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Research Article

High-Temperature SOI/SiC-Based DC-DC Converter Suite

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A complete design strategy (mechanical and electrical) for a 25 W 28 V/5 V dc-dc converter utilizing SiC and SOI electronics is presented. The converter includes a high-temperature SOI-based PWM controller featuring 150 kHz operation, a PID feedback loop, maximum duty cycle limit, complementary or symmetrical outputs, and a bootstrapped high-side gate driver. Several passive technologies were investigated for both control and power sections. Capacitor technologies were characterized over temperature and over time at 300°C, power inductors designed and tested up to 350°C, and power transformers designed and tested up to 500°C. Northrop Grumman normally-off SiC JFETs were used as power switches and were characterized up to 250°C. Efficiency and mass optimization routines were developed with the data gained from the first prototype. The effects of radiation on SiC and SOI electronics are then discussed. The results of the first prototype module are presented, with operation from 25°C up to an ambient temperature of 240°C .

1. INTRODUCTION

The weight of a power electronic converter can be significantly reduced by allowing the active power devices to operate at elevated temperatures, minimizing the requirements of the bulky cooling system. High-temperature power converters would find new applications in space vehicles (i.e., satellites, shuttles, etc.), where increased power density results in important launch cost reductions or increased payload.

Other applications of this technology are electronics needed for extreme environments, such as the downhole orbital vibrator (DHOV) [1]. High-temperature power electronics could increase mapping resolution by an order of magnitude, significantly reducing operation times for geological exploration activities while improving the capability to discover hidden petroleum reserves.

This paper presents a suite of high-temperature (300°C) dc-dc converters developed using silicon carbide (SiC) power devices (i.e., power switches and diodes) and high-temperature HTMOS devices. Power electronic converters have been previously demonstrated at 250°C operation in [1]. The work presented in this paper is a stepping stone to higher temperatures (300°C) and lighter weight due to converter optimization. The paper first outlines the dc-dc converter electrical design approach in Section 2. Next, the efficiency and mass optimization method is described in Section 3. Section 4 focuses on the mechanical design of the dc-dc converter. Section 5 discusses potential advantages of the design in terms of radiation tolerance due to the use of silicon on insulator (SOI) and SiC components. Finally, Section 6 presents 25 W 28 V/5 V dc-dc converter prototype and testing results.

2. MCPM ELECTRICAL DESIGN

The prototype converter is rated for 28 V input voltage and 5 V output voltage at 25 W. These low-power and low-voltage levels were chosen to ease the design of the power stage and to provide a safe environment for testing control and gate driver circuitries. The half-bridge converter topology was selected due to its versatility and ability to demonstrate a variety of components used in power processing (i.e., transistors, diodes, capacitors, inductors, and transformers).

The PWM controller was built utilizing high-temperature SOI (HTSOI) components (i.e., HT1104 SOI quad

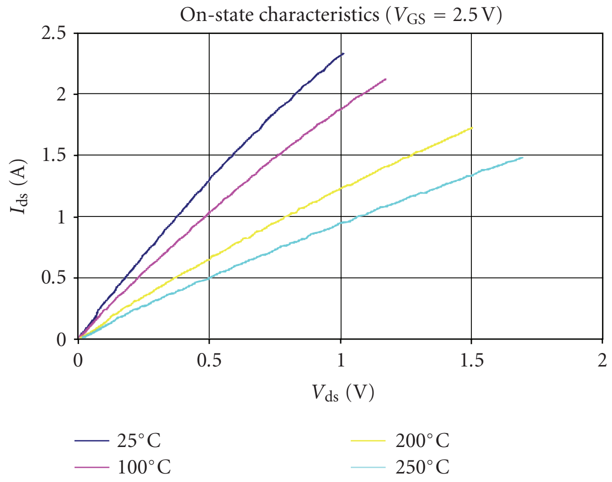

Figure 1: On-state characteristics of Northrop Grumman SiC JFETs.

