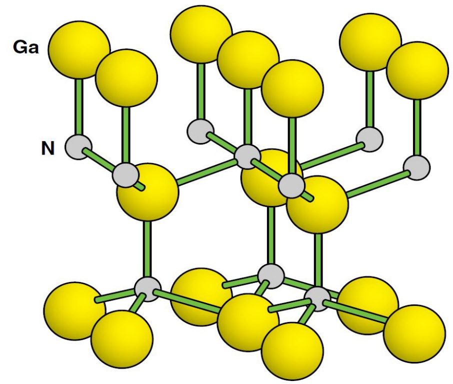



OPTELEX - Optical and RF Engineering

# Going towards gallium nitride

The reasons to start the natural migration between Silicon and GaN technologies

*Carlo Mozetic - june 2021*

# No more improvements for Si devices

- The rate of improvements in silicon devices has leveled off, as their performance is now close to the theoretical limit as determined by the underlying fundamental physics of these materials and processes. This means they will have no more improvements in key parameters such as Rds(on) resistance, voltage ratings, switching speed, packaging, efficiency and other attributes.
- GaN is a high electron mobility transistor (HEMT) with a higher critical electric field strength than silicon. High electron mobility means that GaN has a higher electric-field strength than silicon dies, and also means that a GaN device will have a smaller size for a given on-resistance and higher breakdown voltage than a silicon semiconductor. GaN also offers extremely fast switching speed and excellent reverse-recovery performance (critical for low-loss), therefore intrinsically it has high-efficiency performance. GaN transistors with 600/650V ratings are now widely available and are a good fit for a very large proportion of applications. That’s why power devices based on gallium nitride today are very attractive.

# Materials properties and comparison

**Table 1** Material properties of Silicon, GaN, and SiC

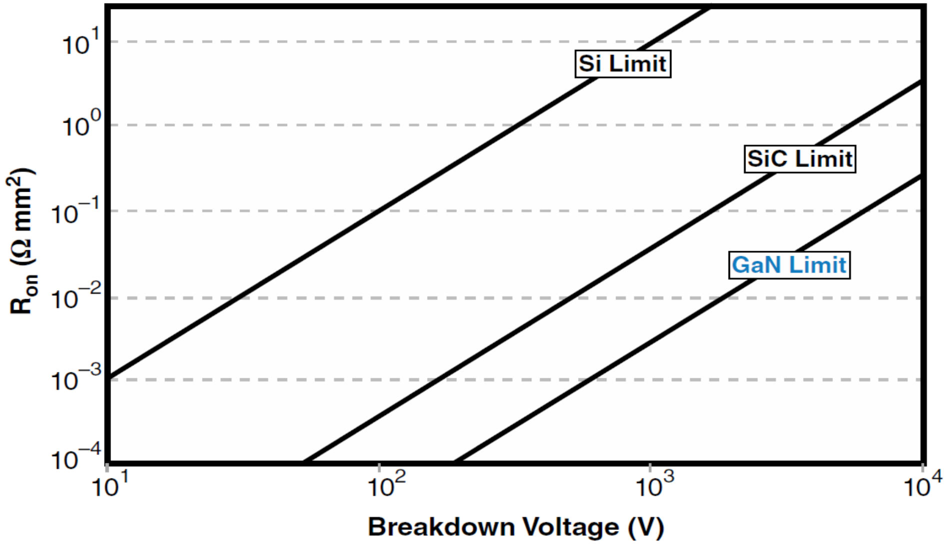
| Parameter | | Silicon | GaN | SiC |
|---|---|---|---|---|
| Band Gap $E_g$ | eV | 1.12 | 3.39 | 3.26 |
| Critical Field $E_{Crit}$ | MV/cm | 0.23 | 3.3 | 2.2 |
| Electron Mobility $\mu_n$ | $cm^2/V{\cdot}s$ | 1400 | 1500 | 950 |
| Permittivity $\varepsilon_r$ | | 11.8 | 9 | 9.7 |
| Thermal Conductivity $\lambda$ | $W/cm{\cdot}K$ | 1.5 | 1.3 | 3.8 |

The band gap of a semiconductor is related to the strength of the chemical bonds between the atoms in the lattice. These stronger bonds mean that it is harder for an electron to jump from one site to the next. Among the many consequences are lower intrinsic leakage currents and higher operating temperatures for higher band gap semiconductors. Based on the data in Table 1 GaN and SiC both have higher band gaps than silicon.



