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# GaN Technology

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# GaN Technology

Qorvo 2nd Special Edition

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# Introduction

**G**allium nitride (GaN) transistors, first demonstrated in the 1990s, are now widely available for commercial and defense applications — and engineering may never be the same. Skeptical? Understandable. But after you read this book, you may be a true believer.

GaN's popularity is rooted in its high-current, high-voltage capabilities. These traits make it valuable for many applications, including microwave radio frequency (RF) and power switching.

GaN's unique material properties make it the new go-to technology in many applications, such as 5G communications, automotive, lighting, radar, and satellites. But GaN manufacturers and developers aren't stopping there. They continue to advance GaN by revolutionizing the technology. These innovative endeavors will continue to open new application areas in the future.

This book provides a solid basic introduction to GaN. It looks at the technology and what's driving GaN implementations, helping you understand the benefits that make it so desirable. It also surveys the current state of how various industries are using GaN, in both mature and cutting-edge applications. After reading this book, you'll understand how GaN is revolutionizing the electronics engineering industry — and how it will continue to do so going forward.

## Foolish Assumptions

It has been said that most assumptions have outlived their usefulness, but we assume a few things nonetheless! Mainly, we assume that you're a stakeholder in the technology or semiconductor industry with more than a passing interest in a technology like GaN. Perhaps you're an engineer, a design architect, a technician, a technical leader, a salesperson, a technology student, or an investor. We also assume that you have some knowledge of semiconductor technologies. As such, this book is written primarily for somewhat technical readers like yourself.

If any of these assumptions describes you, then this book is for you! If none of these assumptions describes you, keep reading anyway. It's a great book and when you finish reading it, you'll know enough about GaN technology to be dangerous!

## Icons Used in This Book

Throughout this book, we occasionally use icons to call attention to important information. You won't see the typical cute grinning faces or other flashing emoticons, but you'll definitely want to stop and pay attention! Here's what you can expect.



REMEMBER

The Remember icon flags key definitions and essential takeaways that you'll want to commit to memory.



TECHNICAL  
STUFF

Explore highly technical aspects that may appeal to your inner geek.



TIP

Seek out the target for tips that can save you time.

## Beyond the Book

Although this book is full of good information, we could only cover so much in 48 pages! So, if you find yourself wanting more after reading this book, just go to [www.qorvo.com/gan](http://www.qorvo.com/gan), or [www.qorvo.com/design-hub](http://www.qorvo.com/design-hub), where you can get to more information about Qorvo's GaN technology and products.

And who, you might ask, is Qorvo? Qorvo is a leader in the development of GaN process technology. Its latest devices support markets such as defense, commercial, and space — in many wideband, low-noise, high-frequency, and high-power solutions. In other words, Qorvo makes all kinds of good stuff using GaN technologies, so this is a topic we're pretty passionate about.

## IN THIS CHAPTER

- » Surveying the history and evolution of GaN technology
- » Identifying today's key GaN applications and markets
- » Comparing GaN to other technologies
- » Summarizing the benefits of GaN

# Chapter 1

# Exploring the GaN Technology Market

**G**allium nitride (GaN) technology, a relative newcomer among semiconductor technologies, is revolutionizing the world today. GaN's benefits stem from its unique material properties: wide bandgap, high breakdown voltage, high thermal conductivity, high electron mobility, and high saturated electron velocity.

This chapter kicks things off by presenting some basic facts about GaN and its benefits and surveying the industries and applications that are using it.

## GaN: Yesterday and Today

GaN's potential as a high-power and high-frequency semiconductor transistor-based material was first recognized and explored in the early 1990s. By the mid to late 2000s, GaN had made its way into production applications for defense and aerospace and commercially in light-emitting diodes (LEDs) for solid-state lighting.

Since then, GaN has seen increased acceptance in radio frequency (RF) electronics and widespread adoption in commercial wireless applications including 5G. RF adoption has been aided by GaN material advances that enable the creation of superior high-power-density, high-efficiency RF amplifiers.



GaN is a direct bandgap semiconductor technology that belongs to the III–V group, like gallium arsenide (GaAs) and indium gallium phosphide (InGaP). A III–V compound semiconductor is an alloy containing elements from groups III and V in the periodic table. (We break that down in more detail in Chapter 2.)

Many semiconductor market analysts still describe GaN as a relatively new technology. However, in just a few short years, GaN has already jumped from newcomer to frontrunner in many applications. GaN not only is dethroning well-entrenched incumbent silicon technologies like laterally diffused metal-oxide semiconductor (LDMOS), but also is helping to boost overall system performance when used alongside other technologies like GaAs.



GaN's ability to complement established technologies like GaAs is helping accelerate its adoption in both defense and commercial applications. GaN is also helping to improve system performance in applications struggling to meet the upper power, frequency, and efficiency requirements of next-generation systems. It is, therefore, becoming the go-to technology for new wider-bandwidth, higher-frequency RF applications.

## Understanding GaN's Global Market Impact

The GaN market has already exceeded the billion-dollar mark. GaN's unique benefits — the ability to handle extreme temperature, wide bandwidth, high power, high voltage, and high input power — are catapulting the technology into many markets simultaneously, as shown in Figure 1-1.

The primary markets are defense, aerospace, telecom infrastructure, and satellite communications. But GaN is also used in many other applications. For completeness, here's a more comprehensive list describing the sub-markets for each of the high-level markets shown in Figure 1-1:

# GaN RF

## Technology

GaN on SiC  
GaN on Si  
GaN on Diamond  
GaN on GaN

## Markets

Defense & Aerospace  
Wireless Infrastructure  
Wired Broadband  
Civilian Radar  
Satellite Communications  
RF Energy  
Test & Measurement

**FIGURE 1-1:** GaN RF technologies and markets.

- » Defense and aerospace
  - Electronic warfare jammers
  - Defense communications, including tactical radio, satellite communications, data links
  - Defense radar, including airborne, ground-based, and naval
  - Civilian radar, including air traffic control and weather radar
  - Satcom, including defense and civilian
- » Wireless infrastructure
  - Macro/micro base stations, including remote radio heads (RRHs) and active antenna systems (AASs)
  - Small cells
  - Wireless backhaul
- » Wired broadband
- » RF energy
  - Medical
  - Industrial
  - Scientific
  - Automotive
- » Test and measurement

## GaN in defense

Defense is an area where GaN has consistently led and is projected to continue leading. GaN plays a key role in enabling higher-performance military systems such as active electronically scanned array (AESA) radars and electronic warfare (EW) systems, both of which require high power, small form factors, and highly efficient thermal properties. GaN provides a much-needed solution that supports the high power density, high efficiency, wide bandwidth, and long lifetime needed for many defense applications.

## GaN in 5G telecommunications

5G has ushered in a new era in multiple-input, multiple-output (MIMO) technology with its implementation of massive MIMO wireless base stations. Massive MIMO systems help wireless carriers improve performance, minimize cost, and increase capacity when rolling out 5G infrastructure.

With the transition to massive MIMO, the industry is shifting from LDMOS power amplifiers to cooler-running, smaller, higher-power GaN-based solutions. Here are some of the key advantages of GaN on silicon carbide (SiC) technology for base stations, compared to LDMOS:

- » **Smaller array sizes:** Because GaN on SiC provides higher power output and has superior thermal characteristics compared to LDMOS, wireless carriers can use smaller arrays to produce the same output power. GaN on SiC can offer up to a 20 percent smaller array size compared to LDMOS.
- » **Reliability:** GaN can operate reliably even at high temperatures. This is critical for 5G base stations because these systems are moving from an air-conditioned room below the wireless tower to the top of the tower. GaN on SiC offers high reliability even in the harsh tower-top environment.
- » **Better heat dissipation:** GaN on SiC has much better thermal conductivity than LDMOS, so it can dissipate heat more efficiently, leading to cooler-running systems.

- » **Higher-frequency operation:** Unlike LDMOS, GaN on SiC can operate at the higher sub-6 GHz and millimeter-wave (mmWave) frequency ranges used by 5G, while offering 10 percent to 15 percent more efficiency.
- » **Lighter weight:** Weight is a crucial factor in base station applications, which is a key reason that smaller form factors are important. Higher-efficiency GaN enables smaller heat sinks, which reduce the size and weight of the overall system. This is a big deal for the people who install 5G on towers, because lighter weight means easier installation.

To deliver the full potential of 5G's multi-gigabit per second speeds and ultra-low latency to customers, mobile operators must improve system performance. This means they need to invest in spectrum acquisition, network infrastructure, and transmission technologies. Among the most important 5G transmission technologies are massive MIMO wireless base stations operating in the sub-6 GHz and mmWave frequency ranges.



Massive MIMO base stations use many antennas to transmit and receive data rather than the classic single antenna used in conventional wireless communications. These massive MIMO systems support spatial multiplexing, where each channel carries independent information to the receiver. This provides more reliable signals and a significant increase in throughput.

