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

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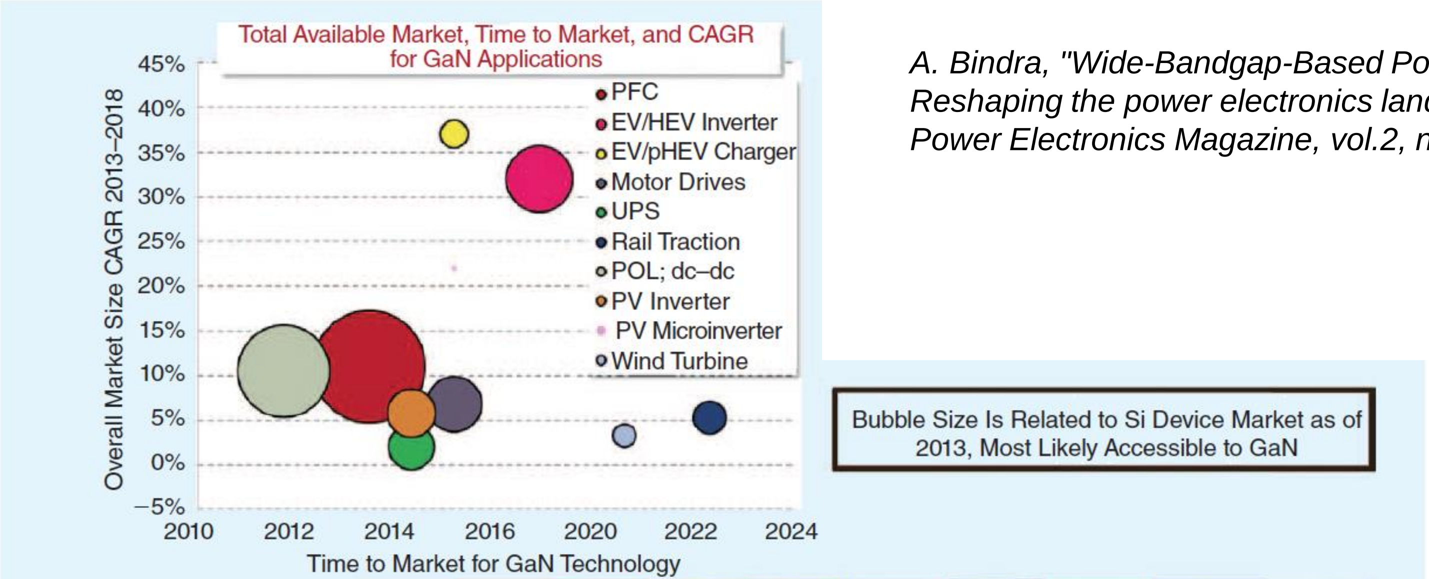
Introduction

- 600 V GaN High Electron Mobility Transistors (HEMT) have superior properties, compared to Si superjunction transistors.
  - For the same $R_{DS(on)}$.
  - Lower Q_g and Q_{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

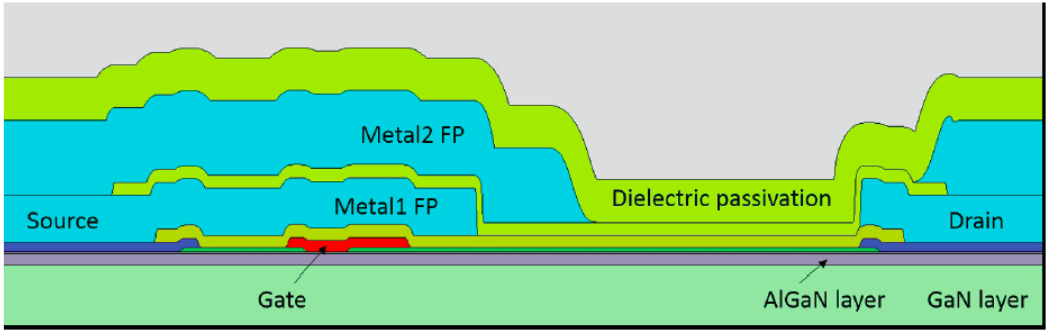
A. Bindra, "Wide-Bandgap-Based Power Devices: Reshaping the power electronics landscape," IEEE Power Electronics Magazine, vol.2, no.1, Mar. 2015.



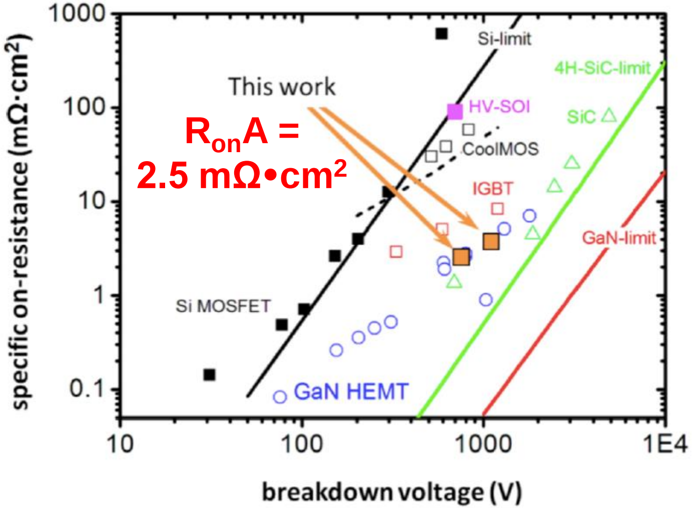
	POL; dc–dc	PFC	EV/HEV Inverter	EV/pHEV Charger	PV Inverter	PV Micro Inverter	Motor Drives	UPS	Rail Traction	Wind Turbine
Expected Time to Market for GaN Mass Volume Introduction	2012	2014	2018	2016	2015	2016	2016	2015	2022	2020
CAGR 2013–2018 in%	10.5%	11.0%	32.0%	37.0%	5.8%	22%	6.8%	2.0%	5.3%	3.3%

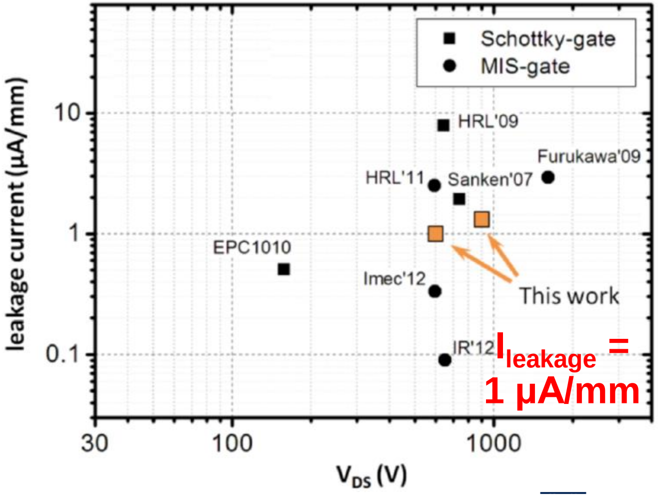
FIG 2 Yole's report suggests that automakers will begin to adopt GaN power devices in inverters, dc–dc converters, and onboard chargers, generating revenue of US$150 million by 2020. POL: point of load. (Figure courtesy of "Power GaN Market" report, Yole Développement, July 2014.)

