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Current Status and Future Trends of GaN HEMTs in Electrified Transportation

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ABSTRACT Gallium Nitride High Electron Mobility Transistors (GaN HEMTs) enable higher efficiency, higher power density, and smaller passive components resulting in lighter, smaller and more efficient electrical systems as opposed to conventional Silicon (Si) based devices. This paper investigates the detailed benefits of using GaN devices in transportation electrification applications. The material properties of GaN including the applications of GaN HEMTs at different switch ratings are presented. The challenges currently facing the transportation industry are introduced and possible solutions are presented. A detailed review of the use of GaN in the Electric Vehicle (EV) powertrain is discussed. The implementation of GaN devices in aircraft, ships, rail vehicles and heavy-duty vehicles is briefly covered. Future trends of GaN devices in terms of cost, voltage level, gate driver design, thermal management and packaging are investigated.

INDEX TERMS Electric vehicle, gallium nitride, high electron mobility transistor, hybrid electric vehicle, wide bandgap devices.

I. INTRODUCTION

Most vehicles currently on the road are powered using fossil fuels in the internal combustion engines. With the limited supply of fossil fuels, the current transportation system is neither sustainable nor is it environmentally friendly due to the carbon dioxide (CO_2) produced from the reaction of these fuels with air. Due to the increased fuel costs, as well as harmful emissions for the environment, transportation applications are moving towards becoming electrified or more electrified. Transportation electrification is particularly of interest because of increased efficiency, reduced harmful emissions and better overall performance offered by these applications [1].

With transportation electrification, the negative effects of greenhouse gas (GHG) emissions on global warming as well as the dependence on oil and gas can be reduced significantly. The design of higher efficiency vehicles is enabled with electric energy storage systems (EESS), power electronic converters and electric machines. Electrifying transportation has many advantages. For instance, in electrified powertrain applications, the selection of the powertrain architecture, design of different components within the powertrain, along with controls and software are coupled together to improve the reliability and performance of the vehicle [2]. These advantages along with the step towards reducing global warming effects are desirable for both the public and private sectors. Among aircraft, ships, trains, trucks and electric vehicles, the latter has had the most progress in the industry so far as can be seen from the increased number of electric vehicles on the road in recent years. Reducing weight and increasing the efficiency of these transportation mediums is a major step in their electrification where benefits of wide bandgap (WBG) devices can be realized [3], [4].

The comparison of GaN HEMTs with SiC in different applications have been vastly discussed in literature. However, a comprehensive analysis of GaN HEMTs and future implications in electrified transportation applications such as in electric vehicles, more electric aircraft, more electric ship, electrified heavy-duty and off-road vehicles and electric trains need to be covered. This paper discusses the current status and future trends of GaN HEMTs in electrified transportation mediums. The future of GaN in these applications and the steps required to overcome current limitations are investigated.

Section II compares and analyzes WBG devices and Si in terms of their device properties. Failure modes of GaN HEMTs is briefly covered in this section. Section III covers

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the challenges facing current EVs and the future requirements for these vehicles. A detailed look at the components of an EV along with the application of GaN in these components is presented. A summary of different transportation mediums and the current and future switch technologies in these mediums is also summarized in section IV of the paper. Future trends and roadmap of GaN devices in terms of device technology is presented in section V.

II. WIDE BANDGAP DEVICES

In this section GaN, SiC and Si devices are compared in terms of device characteristics and application. Failure modes of GaN HEMTs are discussed to confirm reliability and robustness and justify the benefits of transition to GaN power transistors. Limitations facing current GaN technology is also discussed.

A. DEVICE COMPARISON

In power electronic applications, semiconductors such as diodes and metal–oxide–semiconductor field-effect transistors (MOSFETs) incur losses in the power system. To improve efficiency from a power electronics perspective, the semiconductors used need to be carefully selected to ensure low switching and conduction losses. Therefore, the power devices used in these applications must be highly efficient, robust and power dense [5]. In the past, silicon (Si) was widely used in power electronic applications. However, it has reached the limit of maximum switching frequency and device thermal dissipation due to Si inherent properties [6]. Hence, Si should be used with other semiconductors that make up for its shortcomings when it comes to switching efficiency and thermal characteristics. With the increased concern for size, weight, efficiency and power density of these devices, benefits of WBG devices are recognized [7], [8].

WBG devices are semiconductors with high activation energies. These semiconductors have larger band gap compared to conventional semiconductors. The wide bandgap allows electrons to move at higher velocities enabling higher switching speeds. WBG devices permit the design of power electronics with higher efficiency, higher temperature limits, higher voltage blocking capability and faster switching transient than conventional Si-based systems [9], [10]. The type of preferred switch used in different applications varies according to the Drain-Source voltage (V_{DS}). For devices operating at voltages between 100 V to 600 V, GaN devices can be used. For voltages above 1200 V SiC is a suitable candidate. It is worth mentioning that in industry, Si devices are widely used and the use of WBG devices in conjunction with Si Metal Oxide Semiconductor Field Effect Transistors (MOSFETs), forming hybrid topologies is gaining more attention in recent years.

GaN is available in both lateral and vertical structures. Lateral GaN devices are suitable for high-frequency and medium power applications whereas vertical GaN devices can be used in high power modules [11], [12]. Vertical GaN devices are not yet commercially available and significant research is being conducted to commercialize these devices and exploit the superior GaN material properties.

GaN devices are available in normally-OFF and normally-ON modes. The GaN Heterojunction Field-Effect Transistor (HFET) consisting of AlGaN/GaN heterojunction includes a layer of high-mobility electrons referred to as two-dimensional electron gas (2DEG). This 2DEG layer forms a native channel between the drain and source of the device. The substrate for this material is typically Si but SiC and diamond can also be used. Due to the 2DEG channel, the HFET is a depletion-mode (normally-ON) device. This type of device is not suitable for applications such as voltage source converters, due to the potential for overshoot during startup or loss of power control. Hence, the enhancement-mode (e-mode) normally-OFF switching devices are preferred in power electronic applications since they offer more failsafe operation with simpler gate driver circuits. For this reason, there is significant effort in fabrication of normally-OFF GaN HFETs leading to the emergence of cascode devices. A cascode device includes packaging of the depletion-mode GaN HFET in series with a low-voltage e-mode MOSFET, typically Si, to form a normally-OFF device. The output voltage of the MOSFET determines the input voltage of the HFET while they share the same channel current in the on-mode with the blocking voltage distributed at off-mode. The drawback of GaN cascodes include increased packaging complexity from the series connection of the two devices thereby introducing parasitic inductances which can affect device switching performance. Transphorm offers GaN-on-Si HFET cascodes at 600 V, using the aforementioned cascode circuit. The gate can be modified to shift the threshold voltage positively making an e-mode device [13].

TABLE 1. Parameter Comparison of Si, SiC and GaN.

Parameter	GaN	SiC	Si
Electron mobility (cm^2 /V*s)	1800	900	1400
Energy gap (eV)	3.5	3.26	1.12
Breakdown electric field (MV/cm)	3.3	3	0.3
Thermal conductivity (W/cm*K)	1.3	4.9	1.5
Saturation drift velocity (Mcm/s)	27	27	10

Most of the commercially available GaN devices are lateral HEMTs [13]. The lateral structure of GaN switches has lower gate-drain capacitance (C_{gd}) and gate-source capacitance (C_{gs}) compared to Si switches. This makes the total gate charge of the switch much smaller for GaN devices (7.5 nC) compared to Si devices (15 nC). Since the total gate charge is directly related to the switching transient, higher switching efficiency is realized for GaN [14]. GaN has unique features such as high saturation drift velocity, high thermal stability, and large conduction band discontinuities which make it a great material for use in high power electric devices [15], [16]. Table 1 compares WBG devices to Si in terms of the electron mobility, energy gap, breakdown electric

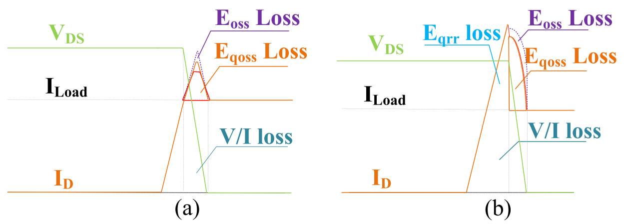

FIGURE 1. Hard-switching turn-on loss of: (a) GaN HEMT, (b) SiC MOSFET.

TABLE 2. Electrical characteristics of SiC MOSFET and GaN E-HEMT.

Characteristic	GaN E-HEMT GS66508T	SiC MOSFET C3M0065090J
V_{DS}(max) (V)	650	900
I_D @ 25°C (A)	30	35
$R_{DS(on)}$ @ 25°C (mΩ)	50	65
V_{GS} (V)	-10/+7	-4/+15
C_{ISS} (pF)	260	660
C_{OSS} (pF)	65	60
C_{RSS} (pF)	2	4
Q_g (nC)	5.8	30.4
Q_{gs} (nC)	2.2	7.5
Q_{gd} (nC)	1.8	12
Q_{rr} (nC)	0	245

field, thermal conductivity, and saturation drift velocity [17]. The thermal properties depend, to a great degree, on the packaging technology used which will be discussed further in the paper. From Table 1, it is seen that GaN is superior to SiC and Si in terms of electron mobility, energy gap, and breakdown electric field. The thermal conductivity of GaN is lower than Si and SiC which means that heat propagates poorly from the junction to the case and heatsink, if present, implying its poor heat conduction property. The lower thermal conductivity of GaN leads to higher thermal resistance which implies that GaN devices will experience higher operation temperatures for the same dissipated power. The saturation drift velocity of GaN is similar to SiC.

