Radiation-Tolerant, GaN-based Point of Load Converters for Small Spacecraft Missions

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Outline

- Acknowledgements
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- Challenges
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  - Power Electronic Benefits
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- Converter Design
- Results
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  - Efficiency
  - Thermal
- Conclusions

Key Terms
- GaN: Gallium Nitride
- HEMT: High-Electron-Mobility Transistor
- PoL: Point-of-Load Converter
- COTS: Commercial-Off-The-Shelf
Acknowledgements

- NSF Center for Space, High-Performance, & Resilient Computing
  - Founded in Sep. 2017, replacing highly successful NSF CHREC Center
  - Leading ECE research groups at four major universities
    - University of Pittsburgh (lead)
    - Brigham Young University (partner)
    - University of Florida (partner)
    - Virginia Tech (partner)
  - Partners with over 30+ industry and government partners including NASA, Honeywell, and Lockheed Martin...

- Electric Power Systems Lab at University of Pittsburgh

- IUCRC Program at National Science Foundation
  - Industry-University Cooperative Research Centers (IUCRC)
  - SHREC is National Research Center and Consortium

- DoD Space Test Program (STP) Houston
  - Sponsored program to launch research experiments to ISS

See nsf-shrec.org for more info
CubeSat-sized Spacecraft Supercomputing for Image and Video Processing (SSIVP)
- Five flight-qualified CSPv1 computers with two cameras, one μCSP on Smart Module with GaN converter experiment, power card and backplane for power distribution and interconnects
- Thermal and vibration testing passed at NASA Goddard, special thanks to Branch 587/596
- Machined aluminum enclosure occupies 3U of space on pallet
- Preliminary launch date for STP-H6 is early 2019
  - Experiment to be tested from 401.1 km to 408.0 km at 51.64° inclination
CSPv1 Flight Computer

- NSF SHREC developed flight-qualified space computer combining:
  - Hybrid System-on-Chip
    - Fixed-logic CPU
    - Reconfigurable-logic FPGA
  - Mix of Rad-Hard and COTS technology
  - Fault-Tolerant Computing
- Zynq 7020 (ARM dual-core Cortex-A9 + Artix-7 FPGA)
  - (1-4) GB NAND Flash, (256 MB – 1 GB) DDR3
  - Powered from a 3.3V and 5V feed, onboard converters used for 2.5V, 1.8V, and 1.0V power generation
- 2.8W max power draw at 100% capacity
- Success of STP-H5/CSP mission raised the Technology Readiness Level of CSPv1 card to flight-proven technology
  - Over 3500hr of flight uptime
µCSP and Smart Module

• Smart Module
  o SSIVP Smart Module integrates **GaN converter experiment** and measurement circuitry
  o TI INA260 ADC used for measuring input and output power of GaN converters
  o 4.7Ω power resistor used for fixed load on GaN converters, mounted to back of smart module

• µCSP
  o Commercial Microsemi SmartFusion2 hybrid SoC with fixed-logic ARM Cortex-M3 microcontroller
  o 64 MB NOR Flash and 1 GB LPDDR3
  o Dedicated Watchdog Unit
  o Average 0.6W of power draw
Challenges

- Space PoL Converters are historically expensive, large, heavy, and inefficient
  - Many average from 63% to 75% peak efficiency
  - Switching frequencies of 100kHz - 500kHz

- Proposed Converter
  - Mix of COTS controllers and radiation-tolerant GaN devices provides high efficiency and power density
  - High frequency (2 MHz) operation makes converter layout significantly more important
  - Small size increases importance of thermal conductivity

- COTS controllers are not designed to operate in radiation-heavy and harsh environment of space
  - Must be used to drive GaN transistors at high frequencies and low gate voltages
Why GaN?

- GaN HEMTs are approximately ¼ area of COTS and Rad-Hard MOSFETs
- Two package types used to provide a reliability and efficiency comparison for PoL experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TDG100E15B</th>
<th>EPC2014C</th>
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</thead>
<tbody>
<tr>
<td>Drain-Source Voltage</td>
<td>3.8 - 42V</td>
<td>4.5 - 38 V</td>
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<tr>
<td>Threshold Gate-Source Voltage</td>
<td>1.3 V</td>
<td>1.4 V</td>
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<tr>
<td>Maximum Gate-Source Voltage</td>
<td>7 V</td>
<td>6 V</td>
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<tr>
<td>Maximum On Resistance</td>
<td>21 mΩ</td>
<td>16 mΩ</td>
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<tr>
<td>Gate Charge</td>
<td>6.2 nC</td>
<td>2.5 nC</td>
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<tr>
<td>Package Type</td>
<td>SMD-0.6 Ceramic</td>
<td>Passivated BGA Die</td>
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<tr>
<td>Package Size</td>
<td>10.16mm x 7.52mm</td>
<td>1.702mm x 1.087mm</td>
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</table>
Power Electronic Benefits

- Band gap of GaN is 3.4eV vs Silicons 1.2eV
- GaN thermal conductivity is 1.3 W/cmºC versus Silicon conductivity of 1.49 W/cmºC
- Low gate capacitance allows for faster turn on time and reduces switching losses
- Low ON resistance compared to radiation-hardened silicon reduces conduction losses
Schottky metal gate of GaN HEMTs reduces chances of Total Ionizing Dose (TID) high energy particles causing accumulation of charges building up on gate.

