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200ºC OPERATION OF A DC-DC CONVERTER WITH SiC POWER DEVICES (PREPRINT)

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14. ABSTRACT
Design, operation, and performance evaluation of a 180 W, 100 kHz, 270 V/28 V two-transistor forward dc-dc power converter are reported for elevated temperatures up to 200ºC. Use of SiC power semiconductor devices, and high temperature powdered ferrite (for magnetics design), and characterization of ceramic (X7R) capacitors' leakage current over temperature are presented as well.

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I. INTRODUCTION

High temperature electronics is becoming increasingly important in a multitude of applications [1] including automobiles (on-engine and in-transmission environments), well drilling (instrumentation for oil and gas recovery), and aircraft and spacecraft (turbine engines, motor drives, space propulsion systems). Advances in silicon-on-insulator (SOI) technology and the steady development of wider band semiconductors such as silicon carbide (SiC) are enabling the practical deployment of high temperature electronics in the near future. As temperature increases in a semiconductor, intrinsic carrier density increases thereby increasing the leakage current. Additionally, device parameters vary, electromigration of interconnection traces increase, dielectric breakdown strength decreases, and TCE mismatches stress the die mechanically. Even with the use of SOI technology [2,3], these effects limit the maximum ambient use temperature of Si power devices to 200^{o}C. Above 200^{o}C, use of wider bandgap semiconductor materials become imperative [4,5] since they produce a smaller concentration of intrinsic carriers than Si at elevated temperatures. Among the wide bandgap materials, SiC technology is far ahead of GaN and diamond technologies. SiC Schottkys are commercially available, and the use of SiC BJTs, JFETs, and MOSFETs has been reported at the developmental level. In the passive components domain, high temperature ferrite magnetic material has been developed recently, [6,7] and the development of high temperature high frequency capacitors with acceptable drop in capacitance value and decrease in leakage currents is in progress [8]. Previous studies [9-12] have reported high temperature operation of SiC diodes, JFETs, and MOSFETs as well as power converters utilizing these devices. This paper presents the operation of a 180 W, 270 V/28 V, 100 kHz two-transistor forward dc-dc converter at elevated temperatures up to 200^{o}C, utilizing SiC power devices and high temperature magnetics.

II. DESIGN OF THE POWER CONVERTER

A 180 W, 270 V/28 V, 100 kHz two-transistor forward converter was designed to operate with a minimum load power of 15 W under continuous conduction mode and a peak-to-peak output ripple of 140 mV (i.e., 0.5% of the output voltage). The two-transistor forward converter [13] power stage is shown in Figure 1. This converter goes through three different modes of operation within a switching cycle: energy transfer mode (S_1 and S_2 are on, and D_1 conducts), transformer reset mode (RD_1 and RD_2 conduct applying reverse input voltage to the transformer winding, and output inductor current freewheels through D_2), and dead time mode (all primary switches are off while the output inductor current is freewheeling through D_2). Because of the way the transformer core reset is achieved, the maximum duty cycle is limited to 0.5. For this design, a maximum duty cycle of 0.45 is used. Key advantages of this topology are: transformer leakage inductance energy is fed back to the input capacitor via RD_1 and RD_2, and maximum voltage stress on the primary switches is limited to the input voltage level requiring no primary-side snubber circuits. Additionally, voltage shoot-through is absent in this topology since S_1 and S_2 are turned on and off at the same time.

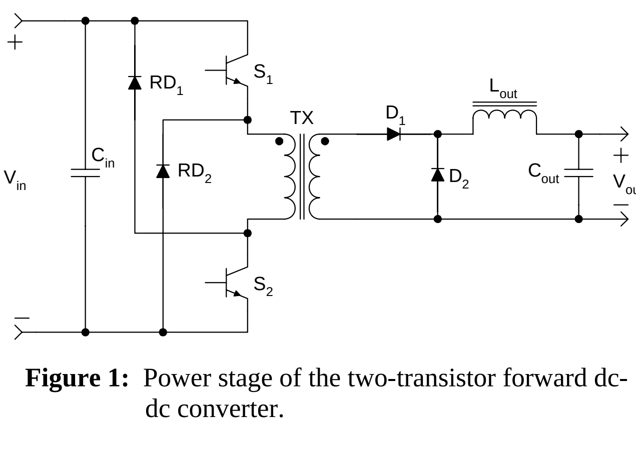


Figure 1: Power stage of the two-transistor forward dc-dc converter.

A. SiC power semiconductor selection

The power semiconductors used in the power stage design are shown in the table below. All three devices are from Cree Incorporated.

