Monolithic integration of GaN power transistors integrated with gate drivers

October 4, 2016

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Potential Application for WBG semiconductors

- GaN power transistors are suited for high-frequency applications.

Production
Normally-off GaN Gate Injection Transistor (GaN-GIT)

<table>
<thead>
<tr>
<th></th>
<th>600V/15A</th>
<th>600V/15A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>TO-220</td>
<td>SMD</td>
</tr>
<tr>
<td></td>
<td>30V normally-off</td>
<td>GaN-GITs (2014)</td>
</tr>
</tbody>
</table>

Proto-type

30V normally-off GaN-GITs (developed in 2014)
Advantages of GaN for Power device

- GaN inherently has superior material properties for Power switching device
- Unique feature of GaN is 2-Dimensional Electron Gas (2DEG) which serves both high electron density and high electron mobility

Comparison of material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Bandgap (eV)</th>
<th>Maximum Electric Field (MV/cm)</th>
<th>Saturation drift velocity ( \times 10^7 ) (cm/s)</th>
<th>Electron Mobility (cm²/Vs)</th>
<th>Baliga’s FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>3</td>
<td>1500</td>
<td>1000</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>SiC</td>
<td>2</td>
<td>1000</td>
<td>1000</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>Si</td>
<td>1</td>
<td>1000</td>
<td>1000</td>
<td>500</td>
<td>1</td>
</tr>
</tbody>
</table>

AlGaN/GaN Hetero-junction FET

- High sheet carrier density induced by polarization effects at the AlGaN/GaN hetero-interface without any doping
- GaN-FET can be fabricated on cost-effective Si-substrates
- Normally-on operation
Normally-off GaN Gate Injection Transistors - GIT -

**Gate Injection Transistor (GIT)**

- **Source**
- **Gate**
- **Drain**

![Diagram](image)

- p-AlGaN
- i-AlGaN
- Large drain current
- $\mu_h << \mu_e$
- i-GaN

**Recovery characteristics**

![Graph](image)

**Normally-off operation**

- $V_g=0V$: p-AlGaN lifts up the potential at the channel.
- $V_g>V_f$: Hole injection $\rightarrow$ Electron generation $\rightarrow$ Large Drain current

**Very low RonQg**

- $\text{RonQg}$ of 600V GIT is $0.7 \ \Omega nC$ which is $1/13$ of that of the latest SJ-MOSFET.

**Good Recovery characteristics**

- GIT can be operated as a free-wheeling diode with very small charging current.
Power supply

- Power converter have progressed with overcoming design trade-off among power density and efficiency, cost.
- To make more advanced, GaN-FETs have been actively investigated.

GaN power devices used in Power supply

- AC-DC Power Supply
  - PFC
  - Isolated DC-DC converter

- DC12V Bus
  - Non-isolated DC-DC converter

Today’s topic

- Totem-pole PFC using GITs reported by Panasonic on PCIM2014
- 1MHz resonant converter using 600V normally-off GaNs reported by Fraunhofer ISE on ECSCRM2012
- 5MHz/50A GaN POL converter reported on PCIM2014
- GaN POL power IC integrated with gate drivers reported on ISPSD14
For smaller POL converter

- Increasing frequency greatly helps to reduce the system size.
- Low RonQg power device and low parasitic inductance are key factors.

Advantage by increasing frequency

- Compact size with increasing frequency
- Low RonQg power device
- Low parasitic inductance
30V-class normally-off GaN-GITs

- RonQg of developed 30V GaN-GIT is reached to 19.1mΩnC\(^*1\). -> 36% smaller than that of reported Si-MOSFET\(^*2\).

\[ V_g = 4 \text{ V} \] \( R_{on} = 1.8 \text{ mΩ} \)
\[ V_g = 3 \text{ V} \]
\[ V_g = 2 \text{ V} \]

Drain current (A)

Drain voltage (V)

\[
\begin{array}{cccc}
R_{on} & Q_g & R_{on}Q_g & \text{Breakdown voltage} \\
(\text{mΩ}) & (\text{nC}) & (\text{mΩnC}) & (\text{V}) \\
1.8 & 10.6 & 19.1 & 30 \\
\end{array}
\]

\*1 H. Umeda, et al., PCIM2014

Impact of the parasitic inductance

- Parastic inductance on power loop ($L_{\text{Power\_Loop}}$) increase the spike voltage → It limits $\frac{dI}{dt}$ and causes gate oscillation, increase noise.
- Parastic inductance on gate loop ($L_{\text{Gate\_Loop}}$) increase the gate charging time.

