# A Very High-Temperature (400+ $^{o}$C) Inverter for Energy Storage Applications Utilizing Silicon on Insulator (SOI) and Silicon Carbide (SiC) Electronics[1]

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## I. Introduction

The requirements of modern high-performance power electronic systems are quickly growing beyond the limitations set by the intrinsic properties of silicon (Si) devices normally employed in this area. Wide band gap devices, such as silicon carbide (SiC), hold the promise of vastly exceeding the capabilities of Si devices by offering higher blocking voltages, higher switching frequencies, lower switching losses and higher operating temperatures. High-voltage (i.e., > 600V) high-power DC/AC power electronics, such as those used for energy storage applications or renewable energy sources, will greatly benefit from the inherent advantages of SiC devices. The increased switching frequency of these devices combined with their lower switching losses and higher temperature of operation will directly translate into more efficient, lighter and smaller power electronics systems (i.e. improved power density through high temperature operation).

The use of higher switching frequencies at higher power levels will require a drastic minimization of parasitic elements such as straight inductances and capacitances. Hence, to unlock the full potential of SiC-based power electronics, the power stage (i.e., power devices) and control stage (i.e., controller) of power converters should be integrated into a single module that allows the minimization of parasitic elements. This approach is known as a multichip power module (MCPM) approach, APEI, Inc. patented technology [1]. The physical proximity of the power and control stage in the MCPM approach requires the control stage operates in a high temperature environment whose maximum temperature is similar to the maximum junction temperature of the power devices. Currently, there are very few control components that will operate above 150 °C. A possible candidate is the line of silicon-on-insulator (SOI) HTMOS parts developed by Honeywell that is guaranteed to operate at 300 °C, and the hardware demonstrated in this paper by APEI, Inc. utilizes this approach.

Researchers at Arkansas Power Electronics International, Inc. (APEI, Inc.) have performed extensive research in the area of SiC device applications and high-temperature packaging. APEI, Inc. researchers have also packaged and characterized SiC JFET power switches at temperatures up to 500 °C. Currently APEI, Inc. is in process of transferring these packaging technologies into applications by developing SiC/SOI-based DC/AC MCPMs capable of operating up to 300 °C (400+ °C at the junction of the bare-die SiC power devices). This paper presents an update on status of current work describing the MCPM design approach for a DC/AC power converter. Section II illustrates the high-temperature MCPM design of the power converter and presents preliminary thermal simulation results. Section III describes the design and development of the control and power stages. This section also presents high-temperature testing results of the control stage and the power switches.

## II. DC/AC Power Converter using the MCPC Approach

### *A. Mechanical Design*

As previously mentioned, the integration of the control and power stages into a single module significantly reduces size, weight, and parasitic effects. This approach, known as MCPM, uses multiple layers to separate the power and control circuitry of the module [1-4]. Figure 1 illustrates a cross-section of the MCPM design while Figure 2 illustrates an isometric view of a single-phase DC/AC power module using the MCPM approach. From these figures it is clear that the close proximity of the control and power stage imposes temperature restriction in the design of these stages. The elevated temperature of operation (i.e., 300 °C for the control stage, 400+ °C at the junction of the power device) not only required the careful selection of materials and components but also the development of several new assembly techniques including new substrate materials, die attach methods and solder methods.

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The control stage of the MCPM houses all the control components (i.e., microcontroller, memory, passive, etc.). The substrate of the control stage is implemented using a high-$T_g$ polyimide material allowing for fine traces and multiple layers. The metallization traces on these layers are flash gold plated for improved reliability. The control components are bare-die devices that are wirebonded with high reliability gold wire. In addition to the bare-die components other components such as surface mount passives, and magnetic elements are also housed in the control stage. The control board is mounted to the high power substrate by a high temperature adhesive laminate. The power stage of the MCPM allocates the power devices (i.e., SiC JFET, diodes and filtering capacitors). The substrate of the power stage is an APEI, Inc. proprietary power substrate. This proprietary power substrate provides improved reliability at high temperatures and under extensive thermal cycling over commonly used direct-bond-copper (DBC) power substrate. This type of substrate provides an excellent thermal path between the power devices and the heatspreader. The metallization traces on this power substrate are designed specifically for high-current high-voltage applications.