The lower on-resistance ($R_{DS(on)}$) of GaN versus Si is one of the main reasons for its small chip size, which is about 10 times smaller than Si-based devices [18]. For instance when comparing the EPC2010 200 V/12 A GaN MOSFET to the RCX120N20 200 V/12 A Si MOSFET, the GaN MOSFET has an on-resistance of 0.025 Ω whereas the Si MOSFET has an on-resistance of 0.325 Ω [19]. Due to the lower $R_{DS(on)}$, GaN has lower conduction loss compared to Si and SiC. Its low conduction loss allows for simpler cooling and heat sink systems which is desirable for industries looking into the design and manufacturing of more power dense and less expensive systems [20], [21]. The cost of GaN devices currently available in the market is significantly higher than Si devices, which is why most industries have not yet vastly adopted this technology. However, in the near future with the advancements in GaN technology and their mass production, GaN devices are expected to have a price range similar to today's Si devices [22].

Compared to SiC, the strong temperature dependency of $R_{DS(on)}$ of GaN aids current sharing in parallel operation which is desirable in high power applications where paralleling of multiple switches is common [23]. For the same current, SiC MOSFETs need a higher gate voltage compared to the gate voltage of GaN devices [24], [25]. The high breakdown electric field of GaN as well as its high electron mobility permits switching at frequencies about 30 times that of Si-based devices, showing benefits in high frequency applications such as EVs and PHEVs [26], [27]. The superior switching performance of GaN is due to the extremely low input, output and miller capacitance of the e-GaN HEMTs [8]. GaN transistors have an input capacitance (C_{ISS}) of about 30 times lower than Si MOSFETs [51]. The small C_{ISS} of GaN HEMTs and small Q_g lower the gate driver loss while reducing the delay time. Their low parasitic inductance results in lower switching losses with GaN E-HEMTs enabling the design of higher efficiency power systems. The electrical characteristics of GaN E-HEMT GS66508T and the Cree SiC MOSFET C3M0065090J are shown in Table 2. These characteristics influence the performance of the devices [28].

The loss comparison of GaN and SiC are demonstrated in Fig. 1. In hard switching, the collector current and collector-emitter voltage change suddenly causing switching noise and losses which is shown by the overlap of the V/I curves. Hard switching is used for simple switch, motor drive inverter and switched-mode power supply applications [29]. The E_{qoss} loss occurs when the low side current I_D charges C_{OSS} and V_{DS} starts to fall. Thus, the E_{oss} loss occurs when the parasitic capacitance of the switch is being charged. At turn-on, the capacitance discharges through the channel of the switch, incurring loss. As can be seen from Fig. 1(a), GaN has no E_{qrr} loss since it has no body diode which makes the E_{qoss} loss more apparent for GaN HEMTs. Due to the body diode of SiC MOSFETs, E_{qrr} loss is present for these devices.

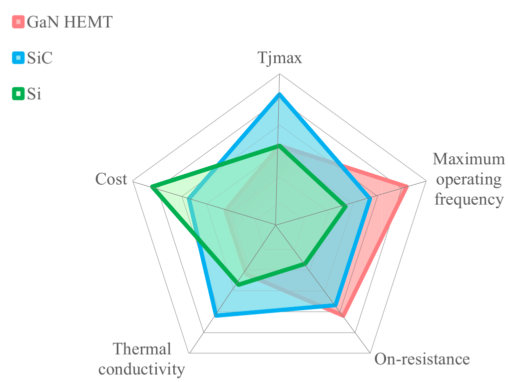

FIGURE 2. Material properties of GaN HEMT, SiC and Si.

The material properties of GaN, Si and SiC are compared in Fig. 2. The superiority of each property is considered in Fig. 2. These properties are based off of 650 V GaN, SiC and Si switches at 22.5 A, 30 A, 60 A, 80 A and 150 A from

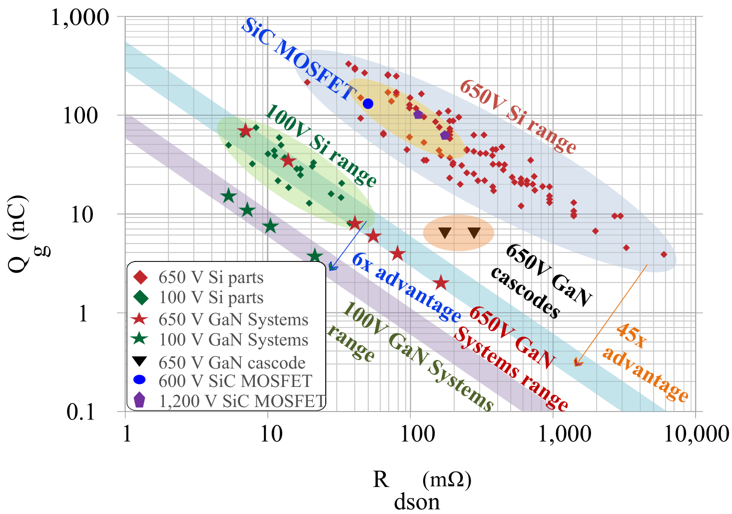

FIGURE 3. Q_g **versus** $R_{DS(on)}$ **of Si, SiC and GaN devices.**

Mouser Electronics and GaN Systems. To have a fair comparison, multiple devices of similar ratings were compared. The average value for GaN, SiC and Si in terms of $R_{DS(on)}$, T_{jmax}, thermal conductivity, maximum frequency and cost was extracted. From Fig. 2, it is seen that GaN has lower $R_{DS(on)}$ compared to SiC and Si. The $R_{DS(on)}$ of Si doubles from 25 °C to 125 °C and the on-resistance of SiC is higher compared to GaN, which is shown in Table 2 [30]. Therefore, GaN dominates this parameter. The thermal conductivity of GaN is lower than Si and SiC. SiC has the highest thermal conductivity and therefore is the most efficient at conducting heat. It should be pointed out that the thermal operation is also attributed to the packaging of these devices and not only related to the intrinsic properties of the die. SiC has the highest T_{jmax} of around 175 °C to 200 °C whereas Si and GaN are at about 150 °C [30]. Therefore, SiC dominates in terms of maximum junction temperature. The operating frequency of GaN is much higher than Si and SiC and extends in the MHz range. This means that GaN is superior in terms of maximum operating frequency. The cost of GaN HEMTs is higher than SiC and Si with Si having the lowest cost. Therefore, Si is the most cost-effective semiconductor among the three devices.

The gate charge (Q_g) versus $R_{DS(on)}$ of Si, SiC and GaN to demonstrate the device switching and conduction performance are shown in Fig. 3. From Fig. 3, it is evident that 100 V GaN transistors have lower switching charge requirements than 100 V Si MOSFETs. Additionally, E-mode devices have superior $R_{DS(on)}$ and Q_g performance. It can also be seen that the 650 V GaN cascode and SiC MOSFETs underperform compared to the 650 V GaN MOSFETs, 100 V Si and 100 V GaN MOSFETs due to the higher switching charge requirements.

As outlined earlier, GaN switches obtain the lowest losses among similar Si and SiC devices. This is partly attributed to the zero reverse recovery charge (Q_{rr}) of GaN which is due to the absence of a body diode in its structure. The zero Q_{rr} has the following benefits [31]–[36]:

- No need for anti-parallel diodes in GaN transistors
- Enables high efficiency AC/DC power conversion
- No Q_{rr} loss and minimal rectifier conduction loss
- Fast turn on dv/dt due to the absence of Q_{rr} which is critical in order to control the miller effect
- Prevent the dead time from expanding during light load conduction
- No Q_{rr} period which translates to their capability of switching at high frequencies

Some of the challenges associated with GaN are the high electromagnetic interference (EMI), gate ringing and oscillation due to the parasitics rising from the power circuit, device packaging and the device control loop. The dead-time resulting from the higher frequency reduces voltage significantly leading to power loss [37]. With the smaller switching times, the common mode and differential mode noise associated with GaN devices increase accordingly [38]. Innovative techniques are required to reduce the switching losses while lowering the EMI simultaneously [39]. Since GaN technology has not yet matured in industry and due to its extremely fast switching transitions, control of these HEMTs is challenging and complex. As this semiconductor technology matures, multiple control techniques will be developed and become common practice as is the case for Si MOSFETs today, reducing control design complexity.

