On-line Junction Temperature Measurement of CoolMOS Devices

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***Abstract*— To operate power electronic devices at high ambient temperatures it has to be ensured that the maximum specified junction temperature is not exceeded at any time during operation. This paper presents a method to calculate the actual junction temperature by measuring voltage and current at a power MOSFET during operation of a converter. Based on this temperature, the actual transferred power of a converter can be controlled to ensure a safe operation within the specified temperature limits.**

I. Introduction

Nowadays, power electronic devices are operated at high temperatures - either to operate electronic systems at high ambient temperatures (e.g. geothermal exploration, power systems, combustion engines, etc.) or to minimize the volume of the heat sink. In both cases it has to be ensured that the junction temperature remains below the maximum specified junction temperature. Operating the devices at a higher junction temperature could result in a reduced reliability or even in a thermal runaway of the semiconductor which finally leads to the destruction of the device.

To prevent these failure modes, there are several methods to ensure a safe operation. One possibility is to measure the heatsink temperature and based on these data the junction temperature is calculated using a thermal model of the system. The disadvantage of this method is that the result depends on the accuracy of the system model. Furthermore, the influence of a fluid based direct cooling of the semiconductors (e.g. by operating the devices in an insulating liquid) is very difficult to consider in the model. Another possibility is to oversize the heatsink to ensure a safety margin leading to an increased volume of the system.

To avoid these problems, a direct measurement of the junction temperature during operation would be advantageous. If the actual temperature is available, the control unit of a power converter could regulate the actual transmitted power in dependence of the junction temperature. In general, by reducing the transmitted power the power loss in the semiconductor devices is also reduced which leads to lower thermal losses and consequently a lower junction temperature. This control method enables the converter to operate at a lower power level when the maximum junction temperature is reached instead of switching off the whole system. A known approach to measure the temperature of the semiconductor devices is the inspection of an opened power module with an infrared camera [1]. Since infrared cameras are very expensive and bulky and operating a converter with open modules is problematic, this method can only be performed in a laboratory environment. Furthermore, this method is not applicable for encapsulated semiconductor devices (such as TO247, etc.).

In this paper, an innovative method is proposed which enables temperature sensing of a CoolMOS chip by only measuring electrical parameters of the device.

II. Fundamentals

In several applications MOSFETs are employed. In 1999, CoolMOS devices appeared in the market. These devices belong to the group of superjunction MOSFETs and can be characterized by a fast switching behavior und very low on-state losses [2], [3]. To evaluate the junction temperature of a device, a temperature dependent characteristic can be taken into account [4]. The idea of the proposed junction temperature measurement method is to determine the junction temperature by measuring the on-state resistance during operation. As depicted in Fig. 1, the on-state resistance strongly depends on the junction temperature and changes its value between 20°C and 120°C by a factor of about two. If this value is available for the control circuitry in a converter, the transferred power could be controlled depending on the junction temperature.

The on-state resistance of a MOSFET device comprises of the sum of several resistances (e.g. resistance of the package, source layer, channel, accumulation layer, n^--Layer and substrate). The composition of these resistances on the total on-state resistance for a power MOSFET is depicted in Table I. The composition of the resistances of a CoolMOS device is similarly.

It can easily be recognized, that the on-state resistance is mainly determined by the resistance R_{epi} of the n^--

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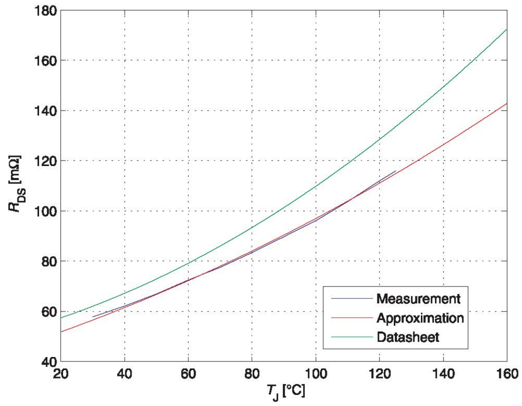