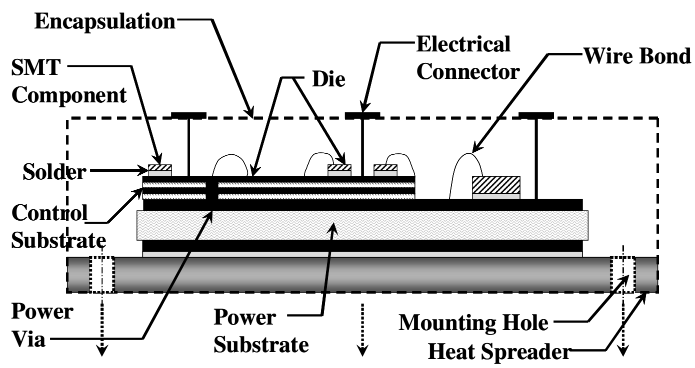


Figure 1. Cross-section of a possible MCPM design.

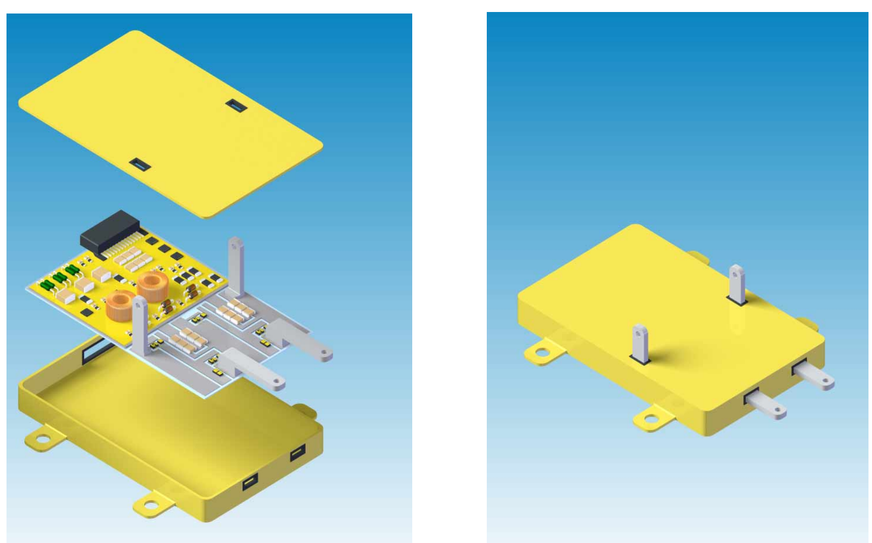

Figure 2. Isometric view of a high-temperature single-phase DC/AC MCPM power module (left) and fully assembled module (right).

The heatspreader of the MCPM is a metal-matrix-composite material (such as AlSiC), which is a ceramic matrix injected with a metal. These heatspreader materials offer excellent thermal conduction capabilities while simultaneously providing a close CTE match to the power substrate and power devices, thus reducing stresses and the chances of thermal cycle/thermal shock failures.

*B. Thermal Simulation*

To verify the MCPM design for high-temperature operation, thermal simulations were carried out using Flotherm software. The thermal model of the DC/AC MCPM module uses the three-phase version of the MCPM design. The model includes the SiC power JFETs and the SOI control devices. Figure 3 (left) shows a 3D view of the MCPM thermal model containing the DBC power substrate, the polyimide control substrate, the SiC and SOI devices, and the heatsink and heatspreader.

Figure 3 (right, top) shows the SiC/SOI-based MCPM under power conditions. At this operating point the junction temperature of the SiC JFETs is approximately 300 °C while the junction temperature of the SOI control components reaches 240 °C. Custom packaged SOI components are capable of operating at 325 °C allowing the maximum junction temperature of the power devices to reach 400+ °C under maximum load.

