# Computer-Controlled Thermal Cycling Tool to Aid in SiC Module Package Characterization

M. Hernández-Mora[1], J. M. Ortiz-Rodríguez[1], B. Grummel[2,1], A. R. Hefner, Jr. [1], D. Berning[1], C. Hood[1], P. McCluskey[3]

[1] Semiconductor Electronics Division*
National Institute of Standards and Technology
Gaithersburg, MD 20899-8120

[2] Power Semiconductor Research Lab
School of Electrical Engineering and Computer Science
University of Central Florida
Orlando, FL 32816

[3] CALCE/Department of Mechanical Engineering
A. James Clark School of Engineering
University of Maryland
College Park, MD 20742

***Abstract*–A software-controlled thermal cycling test system developed for SiC module package characterization is presented. The software interface permits the flexible definition of testing parameters such as variable data acquisition rates, customizable cycle transition's duration, and the independently controlled heating and cooling rates of the test. The cycle's heating is provided by a controlled power supply, while two independent mass flow controllers provide the cycle's cooling control, which can be a combination of air and water flows depending on the test conditions. The interface provides visual feedback by continuously showing the heatplate temperature and the thermal cycling measurements *in situ*. The system has shown to be a useful tool in a comprehensive package degradation project through the monitoring package and electrical variation due to thermal cycling.**

## I. INTRODUCTION

Silicon carbide (SiC) material and device fabrication technology has led to the development of new high-voltage, high-frequency (HV-HF) power devices with 10 kV, 20 kHz power switching capability [1]. SiC devices are suitable for high-temperature applications because they are wide bandgap semiconductors, but in order to be reliable, the packages for these high power devices must also withstand the high temperatures that they face during normal and sometimes extreme operational environments. One emerging market for high power SiC devices is the automotive industry in the development of hybrid and electric vehicles. Hybrid vehicle technology has a higher desired operating temperature capability than other common circuit-fabrication technologies [2]. The challenge for this market is to produce new silicon and SiC automotive components that can operate in the widest range of possible operating conditions, while functioning with high reliability at extreme temperatures with minimal additional expense.

Typical packaging faces the degradation of common plastic encapsulants along with creep and fatigue of typical die attach materials and solders at temperatures above 200 °C [2, 3]. Two main factors generate thermal fatigue for these power electronic components in the harsh conditions present in the engine compartment of a car: thermal cycling due to engine heating/cooling and the self-heating generated by the operational power cycling.

Reliability issues in high-temperature module packages occur from differences in the coefficients of thermal expansion (CTE) of the attached module materials, in particular because the active devices tend to have lower CTEs than the packaging materials such as copper which are much higher [3]. The solders used in surface-mount components on the ceramic substrate are most problematic when module material temperatures are above 150 °C. Solders must have melting points safely above device operational temperatures but remain below higher temperatures that degrade the system components during assembly [3].

The lifetime of the solder joints may be estimated using modeling methods that can be based on either energy [4], strain [5], or both, and often involves finite element simulation analysis. Prediction of this lifetime is still primarily based on experimental evaluation using tools such as thermal cycling to replicate the thermal environment of a common engine mounted electronic case. Package inspection is also useful, delamination or cracks due to thermal cycling can be detected with the aid of scanning acoustic microscopy [6]. Studies have demonstrated that solder lifetime is not only dependent on cycling temperature variation but also on the low and high-temperature dwell times during thermal cycling tests; solder stress values are important during the low dwell temperature while solder strain is important during the high-temperature dwell. The solder will also exhibit much greater creep if the high-temperature dwell is above half its homologous temperature value [7]. These failure modes suggest that it is important to create a thermal cycling test system that supports many different cycle transition characteristics so that effects such as those mentioned can be studied in greater detail [7, 8].