NXP GaN HEMTs



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





J. Donkers et.al, "600V-900V GaN-on-Si Process Technology for Schottky Barrier Diodes and Power Switches Fabricated in a Standard Si-Production Fab," in CS MANTECH Conference, 2013.

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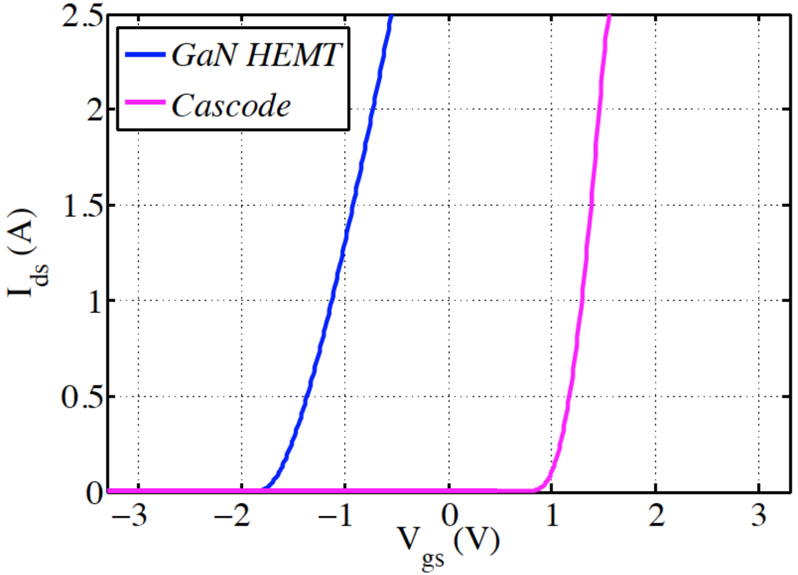
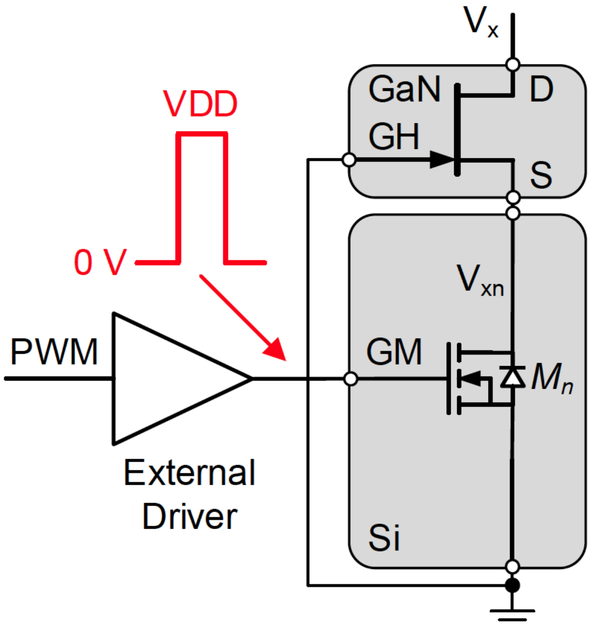
Cascode Drive (CD)

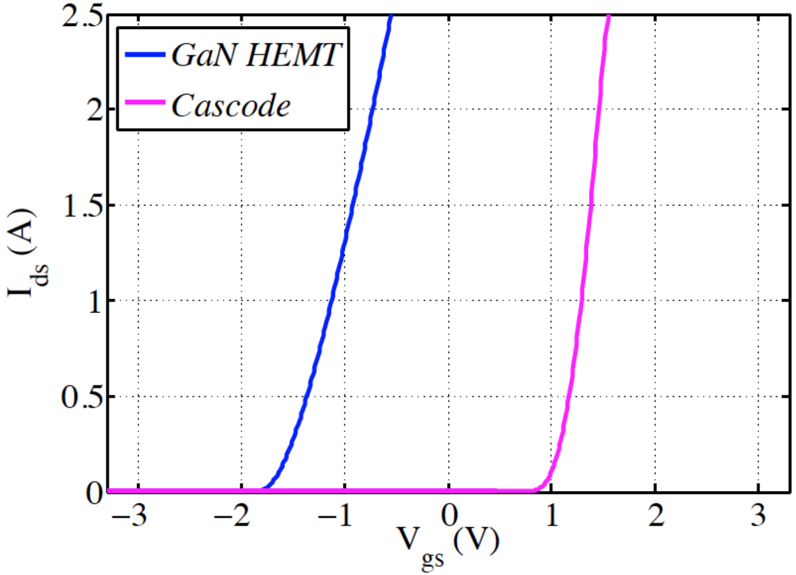
- Popular technique to achieve normally-off characteristic.
- Gate of the GaN HEMT (GH) is tied to the source of the MOSFET.
- A conventional MOSFET driver can be used.
- The Low-Voltage (LV) MOSFET body diode acts as the body diode of the cascode device.

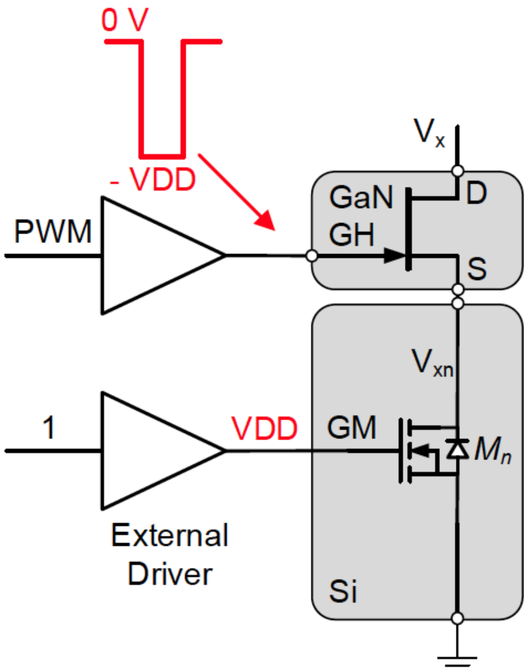




HEMT Drive (HD)

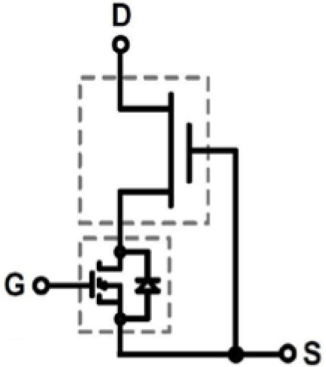
- Directly drive the GaN HEMT with a negative gate swing.
- Requires a negative supply voltage.
- LV MOSFET is still needed to turn off the current path if the negative supply voltage is absent (during power down).
- LV MOSFET is kept on during normal operation.