Parasitic inductance on Power Loop

$V_{\text{Spike}} \propto L_{\text{Power\_Loop}} \cdot \frac{\Delta I_{DS}}{\Delta t}$

→ limit $\frac{dI}{dt}$ to keep $Vds$ under $BVds$
→ causes gate oscillation
→ generate Noise

Parasitic inductance on Gate Loop

→ Reduction of $L_{\text{Gate\_Loop}}$ also effectively increase gate charging speed
This Work: GaN-based IC with gate driver

- GaN transistors and GaN gate drivers are integrated to a compact chip

Conventional

High-side Transistor (Hi)
Capacitor (C)
Inductor (L)
Si-based Gate Drivers
Low-side Transistor (Lo)

This Work

One Chip
GaN-based IC
Impact of Integration: Small Parasitic Inductances

- Switching speed is increased by reduction of parasitic inductances

Simulated turn-on switching waveform

- $V_{\text{gate driver}}$
- $V_{\text{in}}$
- GaN Transistors
- $L_1$ to $L_4$ = 4.5nH
- $12.5V/ns$
- $L_1$ to $L_4$ = 1nH
- $15.8V/ns$
- Voltage ($V$)
- Time (ns)

12V $\Rightarrow$ 1.8V $I_{\text{out}} = 6A$
2MHz operation
Impact of Integration: Small Parasitic Inductances

- Operation loss is reduced by the reduction of parasitic inductances.

Simulated operation loss

12V ⇒ 1.8V
I_{out}=6A
@ 2MHz

L1+L2
(L3=L4=0)

L3+L4
(L1=L2=0)
GaN Gate Driver : DCFL (Direct Coupled FET Logic)

- High power consumption in GaN gate driver of DCFL.

Circuit Design

DCFL
Large Wg
D-Tr.
E-Tr.1
Vout
5V
VG
lin

Switching Power Device

Charge Current

Short-Circuit Current

Time Chart

Vout
lin
High

VG
tr tf

Short-Circuit Current Flowing
GaN Gate Driver: DCFL with Buffer Amplifier

- Low power consumption in GaN gate driver by buffer amplifier.

Circuit Design

- DCFL
- Buffer Amplifier
- Switching Power Device

Time Chart

- VG
- Vout
- lin
- Short-Circuit Current

Panasonic
GaN Device Structure and Characteristics

- D-mode HFET and E-mode GIT are monolithically fabricated.

Device Structure

- GaN-GIT
- GaN-HFET
- Gate
- Schottky Gate
- AlGaN
- GaN
- Buffer layer
- Isolation layer
- Si Substrate

Device Characteristics

- Ron (Ωmm)
- Ids (A/mm)
- Vgs (V)

Graph:
- HFET
- GIT
- Ron (Ωmm) range: 0 to 30
- Ids (A/mm) range: 1E-10 to 1E+2
- Vgs (V) range: -4 to 8
GaN gate driver is about 40% faster than Si gate driver.

- \( t_{r} = 7\) ns
- \( t_{f} = 5\) ns
- \( C_{\text{load}} = 1500\) pF
- Pulth Width: 50\(\) ns
Power consumption is reduced about 98.5% by using GaN DCFL with buffer amplifier.
GaNs-based DC-DC Converter IC

- Compact chip size is 5.1mm x 2.3mm
- GaN-based IC reduces the system size
Operating Efficiencies of DC-DC Converter

- Peak efficiency of 88.2% is achieved with 12V - 1.8V DC-DC conversion at 2MHz.
Analyzed operating loss of GaN-based IC

- Switching loss have been reduced 15% by using GaN-based DC-DC converter IC.

12V ⇒ 1.8V, I_{out}=6A, \@2MHz

<table>
<thead>
<tr>
<th></th>
<th>Discrete</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Loss (W)</td>
<td>0.80W</td>
<td>0.68W</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>87.8%</td>
<td>88.2%</td>
</tr>
</tbody>
</table>
Summary

Compact GaN-based DC-DC Converter IC with High Speed Gate Drivers for Highly Efficient DC-DC Converters

- **GaN Gate Driver**
  - DCFL with buffer amplifier
  - Monolithically fabrication of HFET and GIT
  - High speed switching \( (t_r + t_f = 12\text{ns}) \)

- **GaN-based IC**
  - 5.1mm X 2.3mm Compact chip size
  - Peak Efficiency \((12V-1.8V) : 88.2\%@2MHz\)

This work is partially supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan, under the Strategic Development of Energy Conservation Technology Project.