What kind of RF front-end (RFFE) components do these 5G massive MIMO base station systems need? They must be integrated components that are highly linear and extremely efficient, with low power consumption. GaN meets these requirements. Moreover, using GaN in the RFFE reduces the number of active elements that a massive MIMO array needs in order to meet base station system output power requirements such as Equivalent Isotropic Radiated Power (EIRP).



EIRP is the maximum amount of power that an antenna array can radiate given the antenna's gain and the RF subsystem's transmitter power. Using GaN, system designers can easily achieve the 5G specified EIRP levels per tower. And they can achieve this with fewer, smaller antennas, so they can get to market faster with lower capital expense.

# Comparing GaN to Other Technologies

Although GaN is replacing other technologies in a growing number of market areas, there are still incumbent technologies that compete directly with GaN. Ultimately, GaN gives system designers and device engineers another technology alternative to create best-in-class products while minimizing the tradeoffs between system and user requirements.

In any RF system, the optimal technology depends on the performance parameters designers are aiming to achieve. In most applications, the technology choice depends on frequency, power-level, efficiency, size, and price. The primary technology options available include GaN on silicon carbide (SiC), GaN on silicon (Si), GaAs, and LDMOS. Table 1-1 compares their characteristics and suitable RF applications.

**TABLE 1-1** Comparing GaN Technologies and GaN's Key Competitors

Function	GaN on SiC	GaN on Si	GaAs	LDMOS
RF/E device	TX PA, RX LNA, RF Signal Control	TX PA, RX LNA, RF Signal Control	TX PA, RX LNA, RF Signal Control	TX PA
Operating voltage	High	High	Low	High
Power density	High	High	Low	Low
Thermal resistance	Low	Medium	Medium	Medium
Bandwidth	Wide	Wide	Wide	Narrow

A quick look at this table shows why the world is shifting away from LDMOS. GaN provides an all-around competitive advantage for designers developing systems requiring power, wide bandwidths, high operating voltage, and high thermal requirements.

As a result, many engineers are now wondering whether GaN will ultimately replace technologies such as LDMOS. To answer this question, here are some key questions to ask:

- »» Does GaN enable existing and new applications?
- »» Is it easy to use and does it provide a plug-and-play replacement?
- »» Is it as reliable as or more reliable than current technologies?

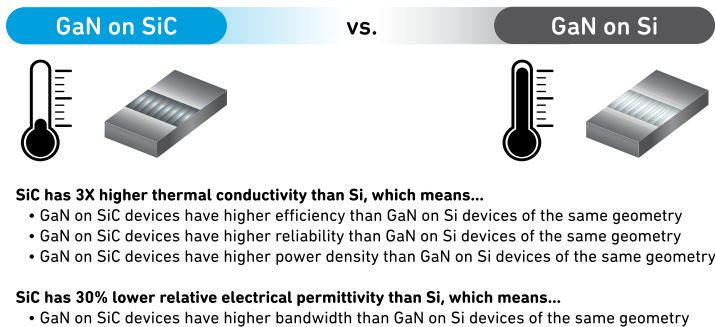
GaN already meets all these prerequisites for replacing incumbent technologies — most notably in new applications like 5G. GaN in 5G already supports faster data speeds, increased RF range, increased temperature robustness, high input power level robustness, smaller sizes, and more efficient power consumption.



REMEMBER

As we note earlier, GaN's RF system benefits stem from its unique material properties of wide bandgap, high charge density, high electron mobility, and high temperature tolerance. These properties translate into the RF benefits of high power added efficiency (PAE), high power output, small form factor, wide bandwidth, and ruggedness. With the benefits of high PAE and high operating voltage, GaN enables systems to run with lower operating current and cost. Furthermore, system designers can design systems with fewer components, which helps them free up design time and get to market faster. In addition to its high thermal conductivity, GaN is known for its low sensitivity to radiation.

As you probably guessed from Table 1-1, GaN manufacturing processes mostly use silicon carbide or silicon substrates (GaN on SiC and GaN on Si, respectively). Each substrate has its advantages. Silicon is relatively inexpensive compared to silicon carbide. However, in many aspects, GaN on SiC provides greater benefits compared to GaN on Si due to its higher reliability and power, as shown in Figure 1-2. This makes GaN on SiC the best option for many applications in 5G telecom, defense, aerospace, and more.



**FIGURE 1-2:** The advantages of GaN on SiC versus GaN on Si.

Figure 1-2 highlights the differences between the GaN-on-SiC and GaN-on-Si substrates. Additionally, we noted that synthetic diamond is another alternative substrate material. Si provides the least heat dissipation at the lowest cost, and diamond provides the best thermal dissipation at the highest cost. However, the best trade-off between cost and thermal performance is the SiC substrate material. This is why the SiC substrate is most often used for high-power, high-efficiency applications especially in defense and infrastructure.

## IN THIS CHAPTER

- » Examining GaN's superior material properties
- » Surveying GaN thermal properties and high reliability
- » Comparing GaN technology processes and substrates
- » Identifying the ways GaN technology is advancing

# Chapter 2

# Taking a Deep Dive into GaN Technology

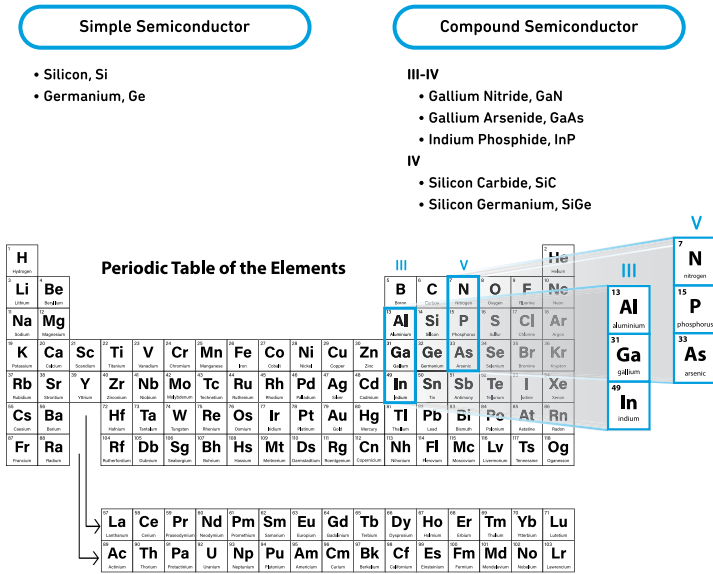
This chapter digs a bit deeper into gallium nitride (GaN) technology — its properties, its benefits, the different manufacturing processes, and the latest advances. This deeper dive provides a window into why GaN is becoming such a major player in today's technology-driven world.

## GaN: A Proven Technology

GaN is a well-proven compound semiconductor technology. Compound semiconductors have been the dominant microwave integrated circuit (IC) technology in high-performance applications since the 1980s. That's because they offer a superior combination of speed and power compared to simple silicon-based semiconductor devices.

Compound semiconductors are made from two or more different groups on the periodic table, whereas simple semiconductor devices are made from a single element such as silicon (Si).

As shown in Figure 2-1, GaN is one of several compound semiconductors that combine elements from the third and fifth columns of the periodic table and are, therefore, called III–V compound semiconductors.



**FIGURE 2-1:** Simple and III–V compound semiconductors.

These III–V semiconductors are used in a variety of applications. Gallium arsenide (GaAs) has been the most widely deployed over the last four decades, with billions of ICs operating worldwide. GaN offers an even better combination of speed and power handling than GaAs. Its superior power capability at a given transistor speed enables it to displace other technologies in thousands of applications over a wide range of frequencies.

GaN monolithic microwave integrated circuits (MMICs) and discrete transistors initially entered production in the late 2000s, targeting the highest power level solid-state applications. In millimeter-wave (mmWave) applications, GaN has displaced GaAs at the higher power levels, enabling tens of watts of power in the Ka-Band compared to the watt-level power provided by MMICs in competing technologies. At lower frequencies such as the L-band, GaN transistors can provide more than 1,000 watts!

As we mention in Chapter 1, GaN can use several substrate materials, such as Si, silicon carbide (SiC), GaN, and diamond. GaN's compatibility with high thermal-conductivity substrates such as SiC enhances its superiority for high-power applications.

## How GaN's Intrinsic Material Properties Create a Superior RF Transistor

Field-effect transistors (FETs) constructed using GaN are conceptually similar to those using a gate contact or junction in other semiconductor materials such as GaAs, indium phosphate (InP), or Si. In the case of GaN radio frequency (RF) devices, the implementation is typically a depletion mode high-electron-mobility transistor (HEMT).

