HIGH TEMPERATURE ELECTRONICS (> 485 °C) FOR VENUS EXPLORATION

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Abstract – Venus is an extreme environment, with an average surface temperature in excess of 485 °C at 92 atmospheres of pressure, and a high concentration of sulphuric acid vapour at high altitudes. Venus robotic probes and landers would require motors and/or actuators (and their drivers) to perform a wide variety of functions in this environment, from moving and controlling robotic arms and drills, to providing traction for surface propulsion. Silicon carbide (SiC) has a theoretical junction temperature limit in excess of 600 °C, making it a prime semiconductor material for Venus exploratory electronics systems. APEI, Inc. is currently developing a high temperature SiC multichip power module (MCPM) electronic motor drive solution to address this requirement.

1. INTRODUCTION

Silicon Carbide (SiC) has a theoretical junction temperature limit in excess of 600 °C [1], which makes it a prime candidate semiconductor for severe environments. Developing a SiC power electronic motor drive that could be integrated with the casing of the DC motor would significantly reduce the weight of the required electronic environmental shielding and the complexity of the overall electronics system. SiC electronics not only could extend the life of a Venus atmospheric probe or lander beyond days or weeks, but would operate reliably through the implementation of simple passive thermal management strategies. Avoiding complicated advanced active thermal management strategies not only improves reliability, but significantly reduces the complexity, weight, and volume of the overall electronics systems. SiC power electronics offer other potential advantages over silicon as well, including 1/10th the switching losses, 10× the power density, 10× the breakdown voltage, and switching frequencies into the 10s of GHz range [2]. All of these advantages offer the potential to develop highly miniaturized, highly reliable, light weight extreme environment power electronics drive systems that can be integrated directly with DC motors or actuators.

The development of a SiC multichip power module (MCPM) motor drive for the exploration of Venus requires the addressing of several challenges:

1. SiC digital and power electronics that can survive the high-temperature ambient environments of ~ 500 °C with passive thermal management strategies.
2. Passive and magnetic components that can operate reliably within the required conditions.
3. Hermetically sealed electronic packages that can survive the high-temperature, high pressure, and chemical composition of the Venus atmosphere.

The paper is divided as follows: Section 2 presents the current state of the high temperature SiC devices, Section 3 describes high temperature passives, Section 4 shows the high temperature packaging approach, Section 5 describes other applications of this technology, and lastly, Section 6 describes ongoing work for extending component temperature ranges.

2. HIGH TEMPERATURE SIC DEVICES

APEI, Inc. has partnered with several SiC power switch manufacturers and tested the ability of the devices to operate at high temperatures. The results of the findings are presented next.

2.1 Power Devices

Two different device types, one from SemiSouth and one from SiCED were tested.

The SemiSouth 100V bare die JFET consisted of all gold metallization pads. The device was packaged into a gold plated beryllium oxide 3-pin package by APEI, Inc. The package is depicted in Fig. 1 without a lid. Both the package and the devices were tested successfully up to 500C. After 500 ºC, the adhesion of the die attach material was lost, resulting in die lift and caused loss of connection to the device, ultimately causing failure. The initial test setup used to capture switching curves is seen in Fig. 2. Fig. 3 and 4 displays the room temperature and the high temperature (500 °C) blocking voltages, respectively. In Fig. 3 and 4, channel 1 is a command signal generated by a function generator, channel 2 is the drain to source voltage, and channel 3 is the drain current.

