Gallium Nitride Versus Silicon Carbide: Beyond the Switching Power Supply

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Editor's note: *This article was jointly produced by* IEEE Spectrum *and* PROCEEDINGS OF THE IEEE *with similar versions published in both publications.*

Can advanced semiconductors cut emissions of greenhouse gases enough to make a difference in the struggle to halt climate change? The answer is a resounding yes. Such a change is actually well underway.

Starting around 2001, the compound semiconductor gallium nitride (GaN) fomented a revolution in lighting that has been, by some measures, the fastest technology shift in human history. In just two decades, the share of the global lighting market held by gallium-nitride-based light-emitting diodes (LEDs) has gone from 0% to more than 50%, according to a study by the International Energy Agency. The research firm Mordor Intelligence recently predicted that, worldwide, LED lighting will be responsible for cutting the electricity used for lighting by 30%–40% over the next seven years. Globally, lighting accounts for about 20% of electricity use and 6% of carbon dioxide emissions, according to the United Nations Environment Program.

This revolution is nowhere near done. Indeed, it is about to jump to a higher level. The very semiconductor technology that has transformed the lighting industry, GaN, is also part of a revolution in power electronics that is now gathering steam. It is one of two semiconductors—the other being silicon carbide (SiC)—that have begun displacing silicon-based electronics in enormous and vital categories of power electronics [1].

GaN and SiC devices perform better and are more efficient than the silicon components they are replacing. There are countless billions of these devices all over the world, and many of them operate for hours every day, so the energy savings are going to be substantial. The rise of GaN and SiC power electronics will ultimately have a greater positive impact on the planet's climate than will the replacement of incandescent and other legacy lighting by GaN LEDs.

Virtually everywhere alternating current must be transformed to direct current (dc) or vice versa—for example, in the wall charger that recharges your phone or laptop and in the much larger chargers and inverters that power electric vehicles—there will be fewer wasted watts. And there will be similar savings as other silicon strongholds fall to the new semiconductors, too. Wireless base-station amplifiers are among the growing applications for which these

Digital Object Identifier 10.1109/JPROC.2023.3254279

emerging semiconductors are clearly superior. In the effort to mitigate climate change, eliminating waste in power consumption is the low-hanging fruit, and these semiconductors are the way we will harvest it.

Wireless, automotive, consumer electronics, decentralized and renewable power generation, and many other industries are going to benefit as GaN and SiC continue displacing silicon. There are billions of dollars at stake, because all of these industries are growing, and some quite rapidly.

This is a new instance of a familiar pattern in technology history: two competing innovations coming to fruition at the same time. How will it all shake out? In which applications will SiC dominate, and in which will GaN prevail? A hard look at the relative strengths of these two semiconductors gives us some solid clues.

I. WHY POWER CONVERSION MATTERS IN CLIMATE CALCULATIONS

Before we get to the semiconductors themselves, let us first consider why we need them. To begin with, power conversion is everywhere. And it goes far beyond the little wall chargers that sustain our smartphones, tablets, laptops, and countless other gadgets.[1]

Power conversion is the process that converts power from the form that is available to the form required for a product to perform its function. And because some of these products run continuously, the energy savings can be enormous. Consider electricity consumption per capita in the state of California remained essentially flat from 1980 even as the economic output of the state skyrocketed. One of the most important reasons why the demand remained flat is the efficiency of refrigerators and air conditioners, which increased enormously over that period. The single greatest factor in this improvement has been the use of variable-speed drives based on power electronics such as the insulated gate bipolar transistor (IGBT), which enabled engineers to convert power with very high efficiency.

SiC and GaN are going to enable far greater reductions in emissions. GaN-based technologies alone could lead to a savings of over 1 billion tons of greenhouse gases in 2041 alone, just by deploying GaN in the United States and India over the next two decades, according to an analysis of projections by the International Energy Agency, Statista, and other sources [5], [6].[2] The savings in energy in the United States and India in 2041 could reach 1400 TWh—or 10%–15% of the projected energy consumption by the two countries that year.

