



(Ultra)wide-bandgap semiconductors for electric vehicles

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The power electronics charging the battery or driving the motor is often the limiting factor for cost and efficiency. In the race for lowering electric vehicle (EV) costs and enabling widespread adoption, careful design of the power electronics is key. EV manufacturers spend a significant amount of effort in evaluating various power-conversion circuit topologies and various power switches to optimize the cost and efficiency of the EV. The right power electronics material can enable improvement in range as well as reduction in size, weight, and cost. This article discusses the essential role of power electronics in EVs and introduces potential materials capable of meeting these requirements, shedding light on their respective advantages and limitations in addressing the evolving needs of power electronics in the context of EVs.

Introduction

Power electronics in electric vehicles (EVs) play a role whenever there is a conversion of power from AC to DC, DC to AC, or DC to DC (**Figure 1**). In any EV there are three key power conversions areas:

1. **Charging:** The battery in an EV is a DC battery with a fixed bus voltage (400 V bus is common today). The battery needs to be charged using an AC grid that can be single or three-phase.
2. **Motor drive:** The motor in an EV is typically an AC motor (induction, or permanent magnet, or reluctance) that requires three-phase AC power (variable frequency). This power needs to come from the DC battery.
3. **Powering the electronics:** The electronics in the EV (sensors, control, etc.) require low-voltage DC power (typically 12 V) to function. Many EVs also have a low-voltage auxiliary battery for powering the electronics. This low-voltage (12 V) auxiliary battery needs to be charged from the high-voltage (400 V) DC battery.

The exact specifications of each system can vary depending on the type of EV (compact, sedan, SUV, truck, semi, bus, etc.), but these three systems are present for all EVs. In this article, our goal is to present a comprehensive picture of the power

applications landscape in EVs, requirements for a power switch, and the power switch materials and device that will drive the next-generation EVs.

EV power-conversion applications

Charging

Charging can be further divided into pole-charging and onboard charging.^{1,2} In both cases, the AC grid voltage is converted to a DC voltage for charging the battery. The AC grid could be single or three-phase. For pole-charging, the power-conversion system is outside the EV and installed in a specific location (e.g., Tesla supercharging system). Since the power converter is not on the EV, typically size or weight is not a severe constraint. Also, many pole-charging systems are directly connected to a three-phase grid and can provide very high-power levels for fast charging. The grid voltage levels here range from 120 V all the way to 480 V depending on the country and grid architecture (one-phase, two-phase, three-phase).³ The onboard charger is also similar to the pole-charger, but this system is installed on the EV itself. This is done to support at-home charging directly from power outlets. Because size and weight is a constraint here, typically onboard chargers do not support very high-power levels such as pole-based fast charging.

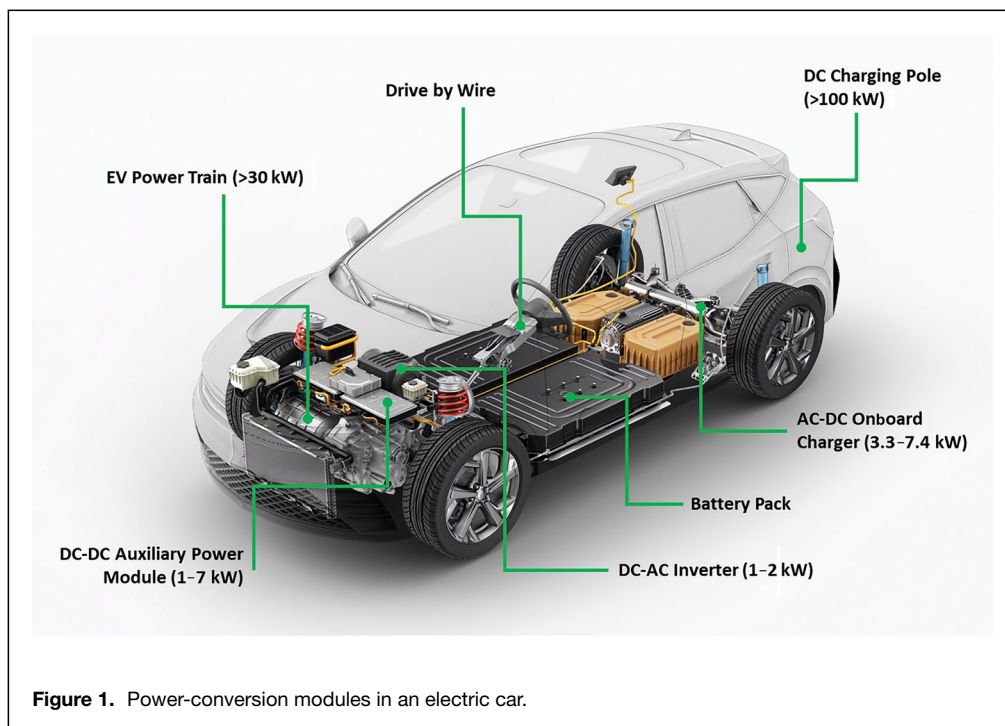
Next, let's look at some numbers. Today, a typical battery pack of a sedan is 50–100 kWh, depending on the range and