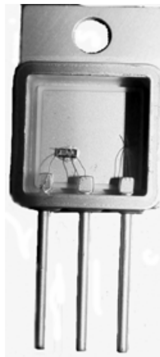

Fig. 1. APEI, Inc. packaged SemiSouth SiC JFET for high temperature operation

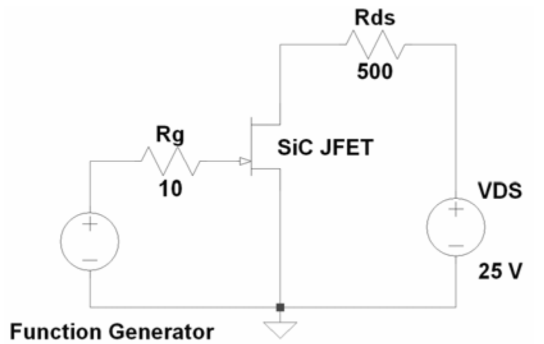

Fig. 2. Initial setup for temperature testing

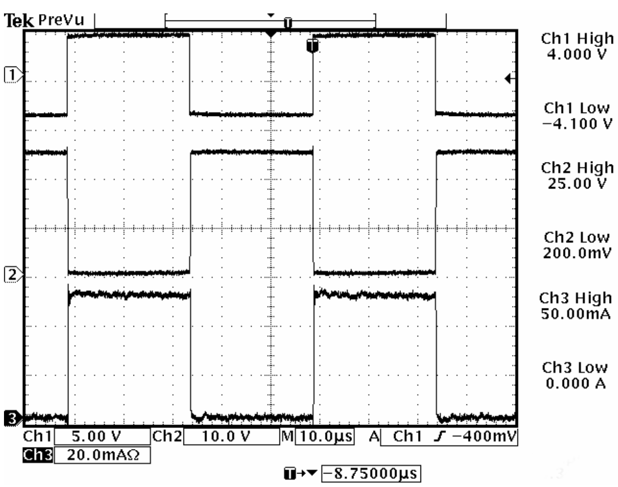

Fig. 3. Blocking voltage operation at 25 °C

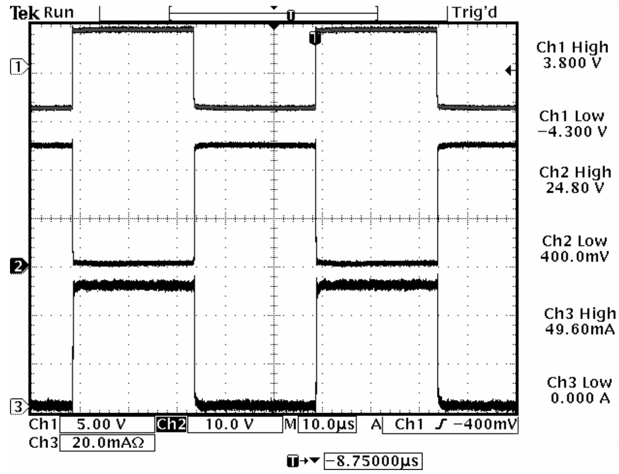

Fig. 4. Blocking voltage operation at 500 °C

Fig. 5 and 6 illustrate the on-state curves obtained at different temperature. As temperature increases, the on-resistance increases. For instance, at room temperature with a gate-to-source voltage (Vgs) of 3V and drain-to-source voltage (Vds) of 30V; the drain-to-source current (Ids) is 0.66A. At 350 ºC, the Ids is only 0.14 A at the same Vgs and Vds settings.

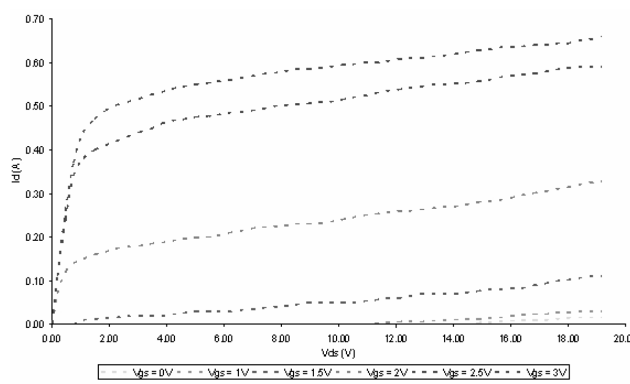

Fig. 5. On-state curve for the packaged SemiSouth SiC JFET at 25 ºC

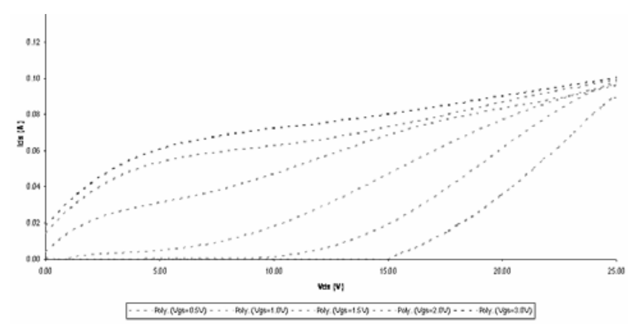

Fig. 6. On-state curve for the packaged SemiSouth SiC JFET at 350 ºC

APEI, Inc. also obtained and tested bare die SiC JFETs from SiCED. A device was attached to a direct bond copper (DBC) substrate using a high temperature epoxy and the source pads were attached with 8-mil power aluminum wirebonds. The gate terminal was bonded using 1 mil Al wire as seen in Fig. 7.