OPTELEX
Optical and RF Engineering

# Materials properties and comparison




The natural structure of crystalline gallium nitride is a hexagonal structure named "wurtzite" (see slide 1). Because this structure is very chemically stable, it is mechanically robust and can withstand high temperatures without decomposition. This crystal structure also gives GaN piezoelectric properties that lead to its ability to achieve very high conductivity compared with other semiconductor materials.

# Types of GaN devices

**There are two broad types of GaN devices:**

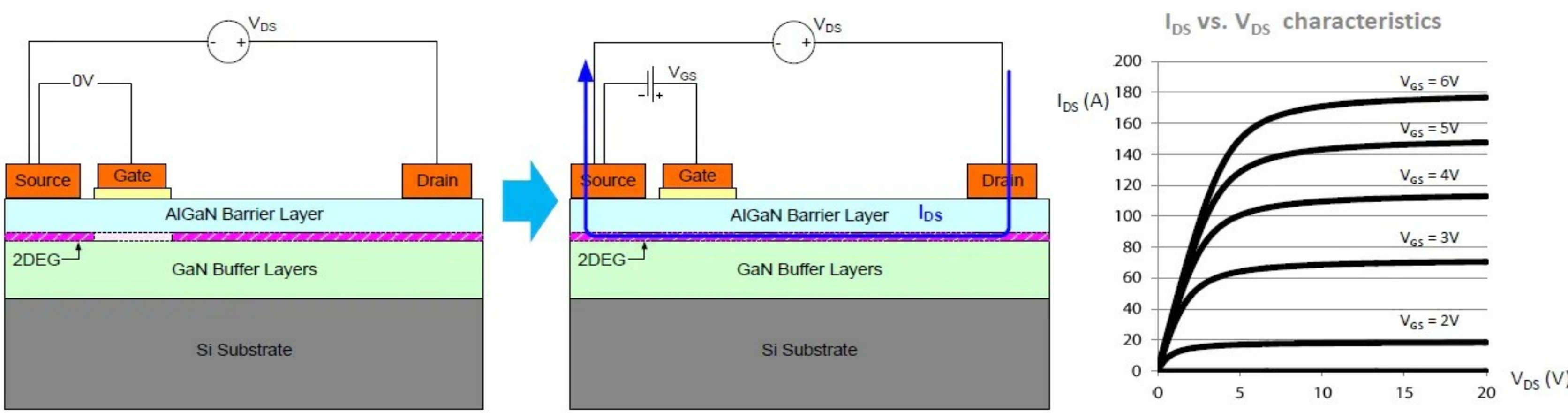
- **Those operating in <u>depletion mode</u>:** The depletion-mode GaN transistor is normally on; to turn it off, a negative voltage relative to the drain and source electrodes is needed (most of this type will replace LDMOS).
- **Those operating in <u>enhancement mode</u> (called e-mode):** The enhancement-mode transistor is the opposite, as it is normally off and is turned on by positive voltage applied to the gate (most of this type will replace MOSFETs).

The difference is more than just a matter of their complementary operating modes.

For the depletion-mode device, there are start-up issues to contend with when power is applied (the "sequencer" circuit); a negative bias must first be applied to the power devices to turn it off and so avoid a start-up short circuit.

In contrast, enhancement-mode devices are off and do not conduct current when there is zero bias on the gate, which is the desired start-up state.

# Enhacement mode GaN

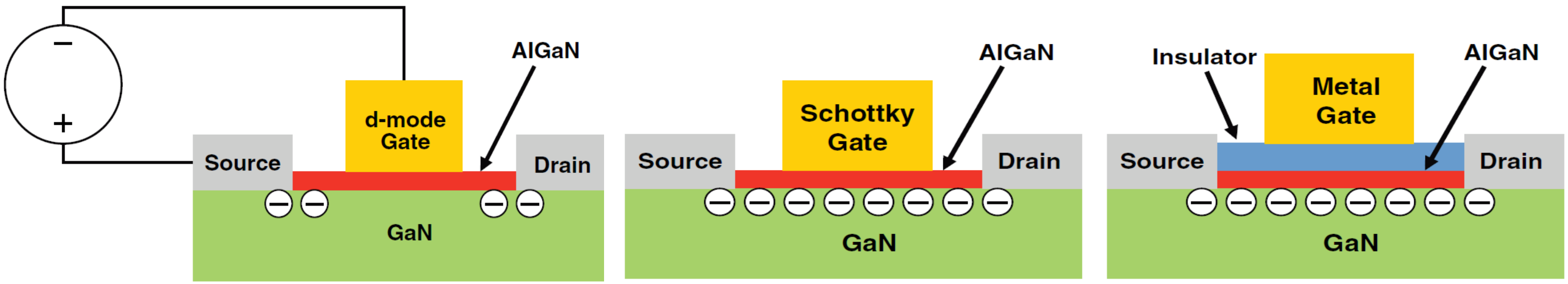



A GaN MOSFET power switch is built on a silicon substrate (Si or SiC), with a lateral two-dimensional electron gas (2DEG) channel formed on a AlGaN/GaN hetero-epitaxy structure that provides very high charge density and mobility; the enhancement-mode GaN device does not conduct when the gate drive is at zero but does conduct when the gate drive exceeds the threshold.