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The National Institute of Standards and Technology (NIST) uses various methods to electrically and thermally characterize SiC devices and module packages [9-12]. A computer-controlled thermal cycling tool, presented in this paper, has been developed to aid in SiC module package characterization. The tool has been designed at NIST to permit a variety of independent thermal cycling transition settings. This will aid in the development of more complete device and system models which can be extended beyond typical electro-thermal characteristics into a more complete model that includes predictable device degradation and package thermo-mechanical characterization.

## II. Thermal Cycling System Overview

An overview of the NIST thermal cycling system is shown in Fig. 1. The device under test (DUT) is placed on a temperature- controlled heatplate which is located inside an enclosure made of high-temperature resistant material to isolate it from the surroundings both for safety purposes and to maintain heatplate temperature stability.

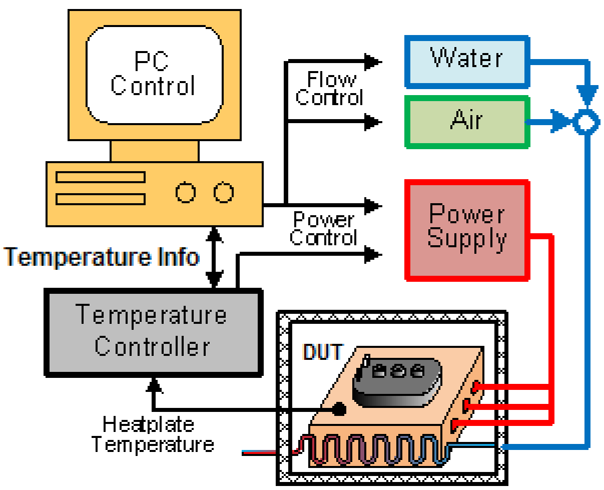



Figure 1. Thermal cycling system basic schematic.

The heatplate has a series of internal electric heating elements connected in parallel to a 100 V, 10 A DC power supply for a maximum heating power output of 1 kW. The heatplate also has an internal cooling coil for lowering its temperature by using the computer-controlled flow of air or chilled water. The heatplate temperature is constantly monitored by a temperature controller using a thermocouple located close to the baseplate of the DUT. The power supply output can be controlled either from the computer interface or directly by the temperature controller. The control method is determined by the existing conditions of the cycle and the actual temperature of the heatplate during the testing procedures.

Fig. 2 shows the thermal cycling test system user interface designed and implemented with LabWindows/CVI†, an instrument control software environment. This interface is divided into independent tabbed panels with specific functionalities the user can choose from to set up a thermal cycling test.

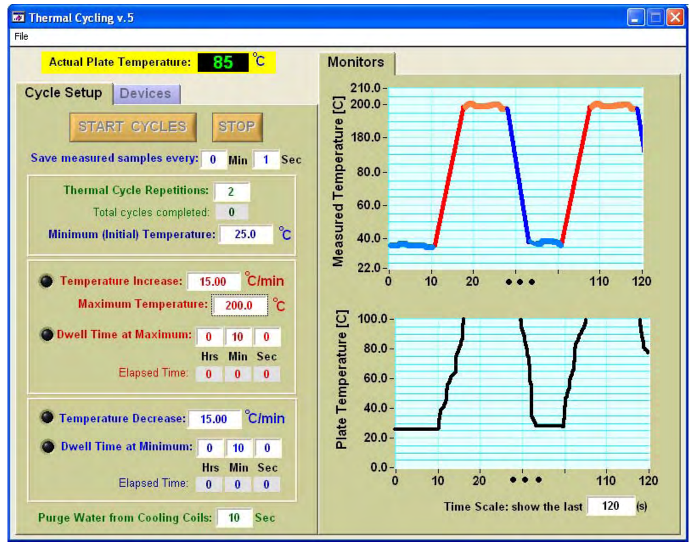



Figure 2. Thermal cycling test system user interface.

