High-Efficiency High-Density GaN-Based 6.6kW Bidirectional On-board Charger for PEVs
- 2016 Annual Merit Review Meeting

Dr. Charles Zhu, Principal Investigator
DPM, Livonia, MI
June 8, 2016

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Project Overview

Project Objective

Project Milestones

Prior Arts and Program Goals

Approaches

Technical Accomplishments and Progress
  - GaN device delivery and test
  - 3.3kw GaN-based concept OBC test
  - 6.6kw GaN-based A-Sample design and build
  - CPES Alternative design, build and preliminary test

Responses to Previous Year Reviewer’s Questions

Partners

Proposed Future Works

Summary
**Timeline**
- Period 1 Start – FY14
- Period 1 Finish – FY15 (extended for 3 mo., no cost)
- Project Finish – FY17
- 38% complete

**Budget**
- Total project funding DOE share – $1,487,594
- Total Period 1 funding DOE share - $588,741
- Funding received in Period 1 (FY14 and 15): $519,849

**Barriers**
- Parasitic parameters in GaN device and PCB restricts the switching frequency
- Topology and control Scheme for bi-directional power flow
- Thermal design to remove heat
- High frequency magnetics
- GaN device cost

**Partners**
- Transphorm
- CPES at Virginia Tech
- Fiat Chrysler Automobiles
The objective of this project is to design, develop, and demonstrate a 6.6kw isolated bi-directional On-Board Charger (OBC) using Gallium Nitride (GaN) power switches in a vehicle capable of achieving the specifications identified in Table 1, below. The developed OBC will reduce size and weight when compared to commercially existing Silicon (Si) based OBC products in automobiles by 30%-50%.

### Table 1: Parameter Requirement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Frequency</td>
<td>0.3 - 1 Mega-Hertz (MHz)</td>
</tr>
<tr>
<td>Power Efficiency</td>
<td>95%</td>
</tr>
<tr>
<td>Power Rating</td>
<td>3.3 kilo-Watt (kW) at 120 Volts Alternating Current (VAC), 6.6kW at 240 VAC (Auto sensing depending on AC input voltage)</td>
</tr>
<tr>
<td>Plug-In VAC</td>
<td>120/240 VAC</td>
</tr>
<tr>
<td>High Voltage (HV) Battery Voltage Range</td>
<td>250 - 450 Voltage Direct Current (VDC)</td>
</tr>
<tr>
<td>Nominal Battery Voltage</td>
<td>350 VDC</td>
</tr>
<tr>
<td>AC Line Frequency</td>
<td>50 - 60 Hz</td>
</tr>
<tr>
<td>Maximum Coolant Temperature</td>
<td>70°Celsius (C)</td>
</tr>
<tr>
<td>Ambient Temp Range</td>
<td>-40 to 70°C</td>
</tr>
<tr>
<td>Controller Area Network (CAN) Communication</td>
<td>Yes</td>
</tr>
</tbody>
</table>
FY 2015 Objective: Technology Design and Development

- Design, build and test Iteration III GaN device
- Iteration III GaN device switching performance evaluation
- Advanced circuit development for GaN device application
- Build and test the A-Sample charger