II. WIDE-BANDGAP'S ADVANTAGES

Like ordinary transistors, power transistors can act as amplifying devices or as a switch. An important example of the amplifying role is in wireless base stations. Such an installation has electronics that amplify signals for transmission to smartphones and are an integral part of the web backbone. All over the world, the semiconductor used to fabricate the transistors in these amplifiers is shifting from a silicon technology called laterally diffused metal–oxide–semiconductor (LDMOS) to GaN. The newer technology has many advantages, including a power efficiency improvement of up to 10%.

In power-conversion applications, on the other hand, the transistor acts as a switch rather than as an amplifier. The standard technique for power conversion is called pulsewidth modulation. In a common type of motor controller, for example, pulses of dc electricity are fed to coils mounted on the motor's rotor. These pulses set up a magnetic field that interacts with that of the motor's stator, which makes the rotor spin. The speed of this rotation is controlled by altering the length of the pulses: a graph of these pulses is a square wave, and the longer the pulses are "on" rather than "off" the more rotational speed and torque the motor provides (Fig. 1). The on-and-off switching is accomplished by the power transistors.

Pulsewidth modulation is also used in switching power supplies, one of the most common examples of power conversion. Switching power supplies are the type used to power virtually all personal computers, mobile devices, and appliances that run on dc. Compact power converters have to operate at high-frequencies, much higher than the line frequency, to reduce the size of the transformer. To achieve this, the input ac voltage is converted to dc, and then that dc is "chopped" into a high-frequency alternating-current square wave. This chopping is done by power transistors, which create the square wave by switching the dc on and off. The square wave is applied to a transformer that changes the amplitude of the wave to produce the desired output voltage. To get a steady dc output, the voltage from the transformer is rectified and filtered.

The important point here is that the characteristics of the power transistors determine, almost entirely, how well the circuits can perform pulsewidth modulation—and therefore, how efficiently the controller regulates the voltage. An ideal power transistor would, in the "OFF" state, completely block current flow even when the applied voltage is high. This characteristic requires high electric breakdown field strength, which determines how much voltage the semiconductor can withstand before breaking down. On the other hand, when it is in the "ON" state, this ideal transistor would have a very low resistance to current flow. This feature results from the very high mobility of the charges—electrons and holes—within the

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[1] Sources: IDC (Data Center/Comm Infrastructure); Statista (Power Adapters/Compute); Yole, IHS (Broad Industrial); Forbes, Frost and Sullivan, IEA, Inside EVs, Statista, Robotics&Automation (Automotive). TAM values are then calculated based on available technology, competition and value add to market.

[2] The overview of India's energy requirements was based on IEA's India Energy Outlook 2021 [8]. This was supplemented by inputs from Statista and other trade journals to get more India specific information or how Indian consumption patterns might change as the per capita GDP increases, such as: https://ourworldindata.org/grapher/road-vehicles-per-1000-inhabitants-vs-gdp-per-capita

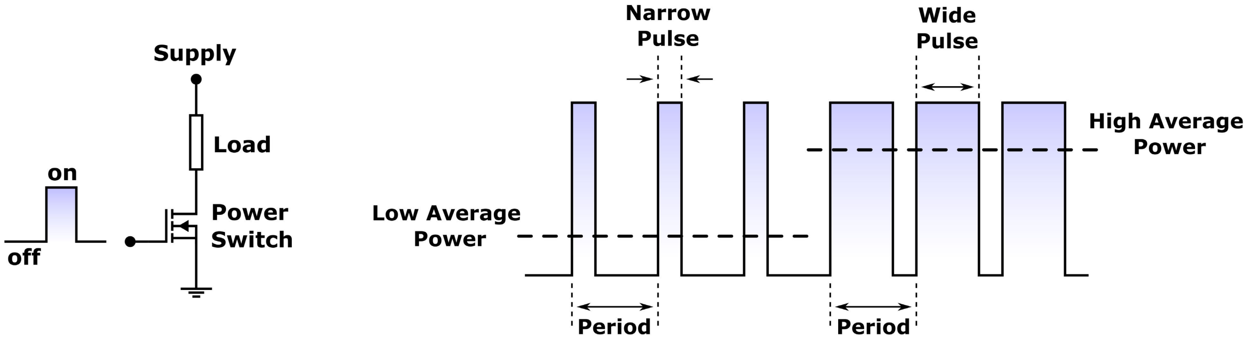

Fig. 1. *Pulsewidth modulation, the longer the pulses are "on" rather than "off," the higher is the average power transmitted to the load. The on-and-off switching is accomplished by the power transistors.*

semiconductor's crystalline lattice. Think of breakdown field strength and charge mobility as the yin and yang of a power semiconductor (Fig. 2).

