Application Note AN-007: *A Comparative Review of GaN, LDMOS, and GaAs for RF and Microwave Applications*

by Anthony Combs

Introduction

Anyone having anything to do with the RF industry in the last 10-15 years is undoubtedly aware of the existence of gallium nitride (GaN) and its gradual introduction to the market. Countless technical papers, application notes, blogs, and vlogs have been dedicated to touting GaN's superiority over its Si- and GaAs-based competitors. Separating fact from fiction, it is critical to understand the differences between these technologies so their advantages (and disadvantages) for any given application can be best understood.

GaN is widely considered a breakthrough technology due to its substantial improvements in high power density and reliability. As an early adopter of GaN, NuWaves Engineering is a forward-thinking company keen on the latest in state-of-the-art RF power amplifier (PA) technologies. This application note serves to provide an overview on the pros and cons of GaN and competitive alternates for RF/microwave applications.

Traveling Wave Tubes

Traveling wave tubes (TWTs) have historically been the go-to for RF power amplification at high power and high frequencies. TWTs are vacuum tubes specially designed for the electronics industry for the amplification of RF signals from 300 MHz up to millimeter-wave frequencies (as high as 50 GHz). While capable of handling high levels of power and are still used in certain applications, TWTs are largely considered antiquated legacy components due to their poor reliability, large size, and padded design margins for design-to-operational discrepancies.

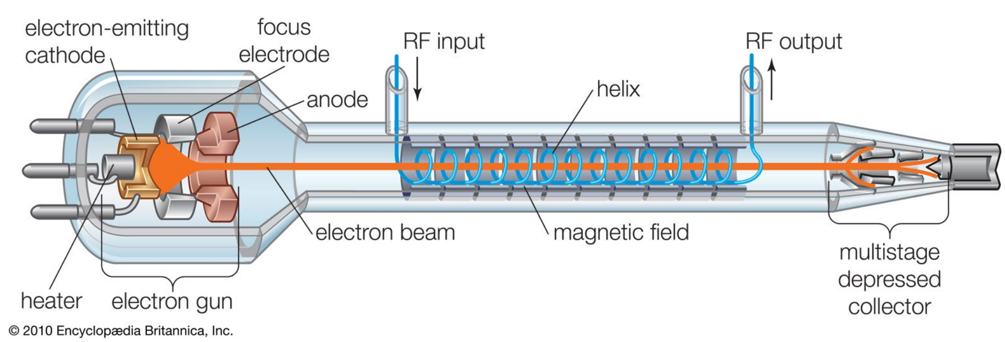

Figure 1. A diagram of a typical traveling wave tube amplifier (Britannica, 2010).

Laterally Diffused Metal Oxide Semiconductor Field Effect Transistors

Laterally-diffused MOSFETs (LDMOS) have significant advantages in terms of being able to provide high power amplification at low cost, as most LDMOS devices are silicon based. LDMOS components can handle over 100 watts of RF output power at higher frequencies and up to kilowatts of power at lower frequencies (<=1 GHz). While manufacturers work towards continuous improvements, a general rule of thumb "good for wideband <1 GHz, good for narrowband >1 GHz". Additionally, LDMOS is considered to be extremely rugged and reliable and has been known to operate into high impedance mismatches without damage and negligible degradation. LDMOS also has the advantage of high operating voltages up to 50 V. Power densities for LDMOS devices are typically between 1-2 W/mm. 3-4 GHz is generally considered the limit for operational frequencies for LDMOS, as output impedances become increasingly difficult to match.

Gallium Arsenide

GaAs as a semiconductor material is both versatile and, like Si LDMOS, fully matured. GaAs transistors are capable of operating over a very wide frequency range, ranging from 30 MHz to millimeter-wave frequencies as high as 250 GHz, and can serve both narrowband and wideband applications. GaAs devices are also known for generating very little internal noise and for their high sensitivity. Power density for GaAs is typically around 1.5 W/mm. Where GaAs falls short is in its power handling capabilities, as it is limited to roughly 5-10 watts of output power due to its low breakdown voltage, which generally falls between 5-12 V, and inability to withstand higher temperatures of GaN and Si. Higher output powers up to 20-40 W using GaAs are possible, though, as multiple GaAs devices can be used in push-pull, parallel, or output combining configurations. However, such configurations do not come without a trade off in efficiency and real estate for peripheral circuitry.

Gallium Nitride

GaN has rapidly become the darling of semiconductor technologies within the RF/microwave world. GaN's primary advantage over competing technologies is its high power density, which can be as much as 5X that of a comparable GaAs device. In layman's terms, that means five times the output power in an 80% smaller package size.

GaN is capable of outputting anywhere from tens to hundreds of watts, and can operate up to mm-wave bands with improved efficiency and bandwidth compared with Si and GaAs devices. This is partially because GaN devices have a smoother transition curve into saturation, meaning that amplifiers can operate further into the saturated region where efficiency is higher. GaN devices also have high breakdown voltages, ranging between 28-50 V. The resulting lower capacitance and higher resistive impedances produce higher overall impedances, which simplifies the matching process and enables broadband functionality that was previously inconceivable.