Device ref. designator	**Device type**	**Part #**	**Key specifications**
S_1, S_2	BJT	---	1000 V, 5 A, Tj,max >300°C, TO-257
RD_1, RD_2	Schottky	CSD10060	600V, 10 A, V_F=2.0 V @ 10 A, Tj = 175°C, TO-220
D_1, D_2	Schottky	CSD20030	300V, 20 A, V_F=1.4 V @ 10 A, Tj = 175°C, TO-247

Development of 4H-SiC BJTs with high dc current gain and associated high temperature current-voltage characteristics have been recently reported [14]. These 1000 V/30 A devices with an active area of 3×3 mm^2 show fast switching properties and a sharp avalanche behavior at a collector-emitter voltage of 1000 V. The dc characteristics of these devices at room temperature include a forward voltage drop of 2 V at 30 A of collector current with a current gain of 40 representing a current density of 333 A/cm^2. The reported dc current gain for these devices is 30 at 275°C.

The switching devices used in the two-transistor forward power converter implementation are from the same family of devices reported in [14], and are currently not available commercially. SiC Schottky rectifiers, however, are commercially available with 600 and 1200 V blocking voltage ratings and current handling capabilities of up to 20 A. The positive temperature coefficient of V_F makes these devices very amenable to paralleling in order to achieve high current handling capability. Figure 2 below shows the V_{BE} and V_{CE} variation with temperature for the BJT used in the design, and Figure 3 shows the forward voltage drop variation of the 300 V Schottky used in the output rectifier design.

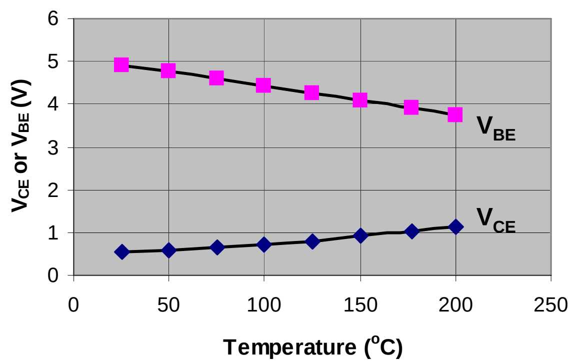


Figure 2: SiC BJT junction voltages for a dc current gain of 10 (I_B = 0.2 A; I_C=2 A).

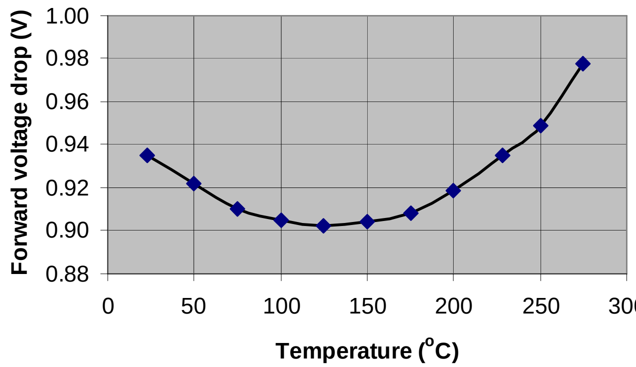


Figure 3: SiC Schottky diode (CSD20030) forward voltage drop for a dc forward current of 6.5 A.

B. Transformer design

A planar core of E46410 configuration made of Fe-Mn-Zn ferrite material with a Curie temperature in excess of 300°C [6,7] was used in designing the transformer. Key magnetic properties of this high temperature material are: relative permeability of 500-1000 at 25°C, saturation flux density of 0.48 T at 25°C/0.3 T at 200°C/0.1 T at 300°C, coercive force of 0.5 Oe at 25°C and 0.35 Oe at 200°C, power loss of less than 1 W/cc @200 kHz/0.08 T, and a resistivity of 100-200 Ω-cm.

For this design, the turns ratio (primary-to-secondary) was calculated using (1)

$$TX\_ratio = \frac{V_{in,\min} D_{\max}}{V_{out}} \tag{1}$$

where, $V_{in,\min}$ is 250 V, $D_{\max}$ is 0.45, and V_{out} = 28 V.

The transformer turns ratio used in the design is 3.5 to account for converter losses. The primary number of turns was calculated using (2)

$$N_p = \frac{V_{in,\min} D_{\max}}{f_s A_e B_{\max}} \tag{2}$$

where, $V_{in,\min}$ is 250 V, $D_{\max}$ is 0.45, f_s is 100 kHz, A_e is 516×10^{-6} m^2, and $B_{\max}$ is 0.08 T.

