Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 05 , May - 2026

Gallium Nitride (GaN) based Electric Vehicle Chargers: A study on Performance, Challenges, and Future Perspectives

Vedant Kumar Saha
Scholar, B. Tech. (Electronics and Communication Engineering), National Institute of Technology Raipur, Chhattisgarh, India.

Dr. Sapan Kumar Saha
Chief Operating Officer (ESG & Energy), Nandan Group of Industries, Raipur & BEE- Certified Energy Manager (NPC Govt. of India) Raipur, Chhattisgarh, India.

Abstract: GaN, a wide-bandgap semiconductor material, has become a crucial technology for the creation of next-generation EV charging infrastructure because of its excellent electrical characteristics, small size, and high efficiency. The performance, challenges, and future perspectives of electric vehicle (EV) chargers based on gallium nitride (GaN) are examined in this study. The study offers a thorough examination of GaN's benefits over conventional silicon-based technologies, talks about the operational and technical difficulties in implementing GaN-based EV chargers, and outlines possible directions for further study and advancement in this field. The effects of GaN on power density, cost-effectiveness, thermal management, and integration with new fast-charging standards are thoroughly examined. This study examines how GaN technology can be incorporated into the EV ecosystem by assessing its performance metrics, discussing the technical and financial obstacles—such as high manufacturing costs and dependability in high temperatures—and outlining the future prospects that will determine the direction of high-efficiency power electronics.

Keywords: GaN, Electric Vehicle (EV), Charger, Power Electronics, Efficiency, Semiconductor, Wide-Bandgap, Fast Charging.

1. INTRODUCTION

Electric vehicles (EVs) are at the forefront of the global automotive industry due to the shift towards sustainable mobility. However, the creation of effective, quick, and small charging infrastructures is still crucial to the general adoption of EVs [1]. In terms of power density, switching speed, and thermal management, conventional silicon (Si)-based power electronics, which have been the industry standard for decades, are progressively approaching their theoretical limits [2]. Gallium Nitride (GaN), a wide-bandgap (WBG) semiconductor, has emerged as a revolutionary option for the upcoming generation of EV chargers in order to overcome these obstacles [3]. GaN has higher breakdown voltages and better electron mobility than silicon, enabling much faster switching frequencies and lower energy losses [4]. These characteristics enable the design of "on-board" and "off-board" chargers that are not only smaller and lighter but also capable of delivering rapid charging speeds with minimal heat dissipation [5].

Power electronics is the foundation of energy conversion in a variety of industries, such as consumer electronics, electric vehicles, telecommunications, and renewable energy [6]. Although silicon-based semiconductors have long dominated the market, there is a need for substitute materials due to their physical drawbacks, such as slower switching rates and lower breakdown voltage [7]. Currently, the automotive industry is going through a revolutionary phase characterized by connectivity, autonomous driving, and electrification. Original equipment manufacturers (OEMs) are investing more in hybrid and electric vehicles (EVs) due to the EV market's rapid expansion, which began in China and will soon spread to Europe, the US, and other regions. By 2030, these cars are expected to make up around 50% of all car sales [8].

The global market for electric vehicles (EVs) has evolved from a specialized sector to a key component of the global shift to zero-emission transportation. Over 17 million electric vehicles were sold worldwide in 2024, making up more than 20% of all new cars sold. Experts predict that the worldwide EV market will generate around $1 trillion in revenue by 2026, and buyers will have access to more than 1,000 distinct models [9]. China, Europe, and the United States, which together accounted for around 95% of global EV sales in 2024, presently dominate the market. China continues to be the unchallenged leader, accounting for more than 70% of global production and about half of all new sales. While some European markets have seen a minor slowdown in growth due to the phase-out of subsidies, emerging economies in Asia and Latin America are experiencing rapid increases, with sales in some regions rising by more than 60% annually [10]. Predicted global automotive sales is shown in figure 1.

The Critical Requirement for Fast Chargers: As EV adoption moves from early adopters to the mass market, the availability of fast and ultra-fast charging has become a primary driver for consumer purchase decisions. McKinsey & Company found that 80% of EV owners consider fast charging availability crucial when choosing a vehicle [11].

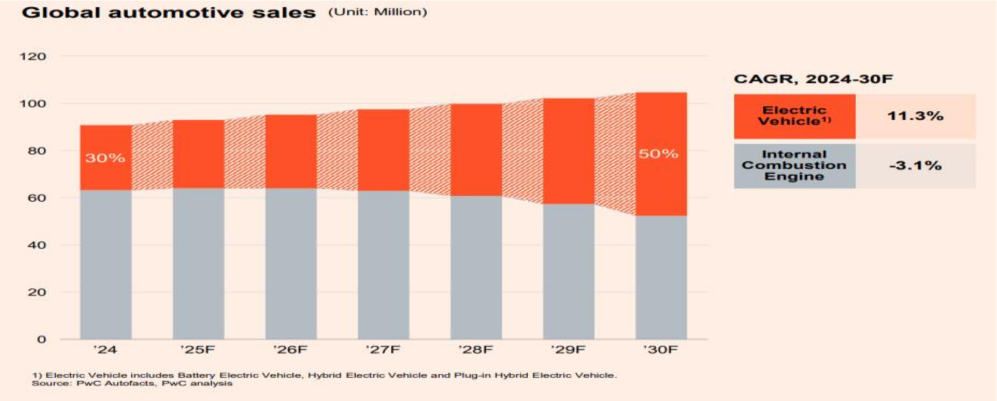


Figure 1: Global Automotive sales
[source: PwC Semiconductor Center of Excellence, Korea]

Increasing trends of use of electric vehicles is growing quickly as businesses and governments push for more environmentally friendly modes of transportation. The creation of dependable and effective EV charging systems is essential to this transition. Larger systems and longer charging times result from the efficiency, size, and thermal management constraints of conventional silicon-based power electronics [12]. These issues may be resolved by the wide-bandgap semiconductor material gallium nitride (GaN). Wide bandgap (WBG) semiconductor materials, primarily silicon carbide (SiC) and gallium nitride (GaN), are becoming increasingly popular in the power electronics industry [13]. GaN in particular stands out as a game-changing technology that offers notable improvements in both industrial deployment and research innovation [14]. Higher switching frequencies, lower losses, and better thermal performance are just a few advantages GaN-based devices possess over their silicon equivalents [15]. The deployment of fast-charging infrastructure, which is essential for the mainstream adoption of EVs, is expected to be accelerated by the incorporation of GaN in EV chargers [16]. This study examines the performance of GaN-based EV chargers, highlights the difficulties in their creation and application, and offers an outlook on potential future developments.

2. LITERATURE REVIEW

2.1 Synthesis of GaN Material

“Gallium nitride (GaN) was synthesized by injecting ammonia gas into molten gallium at 900–980°C under atmospheric pressure. GaN crystals were largely formed by direct reaction between Ga and the gaseous N source at the surface of the NH_3 bubbles in the melt. GaN synthesized by this method may be useful as a starting material for bulk growth” [17].