GaN and SiC come much closer to this ideal than the silicon semiconductors they are replacing. First, consider breakdown field strength. Both GaN and SiC belong to a class called wide-bandgap semiconductors. The bandgap of a semiconductor is defined as the energy, in electron volts, needed for an electron in the semiconductor lattice to jump from the valence band to the conduction band. An electron in the valence band participates in the bonding of atoms within the crystal lattice, whereas in the conduction band, electrons are free to move around in the lattice and conduct electricity.

In a semiconductor with a wide bandgap, the bonds between atoms are strong and so the material is usually able to withstand relatively high voltages before the bonds break and the transistor is said to break down. The bandgap of silicon is 1.12 eV, as compared with 3.39 eV for GaN. For the most common type of SiC, the bandgap is 3.26 eV.

Electron mobility is given in units of centimeters squared per volt second (cm^2/V·s). The product of mobility and electric field yields the velocity of the electron, and the higher the velocity, the higher the current carried per electron. For silicon, this figure is 1500; for SiC, it is around 800; and for GaN, it is about 2200. GaN's unusually high value is the reason why it can be used not only in power-conversion applications, but also in microwave amplifiers. GaN transistors can amplify signals with frequencies as high as 100 GHz—far above the 3–4 GHz generally regarded as the maximum for silicon LDMOS. For reference, 5G's millimeter-wave frequencies top out at 52.6 GHz (but are not yet widely used). However, frequencies up to 75 GHz are being deployed in dish-to-dish communications, and frequencies as high as 140 GHz for in-room communications are being explored. The appetite for bandwidth is insatiable.

These performance figures are important but they are not the only criteria by which GaN and SiC should be compared for any particular application. Other critical factors include ease of use and cost, for both the devices and the systems into which they are integrated. Taken together, these factors explain where and why each of these semiconductors has begun displacing silicon—and how their future competition may shake out.

III. SiC LEADS GaN IN POWER CONVERSION TODAY...

The first commercially viable SiC transistor that was superior to silicon was introduced by Cree (now Wolfspeed) in 2011. It could block 1200 V and had a respectably low resistance of around 80 mΩ when conducting current. Today, there are three different kinds of SiC transistors on the market. There is a trench metal–oxide–semiconductor field-effect transistor (MOSFET) from ROHM; a double-diffused MOS (DMOS) from Wolfspeed, Infineon, STMicro, ONSemi, and others; and a vertical junction field-effect transistor from Qorvo.

One of the big advantages of SiC MOSFETs is their similarity to traditional silicon ones. A SiC MOSFET operates in essentially the same way as an ordinary silicon MOSFET. There is a source, a gate, and a drain. When "on," electrons flow from a heavily doped n-type source through a gate where the electron charge modulates the flow of electrons,

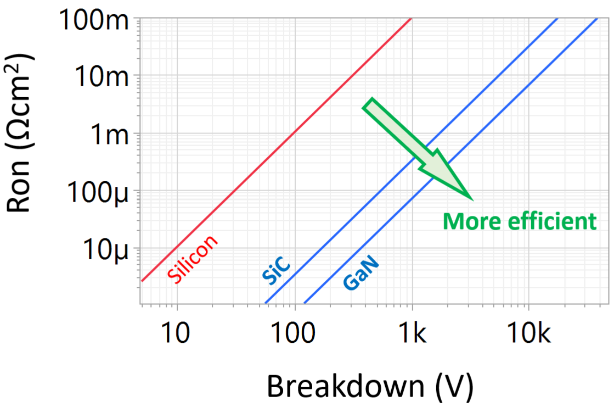

Fig. 2. *Thanks to their material properties, SiC and GaN enable power devices with high breakdown voltage and low specific on-state resistance (R_{on}) than silicon.*

