Part 4

Experimental Analysis of 1st Gen. 600 V GaN M-BDSs

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The Switch: 600 V / 140 mΩ GaN M-BDS 1. Gen. Samples

BDS Realization with Unipolar Devices

- $R_{on}$
- $R_{total} = 2R_{on}$
- $R_{total} = R_{on}$

- 4 x Single switch for same $R_{on}$

Monolithic Bidirectional Realization (M-BDS)

- ±600 V
- 140 mΩ
- PG-DSO-20-85 Package

GaN M-BDS Internal Structure

- Infineon 600 V CoolGaN™ Technology
- Normally-off (Gate Injection Transistor, GIT)
- Two gates (one per blocking direction)
- Internal common-drain configuration

Same chip region used for blocking both voltage polarities!
The Topologies

GaN/SiC 3-Level T-Type AC-DC PFC Rectifier / DC-AC Inverter

All-GaN AC-AC Current-Source Converter

1200 V / 140 mΩ SiC

600 V / 140 mΩ GaN M-BDS
GaN M-BDS Gate Drive Considerations
GaN Gate Injection Transistor (GIT) Gate Behavior

Simplified MOSFET Gate Turn-On

\[ I_{pk} = \frac{V}{R_g + R_{g,int}} \]

Simplifying assumption: \( C_{gs} = \text{const.} \)

Simplified Gate Injection Transistor (GIT) Gate Turn-On

\[ I_{ss} = I_{Dgs} = \frac{(V - V_{Dgs})}{(R_g + R_{g,int})} \]

\( D_{gs} \) clamps at typ. 3.5 V

Losses in \( D_{gs} \)!

Requirements for GIT gate drive

- Small \( R_g \) for fast transients (charging/discharging of \( C_{gs} \))
- Large \( R_g \) during steady-state (small \( I_{Dgs} \) of a few 10 mA)

Standard RRC Gate Drive Operating Principle

Capacitor to Decouple Transient Low-Impedance Paths

- \( C_s >> C_{gs} \) (typ.): Decoupling of High-Current Paths
- \( R_{ss} >> R_{on}, R_{off} \): Steady-state current (milliamperes)
- \( D_1 \): Separate turn-on/turn-off gate resistors with HB driver

Note: **Dedicated driver ICs** with multiple outputs as alternative

Note: **Bipolar supply** to ensure negative \( v_{gs} \) at all times (not just transiently; relevant for CSI commutation cells)

Assumptions: \( R_{g,int} = 0 \ \Omega, \ C_s >> C_{gs} \), simplified gate model (\( C_{gs} = \text{const.} \))

Note: unipolar supply possible; bipolar supply for better robustness against parasitic turn-on in current-source converter commutation cells (see later).
**Advanced RRC Gate Drive Operating Principle**

### Eliminating the Duty-Cycle Dependency of Dynamics

- **D₂**: Prevents full discharge of $C_s$ via $R_{ss}$
- **D₄**: Decouple $R_{ss}$ during off-state
- **D₄**: Discharge path for $C_s$ during off-state (via $R_{off}$ and $D₄$) and clamping of gate to negative supply voltage
- **D₅**: Prevents negative voltage across $C_s$ (e.g., due to Miller current or other distortions; inactive during normal operation)

- Straightforward option with standard HB driver IC and a few Schottky diodes

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Advanced RRC Gate Drive for M-BDS: Realization

- Two gates per M-BDS / Two isolated power supplies / Two control signals
- Mostly vertical gate loop (ca. 8...10 nH incl. package) / Adv. RRC network on TOP / HB driver supply decoupling on BOT

Remark: Integration of gate drive → Significant reduction of PCB area!
Advanced RRC Gate Drive for M-BDS: Layout / Measurements

- Two gates per M-BDS / Two isolated power supplies / Two control signals
- Mostly vertical gate loop (ca. 8...10 nH incl. package) / Adv. RRC network on TOP / HB driver supply decoupling on BOT