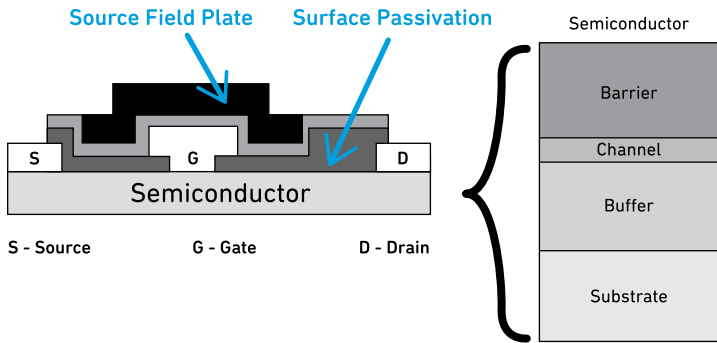


A depletion mode HEMT applies a negative bias to the gate electrode. This cuts off the current between the drain and the source. A depletion mode FET is designed to be in an on state when the gate voltage applied is zero; it can be turned off by pulling the gate below the threshold voltage.

The GaN device consists of a vertical material structure defining many of the intrinsic characteristics and a horizontal structure providing contact to the material structure and control of the charge flow (see Figure 2-2). As with other FETs, the horizontal structure includes the source, drain, and gate contacts. Often, there are other structures in close proximity to provide field control, such as the source field plate identified in Figure 2-2.

### WATCH IT HAPPEN

Qorvo has developed a helpful video explaining how to properly turn a GaN HEMT transistor on or off. Check out "How to Bias GaN Transistors: An Introduction Tutorial" at [www.qorvo.com/design-hub/videos/how-to-bias-gan-transistors-an-introduction-tutorial](http://www.qorvo.com/design-hub/videos/how-to-bias-gan-transistors-an-introduction-tutorial).



**FIGURE 2-2:** Basic GaN FET geometry.

Here's what's going on in Figure 2-2:

- »» The **barrier** provides two critical functions: isolation between the gate and channel and charge capacity to enable electron flow. It's typically made of aluminum gallium nitride (AlGaN).
- »» The **channel** is pure GaN. It provides the conduction path for current between the drain and source contacts. The high saturation velocity and mobility of GaN enable high speed and current levels between the drain and source of the device.
- »» The **buffer** constrains the charge flow within the channel to avoid leakage into the substrate and guarantees isolation between transistor devices.
- »» The **substrate** dominates the mechanical and thermal properties of the device. High-power dissipation devices benefit from a substrate with high thermal conductivity. SiC is a convenient substrate material that provides excellent thermal properties while being compatible with GaN material growth and MMIC fabrication.

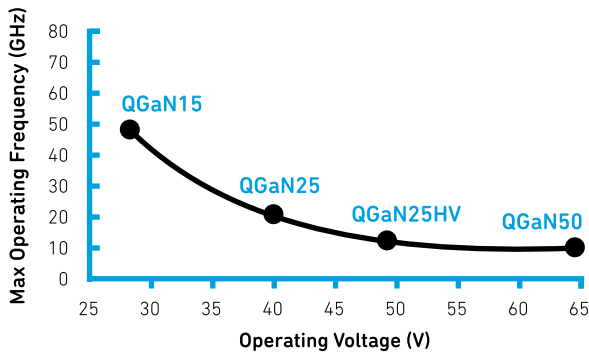
Here are the critical functions of the horizontal structure:

- »» The device's **gate** controls current flow through the device from the drain to the source contact. The length of the gate determines the speed of the device and the time for electron flow through the region of control.

» **Source** and **drain** contacts provide low-resistance access to the intrinsic device. The separation between the gate and these contacts not only creates undesirable parasitic access resistance, but also enables the increased breakdown voltage necessary to support the intended operation.

## Deciphering the GaN Process Options

The FET can be optimized for targeted applications by trading between transistor speed, current capability, breakdown voltage, efficiency, and reliability. To meet the needs of diverse GaN applications, manufacturers offer several variations in process technology, spanning a broad range of frequency and power levels. With more than one GaN process to choose from, a circuit designer can optimally match a specific GaN process technology to an application, making design easier and faster. Figure 2-3 shows Qorvo's range of GaN process technologies, which are designed to accommodate many applications across several market areas.



Parameter	QGaN15	QGaN25	QGaN25 HV	QGaN50
Operating Voltage ( $V_{ds}$ )	Up to 28V	Up to 40V	Up to 48V	Up to 65V
Power Output	4W/mm	6W/mm	8W/mm	10W/mm
PAE	50%@35 GHz	60%@10 GHz	80%@3.5 GHz	78%@2.7 GHz
Gain	9 dB@35 GHz	13 dB@10 GHz	21 dB@3.5 GHz	21 dB@2.7 GHz
Target Application Frequency Range	DC-60 GHz	DC-25 GHz	DC-12 GHz	DC-8 GHz

**FIGURE 2-3:** Qorvo GaN process technology options under class AB performance.

For example, a very high-power application like a 1 kW transistor operating at 2 GHz will benefit from a GaN process with a higher breakdown voltage, because it increases operating voltage and RF power density. The increased operating voltage also allows a more efficient output. The tradeoff can be increased access resistance and reduced transistor speed. The Qorvo GaN50 process is capable of operating at 65 V and providing these advantages.

A mmWave power amplifier (PA) application, like a 20 W MMIC at 30 GHz, requires a high-speed device that provides high gain at high frequency. The device design tradeoff will favor reducing the gate length, minimizing access resistance, and maximizing current capacity. The result can be reduced breakdown voltage and power density. The Qorvo GaN15 process is capable of operating up to 28 V and providing these advantages.

In both of these examples, the GaN device provides a higher operating voltage than other technologies, demonstrating the intrinsic speed and voltage advantages of the technology. The advantage of a higher operating voltage is not limited to the PA circuit alone — it delivers benefits throughout the entire system.

For example, a common application for GaN PAs is a phased array antenna system, which can require hundreds or thousands of individual power amplifiers.

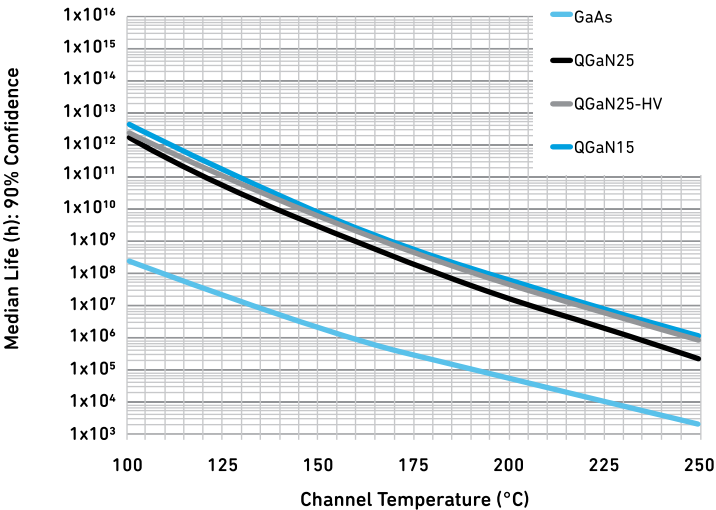
Distributing the DC power supply across these antenna array systems is always a challenge because the power supply consumes space, adds weight, and induces DC power losses. But the higher operating voltage of GaN enables lower DC currents and superior size, weight, power, and cost (SWaP-C) to meet the DC power distribution challenge required for these systems.

## Assessing the Reliability of GaN Devices

Reliability is very important in all electronic systems, so it's a key concern when choosing semiconductors. One of GaN's key advantages is that it can operate at higher voltages and power densities than other semiconductors. GaN can meet these stringent requirements with proven reliability at high junction

temperatures, achieving mean time-to-failure (MTTF) of greater than  $10^7$  (10 million) hours at 200°C and greater than  $10^6$  (1 million) hours at 225°C. GaN's higher safe operating channel temperature and extended lifetime enable system designers to push the limits of their applications and products.

GaN manufacturers differ in their approach to failure analysis — some rely on thermal imaging, while others use a combined approach of thermal imaging, product package testing, and modeling. But the one thing all manufacturers and standards bodies agree on is that GaN is more reliable than other technologies in high-power, high-temperature applications. As shown in Figure 2-4, the reliability of GaN far exceeds the reliability of GaAs-based transistors.

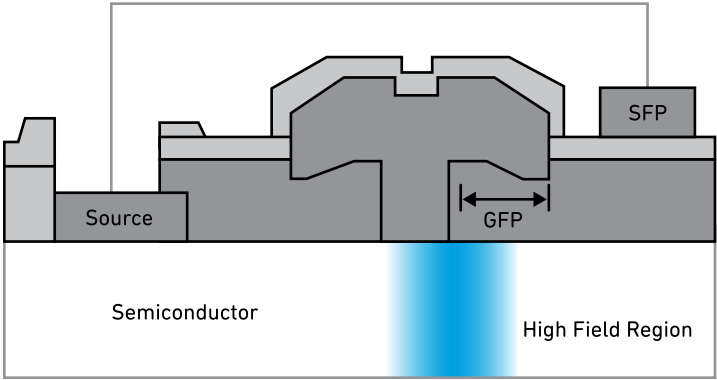


**FIGURE 2-4:** An example of GaN versus GaAs technology device reliability using the Qorvo MTTF curve.

GaN applications often subject devices to higher-stress operating conditions such as higher current densities, higher environmental temperatures, and higher electric fields. Whether they're a result of device design or usage, these problems can be caused by piezoelectric effects, thermal mismatches, or packaging.