OPTELEX
Optical and RF Engineering

# Depletion mode GaN



(a) (b)

Cross section of a basic depletion-mode GaN HEMT with (a) Schottky gate, or (b) Insulating gate. In power conversion applications, d-mode devices are inconvenient because, at the startup of a power converter, a negative bias must first be applied to the power devices (such as GaAs and InP microwave devices). If this negative bias is not applied first, a short circuit will result between drain and source.

Anyway d-mode Gan HEMT has lower parasitic capacitance (Ggs - Cgs) and therefore has higher frequency limits; for this reason they are recommended for all RF/MW power applications.

# d-mode GaN: bias setup procedure

**To turn on the circuit**:

- Terminate the RF output with a 50 ohm load.
- Connect the RF input to a 50 ohm source with the RF off.
- Connect the gate voltage $-V_{gs}$ and set it at -5 V.
- Connect the drain voltage $+V_{dd}$ and increase it slowly to the nominal value.
- Increase slowly the gate voltage from -5 V to the proper $-V_{gs}$ to obtain the correct $I_{dqa}$.
- Raise the RF input slowly.
- Check the RF output power, the drain current and the temperature of the heat sink.

**To turn off the circuit**:

- Switch off RF input power.
- Decrease slowly gate voltage $-V_{gs}$ to -5 V.
- Decrease the drain voltage $+V_{dd}$ to 0 V and disconnect it.
- Disconnect the gate voltage $-V_{gs}$.



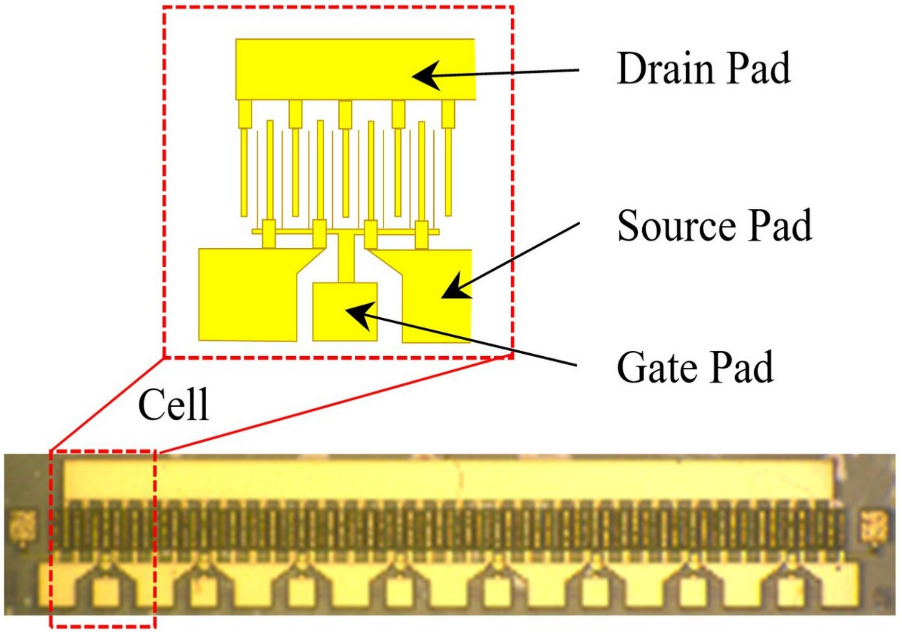
OPTELEX
Optical and RF Engineering

# LDMOS versus GaN

Comparison between LDMOS and GaN technologies.

| | LDMOS | GaN |
|---|---|---|
| Maximum frequency | 10 GHz | 30 GHz |
| Power density | 2 W/mm | 10 W/mm |
| Efficiency at P1dB | 60% | 70% |
| Bandwidth | 500 MHz | 2500 MHz |
| Maximum temperature | Lower | Higher |
| Breakdown voltage | Lower | Higher |
| Maximum operating voltage | Lower | Higher |
| Cgs | Higher | Lower |
| Cds | Higher | Lower |
| Rin | Lower | Higher |
| Rout | Lower | Higher |
| Maximum RF power | 1.5 kW | 1 kW |
| Price | Lower | Higher |
| Robustness against impedance mismatches | Higher (65:1) | Lower (20:1) |