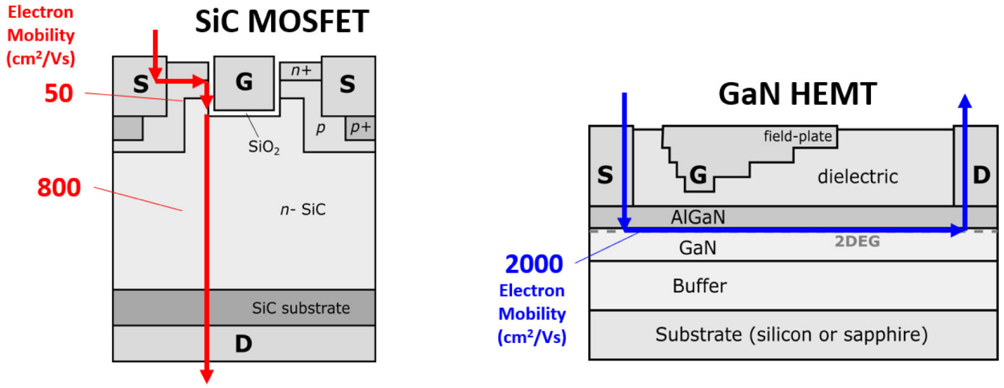

Fig. 3. ***SiC MOSFET operates in essentially the same way as an ordinary silicon MOSFET. There is a source, a gate, and a drain. When "on," electrons flow from a heavily doped n-type source through a gate where the electron charge modulates the flow of electrons, which then drift through a lightly doped bulk region before being "drained" through a conductive substrate. GaN's main advantage is its extremely high electron mobility. Electric current, a flow of charges, equals the concentration of the charges multiplied by their velocity. So, you can get a high current because of high concentration or high velocity or some combination of the two.***

which then drift through a lightly doped bulk region before being "drained" through a conductive substrate (Fig. 3 left).

Because this structure is so similar to ordinary silicon transistors, the packaging of SiC transistors and modules is indistinguishable from those of silicon devices. They are the usual TO-247 and TO-263 packages, among others. This similarity means that there is a little learning curve for power engineers making the switch to SiC.

SiC has other advantages relative to GaN. SiC MOSFETs are inherently "fail-open" devices, meaning that if the control circuit fails for any reason, the transistor stops conducting current when it does so. This is an important feature because this characteristic largely eliminates the possibility that a failure could lead to a short circuit and a fire or explosion. However, the price paid for this feature is the lower electron mobility in parts of the device, which increases its resistance when it is conducting current.

Another advantage is that SiC devices are fabricated on substrates of SiC. This means that when the devices are created, there is no mismatch between the crystal lattice of the devices and that of the substrate on which they are fabricated. This lack of mismatch results in potential advantages such as reduced threading dislocations, which are tears in the materials caused by mismatch that can leak current.

IV. ... BUT GaN IS GAINING

GaN brings its own unique advantages. The semiconductor first established itself commercially in 2000 in the markets for LEDs and semiconductor lasers. It was the first semiconductor capable of reliably emitting bright green, blue, purple, and UV light. But long before this commercial breakthrough in optoelectronics, I and other researchers had already demonstrated the promise of GaN for high-power electronics. GaN LEDs caught on quickly because they filled a void for efficient lighting. But GaN for electronics had to prove itself superior to existing technologies: Si "CoolMOS" transistors for power electronics and, for radio frequency electronics, silicon-LDMOS, and gallium-arsenide transistors.

GaN's main advantage is its extremely high electron mobility. Electric current, a flow of charges, equals the concentration of the charges multiplied by their velocity. So, you can get a high current because of high concentration or high velocity or some combination of the two. The GaN transistor is very unusual because most of the current flowing through the device is due to electron velocity rather than electron charge (Fig. 3 right). What this means in practice is that, in comparison with Si or SiC, less charge has to flow into the device to switch it on or off. That, in turn, reduces the energy needed for each switching cycle and contributes to high efficiency.