<table>
<thead>
<tr>
<th>#</th>
<th>Milestone</th>
<th>Type</th>
<th>Due Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS 1.1</td>
<td>Si-Based Conceptual Bi-directional Charger Design Complete</td>
<td>Technical</td>
<td>March 2015</td>
</tr>
<tr>
<td>MS 1.2</td>
<td>Si-Based Concept Bi-directional Charger Build Complete</td>
<td>Technical</td>
<td>June 2015</td>
</tr>
<tr>
<td>MS 1.3</td>
<td>Si-Based Concept Bi-directional Charger Test</td>
<td>Technical</td>
<td>Sept. 2015</td>
</tr>
<tr>
<td>MS 1.4</td>
<td>A-Sample Charger Design Completed</td>
<td>Technical</td>
<td>Nov. 2015</td>
</tr>
<tr>
<td>DP 1</td>
<td>Analysis of the test result of the concept bidirectional charger</td>
<td>Go/No Go</td>
<td>Nov. 2015</td>
</tr>
<tr>
<td>MS 2.1</td>
<td>Build the A-Sample charger</td>
<td>Technical</td>
<td>Feb. 2016</td>
</tr>
<tr>
<td>MS 2.2</td>
<td>Test the A-Sample charger and report</td>
<td>Technical</td>
<td>May 2016</td>
</tr>
<tr>
<td>MS 2.3</td>
<td>Design the B-Sample charger</td>
<td>Technical</td>
<td>June 2016</td>
</tr>
<tr>
<td>MS 2.4</td>
<td>Test the B-Sample charger and report</td>
<td>Technical</td>
<td>Dec 2016</td>
</tr>
<tr>
<td>DP 2</td>
<td>Completion of the B-Sample charger prototype build</td>
<td>Go/No Go</td>
<td>Nov 2016</td>
</tr>
</tbody>
</table>
## Prior Arts and Program Goals

<table>
<thead>
<tr>
<th></th>
<th>Prior Art</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>93%</td>
<td>95%</td>
</tr>
<tr>
<td>Function</td>
<td>Uni-directional</td>
<td>Bi-directional</td>
</tr>
<tr>
<td>Power density</td>
<td>0.45-0.75 kW/L</td>
<td>30% to 50% improvement</td>
</tr>
<tr>
<td>Device</td>
<td>Silicon</td>
<td>GaN</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>&lt;100kHz</td>
<td>0.3-1MHz</td>
</tr>
</tbody>
</table>

- **Delta OBCM (3.3kW)**
- **Delta OBCM (6.6kW)**
- **TDK OBCM (6.6kW)**
- **Panasonic OBCM (6.6kW)**
- **Delta Solar Inverter (5kW)**
Approach
– Reduce number of switching devices

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Si-based</th>
<th>GaN-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>TO-247 Switch</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>TO-247 Diode</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>TO-220 Switch</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Total Devices</td>
<td>76</td>
<td>24</td>
</tr>
</tbody>
</table>

Features
- Low Qm
- Free-wheeling diode not required
- Quiet Tab™ for reduced EMI at high dv/dt
- GSD pin layout improves high speed design
- RoHS compliant
- High frequency operation
Approach
– Increase switching frequency

• Approximately 30% of the volume of OBC is taken by magnetic components and capacitors.
• Increasing switching frequency will reduce the size and cost of these components.
• GaN device has lower switching loss, thus allow higher switching frequency.

<table>
<thead>
<tr>
<th></th>
<th>GaN HEMT</th>
<th>Si MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_{ds on}</td>
<td>63mΩ</td>
<td>58 mΩ</td>
</tr>
<tr>
<td>C_{oss tr}</td>
<td>283nC</td>
<td>1110nC</td>
</tr>
<tr>
<td>Q_g</td>
<td>10nC</td>
<td>64nC</td>
</tr>
<tr>
<td>Q_{rr}</td>
<td>138nC</td>
<td>10000nC</td>
</tr>
</tbody>
</table>
Three Iterations of GaN HEMT devices have been developed and delivered.

<table>
<thead>
<tr>
<th></th>
<th>Iteration I</th>
<th>Iteration II</th>
<th>Iteration III</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN</td>
<td>TPH3205WS</td>
<td>TPH3205WSA</td>
<td>TPH3207WS</td>
</tr>
<tr>
<td>Quantities delivered</td>
<td>180</td>
<td>550</td>
<td>190</td>
</tr>
<tr>
<td>Rds,(\text{on})</td>
<td>63mΩ</td>
<td>52mΩ</td>
<td>35mΩ</td>
</tr>
<tr>
<td>Co_tr</td>
<td>283pF</td>
<td>247pF</td>
<td>430pF</td>
</tr>
<tr>
<td>Qg</td>
<td>10nC</td>
<td>19nC</td>
<td>28nC</td>
</tr>
<tr>
<td>Qrr</td>
<td>138nC</td>
<td>136nC</td>
<td>175nC</td>
</tr>
</tbody>
</table>

I-3 device has 33% lower Rds,\(\text{on}\) than I-2 device. Unfortunately, it also has higher charge, which will make switching performance sacrifice. Delta plan to do performance comparison between I-2 and I-3 devices on A-Sample OBC.
Technical Accomplishments and Progress

Transphorm conducted qualification tests on the Iteration II GaN HEMT device.

