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GaN RF Technology

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Learn:

- The key properties of GaN
- What makes GaN FETs unique
- How GaN compares to other semiconductor technologies
- The thermal challenges of GaN

Andrew Moore
Jose Jimenez

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Qorvo (Nasdaq: QRVO) is a leading provider of core technologies and RF solutions for mobile, infrastructure, and aerospace/defense applications. Qorvo was formed following the merger of RFMD and TriQuint, and has more than 6,000 global employees dedicated to delivering solutions for everything that connects the world. Qorvo has the industry's broadest portfolio of products and core technologies; world-class ISO 9001–, ISO 14001–, and ISO/TS 16949–certified manufacturing facilities; and is a DoD-accredited 'Trusted Source' (Category 1A) for GaAs, GaN, and BAW products and services. For the industry's leading core RF solutions, visit www.qorvo.com.

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Qorvo Special Edition

by Andrew Moore and Jose Jimenez

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Introduction

Gallium nitride (GaN) transistors were first demonstrated in the 1990s and are now widely available for commercial and defense applications. GaN's popularity is rooted in its high-current, high-voltage capabilities, which makes it highly valuable for microwave applications and power switching.

Qorvo is a leader in the development of GaN transistors for radio frequency (RF) applications and their underlying process technology. Its latest devices support low-noise applications, as well as those at higher frequencies and power levels beyond 200 watts.

Qorvo's discrete GaN transistors, monolithic microwave integrated circuits (MMICs), and packaged solutions support a wide range of applications, including next-generation radar, electronic warfare (EW), base transceiver stations (BTS), instrumentation, and cable TV (CATV) infrastructures.

GaN technology outperforms other RF technologies because it can simultaneously offer the highest power, gain, and efficiency combination at a given frequency, and because it operates at a higher operating voltage for a reduced system current. In this book, we fill you in on GaN semiconductors, the GaN field-effect transistor (GaN FET), and some practical considerations for deployment of GaN semiconductors.

Foolish Assumptions

This book is written for both technical and non-technical readers. If you're an executive, salesperson, or design engineer, this book is for you. Unless of course, you're looking for a book on indoor gardening!

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.

This icon points out information that you'll want to put in storage, your memory, or whatever you use to keep track of important information like birthdays and phone numbers for later use.

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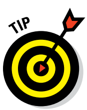

No, this isn't the thing you do to take care of your waitresses and bartenders. You should stop and take notice because there are nuggets of knowledge that could save you some aggravation later on.

Beyond the Book

Although this book is full of good information, we could only cover so much in 24 pages! So, if you find yourself wanting more after reading this book, just go to `www.qorvo.com/gan`, where you can get to more information about Qorvo's GaN technologies and products.

Where to Go from Here

Whether you're new to electrical design and GaN technology or a seasoned design engineer looking to use GaN technology in your designs, you'll find this book useful.

Each chapter in this book stands on its own, so you can skip around if you like. If you're familiar with the topics in a chapter, you can skip it. We provide cross-references to information in other chapters of the book, so you can always find what you're looking for.

Chapter 1

All about GaN

In This Chapter

- Getting acquainted with GaN
- Seeing what makes GaN unique
- Understanding piezoelectricity
- Recognizing the benefit of GaN's high power density

Gallium nitride (GaN) is a binary III/V direct bandgap semiconductor crystal that is most commonly used in general illumination (LED lights) and Blu-ray players. GaN is also used in radio frequency (RF) amplifiers and in power electronics. GaN is a very hard material; its atoms are bonded by a very ionic gallium-nitrogen chemical bond that produces a bandgap of 3.4 electron volts (eV).

In semiconductor physics, the *bandgap* refers to the energy required to free the electron from its orbit around the nucleus and allow it to move freely through the solid. The bandgap is an important material parameter that ultimately determines the mass of the freely moving electrons and the electric field that the solid is able to withstand. GaN has a bandgap of 3.4 eV, which is a big number. That's why GaN is called a *wide bandgap semiconductor*. In comparison, gallium arsenide (GaAs) has a bandgap of 1.4 eV and silicon (Si) has a bandgap of only 1.1 eV.

In this chapter, we fill you in on the basics of GaN and explain the unique characteristics that make GaN ideal for RF power amplifiers and other applications that operate at higher voltages and frequencies.

The Basics of GaN

Gallium (Ga) is a chemical element with atomic number 31. Gallium doesn't exist freely in nature. Instead, it's a byproduct in the production of zinc and aluminum.