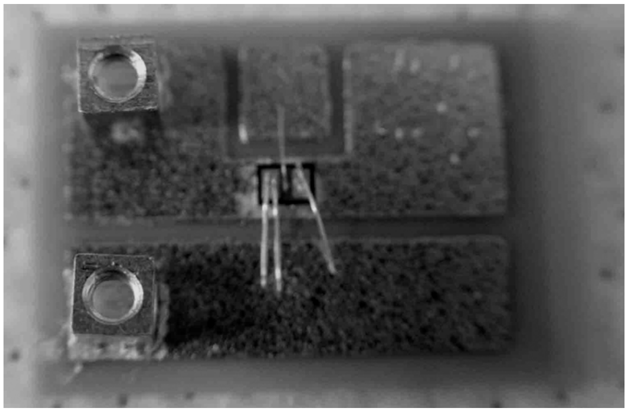

Fig. 7. APEI, Inc. packaged SiCED SiC JFET for high temperature operation

This packaged device was tested successfully to 400 °C as seen in Fig. 7. Fig. 8 illustrates the device switching at room temperature at a VDS of 100V. Note that the gate signal generated from an opamp is seen in channel 4, the command signal for the function generator is seen in channel 3, the VDS is channel 2 and channel 1 is the drain to source current. Fig. 9 shows the device switching at 100V at 400 °C.

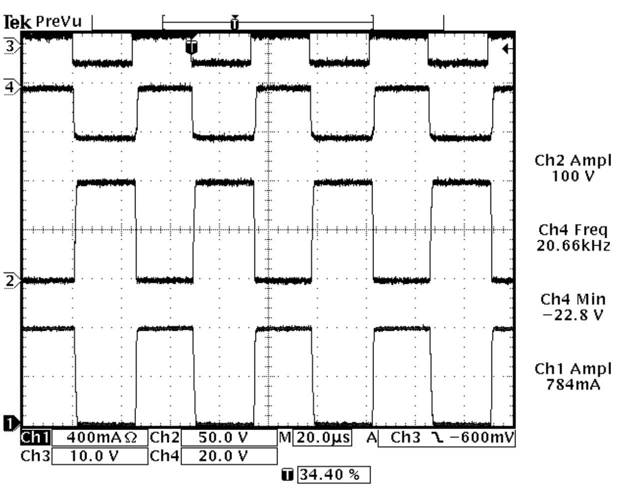

Fig. 8. Blocking voltage operation at 25 °C

The on-state curves are illustrated in Fig. 10 (room temperature) and 11 (350 °C). Note the voltage threshold is approximately -22.3 V and the on-state curves only go up to -20 V. As the temperature increases, the amount of Vgs it takes to turn the device off also increases.

APEI, Inc. has experimentally confirmed the ability of SiC devices to operate at very high temperatures (400 + °C).

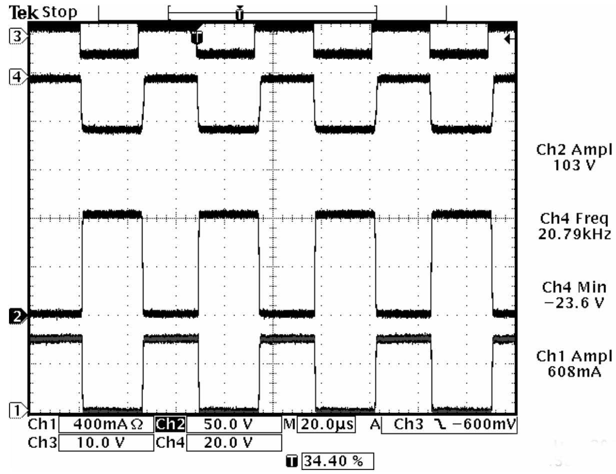

Fig. 9. Blocking voltage operation at 400 °C

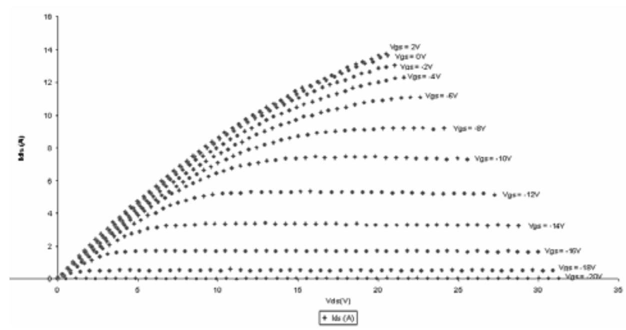

Fig. 10. On-state curves at 25 °C for SiCED SiC JFET using APEI, Inc. packaging technology