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GaN devices have one remaining intrinsic device characteristic to be aware of: stress induced by the inherent piezoelectric nature of GaN. Figure 2-5 illustrates the region of peak stress in a GaN FET. However, this behavior is well characterized and understood in GaN devices. Therefore, it's no longer a problem with today's GaN process technology.



SFP - Source Field Plate  
GFP - Gate Field Plate

**FIGURE 2-5:** The high electric field region of the FET.

Today, GaN devices are used in applications with the most stringent and challenging reliability requirements, including mission-critical systems and space applications. GaN's reliability and robustness extend beyond the transistor to MMIC processes optimized to handle the electrical, thermal, and environmental stresses of the expanding range of GaN applications. Its environmental robustness enables die-level highly accelerated stress test (HAST) compatibility for all of today's GaN processes. GaN packaging and interconnect advancements are improving to keep pace as well.

For example, Qorvo GaN technology today is available in high-volume, mature manufacturing readiness level 10 (MRL 10) processes. MRL is a measure developed by the U.S. Department of Defense (DOD) to assess the maturity of manufacturing readiness. MRL 10 is the highest level of production readiness, indicating that full-rate production and lean manufacturing practices are in place.



TIP

GaN technology continues to advance to support an even wider range of applications. These advances include support for higher operating frequencies and ever-increasing power levels across wideband frequency ranges. As with most other technological advancements, capabilities demonstrated in low volume are migrating to mature, high-volume production processes.

One key GaN technological advance is operation at extremely high frequency — 100 GHz or more — made possible by reducing the GaN gate lengths. Another advancement is in output power level: When the operating voltage of GaN is increased, it can achieve higher power densities at lower frequencies.



TECHNICAL  
STUFF

Today, a very rough rule of thumb for GaN PA design is thousands of watts at 1 GHz, hundreds of watts at 10 GHz, and tens of watts at 100 GHz. That rough figure of merit has tripled over the past five years and continues to increase.

GaN advancements will continue, further increasing GaN PA frequency range and power levels. Other parameters such as high-power amplifier (HPA) bandwidth increases and higher efficiency are also being explored. Continued progress in these areas is enabled by both GaN device performance advancements and progress in circuit design techniques.

GaN has come a long way in 20 years and is now hitting its stride in terms of further improvement in capabilities and broader deployment. We can only imagine the potential for further technological improvement and wider adoption in the future.

- » Integrating GaN into today's applications
- » Surveying the many ways GaN technology is packaged and sold
- » Identifying the importance and benefits of GaN modeling
- » Enhancing GaN PA performance with Doherty and digital pre-distortion

# Chapter 3

## System and Device Design with GaN

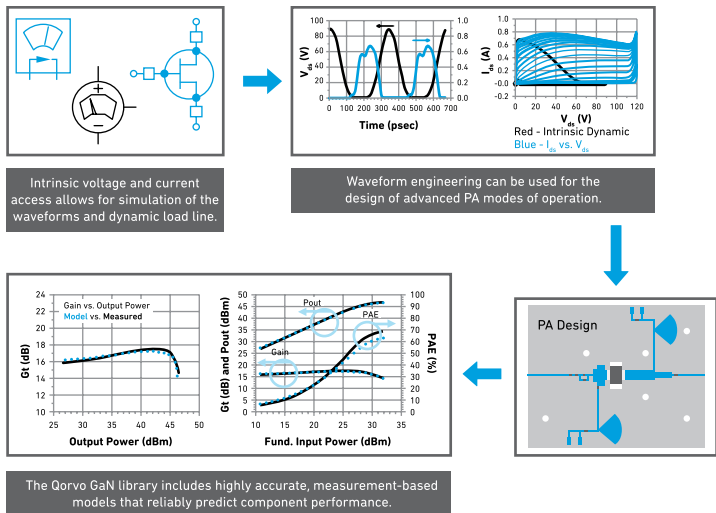
In this chapter, we cover some techniques for designing gallium nitride (GaN) into power amplifiers (PAs) and other applications and describe how GaN is being used in much of the radio frequency (RF) front end. We also explore how technology leaders are providing GaN in discrete, monolithic microwave integrated circuits (MMICs) and highly integrated modules to accommodate many application areas. We also explain the important aspects and advantages of GaN thermal modeling in applications.

### Designing with GaN

Traditionally, GaN PA design has been performed using approximate starting points and a lot of experience and expert knowledge. Using s-parameter and load-pull data can help enhance design success. With GaN discrete products, it's also helpful to use accurate nonlinear models to generate design data faster. For discrete implementation, modeling can help target more precise semiconductor behavior and achieve a better result for a specific application.

For engineers, the first step in designing a GaN PA is the semiconductor manufacturer's product data sheet; the second step is viewing the s-parameters. PA design engineers can also use measured load-pull data to find optimal load impedance targets for precise power and efficiency values at specified frequencies.

Using load-pull data along with simulation models, when available, can enable designers to attain a better outcome. Figure 3-1 shows how simulation models are created for a GaN PA design. These same models are used to generate PA reference designs.



**FIGURE 3-1:** An example of the Qorvo/Modelithics simulation-based nonlinear model process.

These discrete nonlinear GaN models come with variable bias, temperature scaling, self-heating effects, intrinsic current-voltage ( $I-V$ ) sensing, and bond wire settings when applicable. At the most basic level, a nonlinear transistor GaN model must capture the current voltage characteristic curve ( $I-V$  curve) of the transistor at different levels of operation. The  $I-V$  curve dictates the primary power, efficiency, and other key performance drivers of a device.

A model's ability to predict the nonlinear behavior of a PA transistor is based on several key aspects:

- » The representation of the voltage-dependent current source ( $I_{ds}$ )
- » Voltage-dependent capacitances, primarily gate-to-source ( $C_{gs}$ ), drain-to-source ( $C_{ds}$ ), and drain-to-gate ( $C_{dg}$ )
- » Voltage-dependent diode models, which are related to the prediction of breakdown voltage
- » Device parasitic inductance, capacitance, and resistance to represent the overall frequency-dependent behavior of the device

As a relatively recent technology, GaN requires some different modeling and design techniques compared to other semiconductors. GaN effectively expands the boundaries of the I–V curve because it has higher maximum current capability, has higher quiescent voltage operation, and can operate at higher voltage.

In any case, it's imperative to provide engineers with the data to optimize their designs for operation under the targeted application voltage, current, and load conditions. This data speeds up design and helps engineers get the layout right the first time, instead of worrying about whether they'll need to do more costly project spins.

## GaN and the RF Front End

In GaN's early days, it was used as the PA stage amplifying the transmit signal of the RF front end (RFFE), mostly in die form or as a flanged transistor. But there are clear benefits in using GaN for other RFFE components, too. Today, GaN is also being used for the low noise amplifier (LNA), mixer, and switch — either as individual discrete components or as an MMIC. This section reviews the benefits of GaN for these RFFE components.

### GaN PAs

GaN is an obvious choice for achieving the power levels and efficiency required by most high-power applications. It offers high durability and high saturated power in a very small periphery. It

also provides the high efficiency required for many wireless base stations, commercial and military radar applications, and more.

## GaN switches

GaN switches are suitable for many RF switching applications. They feature high breakdown voltages combined with low on-resistance and off-state capacitance. This enables a dramatic increase in power handling capability.

Gallium arsenide (GaAs) field-effect transistor (FET) switches are widely used in the RF industry, typically for power levels of a few watts or less. GaN FETs can use the same circuit architectures to handle much higher power levels of tens of watts. GaN switches provide low switching loss, high isolation, high linearity, and superior power handling. With the demand for systems with higher current, voltage capability, power density, temperature, efficiency, and frequency range, silicon-based switches are approaching their limits. Therefore, GaN switches are replacing silicon in applications requiring these unique capabilities.

## GaN LNAs

GaN LNAs often consume less power than alternative LNA technologies. Choosing GaN for the LNA provides the low noise figure and high input power robustness needed for LNAs.

Typically, GaN devices can withstand input power levels of 2 to 4 watts. This high input power capability is particularly important in many applications. In many radar applications, for example, one method for reducing the possible impact of high input power to the receiver is to add a limiter or circulator at the input. This helps with protection but has the side effect of increasing the noise seen at the LNA. This limiter or circulator fix also reduces the sensitivity of the receiver, with negative impacts on signal range, throughput, and performance. In contrast, the extremely high input power capability of GaN LNAs means that the limiter or circulator is not needed, helping to improve the overall receiver performance.