The GaN compound is formed by gallium and nitrogen atoms arranged, most commonly, in a wurtzite crystal structure. The wurtzite crystal structure (shown in Figure 1-1) is hexagonal and is characterized by two lattice constants (marked *a* and *c* in the figure).

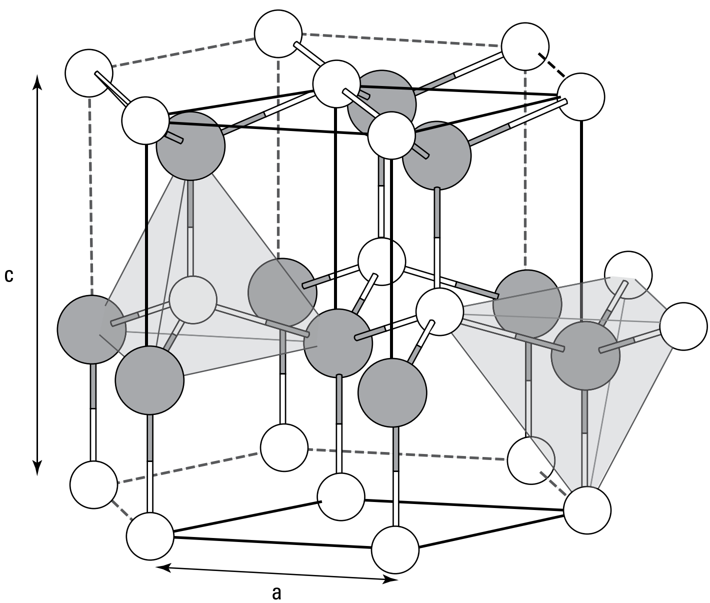

Figure 1-1: The GaN crystal structure.

In the semiconductor world, GaN is usually grown at a high temperature (approximately 1,100°C) by metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE) techniques on a foreign substrate (silicon carbide [SiC] for RF applications, or Si for power electronics applications).

The GaN-on-SiC approach combines the high power density capabilities of GaN with the superior thermal conductivity and low RF losses of SiC. That's why GaN-on-SiC is the combination of choice for high power density RF performance. Today, you can get GaN-on-SiC substrates up to 6 inches in diameter.

TIP

The GaN-on-Si combination has a much poorer thermal performance and higher RF losses but is much cheaper. That's why GaN-on-Si is the combination of choice for price-sensitive power electronics applications. Today you can get GaN-on-Si substrates up to 8 inches in diameter.

Why GaN Outperforms Other Semiconductors in RF Applications

GaN is a relatively new technology compared to other semiconductors, such as Si and GaAs, but it has become the technology of choice for high-RF, power-hungry applications like those required to transmit signals over long distances or at high-end power levels (such as radar, base transceiver stations [BTS], satellite communications, electronic warfare [EW], and so on).

TIP

GaN-on-SiC stands out in RF applications for several reasons:

- **High breakdown field:** Because of GaN's large bandgap, the GaN material has a high breakdown field, which allows the GaN device to operate at much higher voltages than other semiconductor devices. When subjected to high enough electric fields, the electrons in the semiconductor can acquire enough kinetic energy to break the chemical bond (a process called *impact ionization* or *voltage breakdown*). If impact ionization is not controlled, it can degrade the device. Because GaN devices can operate at higher voltages, they can be used in higher-power applications.
- **High saturation velocity:** Electrons on GaN have a high *saturation velocity* (the velocity of electrons at very high electric fields). When combined with the large charge capability, this means that GaN devices can deliver much higher current density.

REMEMBER: The RF power output is the product of the voltage and the current swings, so a higher voltage and current density can produce higher RF power in a practically sized transistor. Simply put, GaN devices can produce much higher power density.

- **Outstanding thermal properties:** GaN-on-SiC devices exhibit outstanding thermal properties, due largely to the high thermal conductivity of SiC. In practical terms, this means that GaN-on-SiC devices don't get as hot as GaAs or Si devices when dissipating the same power. A "colder" device means a more reliable device.

What Piezoelectricity Is and Why It's Important

GaN is piezoelectric. *Piezoelectricity* (pronounced pee-*ay*-zo-electricity) is a fancy word that means electricity resulting from stress.

TECHNICAL STUFF: The word *piezoelectricity* comes from the Greek *piezein,* which means to squeeze or press, and *electric* or *electron,* which means amber, an ancient source of electrical charge.