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cost. To charge this within 15 min, the power required is 200 kW to >300 kW. Such power levels can only be provided with pole chargers designed to handle such high loads. Pole chargers vary from 6 kW (level 1) all the way to >150 kW (level 3) power levels today with companies constantly pushing to higher power for faster charging.² At-home charging using the onboard charger is typically only 6 kW, which translates to a charging time of >12 h. Onboard chargers with 11 kW and 22 kW ratings are also being introduced for faster at-home charging.

As the charging power level increases, typically two trends are seen: (1) more AC input phases are needed, and (2) higher battery bus voltage is needed. The current requirements for high-power charging are extreme and cause losses due to cable resistances. Additional AC phases distribute the current across multiple phases thereby lowering current requirement on the grid side. Higher battery bus voltage (800 V) lowers the current requirement on the battery side. To keep the system size small, designers are also moving toward high-frequency switching. These trends have significant implications for power electronics. More AC phases require complex circuit schemes for power conversion. Higher battery voltage requires power switches with higher blocking voltage. High power requires switches with very low R_{on} . Fast switching requires power switches with very low stored charges.

Motor drive

The DC voltage of the battery is converted to three-phase AC for driving the motor. The AC power needs to be variable frequency to control the rotation speed of the motor depending on the accelerator input. The motor can require a peak power of 100 kW to >200 kW for a compact sedan.⁴ This is typically

the largest power electronics system on the EV (by power level, weight, and volume). In addition, many EVs today also have regenerative braking. This means that when braking, part of the kinetic energy of the vehicle is transferred back from the motor to the battery for improved efficiency.

The key trends seen in this area are the use of multiple phases for the motor-drive to keep current requirements low. Also, higher voltage drive for motors again to keep current requirements low. The power electronics needs to support these trends. Complex circuit topologies are used to

enable bidirectional power flow for driving and regenerative braking.⁵ The power switches also need to have high-voltage blocking capability and very low R_{on} . Motor drives are typically not switched at as high-frequency as chargers so the low R_{on} of the switch is the key. However, recently high-frequency motor drives are also gaining popularity, which would mean that lower stored charges in the switch will play an important role in the future.

DC-DC converter

In EV designs today an auxiliary 12 V battery is also used for powering the secondary electronics. The role of the DC-DC converter is to therefore use power from the 400 V main battery and keep the 12 V auxiliary battery charged.⁶ The typical power level of this system is 1–2 kW. However, with modern EVs adding more and more sensors and control electronics for advanced features such as self-driving, the power requirements of secondary electronics are also increasing. To keep the system size small, high-frequency switching is preferred and therefore low stored charges in the power switch is the key.