Fig. 1. On-state resistance of a SPW47N60C3 CoolMOS manufactured by Infineon

Variable	Description	Value
R_S	package	0,5 %
$R_{\mathrm{n}+}$	source layer	0,5 %
R_CH	channel	1,5 %
R_a	accumulation layer	0,5 %
R_epi	n^--layer	96,5 %
R_sub	substrate	0,5 %

TABLE I

Composition of the R_DS of a 600V power MOSFET [3]

layer. The resistance is antiproportional to the mobility of electrons μ_n:

$$R_\mathrm{epi} \propto \rho \tag{1}$$

$$\rho = \frac{1}{q\mu_\mathrm{n}(T)N_\mathrm{D}} \tag{2}$$

Thereby determines ρ the specific resistance, q the elementary charge, T the temperature and N_D the donor concentration. The only temperature dependent variable in this equation is the mobility μ_n. Taking the following temperature dependent mobility model into account, the mobility can be calculated to [5]:

$$\mu_\mathrm{n}(T) = \mu_\mathrm{n}(300\mathrm{K}) \left(\frac{T}{300\mathrm{K}}\right)^{-x} \tag{3}$$

Recapitulating, the resistance R_epi is proportional to:

$$R_\mathrm{epi} \propto \left(\frac{T}{300\mathrm{K}}\right)^{x} \tag{4}$$

If the value x is set to 2.6 by a curve fitting procedure the resistance R_epi equals the measured value of R_DS with a very good accuracy. In Fig. 1 the measured on-state resistance R_DS and the approximated curve are depicted. Furthermore, the specified on-state resistance specified in the datasheet is given.

In this frist approach the influence of the channel resistance is neglected. In order to take the influence of this resistance into account the dependency of the current on the on-state resistance has to be included.

III. Measurement Principle

The goal of the measurement principle is to determine the on-state resistance during the normal operation of the converter. This can be realized by simultaneously measuring U_DS and I_D while the MOSFET is switched on. As shown in Fig. 1, the resistance value corresponds to only one junction temperature. The calculated resistance must be compared with a look-up table in order to evaluate the corresponding junction temperature.

With this measurement method only an averaged temperature of the complete semiconductor can be determined. Hot spot temperatures can not be detected.

A. Hardware

Since the drain-source voltage U_DS of a MOSFET normally amounts several hundred volts during blocking and only several hundred millivolts during the conduction period, measuring this voltage is quite a challenge and requires special measurement circuits. The goal of this circuit is to cut off all voltages over a certain limit of several volts (e.g. 5 V).

In this approach the topology depcited in Fig. 2 was chosen: This topology is basically an emitter follower [6], [7]. Its main components are a detector MOSFET (T) and a resistor R_1. This circuit cuts off all voltages above a certain value of only a few volts. The gate connector of the detector MOSFET (T) is connected to a constant voltage of 9 V DC. During blocking of the power MOSFET (marked in Fig. 2 as DUT), the detector MOSFET (T) is almost switched off. During on-state of the power MOSFET (DUT), the detector MOSFET (T) is turned on and the voltage at the resistor R_1 equals the drain-source voltage of the power MOSFET (DUT).

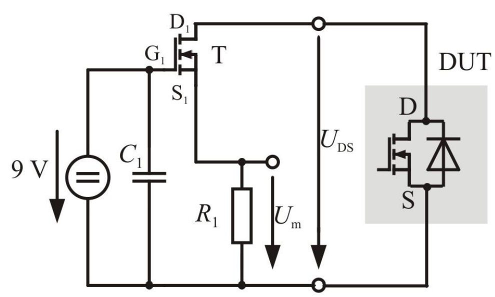

Fig. 2. Emitter-follower to measure U_DS of a MOSFET

Using this circuit, it can be ensured that the voltage U_m never exceeds an upper limit of several volts (which equals approximately the gate voltage of the detector MOSFET). The voltage U_m can now be connected to a DSP or microcontroller and can be measured very accurately without overdriving any operational amplifiers. Without this auxiliary circuit, an accurate measurement of the voltage would not be possible.