B. APPLICATION OF GaN VS. SiC

Different components of an EV such as the on-board charger, traction inverter and DC/DC converter are presented in Fig. 4 in terms of the device voltage and current rating. As can be seen in Fig. 4, GaN and SiC switches typically have the same operating current. However, higher voltages can be obtained with SiC transistors. In the DC/DC converter, depending on the voltage levels either GaN or SiC can enhance efficiency when used along with Si switches. Similarly, for the on-board charger and traction inverter, depending on the operating levels, WBG devices can be used. Benefits in other type of vehicles such as autonomous vehicles can

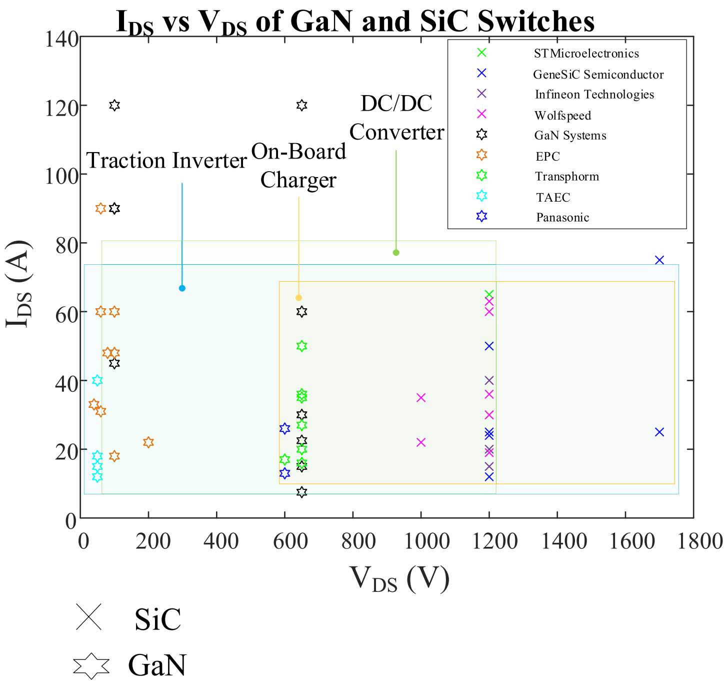

FIGURE 4. **Application of GaN and SiC switches in the on-board charger, DC/DC converter and traction inverter.**

also be realized. Light detection and ranging (Lidar) applications take advantage of the fast switching characteristics of GaN devices for an improved imaging speed and depth resolution which is required in autonomous vehicles [40]. Lidar is a pulsed system which needs fast power devices and small stray inductances. The GaN HEMTs with their improved gate-speed Figure-of-Merit (FOM) and smaller parasitics enable faster sub-*nsec* transitions to extract the full potential of the laser transmitters in such systems [16]. GaN allows the laser beam to be fired at about 10 times higher speed than Si resulting in higher resolution images and more accurate detection [16], [41]. Therefore Si, SiC and GaN can be used in different components of an EV depending on the application.

C. FAILURE MODES OF GaN HEMTs

To justify the transition to GaN power transistors, product-level reliability and robustness must be confirmed through analyzing failure modes of GaN HEMTs. In particular, stress testing must be conducted to ensure device robustness against hard-switching hot-carrier stress and high dv/dt switching. As stated in [42], soft-switching of GaN MOSFETs occurs when the MOSFET channel is turned off due to low drain voltage. The flow of drain current then leads to an increase in the drain voltage by charging the MOSFET output capacitance. During turn-on the drain capacitance discharges through the channel. In hard-switching, the GaN MOSFET is simultaneously subjected to high voltage and current levels leading to hot-carrier generation, requiring robustness of the device. The high slew rates of GaN HEMTs can allow capacitive current to enter into unwanted regions of the device. Hard-switching of GaN causes high instantaneous thermal power dissipation. A double-pulse test which is used for characterization of semiconductor switching dynamics, can be used for hard-switching robustness and dynamic $R_{DS(on)}$ degradation testing of GaN semiconductors. An increase in $R_{DS(on)}$ can reduce efficiency causing thermal runaway. Thus, stable dynamic $R_{DS(on)}$ and robustness of GaN devices can be tested under accelerated conditions using double-pulse test to detect poor performance.

Compared to Si-based counterparts, GaN power transistors previously lacked unclamped inductive switching (UIS) capabilities. UIS is a test where an inductive load is switched on and off by a transistor. The energy stored in the inductor during the on-state is dumped into the transistor after its turn-off leading to high stress on the device. Typically, cascode GaN transistors and P-GaN HEMTs exhibit low intrinsic UIS capability from capacitive charging. This test is important as UIS occurs in automotive power circuits exposing the transistors to these events over their lifetime. Exposing the transistor to UIS will test its reliability when exposed to switched currents. Therefore, UIS is beneficial in testing the reliability of GaN HEMTs and cascodes [43].

In the short-circuit (SC) test, 650 V GaN HEMTs must be capable of handling short-circuit events at V_{DC} values around 400 V while providing sufficient time for gate drive circuit actuation. The hard switch fault (SC type I) test is most commonly used by power device manufacturers. In SC I, the device under test (DUT) is subjected to a faulty event. SC current then flows through it while withstanding V_{DC}. The time in which the DUT will be destructed and result in failure is the short circuit time. The SC time duration must be long enough for the controller to detect the short-circuit condition and safely switch the device off without electrical failure. Among GaN cascodes and p-GaN HEMTs, both devices failed SC test according to M. Fernandez *Et Al.* at $V_{DC} = 400$ V with an on-time of 10 us. SiC MOSFETs have the best SC capability and are therefore more reliable in this test [44].

III. ELECTRIFIED VEHICLE APPLICATIONS

The adaptation of electric vehicles faces many challenges such as range anxiety, limited charging infrastructure, size of power electronics, battery pack capacity and cost. To increase the number of EVs and reach the goals set by the US Department of Energy (DOE) in terms of emission levels, battery pack design and performance criteria, the mentioned challenges need to be addressed. Electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles (PHEVs) comprise multiple power electronics converters for charging the batteries from the utility grid and running the motors of these batteries as their primary function. Achieving high efficiency, ruggedness, small size and low cost is a major challenge for these power electronic converters [45]. Fig. 5 shows the main power electronics in an EV [2], [11], [12], [46]. Each of these subsystems are discussed below in detail for an assessment of the benefits with the use of GaN WBG devices [46].

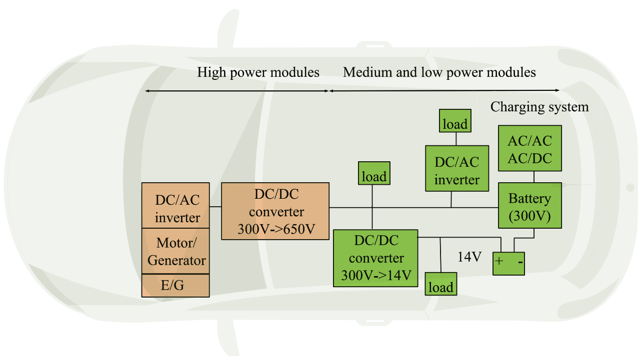

FIGURE 5. Power electronic components in electrified vehicles.

The automotive industry demands the use of high power density transistors with simple circuitry. According to [47], GaN transistors offer the following benefits in this industry:

- Enhancement-mode devices up to 650 V
- 10 times improvement in FOM compared to Si MOSFETs and insulated-gate bipolar transistors (IGBTs)
- Current ratings up to 150 A
- Low cost using Si as a base substrate
- Gate drivers similar to Si MOSFET

A. CHARGERS

To support the transition to EVs, charging infrastructure need to be improved and increased significantly. H. Wang *Et Al.* present a discussion of conductive charging of EVs in [46]. The EV charging equipment at different power ratings are categorized into various '*Levels*'. *Level-1* and *Level-2* chargers supply typical 1.4 kW and 6.6 kW powers, respectively, and may be present on-board the vehicle. Fast charging *Level-3* chargers, on the other hand, are most suitable for off-board chargers mainly due to their weight and cost. *Level-3* charging stations allow from 20% to 80% State-of-Charge (SOC) within 30 minutes. Due to their increased power rating, the off-board Level-3 chargers are powered from 3-Ph AC supply, limiting the scope of using the 650 V GaN HEMTs available now. There exist few topologies such as the Vienna rectifier which stress the HEMTs to lower voltage levels, permitting the use of multiple devices in parallel for higher effective current ratings. In these applications, GaN could be used. Table 11 in [3] lists the typical specifications of the various Levels of EV chargers. EVs use *Level-2* charging infrastructure at different power ratings for in-home charging of the EV using wall connectors. These EVs can charge using *Level-3* charging via the DC charging stations installed across the country. Among those are the Tesla Model S, X, Y and 3 as well as the Nissan LEAF [48], [49]. The on-board chargers are made from cascaded AC/DC power factor correction (PFC) boost and DC/DC converter stages as shown in Fig. 6. The PFC stage is usually without isolation while the DC/DC converter is isolated for safety. The possible use of GaN HEMTs in each of these components is discussed in detail below.

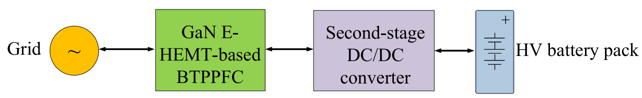

FIGURE 6. Electrified vehicle on-board bidirectional battery charger system.

There are multiple possible topologies for the AC/DC PFC boost stage that are derivatives of the basic boost converter topology. Interleaving is common in these topologies as it helps to reduce the output voltage and input current ripples for improved power quality. Given the typical 390 V output voltage of the PFC boost converter, the 650 V GaN devices could be used as discrete or modules in these converters, depending on the design requirements. The PFC stage also includes input filters to filter the input current harmonics and keep the power distribution network clean by meeting the conducted emission regulations. An increase of the switching frequency in these devices makes it possible to use smaller inductors and capacitors in the input filter and the AC/DC converter itself, resulting in the design of smaller converters which is gaining a lot of attention in industry as the demand for more compact converters is increasing.

