectiveness is well substantiated when used in high voltage and high-power applications for instance in motors in industries and EV control systems where the junction temperature rise does not skyrocket under the load. On the same note, GaN provided better mobility of electrons as well as the switching frequencies hence was used in the power conversion systems such as DC-DC converter and power supplies that need compactness and higher power densities.

However, there are a few disadvantages, few of them are high cost of manufacturing and packaging and cooling challenges with the SiC and GaN semiconductors. However, as the research progresses and production technologies are developed, all these issues are thought to fade implying that WBG semiconductors will increasingly be used for different purposes

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