## GaN mixers

GaN-based mixers are highly linear and handle more input power than GaAs-based mixers. Typically, these high-end GaN-based mixers are used in defense, satcom, and instrumentation applications.

The availability of GaN adds yet another technology for design engineers to use in designing the RFFE. Having this additional technology opens more opportunities.

## Evaluating GaN System Reliability

It's well known that GaN is more reliable than other technologies, due mostly to its unique properties of reliable high-power capability and thermal robustness. Even so, it's also important for designers to create a robust solution around this technology for optimal system-level reliability.

As with all power transistor technologies, careful thermal design is essential to ensure reliable operation. Key to supporting high voltage and efficiency is removing heat from the device to keep the junction temperature in an acceptable range for reliable operation. This can be achieved by precise thermal measurement and choosing a substrate material with optimal thermal properties that can instantly remove the device heat to a heat sink.



TIP

An alternative thermal solution to heat sinks is copper coin technology. With this approach, a slug is embedded into the PCB during fabrication to enable efficient heat transfer from the transistor to the carrier on which the PCB is mounted. This method provides a cost-effective way to provide better heat transfer than more expensive heat sinks or fans.

Although the copper coin method of cooling can provide substantial device temperature improvements, there is a minor effect on RF performance. Plus, care must be taken to ensure that the PCB remains planar and that good contact is made between the copper coin and the ground paddle of the device package.

## Comparing GaN to TWTAs

GaN processes use commercially available materials and manufacturing platforms that provide optimal reliability, reduce cost, and offer high performance, as shown in Table 3-1. As a result, both GaN on silicon carbide (SiC) and GaN on silicon (Si) offer engineers a competitive, reliable solution at a lower cost than legacy traveling wave tube amplifier (TWT) technology.

**TABLE 3-1** Comparing GaN and TWTA Amplifiers

	TWTA	GaN on SiC	GaN on Si
Performance	High	High	Medium
Size	Large	Small	Small
Ease of use	Low	High	High
Reliability	Low	High	Medium
Cost	\$\$\$	\$\$	\$

As an example, in commercial and military radar applications where operation is required in the gigahertz frequency ranges, GaN has proven to be the ideal solution, especially in the transmit stage. It has replaced the TWTA in many of those applications. Today’s military-based radars, operating with active electronically scanned arrays (AESAs) and phased array modules, benefit by using GaN especially because they can use MMIC technology, making design easier and smaller.

## Aligning GaN Thermal Properties and Applications

Increasing power can mean an increase in thermal management challenges. High operating temperatures can cause device performance degradation and decrease product lifetime. Because of this, design engineers are constantly assessing thermal implications to mitigate potential problems at the device and system level.

Because GaN has superior thermal properties, it’s being considered for many applications that need to operate in elevated temperatures and extreme environments. GaN’s extremely high operating channel temperature of 225°C liberates the system designer from a thermal design perspective. For example, some applications that required liquid cooling when implemented with laterally diffused metal-oxide semiconductor (LDMOS) or GaAs can move to air cooling when using GaN.



TIP

Even though GaN can take the heat better than many semiconductor technologies, engineers must still fully understand thermal design and analysis in order to build a robust, reliable end product. It's important to gain a complete understanding of GaN's thermal properties before entering product design rollouts.

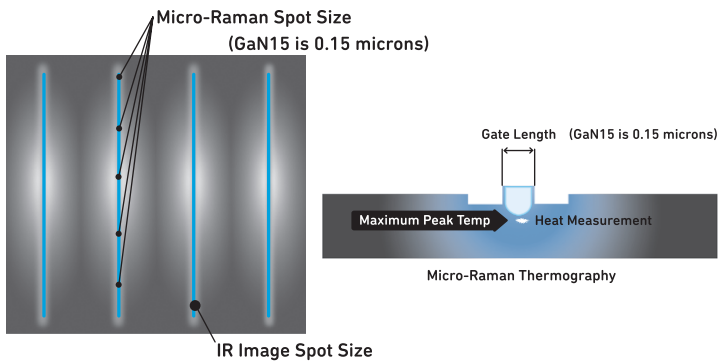
## Estimating the $T_{CH, MAX}$

The reliability of semiconductors such as GaN is determined by estimating the device's maximum channel temperature ( $T_{CH, MAX}$ ) to ascertain its estimated lifetime. These values are collected by measuring and modeling thermal resistances, device dissipation, and heat transfer. For semiconductor devices, measurements are performed primarily with infrared (IR) imaging microscopes. These IR scopes help identify device hotspots that could ultimately lead to faulty areas on the semiconductor.

Because GaN technology can operate at higher temperatures than most semiconductor materials, it's important to measure the channel temperature more accurately. Therefore, some GaN designers and semiconductor manufacturers have opted to perform additional measurements beyond IR scans.

Why? IR imaging accuracy is limited in terms of measuring GaN channel temperatures because of the spatial resolution limits, the difficulty imaging a reflected surface, and chip surface structures like air bridges. Additionally, even if accurate IR image values are obtained, the true maximum channel temperature really resides below the device gate, as shown on the right side of Figure 3-2.

To obtain more accurate measurements of channel temperature, one approach is to use a thermal modeling analysis method called finite element analysis (FEA). Using 3D modeling or FEA in conjunction with micro-Raman thermography and comparing these results with RF testing and IR imaging provides an accurate thermal value. Using this combined data set, an FEA model for a packaged part can be determined, revealing the true  $T_{CH, MAX}$ . Moreover, as shown on the left side of Figure 3-2, the micro-Raman spot size enables much more precise measurements of the temperature at different locations below the gate — as opposed to an IR image spot size measurement. This provides a more accurate measure of peak channel temperature.



**FIGURE 3-2:** Measuring  $T_{CH, MAX}$  using micro-Raman thermography.



Micro-Raman thermography is a noninvasive optical technique, based on Raman scattering spectroscopy, that enables temperature measurements with sub-micron spatial and nanosecond time resolution. It probes the temperature-induced phonon shift in a material, with respect to a reference phonon frequency measured at ambient temperature.

Determining the true device  $T_{CH, MAX}$  in order to calculate the expected device lifetime is a multistep process. First, you determine the channel temperature, by performing either 3D thermal modeling or finite element analysis (FEA) and by comparing it to empirical measurements including micro-Raman thermography. Then you verify it with RF testing and IR imaging and use the combined data to obtain an accurate measure of GaN channel temperature and device reliability.



FEA is a combined approach for measuring true channel temperature and device reliability for GaN. It's a three-pronged approach using measurements from backside part temperature, die or part attachment measurements, and IR imaging to create an FEA model in order to accurately estimate GaN device lifetime.

## SEE HOW IT'S DONE

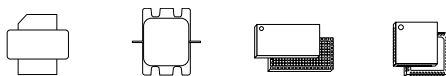
Want to see a detailed explanation of this methodology? Watch the tutorial video "Understanding GaN Thermal Analysis" at [www.qorvo.com/design-hub/videos/understanding-gan-thermal-analysis](http://www.qorvo.com/design-hub/videos/understanding-gan-thermal-analysis).

## Continuous wave versus pulsed operation

Another important design and reliability factor to consider is how the GaN device will operate in a system. Will the device be on continuously (continuous wave [CW] operation) or will it be pulsed on and off (pulsed wave operation). Each of these operating methods affects the value of  $T_{CH, MAX}$ , which is dependent on the specific operating conditions and changes with the pulse width and duty cycle chosen. For example,  $T_{CH, MAX}$  is at its highest in CW operation after the system has achieved thermal steady-state operation.

## Assessing GaN Packaging Formats

GaN comes in die form and in a few packaged formats: prematched transistor, internally matched field-effect transistor (IMFET), power amplifier module (PAM), or MMIC. Each has advantages and tradeoffs, as shown in Figure 3-3. Each can provide best-in-class thermal, size, and parameter performance for specific applications.



Parameter	Unmatched or Pre-Matched Transistor	IMFET	PAM	MMIC & FEM
Multiple Gain Stages	No	No	Yes	Yes
Output Power	Very High	High	Medium	Medium
Quantity or External Components Required	High	Low	Low	Low
Matching	Unmatched, Pre-Matched, Input Matched to 50 $\Omega$	Input/Output Matched to 50 $\Omega$	Input/Output Matched to 50 $\Omega$	Input/Output Matched to 50 $\Omega$
System Design Complexity	High	Medium	Low	Low

**FIGURE 3-3:** Comparison between GaN format types.

Here's a quick explanation of how these GaN format types are used:

- » **Unmatched or prematched transistors:** These devices work well in applications where engineers need design flexibility, such as the ability to optimize their system for certain frequency ranges or bandwidth requirements.

These devices also allow engineers to create solutions using Doherty PA designs, as in 5G remote-radio head or advanced array system designs.