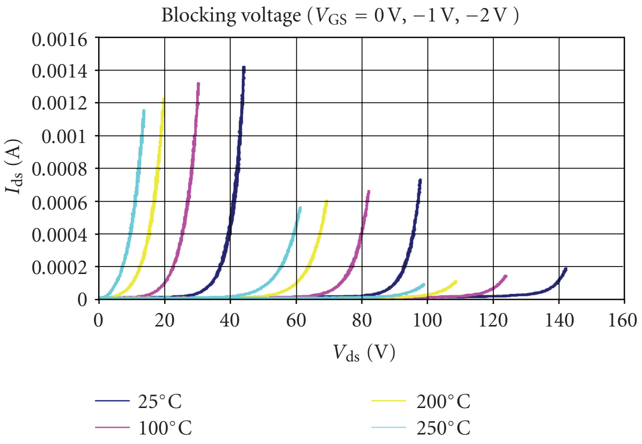

Figure 2: Blocking voltage of Northrop Grumman SiC JFETs.

op-amps and HT1204 SOI quad analog switches) manufactured by Honeywell, Plymouth, Minn, USA. This suite of HTSOI components operates at temperatures as high as 300°C. In this design, an op-amp stage serves as a relaxation oscillator, which feeds into two analog switches configured as inverters. The inverters drive RC networks, which produce two near-linear triangle waves. The triangle waves are compared to the output of the error amplifier with two op-amp stages configured as differential amplifiers. The outputs of the differential amplifiers are passed through analog switches to complete the comparison process and produce pulse-width-modulated (PWM) signals.

The power switches used in the power stage of the converter are normally off 4H-SiC JFETs manufactured by Northrop Grumman, Los Angeles, Calif, USA. SiC JFETs are most commonly available in the normally on type, which requires special gate driver circuitry. These normally off devices can enable the use of more conventional gate drive techniques. These devices were initially characterized by a temperature up to 250°C. Figure 1 shows the on-state characteristics of a single cell in the device (there are 7 cells on a single die) with V_{GS} = 2.5 V. The on-resistance of the device increases with increasing temperature from 400 mΩ at 25°C to 1 Ω at 250°C. Figure 2 shows its blocking voltage for several values of gate voltage. The blocking capability of the devices decreases with increasing temperature, which allows about 90 V at 250°C with V_{GS} = −2 V.

Once the devices were characterized, a set of specifications was determined for the design of the gate driver circuitry. The gate drivers were built utilizing high-temperature SOI power MOSFETs (i.e., HTNFETs) manufactured by Honeywell and SiC Schottky diodes of Cree, Inc., Durham, NC, USA. The outputs of the drivers are ac-coupled into the gates of the power transistors and clamped with diode networks to provide +/− drive capability. The high-side driver is a unique variation of a bootstrapped floating driver in which the pull-up and pull-down networks float independently, each with its own bootstrap capacitor.

High-value capacitors are a particular problem in high-temperature power electronics. Arkansas Power Electronics International, Inc., Fayetteville, Ark, USA, is working with TRS Technologies, Inc., State College, Pa, USA, to develop high-temperature capacitor solutions; however, it was necessary to determine the high-temperature capability of currently available technologies for demonstration purposes. Several technologies were tested at 300°C for a period of two weeks (330 hours). The NP0 and X8R ceramic types performed well for the duration of the test. NP0s varied little over the temperature range and over time. X8Rs decreased to approximately one third of their nominal capacitance at 300°C, and varied little over time. Although the capacitance of the X8Rs decreased greatly at high temperature, the capacitors obtained higher energy storage density than NP0s; therefore, X8R technology was used for the filter capacitors in the demonstration prototype.

For the power transformer and the output inductor, several core and winding materials were considered [2]. Using these materials, APEI engineers developed a transformer that operates at an ambient temperature of 500°C. The transformer was tested for two months (1500 hours) at 500°C with no observable degradation in characteristics.

3. MCPM EFFICIENCY AND MASS OPTIMIZATION

Optimization software was also developed, which calculates all of the necessary components for the dc-dc converter and analyzes the impact of changing parameters on other systems. This software selects the optimal operating conditions (i.e., switching frequency, baseplate temperature, etc.) and component technologies (i.e., magnetic cores, power switches, etc.) which will provide the most lightweight power management and distribution system available. Additionally, the software can evaluate the effects that the chosen operating conditions have on the power generation and thermal management systems.