Based on above calculations, the transformer was designed with 28 turns in the primary and 8 turns in the secondary. The design assumed a peak flux density of 0.08 T in order to avoid magnetic saturation of the core for up to 300°C. The primary winding used one strand of #24 copper wire with Fluorene Polyester (FPE) coated insulation. The breakdown strength of FPE is approximately 10 kV/mil for up to 300°C. The secondary winding was implemented with one strand of 0.3125"x0.003" copper foil using Kapton polyimide film tape as the insulating material (rated for operation up to 260°C).

C. Output inductor design

The E46410-shaped high temperature core was also used in designing the inductor. Based on the minimum load current requirement of 0.62 A, a minimum duty ratio of 0.34, an output voltage of 28 V, and a switching frequency of 100 kHz, the required value of 150 μH for the output filter inductance was calculated using (3).

$$L_{out} = \frac{V_{out}(1 - D_{\min})}{2 f_s I_{o,\min}} \qquad (3)$$

The required air gap of 1.8 mm (70 mils) in the center leg of the core was calculated using (4) for energy storage purpose. The values used to calculate the air gap length are: $\mu_0 = 4\pi\times10^{-7}$ T*m/A, $L_{out} = 150$ μH, $I_{o,\max} = 7$ A, $B_{\max} = 0.1$ T, and $A_e = 516\times10^{-6}$ m^2.

$$l_g = \frac{\mu_0 L_{out} I_{o,\max}^2}{B_{\max}^2 A_e} \qquad (4)$$

A peak flux density of 0.1 T was used in the design with a peak-to-peak ac flux density of only 15 mT in order to guarantee 200°C operation of the inductor. In winding the output filter inductor, 24 turns of six strands of FPE-coated #24 wire were used.

D. Capacitor selection

For higher dielectric constant capacitors such as ceramics, capacitance generally decreases and leakage current increases with increasing temperatures [8]. For low capacitance values, C0G (Class I) ceramic capacitors are likely the best choice due to lower dissipation factor and stable temperature characteristics. However, due to the need of capacitance in the range of 10-30 μF for this power converter design, X7R (Class II) ceramic capacitors are the next best alternative. For this design, the input filter capacitance of 10 μF consisted of two 5 μF/300V/X7R (AVX) capacitors. The output filter capacitance of 45 μF, however, consisted of three 15 μF/25V Class-II high temperature (200°C) capacitors from Novacap. It shall be noted that the capacitance of high temperature capacitors from Novacap drops significantly in value between 150°C and 200°C.

III. EXPERIMENTAL SETUP AND TESTING

Power stage of the converter was built using two pieces of FR-4 board and 5 mils copper strips, high temperature wire (260°C; MIL-W-25038/1), and high temperature solder (240°C liquidus temperature; 95Sn/5Sb). Figure 4 shows a pictorial view of the power stage of the converter placed outside the oven. The power semiconductor devices are located on the bottom side of FR-4 boards. The complete power stage was placed inside an oven with the control board placed outside. This necessitated long wires out of the oven to be able to feed base-emitter signals to the BJTs. The control circuit used to drive the BJTs is shown in Figure 5. Additionally, long wires out of the oven were needed for connecting to the input source and output load, and for monitoring voltages at various points of the converter. The converter was tested for ambient (board) temperatures of 25°C to 200°C, in steps of approximately 25°C. The measured power stage efficiency of the converter, shown in Figure 6, remained between 90% and 91% in the 25°C to 175°C range. However, the converter efficiency dropped from 90% at 175°C to 88.3% at 200°C.

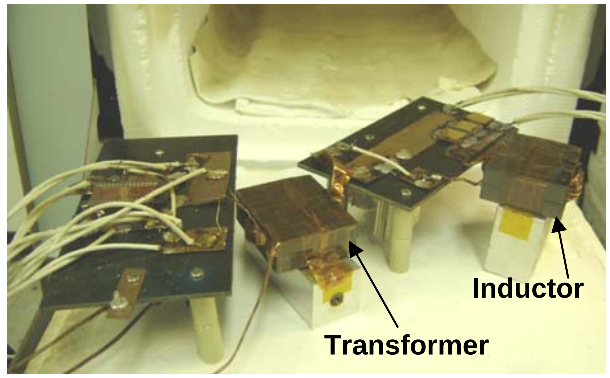


Figure 4: Pictorial view of the converter power stage (outside the oven).