GaN is piezoelectric because the gallium-nitrogen bond is ionic and because the successive planes of gallium and nitrogen atoms are not at equal distance (see Figure 1-2). When we squeeze the atoms in a plane, the planes of atoms above and below move different distances, creating a net charge, an electric field, and a voltage.

Now that you know why GaN is piezoelectric, you may be wondering why the piezoelectric property of GaN is so important. Piezoelectricity in GaN is responsible for part of the charge in GaN transistor electron channels. Piezoelectricity is also responsible for some of the degradation modes of the transistors, which we discuss more in Chapter 3.

REMEMBER: Piezoelectric properties are used daily in some of our more common consumer devices, such as smartphones. The piezoelectric substrate used in bulk acoustic wave (BAW) and surface acoustic wave (SAW) filters — filters that Qorvo produces by the millions — is the key enabler of the multi-band capabilities of smartphones.

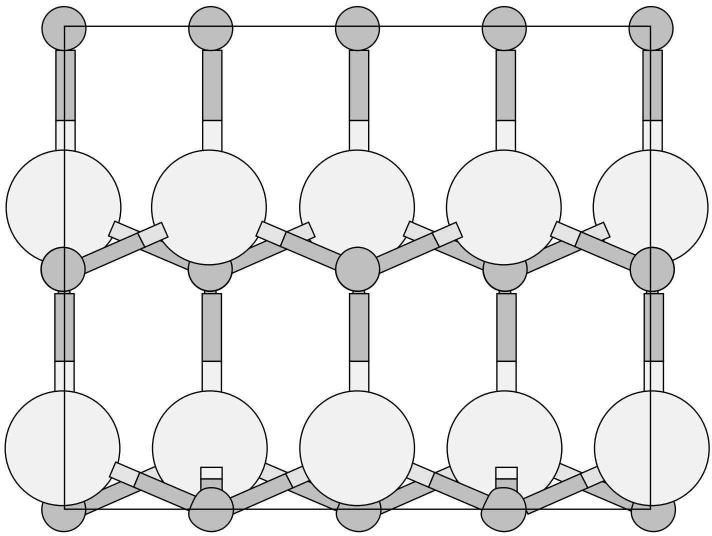

Figure 1-2: A plane view of a GaN lattice.

The Benefits of GaN's High Power Density

As we mention earlier, GaN-on-SiC is a high-RF power density semiconductor. In field-effect transistors, power density is typically expressed as watts per millimeter (W/mm), because power scales with gate periphery and not gate area. Obviously, a higher power density means that more power can be produced using a smaller amount of device periphery, so a smaller device can meet a given power requirement.

Now, smaller devices don't just mean lower cost of material. They also mean

- **Lower capacitances:** A circuit designer can design an amplifier with wider bandwidth.
- **Lower combining losses:** You get higher efficiency, gain, and, ultimately, power.

Today's mobile communications infrastructure, as well as advanced military systems such as phased array radars, communications, and EW, require high-frequency, high-bandwidth, high-power, high-efficiency devices. These applications are where GaN differentiates itself from other materials.

Chapter 2

Introducing the GaN Field-Effect Transistor

In This Chapter

- Understanding field-effect transistors
- Getting acquainted with the GaN FET geometry
- Making sense of the GaN FET fabrication process
- Comparing the GaN FET with other FET technologies
- Looking at advanced GaN FET geometries

Field-effect transistors (FETs) are a mainstay of solid-state electronics and have been around for decades. In this chapter, we show you how the advantages of gallium nitride (GaN) discussed in Chapter 1 (such as high current, high breakdown voltage, and its outstanding thermal properties) can be applied to a FET to make the GaN FET a powerful device.

How Field-Effect Transistors Work

The field-effect transistor is a type of transistor commonly used for amplifying weak signals (such as wireless signals).

In a FET, current flows along a semiconductor path, known as the *channel.* At one end of the channel is an electrode called the *source,* and at the other end of the channel is an electrode called the *drain.* Electrical current can be modified by applying a voltage to a control electrode called the *gate.* Small changes in gate voltage can cause a large variation in the current from the source to the drain. Because the power required to control the channel is much smaller than the power the transistor can deliver to a load, the FET can amplify a radio frequency (RF) signal.

