Gallium Nitride High-Electron-Mobility Transistor

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In recent years, GaN-based devices have been widely used in a variety of application fields. GaN-based high-electron-mobility transistors (HEMTs) are superior to conventional silicon (Si) based devices in terms of switching frequency, power rating, thermal capability and efficiency, which are crucial factors to enhance the performances of advanced power converters. This paper addresses some fundamental issues concerning intrinsic features of GaN material and key technology in practical application of GaN-based power switching devices.

Keywords: gallium nitride (GaN) ; silicon carbide (SiC) ; Power converter

1. Introduction

In recent years, Gallium nitride (GaN) has become a popular semiconductor material widely used in the fabrication of advanced electronic and power switching devices. Compared with conventional silicon (Si) material, GaN has a number of intrinsic merits, e.g. wide bandgap, high critical breakdown electric field, high thermal conductivity, and high electronic saturation velocity. GaN-based power switching devices benefit from the two-dimensional electron gas (2DEG) can offer small on-resistances, high current capabilities, and power densities[1]. In the past five years, commonly used GaN-based power switching devices include enhancement mode (E-mode) GaN high electron mobility transistors (HEMTs), cascode GaN HEMTs, and lateral GaN MOSFETs. Unlike using depletion-mode (D-mode) GaN HEMTs, which are normally on, the potential danger of short circuit can be greatly decreased using the normally off devices. It is worth mentioning that a cascode GaN HEMT constructed by a high-voltage D-mode GaN HEMT and a high-speed, low-voltage, and normally-off Si MOSFET allows the on-state losses and switching losses to be significantly reduced while retaining the desired normally-off characteristic. Compared with GaN HEMTs, lateral GaN MOSFETs are less susceptible to hot electron injection and current collapse, and have higher cut-off voltages, making them an even more promising choice for high-voltage applications. However, lower channel mobility due to the absence of 2DEG is an obvious drawback [1][2]. Driving design is a challenging task in using GaN HEMTs, single channel techniques are normally used in high-switching-frequency design cases because this method offers higher reliability than that of simultaneously driving both high-side and low-side GaN HEMTs using a dual-channel driving technique. The driving of a cascode GaN HEMT is relatively easy since it is similar to driving a Si-MOSFET. On the other hand, driving an E-mode GaN HEMT has to consider some complex factors because of E-mode GaN HEMT’s high voltage and current slew rates, low threshold voltage, and low allowable gate voltages. The high switching speed also makes parasitic issues become severe, and thus the layout requires special considerations. The constraints related to low driving voltage can be handled with a separate turn-on and turn-off driving path design. To avoid voltage overshoot due to high slew rate, voltage clamp is commonly used. To mitigate parasitic induced issues, it is recommended to use a Kelvin connection and an optimized circuit board layout so that the overlapping between power loop and driving loop is minimized. To ensure successful turn-off operations, negative driving voltage can be used, but this may increase reverse conduction loss and requires extra power supply units. Voltage clamp is a good alternative [3][4][5].

2. Key Application Issues

Semiconductor devices are very commonly used in a variety of power conversion systems. Enhancing the power conversion efficiency means improving the overall energy utilization rate. Because Si-based power switches have low linearity in output capacitance, high output charge, high reverse recovery charge, and high gate charge, they are not expected to be used in designing advanced power converters meeting the required high system efficiencies and power densities [6]. WBG materials such as GaN and SiC offer substantial advantages over Si for power semiconductor applications, as shown in Figure 1.