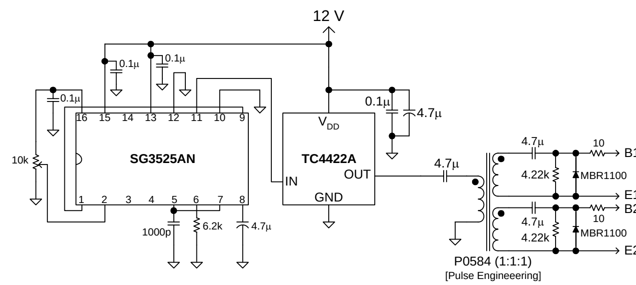


Figure 5: Control circuit used to drive the SiC BJTs.

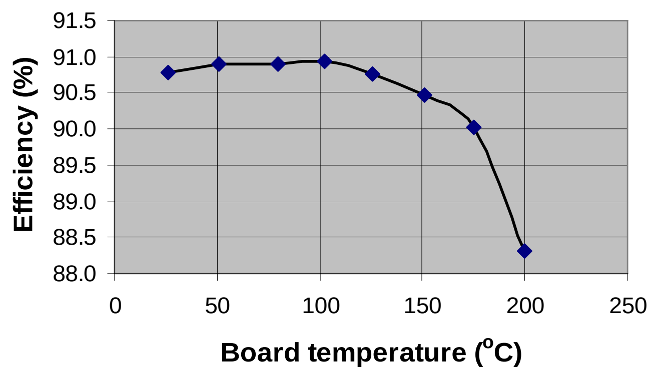
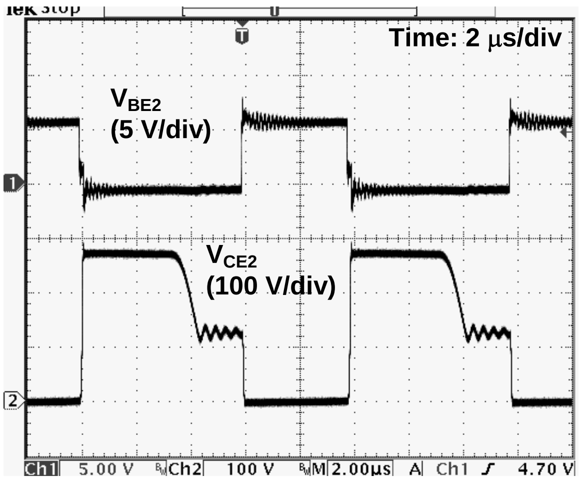
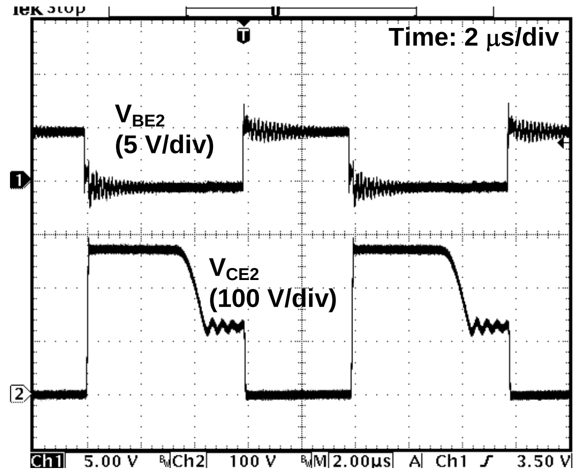


Figure 6: Efficiency of the converter as a function of temperature (P_{out} = 180 W).

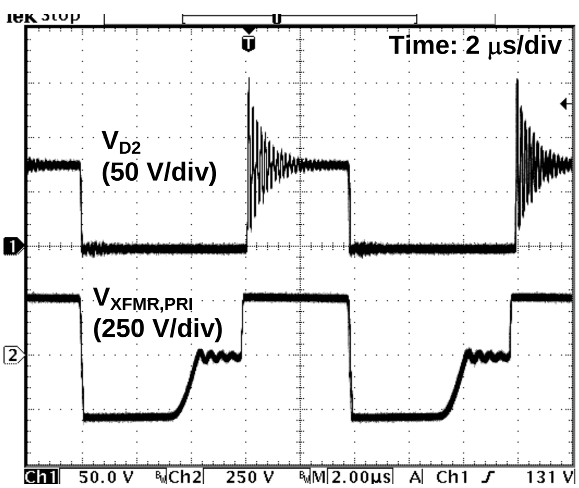
Figure 7 in the next page shows the base-emitter and collector-emitter voltages of the primary switch (S_2), output diode (D_2) voltage, and transformer (TX) primary voltage waveforms at 26°C and 200°C. The V_{BE2} waveform looks noisy primarily due to lead inductance of long wires used to connect the control board outside the oven to the BJT inside the oven. The V_{D2} waveform shows the high frequency ringing at primary switch turn-on due to resonance between the transformer leakage inductance and the output diode junction capacitance. This ringing can be reduced significantly by the use of a snubber circuit in the secondary side of the converter. The $V_{XFMR,PRI}$ waveform clearly shows the complete demagnetization of the core and the associated dead time. Most importantly, it shall be observed that the waveforms shown in Figure 7 clearly demonstrate that the operation of BJTs, Schottkys, and the transformer are practically unchanged over the wide temperature range of 26°C to 200°C. This led to testing the converter in excess of 200°C. However, the converter failed shorted at 215°C.