Meanwhile, GaN's high electron mobility allows switching speeds on the order of 50 V/ns. That characteristic allows power converters based on GaN transistors to operate efficiently at frequencies in the multiple hundreds of kHz, as opposed to about 100 kHz for silicon or SiC.

Taken together, the high efficiency and high frequency enable the physical size of a power converter based on GaN devices to be quite small and lightweight: High efficiency means smaller heat sinks, and operation at high frequencies means that the inductors and capacitors can be very small, too.

One disadvantage of GaN semiconductors is that the electron channel is naturally on, requiring a gate negative voltage to switch off the device. This complicates the design of devices that are fail-safe—in other words, that fail open when the control circuit fails.

There are two options to achieve this "normally off" characteristic. One is to install a p-type gate that removes the charge in the channel when there is no voltage applied to the gate and that conducts current only on the application of a positive voltage to that gate. These are called enhancement-mode devices (Fig. 4 left). They are

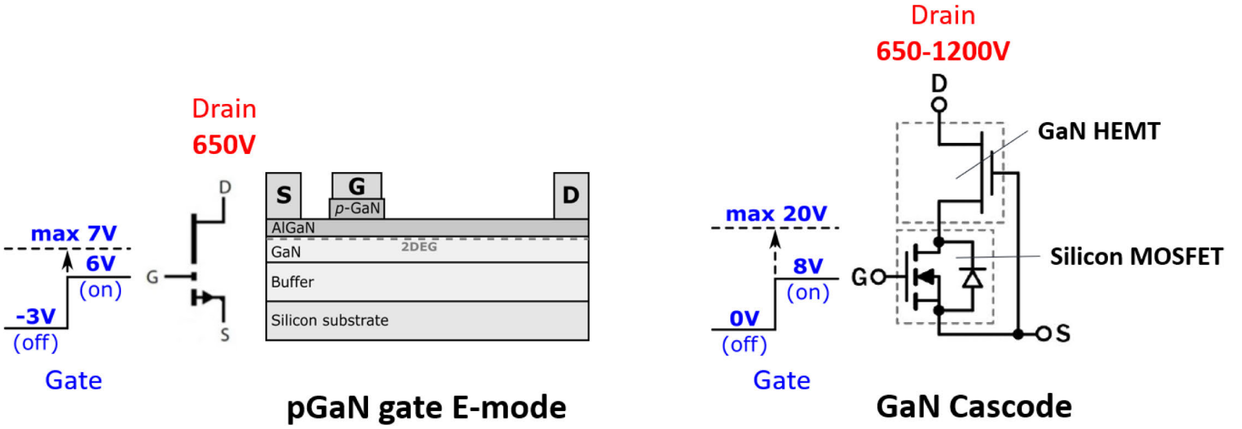

Fig. 4. *There are two options to achieve this "normally off" characteristic. One is to install a p-type gate that removes the charge in the channel when there is no voltage applied to the gate and that conducts current only on the application of a positive voltage to that gate. These are called enhancement-mode devices. The other option is called the cascode solution. It uses a separate, low-loss silicon field-effect transistor to provide the fail-safe feature in tandem with the GaN transistor.*

offered by Navitas, GaN Systems, Infineon, Innoscience, and EPC, for example. The other option is called the cascode solution. It uses a separate, low-loss silicon field-effect transistor to provide the fail-safe feature in tandem with the GaN transistor (Fig. 4 right and Fig. 5). This cascode solution is used by Transphorm, Power Integrations, and Texas Instruments.

No comparison of semiconductors is complete without a consideration of costs. A rough rule of thumb is a smaller die size means a lower cost. Die size is the physical area of the integrated circuit containing the devices.

SiC devices now generally have smaller dies than GaN ones. However, SiC's substrate, epitaxy, and fabrication costs are higher than those for GaN and, in general, the final device costs for applications at 5 kW and higher are not much different today. Future trends, though, are likely to favor GaN. I base this belief on the relative simplicity of GaN devices, which will mean lower production costs that enable them to overcome larger die sizes.