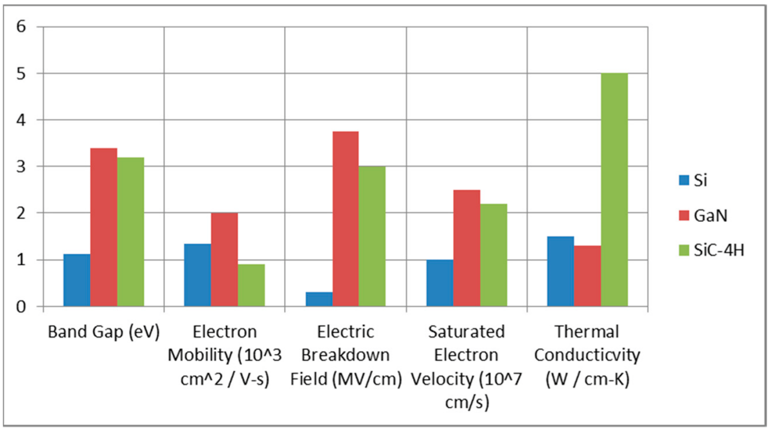

Figure 1. Comparison of Si, gallium nitride (GaN), and silicon carbide (SiC) for power semiconductor applications.

As can be seen in Figure 1, SiC offers superior thermal conductivity, while GaN has the highest bandgap and electron mobility. Over the past few years, WBG material-based switching devices were intensively researched to achieve their full potential. These devices, with proper design, not only benefit existing power conversion systems but also provide new possibilities in improving some of the existing power electronic systems. SiC-based devices outperform Si-based devices tremendously in high-power (over 600 V) applications and are currently considered the most suitable devices for efficient power conversion at the abovementioned voltage level. However, quality material for SiC-based devices is quite limited and, thus, increasingly costly. As a result, GaN-based devices are considered potential alternatives to SiC-based devices in applications of low- to medium-level voltage. Commercially available GaN-based power switching devices offer an operating voltage ranging from 100 V to 1200 V, high switching frequency and operation temperature capabilities, and reduced switching losses. However, the very low threshold voltage (V_{GS_th}) in normally off GaN devices is a technical problem in practical applications. Moreover, SiC-based devices still dominate applications with voltage levels over 1000 V [7][8].

GaN HEMTs are naturally on because of the two-dimensional electron gas (2DEG) that allows high current. Normally on GaN HEMTs, also known as depletion mode (D-mode) GaN HEMTs, can be turned off by applying negative V_{GS_th}. Technical reports verify that various methods can be used to deplete the 2DEG path of a D-mode GaN HEMT and to realize the desired normally off switching characteristics. Commercially available normally off GaN HEMTs are divided into two types: enhancement mode (E-mode) and cascode configuration. E-mode GaN HEMT can be turned on by applying positive V_{GS_th}. Generally, the sum of external resistance and driver output resistance should be designed as much larger than the internal resistance of an E-mode GaN HEMT in order to reduce the influence of internal resistance on the switching speed and reduce voltage overshoot. In practice, cooling is also crucial for further reducing conduction losses. In the aspect of driving E-mode GaN HEMT, the limit of peak driving voltage, the damping of driving charges, and the input/output propagation delay should be taken into consideration. Also, it is recommended to incorporate a Miller clamp, negative voltage source, and separate paths for turn-on and turn-off processes [9]. Cascode GaN HEMT combines a D-mode GaN HEMT and a normally off high-speed Si metal–oxide–semiconductor field-effect transistor (MOSFET) to realize a normally off characteristic, and it can be turned on by applying positive V_{GS_th} on the Si MOSFET. For switching frequency over 100 kHz, it is recommended to use separate turn-on and turn-off paths, Kelvin source connection, ferrite beads, and minimized turn-off resistance and inductance of the driving loop [10]. Various driving circuits for GaN HEMTs were explored in References[9][10][11][12][13][14][15][16][17][18]. Discussion and designs for GaN HEMT driving circuits were provided in References[19][20][21]. The designs of special undervoltage lockout circuit and low-inductance driving circuits were discussed in References and [23], respectively.