Larger EVs

So far, we have focused on the small consumer EVs, such as compact cars, sedans, and SUVs. However, larger vehicles are also transitioning toward battery electric. This includes semis, buses, tractors, and even small aircrafts. As vehicle size increases, the power requirements for charging and motor-drive also increase. Higher voltages and higher currents are typically required. The power electronics needs to change therefore to support these power levels. For instance, Tesla

semi uses a 1000 V bus voltage, is expected to use a >500 kW battery pack and require >1 MW power while charging. Power switches with very high blocking voltage, and very low R_{on} are required. High switching speed will also be a requirement depending on the size and cost constraints.

For aircrafts, typically only smaller aircrafts are transitioning to battery electric today, but work is ongoing to realize larger aircrafts with electric motors that can compete versus jet engines. For trains, however, use of electric power has been standard for a long time because electric lines can be laid out above the fixed train tracks. No battery storage is needed in this case, but the electric power from the grid lines does need to be converted to drive an electric motor. The input power in this case can come from a variety of sources ranging from 1 kV DC to 25 kV AC. The requirements for the power switch can also vary significantly based on applications. Typically, electric trains require switches with very high-voltage blocking capability and very low R_{on} .

How does power conversion happen?

A very common building block of a power converter is a half-bridge circuit that converts an input voltage to any output voltage using pulse width modulation (PWM) control.⁷ The half-bridge circuit consists of two power switches (**Figure 2**). A PWM signal is used to switch the high-side and low-side devices in a way such that when the low-side device is ON, the high-side is OFF and vice versa. The frequency of the PWM signal is referred to as the switching frequency. The typical amplitude of this PWM signal is 10–15 V, which is applied to the gate terminal. When low-side is ON, the voltage across it is zero and when it is OFF the voltage across it is equal to V_{in} . By tuning the duty cycle of the PWM signal, the average voltage across the low-side can be tuned to be smaller than V_{in} (**Figure 2** top-right inset). Passive filtering (inductors and/or capacitors) is then used at the output to smooth out the output voltage and achieve a clean V_{out} . The filtering components

tend to be large and can add significant cost. As the switching frequency is increased, the filtering components can be reduced in size (smaller L or C is required to filter out higher frequency ripple). This has a significant impact on system size, weight, and cost.

The switching frequency is primarily limited by the power switch technology (at least up to few 100 kHz). There are two sources of loss in the power switch (**Figure 2** top-left inset). At each turn-on or turn-off transition in the switching cycle, there are switching losses due to overlap between the current and voltage wave forms. Switching losses depend on the amount of charge stored in the switch that needs to be supplied and removed at each transition. During the on-state, there are conduction losses that primarily depend on the on-state resistance of the switch. Lower stored charge for the same R_{on} will result in lower switching losses allowing for system designers to increase switching frequency and reduce system size and cost. *This is the goal of any new power switch technology: lower the stored charge for the same R_{on} .* Often the only way to achieve this is by utilizing the intrinsic properties of advanced materials such as wide-bandgap (GaN, SiC), or ultrawide-bandgap (UWBG) [Ga₂O₃, Al(Ga)N, diamond, BN, etc.]. Although only DC-DC conversion is described here, this circuit serves as a building block for more complex power-conversion topologies such as AC-DC, DC-AC, and others.^{8–12} The basic principles of R_{on} , blocking voltage, and stored charge are universal to all power-conversion topologies.

What is needed from a power switch?

The two basic requirements are blocking voltage and on-resistance. For 400 V battery EV applications, typically 650 V switches are sufficient, 800 V battery EVs require 1200 V switches, and so on. The choice of switch technology will depend on which technology can offer the best cost-performance tradeoff at a given voltage level.

Reducing the R_{on} reduces the conduction losses in the power switch (**Figure 3**). However, lower R_{on} is achieved by increasing die size, which in turn, increases the stored charges and the switching losses. This is a multiway tradeoff between system size (switching frequency), switching losses, conduction losses, and cost. Any losses in the power switch manifest as heat that needs to be drained away from the switch to avoid overheating. The ability of the switch material to effectively dissipate heat is also important.

