Innoscience
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POWER THE FUTURE

AN007

Application Note

Introduction of InnoGaN Characteristics

Content

1 Characteristics GaN HEMT Device

1.1 Overview

After decades of development, silicon-based semiconductors power devices have gradually approached their metirial limits in performance. Power devices with the 3rd-generation semiconductor metirial, such as silicon carbide (SiC) and gallium nitride (GaN)— are considered to have the potential of further reduce the cost and improve the efficiency. GaN HEMT (Gallium Nitride High Electron Mobility Transistor) is widely favored in applications below 650V, for effectively increasing the switching frequency, reducing the losses, and improve the power density.

2 Material Characteristics of GaN

GaN is one of the wide bandgap (WBG) semiconductor meterial. Compared to Si, it features a wider bandgap, higher breakdown electrical field, higher electron mobility, and higher electron saturation drift speed. Wider bandgap means that electrons in the semiconductor need more energy to transition from the valence band (non-conductive) to the conduction band (conductive), therefore increasing the breakdown electrical field and temperature stability. GaN's breakdown electrical field is 10 times that of Si. Its electron mobility is approximately 1.5 times that of Si, which effectively reducing the specific on-resistance (Ron,sp). In other words, GaN device have smaller die sizes for the same on-resistance (Rdson), which helps reduce the cost and the parasitic parameters of the devices. Electron saturation drift speed represents the maximum overall drift speed of electrons as the electric field increases, which has a significant impact on the switching frequency of the devices. GaN's electron saturation drift speed is 2.5 times that of Si, which can significantly improve the device's switching frequency.

Table 1 Comparison of Material Characteristics of GaN vs Si

特性	Si	GaN
Bandgap Width Eg（eV）	1.12	3.44
Critical Field Ec（MV/CM）	0.3	3.8
Electron Mobility μ_n（cm^2/V-s）	1350	2000
Electron Saturation Drift Speed V_{sat} （10^7cm/s）	1.0	2.5
Thermal Conductivity λ（W/cm-K）	1.5	1.3

3 Device Structure of GaN HEMT

The commercial GaN HEMTs are mainly in lateral structures. All the layers are distributed from bottom to top in the sequence of the substrate, buffer layer, GaN epitaxial layer, and AlGaN barrier layer. A polarization effect occurs at the interface between the AlGaN barrier layer and the GaN epitaxial layer, forming a layer full of electrons iand known as two-dimensional electron gas (2DEG). The 2DEG performs as a natural conductive channel, which enables the GaN HEMT to remain normally on and forms it a depletion-mode (D-Mode) device.

When using D-Mode devices in power electronic converters, negative voltage is necessary between G and S to turn off the device. This increases the complexity of the driving circuit and leads to high risk of short through. Therefore, enhancement-mode (E-Mode) devices, which are normally off, are much more faverd in power converter designs.

InnoGaN devices are discrete E-Mode GaN HEMTs that requires positive Vgs voltage for gate driving. InnoGaN places a pGaN layer beneath the gate of the GaN HEMT. The pGaN layer creates a depletion region in the GaN epitaxial layer beneath the gate to deplete the 2DEG. As the Vgs voltage increases, the 2DEG beneath the gate gradually recovers and then allow for larger current Ids to flow through the channel. The threshold voltage Vth is defined as the Vgs voltage at which Ids capability reaches a specified value.

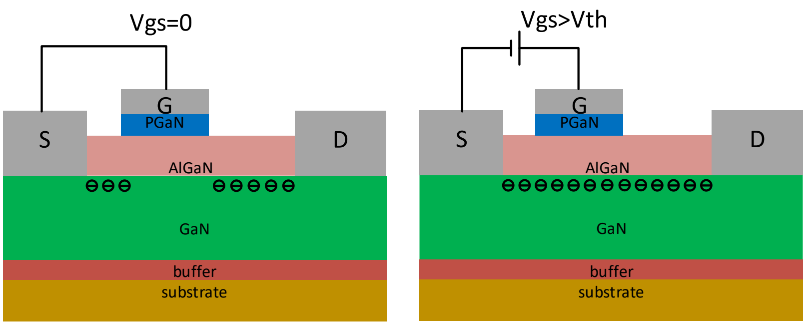


Figure 1 Device Structure of E-Mode GaN HEMT

4 Electrical Characteristics of InnoGaN HEMT

The differences in material properties and device structures between InnoGaN and Si MOSFETs result in differences in their electrical characteristics, which can be summarized as follows.