- » **IMFETs:** These are discrete transistors or power bars for high-power solutions. These internally matched GaN FETs are commonly used in both radar and wireless infrastructure applications.
- » **PAMs:** PAMs are designed to support high-power applications like commercial 5G multiple-input, multiple-output (MIMO) and defense radar. They're amplifiers with two or more stages that are internally matched for 50-ohm input and output. They're specifically designed to reduce system size, weight, power, and cost (SWaP-C), simplifying design, and reducing time to market.
- » **MMICs and front-end modules (FEMs):** These integrate multiple functions onto the same die in one small package. MMICs are typically used in high-frequency operations where power added efficiency (PAE) and low RF losses are important system targets. FEMs are system-in-package (SIP) solutions that help designers take advantage of GaN's high power density, thermal conductivity, and small size.

## Exploring GaN System Design and Implementation

Mature technologies like GaAs can support large bandwidth and high-frequency bands — but they have lower power density compared to GaN. Accordingly, GaAs high-electron-mobility transistor (HEMT) remains a viable solution for both transmit and receive components in applications where lower transmit power per element is acceptable and receive chain noise figure is key.

GaAs gate lengths continue to decrease, helping to lower the noise figure, which also improves RF range and sensitivity. Smaller gate lengths on GaAs with all other factors held constant help improve performance, but this comes at the cost of electrostatic discharge (ESD) sensitivity and input power survivability. However, GaN on SiC offers the advantages of wide bandwidth with higher power

density compared to GaAs — in addition to the benefits of higher input power, which helps increase survivability, and a lower noise figure. Additionally, the high input impedance of GaN allows for easy RF matching implementation on systems.

Using higher power density GaN transistors allows for easier designs and fewer matching components in systems. It also means fewer system components are used overall, thus lowering RF chain loss compared to GaAs and LDMOS. With GaN's higher transmit power and low receive noise figure, it can achieve longer RF ranges and higher signal resolution.

In radar applications, this means the system can see a smaller target farther away, providing more time to react to the target's movements. Traditional radar systems required short pulse widths, narrow instantaneous bandwidths, and small duty cycles. Today however, there is a drive across all radar bands to increase the duty cycles three- to fivefold, up to a 50 percent duty cycle or higher — near continuous wave operation in some cases.

Radar AESA systems may use from hundreds to tens of thousands of amplifiers. Using GaN, each array element's power can be increased to boost range. Alternatively, each element can use fewer GaN devices to achieve a desired output power compared with other technologies like GaAs and LDMOS, thus reducing cost and complexity.

A GaN PA has maximum efficiency at saturation. For linearity, the opposite is true: The most linear operation is at lower or backed-off output power. In 5G systems, linearity is a key parameter. So, to maximize linearity in high-power 5G advanced antenna system (AAS), a technique called digital pre-distortion (DPD) is used (see Figure 3-4).

PAs in 5G base stations are typically optimized for efficiency, requiring PAEs of 50 percent to 70 percent. Linearity is then recouped using DPD. Efficiency is critical because of the high signal output power and associated energy consumption. The added benefit is that these systems run cooler, which is important because they're mounted at the top of the base station antenna rather than inside an air-conditioned building at the bottom of the structure.

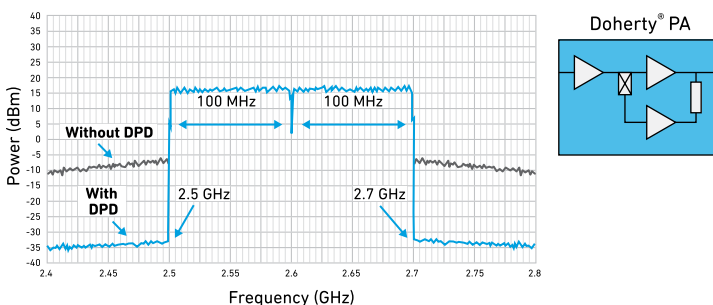
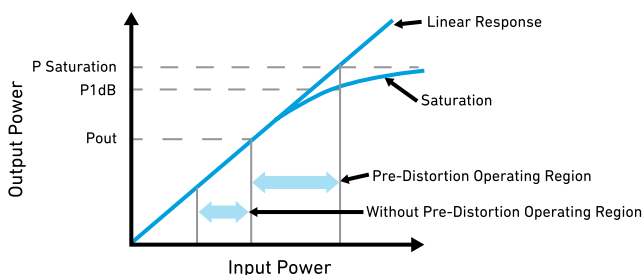


FIGURE 3-4: DPD and Doherty PA configuration.



DPD is a hardware- and software-based solution that removes distortion using digital signal processing techniques. It enables designers to optimize the PA for lower power dissipation while maximizing output power and achieving high linearity.

## Looking at the GaN Doherty PA and Digital Pre-Distortion

With some innovative RF systems, such as 5G base stations, there's a push to increase PA output levels, efficiency, and linearity. To effectively attain all three of these parameters at one time, it's beneficial to use DPD. DPD can also minimize out-of-band PA distortion.

Many GaN PAs use a Doherty configuration to boost efficiency of the device at back-off output power. With a Doherty configuration, engineers can minimize system power consumption

and attain efficiencies of 60 percent or more (at back-off output power), significantly reducing the energy required to run power-thirsty PA systems. When using Doherty, DPD is essential. As shown in Figure 3-4, using DPD and a Doherty configuration enables higher efficiency and linearity.

## Examining High-Voltage GaN

For some applications, obtaining the highest possible output power is critical. As we note earlier, a PA is most efficient near saturation or peak output power. Increasing the drain voltage of a GaN transistor provides higher power output at saturation. However, this technique may make sense for some applications but not for others.

Radar is one application where high-voltage GaN is forging the way to a new era. Radar systems often require power amplification in the high hundreds to thousands of watts. They achieve kilowatt-level amplification by combining multiple solid-state power transistors or using TWTAs.

GaN technology can achieve these output power levels with fewer transistors than other technologies by using a higher operating voltage. For example, at 65-volt operating voltage, GaN can achieve kilowatt amplification while maintaining low thermal requirements. Plus, it meets military target parameters for identifying friend or foe and distance measurement in a smaller form factor more reliably and with fewer transistors than other technologies.

As an added benefit, high-voltage GaN reduces design complexity because it requires fewer transistors to attain high power levels. These high-voltage high-power transistors are also highly efficient, attaining 70 percent to 80 percent efficiency in some cases.

Here are some key benefits of high-voltage GaN:

- » **Higher power density:** It reduces the number of transistors and overall component size and weight.

- » **Lower power consumption:** It reduces the system-level current losses and the demand on power supplies.
- » **Easier matching capability:** Output power can be raised while keeping usable output impedances.

Today, GaN is designed for 28–32, 48–50, or 65 volts drain bias (refer to Figure 2-2), but higher voltage ranges are being explored for new and existing markets to gain further performance benefits in systems.

## IN THIS CHAPTER

- » Examining the military, aerospace, and commercial applications of GaN
- » Assessing the tradeoffs between the number of array elements and process technology
- » Identifying the future applications of GaN

# Chapter 4

## Seeing How GaN Is Changing Markets

This chapter explores how gallium nitride (GaN) is finding its way into many existing and new military, aerospace, and commercial applications. Continuous advances in GaN technology are helping to fuel its popularity with engineers. In this chapter, we take a deeper look into some of the new applications and industries where GaN is poised to lead.

### Examining GaN Usage in Military and Aerospace

Many of today's aerospace and defense systems require highly reliable, rugged components with radio frequency (RF) output power levels well into the kilowatts (kW). Historically, many of these systems relied on vacuum tube technology to generate these kW of power. But since the development of high-power semiconductors, some applications have migrated their system designs to solid-state power amplifiers (SSPAs). The SSPAs were initially based on laterally diffused metal-oxide semiconductor (LDMOS) or gallium arsenide (GaAs), but now these systems are

beginning to use GaN, which makes them more reliable, robust, and capable of wider bandwidths.

## Military satellites

Today's military satellite software-defined radio architectures enable continuous secure communications all the way to the tactical field edge. The satellite communication networks consist of user terminals and satellites, in addition to ground networking that provides control and interface functions. From the RF microwave perspective, the satellite terminal has several components that enable connectivity.



REMEMBER

Today's satellite network systems communicate large amounts of data, video, and voice at much faster rates than in the past. They wirelessly connect quickly and securely over multiple channels and operate over a wide spectrum in a complex communications environment. Because GaN is much more reliable, high powered, and robust than other semiconductor technologies, it's playing a larger role in these systems as manufacturers migrate away from traveling wave tube amplifier (TWTA) and GaAs technology.

A related seismic shift in the market for military and space satellite networks has been taking place for several years. As GaN power densities have increased, it has allowed for combining of solid-state monolithic microwave integrated circuits (MMICs) to reach the power levels previously only realized with TWTAs. An example of this type of solution is Qorvo's Spatium, which uses a patented spatial combining technique to offer high RF power, high efficiency, and broadband operation.

Spatium uses broadband antipodal fin-line antennas as the launch to and from an oversize coaxial waveguide, splitting into multiple microstrip circuits.