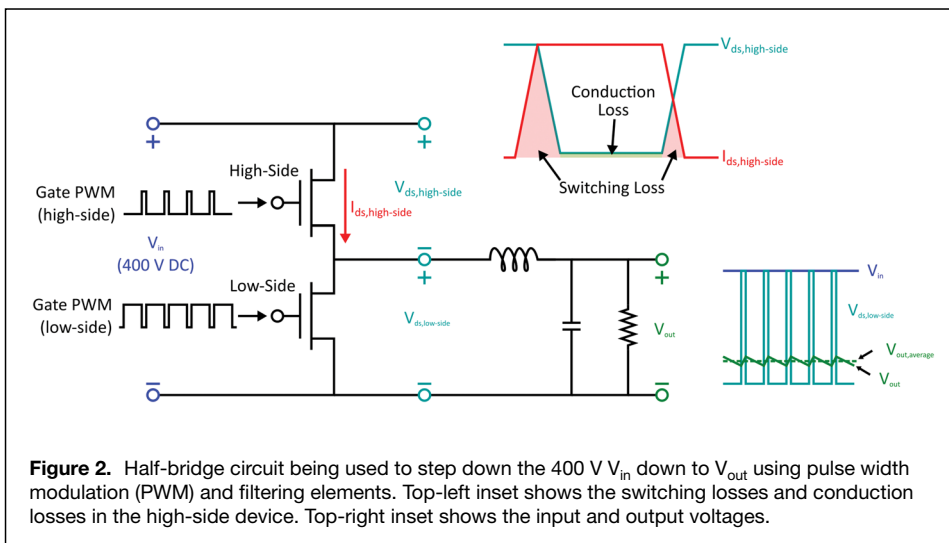


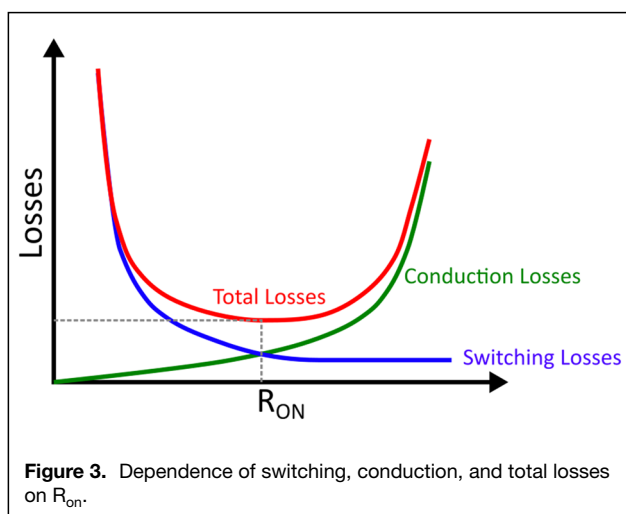
Figure 2. Half-bridge circuit being used to step down the 400 V V_{in} down to V_{out} using pulse width modulation (PWM) and filtering elements. Top-left inset shows the switching losses and conduction losses in the high-side device. Top-right inset shows the input and output voltages.

Future power switch technologies are expected to continue pushing this envelope further as will be described later.

Reliability is another key aspect of power switches. Many applications require switches to operate in extreme conditions (high-voltage, high current, high temperature) continuously for >10 years. Typically, there are strict reliability requirements set by the industry such as JEDEC qualification or AEC qualification. Accelerated lifetime testing is also needed to have a model in place for all wear-out/failure modes. Different material systems and device technologies will have different failure modes that need to be understood.

Robustness is another requirement for specific applications. Short-circuit capability of 3–5 μs is needed by many motor-drive applications to allow for safe turnoff in case of a short-circuit event. Typically short-circuit survivability is improved by reducing the maximum saturation current that can flow through the switch. However, this can increase R_{on} and slow down the switching speed. For some applications it will make sense to trade off the R_{on} and switching performance for short-circuit survivability. Innovations in this area will be of great benefit. Another robustness metric is radiation hardness for some terrestrial and space applications. Typically, the switch will be overdesigned to withstand higher field for radiation hardness. Again, improvements in materials to make the switch radiation hard will be of great importance.