Table 2 Comparison of parameters of InnoGaN and Si MOSFET.

Parameters	INN650D080BS	Si MOSFET
Vds(V)	650	650
Ron@25℃(mΩ)	60	66
Vgs(V)	-6/+7	-20/+20
Vth(V)	1.2	3.5
Ciss(pF)	240	2721
Co(tr)(pF)	179	990
Qg(nC)	6	67
Qrr(nC)	0	570
Vsd(V)	2.6	1

4.1 Breakdown Voltage Characteristics

GaN HEMTs do not have avalanche breakdown characteristics as that the Si MOSFETs have. However, InnoGaN devices retain sufficient voltage margin for different overvoltage conditions with the superior characteristic of the high breakdown field.

In practical switch-mode power supplies, devices will experience periodic voltage spikes. InnoGaN specifies the device's ability to withstand periodic voltage in terms of $V_{DS,pulse}$. For example, $V_{DS,pulse}$ refers to the ability to withstand repeatitive pulse voltages with a width < 100ns and a peak voltage of 750V for 650V InnoGaN products.

Additionally, transient events such as lightning strikes, surges, or load transients may also cause overvoltage on the devices. InnoGaN specifies the ability to withstand transient overvoltage in terms of $V_{DS,transient}$. For a 650V device, An 800V $V_{DS,transient}$ indicates the device can withstand a single surge voltage with a width < 200us and a peak voltage of 800V. Practical test results showns that high-voltage InnoGaN devices can survive the single pulse withstand voltage of up to 1500V.

Parameter	Symbol	Values	Unit	Note/Test Condition
Drain source voltage	$V_{DS,\ max}$	650	V	V_{GS} = 0 V; T_j = -55 °C to 150 °C
Drain source voltage transient [1]	$V_{DS,\ transient}$	800	V	V_{GS} = 0 V
Drain source voltage, pulsed [2]	$V_{DS,\ pulse}$	750	V	T_j = 25 °C; total time < 10 h
				T_j = 125 °C; total time < 1 h

1. $V_{DS,\ transient}$ is intended for non-repetitive events, t_{PULSE} < 200 μs.

2. $V_{DS,\ pulse}$ is intended for repetitive pulse, t_{PULSE} < 100 ns.