# The main improvement: power density



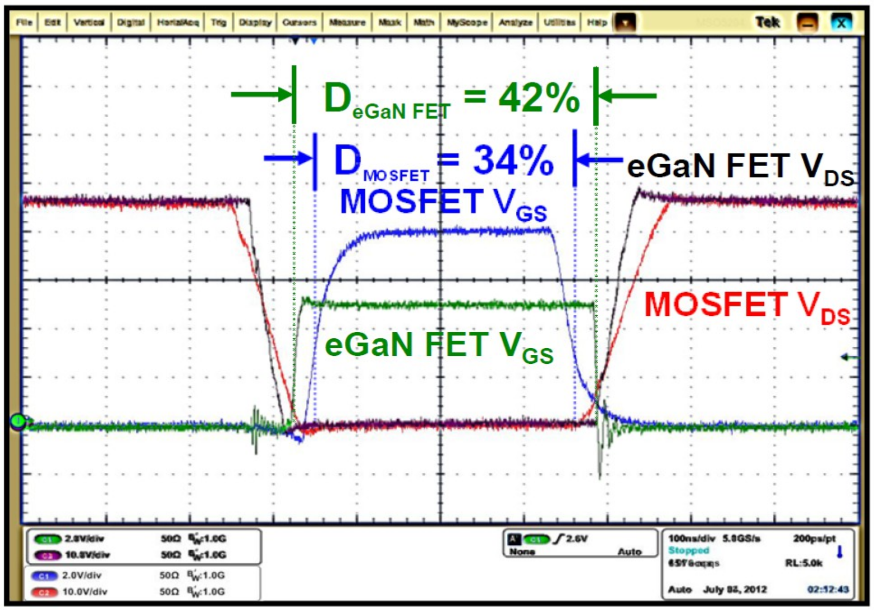

**GaN's primary advantage** over competing technologies is its **high power density**, which can be as much as 5X that of a comparable Si or GaAs device. In layman's terms, **that means five times the output power in an 80% smaller package size**.

# e-GaN are faster than Si-MOSFETs


GaN can switch faster than silicon-based MOSFETs, with dV/dt slew rates in excess of 100V/nsec. Overall GaN turn-on times are about four times faster than MOSFETs with the same $R_{ds(on)}$ rating, while turn-off time is about twice as fast. However, without a proper driver circuit a high-speed dV/dt slew time can affect efficiency adversely by creating a shoot-through condition between paired devices in a bridge during the switching transition.

A representative GaN device is the “GaN Systems GS66516B”, a 650V, enhancement-mode, GaN-on-silicon power transistor that combines high current, high voltage breakdown, and high switching frequency. On resistance is only 25mohm, and maximum drain-source current is 10A, while switching frequency can be as high as 10MHz and even higher.

# Better switching speed and waveform



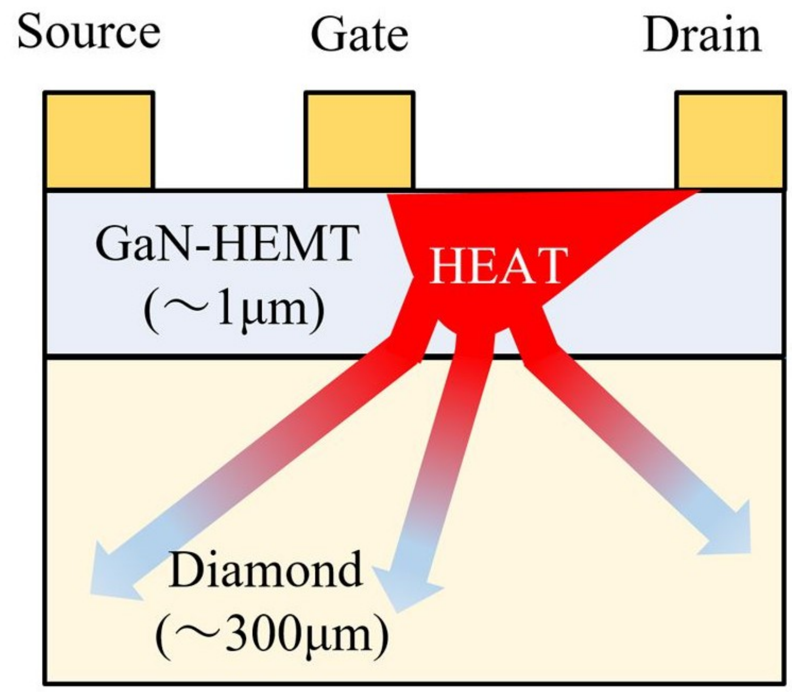

Better switching performances improves class-D audio amplifiers performances:

Low Rds(on) + low Cos + high damping factor = low open loop output impedance (therefore higher efficiency and lower IMD)

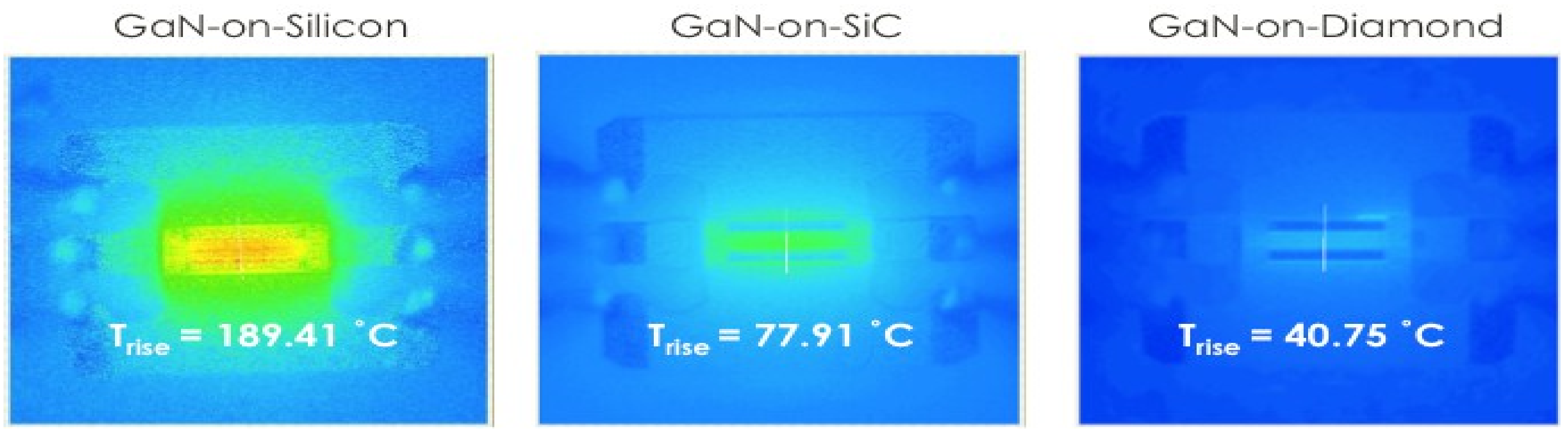
Fast switching + no reverse recovery (Qrr) = lower THD

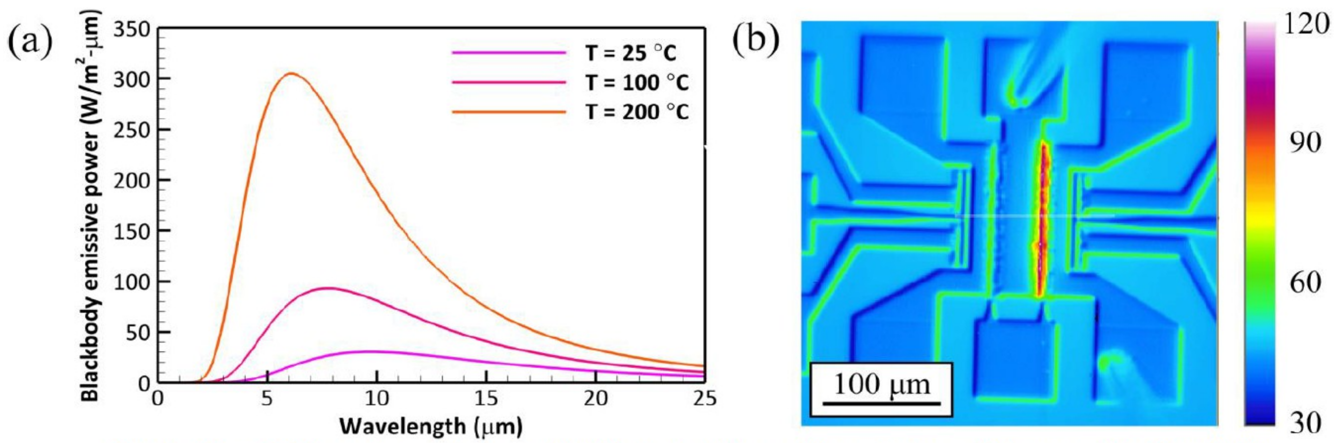
# Heat exchange improvement

Today, most existing GaN-HEMTs are created using a GaN epitaxial layer grown up on a silicon substrate (or preferably SiC). In 2003 Felix Ejeckam invented the idea of lifting GaN thin films from its original growth substrate and transferring it to a synthetic CVD diamond substrate. CVD diamond (Chemical Vapor Deposition) exhibits the highest thermal conductivity known to humans. Early indications show that GaN-on-Diamond can produce power densities up to 10X that of currently available GaN-on-Si and GaN-on-SiC