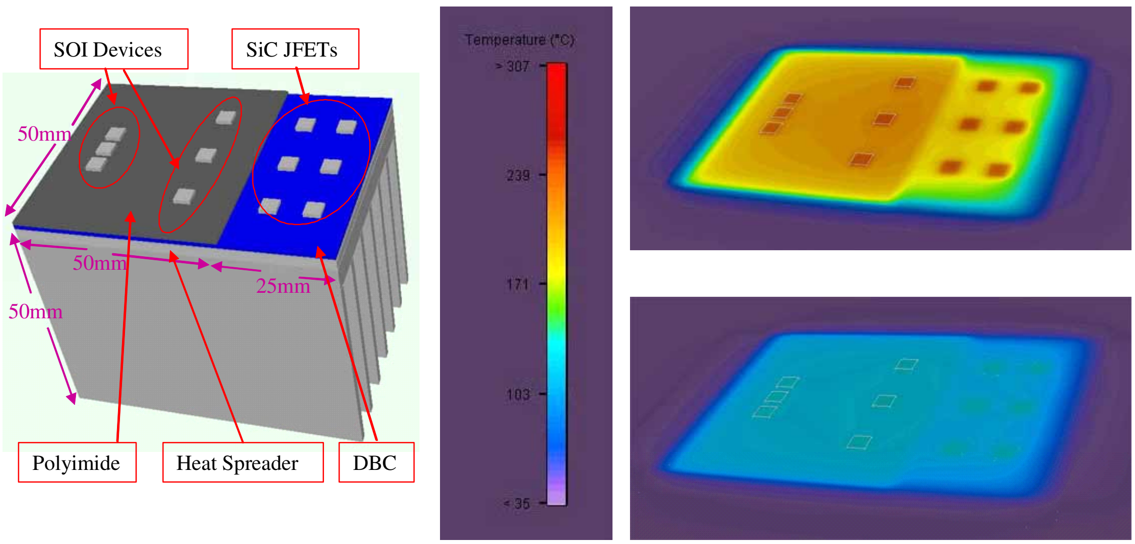


Figure 3. 3D view of three-phase MCPM thermal model (left), Flotherm simulation of the SiC/SOI-based MCPM (right top) and the Si-based MCPM (right bottom).

To clearly illustrate the advantages of the SiC/SOI-based MCPM, another simulation using the same heatsink and geometrical/mechanical design, but with Si control electronics and Si power switches, is shown in Figure 3 (right bottom). The junction temperature of the Si power switches is kept to approximately 150 °C (154 °C in the simulation) which is the maximum junction temperature of Si power devices. With the Si power devices operating at their maximum temperature the maximum power delivered by the converter is approximately 1.3 kW. These results clearly illustrate a theoretical power density increase of approximately 3× through the use of high-temperature SiC and SOI technology.

## III. Electrical Design of the DC/AC Power Converter

### *A. Electrical Design of the Control Stage*

The control circuitry of the DC/AC power converter is designed to operate at a maximum temperature of 300 °C. The control circuitry uses the HTMOS high temperature products developed by Honeywell including the HT83C51 microcontroller. Honeywell's SOI HTMOS parts are guaranteed to operate at 300 °C for a period of one year, and five years at 225 °C. The control selection of the single-phase DC/AC power converter, shown in Figure 4, is divided into several blocks. The core control block (block 1) contains an SOI microcontroller, latch, SRAM, and in-house developed software to generate the control signals required for a single-phase DC/AC power converter. Note that this core control block is the same for APEI, Inc.'s three-phase DC/AC power converter.

The in-house developed software is responsible for generating PWM signals that are inputs to the current drive block while responding appropriately to protection events. The heart of this block is the HT83C51 8-bit microcontroller. The HT83C51 merits lie primarily in its temperature performance and proven architecture, but it has limited arithmetic instructions. Even though the HT83C51 does contain hardware support for PWM generation that reduces the CPU bandwidth burden of generating sinusoidal PWMs, its processing power is limited. To save processing bandwidth, the sine wave values used to generate the sinusoidal PWM are pre-generated and stored in a table. Those values are successively fetched from the table, as needed, to meet the desired output frequency (e.g. 60 Hz for this application). The PWM generation depends on an internal interrupt to maintain timing at the switching frequency. Any calculations effecting PWM duty cycle must be accomplished in the limited time between interrupts. The maximum switching frequency generated by the hardware PWM unit is 1/1024$^{th}$ the input clock frequency of the HT83C51. The switching frequency is not variable unless the application allows for a significantly slower switching frequency.