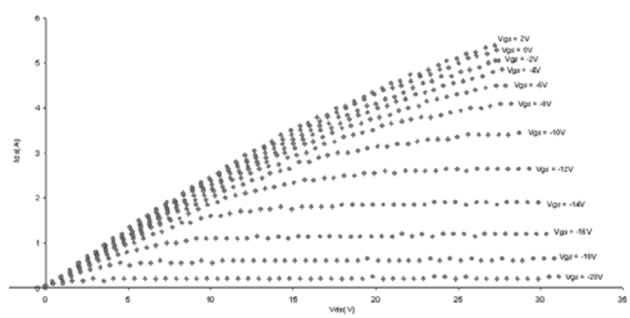

Fig. 11. On-state curves at 350 °C for SiCED SiC JFET using APEI, Inc. packaging technology

2.2 Digital Devices

The Lateral Trench Junction Field-Effect Transistor (LTJFET) from SemiSouth serves as a building block for temperature-tolerant radiation-hardened fast SiC electronics that may include built-on-chip digital control circuitry and a power transistor with control levels compatible to 3.3 V CMOS or 3.3 V TTL (LVCMOS or LVTTL).

In order to show feasibility of the LTJFET ICs, simple logic gates have been built using discrete enhancement- and depletion-mode vertical power JFETs by SemiSouth. These circuits were tested by SemiSouth with a 2.75 V power supply and input levels of 0.25 V (LOW) and 2.75 V (HIGH). Fig.12 shows a truth table and measured waveforms of a hybrid SiC NOR gate, where enhancement- and depletion-mode vertical SITs were wirebonded on an alumina substrate.

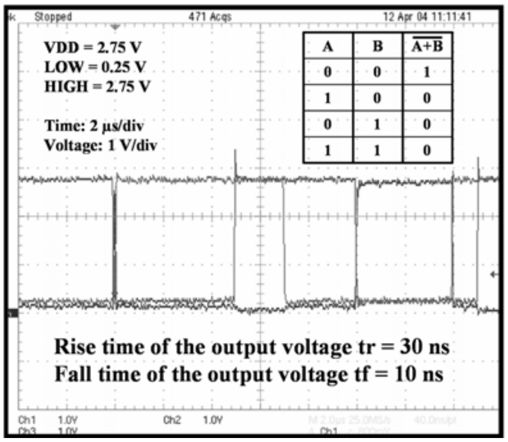

Fig. 12. Measured waveforms of a SiC logic gate (NOR) built with discrete SiC static induction transistors (SITs) (Courtesy of SemiSouth).

3. HIGH TEMPERATURE PASSIVES

3.1 Capacitors

Improvements in current dielectric materials and identification of new materials capable of operating reliably at high temperatures play a crucial role in the realization of high power density converters. APEI, Inc. has identified a number of high temperature capacitor technologies.

Twelve candidate materials were evaluated for high temperature operation The test results presented in Fig. 13 shows the relative change in capacitance over temperature under biased conditions (one-half the rated voltage or maximum of 25 V). The temperature testing was performed on various electrolytic, aluminium, Y5T, metallized polyester, polypropylene film, metallized polymer film, metallized film, tantalum, wet tantalum, X7R, NPO, and COG materials. It should be noted that the maximum applicable voltage was limited to 25 V due to the voltage restrictions of the RLC meter used to obtain data. The components were tested at room temperature before starting at 100 ºC. The temperature was raised with increments of 10 ºC with dwell times of ten minutes at each temperature.

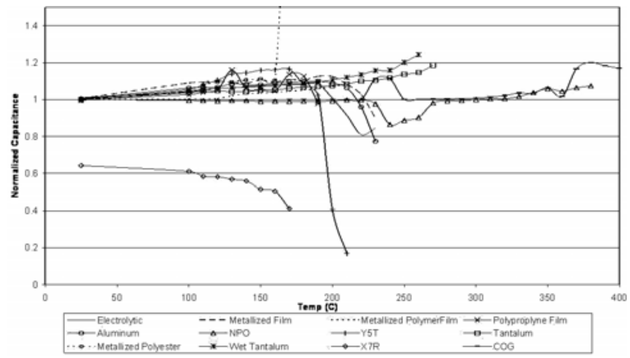

Fig. 13. Capacitor materials tested at 25 V vs. temperature

Electrolytic capacitors are normally rated to 125-150 °C; however, obtained data displays that operation at 230 °C can be maintained for short durations. Aluminium capacitors are grouped in the same family as electrolytic capacitors. Their characteristic behaviour mimics the curves seen in the electrolytic tests. These capacitors have poor long term reliability at extended temperatures.

Polypropylene has a high dielectric strength compared to polycarbonate and polyester films. These films also operated up to 230 °C as seen in Fig. 13.