GaN devices are almost always fabricated on a low loss, high thermal conductivity substrates, such as silicon carbide (GaN-on-SiC), to help with GaN's poor thermal management characteristics. Silicon is another common substrate used for GaN devices (GaN-on-Si). GaN-on-Si is a cheaper alternative due to the ability to leverage silicon fabrication processes, though at the expense of reduced performance compared with GaN-on-SiC. The reduced thermal conductivity of silicon compared with silicon carbide limits output power to around 10 W. GaN-on-Si is also limited to applications under 6 GHz, as the gain, efficiency, and output power of the devices fall off as frequency increases.

Perhaps most excitingly, synthetic diamond has been of increasing interest to use as a substrate for GaN devices. Diamond has the highest thermal conductivity of all materials known to man, and early indications show that GaN-on-Diamond can produce power densities up to 10X that of currently available GaN-on-SiC. To-date, even synthetic diamond manufacturing processes have proven prohibitively expensive, which has kept GaN-on-Diamond from being widely adopted. However, as these processes are improved and gain traction, the tremendous thermal management benefits offered by diamond will supersede its costs, opening up new possibilities in RF/microwave design.

Figure 2. The NuPower Xtender SCISR-20 Tri-Band Bidirectional Amplifier capitalizes on the extreme power density and frequency flexibility offered by GaN to deliver 20 W Psat in L/S-bands and 10 W Psat in C-band. This tremendous capability comes in a small form factor at just 7.25" x 4.50" x 1.375", roughly the size of a typical novel.

LDMOS vs GaAs vs GaN: Which Should I Use and When?

Given the extraordinary benefits provided by GaN technologies, one could easily assume that GaN is the outright replacement for LDMOS and GaAs for all applications. It is, of course, never that simple, and many expect LDMOS and GaAs to continue to be used for many years to come. Table 1 presents an overview of the three technologies. Generally speaking, GaN is a no-brainer decision for applications above 3 GHz requiring output powers of >25 W. Outside of those general conditions, the decision between LDMOS, GaAs, and GaN becomes a more intimate one requiring thoughtful consideration of performance trade-offs and cost. High power applications requiring operation below 3 GHz, such as wireless base stations, often benefit more from using cheaper and fully matured LDMOS technologies. Applications exceeding 30 GHz are also considered within GaAs domain. Consider too that silicon manufacturers are in their 10th generation of silicon wafer fabrication and grow them in 12" to 18" wafers. By contrast, GaN is in its 2nd generation and can only be grown in 4" wafers while the input costs remain comparable. Therefore, low-power applications will likely continue to be best served by cheaper GaAs devices until the cost of GaN is reduced by wider industry adoption in combination with technological advancements.

Table 1. Performance Characteristics Overview of GaN, GaAs, and LDMOS Technologies.

	GaN	GaAs	LDMOS
Frequency	Up to 30 GHz	Up to 250 GHz	Up to 3-4 GHz
Power	10-100s of watts, high power density (5-10 W/mm)	10-20 watts, low power density (1.5 W/mm)	100-1000s of watts, low power density (1-1.5 W/mm)
Cost	High (4-5 $/Watt)	Moderate (1-2 $/watt)	Low (1-2 $/watt)
Bandwidth	Wide	Narrow to Moderate	Narrow (>1 GHz) Wideband (<1 GHz)
Linearity	Poor[1]	Moderate	High

Conclusion

The introduction of GaN-based technologies has been nothing short of transformative for the RF and microwave communications community and its beneficiaries. Ever greater power density and flexibility of operational frequencies, amongst other advantages, have enabled new breakthroughs with implications reaching far beyond a mere amplifier module or front end. Particularly for the airborne world, the rise of GaN has contributed to smaller unmanned airframes with greater range than was previously conceivable. The realm of space exploration has also benefitted greatly, where minimizing size and weight is inherently critical to mission success. While the impact of GaN cannot be ignored, it remains clear that, as in all new technologies, there is a trade-space with pros and cons which must be carefully navigated by the astute engineer. LDMOS and GaAs are not going anywhere anytime soon, and undoubtedly the Element X will one day become the

[1] Oftentimes, linearity is misinterpreted by referencing only the P1dB compression point, which does not accurately depict linear performance of GaN-based devices. The gradual compression curve unique to GaN typically results in lower P1dB values, even though true performance may meet an engineer's criterion for a given application. Linearity is better defined as operating at a point on the transfer curve where an important parameter is reached for the intended application. For example, it is not uncommon to see acceptable EVM measurements in a GaN device with a very low P1dB value.

GaN of tomorrow. However, we live in the present, and today, the manufacturers of GaN have their sights set on a very bright future. As the technology matures, processes are refined, and wider adoption drives down cost, it can be expected that GaN will become nearly as ubiquitous as the electromagnetic waves which radiate from it.

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