<table>
<thead>
<tr>
<th>Document #</th>
<th>Revision</th>
<th>Process Owner</th>
<th>Effective Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>700254</td>
<td>1</td>
<td>Ronald Barr</td>
<td>Nov. 11, 2015</td>
</tr>
</tbody>
</table>

**Title:** Qualification Report TPH3205WS

- a) AEC-Q101: Stress Test Qualification for Automotive Grade Discrete Semiconductors
- b) JESD47: Stress-Test Driven Qualification of Integrated Circuits
- d) JESD22-A108C: High Temperature Reverse Bias (HTRB)
- e) JESD22-A110D: Highly Accelerated Temperature and Humidity Stress Test (HAST)
- f) JESD22-A104D: Temperature Cycle (TC)
- g) JESD22-A122: Power Cycle (PC)
- h) JESD22-A103C: High Temperature Storage Life (HTSL)
- i) JESD22-A115B: Electrostatic Discharge Machine Model
- j) JS-001-2012: Electrostatic Discharge Human Body Model
- l) MIL-STD-883E, 2002.3 Condition A: Mechanical Shock
Selected Topology for Concept Design

Bi-Direction AC/DC

120/240Vac

Bi-Directional DC/DC

400Vdc

250Vdc~450Vd

Topology: PFC/Inverter

Topology: DBA derived LLC

PROs

• Mature DC/AC design

• Soft switching DC/DC

CONs

• Higher loss of DC/AC due to hard switching

This is Plan A – Delta design OBC with this topology
Technical Accomplishments and Progress

- 3.3kW bi-directional charger concept prototype PCB
**Technical Accomplishments and Progress**

- 3.3kw GaN-based Concept OBC Test Result

**Charger Mode Efficiency**

**Charger Mode Power Factor**

**Test condition:**
- 240Vac input
- full load
Technical Accomplishments and Progress

- **3.3kw GaN-based Concept OBC Test Result**

  Test conditions:
  - D2D+D2A whole stage
  - Vbus=400v
  - Vac=240v
  - Pmax=3300w
  - R load
  - W/O EMI filter loss

  Inverter Load jump
  600W→1500W→600W

  Inverter Mode Efficiency

  - 250Vbat: 89.99%, 91.60%, 93.25%, 94.60%, 94.64%, 94.60%, 94.49%, 94.39%, 94.14%
  - 300Vbat: 89.98%, 92.34%, 93.98%, 94.75%, 95.05%, 95.08%, 95.02%, 94.87%, 94.69%, 94.48%
  - 350Vbat: 88.77%, 92.12%, 93.63%, 94.67%, 95.08%, 95.29%, 95.30%, 95.25%, 95.13%, 95.01%
  - 400Vbat: 89.65%, 91.60%, 92.82%, 93.66%, 94.30%, 94.63%, 94.80%, 94.82%, 94.75%, 94.71%
  - 450Vbat: 89.20%, 91.03%, 92.26%, 92.95%, 93.60%, 93.99%, 94.28%, 94.35%, 94.31%, 94.26%
Technical Accomplishments and Progress

- A-Sample Design

Parallel of two 3.3kw modules
- The synchronous signal and AC side sensing signal are isolated
- Use droop control to reduce circulating current
Technical Accomplishments and Progress

- 6.6kw A-Sample OBC

Picture of A-Sample prototype
Dimension: 296x250x75mm
Technical Accomplishments and Progress

- **Charger Mode Soft Start**

  Test condition: Vbus=400v; Vbat=450v; Po=1kw

  Ch1:Vbus, Ch2:Vgs_Q1011, Ch3:Ip, CH4: Vbat

  - The power on set point is 380v and the power off set point is 370v.
  - The max frequency is limited at 800khz.
Technical Accomplishments and Progress

