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Practical, Efficient and Safe Power Device Thermal Characterization with B1506A

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Practical, Efficient and Safe Power Device Thermal Characterisation

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Power devices are used in a wide range of applications such as; train, automotive, traction, power generation etc. that are operated in harsh and extreme environmental conditions. Robust design for reliability and safety are paramount in these applications.

A key initial design requirement is the estimation of system maximum operating temperature by taking into account both maximum heat generation and cooling capacity. Once this is known an appropriate power device can be selected that will safely operate under all expected operating temperatures and conditions. To select such a device requires a thorough understanding of power device characteristics over the extremes of expected temperature. For example automotive Si power devices operating with a dedicated cooling system at 65°C are separated from the engine cooling system at 110°C. This requirement for two separate cooling systems originates from the maximum junction operating temperature limit for Silicon. Emerging SiC devices are capable of operating at over 200°C and have the ability to share the engine cooling system. This results in significant savings in both weight and cost. Accordingly, understanding SiC device characteristics at higher temperatures is important while reliable device operation under extreme cold, e.g. -50°C also has to be guaranteed.

Power devices have to operate reliably under wide temperature ranges. 150°C has been the maximum operating temperature for many years. However, it is on the rise (e.g. 175°C) and is projected to go even higher (e.g. 250°C) for SiC and GaN wide band gap devices.

Issues with measurement equipment cable extension

Power device evaluation, at both low and high temperatures, requires not only test equipment but also a thermostatic chamber. Although it is widely used a thermostatic chamber takes a significant time for the temperature to stabilize. It also necessitates the use of long connection cables between test equipment and the chamber which adversely affect measurement s.

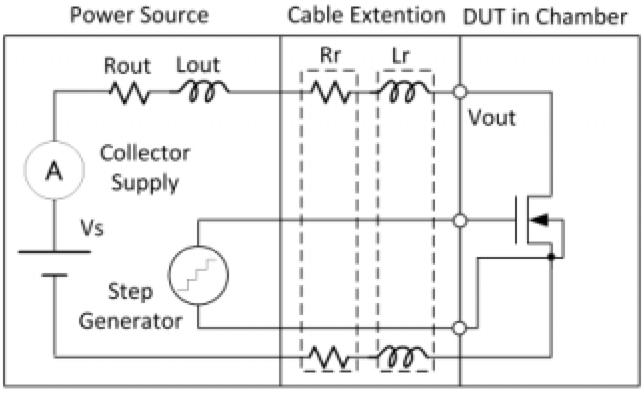

Figure 1: Cable extension from power source to thermostatic chamber

$$Iout = \frac{Vs - Vout}{Rout + Rr} \quad (1)$$

For test equipment that sources ultra-high currents long extension cables result in a reduction of maximum current due to voltage drop from cable residual resistance. Output current (Iout) is expressed by the following equation:

Defining output voltage of test equipment as Vs, resistance of test equipment as Rout, residual resistance of cable as Rr and DUT voltage as Vout.

Referencing Keysight Technologies B1505A or B1506A as an example of ultra-high current test equipment. Figure 2 shows the IV range of the B1505A. Rout on the 1500A range is 40 mΩ. Adding an extension cable with a typical residual resistance of 40 mΩ reduces the maximum current by half.

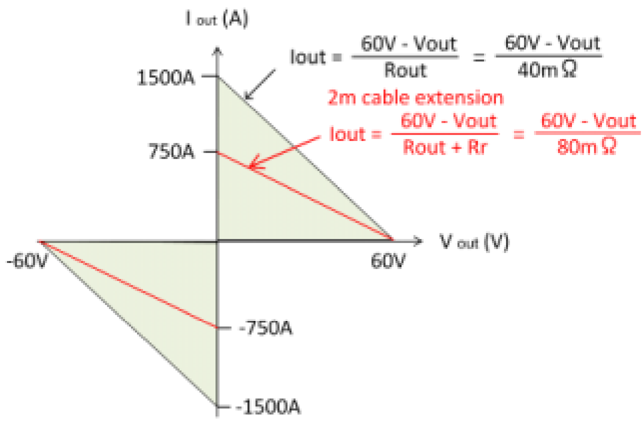

Figure 2: Limitation of output current by extension cable residual resistance

Another extension cable drawback is the limitation of fast pulses. At ultra-high currents fast pulsing is necessary to avoid device self-heating. However, longer cables result in larger pulse widths due to the residual inductance (Lr) of the extension cable. This increases the potential for device self-heating.