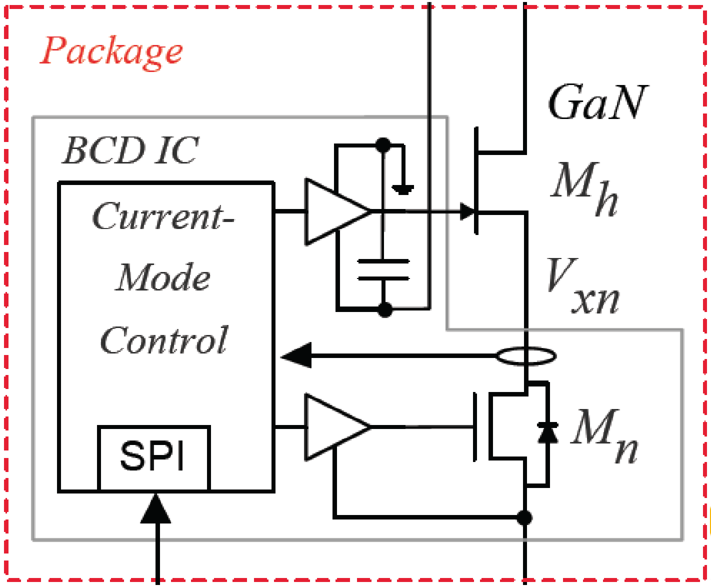


Proposed HEMT driver IC

- Commercially available cascode GaN devices:



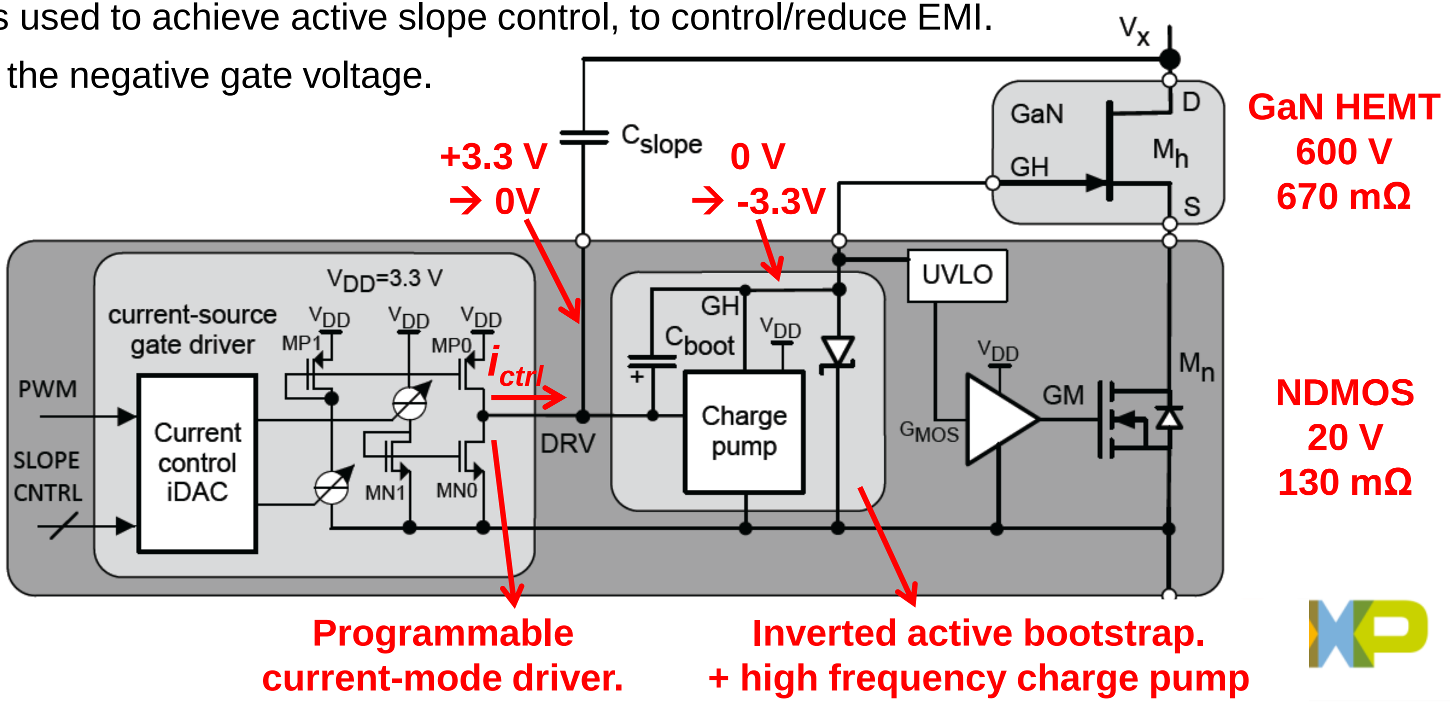
- This work focuses on:
  - Integrated dual-mode driver w/ the cascode device .
  - Integrated digital current-mode control.
  - Co-package the GaN HEMT die and driver/controller die.



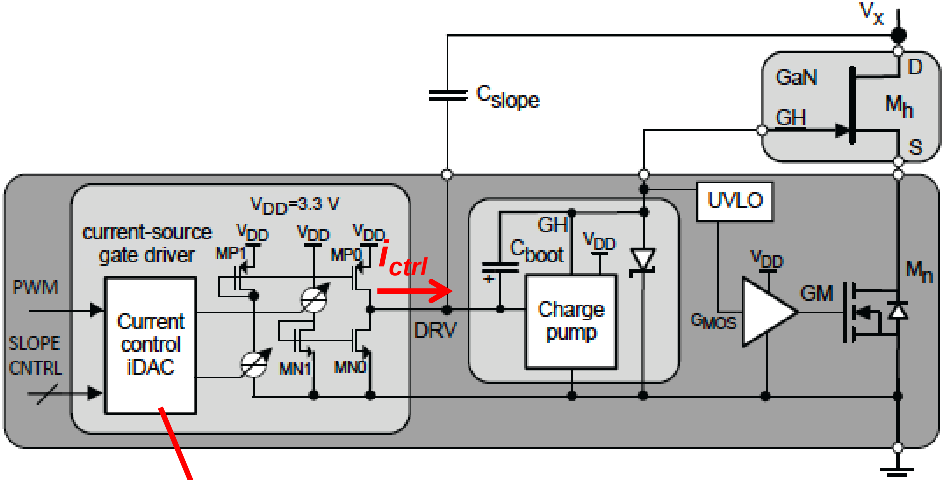
Proposed HEMT-Drive (HD) Mode

- 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.