There are two types of FETs, which are defined based on the state of the channel when no voltage is applied to the gate electrode. *Enhancement-mode FETs* do not conduct current between the drain and source electrodes when the gate electrode is at zero volts. *Depletion-mode FETs,* on the other hand, have the channel fully formed when the gate electrode is at zero voltage; current can circulate between the drain and source as long as there is a potential difference between them. Almost all the GaN FETs for RF applications are depletion-mode FETs. In power electronics, there is a considerable effort to create true enhancement-mode FETs.

FETs can be constructed from a number of semiconductors, with silicon (Si) the most common by far. Other semiconductors using the FET's geometry are gallium arsenide (GaAs), indium gallium arsenide (InGaAs), indium phosphide (InP), and, of course, gallium nitride (GaN).

$a^2 + b^2 = c^2$: The GaN FET Geometry

GaN FET technology is relatively new compared with other FET technologies such as the GaAs FET and Si-based FETs. As in any FET device, the GaN FET has two structures: the vertical semiconductor structure and the horizontal device structure, which we describe in the next sections. Figure 2-1 shows the basic geometry of a GaN FET.

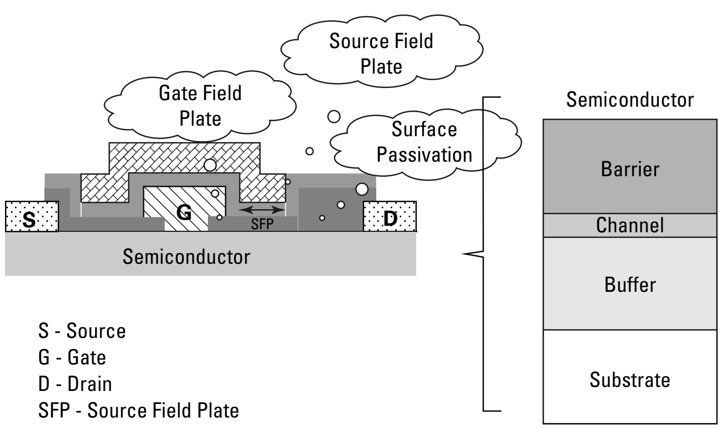

Figure 2-1: The basic GaN FET geometry.

GaN's vertical semiconductor structure

The vertical semiconductor structure of a FET consists of:

- **Gate:** This is the metal layer whose voltage controls the electrical characteristic of the electron channel.
- **Barrier:** This semiconductor layer isolates the gate and the channel so that very low current flows between the channel and the gate. In GaN FETs, the barrier is typically made of aluminum gallium nitride (AlGaN), with the aluminum concentration ranging from 15 percent to 28 percent. The higher the aluminum concentration, the higher the barrier and, thus, the higher the charge capacity of the channel (the charge beyond which electrons start to flow to the gate). High charge channel capacity is good because it increases the current that the FET can flow between the drain and source.

  Increasing aluminum composition also increases the intrinsic strain in the device, reducing its reliability. We discuss this strain more in Chapter 3.
- **Channel:** The channel is the region where electrons flow from the source to the drain. The channel is typically made of high-quality GaN with a large *mobility* and a high *saturation velocity*. Mobility and saturation velocity are two parameters that describe how fast the electrons move in the solid. The higher the mobility and saturation velocity, the larger the current that can circulate between drain and source.
- **Buffer:** The role of the buffer is to restrict the movement of the electrons within the channel. In other words, the buffer acts as a barrier that prevents the electrons from wandering into the substrate. In a GaN FET, the buffer is typically made of GaN doped with carbon (C) or iron (Fe).
- **Substrate:** The substrate is the last and thickest layer of the vertical structure. The substrate provides mechanical support, heat spreading, and electromagnetic confinement. GaN FETs use a foreign substrate (that is, Si or silicon carbide [SiC], but not GaN). Because the substrate is not GaN, it has a different crystal lattice than the buffer. This creates dislocations in the material and ultimately reduces the electrical isolation between gate and channel.

GaN's vertical FET structure delivers higher current densities than Si or GaAs, which is why GaN is great for RF power amplifiers. GaN-on-SiC FET structures also have a high thermal conductivity (about 330 W/mC, compared to approximately 145 W/mC for Si and 52 W/mC for GaAs), which allows GaN FETs to dissipate more power without increasing the device temperature.

On the downside, GaN's gate isolation is lower (approximately µA/mm, compared to pA/mm for Si and nA/mm for GaAs), because of the large number of dislocations in the material.