The DIRECT optimization algorithm [3] was utilized to arrive at the optimum operating point quickly. DIRECT

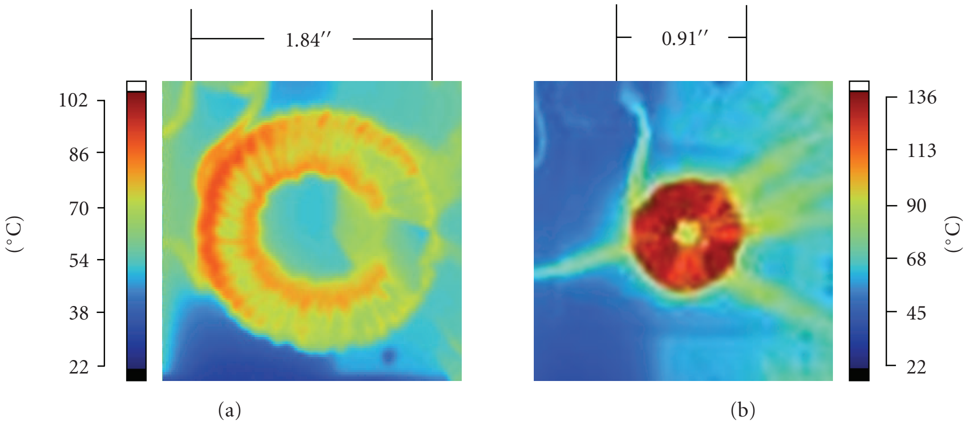

Figure 3: Thermal images of high-power transformers.

identifies potentially optimal hyper-rectangles in the given design space, and iteratively divides these into deeper levels of hyper-rectangles. The main advantage of DIRECT is that the global minimum can be found in a highly discontinuous function, which is usually not the case in less exhaustive algorithms.

The DIRECT algorithm iteratively passes design parameters to a hierarchical function tree, which begins with the topology selection. The topology functions calculate the necessary parameters for the components in a given topology and pass those parameters to the component design functions. For instance, the full-bridge topology function finds the required capacitance for the output capacitor, turns ratio and power requirements for the transformer, output inductor inductance, and dc bias, and so forth. These values are then passed to the respective component design functions, which return the designs to the topology function (e.g., size, weight, part number). Based on these results, the topology selection function chooses the optimal topology (and its corresponding components) for the given operating conditions. Many types of topologies can easily be implemented in the future by entering the required design equations into the program.

One of the most important factors in increasing power density is the highly optimized power transformer design included in the developed software. Figure 3 shows thermal images of two transformer designs rated for 1 kW (operating at 500 W as pictured). These transformers were designed to operate at an ambient temperature up to 300°C, although the thermal images show operation at room temperature. Figure 3(a) shows the initial transformer design. The transformer operates at 75°C (from 25°C ambient temperature) and has 20 W of losses. Figure 3(b) shows the optimized transformer, which operates at 135°C (from 25°C ambient temperature) and has 15 W of losses. Although the optimized design has lower losses, the temperature rise is greater because the power is being dissipated in a much smaller volume. The weight of the transformer was reduced from 171 grams to an impressive weight of 13 grams and the volume from 51 cm^3 to 9 cm^3. Additionally, the transformer design routine was able to calculate the temperature rise of the transformer to within 5°C and the weight to within 1 gram.

Using the results from hardware prototypes, the design processes for several functions were confirmed to be operational and accurate. Other functions produced slightly inaccurate results due to the lack of experimental results, but these were corrected with the information gained in the prototypes. With the validation of the program, an optimal design can be reached. Figure 4 shows a plot of the weight of a 1 kW power system (including resulting weights of the power generation system, the thermal management system, and the dc-dc converter) over a range of switching frequencies and baseplate temperatures. For this case, the minimum weight for this system was found to be at 200°C baseplate temperature and 30 kHz switching frequency. The thermal management system was assumed to be a heatsink utilizing only natural convection cooling. The power generation system was assumed to be a solar array, which has a low power density (i.e., 100 W/kg) compared to other power generation systems. This greatly affects the sensitivity of changes in weight due to efficiency; therefore, this curve will look quite different for a higher power density generation unit.

