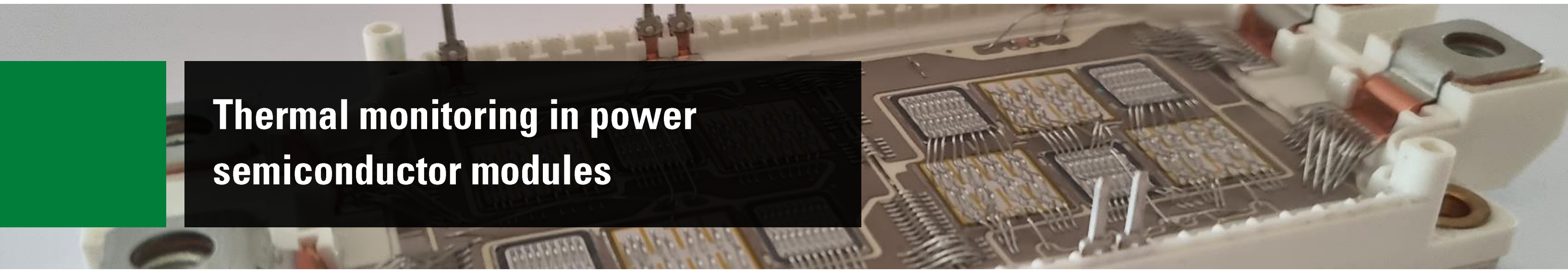

Thermal monitoring in power semiconductor modules

Objectives

This document focuses on using the temperature sensor inside a power electronic component to estimate the chip temperature. The photograph in Figure **1** displays the NTC featured in different power modules.

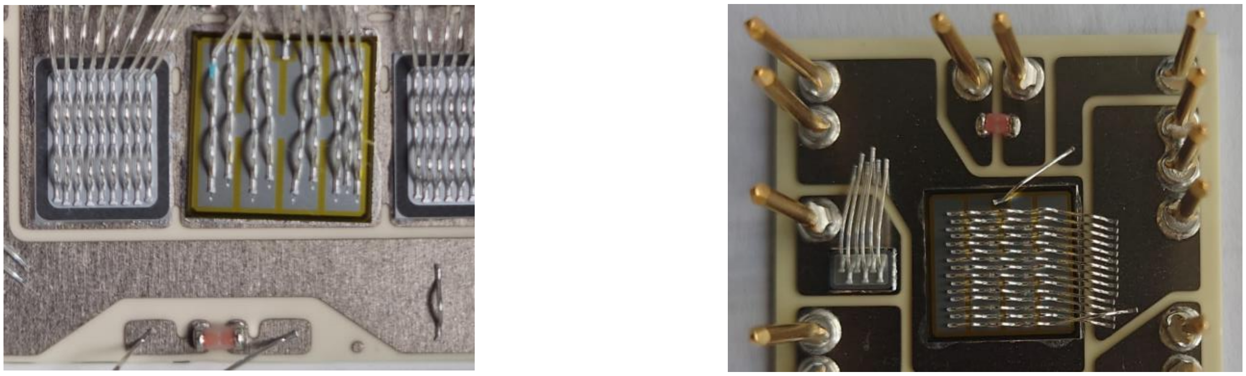

Figure 1: Section with the NTC within a SimBus F and the DCB of a V2-Pack

Applications

Temperature sensing is a task to be done in almost any power electronic design. Therefore, this general topic is independent on the application

Target Audience

This document is intended for all power electronic designers that need to monitor temperatures within their designs.

Contact Information

For more information on the topic, contact the Littelfuse Power Semiconductor team of product and applications experts at PowerSemiSupport@Littelfuse.com

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Introduction

Temperature and temperature swing are the most prominent parameters that degrade power electronic components over time. Consequently, the temperature inside a power electronic component is the information to be accessed to monitor the operating condition of an application and potentially make an estimation about the system's state of health.

Measuring the chip temperature isn't trivial and accurate measurement is either complex and limited to laboratory experiment or demands a sensor on or in the chip.

The more economical solution is a temperature sensor in close proximity to the chip and evaluation of the chip temperature based on a thermal model. The NTC-resistor inside a power module can be used to capture this temperature.

1. Thermal stack and thermal modeling

Physically, the NTC inside any power module is part of the path, the thermal energy takes from the heat source to the heat sink. Not being attached to the heat source directly, the NTC provides an insight to a position close to the heat source - the chip. The thermal stack and the correlating thermal model are depicted in the scheme in Figure 2.