Three forms of protection are included in the design to help prevent catastrophic device failure: over voltage, over current, and thermal protection. For the first two cases the system will sense the event and trigger an external interrupt to respond appropriately (i.e., shutdown). Unlike voltage and current protections, the thermal protection is a polled event. In the case of an over-temperature event the controller will fold back or shutdown the power stage.

The MCPM design also contains start up circuitry to deliver power from the DC source to the low voltage control logic (block 2). Another feature of the MCPM design is the feedback of critical conditions such as over voltage, current, and temperature (block 3). Block 4 takes the low voltage digital signals from the microcontroller and amplifies the voltage and current to drive the isolation transformers in block 5. Block 6 can be customized to drive different types of power switches. In this case the design drives the gate of normally-off JFET. The JFET gate drive circuitry also ensures that there is adequate dead-time between the high and low side switches.

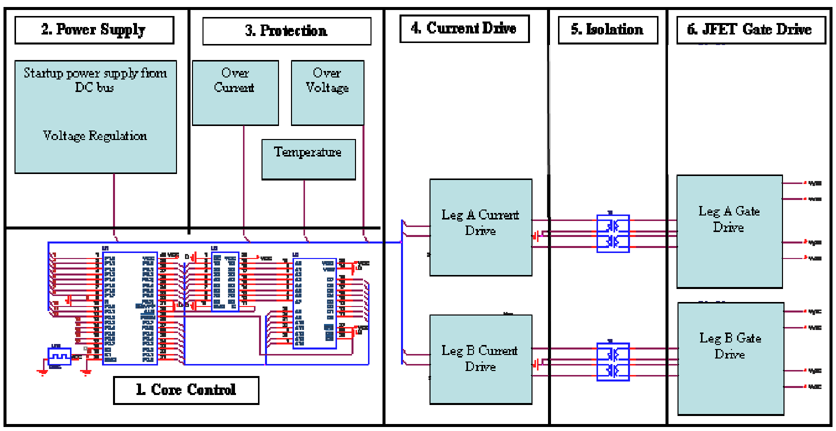


Figure 4. Control stage of the single-phase DC/AC power converter.

Researches at APEI, Inc. have recently completed the assembly of a universal (i.e., single-phase and three-phase) high-temperature control stage for the DC/AC power converter. This control board, shown in Figure 5 (left) was successfully tested in a thermal chamber to 250 °C. Note that according to thermal simulation results junction temperature of the SOI control components reaches a maximum of 240 °C while the module delivers standard power. Figure 6 (left) shows the testing results of the current drive, isolation and JFET gate drive circuitry operating at 300 °C.

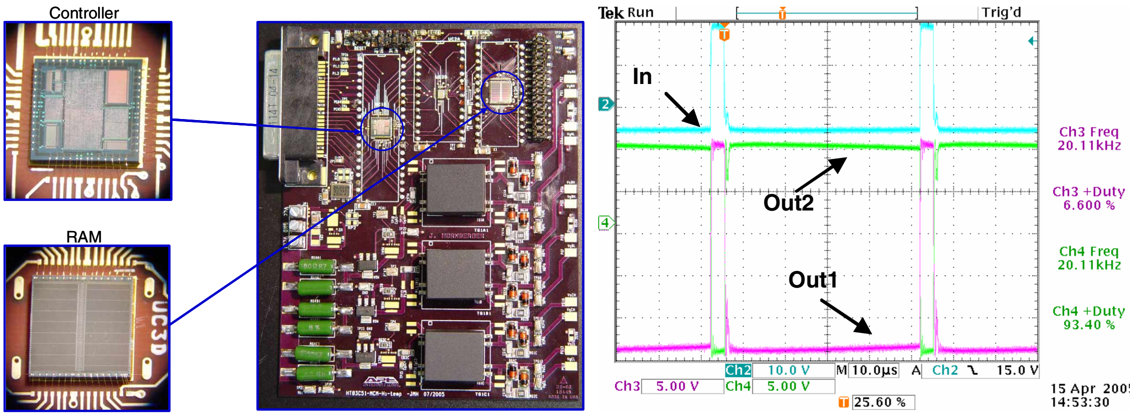

Figure 5. Complete control stage tested to 250 °C (left) and input signal and output signals of the JFET drive circuitry operating at 300 °C (right).