4. MCPM MECHANICAL DESIGN

In order to make the converter compact and lightweight, a high-temperature multichip power module (MCPM) packaging approach was taken combining power devices and control electronics into a single substrate. The packaging design focused on overcoming a few main issues to enable the converter to operate at high temperatures. First, the packaging materials were carefully selected to have closely matched coefficients of thermal expansion (CTE) and a high thermal conductivity. Secondly, interconnects such as wire bonds and die attachments were chosen to be compatible with the substrate metallization and the converter components.

A thick-film approach was chosen for the MCPM substrate due to its ease of processing, inherent high-temperature resilience, and excellent CTE match with the

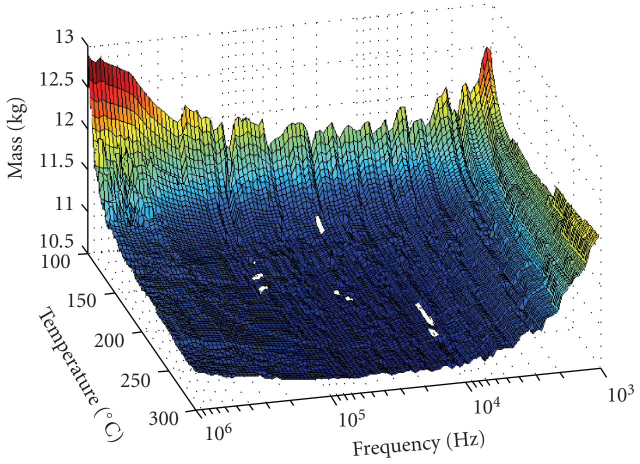

Figure 4: Mass of a power system over frequency and temperature.

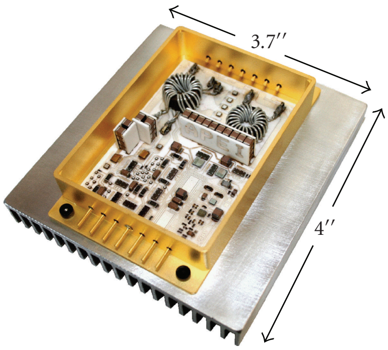

Figure 5: Completed high-temperature SOI/SiC-based dc-dc converter.

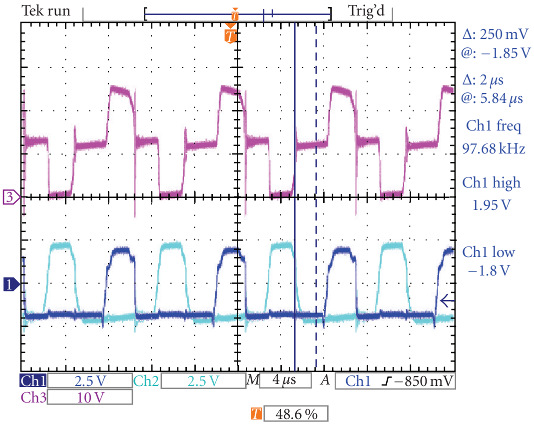

Figure 6: Switching waveforms at 240°C.

bare die devices. Thick-film metallizations are glass-metal structures that provide extremely high film strength and high bond strength with the substrate (the glass frit adheres strongly to the ceramic base). Single-layer substrates are formed on either alumina (Al_2O_3) or aluminum nitride (AlN). Alumina is a much stronger material than aluminum nitride; however, AlN has higher thermal conductivity. For this converter, alumina was chosen, as strength and reliability were traded for thermal conductivity.

The researchers have performed a number of experiments with wire bonds in extreme environments, and found that, given the proper metallization and wire bond interface, wire bonding can be a reliable interconnect at high temperature. Recent extensive testing in other projects has shown 3-mil Au-Au bonding to be highly reliable, even with ΔTs in excess of 600°C (−20°C to +600°C), exceeding military destructive pull-force specifications by 4-5 times on average [4]. For this converter, 3-mil Au wire was utilized for the SiC power JFETs, and 1-mil Al wire was used for connecting the SOI devices.