Time constant (τ) is expressed in equation (2) when the output inductance of test equipment is Lout.

$$\tau = \frac{Lout + Lr}{Rout + Rr + Rx} \quad (2)$$

A typical 2m extension cable has residual inductance of 4 μH. This is added to the sum of Lout and Lr, τ is calculated as 50 μs which results in 4.6τ or a 230 μs pulse width with 99% settling time. The long pulse width degrades measurements due to device self-heating. Figure 3 reveals on-resistance pulse width dependency on a Power MOS FET device.

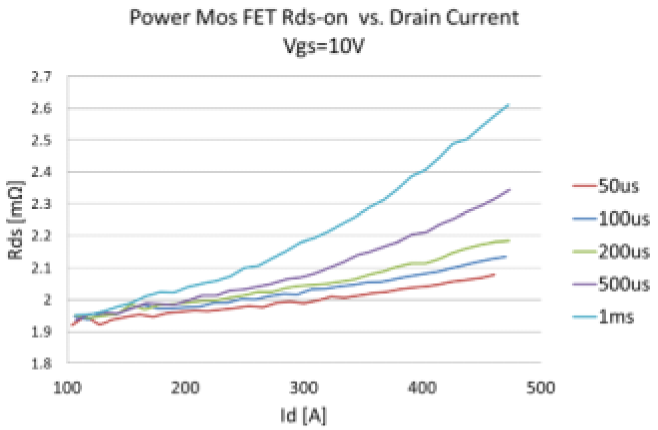

Figure 3: Pulse width dependency of Rds_on measurement

Another common and frustrating issue when using a thermostatic chamber in conjunction with an extension cable is oscillation. Residual inductance along the cable connection between gate and source is likely to initiate device oscillation.

Hot Plate in Test Fixture solution

One solution to the above problem of measuring temperature dependency with ultra-high current is to set up a temperature controlled environment alongside the test equipment. The simplest way is to place a temperature controlled hot plate in a test fixture that has integrated test resources. Figure 4 shows the Keysight B1506A test fixture which has an integrated thermal plate terminal. This configuration allows the measurement of device temperature dependency from ambient room temperature to +250°C. A safety interlock that is enabled by a closed top cover ensures a safe test environment. To efficiently transfer heat from the thermal plate to the device requires the use of a contact sheet or thermal grease. Although this method is quick and simple the temperature around the device is not necessarily uniform. Part of the hot plate is exposed to the air which results in temperature loss via heat radiation and convection. Additionally, heat transfer through device test leads is another source of temperature non-uniformity.

Thermostream*

The use of a Thermostream* enables significantly faster heat transfer than a thermostatic chamber and is popular equipment among semiconductor device manufactures. A hot or cold air stream is delivered to the test environment with precise control. The desired air temperature is obtained by heating dry air which is first cooled to around -100°C using a chiller. The temperature of the dry air is precisely controlled allowing a specified temperature test to be performed. This can be in an open environment as long as a device is placed in the air stream.

The above arrangement works for small size power devices. However, it does not work on large size power devices, such as IGBT modules. The temperature across the IGBT module is not uniform due to different air stream velocities. A more precise uniform temperature controlled test environment is possible by designing an enclosure that fully covers the device. Unlike a thermostatic chamber the shape and location of the enclosure is flexible due to the air stream as the thermal source.

A Thermostream* is ideal for the creation of a thermally controlled temperature environment which is located in the immediate vicinity of the test equipment. However, if there is no enclosure attached the test equipment may get damaged by hot air or condensation. A thermal enclosure attached to the test equipment and the Thermostream* resolves this issue and allows accurate, reliable and repeatable temperature dependency characterization.

* Thermostream* is a product of InTEST corporation. It is not supplied by Keysight Technologies.