In the aspect of device specifications, current voltage ratings of commercial GaN HEMTs are up to 650 V, as shown in Table 1, where V_{ds} represents drain-source voltage, I_d represents drain-source current, V_{TH} represents threshold voltage, V_{gs} represents gate-source voltage, $R_{ds(on)}$ represents on resistance, and C_{iss} represents input capacitance. Transphorm mainly produces 650-V cascode GaN HEMTs and evaluation boards for various applications based on their own GaN HEMTs. GaN System mainly produces 650-V and 100-V E-mode GaN HEMTs. Various GaN half-bridge evaluation boards are also commercialized for potential researchers. Texas Instruments (TI) and Silicon Labs produce both single-channel and dual-channel gate drivers suitable for GaN HEMTs, as shown in Tables 2 and 3, respectively. TI also produces GaN switching modules that integrate GaN HEMTs with designed drivers as shown in Table 4.

Table 1. Commercial gallium nitride (GaN) high-electron-mobility transistors (HEMTs) by Transphorm and GaN Systems.

Manufacturer	Device	V_{ds} (V)	I_d (A)	V_{TH} (V)	V_{gs} (V)	$R_{ds(on)}$ (mΩ)	C_{iss} (pF)
Transphorm	TPH3206PSB	650	16	2.1	±18	150	720
Transphorm	TPH3208PS	650	20	2.1	±18	130	760
Transphorm	TPH3212PS	650	28	2.6	±18	72	1130
Transphorm	TP65H050WS	650	34	4	±20	60	1000
Transphorm	TPH3205WSBQA	650	35.2	2.1	±18	62	2200
Transphorm	TPH3205WSB	650	36	2.6	±18	63	2200
Transphorm	TP65H035WS	650	46.5	4	±20	35	1500
Transphorm	TPH3207WS	650	50	2.65	±18	41	2197
Transphorm	TP90H180PS	900	15	2.1	±18	205	780
GaN Systems	GS66502B	650	7.5	1.3	−10 to +7	200	65
GaN Systems	GS66504B	650	15	1.3	−10 to +7	100	130
GaN Systems	GS66506T	650	22	1.3	−10 to +7	67	195
GaN Systems	GS66508B	650	30	1.3	−10 to +7	50	260
GaN Systems	GS66508P	650	30	1.7	−10 to +7	50	260
GaN Systems	GS66508T	650	30	1.7	−10 to +7	50	260
GaN Systems	GS66516B	650	60	1.3	−10 to +7	25	520
GaN Systems	GS66516T	650	60	1.3	−10 to +7	25	520

Table 2. Commercial GaN HEMT drivers by Texas Instruments (TI).

Driver	Number of Channels	Peak Output Current (A)	Supply Voltage (V)	Rise Time (ns)	Fall Time (ns)	Propagation Delay (ns)
LMG1020	1	7	5	4	1.9	2.5
LMG1205	2	5	4.5–5.5	7	3.5	35
LMG1210	2	1.5	5	5.6	3.3	10

LM5113-Q1	2	5	4.5–5.5	7	3.5	30
UCC27611	1	6	4–18	9	4	14

Table 3. Commercial GaN HEMT drivers by Silicon Lab.

Driver	Number of Channels	Peak Output Current (A)	Input Supply Voltage (V)	Output Supply Voltage (V)	Rise Time (ns)	Fall Time (ns)	Propagation Delay (ns)
Si823x series	2	0.5 or 4	4.5–5.5 or 2.7–5.5	6.5–24	20 or 12	20 or 12	60
Si826x series	1	0.6 or 4	X	6.5–30	5.5	8.5	60
Si827x series	2	4	2.5–5.5	4.2–30	10.5	13.3	60
Si8220/1	1	0.5/2.5	X	6.5–24	30 or 20	30 or 20	60/40
Si8239x series	2	4	2.5–5.5	6.5–24	12	12	30
Si8285/6	1	4	2.8–5.5	9.5–30	5.5	8.5	50

Table 4. Commercial GaN switching modules by TI.

Module	Number of Channels	Voltage and Current Ratings (V, A)	Supply Voltage (V)	Rise Time (ns)	Fall Time (ns)	Propagation Delay (ns)
LMG3410	1	600, 12	5	4.2	15	20
LMG3410R050	1	600, 12	12	15	1.2	20
LMG3410R070 & LMG3411R070	1	600, 40	12	15	4.2	20
LMG5200	2	80, 10	5	X	X	29.5

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