Figure 2 InnoGaN Datasheet

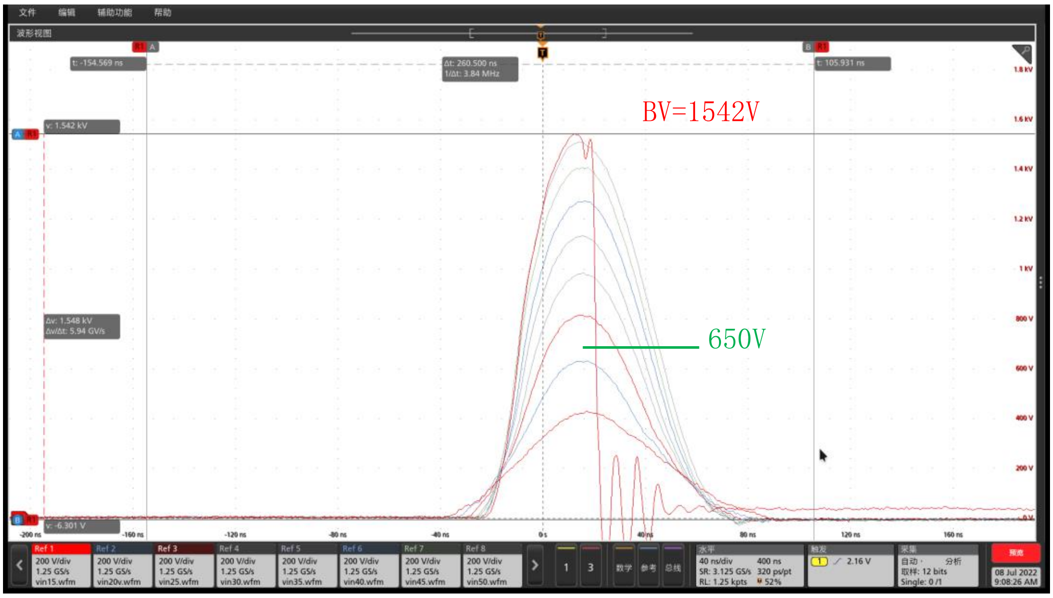


Figure 3 Measured Breakdown Voltage Waveforms of High-Voltage InnoGaN

4.2 Switching Speed

The switching speed is dominant by Ciss (Ciss = Cgs + Cgd). The Vgs slew rate and the switching speed is lower with of larger Ciss InnoGaN exhibits a Ciss that is less than 1/10 that of Si MOSFETs as presented in Table 2. Lower capacitance benefit to improve switching speed, reduce losses, and enable higher frequency. As can be observed from the measured results that InnoGaN shows remarkably faster turn-on speed, which could effectively reducing the overlap time between Vds and Id and thus lowering the switching losses. High-frequency operation of the devices can effectively reduce the size of inductors, transformers, and capacitors in power supplies leading to a significant improvement in power density.

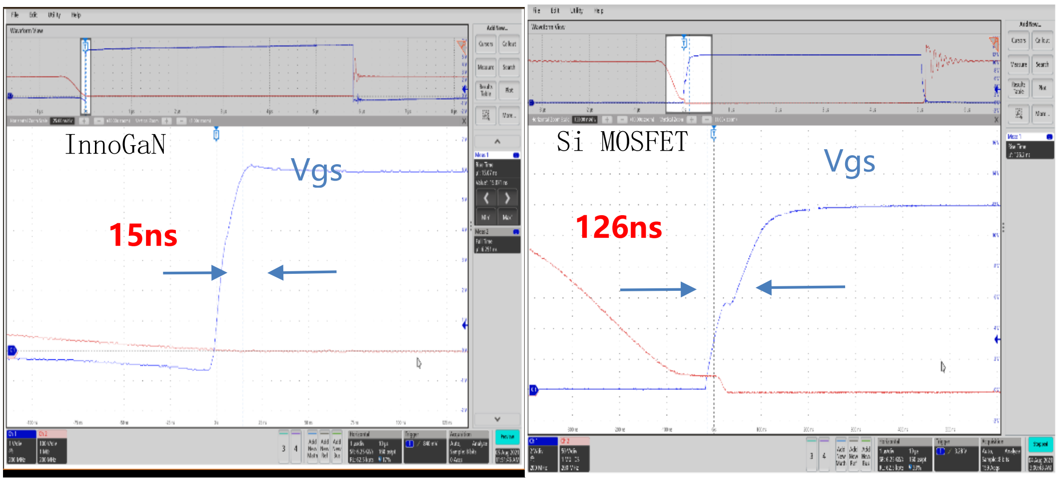
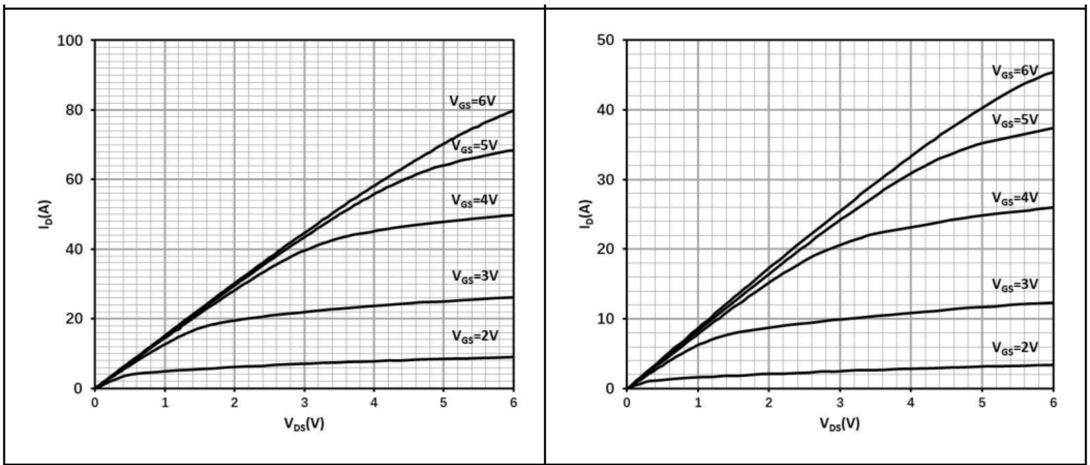