The formula ($2\ Ga + 2\ NH_3 \rightarrow 2\ GaN + 3\ H_2$) depicts that, how gallium metal and ammonia gas react, usually at high temperatures, to produce gallium nitride [18]. Hydrogen gas is produced as a byproduct of this redox reaction, in which Ga is oxidized and N is reduced. Here, Ammonia gas (NH_3) is utilized as a source of nitrogen because gallium (Ga) metal and nitrogen gas (N_2) do not react at atmospheric pressure.

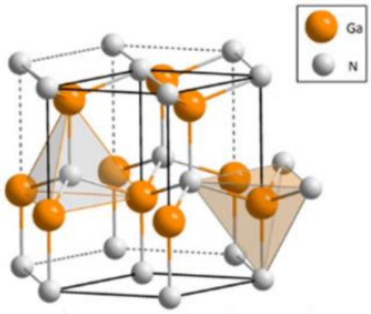


Figure 2: Gallium nitride (GaN) Wurtzite crystal structure.
(Image courtesy: everythingPE [19])

Gallium nitride (GaN) Wurtzite crystal structure, displaying tetrahedral coordination between gallium (Ga) atoms (Orange) and nitrogen (N) atoms (Gray). Gallium nitride (GaN) Wurtzite crystal structure is shown in figure 2. GaN has a melting point of 4532°F/1700°C, the resulting hexagonal crystal structure is extremely robust and durable. GaN can therefore function at higher temperatures than its silicon equivalents. In comparison to silicon, it also has a wider band gap. The energy needed to separate an electron from its orbit is known as the band gap. GaN is insoluble in water, acids, and alkalis at room temperature. GaN is especially appropriate for high frequency applications (in the 1 THz region) due to its high electron mobility of 2000 cm^2 /Vs [20].

2.2 GaN Semiconductor

For electronics applications, wide bandgap (WBG) semiconductors are preferred over narrow band semiconductors (like silicon), all other things being equal, because the large energy separation between the conduction and valance bands enables these devices to operate at higher voltages and temperatures [21]. Bandgaps measure how much energy is required to push an electron into a conducting state; a bigger bandgap enables a material to withstand a stronger electric field so components can be thinner (for a given voltage), lighter, and handle more power than parts consisting of materials with lower bandgaps [22]. GaN and silicon carbide (SiC) in particular have significantly improved uses for power switching and/or power amplifiers. Gallium Nitride (GaN), for instance, has a bandgap of 3.4eV as opposed to the comparatively small bandgap of 1.1eV of the industry mainstay Si. Benchmarking of Merit for WBG Materials Compared to Si in a Radar Chart is shown in Figure 3.

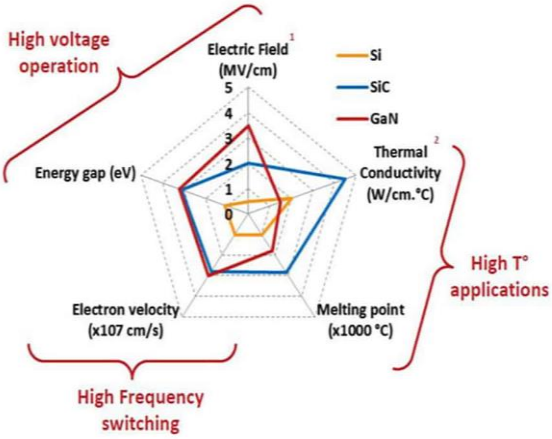


Figure 3: Benchmarking of Merit for WBG Materials Compared to Si in a Radar Chart [Image courtesy: www.tti.com, [23]

Therefore, GaN material is perfect for high-efficiency power electronics because of its characteristics, which include increased electron mobility, reduced on-resistance, and the capacity to function at higher voltages and temperatures. GaN's capacity to facilitate high-frequency switching lowers device power losses, improving energy efficiency. Table 1 highlights the superior material properties of GaN by comparing important parameters between silicon and GaN-based power devices [24].

Table 1: Comparisons between silicon and GaN-based power devices

Type of power device	Parameters						
	Bandgap (eV)	Breakdown Field (MV/cm)	Thermal Conductivity (W/cm K)	Max Operating Temperature (°C)	Electron Mobility (cm²/V·s)	Wafer Diameter	Maximum Frequency
Silicon (Si)	1.1	0.3	1.5	150	1400	8 inches	1 THz
Gallium Nitride (GaN)	3.4	3.3	2.3	600	2000	3-6 inches	3.8 GHz

(Data courtesy: IEEE [25])

2.3 GaN in Power Electronics for EV Chargers

GaN-based devices are more efficient than conventional silicon-based solutions in power electronics, especially in applications demanding high-voltage conversion. GaN transistors can be used in EV chargers to reduce energy usage, the size and weight of the power converter, and the amount of cooling that is needed. According to studies, GaN can increase DC-DC converter efficiency in EV chargers by up to 30% when compared to silicon-based designs, resulting in quicker charging periods and smaller systems [26]. “GaN is a growing technology that is transforming EV battery traction inverter designs, because of its remarkable performance over conventional Silicon and SiC alternatives [27].” Designers of electric vehicles (EVs) seek to make EVs lighter, more autonomous, and with smaller batteries by supplying more power, decreasing heat dissipation, and reducing system size. Because EVs are built to withstand vibration, extreme heat, and other environmental factors, their powertrains are designed to be lighter and more compact. GaN's capacity to regulate heat eliminates the need for large heatsinks and cooling systems, which reduces the weight of the vehicle [28]. GaN integration is very beneficial to the automotive industry. To control the flow of energy between the battery, motor, and charging system, electric vehicle (EV) powertrains depend on effective power electronics. Higher power density is made possible by GaN devices, which also make power modules lighter and smaller. This improves battery performance, resulting in longer driving ranges and quicker charging times [29] . GaN-based onboard chargers are a popular option for next-generation EVs because they enable quicker charging while producing less heat [30].

3. METHODOLOGY

The performance, challenges, and potential future paths of GaN-based EV chargers are examined in this study using a methodical methodology. The research includes:

- **Performance Analysis:** To assess important performance metrics like efficiency, power density, and switching frequency, experimental data from numerous studies and GaN-based charger prototypes are examined.
- **Challenges in developing GaN-based EV Charger:** A mix of expert interviews and a review of the literature is used to identify the operational and technical obstacles to the broad use of GaN-based chargers.
- **Future Perspectives:** With an emphasis on enhancing the scalability, dependability, and affordability of GaN chargers, possible technological developments and research avenues in GaN-based power electronics are examined.

4. PERFORMANCE OF GaN-BASED EV CHARGERS

We created a simulation model of a common DC-DC converter used in EV charging in order to assess the performance of GaN-based EV chargers. The model's primary components are: First, efficiency calculation: GaN-based and silicon-based converters' power conversion efficiency is modelled by the simulation. Second, power density and size: Based on GaN's exceptional efficiency and switching capabilities, the model assesses the charger's power density. [31].