GaN's horizontal device structure

As in any other FET, GaN's horizontal structure consists of the following sections:

- Source electrode
- Source access region
- Gate-controlled channel region
- Drain access region
- Drain electrode

The most important part of the horizontal structure is the gate. Its size determines the speed of the device. The smaller the gate, the faster the electrons flow through the gate-controlled channel and, thus, the faster the device is. The gates of GaN FETs are often 0.1 to 0.5 µm in length.

The drain-gate access region also is an important section. A long drain-gate region can sustain higher voltages and, thus, deliver higher RF power, but it does so at the expense of dissipated power. As a result, a device technologist should always choose the minimum drain-to-gate spacing to sustain a particular voltage application. Drain-to-source spacing is commonly 3 to 8 µm in length; the drain-to-gate spacing should be longer for increased breakdown and shorter for higher speed and RF efficiency.

The electric field in the horizontal direction of the FET device is highly non-uniform, peaking close to the drain edge of the gate. A very high field is not good, for two reasons:

- High fields at the semiconductor surface reduce the maximum current that a device can deliver in a very short time (a phenomenon called *current collapse*).
- High fields in the channel can produce *impact ionization,* a process in which electrons gather so much speed that they can break the covalent bonds between atoms, a process that can damage the device if not controlled.

The GaN FET horizontal geometry uses field plates to engineer those high fields. There are two types of field plates depending on where they're connected and how they're used:

- **Gate field plate (GFP):** Gate field plates are connected to the gate. They're particularly effective in reducing the fields at the surface of the semiconductor very close to the gate. Thus, gate field plates reduce the current collapse at low drain-gate voltages.
- **Source field plate (SFP):** Source field plates are connected to the source, shielding the gate from the drain (a property called the *Faraday effect*). Shielding the gate from the drain reduces the feedback between the drain and the gate, increasing the RF gain. Source field plates are also used to reduce the fields at the surface at high drain-gate voltages and reduce the current collapse further.

The GaN FET Fabrication Process

Figure 2-2 shows a typical GaN FET fabrication process. It starts with a SiC substrate where the main vertical semiconductor layer (buffer, channel, and barrier) is grown. As we mention in Chapter 1, this growth is done by metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE).

The horizontal geometry is created using five basic steps:

1. **Device isolation:** Device isolation is performed by ion implantation or *mesa formation* (removal of the channel layer). Isolation between FET devices is essential for creating RF circuits.
2. **Ohmic metallization:** Ohmic metallization creates the source and drain electrodes. In GaN, ohmic metallization has to be done at a very high temperature, much higher than in other semiconductors.

3. **Nitride passivation:** After the drain and source are formed, the semiconductor is then passivated, most commonly using silicon nitride.

4. **Nitride openings and gate metal deposition:** Openings are created in the silicon nitride, and metals are deposited on them, which creates the gates. The basic FET transistor has been created!

5. **Additional nitride and metal layers:** After several additional layers of nitrides and metals are deposited, these layers create source field plates, interconnects, and capacitors. These layers also protect the device from external factors.

Finally, the substrate is thinned (typically to 100 µm), the bottom of the substrate is metallized, and *vias* (short paths between the top and bottom of the substrate) are created. Vias reduce the inductance between the device and the ground (the bottom metallization layer).

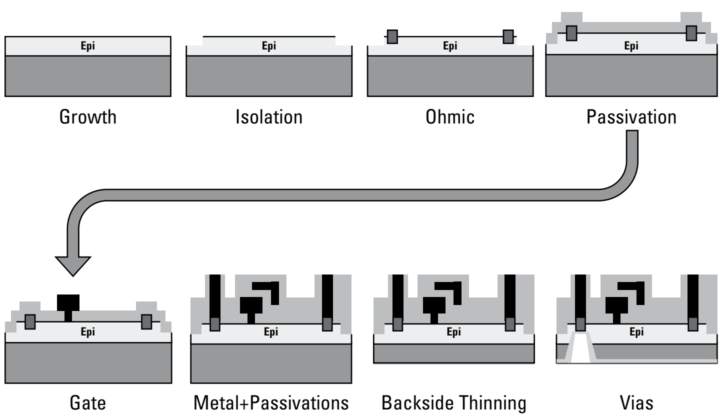

Figure 2-2: A typical GaN process flow.