Finally, it is important to note that power switches need to be compatible with power-conversion topologies. A common topology called half-bridge requires the switch to block voltage in one direction and conduct current in forward and reverse directions. Some other topologies require the use of bidirectional switches that can block voltage and conduct current in both directions.

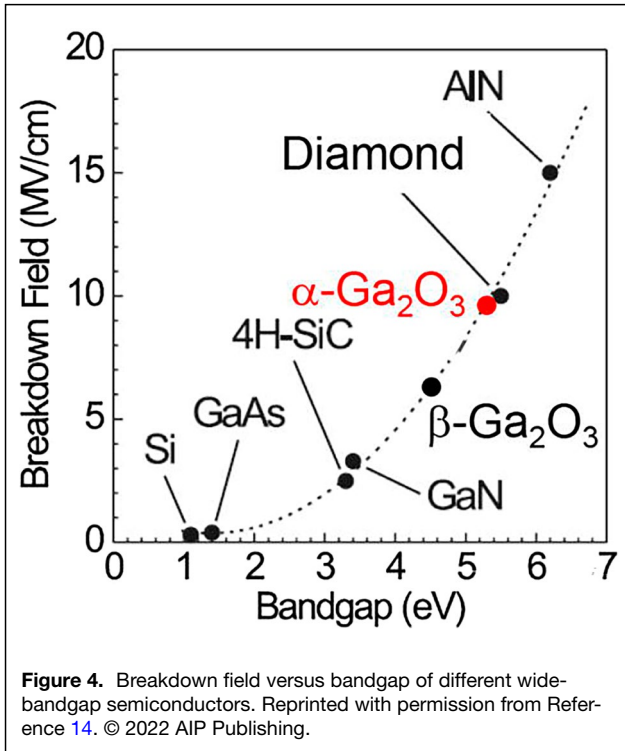


What materials properties are needed for power switches?

As mentioned earlier, the two basic requirements for a power switch are *large blocking voltage* (V_{BD}) and *low on-resistance* (R_{on}). The breakdown voltage of Si-based devices is limited due to the small bandgap (1.1 eV) and breakdown electric field (3×10^5 V/cm) of silicon. Large breakdown voltage devices in silicon, such as insulated-gate bipolar transistors (IGBTs), have switching losses due to conductivity modulation proportional to the standoff voltage.¹³ Therefore, to build a high-voltage power system, multiple silicon devices need to be connected in series, each having an independent control electronics, leading to a complex system that can no longer meet the efficiency and reliability requirements for these high-power electronic applications.

Wide-bandgap (WBG) materials such as GaN and SiC, with bandgaps of 3.3 eV and 3.4 eV, respectively, have emerged as the front-running replacements for silicon for high-power electronics,^{14–22} as they can provide higher efficiency at higher operating frequencies. Recently, UWBG semiconductors, including $\beta\text{-Ga}_2\text{O}_3$, $\alpha\text{-Ga}_2\text{O}_3$, diamond, high Al content AlGaN, and AlN have drawn a great deal of interest for high-voltage (HV) applications^{1,7,23,24} beyond those accessible with GaN and SiC. **Figure 4** demonstrates the relation between breakdown field and bandgap of different wide-bandgap semiconductors. The Baliga figure-of-merit (BFOM)²⁵ has been commonly used in the realm of power semiconductor devices particularly for assessing the efficiency and performance of wide-bandgap semiconductors. The formula for BFOM is $V_{\text{BD}}^2/R_{\text{on}}$, meaning a higher BFOM indicates a more favorable tradeoff between breakdown voltage and on-state resistance, leading to improved power device performance. Basically, this FOM is based on the fact that a larger voltage can be held within a thinner drift region in materials with a larger breakdown field (E_{BD}), if doping concentrations remain unchanged. A thinner drift region means lower on-resistance. It's important to highlight that the calculation of this FOM focuses solely on fundamental materials properties, such as electron mobility and breakdown field. Notably, variations in device topologies are not taken into consideration in this calculation. Moreover, it is important to note that some UWBG semiconductors such as diamond and AlN suffer from low doping efficiency due to large ionization energy of *p*-type and *n*-type dopants. This means a higher doping concentration is needed to achieve a certain free carrier concentration. A higher doping concentration leads to more impurity scattering and consequently lower mobility.²⁶