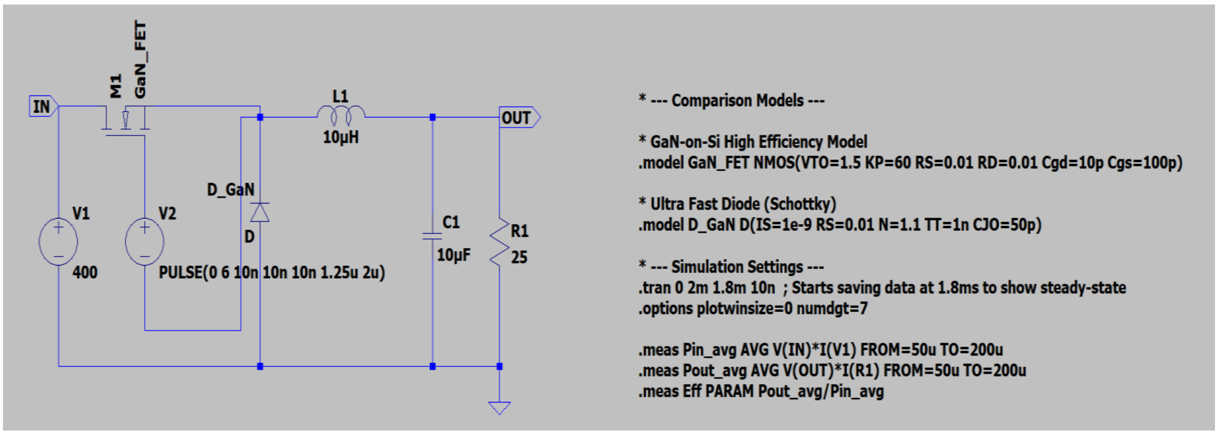
4.1 GaN-based EV Charger Simulation Model: The power converter is modelled as a mix of a high-efficiency GaN HEMT (High Electron Mobility Transistor) and additional auxiliary parts including inductors and capacitors. The simulation was carried out using LTspice Program for GaN-based EV Charger.

4.2 Basic Simulation Setup: To simulate a DC-DC converter, which is frequently utilized in EV chargers for step-down voltage conversion, a typical buck converter was selected as the converter topology [32]. The simulation's GaN HEMT transistor model takes into account its low conduction losses and high-frequency switching capabilities. Power levels of 50W to 350W, which are typical for Level 2 and fast-charging EV chargers, were simulated for the converter [33].

4.3 LT spice Simulation of Buck Converter for Si and GaN Devices: LTspice was used to build and simulate a DC–DC buck converter in order to assess the performance differences between silicon (Si) MOSFETs and GaN-based devices in EV charging applications [34]. This simulation's goal is to reduce a high DC input voltage of 400 V to a regulated output voltage of roughly 250 V, which is a common requirement in EV battery charging systems. A MOSFET switch, diode, inductor, capacitor, and resistive load make up the converter with output voltage controlled through PWM duty cycle.

4.4 Silicon vs GaN Modelling Approach: The same buck converter construction is employed in both situations rather than completely distinct circuit topologies. By altering the MOSFET model parameters to represent their physical properties, silicon and GaN devices can be distinguished from one another [35].

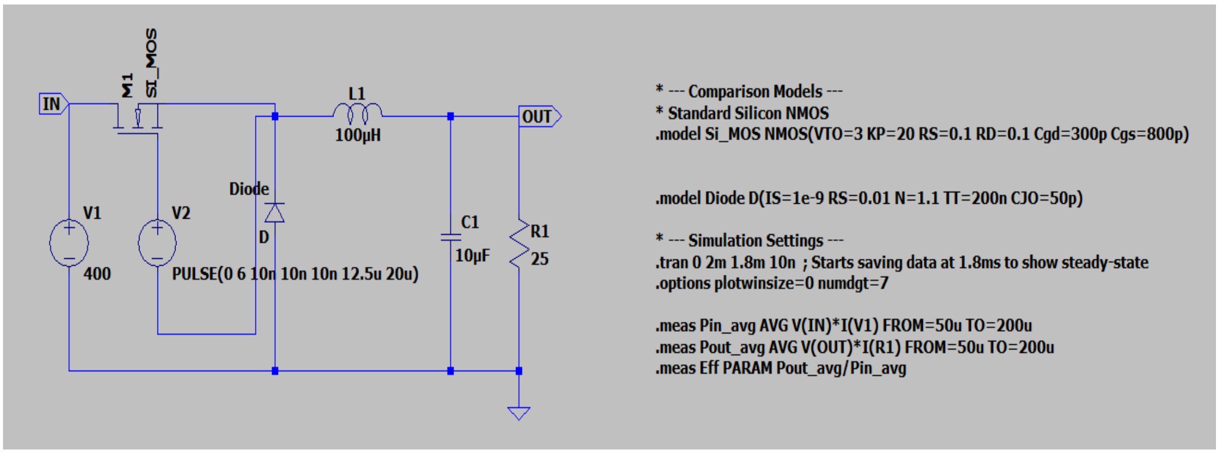
4.5 GaN FET Model: Lower threshold voltage (VTO), very low on-resistance (RD), significantly decreased parasitic capacitances (Cgd, Cgs), and a smaller inductor (10 μH) are all reflected in the model of the GaN-based device. Cgs (gate-to-source) affects turn-on speed, while Cgd (gate-to-drain), or Miller capacitance, dominates high-frequency limitations and Miller effect feedback [36]. Faster switching, lower switching and conduction losses, increased efficiency at high frequencies, and a more compact device are all made possible by this [37] . LTspice Simulation model for GaN-based DC-DC buck converter is revealed in figure 4.



```
* --- Comparison Models ---

* GaN-on-Si High Efficiency Model
.model GaN_FET NMOS(VTO=1.5 KP=60 RS=0.01 RD=0.01 Cgd=10p Cgs=100p)

* Ultra Fast Diode (Schottky)
.model D_GaN D(IS=1e-9 RS=0.01 N=1.1 TT=1n CJO=50p)

* --- Simulation Settings ---
.tran 0 2m 1.8m 10n  ; Starts saving data at 1.8ms to show steady-state
.options plotwinsize=0 numdgt=7

.meas Pin_avg AVG V(IN)*I(V1) FROM=50u TO=200u
.meas Pout_avg AVG V(OUT)*I(R1) FROM=50u TO=200u
.meas Eff PARAM Pout_avg/Pin_avg
```