That said, for GaN to be viable for many high-power applications that also demand high voltages, it must have a cost-effective, high-performance device rated for 1200 V. After all, there are already SiC transistors available at that voltage. Currently, the highest rated commercially available GaN transistors are rated 900 V, produced by Transphorm, a company I cofounded in 2007 with Dr. Primit Parikh. Lately, we have also demonstrated 1200-V devices, fabricated on sapphire substrates, which have both electrical and thermal performance on par with SiC devices [4].

Projections from the research firm Omdia for 1200-V SiC MOSFETs indicate a price of 16 cent/A in 2025 [2]. In my estimation, because of the reduced cost of GaN epitaxial and sapphire substrates, the price of first-generation 1200-V GaN transistors in 2025 will be less than that of their SiC counterparts. Of course, that is just my opinion; we will all know for sure how this will shake out in a couple of years.

Furthermore, in these devices, the higher intrinsic electron-transport properties of GaN are preserved, as are the benefits of switching faster than SiC (lighter, smaller components, and so on).

V. GaN VERSUS SiC: HANDICAPPING THE CONTESTS

With these relative advantages and disadvantages in mind, let us consider individual applications, one by one, and shed some light on how things might develop (Fig. 6).

1) *Electric Vehicle Inverters and Converters:* Tesla's adoption of SiC in 2017 for the onboard, or "traction," inverters for its Model 3 was an early and major win for SiC. In an electric vehicle (EV), the traction inverter converts the dc from the batteries to ac for the motor. The inverter also controls the speed of the motor by varying the frequency of the alternating current it is feeding to the motor. Today, Mercedes Benz and Lucid are also using SiC in their inverters, and other EV makers are planning to use SiC in upcoming models, according to news reports [7]. The SiC devices are being supplied by companies including Wolfspeed, ROHM, OnSemi, and Infineon.