- Inverter Mode Battery Side Current Ripple

Test condition: Vbat=400v/450v; Vac=240v; R load

400v input 3.3kw  
CH1: Ibat_ripple  CH3: resonant current  450v input 3.3kw

The battery side output current ripple is lower than 10%.
Technical Accomplishments and Progress

- Inverter Mode Dynamic Load Response

Test condition: $V_{bat}=450\,v; \, V_{ac}=240\,v; \, R\, \text{load}$

$CH1: V_{ac} \, Ch2: V_{gs-D2D}, \, CH3: \, \text{resonant current}, \, CH4: \, V_{bus}$

![Graph showing dynamic load response with test conditions](image)

0w $\rightarrow$ 1800w

900w $\rightarrow$ 2700w
Technical Accomplishments and Progress

- CPES alternative Topology (PFC + Semi-DCX)

1st Stage: Totem-pole PFC
   (CRM ZVS operation)
   1200V SiC Device

2nd Stage: CLLC
   (Almost fixed frequency)
   600V GaN Device

Developed by CPES
Technical Accomplishments and Progress

- CPES alternative Topology (PFC + Semi-DCX)

- All fast switch can achieve soft switching
- Large current ripple can be compensated by two phase interleave

Soft Switching to Eliminate Turn on Loss

Developed by CPES
Technical Accomplishments and Progress

- CPES alternative Topology (PFC + Semi-DCX)

Split core structure can reduce the required number of PCB layers.
Technical Accomplishments and Progress

- CPES alternative Topology (PFC + Semi-DCX)

**PFC (>300kHz)**

- Height: 420mm (16.5in)
- 270mm (10.6in) w/ cold plate

**DC/DC (~500kHz)**

- 24W/in³

- Change to electrolytic cap:
  - 32W/in³ > 38W/in³
  - 0.1% Efficiency Drop

Developed by CPES
Technical Accomplishments and Progress

• CPES alternative Topology (PFC + Semi-DCX)

Over 96% efficiency is achieved over the whole battery voltage range

Developed by CPES
Delta Products Corporation (Primary Recipients)
Administrative responsible to DOE, single point of contact
Technical direction and program management
Timing and deliverables, budget control
OBCM Prototypes development and testing, system integration
Commercialization

Transphorm, Inc.
High frequency GaN device development
GaN device characterization and qualification

CPES at Virginia Tech
GaN device in circuit evaluation
High frequency circuit topology selection and evaluation
High-frequency magnetic components development

FCA US LLC
Vehicle integration and testing
Commercialization
Proposed Future Work

- **Remainder of FY 2016**
  - Compare performance of Iteration III and Iteration II Device in PBC modules
  - Test A-Sample GaN-based OBCs
  - Develop B-Sample GaN-based OBC
  - Develop and finalize market introduction plan at device level and charger level.
  - Confirm host vehicle and integration plan.

- **FY2017**
  - Develop vehicle test plan.
  - Vehicle integration.
  - Test the OBC in vehicle.
Summary

• **DOE Mission Support**
  • Test and test one concept bi-directional OBC.
  • Design and build the first generation of GaN-based OBC.

• **Approaches**
  • Reduce switching devices from 76 Si devices to 24 GaN devices
  • Increase switching frequency to reduce passive components size
  • Develop software switching technology to reduce switching loss

• **Technical Accomplishment**
  • Developed and evaluated three iterations of GaN devices.
  • Designed, built and tested concept 3.3kw GaN-based OBC to verify architecture and high frequency switching circuit
  • Designed and built A-Sample 6.6kw GaN-based OBC to verify thermal performance and packaging design
  • Developed alternative topology with SiC/GaN devices
Summary

• Future Work
  • Test A-Sample 6.6kw OBC samples
  • Design, build and test B-Sample OBC samples
  • Test prototype of PFC + Semi-DCX topology
  • Test OBC in vehicle
  • Create commercial plan

To learn more about Delta, please visit www.deltaww.com.