Figure 4: LTspice simulation model for GaN-based DC-DC buck converter

4.6 Silicon MOSFET Model: The silicon-based MOSFET is modelled with; higher threshold voltage (VTO), higher on-resistance (RS), larger parasitic capacitances (Cgd, Cgs), larger inductor (100 µH). These parameters result in: Higher conduction losses, slower switching, increased switching losses, increase in physical size and weight [38] . Figure 5 portrays LTspice simulation model for Si-based DC-DC buck converter.



```
* --- Comparison Models ---
* Standard Silicon NMOS
.model Si_MOS NMOS(VTO=3 KP=20 RS=0.1 RD=0.1 Cgd=300p Cgs=800p)


.model Diode D(IS=1e-9 RS=0.01 N=1.1 TT=200n CJO=50p)

* --- Simulation Settings ---
.tran 0 2m 1.8m 10n  ; Starts saving data at 1.8ms to show steady-state
.options plotwinsize=0 numdgt=7

.meas Pin_avg AVG V(IN)*I(V1) FROM=50u TO=200u
.meas Pout_avg AVG V(OUT)*I(R1) FROM=50u TO=200u
.meas Eff PARAM Pout_avg/Pin_avg
```

Figure 5: LTspice simulation model for Si-based DC-DC buck converter

Illustration: In this work, MOSFETs in LTspice are used to imitate both silicon and GaN devices. By suitably altering crucial device parameters including threshold voltage, on-resistance, and parasitic capacitances calibrated to imitate their respective properties, the behavior of Si and GaN may be distinguished. A fair comparison is made possible by the parameters chosen to produce a controlled output of roughly 250V under the same input conditions. It is relevant to point out that choosing different parameters can affect the simulation's outcomes.

4.7 Output Voltage Performance: The output voltage characteristics of the silicon-based and GaN-based DC–DC buck converters were analysed under identical input conditions of 400V DC. The duty cycle was selected based on the theoretical relation, targeting an output voltage of approximately 250V [39]. In line with the erstwhile research work output voltage performance has been observed for the study.

$V_{out} = D.V_{in}$ (Where D is duty cycle, V_{out} - Output Voltage, and V_{in} - Input Voltage)

Result depicting output voltage waveform for GaN based DC-DC buck converter is shown in figure 6 and output voltage waveform for Si based DC-DC buck converter is shown in figure 7. The silicon-based converter produced an output voltage in the range of approximately 247–251V, closely matching the theoretical expectation. In contrast, the GaN-based converter demonstrated a slightly higher output voltage of 251.6V with more stability and, in certain operating conditions, maintained an output voltage closer to the ideal value with reduced deviation. This difference can be attributed to the lower conduction resistance and faster switching characteristics of GaN devices. Reduced on-state resistance minimizes voltage drop across the switching element, while faster switching reduces transition losses, allowing the GaN converter to maintain output voltage closer to the ideal value. Furthermore, the GaN-based converter exhibited lower voltage ripple compared to the silicon-based implementation. This is primarily due to high-frequency switching, which enables better filtering using smaller passive components.

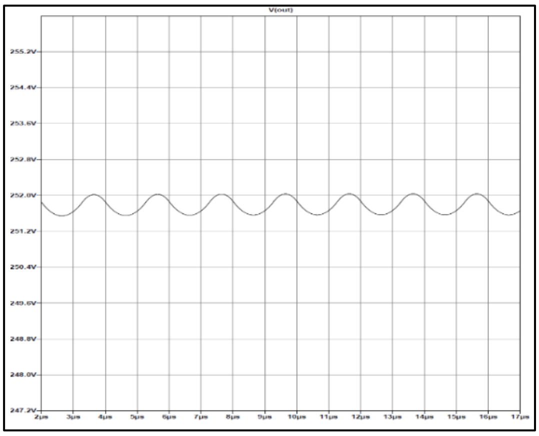


Figure 6. Output voltage waveform for GaN based DC-DC buck converter

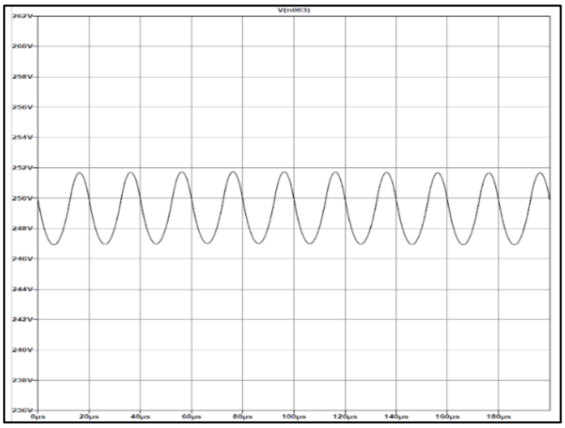
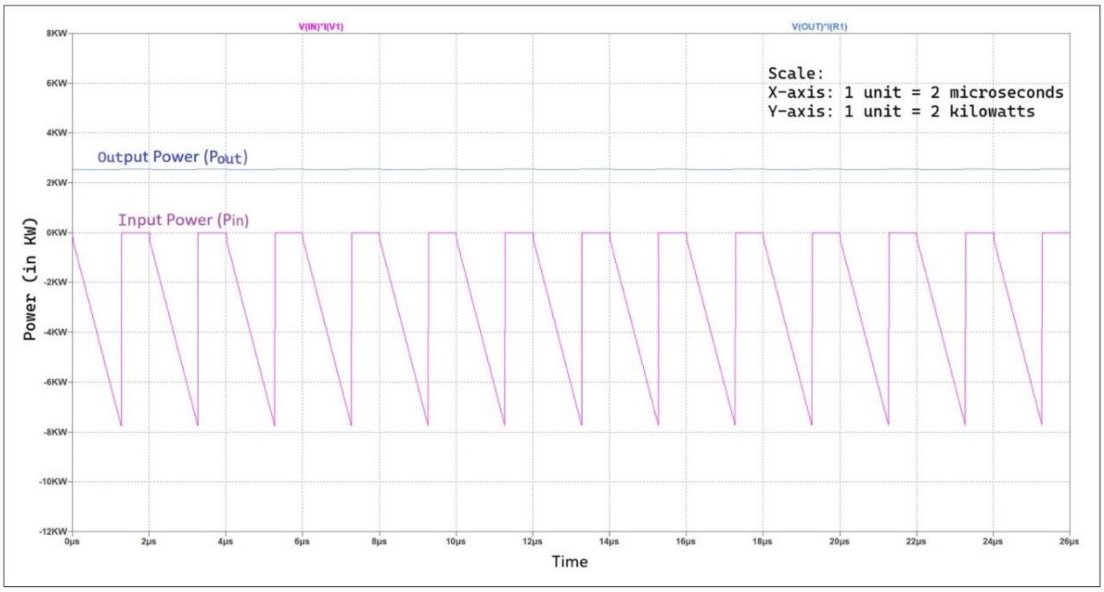


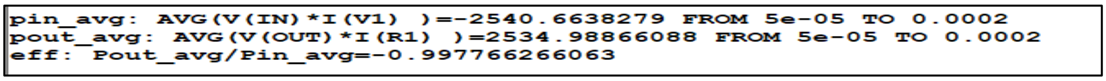
Figure 7: Output voltage waveform for Si based DC-DC buck converter