Figure 4 Comparison of Turn-On Speed between InnoGaN and Si MOSFET

4.3 Gate Driving Characteristics

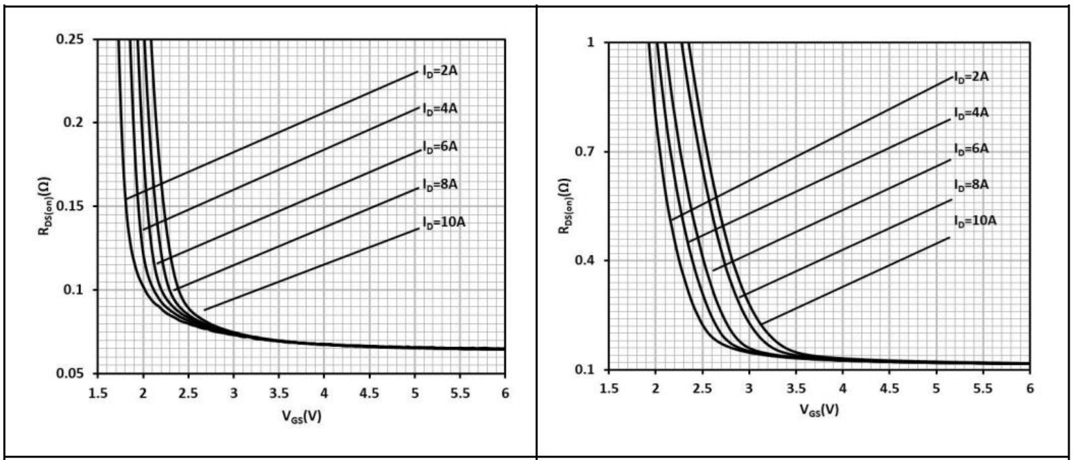
The gate driving voltage levels of InnoGaN HEMT differ from those of Si MOSFETs. The safety range of Vgs voltage is specified in the datasheets. Additionally, Vgs voltage determines the channel current capability of the devices. As can be seen from the output characteristic curves, the channel is more enhanced with higher Vgs voltage, thus leading to high current-capability of the device.



$I_D = f(V_{DS}, V_{GS})$; T_j = 25 °C	$I_D = f(V_{DS}, V_{GS})$; T_j = 125 °C

Figure 5 InnoGaN Output Characteristic Curves

The on-resistance Rdson is influenced by both Ids and Vgs. When Vgs voltage is near the threshold and not high enough, the channel of the device is not fully enhanced, resulting in significant differences in Rdson at different Ids. For 650V InnoGaN devices, the channel is fully-enhanced when Vgs voltage is above 5.5V, Rdson decreases to the minimum level and tends to be consistent at different Ids. It is recommanded to increase the of Vgs high level voltage within a safe range to achieve expected current capability and minimize Rdson. For examples, a Vgs high-level voltage range of 5.7V~6.3V is recommended for 650V InnoGaN devices, while 4.7V~5.3V is recommended for InnoGaN devices below 150V.