As depicted in **Figure 5**, WBG semiconductors such as GaN and SiC can provide orders of magnitude lower R_{on} compared to silicon for the same V_{BD} . Theoretically, R_{on} can be further minimized by employing UWBG semiconductors such as diamond, Ga_2O_3 , and AlN. Nevertheless, it is essential to



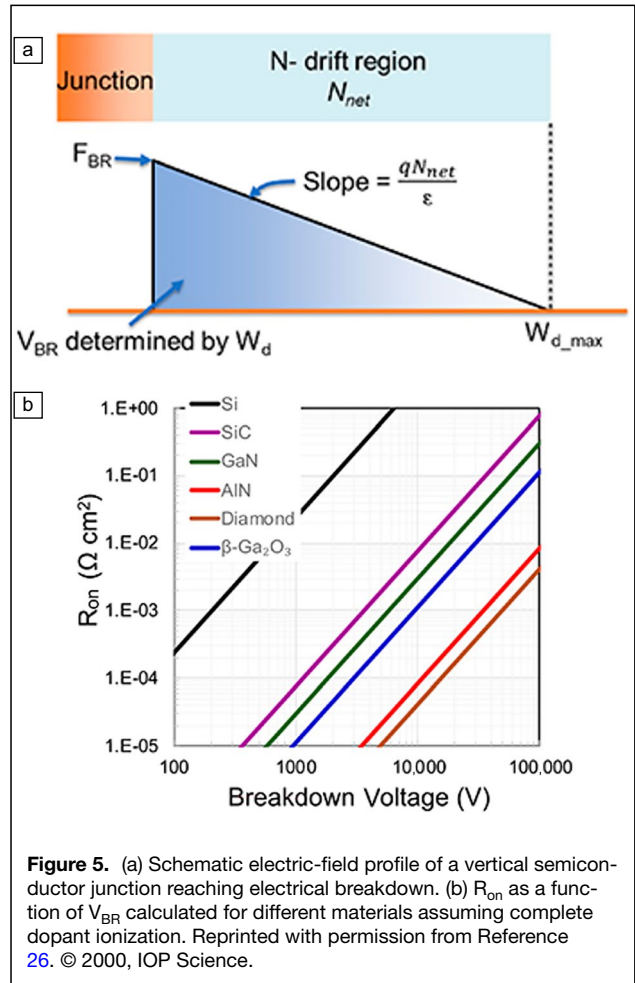
recognize and address the challenges inherent in the development of emerging UWBG semiconductors.

One notable challenge is the potential for shallow doping. For example, although diamond boasts remarkable features such as excellent thermal conductivity, a substantial bandgap of 5.5 eV, and high theoretical electron mobility, its drawback lies in the difficulty of producing large-scale substrates.²⁷ Additionally, the relatively large ionization energy of both *p*-type and *n*-type dopants in diamond leads to low doping efficiency, resulting in decreased electron mobility due to ionized and neutral impurity scattering.

Similarly, AlN faces challenges due to its large ionization energy, and currently, AlN substrates only exist in a semi-insulating form,²⁸ which is undesirable for power devices with a vertical topology. On the other hand, Ga₂O₃ benefits from the availability of melt-growth techniques. Moreover, *n*-type shallow doping is achievable for Ga₂O₃, allowing cost-effective production of large-scale *n*-type substrates. Nevertheless, Ga₂O₃ has its own set of challenges, including the unavailability of *p*-type doping and very low thermal conductivity.²⁹

GaN versus SiC power transistors

In this section, we briefly compare commonly used GaN and SiC power transistors, positioned at the forefront of replacing silicon power transistors. These two materials offer compelling examples of various topologies in power transistors, and the insights gained can be applied to other material systems as well.