A DC/DC converter is needed to match the voltage levels of the PFC with the battery. The various topologies for the isolated DC/DC converter in the on-board charger involve high-frequency switching and energy transfer from the primary to the secondary side of the converter using a high-frequency transformer. A few of the cases also use an output LC filter with the secondary-side of the converter which is a diode rectifier. These circuits have the potential to take advantage of the GaN device characteristics by going higher in switching frequency while dissipating the same overall losses. An increase in the switching frequency and use of smaller values of passive components also improves the dynamic performance of the power converters. The secondary-side Si fast rectifier diodes could be replaced with Silicon-Carbide (SiC) schottky barrier diodes for a significant minimization of the reverse recovery losses in the diodes and the synchronous rectifier. With popular interest in the integration of the electric vehicles with the grid through Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) energy transfer for an intelligent energy management ecosystem, the future EV chargers may need to have bidirectional power transfer capabilities [50]. There exist both bidirectional half-bridge and full-bridge AC/DC PFC converters and DC/DC converters implementing this functionality.

A bidirectional active front end (AFE) charger with a LCL grid filter and single phase dual active bridge is proposed in [51]. This topology serves as a bidirectional battery charger for PHEVs and EVs. This topology can be either Si IGBT based or based on GaN HEMTs. The design using GaN devices showed advantages compared to the Si-based topology. The GaN-based charger at 500 kHz had losses of 60 W whereas the Si-based topology at 24 kHz had losses of about 74 W. With the GaN technology, the switching frequency was increased by about a factor of 20 while reducing the overall power losses. The grid filters in this design can be significantly reduced in size at these higher frequencies. A bidirectional 6.6 kW on-board charger for PEVs is proposed in [52]. In this OBC architecture, both 600 V GaN and 1200 V SiC MOSFETs are used to increase the switching frequency above 300 kHz achieving an efficiency of over 96% and a power density of 37 W/in^3. Obtaining this competitive power density at high efficiency is attributed to the high switching efficiency of SiC and GaN which enables the integration of magnetic components with the PCB winding.

Future EVs are expected to be charged wirelessly. Wireless charging is achieved via electromagnetism. Electric current passes through a coil of wires which is installed on the surface of the parking space. The current creates a magnetic field which transfers power between the primary and secondary coils. The EV can be charged by being placed above the charging device installed on the floor where the car is parked [53]. With current trends, wireless power systems are moving from simple charging pads towards becoming power sources. This can be achieved through increasing the power capability of these systems while operating over a larger area. GaN-based amplifiers can operate over a wider imaginary impedance range compared to Si MOSFET-based amplifiers. With changes in coil technology and design of higher power amplifiers using GaN MOSFETs over Si devices, the design of such large area wireless power systems is possible [54]. This technology can potentially aid in the development of wireless power systems that are large enough to charge an EV.

B. ENERGY STORAGE SYSTEMS

The EV battery is responsible for many challenges facing electric vehicles today which is why extensive research is being conducted in this field. Parameters such as battery state of charge (SOC) and state of health attribute to the safety, reliability, and lifetime of the EV battery [55]. The enhancement in battery technology can provide higher range, making the transition to transportation electrification more desirable for consumers. Since the electric vehicles need to provide high electric range, the batteries are generally oversized. To reduce the volume and mass of these batteries a material with high energy density is required [56].

In an EV the Energy Storage System (ESS) is connected between the battery and the traction drive DC link. The bidirectional DC/DC converter in the Hybrid Energy Storage System (HESS) provides an interface between the energy storage hardware and the inverter. To improve the efficiency of the DC/DC converter and reduce its size, GaN can show potential benefits that are discussed in detail in [58]. The use of WBG devices in these converters results in improved power density and efficiency which can reduce the traction battery size while maintaining the same range.

In [59] a Si-based DAB converter is compared to a hybrid GaN-Si one for both step-up and step-down operations with a resistive load. It was shown that the hybrid topology outperforms the Si converter by 2% in terms of efficiency, showing benefits of hybrid technologies in these systems. A bidirectional fractional buck-boost converter for high power 200 V battery ESS, with a capacity of 50 Ah is proposed in [60]. The converter uses 100 V GaN HEMTs. A 1.2 kW, 100 kHz battery system power prototype was designed achieving peak efficiency of 99.63% with high power density, and low weight. Thus, hybrid Si-GaN designs are more efficient, permitting the use of smaller batteries while maintaining higher driving range and lower SOC depletion rate.

Another challenge associated with the EV battery is its cost. In 2015, the battery pack cost was at 200 USD/kWh for battery electric vehicles (BEVs) and 255 USD/kWh for PHEVs. In 2030, the battery pack cost is expected to decrease to 100 USD/kWh for BEVs and 125 USD/kWh for PHEVs [61]. One of the main benefits of transportation electrification is the net savings in fossil fuel emissions such as CO_2. This can be achieved if the vehicle coupled with electricity, that is generated to charge the battery, has below 700 grammes of CO_2 intensity per kilowatt-hour. The focus of next generation PEVs is to meet the goals set by the US Department of Energy (DOE). These goals include reduction in system cost, complexity, size and weight of the overall vehicle including that of the power electronic components and reducing the electric motor cost by 50%. The EV battery performance can be enhanced by reducing the battery size and weight and increasing the battery power. To reduce the battery size the energy density can increase from 150 Wh/L (in 2014) to 400 Wh/L. The battery weight can be reduced by increasing specific energy from 125 Wh/kg (2014) to 250 Wh/kg. To increase the battery power the specific power can increase

TABLE 3. ESS battery capacity and range for different EV models.

Model	Range (km)	ESS (kWh)
2018 Ford Focus Electric	185	33.2
2017 Volkswagen e-Golf	201	35.8
2018 Chevy Bolt	383	60
2019 Nissan LEAF	363	62
2018 Tesla Model 3 Long Range	499	80.5
2018 Tesla Model X 100D	475	100
2018 Tesla Model S 100D	439	100

from 1000 W/kg (2014) to 2000 W/kg [62]. The Tesla Model 3 battery pack has an estimated specific energy of 250 Wh/kg with the company aiming to increase it to 330 Wh/kg in the near future [63]. The current 4th generation NCM 811 batteries used in the Nissan LEAF e+ (62 kWh) have specific energy and energy density of 224 Wh/kg and 460 Wh/L, respectively. The next generation of NCM 811 batteries are expected to have an energy density of 600-650 Wh/L with specific energy greater than 300 Wh/kg [64]. Since the range of an EV is determined by its battery performance and ESS capacity, it is important to consider the relationship between these two parameters. Table 3 shows the ESS battery capacity and range for different EV models. Improving the efficiency and power density of the DC/DC converters in ESS with GaN can facilitate higher range and further adoption of EVs.

C. ELECTRIFIED POWERTRAINS

An EV powertrain uses a DC/DC boost converter to generate a varying DC link voltage from the HV battery to power a DC/AC inverter driving the motors (induction or permanent magnet synchronous machines) [65]. In the HEV, the DC/DC boost converter and the DC/AC inverter are the key power modules [11]. Both the DC/DC converter and the inverter have bidirectional power flow capability to capture energy from regenerative braking [2]. The HV battery is usually in the range of 200 V-400 V [66]. A variety of topologies are possible for the DC/DC converter, such as a simple boost converter, 3-level converter and composite boost converter [46].

The conventional DC/DC converter and the inverter in the powertrain use 650 V Si-IGBTs or MOSFETs. Due to the motor, the switching frequency is limited to around 10-20 kHz. A hybrid mix of GaN and Si switches can provide benefits in these converters, since the GaN MOSFETs have smaller parasitic capacitance and switching energy values [67]–[69]. This benefit is due to the values and the size of the passive components (inductors, input and output capacitors) in the DC/DC converter varying inversely with the switching frequency [50]. The ability to remove the freewheeling diodes in converters is among the advantages of GaN in these components [70].

GaN HFET on Si provides low losses and high power at a reduced cost. High speed, high current and high breakdown voltage is attainable with HFET devices based off of AlGaN/GaN. Toshiba is one of the manufacturers of AlGaN/GaN HFETs on SiC substrate. The high temperature and high power capability of these devices is another desirable property for DC/DC converters [10].

The composite boost dual-active bridge (DAB) converter discussed in [71], [72] outlines its benefits over a conventional boost topology in terms of power losses, switch voltage stress and the voltage ripple values. The presence of two power processing paths (boost converter and buck converter with DAB converter) reduces the switch voltage stress, making it an ideal candidate for use of the 650 V GaN HEMTs while taking advantage of their reduced switching losses and greater efficiency. Depending on the vertical and lateral structure of GaN, it can be beneficial to different power module components. With the commercialization of vertical GaN, these devices could be used in high power DC/DC boost converters and DC/AC inverters while the lateral structure can be used in high-to-medium frequency applications such as DC/DC buck converters [62]. In DC/DC converters where the voltage is rated above the maximum rating of GaN switches currently available in the market ($>$ 650 V), a hybrid mix of GaN and Si switches may be necessary to account for the lower voltage rating of GaN transistors. For instance, when using a DAB to step voltage down from 600 V to 28 V, use of GaN is restricted on the primary side since the MOSFET rating needs to be higher than 650 V to account for the stress and voltage peaks experienced on the primary side switches when the converter is in operation. Modifying the topology from conventional DAB, into a series-parallel or interleaved configuration can aid in the use of GaN transistors in these topologies as these techniques divide the input, splitting the primary side voltage and therefore permitting the use of 650 V GaN transistors.