5. RADIATION TOLERANCE OF SiC AND SOI

Radiation hardness is a major concern for any project designed for space application. SiC has been considered a promising technology in the arena of rad-hard technology for many years. This is largely due in part to the wide bandgap present in SiC (3.26 eV in SiC compared to 1.12 eV in Si). Due to the wide bandgap, SiC has an innate hardness to displacement damage and ionizing radiation [5]. 6H-SiC also has a carrier removal rate that is about three times lower than that of Si; carrier concentration actually increases by two to three times as the temperature is increased from 25°C to 300°C [6]. These two factors together greatly enhance the attractiveness of SiC for extreme environments when radiation is a factor. Most failures due to displacement damage or ionizing radiation are caused by carrier removal or entrapment. Not only does SiC's greater carrier concentration prove to be advantageous over silicon at lower temperatures, but also SiC has the added benefit of being able to operate at temperatures well above the threshold of silicon while providing no noticeable degradation of performance.

SiC has another unique advantage over silicon in the fact that it is inherently rad-hard to most single-event effects (SEEs); however, SiC SBDs have shown susceptibility to single-event burnout (SEB) failures [7]. The most significant result of the study in [7] was that the bias voltage of the diodes could be derated to satisfy radiation needs. For example, an SiC SBD rated for 600 V reverse bias breakdown shows no SEB failure while operating at 450 V reverse bias with fluences up to 1×108 p/cm^2 (70 MeV).

The control portion of the converter is composed of high-temperature SOI devices, which, much like SiC, are considered to have inherent rad-hard characteristics. SOI devices are much harder to single-event upset (SEU) failures when compared to bulk-silicon devices; this is attributed to SOI having a much smaller sensitive volume for charge collection. Previous radiation testing of Honeywell devices has received recognition for the manufacturing process as truly rad-hard, showing no signs of SEU with linear energy transfer (LET) of up to 120 MeV·cm^2/mg, with statistically zero upsets per day (no orbit dependence) [8].

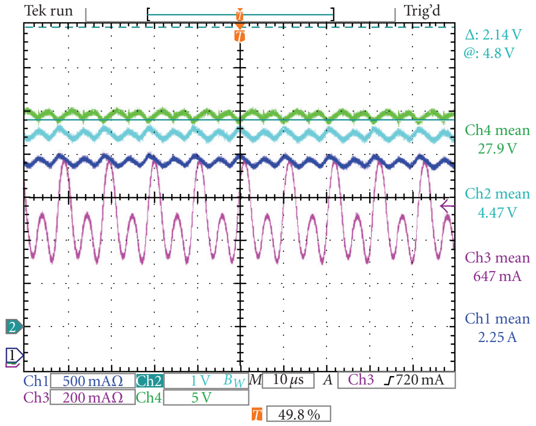

FIGURE 7: Power waveforms at 240°C.

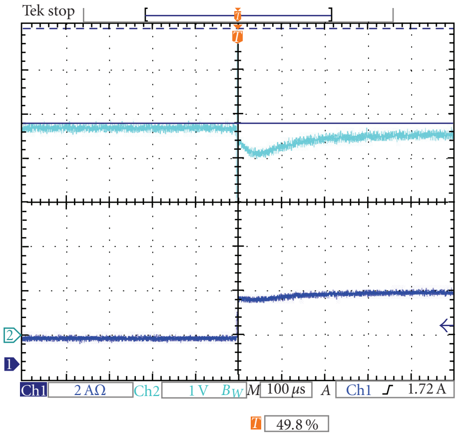

FIGURE 9: Low-to-high current transient.

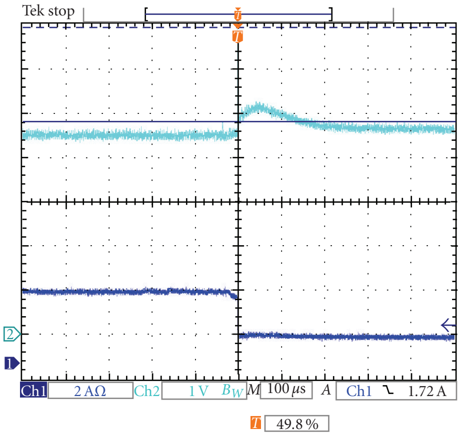

FIGURE 8: High-to-low current transient.