The "*Monitors*" tab is used to track the execution of the thermal cycling procedure by supplying current status information within cycles as well as the actual heatplate temperature. At the bottom of the "*Monitors*" tab there is a control for adjusting the horizontal time axis of the plots allowing the user to zoom in or zoom out to view more details of the measurement. The actual heatplate temperature is shown in the lower plot and it is continuously measured from a thermocouple placed within heatplate after the user initializes all the instruments. The upper right plot tracks the heatplate temperature during a thermal cycling process. Colored sample changes are used to identify status details within the cycle transitions.

The "*Devices*" tab of the user interface, detailed in Fig. 3a, is dedicated to the manipulation of the system hardware during initialization, test setup, and other manual controls performed by the user .This tab does not contain any settings related to the automated controls used during the thermal cycling tests.

The interface's "*Cycle Setup*" tab, shown in Fig. 3b, is used to define the parameters that allow the user to set the specific duration of every part of the cycle during a test.

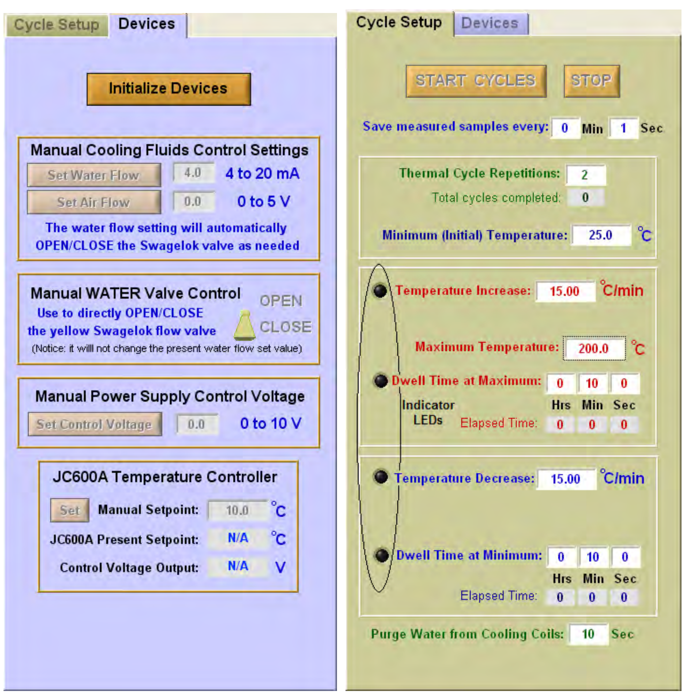
† LabWindows/CVI is a trademark of National Instruments Inc. Certain commercial products are identified in this paper to specify the experimental procedure adequately; nevertheless, this does not imply recommendation or endorsement by the National Institute of Standards and Technology.

## III. Typical Measurement Procedure

A typical thermal cycling test consists of a series of steps and decisions that the user must make to set up a successful measurement.

### *A. System Initialization*

The system is prepared for a test by first allowing chilled water to flow through the heatplate. This is done by manually opening the chilled water control valve as shown in Fig. 1, until the water flow maintains a steady minimum temperature required by the algorithms for system measurement to accurately control the heatplate temperature during the cooling transition of each cycle. Meanwhile, all of the hardware devices for the test are manually turned on and initialized so that they are recognized by the software when it loads the IEEE 488 bus control utilities (GPIB) and enables the data acquisition interface card, these tools are used to interface the software with the system components. Details of the user interface panel sections are shown in Fig. 3. When the software is loaded, no measurements or readings are shown on the user interface panel until the "*Initialize Devices*" button in the "*Devices*" tab (Fig. 3a) is pressed. If any of the instruments fails to be recognized during initialization, the software gives an error message and the user must fix the problem.




(a) (b)

Figure 3. User interface application panel details: (a) "Devices" tab including instruments settings, (b) "Cycle Setup" tab including measurement settings.