This SSPA solution has also been taking hold in commercial and military radar, electronic warfare (EW), satcom, and test and measurement markets. This market acceptance is due to SSPA benefits, including increased solid-state reliability, lower voltage power supply requirements, lower noise figures, lower energy costs, and instant-on capability, all leading to system-level lower total cost of ownership.

## Radar

As spectrum becomes increasingly hard to attain, the challenge of dealing with the immense tsunami of data involved in military communications is intensifying. Optimizing spectrum use requires more complex modulation schemes and the use of active electronically scanned array (AESA) architectures. To support these trends, RF front ends (RFFE) in satellite networks will increasingly take advantage of high-power solid-state wideband technologies like GaN. GaN's continued increases in performance are contributing to solutions that offer high-power output in AESA systems. Today, many of the PAs used in these AESA systems use high-voltage GaN (see Chapters 2 and 3).



REMEMBER

The primary benefits of GaN technology can be distilled down to several attributes including linearity, power, efficiency, reliability, size, and weight. In AESA systems, reliability is very important, and GaN can operate reliably at higher channel temperatures.

New radar systems also require products with higher power added efficiency (PAE), lower channel temperatures, and low noise figure. The high PAE of GaN MMICs means lower power consumption for a specific output power, lower cooling requirements, and lower operating costs.

Moreover, using high-gain, high-PAE GaN MMICs in radar platforms reduces the size and cost of the overall system. This helps meet the tougher size, weight, power, and cost (SWaP-C) requirements of new AESA radar systems. Meeting SWaP-C is very important in air and space-based systems where weight and size must be minimized.

## Electronic warfare

EW consists of defense systems used for protection, support, and electronic attack, such as military radios, communication jammers, and unmanned aerial vehicle (UAV) systems, for land-based, airborne, and naval platforms. The EW market continues to grow and has seen significant technological advancements and electronic component integration.

EW applications require electronic components that provide wideband power and efficiency, small size, and minimal weight. These systems must also operate at high operating temperatures, offer high reliability, and work in very harsh environments. For

this reason, technologies like GaN and GaAs are very heavily leveraged — and we continue to see the transition from tube-based systems to solid-state GaN and GaAs technologies in this EW arena.

Combined, the advances in GaN MMIC technology and GaN packaging are further accelerating the delivery of solutions that improve bandwidth, enable smaller form factors, improve thermal performance, and provide a low-cost plastic package for EW applications. GaN is the new technology of choice as contractors look to develop smaller, wider-bandwidth, higher-capacity, lower-cost, and more-powerful EW solutions.

## Surveying GaN Usage in Commercial Applications

Like many semiconductor technologies, GaN debuted in military and aerospace applications. But since those early days, many commercial markets have adopted it — particularly in 5G infrastructure.

### 5G infrastructure

5G has rapidly adopted GaN for three main reasons: the need for increased power output, the need for higher frequency operation, and the need for reduced power consumption. Because the PA consumes the most energy in the 5G RFFE, system designers focus heavily on improving amplifier efficiency. Luckily for them, efficiency is one of GaN's key attributes.



REMEMBER

A PA is most efficient near saturation. System designers use Doherty and digital pre-distortion to achieve linearity in 5G systems (refer to Figure 3-4).

GaN takes energy efficiency to the next level for many infrastructure applications. GaN reduces system power consumption, saving carriers money and making systems “greener.” These benefits have helped to thrust GaN into the 5G spotlight — especially when it comes to millimeter-wave (mmWave) fixed wireless access (FWA) and 5G base stations, which use massive multiple input, multiple output (MIMO) antenna arrays (see Figure 4-1). Massive MIMO antennas use beamforming techniques

in phased adaptive array technology to improve capacity without increasing the design complexity of intercell coordination. Massive MIMO makes it possible to form beams so that there is almost always only a single user in each beam. This provides each user with their own interference-free, high-capacity link to the base station.

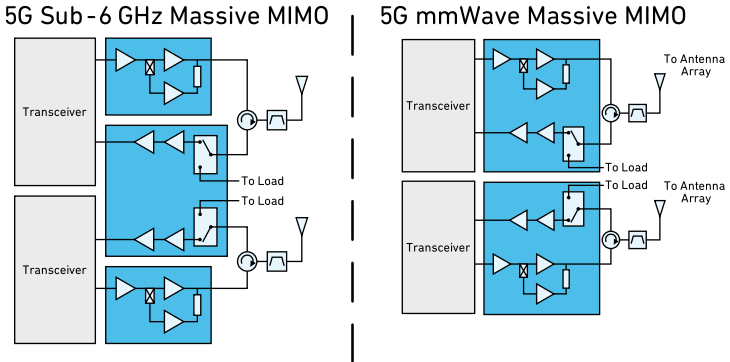


FIGURE 4-1: 5G Massive MIMO RF front-end block diagrams.

For FWA to achieve its targeted gigabit speeds, it must provide very high output power. As Figure 4-2 illustrates, highly efficient GaN Doherty PAs can easily achieve the requirement of 65 dBm effective isotropic radiated power (EIRP).

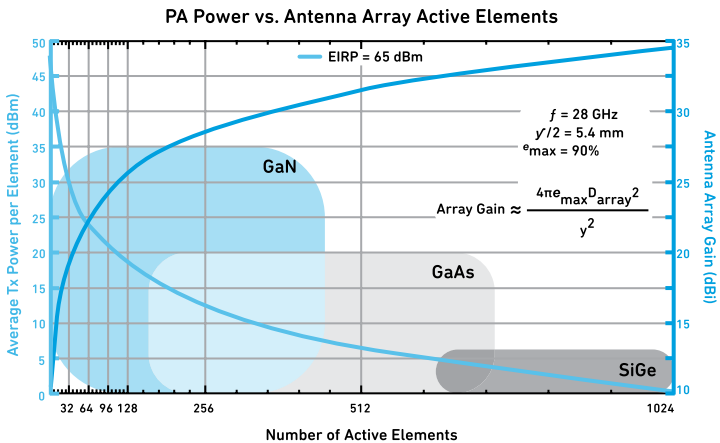


FIGURE 4-2: Tradeoffs between the number of antenna array elements and RFFE process technology.

GaN provides high antenna gain and a low noise figure because these parameters are functions of beamforming gain. To achieve 65 dBm EIRP with a uniform rectangular array, the PA power output required per channel reduces as the number of elements increases, as shown in Figure 4-2. Because GaN produces more power per channel than silicon, it enables antenna arrays to produce the required power output with fewer active elements.

## Wired broadband applications

For many years now, GaN has played a vital role in cable TV (CATV) technology advances across the globe. To support the increased demand for higher-throughput video and broadband services, hybrid fiber coaxial (HFC) network operators are installing fiber capacity deeper into their networks. HFCs can provide the needed power amplification to reduce the distance between the fiber to the home (FTTH) node and the house or business.

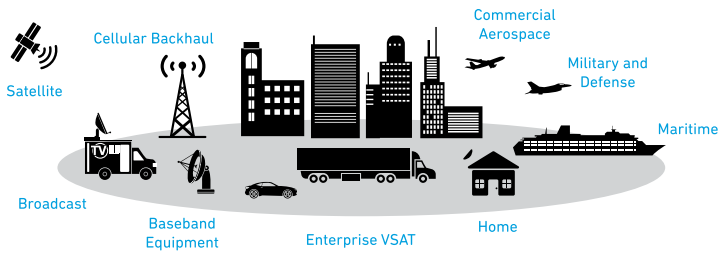
Linearity and efficiency are the major considerations when selecting HFC amplifiers, which is why GaN is a major technology choice. GaN's greater efficiency can provide higher linear output power together with low DC power consumption. This enables CATV designers to achieve wider bandwidths and higher data rates while extending the distance between amplifiers and maximizing reliability.

## Commercial satellite

Both GaN and GaAs are enabling a wide variety of commercial satcom applications such as 5G backhaul, ultra-HD TV transmission, satcom-on-the-move, Internet access for aircraft passengers, and manpack (portable) terminals.

Satcom equipment plays a vital role in the global communications ecosystem and the daily lives of people across the world, as shown in Figure 4-3. It supports a broad and expanding variety of applications in telecommunications, weather monitoring, aeronautical communications, maritime applications, and navigation.

The increased demand for smaller satellites, portables, and mobile satcom devices is driving a need for more compact, lightweight components with lower power consumption. Additionally, these RFFE components need to handle much greater bandwidth and data throughput to support advancements such as 5G, ultra-HD TV, and uninterrupted and secure communications. Plus, there is pressure to reduce development costs and increase reliability.



**FIGURE 4-3:** GaN in the satcom marketplace.

These trends are why manufacturers are moving from tube-based systems to solid-state devices like GaN that support higher data throughput and smaller form factors. GaN offers the significant advantage of high-power amplification in commercial satcom applications. Plus, GaN easily supports the higher-frequency bands used in satcom, such as the X, Ku, K, and Ka bands.