To design this measurement circuit it has to be ensured that the basic behaviour and the electric characteristics of the power MOSFET (DUT) are not influenced. Therefore a fast detector MOSFET device (T) with low parasitic capacitances (e.g. drain-source capacitance) has to be chosen. Certainly it must also be specified for the desired operating voltage. To ensure a safe operation of this device it should be characterized by the same blocking voltage as the power MOSFET (DUT).

The resistance R_1 should be large enough to limit the power dissipation within the detector MOSFET (T). During blocking of the power MOSFET (DUT) the detector MOSFET (T) is almost completely turned off. That means, that the voltage U_{m} equals the gate voltage U_{G1} applied to the detector MOSFET (T) minus the threshold voltage U_{th} of the MOSFET. The current which flows in this status can be calculated to:

$$I_{\mathrm{R1}} = \frac{U_{\mathrm{G1}} - U_{\mathrm{th}}}{R_1} \tag{5}$$

The current I_{R1} also flows through the detector MOSFET (T). Since the voltage drop at the resistor R_1 can be neglected compared to the blocking voltage during blocking of the power MOSFET (DUT), the power loss during blocking can be calculated to:

$$P_{\mathrm{loss}} = \frac{U_{\mathrm{G1}}}{R_1} \cdot U_{\mathrm{DSmax}} \tag{6}$$

During on-state of the power MOSFET (DUT) the drain-source voltage U_{DS} is lower than the gate voltage U_{G1}. The detector MOSFET (T) is turned on. The voltage U_{R1} equals U_{DS} in this case.

The drain current I_{D} can be measured very easily with a shunt resistor or with a closed loop current sensor (e.g. LEM). The measured value has to be preprocessed and can than be easily connected to a DSP or microcontroller for further handling.

B. Measuring Method

By dividing U_{DS} by I_{D} the actual R_{DS} can be calculated. The measured resistance has to be compared with the look-up table in which the dependency between resistance and corresponding junction temperature is stored. There are two methods on which the data in the look-up table are based:

1) Since the data available in the datasheets of the power devices are only worst case estimations and not typical values, the correlation between the R_{DS} and the junction temperature can be calibrated by an experiment and stored within a look-up table.
2) The minimal values for the on-state resistance specified in the datasheet are stored in the look-up table. Assuming that the resistance R_{DS} of a real device is higher or at least equal in comparison to the specified resistance, the actual junction temperature is always lower in the device than determined by the measurement with this method.

In order to determine the actual junction temperature possibility 1 should be addressed. To calibrate the measurement system the on-state resistance R_{DS} of the power MOSFET (DUT) hs to be determined in dependency of the temperature. Therefore, the junction of the MOSFET device has to be heated up to a defined temperature (e.g. 50°C). With a short current pulse the resistance $R_{\mathrm{DS}}(50°\mathrm{C})$ can be determined. At least three measurements are required to determine the characteristic $R_{\mathrm{DS}}(T)$ over the total temperature range. The current pulse must be kept short in order to prevent a self heating of the junction during calibration since this affects the accuracy of the measurement.

Furthermore, it has to be ensured that the junction is heated to a defined temperature. This can be realized by placing the whole heat sink into a fluid to distribute the heat equally.

IV. Realization

A prototype has been developed to evaluate the measurement method during operation. A DC/DC-converter module (single active bridge) has been chosen. This converter topology consists of an input capacitor, an inverter bridge, a transformer, an output rectifier and an output capacitor. As an example, the load is represented by a resistor. The circuit diagram is depicted in Fig. 4. A picture of the realized prototype is shown in Fig. 5.

The input inverter is operated with a phase shift of 180°and a duty cycle of approximately 50%. The resulting current in the transformer is triangular at nominal load conditions. The transformer's input voltage and current are depicted in Fig. 3. In the middle of the conduction period of a switch the current and the voltage are measured. Based on this value the on-state resistance R_{DS} is calculated and afterwards comapred to a look-up table to determine the junction temperature.