Figure 4: Thermal plate in B1506A test fixture

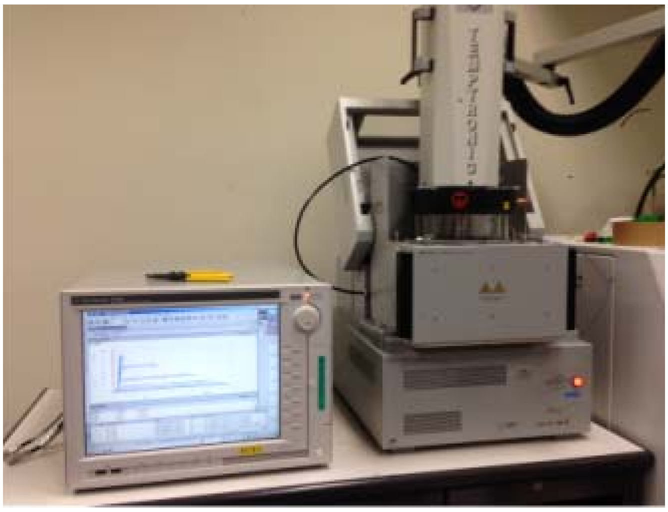

*Figure 5: B1506A Test Fixture Thermal Enclosure for Thermostream**

Thermal enclosure design

This section considers the evaluation of large size power devices, (e.g. IGBT modules) using a Thermostream*. Air forced from the Thermostream* circulates in the enclosure and is then exhausted. Graphical representation of heat transfer is shown in Figure 6. Examination of heat transfer from Thermostream* to the enclosure reveals three component mechanisms. Heat conduction in the enclosure material, enclosure heat convection to the outer air and heat radiation from the enclosure surface. The relationship between heat transfer quantity and temperature difference is expressed by the following thermal resistance equation.

Heat transfer quantity (W) = Temperature difference (°C) / Thermal resistance (°C / W).

As an example, if the air temperature of the Thermostream* is 150°C, the heat transfer quantity depends on the air volume and temperature and represented with the following equation:

Heat transfer quantity (W) = Air volume (m^3/s) * Specific gravity of air (kg/m^3) * Specific heat of air (J/kg °C) * Temperature change of the air (°C) … (3)

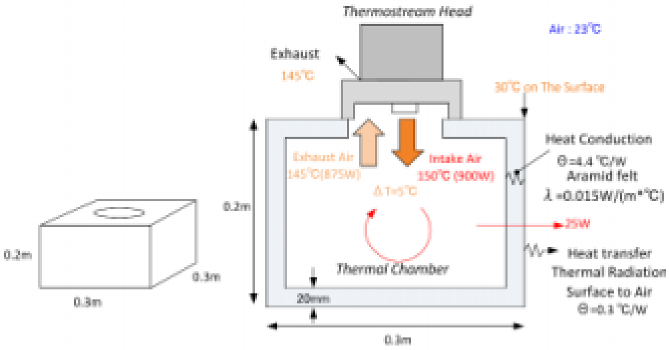

Figure 6: Thermal enclosure heat transfer block diagram

The following conditions apply: Ambient temperature 23°C, specific gravity of air at 150°C (0.83 kg/m^3), specific heat of air (1000 J/kg °C), air volume (0.0085 m^3/s or 18 scfm) which results in heat transfer of 900 W.

Heat from the Thermostream* passes to the outer air through heat conduction in the enclosure plus heat convection and radiation from the surface of the enclosure. This results in the temperature of the enclosure being lower than that of the air stream. Temperature may be better controlled by reducing the thermal loss inside and outside the enclosure thus allowing more accurate and repeatable temperature dependency measurements.

The choice of high temperature heat insulating material for the enclosure is limited. If Aramid Yam felt is used, the heat conductivity is 0.015 W/(m*°C). The thermal resistivity may be expressed as:

Thermal resistance (°C/W) = [1 / Thermal conductivity (W/m°C)] x [Thickness (m) / Area (m^2)] … (4)

For example; with an insulating material thickness of 20 mm and an enclosure size of 0.018 m^3, (0.3 m * 0.3 m * 0.2 m) the thermal resistance is calculated as 4.4°C/W.

The total heat transfer of the system is difficult to calculate as the thermal resistance of heat transfer and enclosure surface radiation is a nonlinear function of temperature. However, it may be solved by computer software. Calculation reveals that the total thermal loss in the enclosure is approximately 25 W. This implies that the average temperature in the enclosure is 145°C while the enclosure outer surface temperature is 30°C. Additionally, the outer surface thermal resistance due to heat convection and radiation is approximately 0.3°C/W. Enclosure temperature loss is significantly reduced if it is surrounded by thermal insulating material.

In this example the enclosure temperature decrease is 5°C whilst still able to accommodate a sizeable power device. However, in practice the thermal insulation effect will not be as efficient as in the above example due to air stream inlet and measurement cables holes in the enclosure.

What happens if the enclosure is not made of heat insulating material but only of heat conducting material, (e.g. aluminium)?

If only aluminium with heat conductivity of 138 W/(m°C) is used to fabricate the same size enclosure the calculated thermal resistance using equation (4) is negligibly small. In this particular case the total thermal resistance of the enclosure is the sum of thermal convection and radiation at the outer surface of the enclosure. The thermal loss and the average temperature in the enclosure is 340 W and 90°C resulting in a temperature decrease of 60°C due to the lack of heat insulating material.