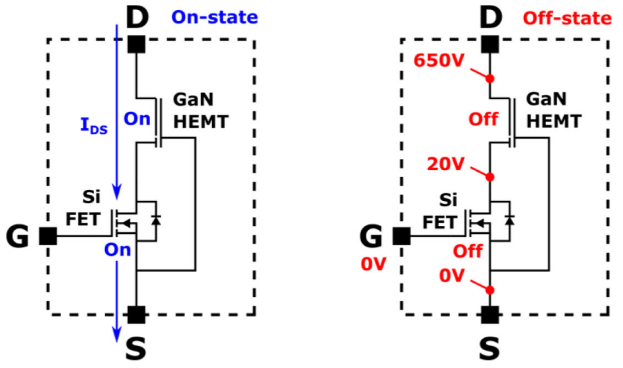

Fig. 5. *Cascode in the ON-state and the OFF-state.*

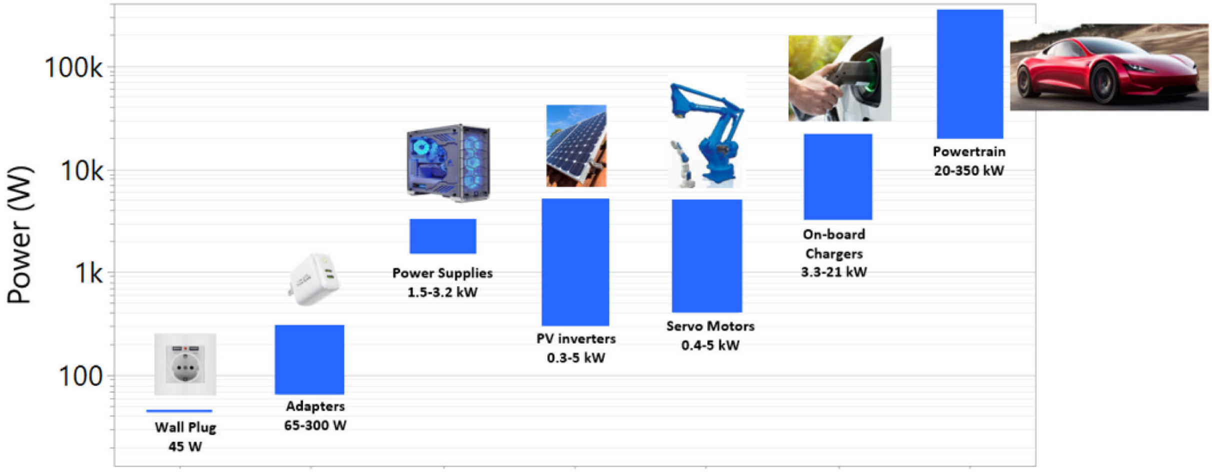

Fig. 6. *Power application spectrum for GaN and SiC power devices.*

EV traction inverters typically range from about 35 to 100 kW for a small EV to about 400 kW for a large vehicle.

However, it is too soon to call this contest for SiC. It is true, though, that to make inroads in this market, GaN suppliers will have to offer a 1200-V device, as I noted above. EV electrical systems now typically operate at 400 V, but the Porsche Taycan has an 800-V system, and other automakers are expected to follow its lead in coming years [3]. I expect to see the first commercial 1200-V GaN transistors in 2025. These transistors will be used not only in vehicles, but also in the high-speed public chargers that are already part of the charging landscape.

The higher speeds possible with GaN will be a powerful advantage in EV inverters because these switches employ "hard-switched" techniques where the devices are switched from on to off without using complex approaches that time the switching to minimize loss (this is called resonant switching). In hard-switched devices, the way to enhance performance is to switch fast from the ON state to the OFF state to reduce losses by minimizing the transition time when the device is simultaneously holding high voltage and passing high current. Such a situation is particularly well suited to the particular strengths of GaN.

Besides an inverter, an EV also typically has an *onboard charger*, which enables the vehicle to be charged from a wall current by converting ac to dc. Here, too, GaN again is very attractive, for the same reasons that make it a good choice for inverters [9].[3]

2) *Electric grid applications:* The domain of very high-voltage power conversion for devices rated at 3 kV and higher will remain the domain of SiC for at least the next decade. These grid applications include systems to help stabilize the grid, convert ac to dc and back again at transmission-level voltages, and other uses.
3) *Phone, tablet, and laptop chargers:* Starting in 2019, GaN-based wall chargers started to become available commercially, from companies such as Power Integrations, Navitas, InnoScience, GaN Systems, and Transphorm. The high switching speeds of GaN coupled with its generally lower costs have made it the incumbent in lower-power markets (25–500 W), where these factors, along with its small size and a robust supply chain, are paramount. These early GaN power converters had switching frequencies as high as 300 kHz and efficiencies above 92%. They set records for power density, with figures as high as 30 W/in^3 (1.83 W/cm^3)—roughly double the density of the silicon-based chargers they are now replacing.
4) *Solar-power microinverters:* Solar-power generation has taken off in recent years, in both grid-scale and distributed applications. For every installation, an inverter is needed to convert the dc from the solar panels to ac to power a home or release the electricity to the grid. Today, grid-scale photovoltaic inverters are the domain of silicon IGBTs and SiC MOSFETs. But GaN will begin making inroads in the distributed market, particularly.

Traditionally, in these distributed installations, there was a single inverter box for all of the solar panels. But increasingly installers are favoring microinverter systems, in which there is a separate microinverter for each panel, and the ac is combined before powering the house or feeding the grid. The advantage is the ability to get intelligence about the operation of each panel to optimize the performance of the array.

Microinverter or traditional inverter systems can be coupled with batteries to create an *uninterruptible power supply (UPS)*. Standalone UPS systems are also used in data-server farms to prevent outages caused by supply

[3] IEA, Inside EVs, Statista, Robotics & Automation, PntPower.com. It includes OBC, DC DC, inverter content, and EV charging poles coupled with GaN technology available and Transphorm internal projections.

interruptions. Also, all data centers use power-factor correction circuits, and for these, GaN has provided a low-loss and economical solution that is slowly displacing Si in this application. The shift is being driven by the demand for highly efficient titanium-class power supplies.

5) *5G and 6G base stations:* GaN's superior speed and high power density will enable it to win and ultimately dominate applications in the microwave regimes, notably 5G and 6G wireless, and commercial and military radar. The main competition here is arrays of silicon LDMOS devices, which are cheaper but have lower performance. Indeed, GaN has no real competitor at frequencies of 4 GHz and above.