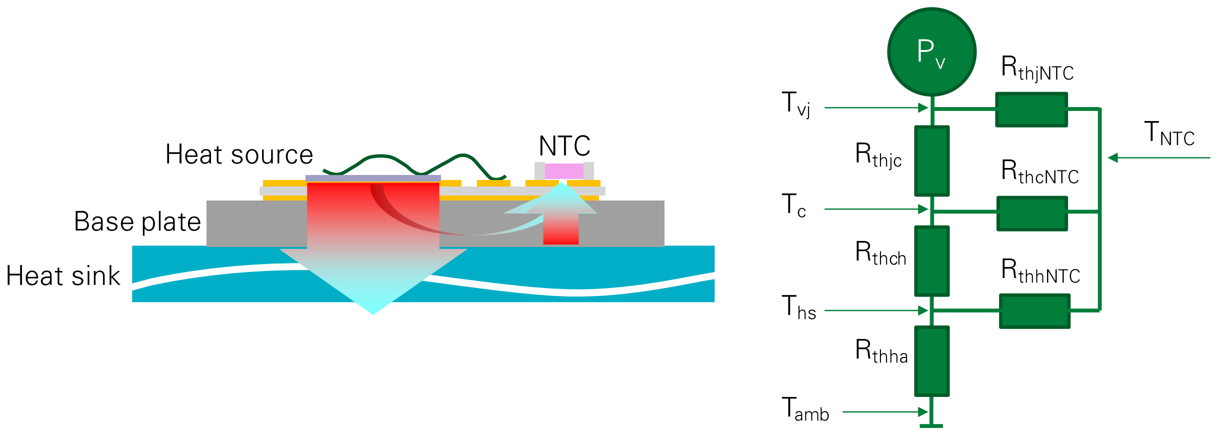


Figure 2. Thermal stack of a typical power semiconductor including the NTC and the simplified thermal model

From the graphical representation, it is also obvious, that the NTC's temperature is closer to the chip's temperature than to the one at the heat sink, though it is anywhere in between. It is also important to notice, that the assembly as well as the heat sink in use influence the thermal model. Because of this, a thermal model to describe the connection between chip and NTC cannot be part of the power semiconductor's datasheet as it clearly depends on the individual setup.

Measuring the correlation between chip temperature and NTC-reading for calibration purpose can be done in a pragmatic way once the setup is defined. Connecting the power semiconductor to a low-voltage, high-current source allows generating the losses and thus the desired chip temperature. Measuring the chip temperature by means of thermocouple or IR-camera and recording the NTC's reading at the same time leads to a look-up table that can be used to later translate the value captured from the NTC back into a chip temperature.

To get a most accurate model, actively operating the heat sources inside the power semiconductor is mandatory. Simply applying the heat from a heat plate will lead to an increase in the NTC's temperature but doesn't reflect the unique properties of the device in use.

It is also important to notice, that the thermal stack includes larger thermal capacitances, so there is a lag between a chip temperature rise and the NTC's response. Therefore, monitoring temperatures using the NTC is good in regards of stationary operation or permanent surveillance and will easily detect failing or degrading cooling system components like clogged fans or jammed pumps in liquid cooling arrangements.
Due to the time constants involved, this procedure is insufficient to protect a device from transient events, in particular short circuit.

2. The NTC's characteristics

The phrase *NTC* is a short version of NTC-resistor. The name describes a resistive component, featuring a well-defined thermal dependency with a negative temperature coefficient; the component's resistance gets lower when the temperature increases. Littelfuse power semiconductor modules that feature the NTC inside all feature the same part, described in the datasheet by the set of parameters given in Figure 3.

Temperature Sensor NTC						
Symbol	Definition	Conditions	min.	typ.	max.	Unit
R_{25}	*resistance*	T_{VJ} = 25°	4.75	5	5.25	kΩ
$B_{25/50}$	*temperature coefficient*			3375		K

Figure 3. NTC parameters as given in a power semiconductor's datasheet

The resistance of the NTC follows an exponential function given by the temperature difference and the temperature coefficient as given in Equation 1

$$R(\vartheta) = R_{25} \cdot e^{B_{25/50} \cdot \left(\frac{1}{T_{NTC}} - \frac{1}{T_{25}}\right)} \qquad 1$$

Taken from the datasheets, the resistance R_{25} is 5000Ω ±5% and the temperature coefficient $B_{25/50}$ is 3375K. The NTC's temperature T_{NTC} is recorded in Kelvin, the reference temperature T_{25} of 25°C is transferred to 298.15K.