Once all of the hardware has been initialized, the temperature controller begins and continuously reads the thermocouple measurement from the heatplate until the application closes successfully later on. The user waits for the chilled water flow to reach a steady minimum temperature, typically around 10 °C, by monitoring the actual heatplate temperature plot shown on the user interface (Fig.2) at the lower right hand. This is necessary for removing room temperature water from the system and it takes several minutes for the water to stabilize at the minimum chilled temperature required for accurate operation of the test system.

Additionally, manual controls are also available for setup or testing purposes. These give the user complete manual control of all the system components when no automated thermal cycling tests are being conducted. For example, the user can test the water and air flow valve controls by setting different rates to verify that the flow valves are opened and the controllers are following the user's commands.

### *B. Thermal Cycling Test Setup*

A typical thermal cycling procedure starts once all equipment is initialized and the chilled water temperature has reached its minimum steady-state temperature. The DUT is firmly attached to the heatplate after applying a thin layer of thermal grease for improved the heat transfer. It is within the aforementioned temperature insulated enclosure. On the "*Cycle Setup*" tab of the user interface (Fig. 3b), the user specifies the characteristics of the thermal cycling test. These include: the minimum and maximum temperature extremes the module package will be subjected; the duration of the dwell times for both the minimum and maximum temperature levels; the desired increment and decrement temperature rate of change for the heating and cooling transitions of each cycle, respectively; the total number of thermal cycles to perform; and the sampling rate of measurements to be plotted and saved during the test. All of these parameters provide dynamic control of the test to the user *in situ*.

The setup of a thermal cycling test procedure is performed on the "*Cycle Setup*" tab. In this tab, parameters are set to define the heating and cooling rates of the test cycle and the duration of the dwell time portions of each cycle. The user selects the sampling rate of the heatplate, which controls how the data are plotted in the "*Monitors*" tab of the interface where test status information is tracked and a log file of the process is created. Each cycle section has a corresponding LED indicator light on this tab that turns on indicating when that cycle process is active, as well as how much time remains during the dwell period according to the initial or current setup conditions.

At the bottom of the "*Cycle Setup*" tab, there is a control for the amount of time necessary to purge any water present in the coils by allowing the air flow to clear the lines. This is very important as any remaining water inside the coils will start to boil with the increase in temperature as the temperature exceeds 100 °C. The water phase change from liquid to vapor may generate an undesirable deviation in the behavior of the specified heating transition slope rate of the cycle around the 100 °C point.

### *C. The Automated Cycling Procedure*

The thermal cycling procedure can be started by pressing the "*START CYCLES*" button in the "*Cycle Setup*" tab once all parameters are specified. The user will be prompted to specify the location for the log file for saving heatplate temperature values.

After a water purge of the system has been completed, the initial heating segment of the cycle will begin. The respective panel LED indicator will turn on to indicate that heating of the heatplate is enabled. The measured temperature data will then be plotted in red color on the "Monitors" panel in the upper right plot indicating that they belong to this heating transition phase. During this phase, the software controls the input voltage signal to the DC power supply to provide a proper output power level required to keep a constant temperature rate change given by the user previously.

The method that the software uses to determine the appropriate voltage control signal required to maintain the constant heating rate slope is based on prior thermal characterizations performed on the heatplate. First, the heatplate is cooled down to the chilled water temperature. Then the output of the power supply is set to constant voltage values that will heat the heatplate from room temperature to a maximum temperature of 200 °C, the typical maximum setting for the thermal cycles. (The system is capable of handling up to 300 °C, however for practical purposes those temperatures are destructive for almost all devices and may also damage power cable connections or other system components.) Fig. 4 shows the heating characterization curves obtained for different power supply control voltage levels between 3.5 V and 10 V. Lower signal voltages cannot reach the required 200 °C.