Due to the device characteristics and the absence of a body diode in GaN HEMTs, the reverse recovery current and the associated losses are eliminated and benefits to the same extent could be obtained with the use of these devices in the inverter stage. In most cases, the existing 105^oC engine cooling loop in the inverter is not enough to handle the high temperatures experienced by this component and therefore a separate coolant loop at $60 - 75^oC$ for the inverter maybe be required. The higher temperature handling capability of WBG devices may eliminate the need of this separate coolant loop [73]. This leads to a more compact powertrain at a lower cost. However, the use of wide bandgap devices in the inverter may or may not have benefits depending on the usage of the vehicle and the variation in the dominance of the switching and conduction losses at different operating points [74]. Due to the 1200 V device rating of SiC and its superior material properties discussed earlier, these devices are recently being used in inverters. Many companies are currently basing their designs on SiC MOSFETs. A 80 kW EV powertrain based on the Nissan LEAF is investigated in [75]. The results show improvements in efficiency in the low speed and high-torque region with the use of SiC MOSFETs in the inverter, giving a substantial gain in the overall efficiency for urban driving. This converts into improvements in the EV driving range and a better MPGe (equivalent miles per gallon). Toyota has also built a SiC inverter prototype for the Prius with improved fuel economy. In recent years, companies such as Toyota and Denso are investigating SiC semiconductors for power control units and more companies are expected to adopt these devices in future EVs [76]. The use of current 650 V GaN HEMTs is limited in inverters. Similar to SiC, higher voltage GaN devices can show similar performance improvements in these components.

D. MOTOR DRIVES

The efficiency of an EV is highly dependent on the efficiency of its power electronic motor drive. When looking at the motor drive, both the inverter and motor are considered. As previously mentioned, increasing power density is beneficial in electrified transportation. Improving the efficiency of the motor drive reduces cost and thermal requirements making future EVs highly competitive against ICE vehicles.

The second generation Chevrolet VOLT Extended-Range EV released by General Motors reduced the size and mass of the traction power inverter module (TPIM). The second generation TPIM eliminates AC cables and can be mounted to the transmission. The maximum AC power for the first generation VOLT-1 TPIM is 111kW versus VOLT-2 TPIM which is 87 kW. The power density increased by 43% for VOLT-2 while the EV range increased by 30% leading to 11% improved fuel economy. Thus, the benefits of designing smaller TPIMs are realized [77].

Due to the limited voltage rating of GaN switches currently available in the market, fully GaN-based inverters at the required power level for EVs, are not available. A hybrid GaN/Si inverter configuration can be developed for EV traction inverters. This hybrid topology proposed by GaN Systems, can take advantage of the higher voltage rating of Si IGBTs and faster switching transitions of GaN HEMTs, resulting in a more efficient inverter [78]. The absence of Q_{rr} and optimized parasitics in GaN enables the use of gate driver circuits that accelerate the IGBT's switching transition, lowering the total loss dissipation.

The efficiency of a 1 kW GaN inverter with a DC bus voltage of 150 V is compared to a Si inverter in [19]. Due to the extremely fast switching times of GaN MOSFETs during turn-on and less damped RLC circuit, the GaN inverter experienced higher current spikes and oscillations. Thus, with GaN MOSFETs it is critical for the parasitics on the device package and circuit to be minimized. The GaN inverter dissipated one eighth of the losses of the Si inverter. At full load current with unity power factor, the efficiency of the GaN inverter was 99.41% versus 94.52% for the Si counterpart. It is worth mentioning that the power level of this prototype is lower than the power level required for inverters used in EVs. However, based on this comparison it can be predicted that higher voltage GaN-based inverters and hybrid topologies could outperform conventional Si inverters. The main challenge that remains with GaN HEMTs is the lower voltage rating and higher cost of these switches which are expected to be overcome in the near future, paving the road for possible all-GaN-based inverters.

E. AUXILIARY POWER UNITS

An auxiliary power unit (APU) serves as an interface between the HV battery and the LV battery in an EV. The APU can be an isolated DC/DC converter with bidirectional power flow capability. From the HV battery, the APU charges the LV battery to power the auxiliary circuits. Isolation is needed to prevent the high-voltage from reaching the low-voltage circuits and to prevent electric shock hazard when the chassis is touched by the user. Reverse power flow is needed for pre-charging the DC/DC boost converter in the powertrain at start-up.

A low-voltage electrical system and APU sized at 3 kW output power is necessary in an EV with many auxiliary loads [79]. The presence of a high-frequency transformer for power transfer and large input and output capacitors make it advantageous to switch at higher frequencies with GaN HEMTs for a more power dense system. There exist other auxiliary loads in the EV which may be powered from either of the LV and HV batteries. The air conditioning equipment, sunroof, electric valves, and active suspension are examples of such high power loads [80]. These may need power through DC/DC or DC/AC converters, offering opportunities for use of GaN devices as outlined earlier.

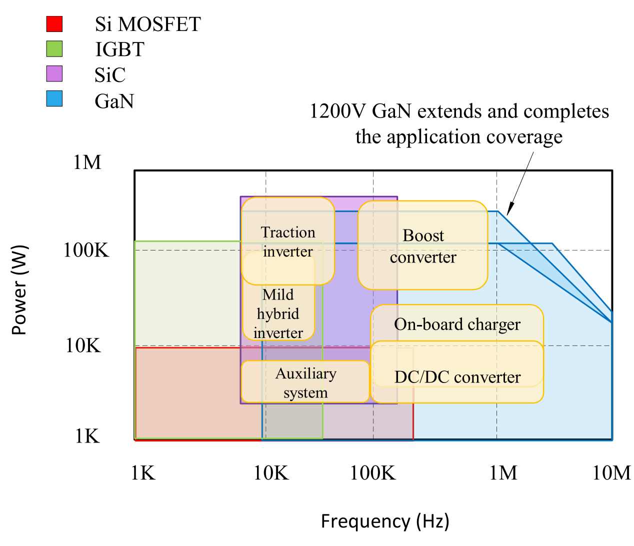

FIGURE 7. Power versus frequency operation of different switch technologies in the traction inverter, converter and on-board charger of electric vehicles.

Fig. 7 shows the power rating versus frequency of Si MOSFETs, IGBTs, SiC and GaN devices [81]. The on-board charger, inverter and converter in an electric vehicle are highlighted in terms of the operating frequency and power levels. The IGBT typically operates in the lower end of the frequency spectrum at high power. Si MOSFETs extend further in frequency but the power handling capabilities of these MOSFETs are lower compared to IGBTs. SiC devices can handle higher power and higher frequencies. GaN extends in the MHz frequency range. With current GaN devices the power handling capabilities are limited. However, in the future with 1200 V GaN devices, the application can be extended to cover higher power and higher frequencies than IGBTs, Si MOSFETs and SiC devices.

The EV performance targets for the on-board charger, DC/DC converter and traction inverter set by U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) are summarized in Table 4 [82]. Among the listed parameters, the power density, specific power and efficiency metrics can be met by 2025 in part, through adopting more WBG technologies in these EV components as outlined earlier.

TABLE 4. EV performance targets for on-board charger, DC-DC converter and traction inverter.

Application	Parameter	2020	2025
On-Board Charger	Cost ($/kW)	50	35
	Specific Power (kW/kg)	3	4
	Power Density (kW/L)	3.5	4.6
	Efficiency	97%	98%
DC/DC Converter	Cost ($/kW)	<50	30
	Specific Power (kW/kg)	>1.2	4
	Power Density (kW/L)	>3.0	4.6
	Efficiency	>94%	98%
Traction Inverter	Cost ($/kW)	8	6
	Power Density (kW/L)	4.0	33

IV. NON-AUTOMOTIVE APPLICATIONS

To fully move towards electrified transportation and reduce the negative impacts of the current transportation system, non-automotive vehicles also need to become more electrified. WBG devices can operate in harsh environments such as on board applications; namely aircraft, spacecraft and other vehicles [83], [84]. Application of these devices in different transportation mediums is outlined in this section.

A. MORE ELECTRIC AIRCRAFT

Electrifying aircraft reduces environmental impacts by increasing fuel efficiency and reducing air travel emissions. With electric aircraft, the maintenance and fuel costs are significantly reduced. This is possible with the use of power electronics technology. There are two types of energy sources used in more electric aircraft (MEA). The primary sources include the engines and the secondary sources include the hydraulic, pneumatic and electric systems [85].