**Measured GaN M-BDS $v_{gs}$**

$V_p = 8 \text{ V}, V_n = 5 \text{ V}$

$R_{on} = 5 \Omega, R_{off} = 4.7 \Omega, C_s = 2.2 \text{ nF}, R_{ss} = 680 \Omega$

**Remark:** Integration of gate drive $\rightarrow$ Significant reduction of PCB area!
3-Level T-Type Inverters/Rectifiers with GaN M-BDSs

Details => Paper @ ECCE USA 2021
3-Level T-Type (TT) Main Converter Stage

- Bidirectional voltage-source AC-DC or DC-AC conversion / **Basic building block** for PFC rectifiers or motor drive inverters
- Phase-modular DC-link-referenced first LC-filter stage => DM and CM filtering

- **Three-level bridge-leg** via connection to DC-link midpoint: **bidirectional conduction & bipolar blocking** => **M-BDS**
- 800 V DC / $S_{x,H}$, $S_{x,L}$: 1200 V, 140 mΩ SiC MOSFET / $S_{x,M}$: 600 V, 140 mΩ GaN M-BDS
3-Level TT Bridge-Leg Commutation Cells

Positive Output Voltage
- High-side commutation cell active

Negative Output Voltage
- Low-side commutation cell active
3-Level TT Bridge-Leg Evaluation Board

- 800 V DC / $S_{x,H}$, $S_{x,L}$: 1200 V, 140 mΩ SiC MOSFET (IMBG120R140M1H) / $S_{x,M}$: 600 V, 140 mΩ GaN M-BDS
- Two commutation loops: High-side / Low-side / Commutation inductance ca. 15 nH
- Advanced RRC gate drive with HB driver (2EDS8265HXUMA1) for M-BDS

Cooling through PCB (thermal vias) / Top-side cooled packages would facilitate improved layouts
Continuous M-BDS Operation at ± 400 V in CCM

Q2: $v_{sw} > 0$ & $i_{sw} < 0$

Q1: $v_{sw} > 0$ & $i_{sw} > 0$

Q3: $v_{sw} < 0$ & $i_{sw} < 0$

Q4: $v_{sw} < 0$ & $i_{sw} > 0$

1 Filter capacitor current not shown for better visibility
Remark: CCM and TCM Operation of TT Bridge-Leg

Exemplary simulations for 800 V DC and 2 kW.

CCM: Continuous Conduction Mode

TCM: Triangular Current Modulation

Zero-Voltage Switching (ZVS) for all transitions

Variable sw. frequency
Continuous M-BDS Operation at ± 400 V with TCM (Soft-Switching)

Q1: $v_{sw} > 0$ & $i_{sw,avg} > 0$

Q2: $v_{sw} > 0$ & $i_{sw,avg} < 0$

Q3: $v_{sw} < 0$ & $i_{sw,avg} < 0$

Q4: $v_{sw} < 0$ & $i_{sw,avg} > 0$

1 Filter capacitor current not shown for better visibility
Transient Calorimetric Loss Measurement: Principle (1)

- Constant power dissipation into metal block

\[ \Delta T(t) = P R_{th} \cdot \left( 1 - e^{-\frac{\Delta t}{R_{th} C_{th}}} \right) \]

**Step 1: Calibration with Known DC Power**
- Record \( \Delta T(\Delta t) \) for several (at least two) known powers
- Fit model and extract model parameters \( C_{th} \) and \( R_{th} \)

**Step 2: Measurement of Unknown Power Dissipation**
- Measure time \( \Delta t \) to reach temperature difference \( \Delta T \)
- Use calibrated model to calculate power dissipation

\[ P(\Delta T, \Delta t) = \frac{\Delta T}{R_{th} \cdot \left( 1 - e^{-\frac{\Delta t}{R_{th} C_{th}}} \right)} \]

Alternative for Step 2
- Record \( \Delta T(\Delta t) \) for unknown power dissipation \( P' \)
- Fit model with known \( R_{th} \) and \( C_{th} \) to identify \( P' \)
Transient Calorimetric Loss Measurement: Principle (2)