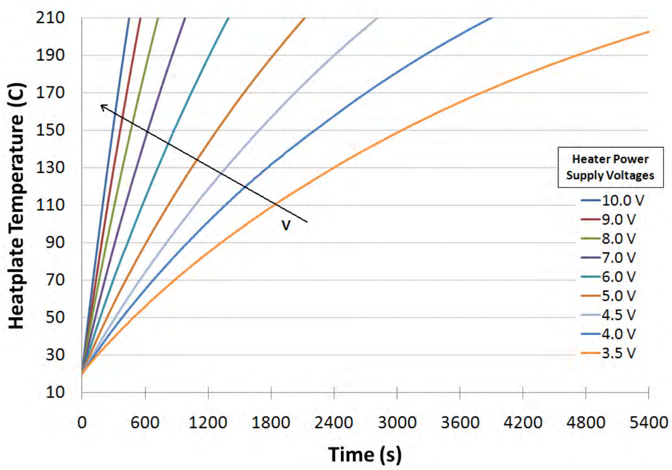


Figure 4. Heating characterization curves of heatplate.

The purpose of the characterization process is to find the rate of temperature change as a function of the applied control voltage and the instantaneous temperature of the heatplate at each moment. Once that relationship is known, the system can automatically adjust the control voltage level to maintain the same constant rate-of-change in the heatplate as the temperature increases with time. The necessary control equation is obtained by differentiating the temperature curves of Fig. 4 to obtain Fig. 5 then applying nonlinear fitting techniques and defining the axes as temperature rate-of-change versus heatplate temperature.

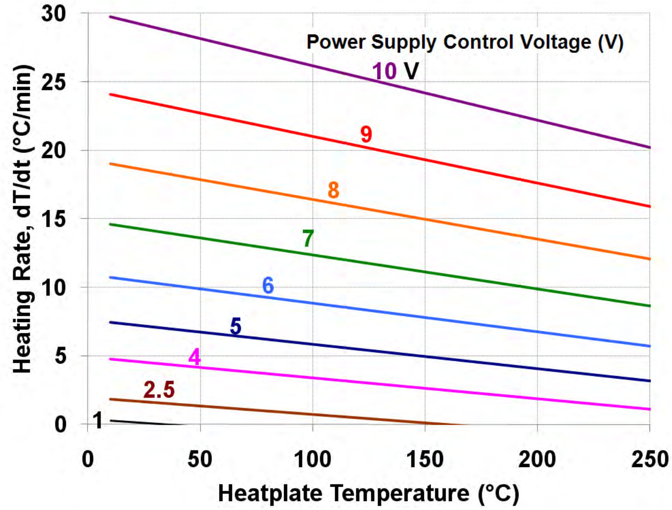


Figure 5. Heating capability characterization for the power supply.

When the heating cycle starts, the maximum dwell temperature becomes the setpoint for the temperature controller. Since the actual temperature is well below this value, the controller maximizes its heating rate by outputting the maximum control signal voltage. This voltage value is monitored by the software, but is ignored because the software is controlling the temperature change rate according to the prior calibration and the user's settings. The cycle controlling algorithm continually compares the computed power supply voltage control value against the temperature controller voltage control output as the heating continues. This comparison is done to determine when the controller will reduce its output control signal level below the value being computed by the algorithm. At that moment, the DC power supply will begin to reduce the power output level to avoid overshooting and to prepare to maintain the constant temperature value needed during the upcoming dwell period. When the heatplate temperature is close to the set dwell temperature, the computer ceases to send the control voltage signal and allows the temperature controller to take over and use its independent temperature control algorithms to maintain the heatplate high-temperature dwell. This switch signals the transition from the heating segment into the dwell period as the temperature controller PID parameters adjust the power supplied to the heatplate.

During the maximum temperature dwell period, the system switches the respective LED indicator and enables a counter of the dwell progress time. This step is simple as the system needs only to wait for the dwell time to complete while allowing the automatic control signal coming from the temperature controller to manage the DC power supply output level autonomously. A color change in the plot samples identifies the transition from the heating period to the dwell period.