Smaller depletion of region of GaN HEMTs reduces damage caused by heavy ions.

The band-gap of GaN HEMTs require much higher energy photons or ions to achieve ionization in the semiconductor, reducing susceptibility to SEEs.
Converter Design

- General Design
  - Synchronous Buck Converter for 12V input to 5V or 3.3V output
    - Using LTC3833 and LM25141-Q1 controllers
    - Single resistor modification needed to change output voltage level
  - Direct, protected gate drive for GaN HEMTs achieved through clamped bootstrap circuit
  - Low circuit board parasitics enable fast switching

- Reduced Cost Boards
  - Designed for 30% inductor current ripple
    - LTC3833 uses 2.2µH inductor
    - LM25141-Q1 uses 3.3µH inductor

- Flight Boards
  - Both controllers use 4.7µH inductor
  - Fixed 5V output over 4.7Ω load resistor

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<tr>
<th>Parameter</th>
<th>LTC3833</th>
<th>LM25141-Q1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage Range</td>
<td>4.5 – 38 V</td>
<td>3.8 – 42 V</td>
</tr>
<tr>
<td>Output Voltage Range</td>
<td>0.6 – 5.5 V</td>
<td>1.5 – 15 V</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>1.9 MHz</td>
<td>2.2 MHz</td>
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<tr>
<td>Gate Drive Voltage</td>
<td>5.3 V</td>
<td>5 V</td>
</tr>
</tbody>
</table>

OSH Park
An electric ecosystem

Mission-Critical Computing
NSF CENTER FOR SPACE, HIGH-PERFORMANCE, AND RESILIENT COMPUTING (SHREC)
Converter Layout

Reduced Cost Boards

Converter Layout

Reduced Cost Boards
Converter Layout

Assembled Reduced Cost Boards

EPC Test Converter
Area: 0.62in²
Weight: 2.32g

E2V Test Converter
Area: 0.85in²
Weight: 4.74g

Representative Rad-hard PoL Converter
Area: 1.16in²
Weight: 16g
Converter Layout

Flight Boards

Representative Rad-hard PoL Converter
Area: 1.16in²
Weight: 16g

EPC Test Converter
Area: 0.62in²
Weight: 2.32g

E2V Test Converter
Area: 0.85in²
Weight: 4.74g
Converter Layout

Assembled Flight Boards

EPC Test Converter
Area: 0.62in²
Weight: 2.32g

EPC Flight Converter
Area: 0.41in²
Weight: 1.31g

E2V Test Converter
Area: 0.85in²
Weight: 4.74g

E2V Flight Converter
Area: 0.64in²
Weight: 3.76g

Representative Rad-hard PoL Converter
Area: 1.16in²
Weight: 16g
Simulation Results
Simulation Results

Average inductor current of 1.05A with ripple value of 771mA or 31%

Gate drive voltage signals for top gate (red) and bottom gate (green)

Average voltage of 4.917V with ripple value of 6mV or 0.1%
Switching Waveforms

Average inductor current ripple of 31.2% measured differential over sense resistor

Gate drive voltage signals for top gate (blue) and bottom gate (green)

Average voltage of 5V with ripple value of 8.2mV or 0.1%
• Efficiency measurements performed using electronic load and oscilloscope
  - Efficiencies seen between 94% to 96% for 5V output
  - Efficiencies seen between 70% to 85% for 3.3V output
  - Converters with EPC HEMTs see higher efficiencies for both LM25141 and LTC3833 controllers
Thermal Performance

- Thermal performance of GaN converters was performed using FLIR thermal camera
  - Transient thermal response performed with a 1A load, reached steady state of 40ºC at 2 minutes
  - Steady state thermal response was performed over 0 to 2A with peak temperature of 60ºC
Proposed Application

- Generic CubeSat power topology uses two isolated rad-hard converters to generate 12V and 5V rails
  - PoL converter off of 5V rail provides 3.3V
  - Low isolated 5V converter efficiency
- Proposed GaN application is using single isolated 28V to 12V converter for powering CubeSat
  - GaN PoL converters used to provide 5V and 3.3V rails from 12V
  - Higher overall efficiency
- Future CubeSat designs integrate GaN converters onto compute boards to minimize number of individual converters
  - Single isolated 28V to 12V converter
  - 12V power input to FPGA/SoC board and GaN PoL converters provide 2.5V, 1.8V, and 1.0V
  - Reduced number of individual converters
Future Work

- Radiation and efficiency testing will be performed on ISS when launched in Spring 2019.
- LANSCE radiation testing on LTC3833, TI LM25141-Q1, and Smart Module measurement circuitry.
- Future converters will be tested with more test cases for efficiency and output voltage ripple:
  - 28V, 12V Input
  - 1V, 1.8V, 2.5V, 3.3V, 5V, 12V Output
  - Output switching voltage will be optimized for use as a direct FPGA powering PoL converter.
- Integration into STP-H7 with CASPR Experiment.
Thank You!

Questions?

See nsf-shrec.org for more info