Half-Bridge with Identical Switches

Switching Loss Extraction

- Calorimetric loss meas. gives total losses
- Conduction losses can be calculated:

\[ P_{\text{cond}} = R_{d\text{s(on)}}(P_{\text{total}}) \cdot I_{\text{rms}}^2 \]

- Switching energies follow from switching frequency

\[ P_{\text{sw}} = P_{\text{total}} - P_{\text{cond}} \]

\[ E_{\text{sw}} = E_{\text{on}} + E_{\text{off}} = \frac{P_{\text{sw}}}{f_s} \quad \text{(for CCM)} \]

Soft-Switching Losses

- \( E_{\text{sw}} = 2E_{\text{off}} \) for TCM
- Direct & accurate measurement of residual soft-switching losses!

Note: Heat sink size \((C_{\text{th}})\) follows from desired temperature rise (resolution), measurement time, and power dissipation

TT Bridge-Leg Switching Loss Characterization: Method (1)

- Different device types (SiC, M-BDS) require loss separation: measure individual case temperatures ($T_{S1,H}$, $T_{S1,M}$, $T_{S1,L}$) and $T_{HS}$

- Thermal network with 11 parameters
- Calibration with DC power injection & particle swarm fit (MATLAB)

- Note: initial, fast transient ignored (therm. cap. of switches, PCB, heat spreaders, etc.)

![Diagram of thermal network and calibration example]
Different device types (SiC, M-BDS) require loss separation: measure individual case temperatures ($T_{S1,H}$, $T_{S1,M}$, $T_{S1,L}$) and $T_{HS}$

- Thermal network with 11 parameters
- Calibration with DC power injection & particle swarm fit (MATLAB)

Loss Extraction with Calibrated Model (Example):

$$P_{S1,H} = \frac{T_{S1,H} - T_{Amb}}{R_{th,1}} + \frac{T_{S1,H} - T_{S2,H}}{R_{th,12}} + \frac{T_{S1,H} - T_{S3,H}}{R_{th,13}} + \frac{T_{S1,H} - T_{HS}}{R_{th,C-HS1}}$$

- Direct to ambient
- Cross couplings
- To heat sink
TT Bridge-Leg Switching Loss Characterization: Results

Calibration Data / Accuracy
- Injected DC power vs. calorimetric measurement

Measured Hard- and Soft-Switching Losses

1200 V / 140 mΩ SiC
(IMBG120R140M1H)

600 V / 140 mΩ GaN M-BDS

Switching Loss Energy (μJ)

Soft-switching
Hard-Sw.

0.576 μJ/A · $I_{sw}$
15.01 μJ + 7.382 μJ/A · $I_{sw}$

0.25 μJ/A · $I_{sw}$
15.27 μJ + 9.6 μJ/A · $I_{sw}$
Performance Evaluation of TT Main Converter Stage: CCM Designs

Specifications / Modeling
- $T_j = 125 \, ^\circ C$, $T_{\text{amb}} = 45 \, ^\circ C$ / heat sink volume: $CSPI = 15 \, W/(dm^3 K)$
- $\Delta i_{L_F,pp} = 30 \%$ (CCM), $\Delta v_{CF,pp} = 2 \%$
- Pareto-optimal inductor designs (N87 or KoolMu)
- Inverter or rectifier designs with $\cos \phi = \pm 1$

- Sweet spot at 2 kW design power:
  $\eta > 99 \%$ at $\rho > 15 \, kW/dm^3$

Further Details => Paper @ ECCE USA 2021
F. Vollmaier, N. Nain, J. Huber, J. W. Kolar, K. K. Leong, and B. Pandya,
"Performance evaluation of future T-Type PFC rectifier and inverter systems with monolithic bidirectional 600 V GaN switches."
Performance Evaluation of TT Main Converter Stage: TCM Designs

Specifications / Modeling

- $T_j = 125 \, ^\circ C$, $T_{\text{amb}} = 45 \, ^\circ C$ / heat sink volume: $\text{CSPI} = 15 \, \text{W/(dm}^3\text{K)}$
- $\Delta i_{L_{\text{F,pp}}} = 30 \%$ (CCM), $\Delta v_{C_{\text{F,pp}}} = 2 \%$
- Pareto-optimal inductor designs (N87 or KoolMu)
- Inverter or rectifier designs with $\cos \phi = \pm 1$