4.8 Efficiency Analysis: The efficiency of both converters was evaluated using average input and output power calculated over steady-state operation. The efficiency is defined as:

$$\eta = \frac{P_{out}}{P_{in}}$$

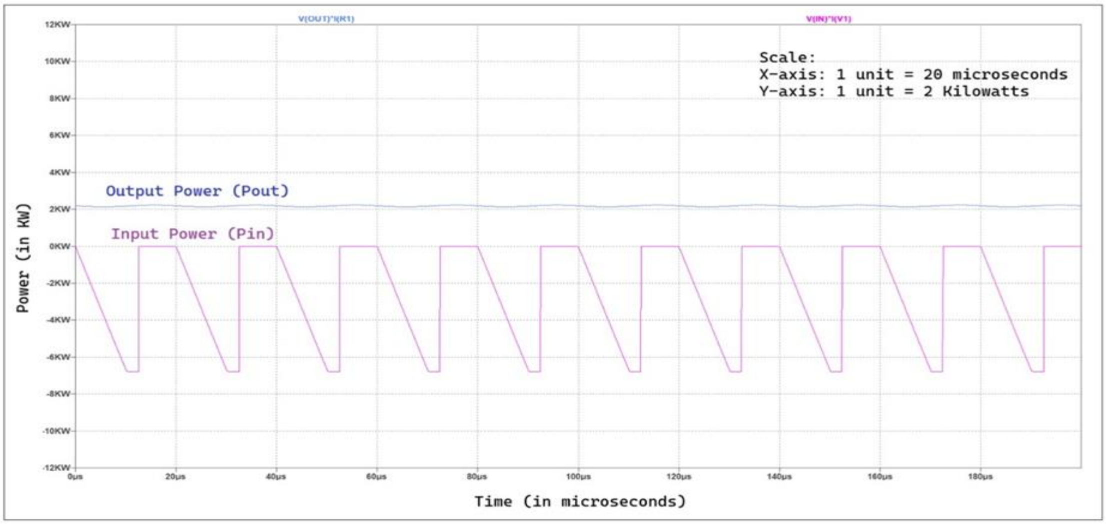
The Si-based converter achieved an efficiency of approximately 88.58% under nominal load conditions. The GaN-based converter demonstrated an efficiency of approximately 99.77%, showing comparable or improved performance depending on operating conditions. Although GaN devices are expected to significantly outperform silicon devices due to reduced switching losses, the simulation results indicate that efficiency gains are strongly dependent on proper circuit optimization. However, under optimized conditions, the GaN-based converter shows clear advantages in terms of reduced conduction losses and improved power transfer efficiency. Input and output power waveform with efficiency analysis for GaN based DC-DC buck converter is revealed in figure 8 whereas figure 9 depicts input and output power waveform with efficiency analysis for Si based DC-DC buck converter.

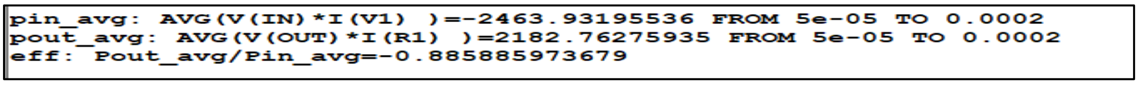




```
pin_avg: AVG(V(IN)*I(V1) )=-2540.6638279 FROM 5e-05 TO 0.0002
pout_avg: AVG(V(OUT)*I(R1) )=2534.98866088 FROM 5e-05 TO 0.0002
eff: Pout_avg/Pin_avg=-0.997766266063
```

Figure 8: Input and output power waveform with efficiency analysis for GaN-based DC-DC buck converter





```
pin_avg: AVG(V(IN)*I(V1) )=-2463.93195536 FROM 5e-05 TO 0.0002
pout_avg: AVG(V(OUT)*I(R1) )=2182.76275935 FROM 5e-05 TO 0.0002
eff: Pout_avg/Pin_avg=-0.885885973679
```

Figure 9: Input and output power waveform with efficiency analysis for Si-based DC-DC buck converter

4.9 Impact of Switching Frequency: One of the key advantages of GaN devices is their ability to operate at significantly higher switching frequencies compared to conventional silicon MOSFETs [40]. In this study, the silicon converter was operated at 50 kHz, whereas the GaN-based converter was operated at 500 kHz. The increase in switching frequency results in a substantial reduction in passive component size, as the inductance requirement is inversely proportional to switching frequency. This enables higher power density and more compact converter design, which is critical for electric vehicle charging applications. However, high-frequency operation also introduces increased switching losses if device parasitic capacitance and gate driving are not optimized [41]. Therefore, while GaN enables high-frequency operation, careful design considerations are necessary to fully exploit its advantages.

4.10 Key Observations: The following observations are drawn from the simulation study: (a) High-frequency operation enabled by GaN devices reduces the size of inductors and capacitors, increasing power density. (b) GaN-based converters demonstrate improved output voltage regulation due to lower conduction losses. (c) Silicon-based converters, while stable at lower frequencies, are limited in terms of switching speed and power density. It is to note that efficiency improvements are dependent on proper optimization of switching parameters and device characteristics. Table 2 illustrates the study's findings that GaN power devices have better characteristics than Si-based power devices.

Table 2: Simulation result for the Si-based and GaN-based power devices

S. No	Parameter	Si-based converter	GaN-based converter
1.	Switching Frequency	50 kHz	**500kHz**
2.	Output Voltage	~247-251 V	**~251.6 V**
3.	% Efficiency	88.58	**99.77**
4.	Voltage Ripple	Higher	Lower
5.	Power Density	Lower	Higher

Discussion: The simulation findings confirm that GaN devices have the potential to improve EV charging system performance. GaN devices enable high-frequency, high-efficiency operation, which is crucial for next-generation rapid chargers, whereas silicon devices offer dependable performance at lower frequencies. The findings, however, also show that GaN alone is insufficient to replace silicon devices. To fully reap the benefits of GaN technology, gate driving, parasitic capacitances, and switching conditions must be properly optimized. When, all things considered, GaN-based converters offer a viable way to increase efficiency, decrease system size, and enable high-power-density designs in applications involving the charging of electric vehicles.

5. CHALLENGES IN DEVELOPING GAN-BASED EV CHARGER

Compared to well-established Si solutions or even its WBG equivalent SiC, GaN's mainstream adoption is still hampered by a number of issues and obstacles despite significant technological advancements and shown performance advantages in EV chargers. For GaN to reach its full market potential in the quickly growing EV charging infrastructure sector, these obstacles must be overcome [42]. Although GaN has many benefits, there are challenges to its practical application in EV chargers. Among these some challenges are shown in Figure 10.