Comparing GaN with Other FET Technologies

Figure 2-3 shows the current-voltage (I-V) characteristic of a FET with a resistive load line. The I-V characteristic of the device is described mainly by three parameters:

- **I_{DMax}**: Maximum saturated current
- **V_{BR}**: Breakdown voltage
- **R_{On}**: On resistance between drain and source

These three parameters by themselves control the RF power performance of the device. RF power is proportional to the current and voltage swings at the load and, thus, proportional to the I_{DMax} and the breakdown voltage of the device.

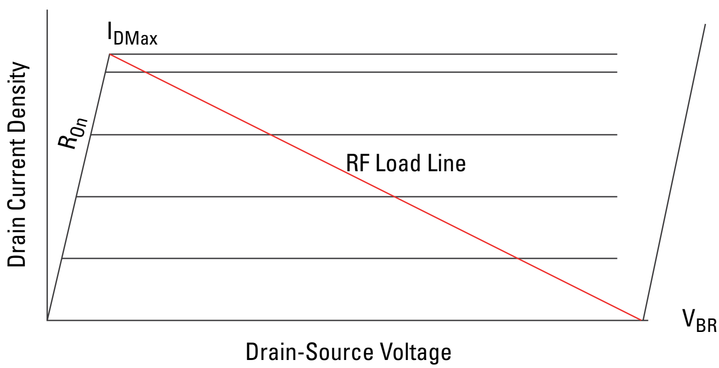

Figure 2-3: Current-voltage characteristics of a FET.

In Chapter 1, we explain that GaN can deliver higher current than other semiconductors because it has a high charge capacity in the channel and a high saturation velocity. In Chapter 1, we also explain that GaN can sustain higher breakdown fields among common semiconductors due to its large bandgap. That's why GaN can deliver the highest RF power density among semiconductors.

REMEMBER

GaN-on-SiC has a power performance of approximately 5 watts per millimeter (W/mm), compared to approximately 1 W/mm for GaAs and 0.3 W/mm for Si.

A low R_{On} is also important because resistance is where losses are generated, reducing the RF efficiency of the device. GaN doesn't have the lowest R_{On} among semiconductors (InP and GaAs are much better), but given the large voltages it sustains, its effect on overall efficiency is smaller.

TIP

Use GaN only when you need the highest RF power handling (current and voltage).

Advanced GaN FET Geometries

Improved GaN FET performance can employ several advanced geometry techniques:

- **Semiconductor barriers:** AlGaN semiconductor barriers normally include a cap and spacer layer at each side of the barrier. The cap layer made of GaN reduces intrinsic strain at the surface, improving device reliability. Aluminum nitride (AlN) spacers improve electron mobility in the channel. Other advanced techniques for semiconductor barriers include the following:
    - **Indium aluminum nitride (InAlN):** Used to get higher electron density and higher speed. InAlN can be lattice-matched to GaN, eliminating the intrinsic strain of more common barriers such as AlGaN.
    - **Gate metal-insulators:** Used to reduce gate current and power dissipation. Typically, insulators include nitrides or atomic layer deposition (ALD) layers, such as aluminum oxide.

      ALD is a process that relies on surface chemistry to deposit thin films of materials onto substrates. ALD reactions use two chemicals, called *precursors.* The reaction of the precursors creates a thin film on the substrate.
- **Channels:** The typical electron channel is made of GaN. Indium may be added to create an indium gallium nitride (InGaN) electron channel. The presence of indium improves the electron mobility and confinement.
- **Buffers:** In most FET implementations, the buffer is made of GaN. More advanced buffers incorporate the use of low-aluminum AlGaN material for increased electron confinement and reduced short-channel effects.

Chapter 3

Practical Considerations for Deployment

In This Chapter

- Identifying reliability and failure modes
- Managing the thermal challenge

In previous chapters, we cover gallium nitride (GaN) technology and GaN field-effect transistors (FETs). In this chapter, we fill you in on some practical considerations for deploying GaN technology in systems. Here, we identify the reliability and failure modes of deploying GaN technology and provide some tips for managing the thermal challenges of GaN.

Reliability and Failure Modes of GaN

One of the primary advantages of GaN transistors is their ability to operate at higher voltages and currents, several times higher than transistors fabricated in other semiconductor technologies. But these advantages also bring unique reliability challenges.

One such challenge arises because of the aluminum gallium nitride (AlGaN) typically used in the barrier between the gate and the electron channel, which we discuss in Chapter 2. Aluminum nitride (AlN) and GaN have different crystal lattice constants. When AlN is grown on GaN, its crystal lattice is forced to look like that of GaN, creating strain. The higher the concentration of aluminum in the AlGaN barrier, the higher the mismatch between lattice constants and, thus, the higher the strain.