Figure 6 (left) shows the three low-side PWM signals generated by the control stage at 250 °C. This figure shows that the control stage generates sinusoidal pulsed-width modulation (SPWM) signals with a switching frequency of 16.6 kHz. Figure 6 (right) shows the high and low side signal of a single leg illustrating that the control stage also inserts the proper dead time.

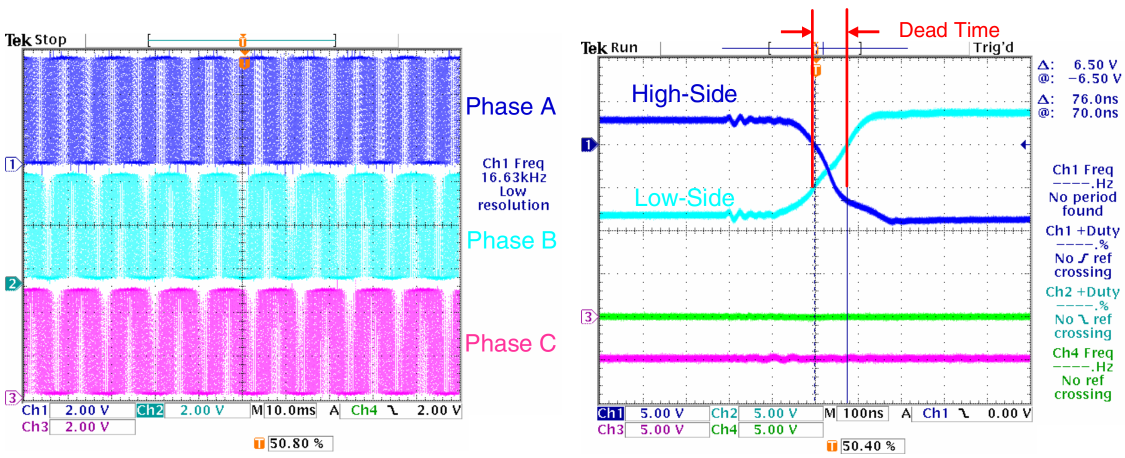

Figure 6. Three-phase PWM signals (left) and high and low side gate signals (right) generated by the control stage operating at 250°C.

*B. Electrical design of the Power Stage*

The power stage of the single-phase DC/AC power converter was designed using normally-off cascoded JEFTs developed by Northrop Grumman. These cascoded JFETs, shown in Figure 7 (left), are rated to 1000 V, 10 A while achieving switching frequencies equivalent to those achieved by power MOSFETs. APEI, Inc. is currently in the process of characterizing these new cascoded devices. However, published results summarized in Table 1 of an earlier generation of such devices show important advantages when compared with Si MOSFETs. In addition APEI, Inc. has built and tested a proprietary high-temperature (300 °C) normally-off power device. To illustrate the concept APEI, Inc. packaged and tested a 1-A version of this device. Figure 7 (right) shows the switching waveforms of the device operating at 300 °C with Vds = 200 V and Id = 408 mA.

Table 1. Comparison of SiC cascade with similar Si MOSFETs.

| Device | Blocking Voltage (V) | Current Rating (A) | $R_{ds,\,on}$ (Ω) | Turn-on Time, $t_r$, (ns) | ***Integral diode reverse recovery time, $t_{rr}$, (ns)*** |
|---|---|---|---|---|---|
| Cool MOS™ | 800 | 4.0 | 1.30 | 15 | 520 |
| HEXFET® | 1000 | 4.3 | 3.50 | 33 | 710 |
| **SiC Cascode** | 1100 | 4.0 | 0.66 | 10 | 100 |