Tantalum capacitors have proven to have high capacitance per unit volume. These capacitors render excellent performance with a high degree of reliability when properly used [3]. APEI, Inc. researchers observed these advantages of tantalum and wet tantalum capacitors as illustrated in Fig. 13.

The X7R becomes very unstable at higher temperatures and will not work for our application. However, the NPO and COG materials capacitors show excellent stability up to 500 ºC and have potential in being used for high temperature applications. However, these capacitors are seldom available larger than 0.22µF.

In conclusion, the NPO and COG materials capacitors show relative stability up to 500 ºC and potential for use in high temperature applications. The COG capacitors are the prime candidates to enable high temperature operation of the MCPM module.

Recent developments in dielectric technology have demonstrated capacitors capable of operation beyond 400 ºC. Specifically the HT300 line of capacitors from TRS Electronics has been tested up to temperatures of 400 ºC.

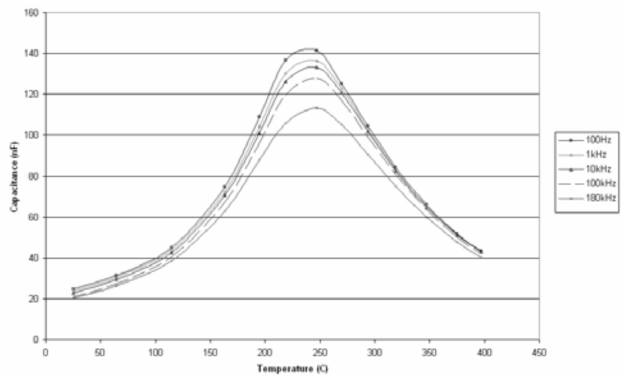

Fig. 14. Temperature dependence of the capacitance for a TRS 100nF/250V capacitor

The capacitor was characterized over temperature under different switching frequencies and is shown in Fig. 14. Further tests indicate that at 200 °C, the HT-300 dielectric operating at 500V outperforms the commercially available component by 10 times at 200 °C and over 100 times at 300°C [4].

3.2 Magnetic Design

It is well known that many magnetic materials do not have an extended temperature range of operation. APEI, Inc. has identified several types of magnetic cores, including powdered cores, tape-wound cores, and ferrite-based cores, that can operate at elevated temperatures when properly designed. Many of the properties of a magnetic core can be obtained from its hysteresis curve. The hysteresis curve, also known as the B-H curve, demonstrates the relationship between the induced magnetic flux density B and the magnetizing field strength H.

APEI, Inc. has tested a ferrite core over temperature. This core was selected because it offers an excellent combination of maximum saturation flux density (approximately 280 mT) and Curie temperature (420 °C). The characteristic B-H curve of this core at different temperatures is shown in Fig. 15 These B-H curves were extracted using an in house characterization circuit.

As expected, the saturation point of the magnetic core decreases when the temperature increases. Initially, the saturation flux density is 255 mT at T = 27 °C. If the temperature is increased to 270 °C, the saturation flux density decreases to 60 mT.

The transformer design is mainly determined by the signal applied to it. For an isolation transformer, it is important to avoid saturation, while maintaining the integrity of the pulse applied. This translates into having the highest possible magnetization inductance while staying below the saturation point at the maximum temperature of operation.

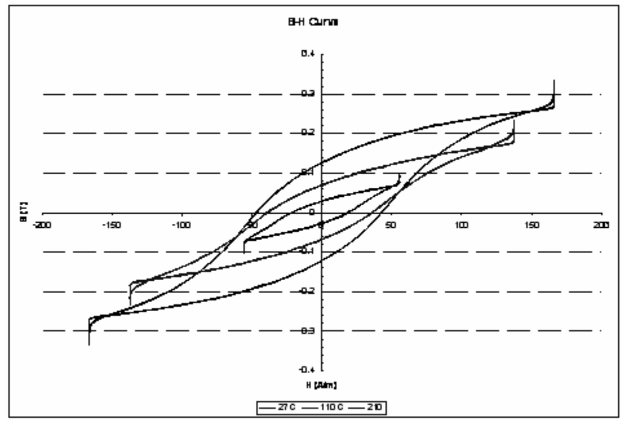

Fig. 15. B-H curves of the nickel-zinc ferrite L01-EA8X-75/1 at different temperatures.

The maximum magnetic flux Φ_{max} is obtained from observing the saturation point of the core at the desired temperature of operation. Based on Φ_{max}, the specific number of turns needed to keep the core from saturating at the desired temperature of operation is determined.

Fig. 16 shows a picture of a packaged high temperature transformer.