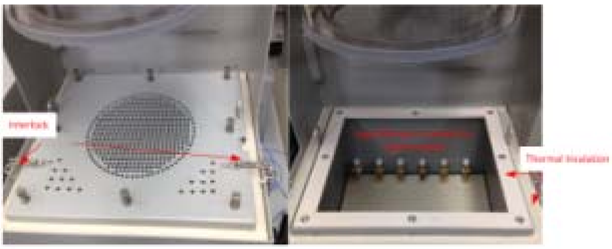

Figure 7: B1506A low thermal loss enclosure with safety interlock

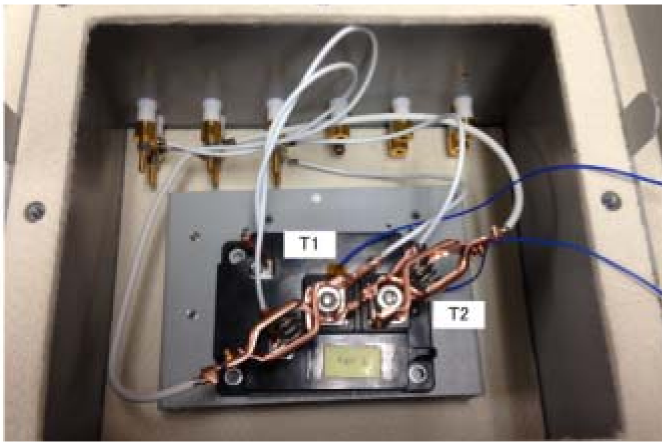

Figure 8: FUJI Electronics IGBT 1MBI800U4B-12 1- Pack module

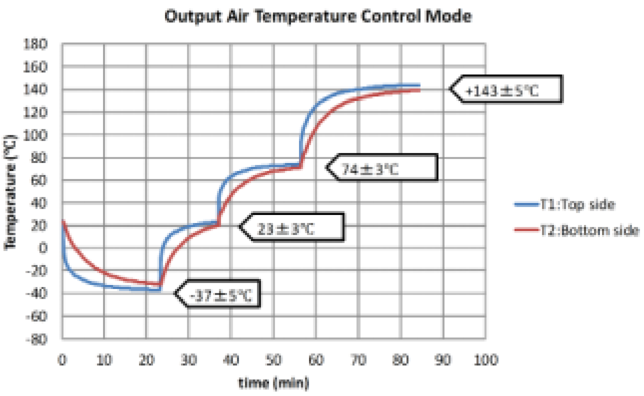

Figure 9: Thermal response of DUT

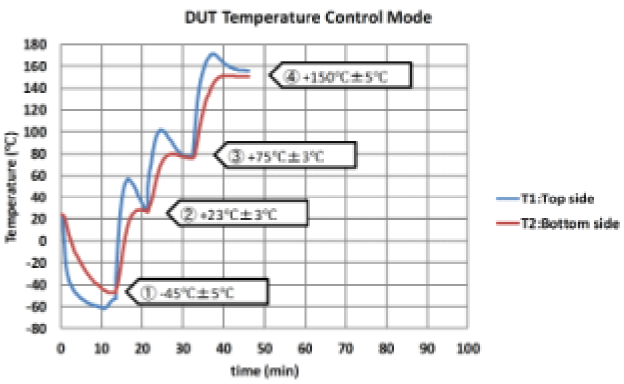

Figure 10: Thermal response of DUT with Thermostream thermal feedback enabled*

A Thermostream* fitted with a low thermal loss enclosure allows temperature evaluation of large power devices.

Figure 7 shows the thermal enclosure developed for Keysight B1506A. Measurement terminals installed at the back of the enclosure are 4 Φ banana terminals and are surrounded by PTFE. The safety interlock is only enabled when the top cover is fully closed thus creating a safe test environment.

Examination of the heat transfer quantity of the Thermostream* via equation (3) reveals dependency on temperature difference.

At an air flow volume of 0.0085 m^3/s (or 18 scrm) and an air stream temperature of 100°C, the heat transfer quantity is approximately 620 W. Increasing the air stream temperature to 200°C results in a heat transfer around 1100 W. Accordingly, a 200°C air stream gives an additional 500 W heat transfer over a 100°C air stream even when the target DUT temperature is 100°C. The time duration to change DUT temperature is proportional to its thermal capacity and given heat transfer quantity. Thus applying an additional quantity of heat transfer reduces the time for the DUT to reach target temperature. Accordingly, the total test time will be reduced by setting the air stream temperature higher than the target DUT temperature. Some Thermostream* models have a function to control DUT temperature quickly and efficiently by monitoring the DUT temperature with a thermocouple and automatically adjusting the air stream temperature.