$$\frac{i_{ctrl}}{C_{slope}} = \frac{dV_x}{dt}$$



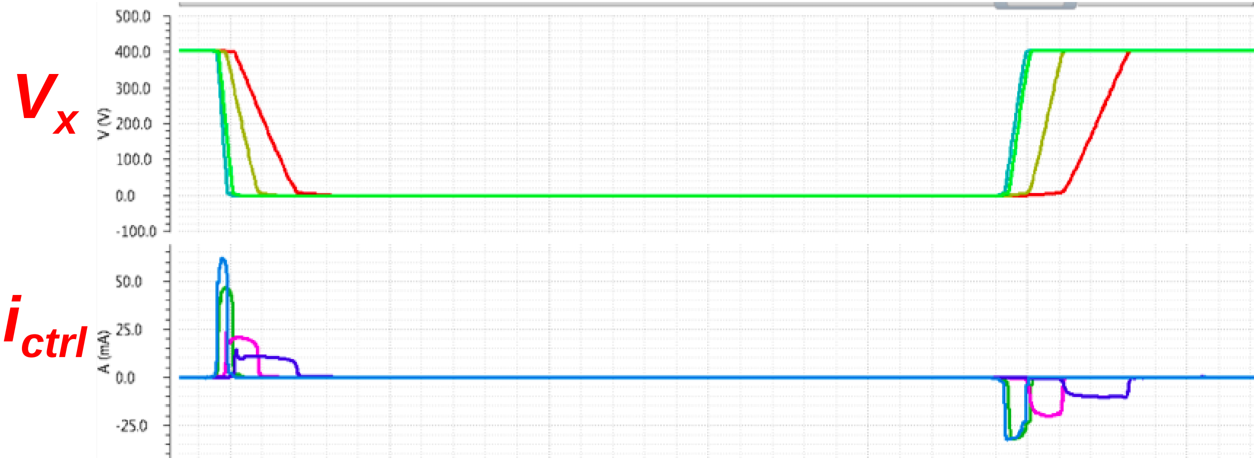
HEMT driver with Slope Control



Programmable current-DAC.

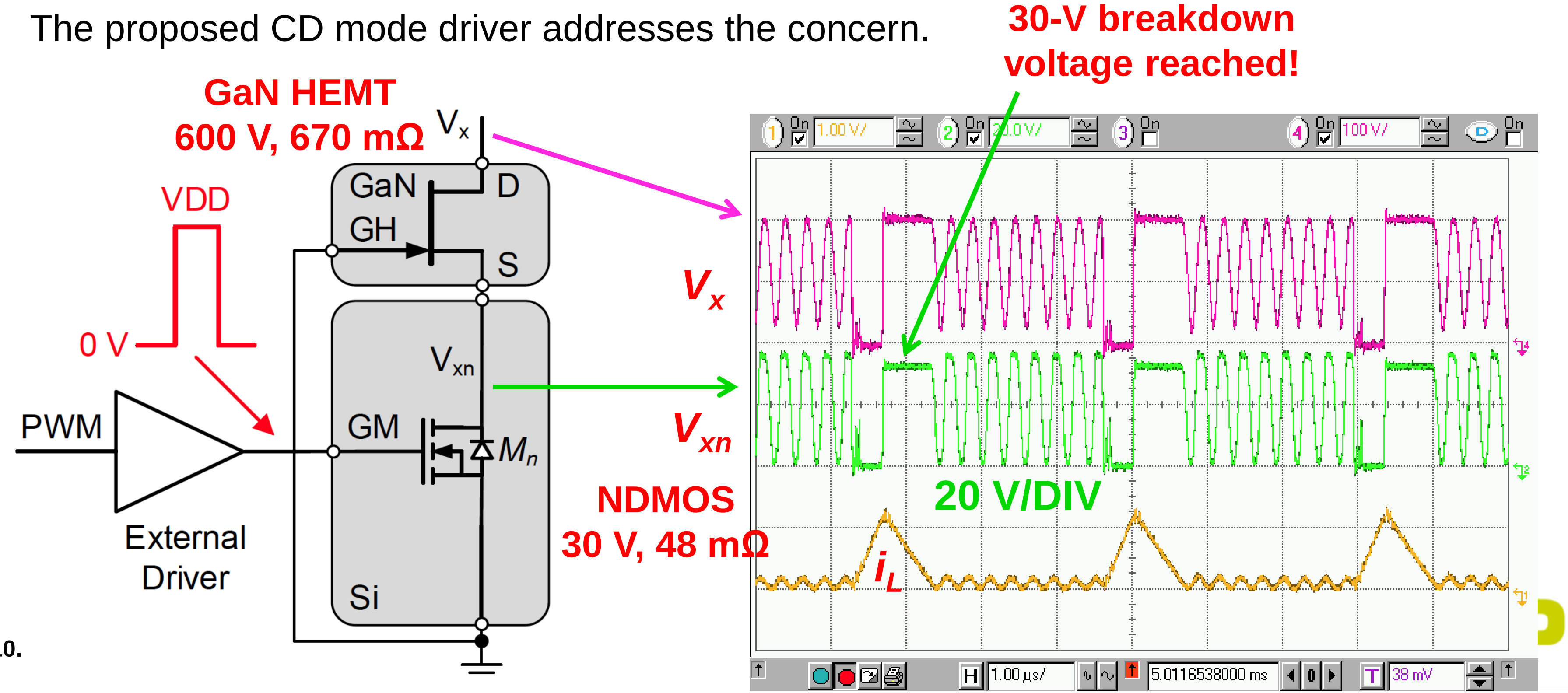
- Different i_{ctrl} can be programmed through SPI to achieve *dV/dt* slopes.