Just as military and aerospace satellite applications are migrating away from TWTAs, commercial satellite solutions are undergoing the same transition. This shift is driven by solid-state GaN used in MMICs or spatial combining products, like Qorvo's Spatium, that offer benefits such as instant-on capability, lower voltage rails needed, lower noise figure, and higher reliability.

## Looking Ahead to GaN's Bright Future

GaN is just getting started on what will be a long and fruitful journey. Despite making big strides in recent years, GaN is still a relatively young technology compared to silicon or GaAs. As GaN technology continues to advance, GaN will grow in popularity for both new and existing applications.

GaN market growth continues to accelerate as it's adopted across a broad variety of RF applications. Demand from military radar, electronic warfare, and wireless communication applications is the primary growth driver. But additional applications — both old and new — are increasingly using GaN because of its many system-level advantages. Here are some of those applications.

### Data centers

Data centers are expanding due to the massive growth in cloud computing. These data centers consume huge amounts of energy,

so reducing energy consumption is a priority. Normally in data centers, rail voltages are converted in steps — first, from 48 V to 12 V, and then from 12 V to as low as 1 V. Because of GaN's high switching speed, small form factor, and high efficiency, data center designers can use GaN DC power transistors to convert directly from 48 V to 1 V. This direct conversion capability saves energy and reduces complexity.

## **Automotive**

Electric vehicles (EVs) use GaN DC power transistors in many ways. The combination of more power-dense batteries, higher-efficiency electric motors, and onboard chargers is helping reduce vehicle mass, which results in greater range. EV system developers are replacing silicon transistors with GaN to satisfy the growing trend for more efficient, faster, and higher-powered systems. GaN's faster switching speeds and thermal management properties result in smaller, lower-cost, cooler solutions for EVs.

## **Wireless charging**

Wireless charging is beginning to spread beyond smartphone applications and will soon be common throughout our homes. Wireless charging is also becoming integrated into automobiles and medical devices. These applications use GaN transistors.

## **Power supply adapters**

Over the years, improvements in silicon switch technology have led to many advances in DC power supply design. However, silicon is now reaching its physical limits. Because GaN DC power transistors can turn on faster than silicon, they can reduce losses as well as increase switching speeds. Manufacturers are, therefore, looking to GaN to enable designers to make improvements such as size reductions, increases in efficiency, and increases in power.

## **Medical**

Manufacturers of medical equipment are migrating GaN into X-ray and magnetic resonance imaging (MRI) machines. Using GaN can reduce size, but there are other benefits as well. MRI machines using GaN are capable of 10 to 100 times higher resolution, enabling medical professionals to discover cancers and other diseases earlier, more accurately, and at less expense.

High-energy RF is also starting to appear in radio frequency ablation (RFA) equipment used to treat malignant tumors. In this method, an RFA probe is inserted into a tumor, guided by ultrasound, MRI, or computed tomography (CT) scanning. Using high-frequency current, the probe creates extremely high temperatures that destroy the tumor cells within a specific area. The dead cells aren't removed but become scar tissue and shrink over time.

## Wireless handsets

Military EW handheld radios have used GaN for many years. It provides the power, high frequency, wide bandwidth, and reliability needed in those harsh military environments. With the onset of 5G and mmWave, telecommunications carriers now need a technology that can provide some of the same capabilities in commercial handsets, including high-frequency band operation, large bandwidth, and high data capacity. These combined requirements can now be met using GaN.

## Scientific applications

GaN is helping to advance technologies used in research, integrated circuit manufacturing, and other cutting-edge applications such as 5G test and measurement. It's moving into particle accelerators and into chemical vapor deposition (CVD) systems, for example.

CVD, a technology for producing high-quality solid thin films and coatings, offers advantages over evaporation and sputtering methods using physical vapor deposition. GaN deployed in electromagnetic compatibility (EMC) test equipment used for pre-compliance testing and troubleshooting provides the high power and wide bandwidth needed for qualifying 5G products.

## Space applications

In space applications, GaN's low power consumption, small size, high power, high reliability, and radiation tolerance are all extremely important. Unlike other technologies, which require special shielding, GaN's natural immunity to radiation makes it the best technology to handle the harsh space environment.

## IN THIS CHAPTER

- » Summarizing the most important facts about GaN technology and its benefits
- » Seeing how GaN is taking military and commercial applications to the next level
- » Envisioning how GaN will evolve in the future

# Chapter 5

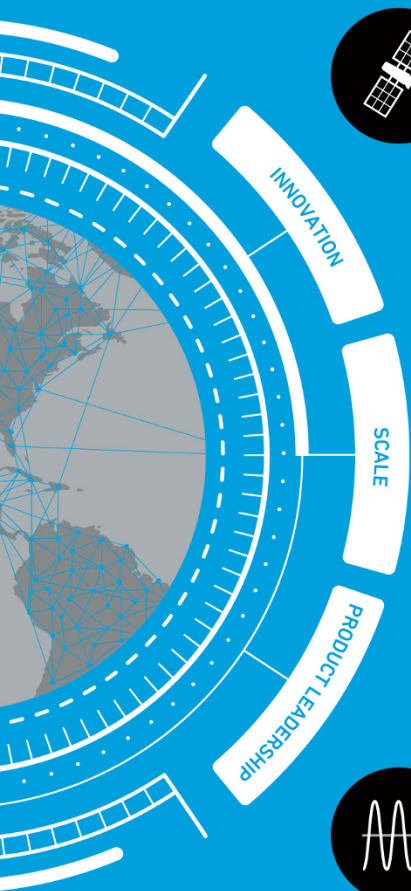
## Ten Key Takeaways

In a hurry? Start here! This quick list summarizes the key points from this book. Read these, and then if something catches your attention, check out the complete explanation in earlier chapters.

- » **Gallium nitride (GaN) is a high-performance compound semiconductor.** GaN is a direct bandgap compound semiconductor belonging to the III-V group, like gallium arsenide (GaAs). Compound semiconductors offer a superior combination of speed and power in many microwave radio frequency (RF) applications.
- » **GaN offers unique benefits for RF applications.** GaN's unique material properties provide high power added efficiency (PAE), high power output, small form factor, wide bandwidth, thermal advantages, and ruggedness for RF systems.
- » **Many commercial, defense, and space systems use GaN.** GaN's unique advantages underpin many new and existing applications, including radar, satellite communications, commercial wireless networks, and cable TV.
- » **GaN is critical for 5G.** To meet 5G requirements for multi-gigabit speeds and ultra-low latency, equipment manufacturers are deploying high-power GaN in massive multiple input, multiple output (MIMO) systems.

- » **GaN is used throughout the RF front end.** GaN was first used to create power amplifiers (PAs) but is now used for low noise amplifiers (LNAs), high-power switches, and mixers.
- » **Multiple GaN process and packaging options support diverse applications.** GaN semiconductor manufacturers have developed multiple process and packaging options that make it easier for system designers to find discrete components, monolithic microwave integrated circuits (MMICs), or modules that fit their specific applications.
- » **GaN is extremely reliable, even in harsh environments.** With a mean time-to-failure (MTTF) greater than 10 million hours at 200°C and 1 million hours at 225°C, GaN is more reliable than other semiconductor technologies.
- » **GaN is available for high-volume production applications.** The U.S. Department of Defense (DOD) classifies GaN at the highest maturity and manufacturing readiness level (MRL), MRL 10, meaning full-rate production and lean production practices are in place.
- » **GaN is expanding into new markets.** Because of its unique properties, GaN is spreading out into many new areas, including automotive, medical systems, and advanced scientific applications.
- » **GaN technology continues to advance.** Innovations in GaN technology and packaging in the future will support higher frequencies, higher voltage, and even wider bandwidth, further fueling GaN adoption.

# Are You Working With The Leader In GaN?



**Space qualified,**  
highest level of reliability



Demonstrated MTTF reliability with  
**200°C/1 million hours**



**Tens of millions**  
GaN products shipped to date



**#1 GaN-on-SiC supplier**  
in defense since 1998



4 GaN process nodes at **MRL 10**  
using USAF MRA tool



**Broadest** portfolio range  
DC-60 GHz

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**QORVO**

# Discover GaN Technology

GaN is a technology used in many high power, high voltage, and high frequency applications. Its technology features make it great for many defense, commercial, and space applications. Although it is relatively new, GaN has been around for several decades. It was first used in the defense arena, but today it's found in many markets — including new 5G cellular and space satellite applications.

GaN has etched its place in the many technology products around us. It is production ready and qualified for use in space and the military. This is why the commercial world has quickly adopted it. Today GaN helps engineers realize their next-generation design aspirations.

## Inside...

- Understand GaN's unique material properties
- Learn how GaN is being used in important radar applications
- Discover how GaN is used in commercial, military, and space
- Learn the best GaN process technology for your application
- Understand how GaN is advancing today's and future markets

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