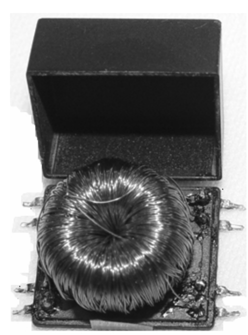

Fig. 16. APEI, Inc. high-temperature transformer

Fig. 17 and 18 show the operation of the transformer at two different temperatures. In these figures the transformer's input signal is displayed using channel 2 while the transformer's output signal is displayed using channel 3. Fig. 17 shows the transformer operating at 150 °C while Fig. 18 shows the transformer operating at 400 °C. Fig. 17 and 18 show the transformer primary and secondary voltage signals operating at 15 kHz.

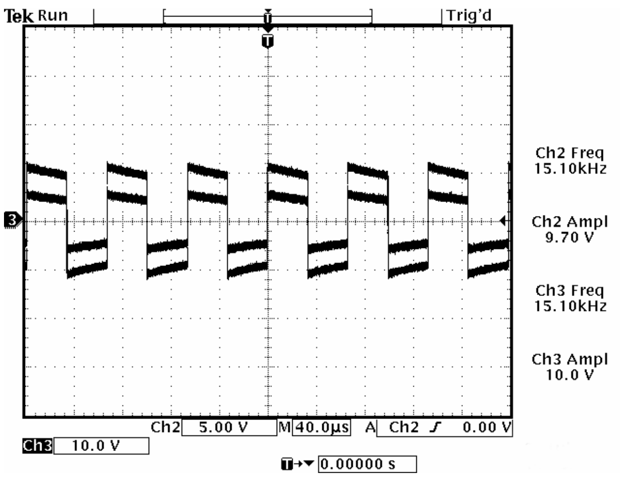

Fig. 17. Isolation transformer operating at 150 °C

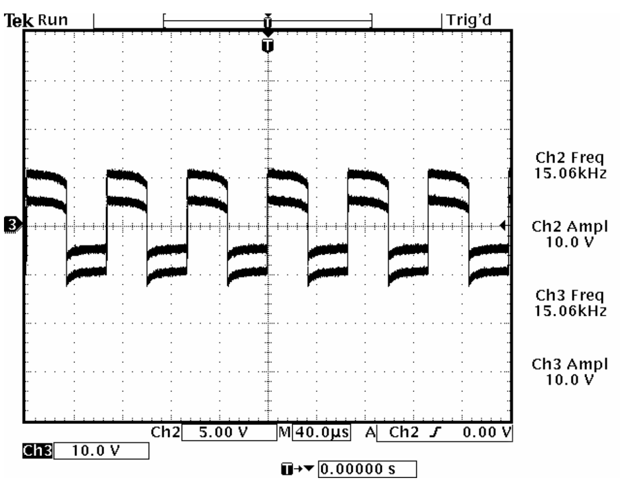

Fig. 18. Isolation transformer operating at 400 °C

This side-by-side comparison shows the output performance of the high temperature transformer in which only a slight degradation is seen at high temperatures.

4. HIGH TEMPERATURE PACKAGING

4.1 Substrates

The primary approach towards the development of a high temperature motor drive is to implement the power electronics in the form of a novel MCPM in which the substrate will be a SiC wafer.

This approach will be the most conducive to effectively securing the operational reliability of the package by minimizing CTE material mismatches throughout the power module. Matching the mechanical properties of the SiC wafer with the SiC electronics, and in turn matching those with a ceramic or MMC case will result in an overall module that minimizes thermal stresses.

The power module will be built upon a SiC wafer substrate utilizing bare die SiC control and power electronic components. The SiC based electronics will be functional to temperatures in excess of 500 °C. The SiC wafer substrate will allow close CTE matching between the case / substrate / electronics and thus improve thermal-stress response, reduce the chances of fracture, and improve package reliability. The module will be hermetically sealed within a ceramic housing to protect against possible corrosive effects from the atmosphere.