$$\frac{i_{ctrl}}{C_{slope}} = \frac{dV_x}{dt}$$



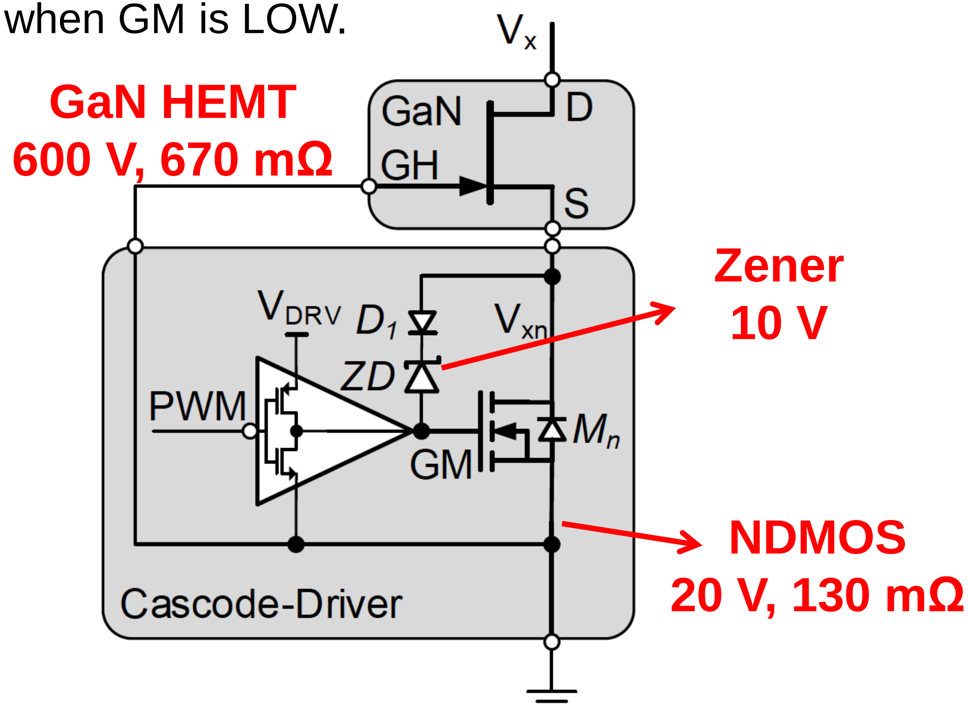
Conventional Cascode-Drive Mode

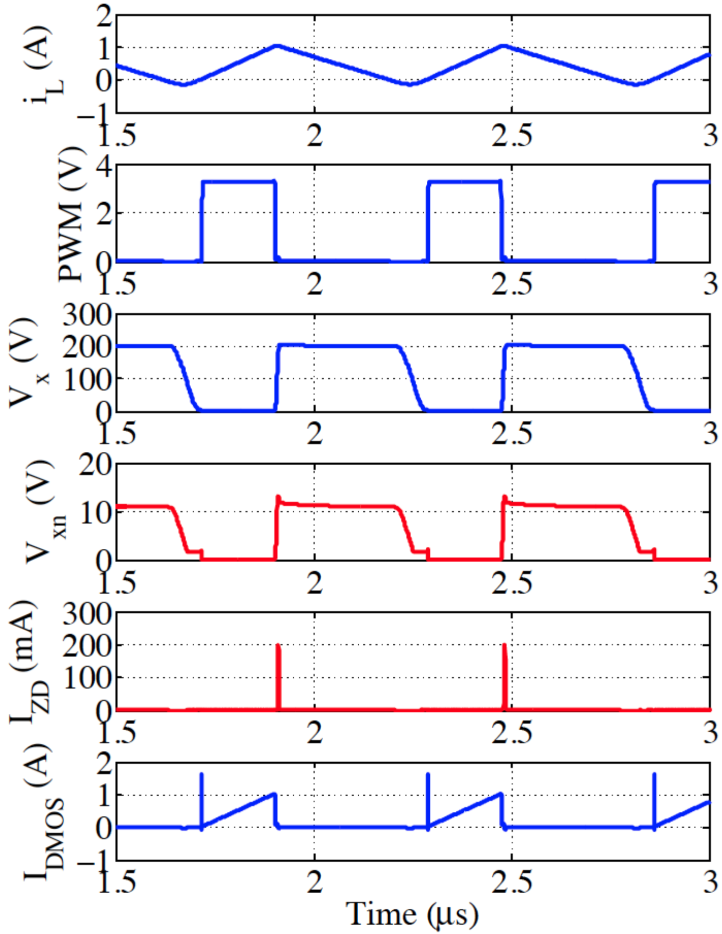
- In conventional cascode-drive (CD) mode, the interconnection between GaN HEMT and the MOSFET (V_{xn}) may reach breakdown voltage of the MOSFET.
- The proposed CD mode driver addresses the concern.



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.

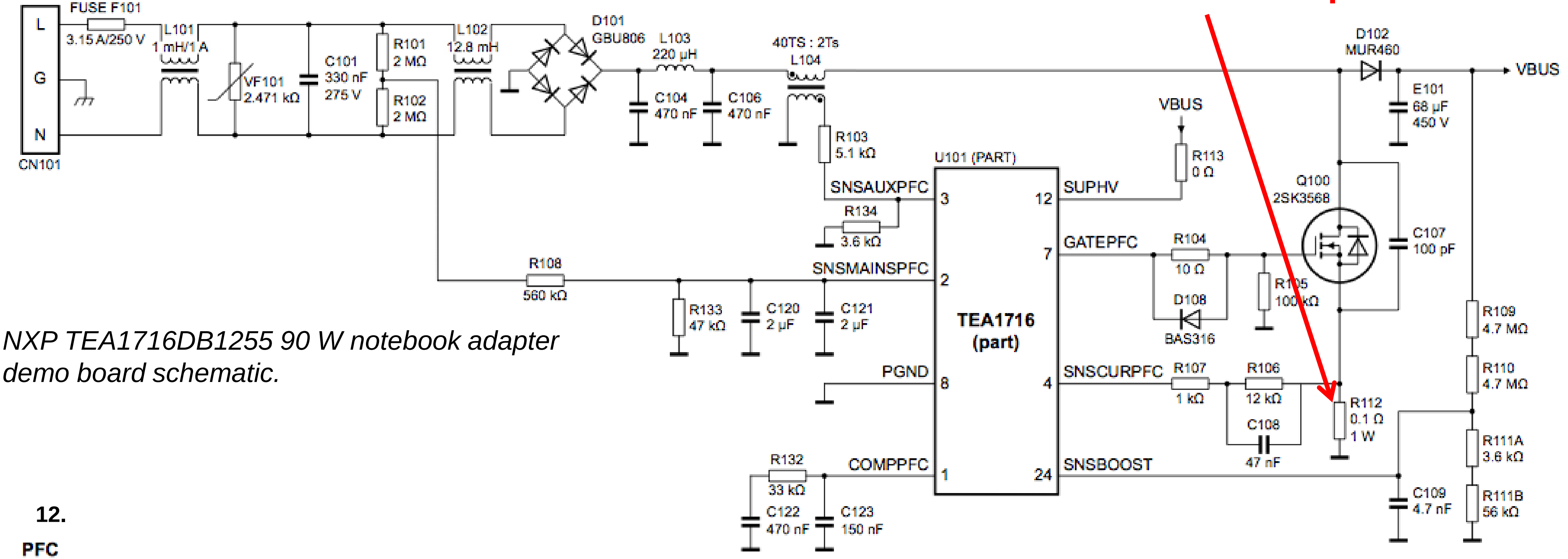




Integrated Current-Mode Control

- 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.

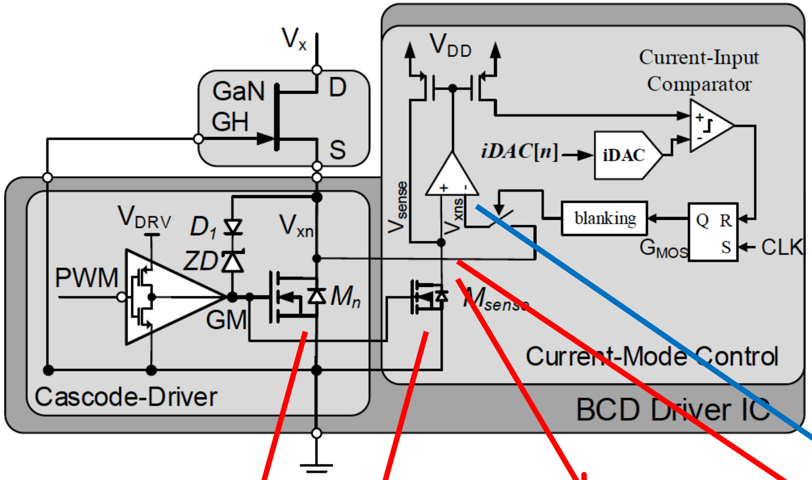
Current sensing resistor for current-mode control and over-current protection.