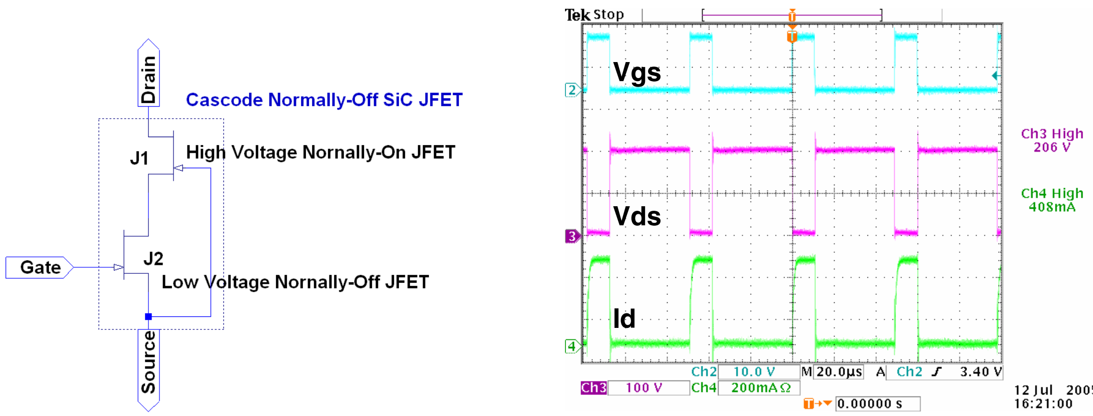


Figure 7. Cascode SiC JFET developed by Northrop Grumman (left) and 300 °C waveforms of the high-temperature normally-on power device developed by APEI, Inc.

Figure 8 shows the complete DC/AC high-temperature MCPM developed by APEI, Inc. These modules are designed using SOI-based control stages and SiC-based power stages. The three-phase version of this AC/DC MCPM is capable of driving up to 5 kW of power at temperatures in excess of 250 °C.

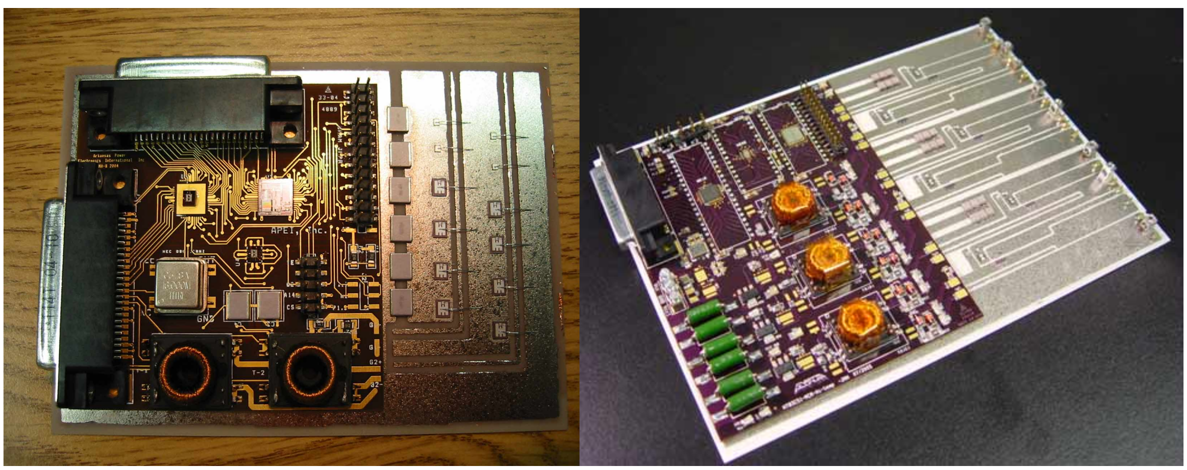

Figure 8. DC/AC high-temperature MCPM, single-phase (left) and three-phase (right).

## IV. Summary

The paper summarized the status in the design on a very high temperature DC/AC power converter using an MCPM design approach. First, the advantage of using SiC devices in high-power high-voltage DC/AC power converters were presented illustrating the needs for a MCPM design in order to unlock the full potential of SiC devices. Next, the concept of high-temperature MCPM design was presented and applied to a DC/AC power converter for energy storage applications. Thermal simulation results were presented showing a potential power density increase of up to 3× through the use of high-temperature SiC and SOI technology. Lastly, the electrical design of the control and power stage was described showing measured results up to 250 °C.

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