Transistors can be categorized into either lateral or vertical topologies based on the direction of current flow. In a lateral topology, as the name suggests, current flows laterally, whereas in a vertical topology, it flows vertically. Vertical configurations are generally preferred for high-power applications because increasing the breakdown voltage is achieved by thickening the drift region, eliminating the need for a larger device footprint. Additionally, the current flow away from surface traps enhances performance, and thermal management is more straightforward in vertical topologies. Conversely, in lateral topologies, boosting the breakdown voltage usually requires expanding the gate-to-drain distance, consuming more wafer space. Furthermore, because the current flows near the surface, surface passivation becomes critical. Despite these challenges, all commercial GaN power transistors adopt lateral topologies (Figure 6a), leveraging the high electron mobility ($\sim 2000 \text{ cm}^2/\text{Vs}$) facilitated by heterostructure formation and polarization doping unique to GaN,^{30,31} which is not possible in SiC. A typical SiC power transistor, on the other hand, is a vertical MOSFET, in which the channel is formed in the *p*-type region, as illustrated in Figure 6b.

SiC MOSFETs are typically considered normally off (E-mode) devices, meaning they default to an off-state and

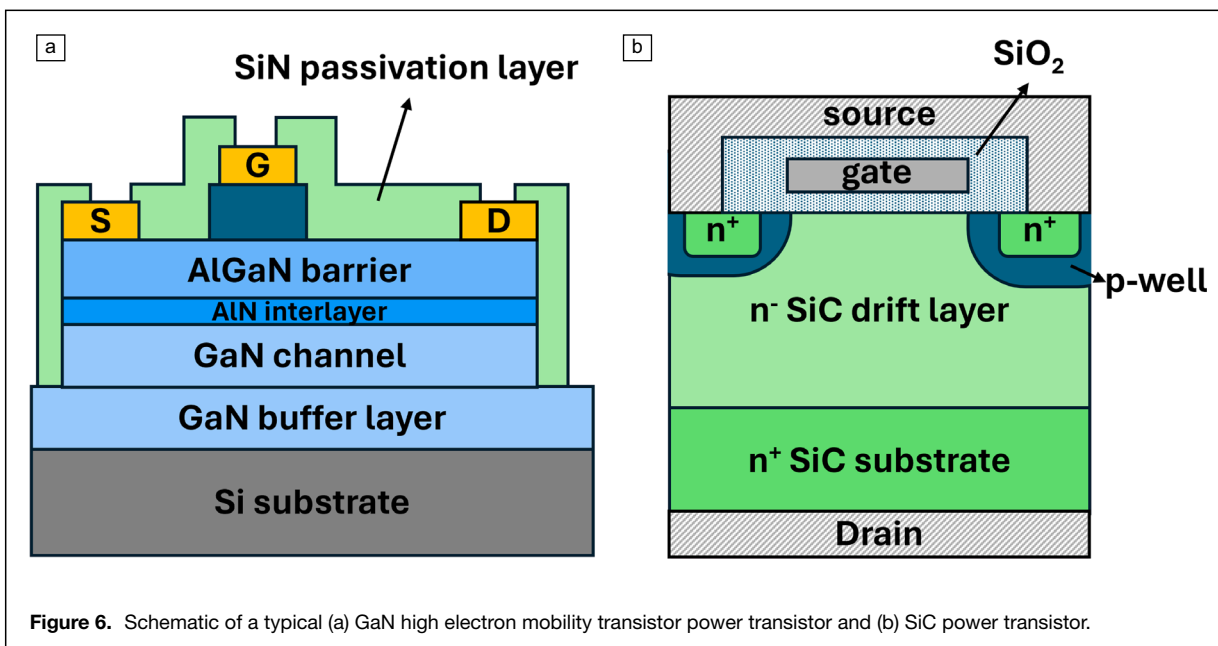


Figure 6. Schematic of a typical (a) GaN high electron mobility transistor power transistor and (b) SiC power transistor.