Plotting the function $R_{NTC}=f(\vartheta)$ reveals the exponential character as depicted in the diagram in Figure 4.

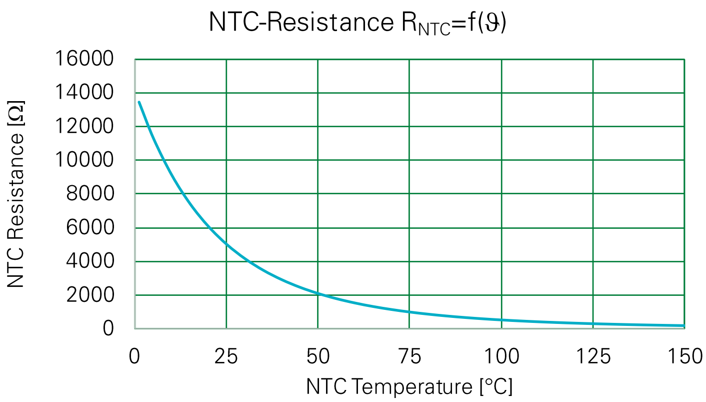


Figure 4. The NTC's resistance as a function of temperature

With little effort, Equation 1 can be rewritten to allow calculating the NTC's temperature from the measured resistance R(ϑ) leading to Equation 2.

$$T_{NTC} = \frac{1}{\frac{ln\left(\frac{R(\vartheta)}{R_{25}}\right)}{B_{25/50}} + \frac{1}{T_{25}}} \qquad 2$$

Within the application, the equation can be solved by means of microprocessors to provide the temperature value for further processing and monitoring.

In case a threshold for safety issues is desired, a comparator can be used as a simple method to generate a warning signal.

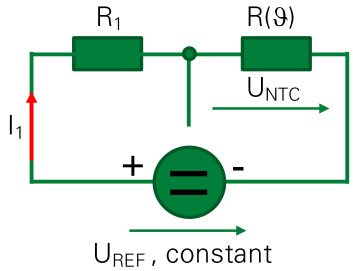
Of course, an implementation of both is always possible.

3. Reading the NTC-value

While in a lab and for static operation the resistance can be captured with a multimeter, the final application demands to get the information as an electrical value.
Two different methods have proven to be feasible. Depending on the designers' preference, either an analog voltage can be generated, or a sequence of pulses is created that can be analyzed.

3.1. Generating an analog signal

The most basic approach consists of a voltage divider where one of the resistors is formed by the NTC as drafted in Figure 5.



$$U_{NTC} = U_{REF} \cdot \frac{R(\vartheta)}{R_1 + R(\vartheta)}$$

Figure 5. Basic voltage divider to generate an analog information

The constant reference voltage U_{REF} drives a current I_1 through the resistors and the voltage across the NTC changes with temperature just as its resistance does. As the current through both the resistors is the same, the NTC's resistance can be calculated according to the relation in Equation 3.

$$R(\vartheta) = R_1 \cdot \frac{U_{NTC}}{U_{REF} - U_{NTC}} \qquad 3$$

The resistance-value calculated can then be used with Equation 2 to calculate the NTC's temperature.

For this setup, it is important to choose a range for the current I_1 that does not heat up the NTC due to losses. The NTC is a glass-passivated component in a package that has a thermal resistance of about 150K/W. In most cases it is desired to choose a current small enough to limit the self-heating to less than 1K and conduct temperature measurements up to 125°C.
In this point of operation, the NTC's resistance R(125°C) is about 290Ω and the power losses tolerable to limit self-heating are 6.7mW. As the total losses in the NTC follow $P_{tot}=I^2 \cdot R$, the maximum current that can be tolerated results from Equation 4.

$$I_{max} = \sqrt{\frac{P_{tot}}{R_{125}}} = 4.8mA \qquad 4$$

To remain on the safe side, restricting to 4mA is reasonable. Given a reference voltage U_{REF}=3.3V, present in most electronic systems, the resistor R_1 then is returned from Equation 5.

$$R_1 = \frac{U_{REF}}{4mA} - R_{125} = 535\Omega \qquad 5$$

A good fit in this scenario is 536Ω found in the E48-list of standard resistors wit 2% accuracy.

It is considered best practice to implement an algorithm that can be fine-tuned by adding a correction factor to compensate for manufacturing tolerances of both, the resistor R_1 and the NTC in place.