# Heat exchange improvement



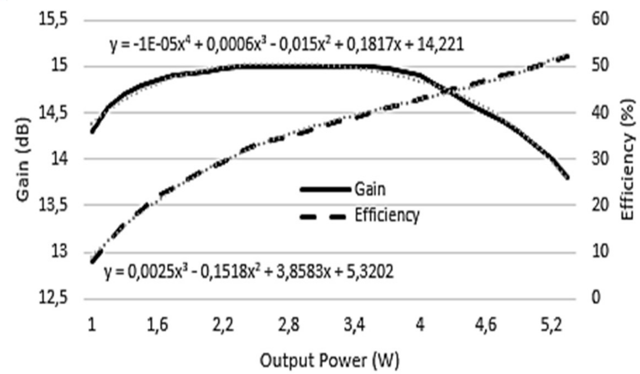

**(a) Blackbody infrared spectrum and (b) Sample infrared temperature (°C) map of GaN HEMT**

# GaN amplifiers are easier to linearize

The following power amplifiers were considered:

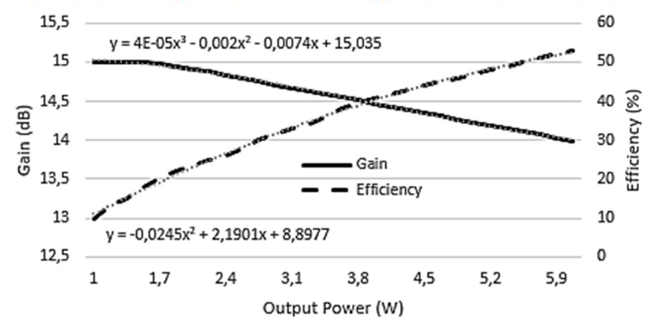
PD57006S-E: an LDMOS amplifier manufactured by ST Microelectronics, with the following characteristics:

- Output power: 5 W
- Power supply: 28 V
- Gain: 14.8 dB
- Efficiency: 50%




NPTB00004A: a GaN amplifier manufactured by MACOM, with the following characteristics:

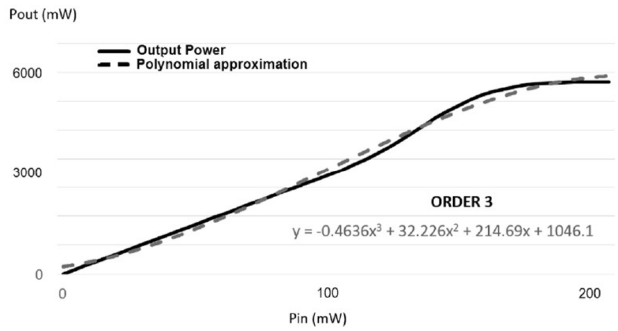
- Output power: 6 W
- Power supply: 28 V
- Gain: 15 dB
- Efficiency: 62%