$R_{DS(on)} = f(I_D, V_{GS})$; $T_j = 25$ °C	$R_{DS(on)} = f(I_D, V_{GS})$; $T_j = 125$ °C

Figure 6 InnoGaN On-Resistance Curve

4.4 Reverse Conduction Characteristics

Si MOSFET depends on the inbuilt body diode for reverse conduction. During the transition from forward conduction to reverse blocking, a reverse current flows through the diode to discharge the parasitic Cds, known as reverse recovery of the diode. This introduces additional losses and noise, and adverse to the efficiency improvement and EMI design. GaN HEMT, on the other hand, does not have body diodes and achieves reverse conduction capability through the 2DEG channel, thereby avoiding the reverse recovery issues.

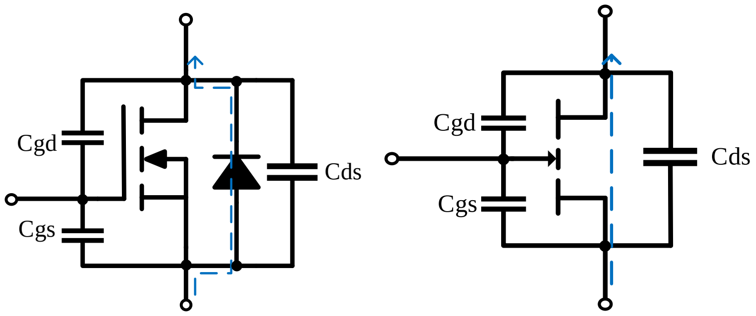


Figure 7 Comparison of Reverse Conduction Paths between Si MOSFET and GaN HEMT

For GaN HEMT, the 2DEG reforms when Vgs>Vth, and the device is turned-on in forward direction. As the structure between the source (S) and drain (D) is basically symmetric inside the device, 2DEG could also reform when Vgd is greater than the threshold voltage at the gate (G) and drain (D) terminals. The threshold voltage between the G and D terminals is referred as Vth_{gd}, where $Vth_{gd} \approx Vth$.

When Vgs=0 and the device is turned off, external current discharges Cds and then flows from Drain to Source, establishing reverse voltage Vsd. When $Vsd=Vgd>Vth_{gd}$, the device conducts reversely with a voltage drop of $Vsd=Vth_{gd}+Id*Rdson$. If the device is turn off with negative voltage (Vgs<0), then Vgd=Vgs+Vsd. Similarly, the device conducts reversely when $Vgd>Vth_{gd}$ with a voltage drop of $Vsd=-Vgs+Vth_{gd}+Id*Rdson$.