Figure 19 illustrates a cross-section of the proposed SiC based MCPM

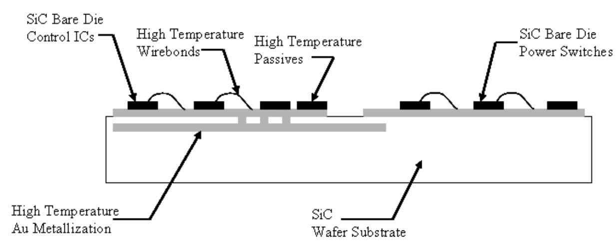

Fig. 19. SiC MCPM cross-section

4.2 Die attach

Die attachment is a major obstacle in realization of reliable high-temperature electronics, one which requires significant technological advances in both materials and in processing. The standard approach employing solder alloys becomes exceedingly difficult as the maximum use temperature of the electronics module is raised. The liquidus temperature of the solder must be higher than the operational temperature of the module, and this liquidus temperature generally must be exceeded by approximately 30-40 °C during processing to ensure a good bond. This exposes the assembly to temperatures higher than what is required during operation, instigating the formation of micro-cracks and defects in the packaging materials. These defects concentrate stresses and eventually may lead to a premature failure

Epoxies are an option under consideration, but offer substantial drawbacks. Conductive epoxies typically consist of an organic binder and a resin filled with metal powder or flakes in order to allow transmission of electrical and thermal energy. The binder is baked out during the curing process, leaving a solid matrix that will remain solid until the resin liquefies.

APEI, Inc. is currently investigating a promising method of die attach, utilizing the process of diffusion to enhance or create a high-temperature bond. The method under investigation is using a Au/Sn solder alloy to initially create a bond, then proceeding to diffuse the Sn through a thick substrate metallization, reducing the ratio of Au to Sn, effectively increasing the melting temperature of the attach.

4.3 Overall System Integration

The final MCPM motor drive will be directly mounted on the motor. By integrating the highly robust power electronic systems at the point of operation within the environment, the weight and complexity of the lander or rover could be reduced. Fig. 20 illustrates one method in which these MCPMs could be integrated with motor systems in an exploration application (traction drives or other robotic appendages). Fig. 21 illustrates an exploded view of the integrated motor drive system.

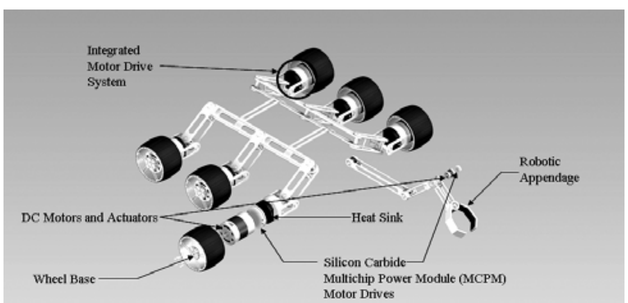

Fig. 20. Conceptual model of integrating high temperature SiC MCPMs with DC motors/actuators in extreme environment robotic landers

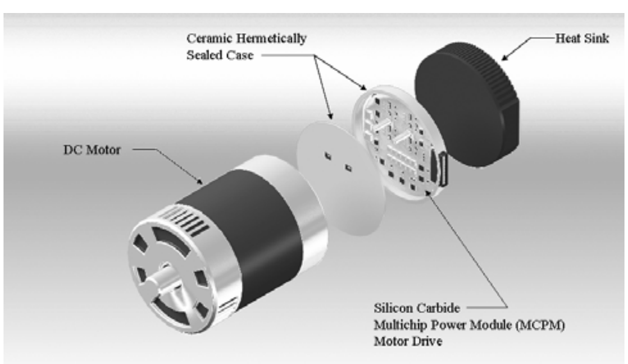

Fig. 21. Conceptual integrated motor drive system

5. OTHER APPLICATIONS OF THIS TECHNOLOGY

The technology currently being developed for a Venus lander/rover is also being developed for various other applications.

5.1 High Power Density Inverters

APEI, Inc. has built and tested a single-phase SiC-based 3 kW proof-of-concept inverter module achieving significant volume reduction (~85 % smaller) when compared with similar state-of-the-art commercially available Si-based single-phase inverter modules. APEI, Inc.'s SiC-based MCPM power inverter module has a power density of 0.67 W/cm^{3}[3] (using only passive cooling).

This power density was achieved primarily by the combination of a highly integrated module design constructed using APEI, Inc.'s MCPM approach and high-temperature operation. To operate at high temperature, the module utilizes SiC power devices in conjunction with high temperature active and passive control circuitry based on high-temperature silicon-on-insulator (SOI) MOS devices (HTMOS).

Fig. 22 shows the fully integrated MCPM inverter module where the control and power stages are attached to an AlSiC metal-matrix-composite (a ceramic matrix injected with a metal) heatspreader. This type of heatspreader offers excellent thermal conduction capabilities while simultaneously providing a close coefficient of thermal expansion (CTE) match to the DBC ceramic substrate.