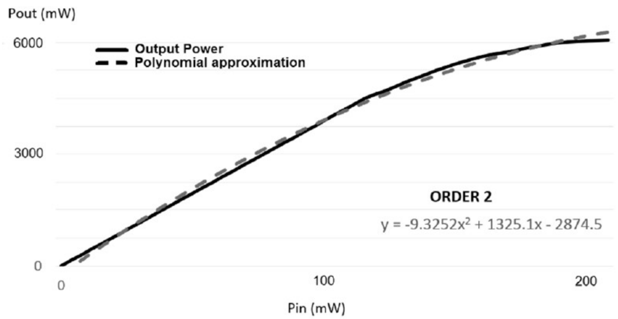


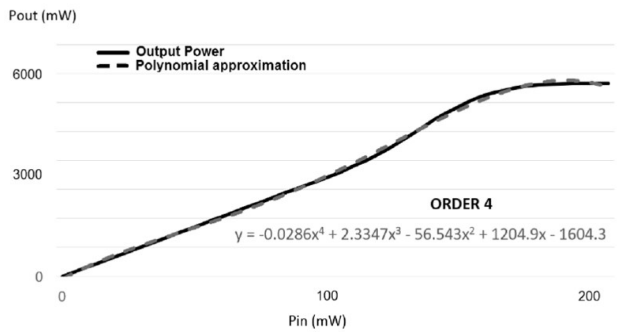

OPTELEX
Optical and RF Engineering

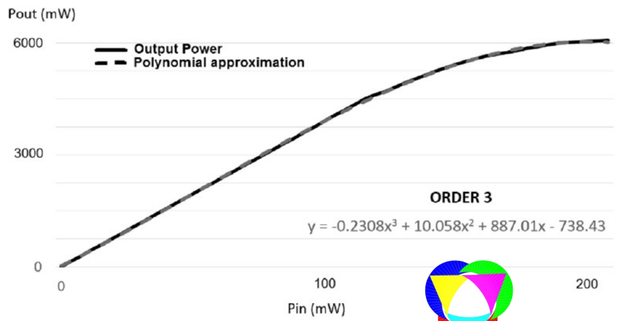
# GaN amplifiers are easier to linearize

| LDMOS (PD57006S-E) | GaN (NPTB00004A) |
|---|---|
| $Gain = -0.00001P_{out}^4 + 0.0006P_{out}^3 - 0.015P_{out}^2 + 0.1817P_{out} + 14.221$ <br> $Efficiency = 0.0025P_{out}^3 - 0.1518P_{out}^2 + 3.8583P_{out} + 5.3202$ | $Gain = 0.00004P_{out}^3 - 0.002P_{out}^2 - 0.0074P_{out} + 15.035$ <br> $Efficiency = -0.0245P_{out}^2 + 2.1901P_{out} + 8.8977$ |



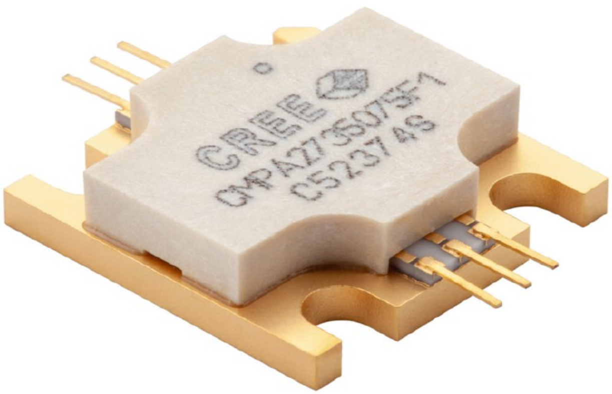



# Broadband internal matching at 50ohm

The higher impedance of gallium nitride (GaN) high electron mobility transistor (HEMT) devices allow the broadband internal matching capability.

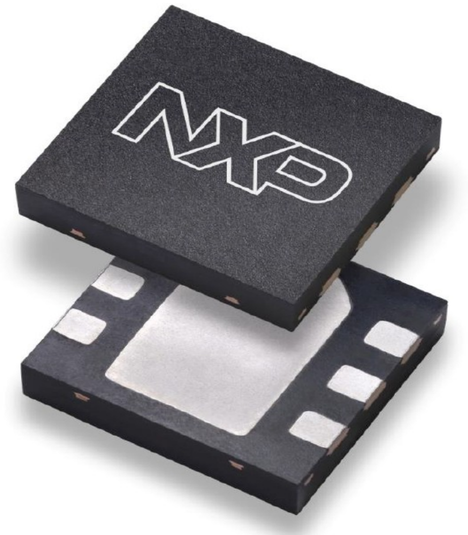
For instance CGHV31500F (650Wpw) and CMPA2735075F1 (76Wpw) are GaN-HEMT internally matched at 50 ohm designed specifically with high efficiency, high gain and wide bandwidth capabilities, which makes both ideal for S-Band radar power amplifiers.

GaN has superior properties compared to silicon or gallium arsenide FETs, including higher breakdown voltage, higher saturated electron drift velocity and higher thermal conductivity.

# More power into smaller packages

The MHT1008N is a single 12.5Wcw RF power LDMOS designed for consumer, medical and commercial cooking applications operating only within the 2450 MHz ISM band.




The A3G26D055N is a dual 27.5Wcw power GaN-HEMT designed mainly for symmetrical doherty applications like 5G/8W cellular base stations requiring very wide instantaneous bandwidth capability (PAR ≥ 8dB @2600MHz).

The A3G26D055N can cover a wide frequency range, from 100MHz to 2690 MHz.

# More efficiency and more ruggedness

The MRF24300N was a 32V 300Wcw single LDMOS designed for industrial, scientific, medical (ISM) applications at 2450 MHz. At max power it had an efficiency of 60.5% and it can tolerate 5:1 of VSWR at all phase angles.