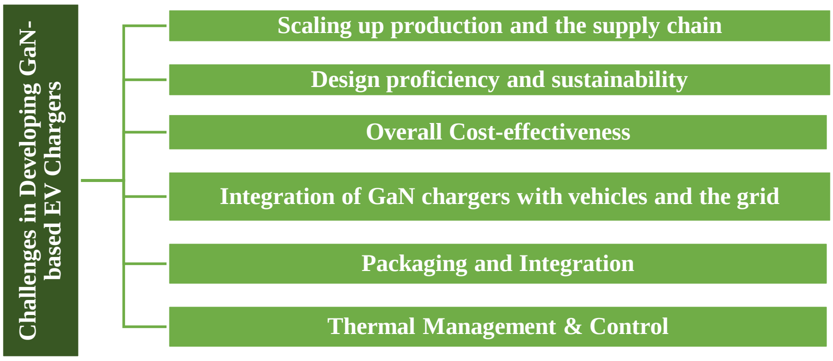


Figure 10: Challenges in developing GaN based EV Charger

5.1 Scaling up production and the supply chain: To meet the expected high demand for GaN devices in the EV charging industry, manufacturing facilities and supply chains must be flexible and cost-effective. Infrastructure for testing and assembly, such as the Outsourced Semiconductor Assembly and Test (OSAT) ecosystem, must be able to handle a large quantity of potentially specialized GaN packaging. Long-term strategic planning is necessary for large-scale adoption in order to provide a consistent supply of raw materials for GaN manufacturing [43].

5.2 Design proficiency and sustainability: GaN technology needs to be combined with a sustainable environment. For a broader range of designers to be empowered, a strong design environment with accurate simulation models, user-friendly tools, thorough application notes, pertinent reference designs, and strong technical support from manufacturers must be continuously developed and made available. Overcoming the first learning curve and possibly investing in reorganizing engineering teams are also essential for businesses hoping to fully utilize GaN potential in product development [44].

5.3 Overall Cost-effectiveness: GaN devices are becoming less expensive with time, their adoption in EV fast chargers still depends on their overall cost effectiveness. Although individual GaN devices may currently cost more than their similar Si counterparts, GaN's ability to operate at higher frequencies may result in significant system-level savings through smaller passive components, lower cooling requirements, and more compact PCBs. The GaN cost-effectiveness crossover threshold varies depending on the specifics of the application, and in some cases, the initial device premium may still be a barrier if it isn't completely offset by proven system savings [45].

5.4 Integration of GaN chargers with vehicles and the grid: Optimizing power conversion is only one aspect of using GaN-based EV chargers successfully. Additionally, it necessitates seamless connectivity with grid systems and larger vehicles, especially for upcoming capabilities like V2G [46]. GaN dynamic performance can help with one of the most important issues: ensuring complete compatibility and adherence to communication standards between the charger, the EV Battery Management System, and grid operators. GaN-based chargers for V2G applications need complex control systems to continuously supply auxiliary services and grid stability. Lastly, in order to guarantee that chargers are safe, meet electromagnetic compatibility requirements, and connect to the grid, all chargers including those that use GaN, must go through extensive testing and certification. This calls for careful planning to handle particular features like GaN electromagnetic interference signature [47].

5.5 Packaging and Integration: GaN chip integration into power systems necessitates specialized packaging capable of handling high frequencies and power densities, which may increase the complexity of the system [48].

5.6 Thermal Management & Control: Despite GaN's better thermal conductivity, fast-switching operations and high-power density may still cause thermal problems that call for sophisticated cooling techniques. The performance and reliability of GaN HEMT (High Electron Mobility Transistor) devices are constrained by serious thermal management issues. The main problem is that these devices operate at high power densities and can produce heat fluxes in the active region of above 10 kW/cm^2. Localized hotspots produced by this concentrated heat output have a significant negative influence on the longevity and performance of devices. A major restriction of GaN HEMTs is the self-heating phenomenon, which causes the device's channel temperature to rise noticeably above the case temperature when in operation. Hotspot temperatures can reach above 200°C in high-power applications, and temperature rises of 100 -150 °C over ambient are frequently noted. This heat gradient shortens the average time to failure and speeds up a number of deterioration processes [49].

6. FUTURE PERSPECTIVES

In the quest for quicker and more effective charging options, GaN-based chargers are essential. Faster charging periods result from their capacity to tolerate greater voltages and frequencies. GaN chargers present a convincing way to satisfy the need for quicker and more convenient charging. Additionally, because GaN chargers are more efficient and waste less energy while charging, they help cut carbon emissions. They are also travel-friendly because to their small size and lightweight construction, which appeals to current consumers who lead busy lives. Incorporating GaN technology not only speeds up charging but also meets the growing demand for portable and sustainable power solutions in an increasingly interconnected world. The future of GaN-based EV chargers is promising. Some of the key areas for future research and development include:

6.1 Better Manufacturing Methods: Advances in GaN crystal growth and wafer bonding methods will improve material quality and reduce prices. GaN-on-GaN technique is the sole way to grow bulk GaN crystals of good structural quality. However, because GaN crystals do not form naturally, the material must first grow on a foreign wafer (seed), after which GaN-on-GaN crystallization should be introduced [50].

6.2 Advanced Cooling Solutions: In this regard, microchannel heat sinks are changing the paradigm of thermal management for high-power electronics because of their superior convective heat-transfer capabilities. Tuckerman and Pease were the first to propose this technology. They created a microchannel heat sink that could cool 790 W/cm2 [51]. Next-generation cooling systems, like microchannel cooling and enhanced heat sinks, will alleviate thermal management problems. Microchannel heat sinks provide outstanding thermal-hydraulic performance, as seen by their high heat transfer coefficients, low thermal resistance, and decreased pressure drop. Furthermore, ultra-high power density chip cooling appears to be a promising use of integrated microchannel technology. With a junction temperature of 225 °C, silicon-based embedded microchannel heat sinks have effectively dissipated heat fluxes of 3 kW/cm2 at a flow rate of 100 ml/min. [52].

6.3 Integration with Smart Grids: GaN-based chargers could be integrated into smart grids to provide dynamic charging, grid balancing, and demand response. Utility companies are increasingly implementing demand-side management (DSM) programs to lower energy use at the end-user side of the metering infrastructure. This aids in preserving equilibrium between the supply and demand for energy in real time. Together with the main components, other DSM architecture solutions like smart meters and sophisticated ICT devices can offer a feasible chance to achieve lower energy consumption costs, maximize the use of renewable energy sources, and give consumers favourable options for their active involvement in the electricity markets [53].

6.4 Superfast Charging: "The technology brings EV charging time closer to the time taken to refuel gasoline vehicles [54]." A significant advancement was made in April 2026 when CATL unveiled the third-generation Shenxing Superfast Charging Battery, which allows for a 10% to 98% charge in about 6.5 minutes. This lithium iron phosphate (LFP) battery, intended for mass-market EVs, offers a 10C rate (10-80% in 3 min 44 s) and increases range, aiming for better performance than existing market options.

7. CONCLUSION

Gallium nitride (GaN) significantly improves the charging performance of electric vehicles by utilizing its wide bandgap and high electron mobility to obtain improved energy conversion metrics. GaN devices can operate at much higher voltages with a reduced "on-resistance", which lowers conduction losses and enables efficiency ratings that frequently approach ~98%. Gallium Nitride (GaN) is replacing silicon in electric vehicle (EV) chargers, offering superior electron mobility and a high critical breakdown field that enables higher switching frequencies. These characteristics improve power density by up to 60% and achieve higher conversion efficiencies, although they introduce challenges regarding electromagnetic interference (EMI) and high heat flux density. Future advancements will focus on bi-directional 800V architectures and mature "GaN-on-Silicon" manufacturing to reduce costs and facilitate vehicle-to-grid (V2G) integration.