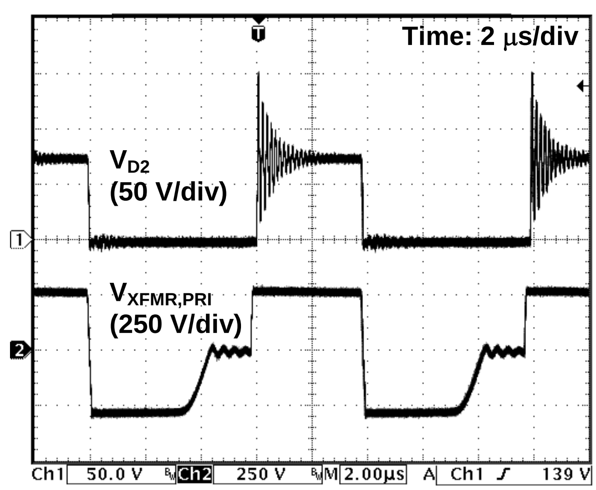
(a) Primary switch (S_2) voltage waveforms at **26°C**



(c) Primary switch (S_2) voltage waveforms at **200°C**



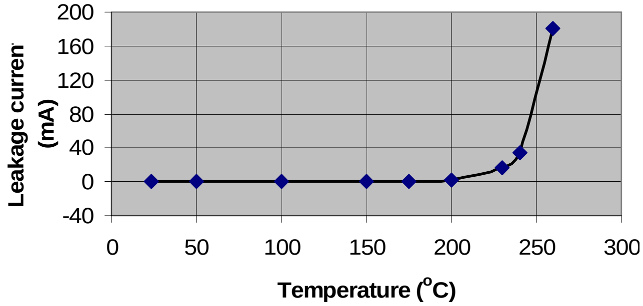
(b) Output diode (D_2) and transformer (TX) primary voltage waveforms at **26°C**



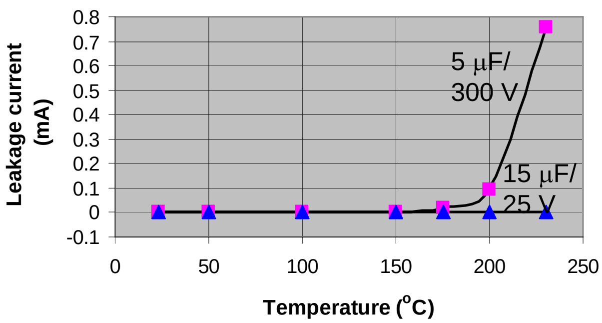
(d) Output diode (D_2) and transformer (TX) primary voltage waveforms at **200°C**

Figure 7: Power converter voltage waveforms under full load at 26°C (left) and 200°C (right).

Upon removing the converter from the oven, it was noticed that the input capacitor (2*5 μF/300V; X7R) cracked; and the power converter ran successfully once the cracked input capacitor was removed. Further testing of this capacitor revealed the fact that the converter failed shorted due to shorting of this capacitor (contributed by excessive leakage current and self-heating/thermal runaway). This led to testing of various X7R and Class-II capacitors for leakage current over temperature under dc condition. Figure 8 shows that leakage current of X7R capacitors (30 μF/300V and 5 μF/300 V) starts to increase exponentially above 175°C. The 5 μF/300V capacitor (used in the power converter design) seems usable to approximately 200°C; however, its reliability will definitely be questionable under ac ripple current excitation. The high temperature Class-II capacitor (15 μF/25 V from Novacap) shows almost no increase in leakage current up to 225°C, and is definitely usable for 200°C design. A pictorial view of the high temperature cracking of X7R capacitors is shown in Figure 9. This experimental study does explain the failure of the power converter at 215°C due to a short created by the leaking X7R input capacitor and the significant decrease in converter efficiency from 175°C to 200°C.