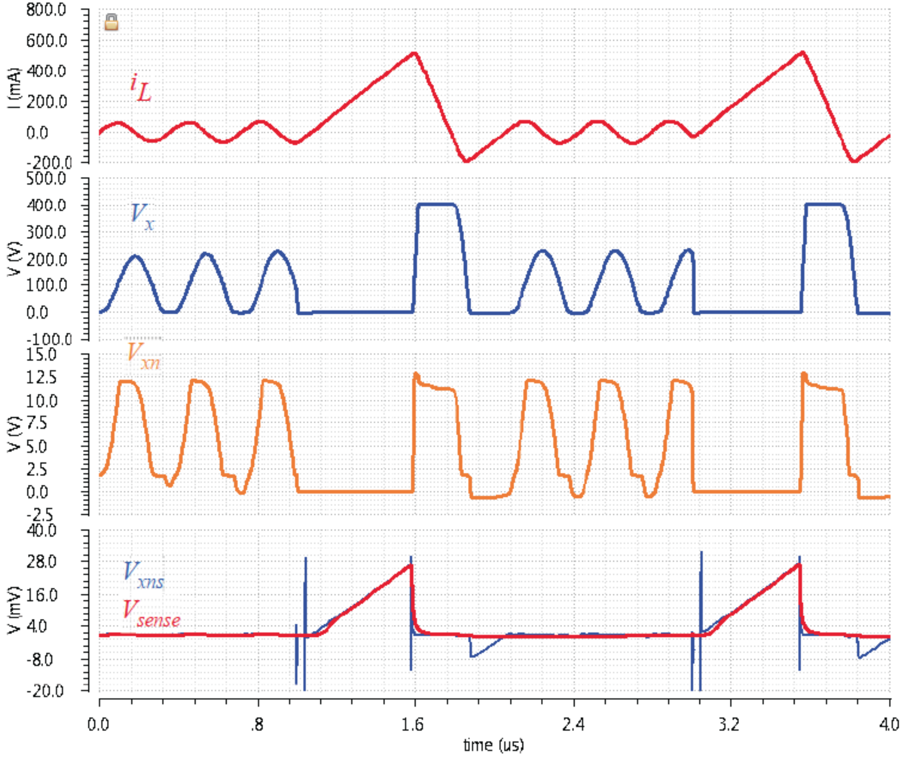


NXP TEA1716DB1255 90 W notebook adapter demo board schematic.

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.





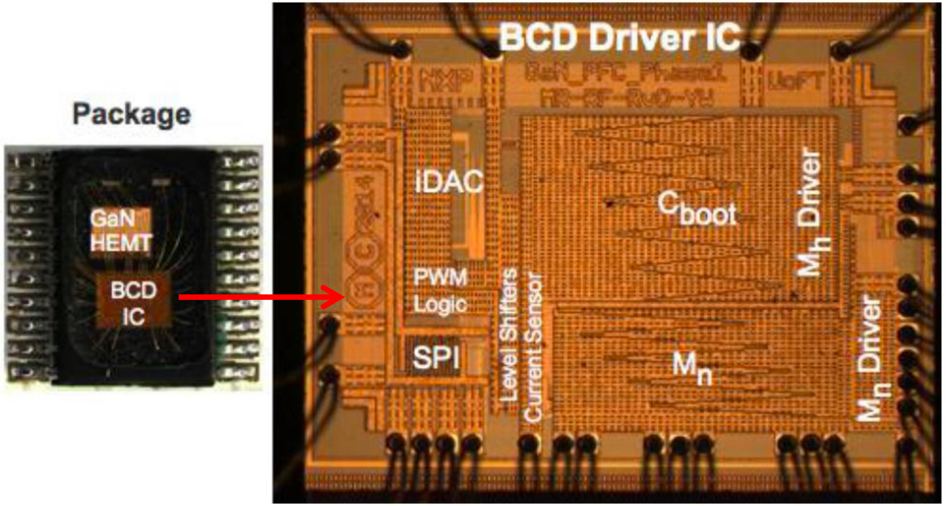
Power-FET **Sense-FET**

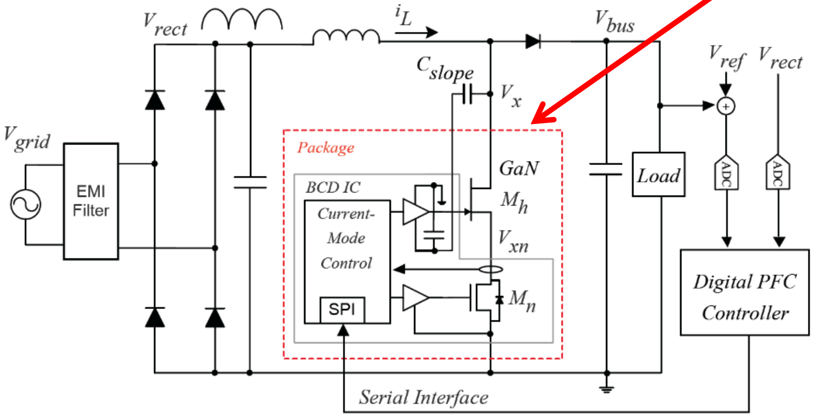
700 : 1

High BW amplifier

Chip Micrograph and Package

- Driver IC die:
  - 140 nm BCD-SOI
  - Measures 1.4 x 2.0 mm^2
  - Analog/Driver VDD = 3.3 V
  - Digital VDD = 1.8 V
- GaN HEMT die:
  - 670 mΩ
  - Measures 1.4 x 1.6 mm^2