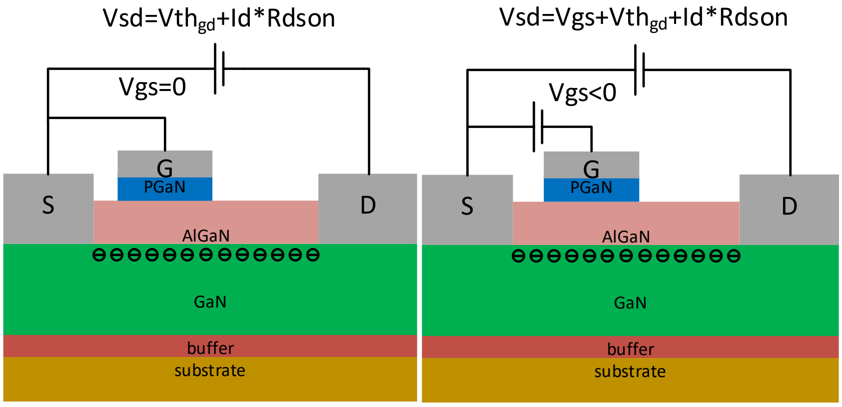


Figure 8 Reverse conduction of InnoGaN

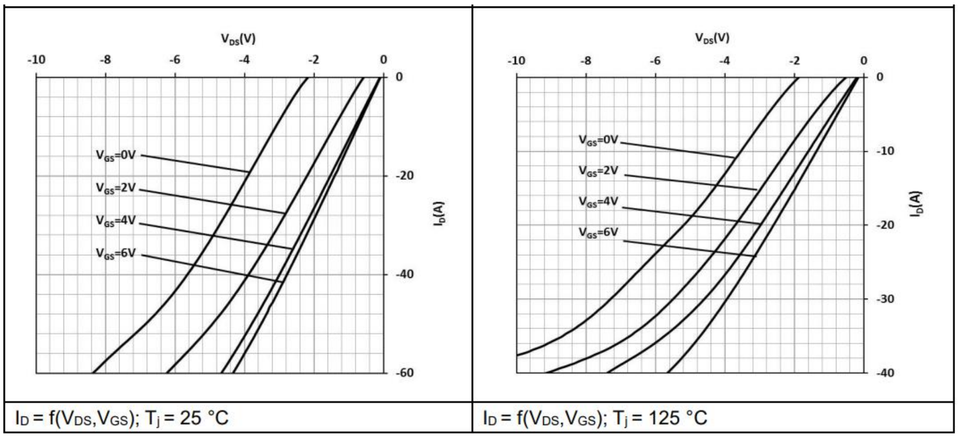


Figure 9 InnoGaN reverse conduction characteristics

During reverse conduction time of GaN HEMT, losses need to be addressed from both perspectives of the reverse conduction voltage drop and dead-time. On one hand, the reverse voltage drop Vsd of GaN HEMT is higher than that of Si MOSFETs. On the other hand, the output capacitance Co(tr) of GaN HEMT is only 1/5 that of Si MOSFET, which significantly shortens the dead-time. In a LLC design example, the dead-time of the InnoGaN solution is only 1/4 that of Si MOSFET, resulting in an overall efficiency improvement of 0.25-0.75%.

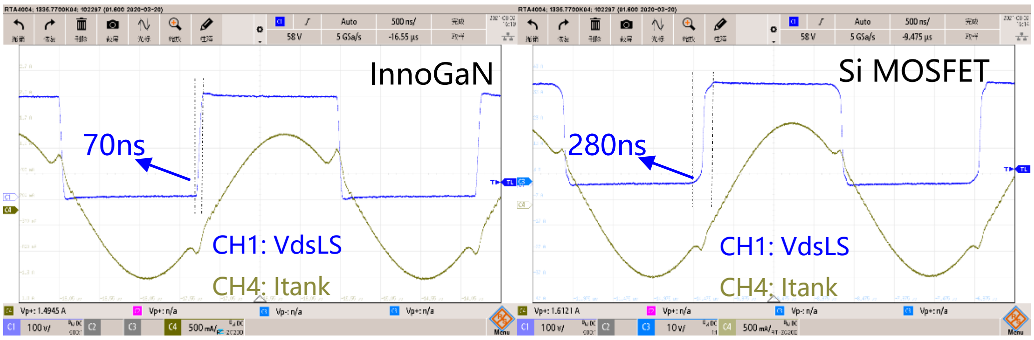


Figure 10 Comparison of LLC Circuit Waveforms

Revision History

Date	Version	Description	作者
2023/11/23	1.0	English translation	AE team

Note:
There is a dangerous voltage on the demo board, and exposure to high voltage may lead to safety problems such as injury or death.
Proper operating and safety procedures must be adhered to and used only for laboratory evaluation demonstrations and not directly to end-user equipment.

Reminder:
This product contains parts that are susceptible to electrostatic discharge (ESD). When using this product, be sure to follow antistatic procedures.