When the maximum temperature dwell time is completed, the system turns on the corresponding LED indicator and again changes the color of the plotted samples. At this moment, the computer controlling procedure determines between the use of air flow or chilled water to cool down the heatplate, if the heatplate temperature is above 100 °C the system will begin the cooling phase with air flow to avoid sudden steam generation inside the heatplate cooling coils. If water is used above 100 °C system hoses can burst from the excessive pressure and damage components. This risk is exacerbated from inadvertent degradation of the system hoses from numerous prior thermal cycles.

The cool down procedure then follows the same techniques used for the heating control of the heatplate, only the flow rates are delivered by either the air flow controller or the water flow controller, never simultaneously. Each is independently characterized to obtain their characteristic cooling rate curves for different levels of signal control. For the air flow control, the heatplate is characterized by previously heating it to above the maximum temperature, 200 °C, and then cooling it by maintaining different constant signal control levels until the heatplate temperature reaches room temperature. To characterize the water flow cooling rate, the heatplate was only heated a few degrees above 100 °C and then cooled down with different constant water flows until it reaching the minimum chilled water temperature.

The characterization curves for these procedures are shown in Fig. 6. Again, the necessary control equations for air and water cooling flows were obtained by applying nonlinear fitting techniques to their respective data.

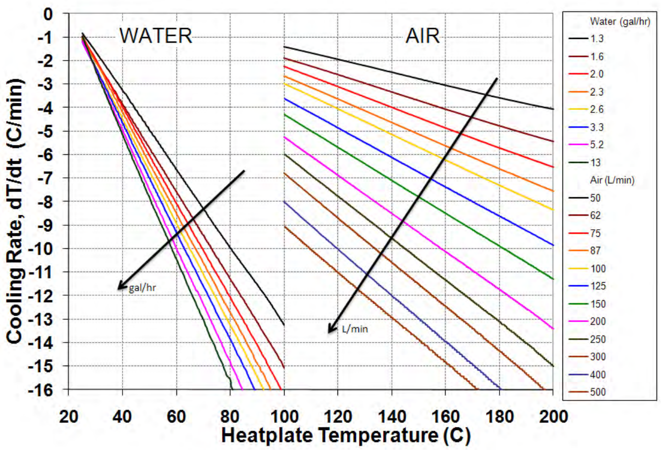



Figure 6. Heating capability characterization for the air and water flows.

The cooling period will finish when the minimum dwell temperature is reached and the system turns on its respective LED indicator enabling a counter to keep track of the dwell time progress. The temperature controller manages the DC power supply output level independently to maintain a constant dwell temperature during this period. Changes in color of the sample plot identify the transition from the cooling period to where the low-temperature dwell segment occurs. Once the dwell time is finished, the system will check to see if there are more cycle repetitions to perform. If so, the process of purging the water from the heatplate coils will start again, and the rest of the cycling process will continue as this section describes. If the last cycle is completing then the temperature controller is set at 10 °C to ensure that the heating power supply will not output power and the system will await a user response in standby.

Standard thermal cycling tests generally require the system to make fast transitions between low and high-temperature dwell periods that should not last more than 20 or 30 minutes depending on the test type whose dwell times last about 10 minutes [13]. These thermal cycling tests are generally accompanied by simultaneous power cycling tests to simulate complete extreme operational environment conditions for the devices. In most cases, the low dwell temperature is close to -40 °C when a controlled temperature chamber is used, and typical high dwell temperatures can range between 85 °C to 125 °C for general use packages.

## IV. Measurements and Results

Using the thermal cycling test system, a package reliability study similar to the one accomplished by NIST in [10] is currently underway for power SiC devices. Fig. 7 shows temperature acquisition for two different thermal cycling profiles similar to those used in the reliability study. Power SiC device packages generally need to be tested for higher temperatures due to their advantage in high-temperature operational capability, but that consequently requires better module package designs than for common commercial devices. The presented thermal cycling system allows for sufficiently high-temperature dwells and temperature ramping rates for robust degradation results.