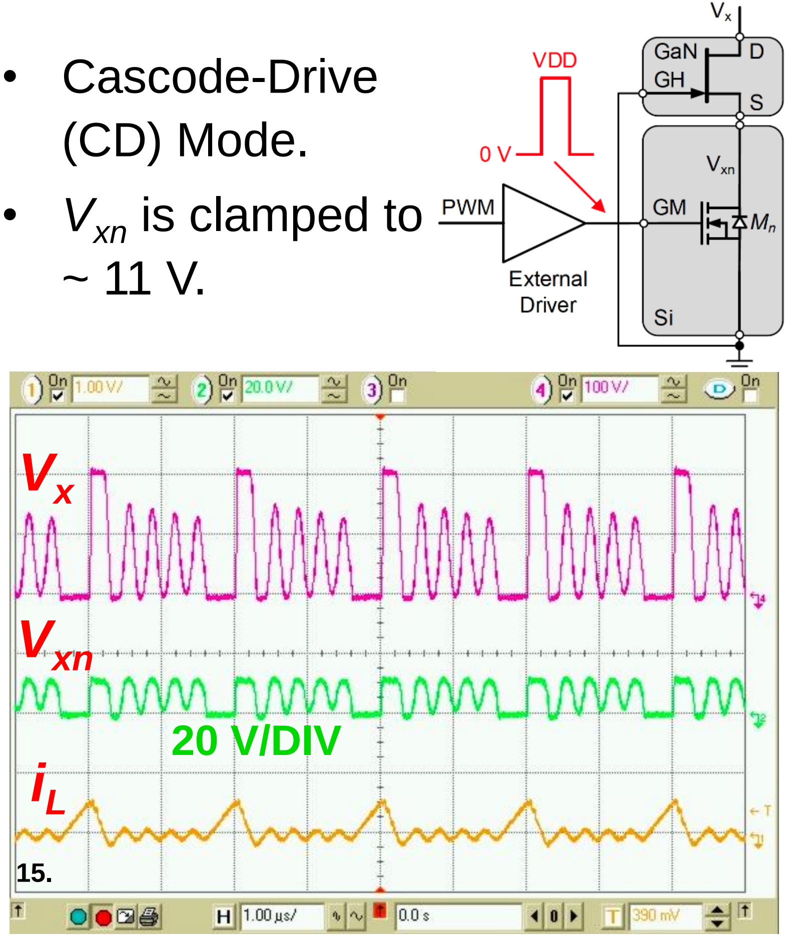




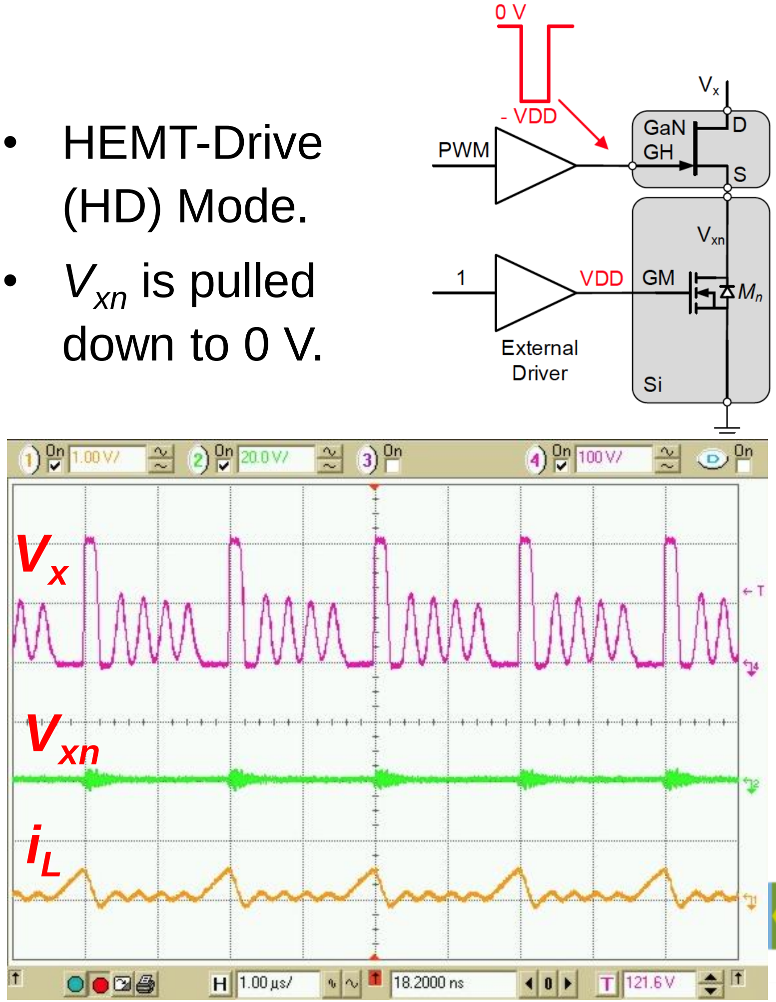
- Co-packaged in TSSOP20 package.
- Target for power-factor-correction (PFC) application.

DCM operation at 500kHz

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

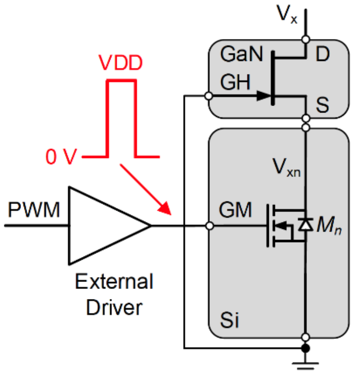


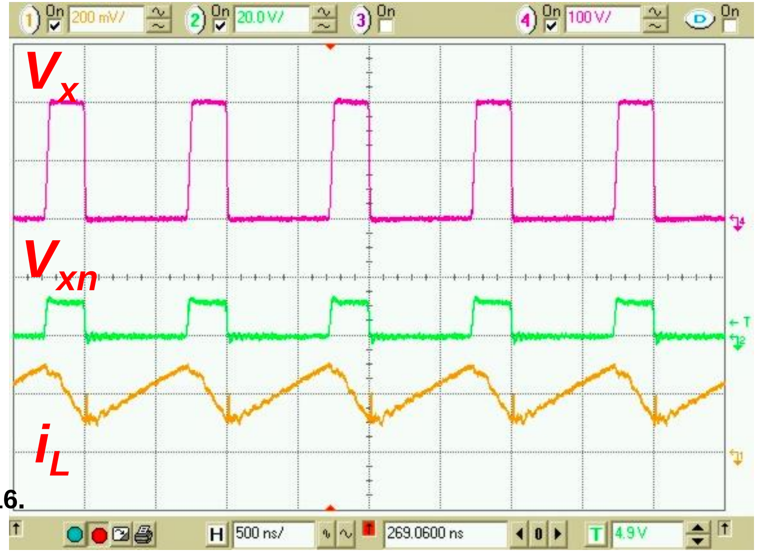
- HEMT-Drive (HD) Mode.
- V_{xn} is pulled down to 0 V.



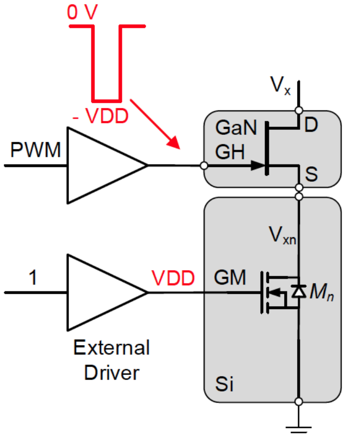
CCM operation at 1MHz

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



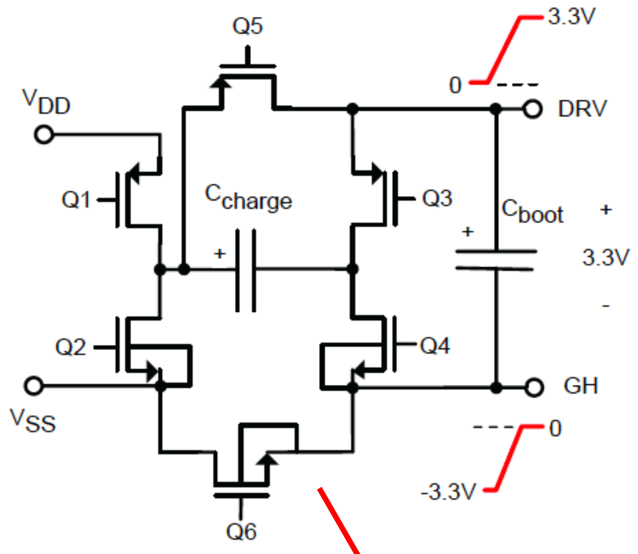


- HEMT-Drive (HD) Mode.
- V_{xn} is pulled down to 0 V.