The new MRF24G300HS is a 50V GaN-HEMT with more or less similar characteristics but it has an efficiency of 73% at the same frequency and it can tolerate 20:1 of VSWR at all phase angles. Internally there are two sections so this device can be used in a single-ended or push-pull configuration.

# Summarizing (1)

| Technology | GaN | LDMOS |
| --- | --- | --- |
| Full form | Gallium Nitride | Laterally Diffused MOSFET |
| Applications | • GaN on SiC (50V) provides high efficiency, power density and higher gain in smaller package<br>• Used for broadband applications due to higher output impedance and lower Cds capacitance<br>• Advantages: GaN transistors have small parasitic capacitance and hence they have easy wideband matching compare to LDMOS transistors of identical power level. | • LDMOS is used for cellular and broadcast narrowband applications due to high power and efficiency<br>• LDMOS(50V) is used for <1.5 GHz applications while LDMOS (28V) is used for frequencies up to 4 GHz<br>• Disadvantages: LDMOS transistor has large Cgs/Cds capacitance due to large peripheral in its design. This will limit the bandwidth. |

# Summarizing (2)

| Technology | GaN | LDMOS |
|---|---|---|
| Fmax | 30 GHz for GaN (50V) | 15 GHz for LDMOS (28V)<br>10 GHz for LDMOS (50V) |
| Power Density (W/mm) | 5-10 for GaN (50V) | 0.8 for LDMOS (28V)<br>2 for LDMOS (50V) |
| Efficiency at P1dB (%) | 70 for GaN (50V) | 60 for LDMOS (28V)<br><55 for LDMOS (50V) |
| Bandwidth (MHz) | 500-2500 for GaN (50V) | 100-400 for LDMOS (28V)<br>100-500 for LDMOS (50V) |
| $C_{ds}$ (pF/ W) output cap. | 1/4 smaller for GaN (50V) | 0.23 for LDMOS (28V)<br>1/2 smaller for LDMOS (50V) |
| $C_{gs}$ (pF/ W) input cap. | 1/2 smaller for GaN (50V) | 0.94 for LDMOS (28V)<br>1/2 smaller for LDMOS (50V) |

# Summarizing (3)

GaN is a relatively new technology compared to other semiconductors, 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 – making it ideal for Sub-6 5G base stations. Its high output power, linearity, and power-efficiency have driven network OEMs to switch from using LDMOS technology for PAs to gallium nitride. LDMOS technology still holds the greatest market share in RF base stations today, but GaN is expected to continue to displace it in 5G Massive MIMO deployments.

The primary advantage of GaN is its higher power density. This is due to a band gap between the conduction and valence bands that is higher than in LDMOS technologies, which provides both high breakdown voltages and power densities. It allows a signal to be transmitted with more power that widens the coverage areas of base stations. The high-power density of GaN PAs also enables smaller form factors that require less PCB space. In a given area systems designers can produce more power than with another technology. Or, for a given power level systems designers can shrink the size of the RFFE and reduce costs.



OPTELEX
Optical and RF Engineering

# Summarizing (4)

This higher power density also allows for GaN power amplifiers to operate at temperatures as high as 120 degrees Celsius – a level silicon-based technologies can’t reach. GaN’s improved thermal dissipation simplifies heat-sink and cooling requirements of systems, further reducing size and cost. GaN’s increased power efficiency also contributes to reducing the expense of running base stations. In a Doherty PA configurations, GaN attains average efficiencies up to 60% with 100-W output power, significantly reducing the energy required to run power-thirsty Massive MIMO systems.

Because of GaN’s wide adoption in base stations, along with broadening applications in other industries like medical, defense and aerospace, the volume of GaN being produced grows year over year. More volume equals greater economies of scale, making GaN a more affordable solution. That is without taking into account the savings achieved from increased energy efficiency, smaller form factors, or multi-band applications. Linearity is also set to improve.



OPTELEX
Optical and RF Engineering

# Summarizing (5)

That's not to say that GaN is always the right choice for every RF power application. LDMOS is often available at a lower price and delivers very competitive linearity at certain frequencies. It's important to remember that at the moment GaN is only on its second generation, mature technologies like LDMOS are on generation 15. GaAs also has its own efficiency advantages in certain market niches. However there's a reason that many major players in LDMOS shifting to GaN production: they recognize how critical GaN is to helping carriers and base-station OEMs achieve their goals for Sub-6 GHz Massive MIMO. Carriers won't need multiple narrowband radios, they'll just need one wideband radio platform that serves multiple bands. GaN offers the range and flexibility to make these systems possible, while also easily scaling to deliver the high frequencies of mmWave transmissions of the future.

**THANKS FOR WATCHING!**