(a) 30 μF/300 V ceramic (X7R) capacitor



(b) 5 μF/300 V ceramic (X7R) and 15 μF/25 V ceramic (Class-II) capacitors

Figure 8: Measured leakage current of ceramic capacitors as a function of temperature.

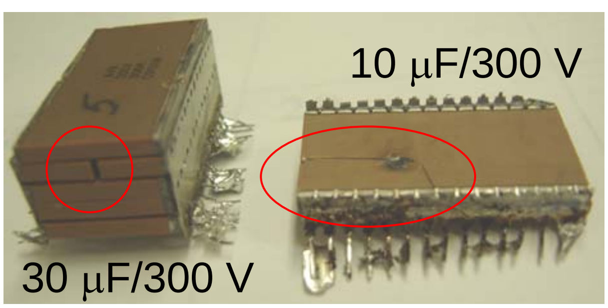


Figure 9: Pictorial view of the high temperature cracking of X7R capacitors.

IV. SUMMARY AND FUTURE WORK

Successful operation of the power converter at elevated temperatures up to 200°C has been reported. Replacing the 300 V/X7R input capacitor with high temperature Class-II or C0G ceramic capacitor would likely permit the operation of the converter to at least 250°C, and this change will be incorporated in the next design update. Implementation of a higher power version (e.g., 1 kW) of the converter using a full-bridge topology is under consideration now. The use of SiC JFETs and MOSFETs as power switch, in place of SiC BJTs, will be studied in the near future as well.

V. REFERENCES

1. H. Alan Mantooth et al., "Emerging capabilities in electronics technologies for extreme environments, Part I: High temperature electronics," IEEE Power Electronics Soc. Newsletter, Vol. 18, No. 1, pp. 9-14, Jan. 2006.
2. J. Goetz, "High temperature electronics for sensor interface and data acquisition," Sensors Expo, 1998.
3. J. M. O'Connor, "225 C High temperature silicon-on-insulator (SOI) ASICs for harsh environments," Proc. IEEE Int. Workshop on Integrated Power Packaging, pp. 2-5, Sept. 1998.
4. A. Hefner et al., "Emerging silicon-carbide power devices enable revolutionary changes in high voltage power conversion," IEEE Power Electronics Soc. Newsletter, Vol. 16, No. 4, pp. 10-12, Oct. 2004.
5. P. G. Neudeck et al., "High-temperature electronics – A role for wide bandgap semiconductors?", Proc. IEEE, Vol. 90, No. 6, pp. 1065-1076, June 2002.
6. R. Spyker et al., "300C Ferrite material for high temperature magnetics," Proc. IEEE Power Electronics Specialists Conf. Rec., pp. 155-160, June 2004.
7. R. Spyker et al., "300C High temperature magnetics," Proc. IEEE Applied Power Electronics Conference, pp. 1275-1280, Feb. 2005.
8. J. S. Bowers, "Comparative characterization of capacitors used in high temperature electronics applications," Proc. IEEE High Temperature Electronics Conf. (HiTEC), pp. 184-190, June 1998.
9. G. Spiazzi et al., "Performance evaluation of a Schottky SiC power diode in a boost PFC application," IEEE Trans. Power Electronics, Vol. 18, No. 6, pp. 1249-1253, Nov. 2003.
10. B. Ozpineci and L. M. Tolbert, "Characterization of SiC Schottky diodes at different temperatures," IEEE Power Electronics Letters, Vol. 1, No. 2, pp. 54-57, June 2003.
11. B. Ray et al. "High temperature operation of a dc-dc power converter utilizing SiC power devices," Proc. IEEE-APEC, pp. 315-321, Feb. 2005.
12. R. M. Nelms et al. "200°C operation of a 500 W dc-dc converter utilizing power MOSFETs," IEEE Trans. Industry Applications, Vol. 33, No. 5, pp. 1267-1272, Sept./Oct. 1997.
13. R. W. Erickson and D. Maksimovic, "Fundamentals of Power Electronics," 2nd edition, ISBN: 0-7923-7270-0, Springer, 2001.
14. S. Krishnaswami et al., "1000-V, 30-A 4H-SiC BJTs with high current gain," IEEE Electron Device Letters, Vol. 26, No. 3, pp. 175-177, March 2005.