For 5G and 6G wireless, the critical parameter is bandwidth, because it determines how much information the hardware can transmit efficiently. Next-generation 5G or 5G+ systems will have nearly 1 GHz of bandwidth, enabling blazingly fast video and other applications.

Microwave communication systems using silicon-on-insulator (SOI) technologies from providers such as Global Foundries are providing a solution using high-frequency Si devices where the low power for each device is overcome by using large arrays of them. GaN and Si will coexist for a while in this space. The winner in a specific application will be determined by a tradeoff among system architecture, cost, and performance.

6) *Radar:* The United States military is deploying many ground-based radar systems based on GaN electronics. These include the Ground/Air Task Oriented Radar, and the Active Electronically Scanned Array Radar built by Northrup-Grumman for the United States Marine Corps. The SPY6 RADAR was delivered to the United States Navy by Raytheon to enhance the range and sensitivity of ship-borne radar.

VI. CONCLUSION

Today, SiC dominates in EV inverters, and generally wherever voltage-blocking capability and power handling are paramount and the frequency is low. GaN is the preferred technology where high-frequency performance matters, such as in base stations for 5G and 6G, and for radar and high-frequency power conversion applications such as adapters, microinverters, and power supplies.

But the tug-of-war between GaN and SiC is just beginning. Regardless of how the competition plays out, application by application and market by market, we can say for sure that the Earth's environment will be a winner. Countless billions of tons of greenhouse gases will be avoided in coming years as this new cycle of technological replacement and rejuvenation wends its way inexorably forward.

Acknowledgment

The author would like to thank Rakesh Lal, Davide Bisi, and Geetak Gupta (all from Transphorm, Goleta, CA, USA) for their help with this article. ■

REFERENCES

[1] "Power GaN device market grows 16% in Q4/2019," *Semiconductor Today*, Mar. 23, 2020. [Online]. Available: https://www.semiconductor-today.com/news_items/2020/mar/yole-230320.shtml

[2] R. Eden and P. Pickering, "SiC & GaN power semiconductor report—202 analysis," Tech. Rep., OMDIA, London, U.K., Jun. 17, 2022.

[3] "Supplier confirms broad shift to 800V systems for luxury EVs by 2025," *Green Car Rep.*, Sep. 2020. [Online]. Available: https://www.greencarreports.com/news/1129601_supplier-confirms-broad-shift-to-800v-systems-for-luxury-evs-by-2025

[4] G. Gupta et al., "1200 V GaN switches on sapphire substrate," in *Proc. 34th ISPSD*, Vancouver, BC, Canada, 2022, pp. 349–352.

[5] Overall Review of Future U.S. Energy Landscape, U.S. Dept. Energy, Jan. 2017. [Online]. Available: https://www.energy.gov/policy/initiatives/quadrennial-energy-review-qer/quadrennial-energy-review-second-installment

[6] N. Jones, "How to stop data centres from gobbling up the world's electricity," *Nature*, Sep. 12, 2018. [Online]. Available: [Online]. Available: https://www.nature.com/articles/d41586-018-06610-y

[7] N. Winton, "Electric car sales set for solid expansion, but long range forecasts tenuous," *Forbes*, Jun. 2018. [Online]. Available: https://www.forbes.com/sites/neilwinton/2018/06/28/electric-car-sales-set-for-solid-expansion-but-long-range-forecasts-tenuous-delphi-technologies/?sh=1d25006067d0

[8] International Energy Agency, "India energy outlook 2021," Tech. Rep., 2021. [Online]. Available: [Online]. Available: https://iea.blob.core.windows.net/assets/1de6d91e-e23f-4e02-b1fb-51fdd6283b22/India_Energy_Outlook_2021.pdf and https://ourworldindata.org/grapher/roadvehicles-per-1000-inhabitants-vs-gdp-per-capita

[9] Transphorm, "Quarterly business update," 2022. [Online]. Available: https://www.transphormusa.com/en/document/transphorm-f2q-2022-business-update/

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