The problems with conventional charging systems are revolutionized by GaN-based EV chargers. GaN devices outperform silicon-based technology in terms of efficiency, power density, and thermal management. To realize their full potential, however, issues with production, cost, and dependability must be resolved. In order to overcome these obstacles and facilitate the broad deployment of fast-charging infrastructure, future research in GaN material science, packaging, and cooling technologies will be essential, hastening the shift to sustainable transportation.

REFERENCES

[1] IEA, "Policies to promote electric vehicle deployment," Global EV Outlook 2021, Paris, 2021.

[2] A. K. Abdulhassan, "Comparative Analysis and Performance Optimization of SiC and GaN Wide Bandgap Semiconductors in Next-Generation Power Converters," *European Journal of Applied Science Engineering and Technology,* vol. 4, no. 1, pp. 194-203, 2026.

[3] P. Rajkumar and I. Vairasundaram, "GaN-Based DC-DC converters for EV fast charging: A review of wide bandgap devices technology," *Siencedirect - Elsevier - Rewsults in Engineering,* vol. 28, December 2025.

[4] Cadence, "resources.pcb.cadence.com," cadence, January 2023. [Online]. Available: https://resources.pcb.cadence.com/blog/2023-gan-advantages-and-disadvantages. [Accessed 07 May 2026].

[5] Tessolve, "Wide-Bandgap Semiconductors: How SiC and GaN Are Transforming Power Electronics," Tessolve Labs, 5 March 20267. [Online]. Available: https://www.tessolve.com/blogs/wide-bandgap-semiconductors-how-sic-and-gan-are-transforming-power-electronics/. [Accessed 06 May 2026].

[6] MPS, "Basic Power Electronics Concepts," Monolithic Power Systems, 2024. [Online]. Available: https://www.monolithicpower.com/en/learning/mpscholar/analog-vs-digital-control/introduction-to-power-conversion-circuits/basic-power-electronics-concepts#:~:text=concept%20and%20use.-,Definition,man. [Accessed 10 April 2026].

[7] A. Rameez, "The Race To Replace Silicon," Semiconductor Engineering, 25 July 2025. [Online]. Available: https://semiengineering.com/the-race-to-replace-silicon/#:~:text=While%20SiC%20offers%20numerous%20benefits,expensive%20than%20silicon%2Dbased%20alternatives.. [Accessed 14 April 2026].

[8] PWC, "Semiconductor and beyond," PwC Semiconductor Center of Excellence (CoE) , 2026. [Online]. Available: https://www.pwc.com/gx/en/industries/technology/pwc-semiconductor-and-beyond-2026-full-report.pdf.

[9] IEA, "Global EV Outlook 2025," INTERNATIONAL ENERGY AGENCY, 2025. [Online]. Available: https://iea.blob.core.windows.net/assets/0aa4762f-c1cb-4495-987a-25945d6de5e8/GlobalEVOutlook2025.pdf. [Accessed 07 May 2026].

[10] Virta_Global, "The global electric vehicle market overview in 2025," 2025. [Online]. Available: https://www.virta.global/global-electric-vehicle-market. [Accessed 07 May 2026].

[11] McKinsey, "Exploring consumer sentiment on electric-vehicle charging," The McKinsey Center for Future Mobility, 9

January 2024. [Online]. Available: https://www.mckinsey.com/features/mckinsey-center-for-future-mobility/our-insights/exploring-consumer-sentiment-on-electric-vehicle-charging. [Accessed 06 May 2026].

[12] S. Hasan and A. Mamoona, “Limitation of Silicon Based Computation and Future Prospects,” in *Communication Software and Networks, 2010. ICCSN '10. Second International Conference*, 2010.

[13] Texas_Instruments, “Driving the electric vehicle evolution with GaN | Technology and innovation,” 9 November 2020. [Online]. Available: https://www.ti.com/about-ti/newsroom/company-blog/driving-the-electric-vehicle-evolution-with-gan.html#:~:text=%E2%80%9CGaN's%20fast%20switching%20speed%20increases,vehicle%20on%2Dboard%20charging%20systems.. [Accessed 10 April 2026].

[14] T. Jixiang, Z. Zhongfu and Z. Gongjie, “A Programmable Gate Driver Module-Based Multistage Voltage Regulation SiC MOSFET Switching Strategy,” *Electronics,* vol. 13, no. 22, p. 4379, 8 November 2024.

[15] EPC, “Gallium Nitride (GaN) Semiconductors,” Efficient Power Conversion Corporation (EPC), 2024. [Online]. Available: https://epc-co.com/epc/gallium-nitride/what-is-gan. [Accessed 10 April 2026].

[16] DST_GOI, “R&D Roadmap on EV Charging Infrastructure,” Government of India, New Delhi, 2024.

[17] M. Shibata, T. Furuya, H. Sakaguchi and S. Kuma, “Synthesis of gallium nitride by ammonia injection into gallium melt,” *Journal of Crystal Growth,* vol. 196, no. 1, pp. 47-52, 1 January 1999.

[18] J. Woo-Sik, “ Reaction mechanism of the nitridation of α-gallium oxide to gallium nitride under a flow of ammonia,” *Elsevier, Science Direct (Materials Letters),* vol. 60, no. 24, pp. 2954-2957 , October 2006.

[19] alexlin, “What is a gallium nitride(GaN) transistor? The difference between GaN and silicon,” JING FU CAI (HONGKONG) INTERNATIONAL CO., LIMITED, 17 November 2023. [Online]. Available: https://www.everythingpe.com/community/what-is-a-gallium-nitride-gan-transistor-the-difference-between-gan-and-silicon. [Accessed 08 May 2026].

[20] Alexlin, “What is a gallium nitride(GaN) transistor? The difference between GaN and silicon,” *alexlin - JING FU CAI (HONGKONG) INTERNATIONAL CO., LIMITED,* 23 November 2023.

[21] EPCI, “Wide Bandgap Semiconductors: Gallium Oxide is Next in Line,” 1 February 2019. [Online]. Available: https://passive-components.eu/wide-bandgap-semiconductors-gallium-oxide-is-next-in-line/.

[22] DoITPoMS, “Direct and Indirect Band Gap Semiconductors,” 2024. [Online]. Available: https://www.doitpoms.ac.uk/tlplib/semiconductors/direct.php.

[23] S. Murray, “Wide Bandgap Semiconductors: Gallium Oxide is Next in Line,” 1 January 2019. [Online]. Available: https://www.tti.com/content/ttiinc/en/resources/marketeye/categories/new-technology/me-slovick-20190131.html.

[24] R. ShriShakthi and Navarajan, “GaN Technology in Power Electronics: Advances and Applications,” *TIJER,* vol. 12, no. 5, May 2025.