The MEA can be improved by removing some of its systems. With the removal of the pneumatic system, the requirements on the gas turbine are relieved thus, increasing efficiency of the turbine. The removal of the hydraulic system can result in overall weight reduction in the MEA [86]. This is beneficial as weight is one of the main challenges currently facing aircraft [87]. The heavy weight is partially due to the heavy power electronic boxes. A second challenge is the cooling and control of power generators and converters which leads to a higher electrical power demand. GaN and SiC have properties such as low losses, high switching capability and high temperature operating capability which aid in addressing these challenges. With movement towards MEA, recent technology has allowed the Boeing 787 Dreamliner to eliminate traditional pneumatic system and change the power sources from bleed air to electric power. Functions such as air conditioning and wing anti-ice systems are then powered electrically. The benefits of 787's more-electric design are [88], [89]:

- More efficient power generation and distribution with expanded range
- Improved fuel efficiency and reliability
- Simpler maintenance and reduced maintenance costs
- Lowered noise and drag

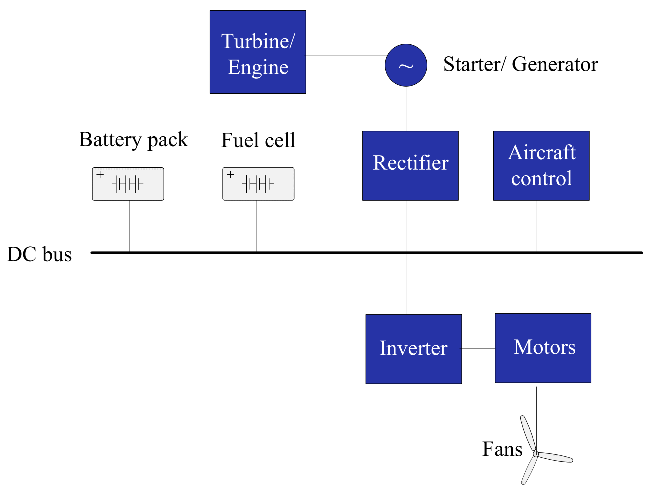

FIGURE 8. More electric aircraft power system.

Generally, in the aerospace industry, the significance of reliability outweighs cost. With GaN HEMTs, the heat dissipated by the power electronics is reduced, enabling the design of smaller and lighter cooling systems. This improves the reliability of the aircraft control system while reducing environmental control dependencies [90]. Additionally, the greater radiation hardness of GaN as well as its ability to operate over a wide temperature range make this WBG device a great candidate for use in these applications [91]. Fig. 8 shows the generic MEA power system layout for hybrid gas electric propulsion aircraft [92].

The DC/DC converters in an aircraft require an EMI filter to filter the noise from the input to the power supply and vice versa. GaN technology can significantly reduce the size and weight of the EMI filter used in these converters [94]. Converters in the aircraft are connected to a low voltage DC bus of around 28 V. SiC devices are becoming common switch technology in MEA applications. GE Aviation designed a 20 kW DC/DC converter that operates from 610 V to 28 V. The 1064000G1 converter is based on GE's custom 1200 V SiC MOSFETs that are packaged in liquid cooled power modules. The planar magnetic technology used in this converter permits high power density and reduced weight. With the described attributes, this converter can be used in more electric aircraft applications [93]. This is an example of how WBG devices aid in the electrification process. The semiconductor technology permits the design of more power dense and reliable power electronic systems, while optimizing efficiency [83], [84], [95].

The converters in the aircraft deal with high currents of about 35 A. GaN Systems currently offers a 650 V 150 A E-GaN HEMT. In applications where current levels are higher, to increase the power level of these converters, GaN transistors must be paralleled [96]. In health monitoring systems of a spacecraft, the rectifier is small but must have the ability to operate at high power. This characteristic allows sufficient sensing data to be obtained and sent at a reasonable rate to the health monitoring system. GaN HEMT based rectifiers can be used in spacecraft health monitoring systems using wireless power transfer. Using GaN HEMT instead of the conventional schottky diode in these systems allows for high power operation. The structure of GaN also makes it a better candidate for Monolithic Microwave Integrated Circuit (MMIC) which is required in the health monitoring sensor tag [97], [98].

B. MORE ELECTRIC SHIP

The electrification of ships will increase system efficiency, decrease operating costs and improve mission capabilities [99]. Electrifying ships is beneficial as the space required in installing electrical propulsion machinery is significantly less than conventional systems leading to more load space in a ship.

All-electric ships (AESs) have emerged with the substitution of mechanical combustion engines with electrical motors, similar to that in an EV. Electric motors are better able to handle variations in demand. Ships currently plug-in to a local grid via shore side connections rather than running engines. This results in saving fuel and reducing harmful emissions. The electric propulsion has many benefits over the mechanical propulsion system. These benefits are stated in [100]:

- Improved dynamic response
- Optimizing space due to locating the internal combustion generators away from propulsion shafts
- Improved control of electric propulsion systems
- Maximized efficiency
- Improved comfort on-ship
- Improved maneuverability

Hybrid electric ship (HES) is a solution to reducing fuel emissions of ships. The lithium battery in the HES is considered the energy storage system [101]. The HES topology is shown in Fig. 9.

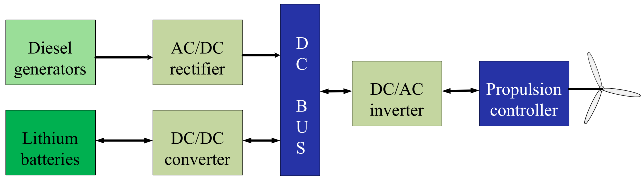

FIGURE 9. Hybrid electric ship topology schematic.

The superior relationship between the on-resistance and breakdown voltage of GaN due to its higher critical electric field strength enables the design of more compact converters [102]. The positive temperature coefficient of this transistor relieves the cooling requirements significantly, thus enhancing the efficiency of ships to a great degree [103]. With GaN the power density of the converter as well as the ability of the switches to operate in high temperature environments improves significantly. The design of higher speed motor drives which reduce the motor size and ultimately reduce the overall system cost is also possible. In ships, reliability is of utmost importance. With the stated benefits of GaN, the topology of the converter in the shipboard electric power system can be further simplified resulting in the design of lower cost and higher reliability converters [104]. In the shipboard electric power system, the conventional line-frequency transformers can be replaced with solid-state transformers through the utilization of WBG devices such as GaN. This results in smaller and lighter transformers. WBG devices also improve the gate drive and protection technologies resulting in more robust designs [105].

There are many hybrid ships currently in use around the world. Among those are the ferries known as the "bird flight line" that run between Germany and Denmark and "Vision of the Fjords" in Norway. For the first, the internal combustion engine and electric drive system are combined in the drive resulting in 15% reduction of CO_2 emissions [106]. For the "Vision of the Fjords", the electricity required for the drives is obtained from diesel generators and 600 kWh batteries. When sailing, the batteries charge up from the energy coming from the engine and when docked, this energy is obtained from hydro-electric power [106]. The "Ampere" in Norway is the world's first electric car ferry developed by Siemens and Fjellstrand [107]. Lithium-ion battery packs are installed on-board and on the ports. Electricity to charge these batteries comes from hydro-electric power plants. Due to being fully electric, the operating costs have been reduced by 80% while the CO_2 emissions are about 5% of conventional ferries [108]. With these benefits, electric ships are not only sustainable but they also provide advantages in terms of cost and reliability making their adoption beneficial in electrified transportation applications.

C. RAIL VEHICLES

With the transition towards more sustainable solutions, small steps have been taken in electrifying trains. For railway traction systems to stay competitive with other means of transportation such as personal vehicles and airplanes, they must operate at higher auxiliary power while reducing the weight and volume of their electronic components in order to provide more space for passengers. Reducing weight also reduces the wear out of the wheels while reducing overall energy consumption.

These transportation mediums also need to operate at higher efficiencies, higher speeds and increase the reliability of their railway traction systems [109]. In the future, all-electric heavy rail systems will be manufactured. The main challenge facing this type of rail system is the high cost. With the implementation of WBG devices in auxiliary converters, higher power density of the traction equipment can be achieved resulting in cost and energy savings [103], [110]. The efficiency of the on-board power converters on the High Speed Rail (HSR) train can increase with GaN. With the aforementioned capabilities of these transistors resulting in the design of more compact power components, this semiconductor technology provides more space for the passengers while permitting travel at higher speeds [111].

There are many companies working towards purchasing electric trains. For instance, Caltrain's new electric trains which are part of the Caltrain Modernization (CalMod) program are set to replace 75 percent of the current diesel locomotive trains as a step towards a more green future [112].

D. HEAVY-DUTY AND OFF-ROAD VEHICLES

Similar to transportation electrification of vehicles, electrifying heavy-duty and off-road vehicles such as trucks require improvements in their power electronic systems. In order to meet the demands of the future set for trucks, the power systems could take advantage of the superior performance of WBG devices alongside Si transistors. The desirable thermal management aspects, high temperature operation capability and low inductance packaging of GaN HEMTs could potentially lead to the design of more reliable and more efficient heavy-duty vehicles.

Generally, the inverters used in these types of off-road vehicles are larger and operate at higher voltage levels compared to electric vehicles. The traction battery in these types of vehicles operates at voltages of about 800 V where the use of the current 650 V GaN MOSFETs is limited. In this case, SiC may be a more suitable alternative. However, in the near future with the increase of the voltage limit of GaN, their use in the inverters of trucks is possible. Hybrid trucks are currently available in the market. They typically use a lithium-ion battery pack along with transmission-mounted motors. As is the case in electric vehicles, regenerative breaking allows for the generation and storage of electricity in hybrid trucks permitting acceleration. Similar to ships, plug-in stations can be installed at rest stops which can be used for heating and recharging of the batteries of these vehicles [113].