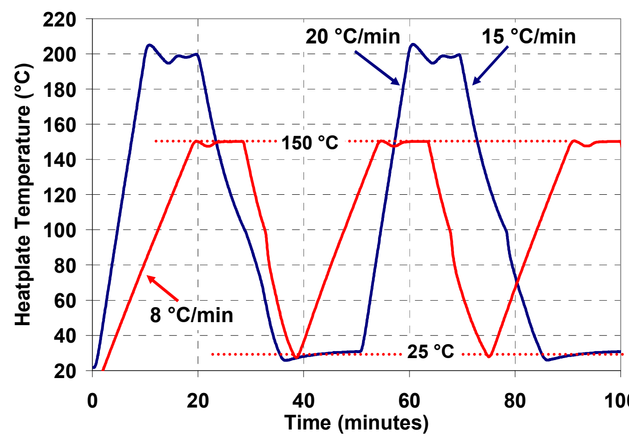



Figure 7. Data from two different thermal cycle setup examples.

Inducing thermal stress in the package internal structure will be of no practical use without a means to monitor the changes that are occurring as the stress progresses. One of the available methods at NIST is temperature-sensitive parameter (TSP) measurement in which a highly temperature dependant semiconductor device parameter, such as $V_{GS}$, is used to monitor the device temperature response from induced power loss *in situ* [12]. For a SiC package, an initial TSP measurement is performed to acquire the thermal response of a known electrical power level pulse applied to the device. Subsequently, as thermal cycling is performed on the package, TSP tests will show any thermal performance change that may be occurring in the package. Fig. 8 shows an example of the changes occurring to the temperature response of a SiC module that has been subjected to a series of thermal cycles and has had TSP monitoring during the process. This information can lead to alternative methods of scanning acoustic microscope analysis where electrical parameters, which can be easily measured from the device at any moment, can be combined with developed electro-thermal models into a more complete model capable of predicting the reliability of the module as the electrical parameters of the device reveal structural changes within the package. Depending on the applied pulse during the TSP tests, the results can show variations in electrical behavior which can be a consequence of internal structural changes within the module materials at different depth levels from the device junction down to the module heatplate.

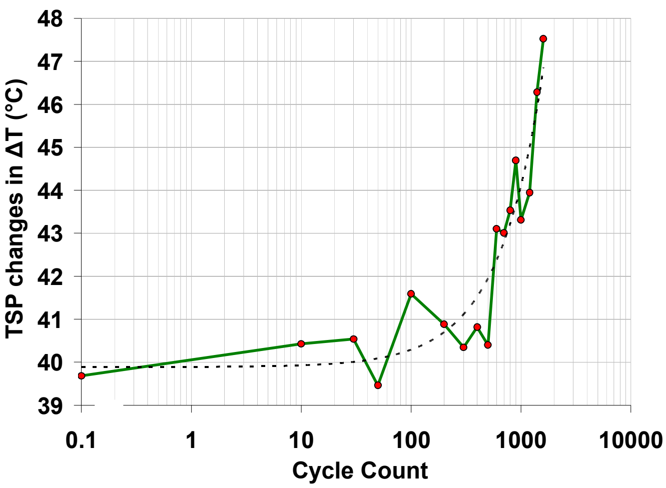



Figure 8. Temperature-sensitive parameter monitoring shows electrical behavior changes in a SiC module after several thermal cycles.

## IV. CONCLUSIONS

A software-controlled thermal cycling test system developed to assist in SiC module package characterization has been presented. The flexibility of the system proves effective to perform different thermal cycling configurations and measurements for SiC modules and packages. The electrical behavior of SiC devices has been monitored using NIST TSP methodology, and results show how the stresses induced from the accelerated thermal cycling tests are affecting the measured electrical parameters as the packages degrade. The combination of electro-thermal models with package characterization and thermo-mechanical modeling can become a valuable tool to developing more complete system models capable of including reliability prediction as part of the simulation parameters in the future.

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