3.2. Generating a pulse-based signal

A basic schematic to fulfill this task is sketched in Figure 6

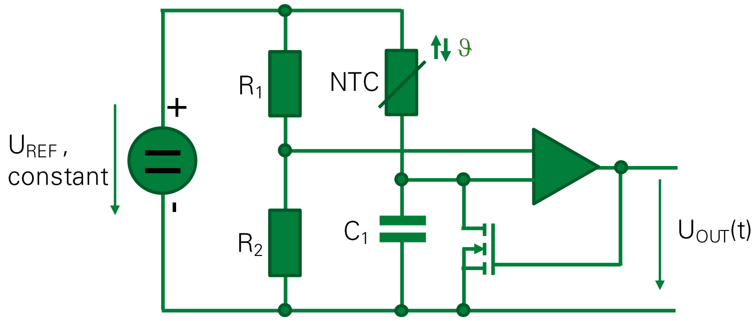


Figure 6. Schematic to generate a temperature dependent pulse-pattern

The voltage divider formed by R_1 and R_2 gives a fixed setpoint for the comparator. The capacitor C_1 gets charged via the NTC and once the setpoint given by the voltage divider is reached, the comparator's output changes from low to high. In turn, the MOSFET is turned on, discharges the capacitor, and the comparator's output toggles back to low. Due to the self-resetting feature, a pulse train $U_{out}(t)$ is generated in which the pulse frequency, respectively the number of pulses per time, becomes a deterministic function of the NTC's temperature.

It depends on the designers' preference to count a certain number of pulses and measure the time it takes or count pulses for a predefined period of time. Both approaches contain the same amount of information and achieve the same accuracy after proper calibration.

Here too, the capacity needs to be chosen carefully to achieve a reasonable response time while at the same time limit self-heating of the NTC by too high currents.

4. Insulation considerations

These power semiconductor modules are UL recognized. This recognition applies to the voltage insulation of the semiconductors to the heatsink. Within the module, the power semiconductor dices and the NTC, as well as the corresponding copper-traces on the DCB are arranged in close proximity. Potting the modules with a silicone gel ensures the insulation of the components for normal operation.

During final testing, the temperature sensor is tested for its electrical parameters. To check the insulation capability of the module, a high voltage test between all components including the NTC and the baseplate is conducted. In addition, a high voltage test between the NTC and all other components is conducted. This verifies the insulation for normal operation is achieved.

Any malfunction, for example a short circuit, may lead to a destruction of the power semiconductors and a mechanical destruction of the module, including melting of bond wires or arcing, resulting in a high energy plasma. This may create an electrical connection from the power circuitry to the copper traces or the terminals of the NTC which could result in high voltage appearing at the NTC's terminals. A scenario of such an event is laid out in Figure 7.

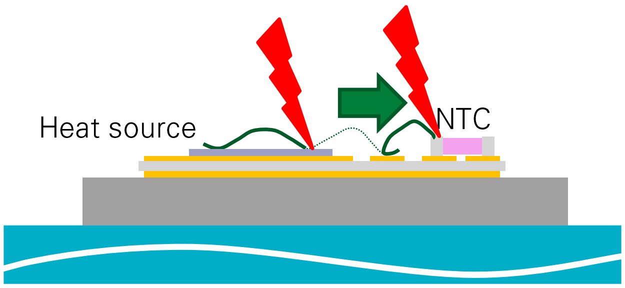


Figure 7. Destructive failure scenario where displacing a bond wire leads to loss of insulation

The European Standard EN 50178 regulates the safety requirements for parts of equipment that can be touched by a person. This also applies in case of a failure as described. Power semiconductors with integrated NTC provide functional insulation but do not fulfill the requirements of the EN 50178 as far as double, or reinforced insulation is concerned.

Therefore, the user of the integrated temperature sensor is requested to apply appropriate safety measures to ensure that persons, other living beings, or things can't be endangered and that no dangerous voltages are applied to parts that can be touched. An appropriate insulation according to the EN 50178 can be achieved using different measures. Suitable optocouplers or signal transformers can be used for galvanic insulation if higher levels of insulation requirements need to be met.

5. Conclusion

Sensing the temperature in power electronic components is a recurring task. Integrated temperature sensors, when handled properly are a cost-efficient part in building reliable solution. Rather rough temperature sensing to detect over temperature events can be achieved using simple comparators. More accurate setups need to be considered to achieve the accuracy needed to monitor subsystems for more advanced features like state-of-health surveillance.

Here, analog approaches as well as digital solutions can be chosen according to the designers' preference.

Revision History

Revision	Date	Major work done
1.0	2001	IXYS AN0034 on using the NCT
2.0	September 2021	Reworked and updated