Over the past few years, electric buses have emerged in the transportation sector. These battery-electric buses are recharged using renewable wind energy power sources. Shinry Technologies Co Ltd is a HEV power supply solutions manufacturer. The Cree 1200 V SiC MOSFETs are used in Shinry's 3 kW and 1 kW DC/DC converters which are used in electric buses [114]. These DC/DC converters obtained an efficiency of 96% with 25% reduction in size and 60% reduction in peak power losses compared to traditional Si-based products. With future 1200 V GaN devices, it can be predicted that high performance DC/DC converters with higher efficiency and power density can be designed for heavy-duty vehicles. In 2014 Proterra Inc. released its Catalyst Model, a fast-charge all-electric bus. The two models 35 ft. and 40 ft. provide a range of 377 km and 528 km with energy up to 440 kWh and 660 kWh respectively. These electric buses are currently on roads and are expected to increase in numbers over the next few years [115]. The roadmap of electrified and more electrified transportation mediums discussed in Sections III and IV is shown in Fig. 10.

V. FUTURE TRENDS

Since the introduction of GaN in industry is fairly recent, future trends are an important discussion when looking at the possibilities this technology can enable in different applications. The biggest challenges and areas for improvement are the high cost of these devices, limited voltage rating of current GaN devices, the complicated gate driver design and control complexity, thermal management with regards to area-specific thermal resistance in GaN-based IC development, and packaging concerns to provide robust housing and ensure long term reliability of these devices. Each of these factors are discussed below for an assessment of where the future of GaN lies.

A. COST REDUCTION

To address the cost issue associated with GaN, GaN devices can be fabricated on Si substrates which is common practice in industry today. The production of CMOS compatible fabrication plants along with the desirable material properties of GaN help obtain higher performance and lower cost power devices. The development of high power ICs on GaN on Si wafers can further reduce these costs increasing demand in power converter applications [116]. Since the introduction of GaN technology into the market, the unit price of these transistors has significantly decreased as more advancements in the semiconductor technology are made. For instance, previously a discrete GaN MOSFET had a unit price of around $75 whereas manufactures such as GaN systems now offer the 650 V, 15 A e-mode GaN at only $12. This proves that as more and more power electronics applications employ GaN technology, with economies of scale, the cost is expected to

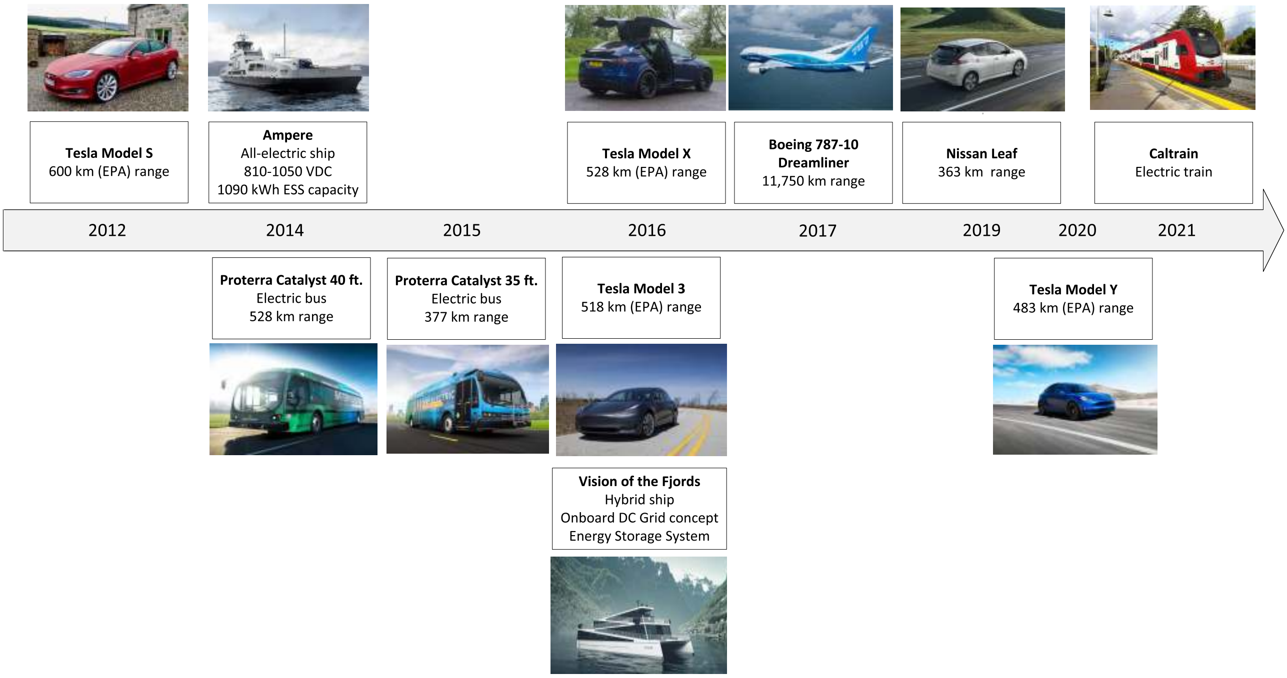

FIGURE 10. **Roadmap of electrified/more electrified transportation mediums in recent years.**

decrease further over the following years. With reduction in cost, GaN HEMTs can be vastly adopted in power electronics thereby increasing efficiency and performance of electrified transportation mediums to a great degree resulting in lower overall system cost. Therefore, the advantages that GaN HEMTs provide outweigh the cost of the transistor, essentially leading to savings in both manufacturing and running costs [116].

B. HIGH-VOLTAGE DEVICES

As previously mentioned, to address the high cost associated with GaN devices, these devices are normally produced on Si substrates as the cost of Si is significantly lower. Growing GaN on Si substrates imposes the challenge of a large difference in the lattice constants and coefficient of thermal expansion (CTE) between GaN and Si. This makes the epitaxy of GaN on Si substrates challenging. This is important since increasing the voltage limit beyond the current 650 V requires significant improvements and innovation in the substrates being used with GaN. Epitaxy also needs to improve to permit the development of thicker epitaxial layers. For 1200 V power applications, imec is investigating the use of polycrystalline AIN (poly-AIN) substrates that have better CTE-match to GaN. This technology is capable of addressing the limitations currently facing these devices as it is allowed to grow thicker higher quality GaN buffers on 200 mm substrates. Therefore, Si-on-poly-AIN substrates are CTE-matched with GaN. There has been significant effort in reducing the $R_{DS(on)}$ and capacitances for GaN devices. For high voltage devices, the $R_{DS(on)}$ scales as (L_{GD}^2). The drain-drift length is about 5 times larger than the limit for 650V devices [116]. Thus, a 10 times improvement in transistor area for a given resistance is expected over the next few years.

Since inverters in electric vehicles and other transportation mediums typically operate at high voltage levels, with the increase in voltage rating of GaN devices, design of fully GaN-based inverters is possible. Most GaN-based DC/DC converters operating in the high voltage range (600 V and higher) require series connected GaN devices due to the limited voltage rating of current GaN transistors. The development of higher voltage rating GaN switches lowers the number of transistors required in these applications, enabling the design of more efficient and power dense power electronic converters. With the reduction in the number of switches, the control complexity decreases significantly. These power dense systems are of great benefit in electrified transportation mediums where weight and volume are an important factor.

C. GATE DRIVER DESIGN

All GaNTM is industry's first GaN power IC Process Design Kit (PDK) which allows the monolithic integration of 650 V GaN IC circuits with GaN MOSFETs. For high-frequency operation, integration of the GaN driver with the GaN MOSFET is of utmost importance. The gate of discrete GaN is vulnerable to noise and voltage spikes due to its fast switching transitions and this can cause damage. Integrating the GaN MOSFET with the driver can mitigate noise to some degree. However, including the GaN MOSFET in a multi-chip module also faces some challenges due to the impedance between the gate of the GaN MOSFET and the Si driver output leading to higher losses. With monolithic integration optimal efficiency, speed and robustness can be achieved. Integrating the driver permits logic circuitry, start-up protection, dv/dt control and dv/dt robustness to all be included in one module. Half-bridge power ICs combine two MOSFETs with the drive and protection circuitry. With the 650 V GaN power IC, the losses in the level-shifter are 10 times lower than Si [116]. Next-generation monolithic integration such as advanced I/O features, over-current and over-temperature protection will enable the design of higher efficiency, higher power density and lower cost power systems [116]. The development of gate drivers with integrated short circuit protection is expected in the near future. This is specially useful in applications where a modular approach is taken and therefore, the size of the packages being paralleled are important. For instance, the modular approach is typically used in the DC/DC converters in aircraft. With advancements in semiconductor technology, the size of the power electronic components designed in industry continue to decrease. With integrated gate drivers, the design of more power dense DC/DC converters is attainable.

Designing the gate drive for GaN HEMTs requires careful design considerations. Typically, separate gate resistor for turn-on and turn-off is recommended. This is important since the R_{GON} can control the slew rate of dv/dt. The value of the turn-on gate resistor must be selected carefully as if it is too high it will slow down switching leading to higher losses and if it is too small it will result in higher switching losses due to gate oscillation. For instance for GaN System's GS66508, the turn-off gate resistor, R_{GOFF}, is recommended to be between 10 to 20 ω. R_{GOFF} starts off from 1 to 2 ω and allows fast pull-down for robust gate drive. The layout of the gate driver with separate outputs is shown in Fig. 11 [117].