- TCM favorable for lower design powers, e.g., 1 kW

Further Details => Paper @ ECCE USA 2021
AC/AC Current-Source Converters with M-BDSs
M-BDS Commutation Cell for AC-AC CSC and DMC

**AC-AC Current-Source Converter (CSC)**

4 x Basic Commutation Cell

**AC-AC Direct Matrix Converter (DMC)**

3 x Basic Commutation Cell
M-BDS Commutation Cell Test PCB: Commutation Loops

- Commutation voltages: line-to-line AC voltages / Commutation capacitors: two AC-side filter capacitors

Note: approximate loops only (partly vertical)
**Remark: Passive Toggling of Commutation Cell’s 3rd Switch**

- **Three** switches connected to common switch node / Example: Commutation from $S_1$ to $S_2$

![Diagram of switch node and voltage waveforms](image)

- **Charging/discharging of $C_{oss}(S_3)$** creates additional losses

- **Risk of parasitic turn-on (dv/dt-induced):**

  => Ensure negative gate voltage at all times!

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1 Note: similar effect also observable in TT bridge-legs
M-BDS Commutation Cell Test PCB: Half-Bridge Configuration

- DUT operation in all **four quadrants** by reconfiguring voltage source / load
  - DC supply between B-C or C-B (± 400 V)
  - Load between p-C or p-B (current direction)

- Impact of $S_1$ presence to be quantified

$S_1$ not placed for initial meas.
Remark: 4-Step Commutation (Positive Current)

- Ensure current path & avoid DC voltage short-circuit / **Current-direction dependent** gating sequence (pos. current shown)
Remark: 4-Step Commutation (Negative Current)

- Ensure current path & avoid DC voltage short-circuit / **Current-direction dependent** gating sequence (neg. current shown)
Continuous M-BDS Half-Bridge Operation at ± 400 V

Q1: \( v_{S3} > 0 \) & \( i_{S3} > 0 \)

Q2: \( v_{S3} > 0 \) & \( i_{S3} < 0 \)

Q3: \( v_{S3} < 0 \) & \( i_{S3} < 0 \)

Q4: \( v_{S3} < 0 \) & \( i_{S3} > 0 \)
M-BDS Half-Bridge Switching Loss Characterization

- Transient calorimetric method / **4-Step commutation sequence** / All four quadrants / Two voltage levels (CSC)

Test PCB

Half-Bridge Hard-Switching Energies ($E_{on} + E_{off}$)

- Note: Preliminary results / Gate setup & timings not yet fully optimized => **Lower switching losses achievable**
Performance of AC-AC CSC with 600 V / 140 mΩ GaN M-BDSs

Motor drives for aircraft applications

Specifications / Modeling
- 115 V rms, 400 Hz grid
- 92 V rms, 600 Hz, 1 kW output (design point)
- $T_J = 100 \degree C$, $T_{amb} = 45 \degree C$ / heat sink volume: $CSPI = 15 \text{ W/(dm}^3\text{K)}$
- $\Delta i_{\text{dc,pp}} = 10 \%$ (peak-to-peak), $\Delta Q_{\text{CF}} = 5 \%$
- Pareto-optimal inductor designs (N87 or KoolMu)

Performance evaluation based on measured M-BDS switching losses

Note: Preliminary results / Work in progress!
Conclusion & Outlook
Conclusion & Outlook

- 600 V / 140 mΩ Infineon GaN M-BDS continuous operation at ± 400 V
- Calorimetric switching loss characterization of M-BDS in GaN/SiC TT bridge-leg and all-GaN CSC commutation cell

**TT DC-AC Converter**

**Current-Source AC-AC Converter**

- Full prototypes under development / System-level experimental performance verification
- GaN M-BDS technology takes flight and promises straightforward designs and superior performance
Thank You!