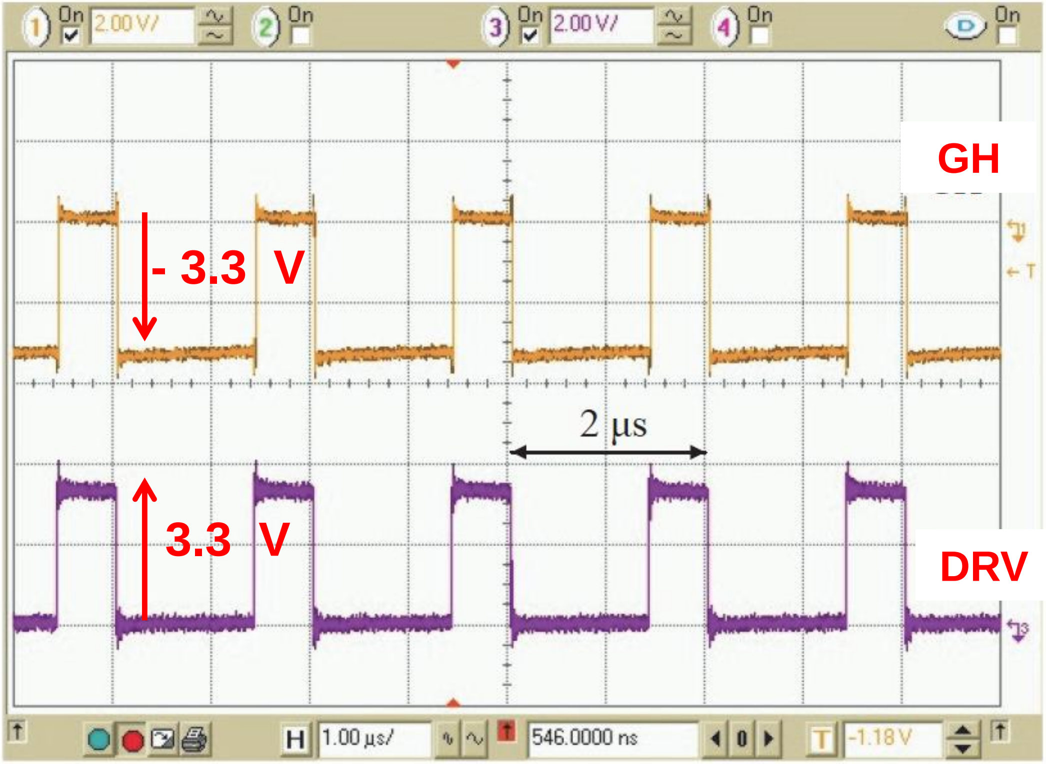


Negative Gate Swing (HD Mode)

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

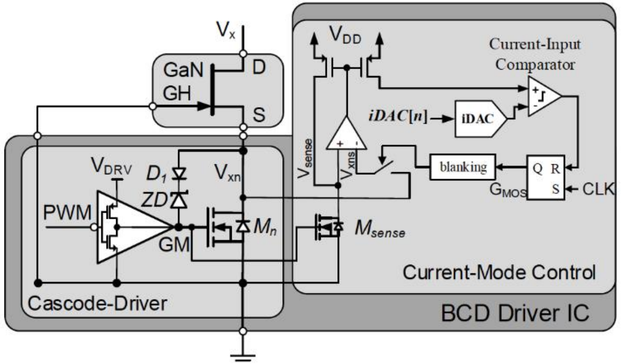


Transistor implementation of the inverted active bootstrap circuit.



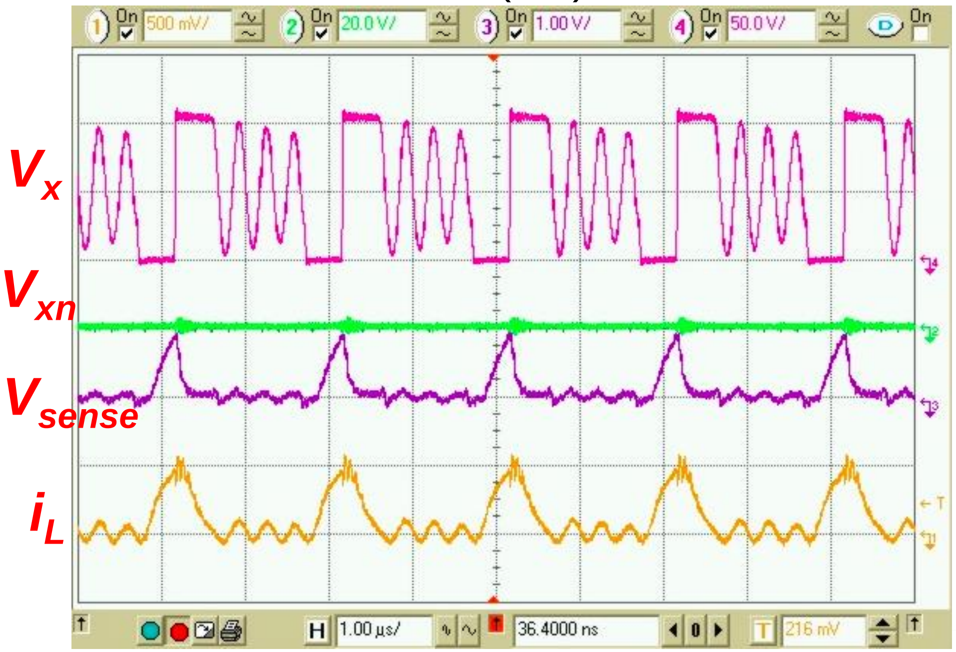
Digital Peak Current Mode Control

- Digital peak current mode in DCM at 500 kHz.
- Current sensor output V_{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_{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.

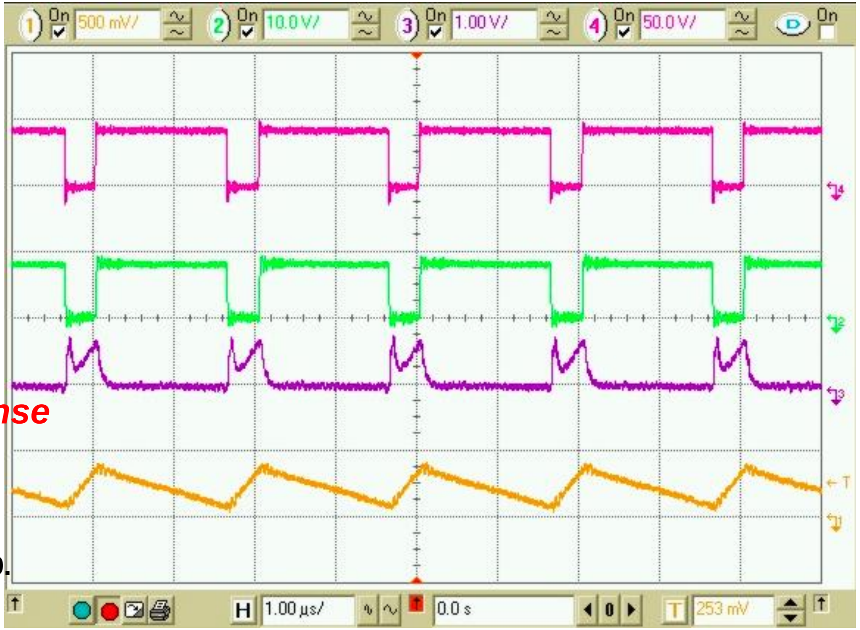
- Cascode-Drive (CD) Mode.

V_x

V_{xn}

V_{sense}

i_L



- HEMT-Drive (HD) Mode.

V_x

V_{xn}

V_{sense}

i_L

HD vs. CD Mode Comparison

- **For depletion-mode GaN HEMT:**

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

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