Large device characterization under low temperature can also be performed using the enclosure. One advantage of a Thermostream* with enclosure is the ability to eliminate condensation. Temperature in a thermostatic chamber is controlled by continuous circulating air. If a temperature gap exists within the chamber condensation may occur as the circulating air is not necessarily dry air. In the case of a Thermostream* and enclosure the dry air stream is injected into the enclosure and then exhausted. The dew point is lower than the setting temperature thus condensation does not occur with the Thermostream* and enclosure combination even with a side wall temperature difference.

Low temperature device evaluation utilising a Thermostream* and enclosure combination is a simple way to avoid condensation.

Automated thermal testing

This section details experimental results derived from the Thermostream* and enclosure combination.

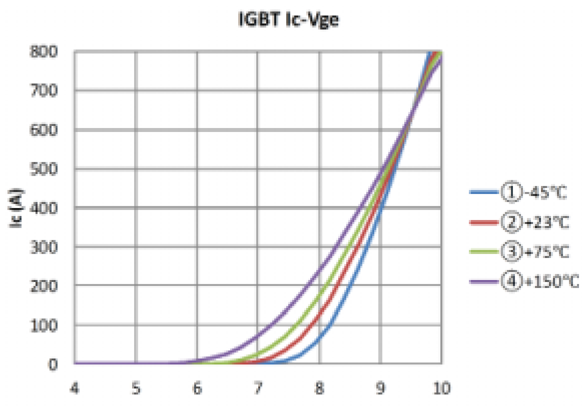

Figure 11: IGBT Ic-Vge characteristics at different Thermostream* tempertures

Two thermocouples are attached to the top and bottom sides of an IGBT module as shown in Figure 8. The IGBT module size is 110 mm x 80 mm. The thermocouples read T1 (top side) and T2 (bottom side) temperatures whose values are used to detect the DUT temperature and automatically trigger measurements. The Thermostream* is programmed to sequentially set the air stream temperature to: +23°C, -45°C, +23°C, +75°C and +150°C. The settling temperature is simultaneously monitored via the temperature difference between T1 and T2. When the temperature difference is less than 5°C the next temperature setting is enabled.

Figure 9 shows the thermal response taken by the two thermocouples attached to the DUT. The IGBT module temperature is well controlled to a small percentage of the programmed air stream temperature due to the trivial thermal loss of the enclosure.
Figure 10 shows the thermal response of the DUT when the Thermostream* adjusts air stream temperature by referencing the DUT thermocouple temperature. Although some temperature overshoot is observed the Thermostream* feedback mechanism reduces the temperature stability time by approximately 50% compared to the control time shown in Figure 9.

A Keysight B1506A can trigger measurement by utilizing the readings of the two thermocouples attached to the DUT. The B1506A automatically initiates measurements after waiting a predetermined soak time and the temperature difference between the two thermocouples is within a specified range.

Figure 11 shows the transfer characteristics of the IGBT module DUT taken simultaneously with the thermal response of Figure 10. The DUT characteristics are automatically measured at specified temperature points from -45°C to +150°C. The complete IGBT temperature characterisation is completed in less than fifty minutes.

The Keysight Technologies B1506A Power Device Analyser was specifically developed for Power Circuit designers. It was designed to automatically evaluate power device characteristics at temperatures from -50°C to +250°C. Testing is performed automatically and safely when the top cover is closed enabling the safety interlock on the insulated thermal enclosure. The length of connection cable between the measurement equipment and the DUT is minimized as the thermal enclosure is placed in the test fixture which also houses the current amplifier. This facilitates accurate ultra-high current temperature dependent measurements by maximizing source current and minimising device oscillation. Additionally, a positive temperature only thermal plate characterization option is also available for Keysight Technologies B1506A.

Emerging wide band gap devices allow significantly higher device operating temperatures with reduced cooling. Accordingly the circuit designer must fully understand the thermal characteristics of the power devices selected. The Keysight Technologies B1506A allows quick and easy thermal evaluation of power devices and is an essential tool for power electronics circuit designers and power device engineers respectively.

Keysight Technologies is created by the spin-off of Agilent Technologies' Electronic Measurement business.

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