[25] V. Bhanu_Teja, S. Arnab, N. Rajender, A. Sandeep and S. C. Yogesh, “Comparison of Si and GaN Power Devices Based SMPS for Satellite Application,” in *IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2018.

[26] P. Rajkumar and I. Vairavasundaram, “GaN-Based DC-DC converters for EV fast charging: A review of wide bandgap devices technology,” vol. 28, December 2025.

[27] A. Diego, “GaN Advances EV Power Design,” *powerelectronics news,* 27 February 2025.

[28] Electronics_News, “GaN Eliminates Fans and Heat Sinks in Power Electronics,” *Electronics Maker.,* 21 March 2017.

[29] K. Rahman, S. Falina, M. Mohamed, H. Kawarada and M. Syamsul, “The role of gallium nitride in the evolution of electric vehicles: energy applications, technology, and challenges,” *American Institute of Physics,* 1 September 2024.

[30] H. M. Ali, “Thermal management systems for batteries in electric vehicles: a recent review,” *Energy Report., 9 (2023), pp.,* pp. 5545-5564,, 2023.

[31] E. Sadullah and A. Oktay, “Comparison of the performance of Si, SiC, and GaN based switching elements in high gain DC-DC boost converter,” *Journal of Electrical Engineering,* vol. 74, no. 5, pp. 392-398, October 2024.

[32] MPS, “Buck Converters,” 2026. [Online]. Available: https://www.monolithicpower.com/en/learning/mpscholar/power-electronics/dc-dc-converters/buck-converters#:~:text=Buck%20converters%20employ%20a%20simple,duty%20cycle%20and%20output%20voltage..

[33] K. Karrame, J. Nallatamby, C. Chang, M. Colas and R. Sommet, “Thermal Characterization and Simulation of GaN-on-SiC HEMT Transistors in Transient and Steady-State Regimes,” in *25th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, 2024.

[34] P. Rajkumar, “GaN-Based DC-DC converters for EV fast charging: A review of wide bandgap devices technology,” *Science Direct,* vol. 28, 2025.

[35] M. Lenzhofer and A. Frank, “Efficiency and Near-Field Emission Comparisons of a Si- and GaN Based Buck Converter Topology,” in *IEEE 18th International Power Electronics and Motion Control Conference (PEMC)*, 2018.

[36] Texas_Instruments, “Key Parameters and Driving Requirements of GaN FETs,” Texas Instruments Incorporated, 2022. [Online]. Available: https://www.ti.com/document-viewer/lit/html/SLUAAM0. [Accessed 04 May 2026].

[37] AstrodyneTDI, “What Is the Future for GaN and SiC in the Semiconductor Industry?,” astrodynetdi.com, 2026. [Online]. Available: https://www.astrodynetdi.com/blog/what-is-the-future-for-gan-and-sic-in-the-semiconductor-industry. [Accessed 04 May 2026].

[38] K. Jagadesh and K. G. Sumeet, “Compact Modeling of the Effects of Parasitic Internal Fringe Capacitance on the Threshold Voltage of High-k Gate-Dielectric Nanoscale SOI MOSFETs,” *IEEE TRANSACTIONS ON ELECTRON DEVICES,* vol. 53, no. 4, 2006.

[39] J. White, “How Does GaN Charger Efficiency Drive Energy Savings and CO2 Reduction?,” Shenzhen Wecent, 27 March 2026. [Online]. Available: https://www.gdwecent.com/how-does-gan-charger-efficiency-drive-energy-savings-and-co2-reduction/. [Accessed 01 May 2026].

[40] EPC, “Why GaN: Benefits of Gallium Nitride,” Efficient Power Conversion Corporation, 2026. [Online]. Available: https://epc-co.com/epc/gallium-nitride/why-gan. [Accessed 03 May 2026].

[41] C. Hsien-Chie, J. Wen-You, L. Yan-Cheng, Y. Ching-Feng, C. Po-Kai and C. Tao-Chih, “Effects of parasitic capacitance on switching transients and thermal performance in a single-phase SiC power MOSFET inverter,” *Scientific Reports,* vol. 16, 14 March 2026.

[42] P. Apurva, K. Sharareh and R. J. Michael, “Barriers and motivators to the adoption of electric vehicles: A global review,” *Green Energy and Intelligent Transportation,* vol. 3, no. 2, April 2024.

[43] S. Jagani, E. Marsillac and P. Hong, “The Electric Vehicle Supply Chain Ecosystem: Changing Roles of Automotive Suppliers,” *Sustainability,* vol. 16, no. 4, February 2024.

[44] Rajkumar and Indragandhi, “GaN-Based DC-DC converters for EV fast charging: A review of wide bandgap devices technology,” *Results in Engineering,* December 2025.

[45] D. Yanling, C. Zhibin and L. Xi, “Cost-competitiveness analysis of mobile chargers in an electric vehicle parking and charging system,” *Transportation Research Part C: Emerging Technologies,* vol. 171, February 2025.

[46] S. Sithara, Acharige, H. M. Enamul, A. Taufiqul, M., H. Nasser, N. H. Kazi, M. Hossain, M. Kashem and Muttaqi, “Grid integration of electric vehicles - Impact assessment and remedial measures,” *Journal of Power Sources,* vol. 650, 15 September 2025.

[47] E. M. Tamasas, B. Issa and R. Reza, “Scalable GaN-Based EV Charging Station with Energy Storage,” in *Annual IEEE Conference on Applied Power Electronics Conference and Exposition (APEC)*, 2023.

[48] N. REZA, “GaN System-on-Chip: Pushing the Limits of Integration and Functionality,” *IEEE Journal of Microwave,* vol. 4, no. 4, October 2024.

[49] PatSnap, “Thermal Management Challenges For GaN HEMT Devices,” PatSnap Eureka turns technology, Tokyo, 2025.

[50] R. Kucharski, T. Sochacki, B. Lucznik and M. Bockowski, “Growth of bulk GaN crystals,” *Journal of Applied Physics,* vol. 128, no. 5, 5 August 2020.

[51] W. Sulaiman and W. Chi-Chuan, “Optimizing microchannel heat sink performance: Effect of step-gap design and contraction on flow boiling stability and heat transfer,” *Applied Thermal Engineering,* vol. 257, no. Part C, 15 December 2024.

[52] A. Ci, X. Bo and C. Zhenqian, “Microchannel cooling for high-performance microelectronic systems: Progress, challenges, and future directions,” *International Communications in Heat and Mass Transfer,* vol. 172, no. 4, March 2026.

[53] m. Sarthak, p. subhasis, m. shubhranshu, R. Pravat, S. Binod, b. mohit, m. z. hossam, m. nallapaneni and k. salah, “Demand side management of electric vehicles in smart grids: A survey on strategies, challenges, modeling, and optimization,” *Energy Reports,* pp. 12466-12490, November 2022.

[54] H. Jiahui, “CATL Unveils Fast-Charging Battery Innovation,” *The Wall Street Journal,* 22 April 2026.