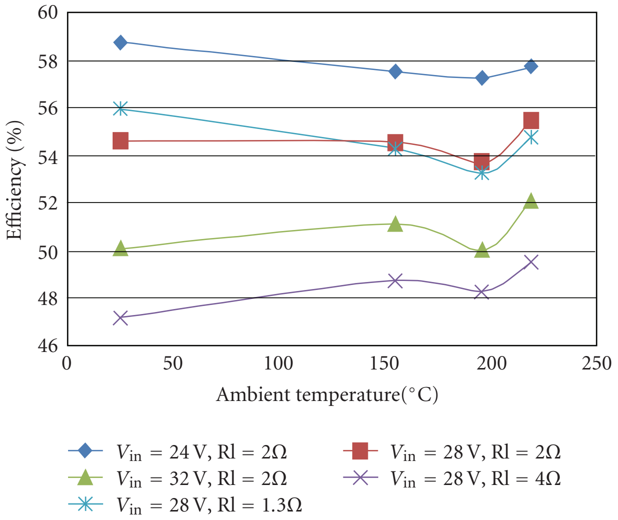

FIGURE 10: Efficiency over temperature.

6. 25-W 28-V/5-V PROTOTYPE DC-DC CONVERTER

Figure 5 shows the completed SOI/SiC-based dc-dc converter. The control and power circuitries were both implemented on the same ceramic substrate. The converter is enclosed by a gold-plated Kovar power package and mounted to an aluminum heatsink. The converter was tested up to a maximum temperature of 250°C and continuously at 240°C for a period of approximately 24 hours.

Figure 6 shows the switching waveforms for the converter at 240°C. Channel 1 (dark blue) and channel 2 (light blue) are the gate-to-source signals seen at the power switches, and channel 3 (pink) is the drain-to-source voltage of the low-side power transistor. Slight distortion can be seen in the drain-to-source signal due to distortion in the gate-to-source signals. This ultimately limits the maximum temperature of operation to about 250°C, though each component in the converter can be operated up to 300°C. With correct temperature compensation of the controller's op-amp stages, the converter will operate at 300°C ambient temperature. This, however, is the topic of another paper.

Figure 7 shows the power waveforms for the converter at 240°C. Channel 1 (dark blue) is the output current, channel 2 (light blue) is the output voltage, channel 3 (pink) is the input current, and channel 4 (green) is the input voltage. The ripple components are small with respect to the dc components of the output waveforms, indicating a clean supply. The input current has a high ripple component, which is most likely caused by the voltage source used to power the dc-dc converter.

Figures 8 and 9 show the transient waveforms for the converter. Figure 8 shows the behavior of the output voltage when the load transitions from high current to low current. Similarly, Figure 9 shows the sag in output voltage when the load transitions from low current to high current. In both cases, the voltage transients are less than the requirement of 1 V, and the settling time of each is about 200 microseconds.

Figure 10 shows the efficiency of the converter over temperature for several levels of input voltage and output power. All of the curves are at a low efficiency level since the forward voltage drop (about 1.4 V) of the output diodes is a significant portion of the output voltage (5 V). For this reason, the main sources of losses in the converter are the output diodes; therefore, efficiency could be increased with synchronous rectification. Generally, converters with higher output voltages will be much more efficient.

The efficiency of the converter is lower for low output power and higher input voltage. This indicates that a significant portion of losses is associated with switching loss in the power switches and core loss in the transformer. At the nominal input voltage (28 V), the medium and high power levels are very close together. The highest efficiency is achieved with the lowest input voltage, further indicating that switching losses are significant. Depending on the power and voltage levels, the efficiency may increase or decrease with increasing temperature up to 200°C. However, all of the curves tend to increase within 200–225°C range.

7. CONCLUSION

The complete design philosophy for a high-temperature dc-dc converter utilizing SiC and SOI electronics was presented. The prototype dc-dc converter presented in this paper was successfully tested up to 240°C. This work has demonstrated the feasibility of using active and passive technologies in extreme environments, and provided a stepping stone to ultra-lightweight power electronic system design.

Future developments include a 120 V/28 V 1 kW dc-dc converter that operates at high junction temperature to reduce heatsink size (ambient temperature will be within the normal industrial range). The new converter will utilize the technology presented in this paper and optimized design methods to create a lightweight power electronic system. Additionally, initial results show an increase in efficiency up to 93%. This change is mostly due to the increased output voltage and partly due to optimized design.

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