The piezoelectricity of GaN then creates even more strain in the system, through the *inverse piezoelectric effect.* If the piezoelectric properties of GaN produce an electric field, then the *inverse piezoelectric effect* means an electric field always produces mechanical strain. The piezoelectric strain adds to the lattice mismatch strain of the AlGaN barrier.

In regular operation, GaN FETs have to sustain high electric fields at the edge of the gate closest to the drain. If the FET is not designed properly, the additional stress on the barrier from the inverse piezoelectric effect can crack and degrade the device. Figure 3-1 shows a GaN FET with a source and drain, and a voltage applied at the gate. Figure 3-2 shows the mechanical degradation of the material due to the inverse piezoelectric effect.

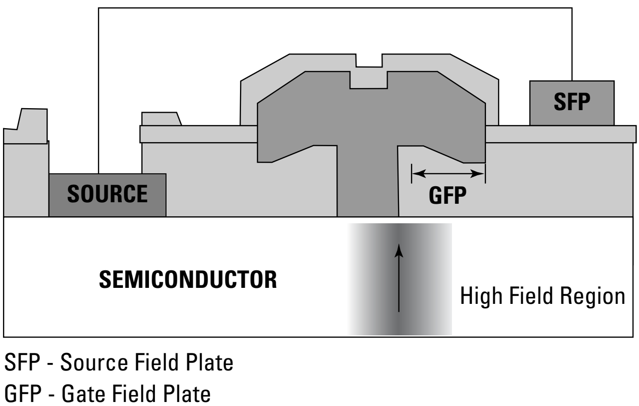

Figure 3-1: A high electric field region of the FET.

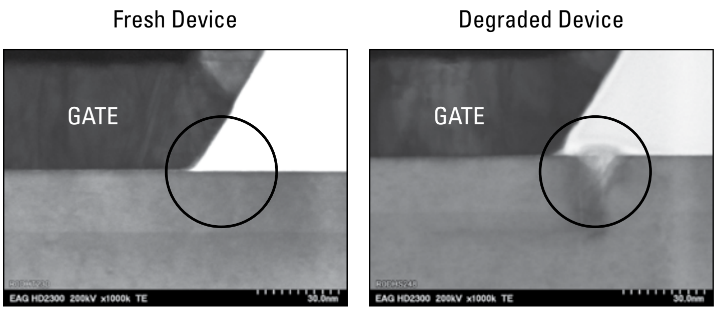

Figure 3-2: Mechanical degradation at the drain edge of the gate.

To reduce and eliminate this intrinsic failure mode of GaN transistors, the technologist needs to properly design the composition and thickness of the semiconductor barrier and improve the strength of the semiconductor surface. When properly designed, this failure mode can be eliminated.

Today, GaN transistor reliability is very good with extrapolated median time to failure (MTTF) in excess of 10 million hours at temperatures as high as 200°C, comparable to or higher than in other semiconductors. More important, companies like Qorvo have shown that devices can operate for 1 million hours at 200°C with fallout rates below 0.002 percent. Figure 3-3 shows an Arrhenius plot of Qorvo's typical reliability performance for its second-generation 0.25 μm GaN FET technology.

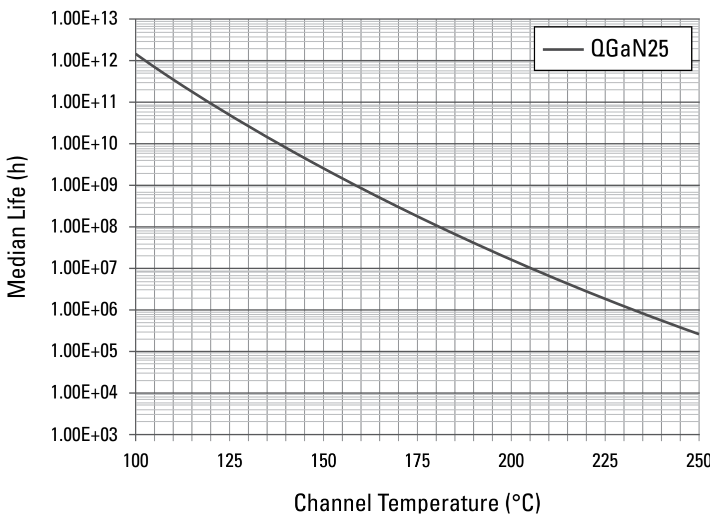

Figure 3-3: Typical reliability performance using Qorvo's GaN FET technology.