necessitate a positive voltage at the gate for activation.³² This inherent off-state proves advantageous in high-power applications, where safety and reliability are paramount, as the device remains off in the absence of a gate signal. In contrast, GaN HEMTs are inherently normally on (D-mode) devices, conducting without a gate signal. Given the preference for normally off operation in power electronics, two current technologies address E-mode GaN power solutions. The first method involves utilizing *p*-type GaN beneath the gate, whereas the second employs a cascode configuration by combining GaN HEMTs with silicon MOSFETs. In the cascode approach, the silicon MOSFET serves as a switch to control the GaN HEMT, enabling E-mode operation. This strategy takes advantage of the established manufacturing processes and reliability of silicon technology while capitalizing on the superior performance of GaN.

A comparison between different technologies

Among Si-based switches, IGBT is used for 600–1200 V applications and CoolMOS for 600–900 V applications. SiC MOSFETs started out as a replacement for IGBT at 1200 V, but are now also being used for 600 V applications. After Tesla adopted SiC for the motor-drive in 2017, there has been a significant increase in SiC demand for EV motor-drive and onboard charger applications.³³ These can range from 6 to >100 kW in power level. GaN started out at 100–600 V initially, but is now moving toward 900–1200 V.³⁴ Today most GaN applications focus on the lower power levels such as 20 W to 65 W phone chargers and 100–140 W laptop chargers. But GaN is expanding to higher power levels, including 1–4 kW power supplies and onboard chargers for 2–4 wheeler EVs. High power typically requires very large die size and the manufacturing technology needs to be very mature to have

good yields. SiC being the more mature technology has been adopted for high-power EV applications, but as GaN matures this can change. This application space of high power with blocking voltage ≤ 1200 V is a significant power electronics battleground for the next decade.³⁵ All technologies offer a wide range of R_{on} at each voltage level.

For the same R_{on} , stored charges roughly follow the trend: Si CoolMOS > SiC MOSFET > GaN HEMT. Among commercially available technologies, GaN can therefore realize the lowest losses at the highest switching frequency. On the other hand, while Si IGBTs usually have very long short-circuited survivability, GaN devices are < 1 μ s and SiC devices are somewhere in between. Recently GaN devices with > 3 μ s short-circuit have been demonstrated.³⁶

Si IGBTs cannot conduct in reverse direction and therefore require the use of a diode in parallel with the IGBT for reverse conduction. Si CoolMOS, SiC MOSFET, GaN devices can conduct current in reverse direction through the body-diode or the channel thus allowing for very low conduction losses.

This typically requires the use of multiple components with Si or SiC. Recently GaN four-quadrant switches (FQS) with full bidirectional capability have been demonstrated.^{37,38} The lateral nature of the GaN HEMT is key to realizing this device. Innovative use of materials properties, device design, and circuit topology can unlock the true potential of materials for power electronics.

Summary

In conclusion, the rapid evolution of EVs necessitates advancements in power electronics to meet the demands of charging, motor-drive, and auxiliary power systems. As outlined in this article, the transition toward higher power levels

and efficiency in EVs requires innovative solutions in power-conversion technology. The utilization of wide-bandgap and UWB materials such as GaN, SiC, and emerging UWBG semiconductors presents promising opportunities for achieving higher efficiency, faster switching speeds, and greater power density. Additionally, the comparison between GaN and SiC power transistors underscores the importance of selecting the most suitable technology for specific applications within the EV ecosystem. As EVs continue to proliferate and expand into larger vehicles and alternative transportation modes, the development of robust, reliable, and efficient power electronics will play a pivotal role in driving the electrification revolution forward. By leveraging the inherent properties of advanced materials and embracing innovative design approaches, the power electronics industry is poised to meet the challenges and opportunities presented by the electrified future of transportation.

Author contributions

Gupta and Ahmadi both contributed to the writing and editing of this article.

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Conflict of interest

Authors do not have a competing interest.

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