A Dual-Mode Driver IC for Depletion-Mode GaN HEMT

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Introduction

- 600 V GaN High Electron Mobility Transistors (HEMT) have superior properties, compared to Si superjunction transistors.
  - For the same $R_{\text{DS(on)}}$.
  - Lower $Q_g$ and $Q_{\text{OSS}}$.
  - Fast body diode with a cascode low-voltage MOSFET.
  - Enable higher switching frequency ($f_s$), which reduces passive component sizes.

- Potential application:
  - Power Factor Correction (PFC).
  - Achievable $f_s$ with Si devices:
    40 kHz ~ 200 kHz.
  - Large passives
    (PFC inductor and EMI filters).

*NXP TEA1716DB1255 90 W notebook adapter demo board.*
Introduction


**Figure 2** Yole’s report suggests that automakers will begin to adopt GaN power devices in inverters, dc–dc converters, and onboard chargers, generating revenue of US$150 million by 2020. POL: point of load. (Figure courtesy of “Power GaN Market” report, Yole Développement, July 2014.)
NXP GaN HEMTs

- Si-fab compatible GaN-on-Si process.
- Depletion mode device (normally-on).
- Ti/Al-based ohmic contacts.
- Ni-based Schottky contacts.

\[ R_{on} A = 2.5 \, \text{mΩ cm}^2 \]

\[ I_{leakage} = 1 \, \mu\text{A/mm} \]

Cascode Drive (CD)

- Popular technique to achieve normally-off characteristic.
- Gate of the GaN HEMT (GH) is tied to the source of the MOSFET.
- A conventional MOSFET driver can be used.
- The Low-Voltage (LV) MOSFET body diode acts as the body diode of the cascode device.
HEMT Drive (HD)

- Directly drive the GaN HEMT with a negative gate swing.
- Requires a negative supply voltage.
- LV MOSFET is still needed to turn off the current path if the negative supply voltage is absent (during power down).
- LV MOSFET is kept on during normal operation.
Proposed HEMT driver IC

• Commercially available cascode GaN devices:

• This work focuses on:
  • Integrated dual-mode driver w/ the cascode device.
  • Integrated digital current-mode control.
  • Co-package the GaN HEMT die and driver/controller die.
Proposed HEMT-Drive (HD) Mode

- Programmable current-mode driver with inverted active bootstrap + charge pump.
  - GaN HEMT gate (GH) is switched to – 3.3 V to turn it OFF.
  - LV MOSFET is always ON during normal operation.
- An external $C_{slope}$ is used to achieve active slope control, to control/reduce EMI.
- An UVLO monitors the negative gate voltage.

\[
\frac{i_{ctrl}}{C_{slope}} = \frac{dV_x}{dt}
\]

Inverted active bootstrap.

Programmable current-mode driver.

+3.3 V $\rightarrow$ 0V

0 V $\rightarrow$ -3.3V

High frequency charge pump

GaN HEMT

600 V

670 mΩ

NDMOS

20 V

130 mΩ
HEMT driver with Slope Control

- Different $i_{ctrl}$ can be programmed through SPI to achieve $dV/dt$ slopes.

$$\frac{i_{ctrl}}{C_{slope}} = \frac{dV_x}{dt}$$
Conventional Cascode-Drive Mode

- In conventional cascode-drive (CD) mode, the interconnection between GaN HEMT and the MOSFET ($V_{xn}$) may reach breakdown voltage of the MOSFET.
- The proposed CD mode driver addresses the concern.

GaN HEMT 600 V, 670 mΩ

NDMOS 30 V, 48 mΩ

30-V breakdown voltage reached!
Proposed Cascode-Drive (CD) Mode

- Adding $D_1$ and $ZD$ (10 V Zener diode) to the output of the MOSFET driver.
- $D_1$ blocks $GM$ from $V_{xn}$ when $GM$ is HIGH.
- $ZD$ clamps $V_{xn}$ to 10.7 V ($Zener + 1$ diode drop) when $GM$ is LOW.

GaN HEMT
600 V, 670 mΩ

Zener
10 V

NDMOS
20 V, 130 mΩ
Integrated Current-Mode Control

- In PFC and other applications, a resistor in series with the power transistor is used to sense the transistor current for:
  - current-mode control.
  - over-current protection.

Current sensing resistor for current-mode control and over-current protection.

NXP TEA1716DB1255 90 W notebook adapter demo board schematic.
Integrated Current-Mode Control

- Closed-loop current sensing circuit forces the sense-FET current to track the power-FET current.
- Then the sense-FET current is mirrored for peak current-mode control.

Power-FET : Sense-FET = 700 : 1
Chip Micrograph and Package

- **Driver IC die:**
  - 140 nm BCD-SOI
  - Measures 1.4 x 2.0 mm²
  - Analog/Driver VDD = 3.3 V
  - Digital VDD = 1.8 V

- **GaN HEMT die:**
  - 670 mΩ
  - Measures 1.4 x 1.6 mm²

- Co-packaged in TSSOP20 package.
- Target for power-factor-correction (PFC) application.
DCM operation at 500kHz

- Cascode-Drive (CD) Mode.
- $V_{xn}$ is clamped to $\sim 11$ V.

- HEMT-Drive (HD) Mode.
- $V_{xn}$ is pulled down to 0 V.
CCM operation at 1MHz

- Cascode-Drive (CD) Mode.
- $V_{xn}$ is clamped to $\sim 11$ V.

- HEMT-Drive (HD) Mode.
- $V_{xn}$ is pulled down to 0 V.
Negative Gate Swing (HD Mode)

- Gate voltage measurement in HEMT-Drive Mode.
- Showing -3.3 V gate swing achieved by the inverted bootstrap circuit.
Digital Peak Current Mode Control

- Digital peak current mode in DCM at 500 kHz.
- Current sensor output $V_{\text{sense}}$ is shown.

- Cascode-Drive (CD) Mode.
- HEMT-Drive (HD) Mode.
Digital Peak Current Mode Control

- Digital peak current mode in CCM at 500 kHz.
- Current sensor output $V_{\text{sense}}$ is shown.
- Larger blanking time is required in CD mode, due to the switching of the NDMOS. Whereas in HD mode, NDMOS is always ON.

- Cascode-Drive (CD) Mode.
- HEMT-Drive (HD) Mode.
## HD vs. CD Mode Comparison

- For depletion-mode GaN HEMT:

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<th>HEMT-Drive Mode</th>
<th>Cascode-Drive Mode</th>
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<tr>
<td><strong>Pros</strong></td>
<td>• Direct gate control.</td>
<td>• Simple w/ conventional MOSFET driver.</td>
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<td>• Active slope control.</td>
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<td><strong>Cons</strong></td>
<td>• Requires negative gate swing.</td>
<td>• Indirect gate control.</td>
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<td>• Large bootstrap capacitor.</td>
<td>• Protection is required to avoid breakdown of LV MOSFET.</td>
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<td>• Still requires cascode MOSFET during power down.</td>
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<td>• More suitable for hard-switching application.</td>
<td>• More suitable for soft-switching application.</td>
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