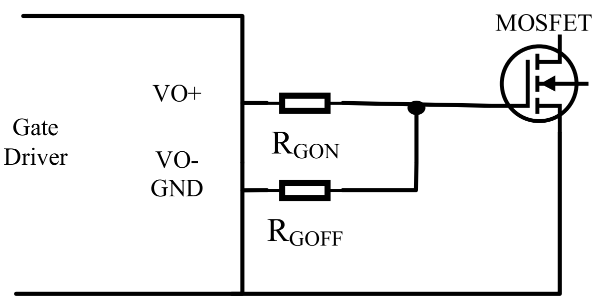

FIGURE 11. GaN E-HEMT gate driver with separate outputs.

Integration of high-speed gate driver, overtemperature and overcurrent protection, and EMI control in one module can maximize performance. Integrating the GaN transistor with its driver offers the following benefits [118]:

- Optimized layout to minimize parasitic inductance
- Low gate-loop inductance while minimizing gate stress
- Minimization of common-source inductance
- Reduction of inductance between the driver output and GaN gate, and the inductance in driver grounding

All power electronic components require careful consideration when it comes to the layout. With the fast switching transitions of GaN, the high dv/dt and di/dt along with low C_{ISS} and $V_{G(th)}$ need to be considered. The gate spikes should be protected to ensure they do not exceed the threshold or maximum rating under the miller effect for safe operation [117]. The high slew rates of GaN compared to Si and SiC make the gate driver design challenging. Thus, integrated gate drivers can improve the gate ringing and oscillations to a great degree, enabling the design of higher performance power electronics in MEAs and EVs.

D. THERMAL MANAGEMENT

Among lateral and vertical GaN structures, the vertical GaN power devices have higher breakdown voltage and current levels without increasing the size of the chip. Vertical structures are more reliable due to their ability to drive the peak electric field away from the surface. The thermal management of vertical GaN is also simpler compared to lateral devices [116]. Due to the benefits offered by vertical GaN structures, significant research and development is being done to commercialize these structures. Thermal management is a key issue when dealing with GaN devices. The minimization of area-specific thermal-resistance is key in GaN-based IC development. In the future, GaN device technologies using high-thermal-conductivity SiC and diamond as substrates are expected to emerge [116].

Lateral GaN on Si substrate devices have their terminals on the same side of the die. Thus, bumps are added onto these chips for mounting purposes. These bumps have limited thermal conductivity while covering a small portion of the die surface area. The GaN transistors are either cooled through these bumps known as topside cooling or through their Si substrate material, known as backside cooling. Thermal dissipation through the topside of the die has the best thermal performance [116]. Based on current integrated modules [119], in the future the design of highly competitive power electronic converters could potentially consist of a phase-leg power module based on GaN devices that integrate the power stage, the gate driver control circuitry and the cooling system into a single enclosure. The integrated module will feature high power capability with improved thermal management. These modules could address some of the current issues facing electrified transportation, as outlined earlier.

E. PACKAGING

Packaging is one of the most important factors in protecting the chip, enabling testing, and mounting onto a PCB. The lifetime of a chip along with its reliability depends to a great degree on the packaging technology used. Additional thermal management and current carrying capability along with isolation against high voltage is possible with the packaging technology employed. Choosing the suitable package without degrading chip performance is an ongoing challenge. For higher voltage chips in the 1200 V and 24 A range, complex interconnection is required on the top side of the chip. If packaging is selected effectively, units can be air-cooled leading to smaller sized devices. For GaN switches operating at higher temperatures, the package needs to enable efficient heat transfer, permitting the use of air-cooling techniques

TABLE 5. Electrified Transportation Specifications [86], [110], [114], [120], [122]–[125].

Field	Specific Applications	Sample Product	I-V Requirements	Current Switch Technologies	Future Switch Technologies
Electric Vehicles	Level-1 Charger	Zencar Level-1 (110 V/15 A)	120 V/15 A	Si IGBT/MOSFET	650 V GaN HEMT
	Level-2 On-Board Charger	TurboDX (240 V/32 A)	240 V/30 A-80 A	Si IGBT/MOSFET	650 V GaN HEMT
	Level-3 Charger	ChargePoint Express 250 (480 V/80 A)	208 V-600 V/100 A	Si IGBT	Si IGBT/MOSFET
	DC/DC Converter/Auxiliary Power Module (APM)	Delta APM DCDC (400 V→12 V)	350 V → 12 V; 48 V → 12 V; 400 V/ 900 V → 12 V, 48 V	600 V Si IGBT & SiC MOSFET & 650 V GaN HEMT	GaN HEMT & SiC MOSFET
	Inverter	Eaton high-voltage inverter (225 kW/800 V)	600 V; 1200 V	600 V Si IGBT & SiC MOSFET	GaN HEMT & SiC MOSFET
	Autonomous Vehicles; LiDAR	LCA2 LeddarEngine	6 V/130 mA	Si IGBT	GaN HEMT
	Wireless Charging	-	220 V-240 V	Si MOSFET	GaN HEMT
More Electric Aircraft	Power Systems	IHI Corporation SiC inverter (35 kW/98% efficiency)	28 V; 270 V; 550 V	Si IGBT & SiC MOSFET	GaN HEMT & SiC MOSFET
	DC/DC Converter	GE 1064000G1 20 kW;610 V/28 V	610 V → 28 V/35 A	Si & SiC MOSFET	GaN HEMT & SiC MOSFET
More Electric Ship	Energy Management System	-	550 V; 800 V	Si & SiC MOSFET	GaN HEMT & SiC MOSFET
Rail Vehicles	DC/DC Converters	Calex 1000 W FX Series; 24S48.21FXW (9 V-36 V→ 48 V)	9 V-160 V→ 12 V, 24 V, 28 V, 48 V, 53 V	Si IGBT	GaN HEMT & SiC MOSFET
Heavy-Duty and Off-Road Vehicles	Batteries	-	24 V/20 A	Si IGBT	GaN HEMT& SiC MOSFET
	DC/DC Converters	Shinry Technologies SiC-based converter (96% efficiency)	220 V-800 V → 12 V, 24 V, 48 V	Si & SiC MOSFET	GaN HEMT& SiC MOSFET

which is simpler compared to liquid-cooling. For PFC systems, packaging of GaN needs to sustain voltages up to 1200 V and currents up to 40 A. Most off the shelf packaging is not suitable for applications requiring GaN, thus research for improving packaging techniques and designing options that provide robust housing and ensure long term reliability is expected to rise in the near future. Power devices need packages with good heat sink die pads (DAPS), robust, ceramic, metal, or plastic housings, ability to mount to a heat sink and output connections with the appropriate size to meet current carrying capability. With advances in power technology, the devices are getting smaller and require small housing while maintaining high performance. For GaN devices, a customized package is required to reduce the DAP size along one edge. This technique provides sufficient gap between the source and drain connections. The control interconnections are made on the opposite side of the DAP and the other sides adjacent to the DAP connect the interconnection pads with the DAP. A clip-bond is used to clip the devices to the leadframe providing a low inductance high current path [121].

For future packaging designs, interconnections can be on the same side of a device and there is no need for wirebonds for source to package base connections, resulting in lower impedance source connections. Use of advanced interconnect materials will also enable development of GaN based products that include multiple GaN transistors which can be beneficial in electrified transportation applications as discussed earlier [121]. For smaller packages, overcurrent protection becomes a challenge as there is smaller space for the heat to dissipate. Therefore, careful consideration must be taken to ensure the transistors are not damaged when exposed to current spikes.

VI. CONCLUSION

With the mass and volume challenges currently facing the transportation industry, a need for lighter designs without compromising efficiency is evident. The high switching frequency, high power density, and high breakdown voltage of GaN make it a suitable candidate for use in this field. The superior switching transitions of GaN compared to SiC and Si permit the design of smaller passive components resulting in overall smaller and lighter systems. The zero reverse recovery charge of GaN compared to Si and SiC counterparts results in the development of more efficient systems. However, the use of GaN HEMTs is associated with challenges such as high EMI and high cost. Extensive research is being conducted by tier one semiconductor companies to release the next generation of high performance GaN transistors. In the near future, it is expected that with the mass production of GaN devices, costs will be reduced leading to an increase in the adoption of GaN technology enabling the design of higher performance electrified transportation mediums. Table 5 summarizes the electrified transportation applications that were presented in this paper in terms of their rating requirements and current and future switch technologies. Sample products for each application are also included, provided if the information was available. Due to the higher voltage and current operating capability of SiC devices, lower cost, higher maturity and reliability compared to GaN, SiC MOSFETs are expected to be widely adopted in future EV, MEA and MES applications. GaN devices can be used alongside Si, forming hybrid topologies to exploit benefits of these devices. With advances in GaN technology, further GaN-based power electronics will emerge in electrified transportation applications.

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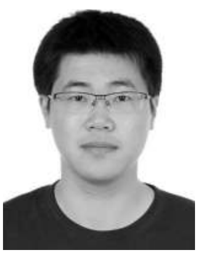

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