Managing the Thermal Challenge with Qorvo's Technology

Device technology for power amplifiers has always been about increasing the radio frequency (RF) power density and gain that a transistor can generate at equal or higher speed. Higher power density and gain reduce the number of gain stages and the combining losses that eventually limit the raw power, gain, and efficiency a chip can deliver at a given frequency.

The push for higher power density led the migration from silicon (Si) to standard gallium arsenide (GaAs) to high-voltage GaAs, and eventually to GaN.

The migration to higher power density FET technologies has also increased the challenge of managing the temperature in the device. Keeping the device “cool” is important because higher temperature degrades its raw performance and reliability. On paper, GaN can deliver a power density in excess of 20 watts per millimeter (W/mm) at relatively high frequencies. In practice, however, its use has been limited to 5 W/mm or less because of the high temperature resulting from dissipating large amounts of heat in a very compact volume.

Thermal management is ultimately the reason why silicon carbide (SiC) is the substrate of choice for high-performance RF applications. SiC’s good thermal conductivity is as important as the GaN semiconductor for delivering high RF power. It’s also the reason why companies such as Qorvo are working with substrates with even better thermal properties, such as diamond.

To manage the thermal challenge today, circuit designers spread the heat sources at the semiconductor surface, increasing the distance between device fingers or making those fingers smaller. But the thermal challenge doesn’t end at the chip level. The packaging engineer also has to help because the heat flux is higher at the chip-package interface. A good thermal interface between the chip and the package is essential to delivering all the RF power density the GaN device can provide.

REMEMBER

In GaN technology, the thermal design is as important as the electrical design.

Chapter 4

Ten Important Facts about GaN Technology

In This Chapter

- Seeing what sets GaN apart
- Recognizing the advantages of GaN

In this chapter, we offer ten important facts to remember about gallium nitride (GaN) technology.

- **GaN devices can deliver ten times more power density than gallium arsenide (GaAs) devices.** The higher power density of GaN devices allows them to deliver wider bandwidth, higher amplifier gain, and higher efficiency as a result of the smaller device periphery.
- **GaN field-effect transistor (FET) devices can operate at five times higher voltage than comparable GaAs devices.** Because GaN FET devices can operate at a higher voltage, designers can more easily implement impedance matching on narrow-band amplifier designs.

  REMEMBER

  Impedance matching is the practice of designing the input impedance of an electrical load in such a way that it maximizes the power transfer from the device into the load.
- **GaN FET devices deliver twice as much current as GaAs FET devices.** Because GaN FET devices can deliver a current that is twice as high as GaAs FET devices, GaN FET devices have intrinsically higher bandwidth capability.
- **GaN heat flux at the device level is as high as five times the heat flux on the surface of the sun!** The *heat flux* is the rate of heat transfer per unit area. Because GaN is a higher power density device, it dissipates heat in

a very small volume, producing a high heat flux. This is also why thermal management of GaN devices is so important.

- **The thermal conductivity of silicon carbide (SiC) is six times higher than that of GaAs and three times higher than that of silicon (Si).** The high thermal conductivity of SiC makes it the substrate of choice for high power density RF applications.
- **The GaN chemical bond is three times stronger than the GaAs chemical bond.** Because of this, GaN has a larger bandgap and is capable of sustaining a higher electric field and, thus, a higher operating voltage.
- **GaN–aluminum gallium nitride (AlGaN) structures are five times more piezoelectric than GaAs–aluminum gallium arsenide (AlGaAs) structures.** In Chapter 1, we explain piezoelectricity and why it's important in GaN. Because of the higher piezoelectricity of the GaN-AlGaN structures, electrical and mechanical properties are coupled.
- **GaN-on-SiC material has approximately 10,000 times higher dislocations density than GaAs does.** For this reason, the gate current tends to be higher than in similar GaAs devices and requires extra attention from the circuit designer.
- **GaN–aluminum nitride (AlN) is 20 times more strained than GaAs–aluminum arsenide (AlAs).** Stress analysis at all levels is important because GaN-AlN is much more strained than comparable GaAs-AlAs systems.
- **Qorvo's GaN devices have a fallout rate of less than 0.002 percent after 1 million hours operating at 200°C.** Bottom line: This technology is ready for deployment.