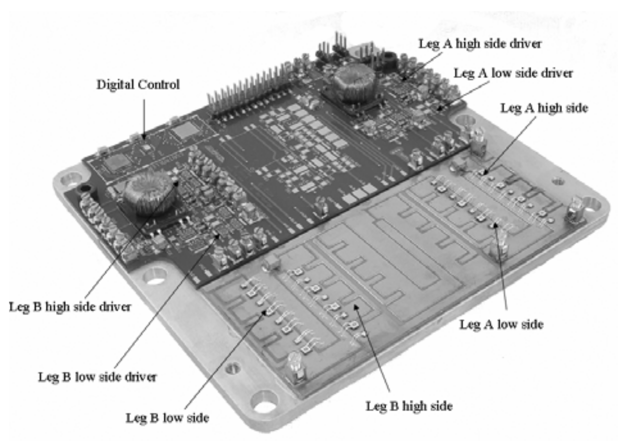

Fig. 22. Single-phase MCPM inverter module

5.2 High temperature RF Transmitters

APEI, Inc. is currently developing technology to allow for reliable RF transmission to be implemented in harsh environment conditions. Specifically, research into the field of high temperature telemetry is being pursued in order to relay information out of harsh environments experiencing temperatures upward of 400°C.

Reliable oscillator signals in the RF range have already been demonstrated at temperatures of up to 290°C. Fig 23 and 24 show a 30 MHz oscillator operating at 175 °C and 290 °C.

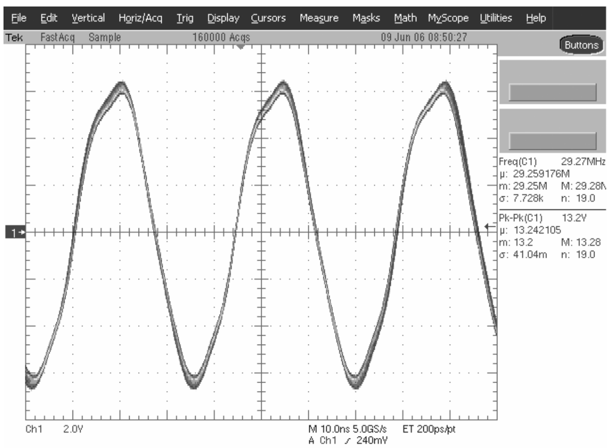

Fig. 23. 30 MHz oscillator operating at 175 °C

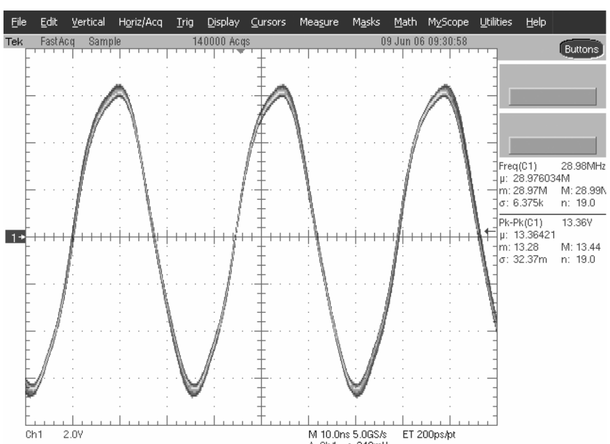

Fig. 24. 30 MHz oscillator operating at 290 °C

6. EXTENDING COMPONENT TEMPERATURE RANGES

There are only a handful of magnetic materials that operate beyond 400 °C, with which APEI, Inc. engineers have fabricated and tested isolation transformers to very high temperatures. These materials could potentially be pushed to 500 °C operation. High temperature capacitors are another area that will require investigation. APEI, Inc. researchers have tested several NPO/COG capacitor technologies up to 400 °C with relative stability. These technologies could potentially be pushed to operate up to approximately 500 °C. APEI, Inc. is teamed with TRS Technologies, a capacitor manufacturing company that specializes in R&D of high performance and high temperature dielectric materials. APEI, Inc. is currently in the process of testing TRS Technologies' HT300 Series prototype capacitors for very high temperature operation in power electronic applications.

7. CONCLUSION

The motor drive power module will be built upon a SiC wafer substrate utilizing bare SiC control and power electronic components. The SiC based electronics will be functional to temperatures in excess of 500 °C. The SiC wafer substrate will allow close CTE matching between the case / substrate / electronics and thus improve thermal-stress response, reduce the chances of fracture, and improve package reliability. The module will be hermetically sealed within a ceramic housing to protect against possible corrosive effects from the atmosphere.

The ability to integrate the motor drive electronics directly with the motors using the MCPM approach will significantly reduce the complexity and weight of the core electronics shielding system while improving the reliability of the mechanical robotic components.

8. REFERENCES

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