In this prototype, a microcontroller from Texas Instruments was chosen which generates the switching signals, evaluates the voltage and current signals and calculates the resistance R_{DS}. The calculated resistances are transmitted via a RS232 interface to a PC where the measured data is visualized.

V. Measurement Results

To present this measurent principle the DC/DC-converter was operated transmitting a power of 3 kW. The CoolMOS devices were mounted on a standard heatsink. The heatsink was cooled by convection cooling. The test period was 120 min. Besides the junction temperature measured with the presented measurement principle the heatsink temperature was logged. The heat sink temperature was measured with a standard temperature sensor (thermocouple).

The characteristics are depicted in Fig. 6. The figure shows the temperature in dependency of the time. It can be clearly recognized that the difference between juntion temperature and heatsink increases at higher temperatures. The reason for this phenomena are higher losses in the semiconductor devices caused by higher on-state resistances. Since the thermal resistance between junction and heatsink stays constant, higher power losses result in a higher temperature difference.

VI. Accuracy Estimation

The accuracy of this measurement method depends on several factors. First, the accuracy of the sensors to acquire voltage and current is important. Second, because only the dominant influence of the n^{-}-layer is regarded in the measurement system and not a possible current dependent influence of the channel resistance the accuracy is restricted.

To check the accuracy of this measurement method, the following experiment has been performed: a power MOSFET device was immersed in a thermal fluid at a temperature of 100°C to ensure a constant temperature within the device. Every two seconds a short current pulse was generated (10 to 20 μs) and the drain-source voltage was measured. It is important to keep the current pulse in this experiment short to prevent a self heating of the junction which would lead to erratic results. Since the junction temperature is always constant the on-state resistance R_{DS} should also be constant for all measurements. The experiment took several hours and about 6000 measurements were performed. To estimate the deviation from the expectation the results were statistically analyzed. Figure 7 shows the Gaussian distribution. The expectation is $R_{\mathrm{DS}}(100°\mathrm{C}) = 102.2\ \Omega$. The standard deviation is 0.7 Ω which means that 68% of the measured values devitate from the expectation within 0.7 Ω. As a comparison, a standard Gaussian distribution with $\mu = 102.2\ \Omega$ and $\sigma = 0.7\ \Omega$ is depicted. At this temperature the deviation of 0.7 Ω corresponds to a temperature of 1K. In order to optimize the accuracy, a sequence of several measured values can be averaged which results in a reduction of σ. Since the thermal time constants are mostly large in

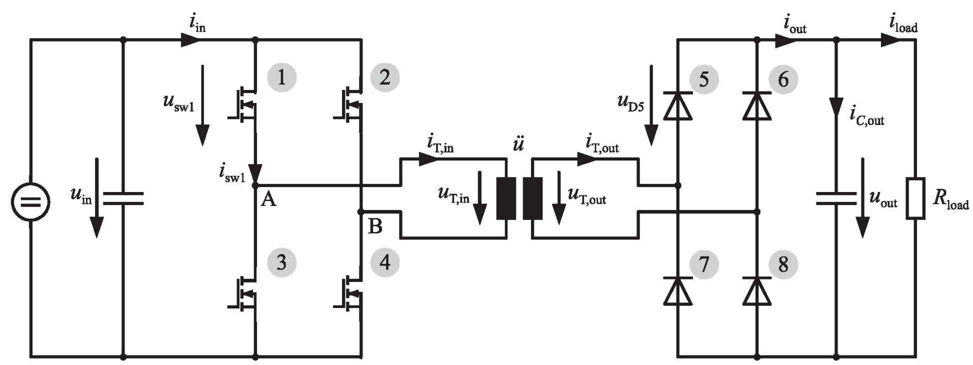

Fig. 4. DC/DC-Converter module (Single Phase Single Active Bridge, SAB1)

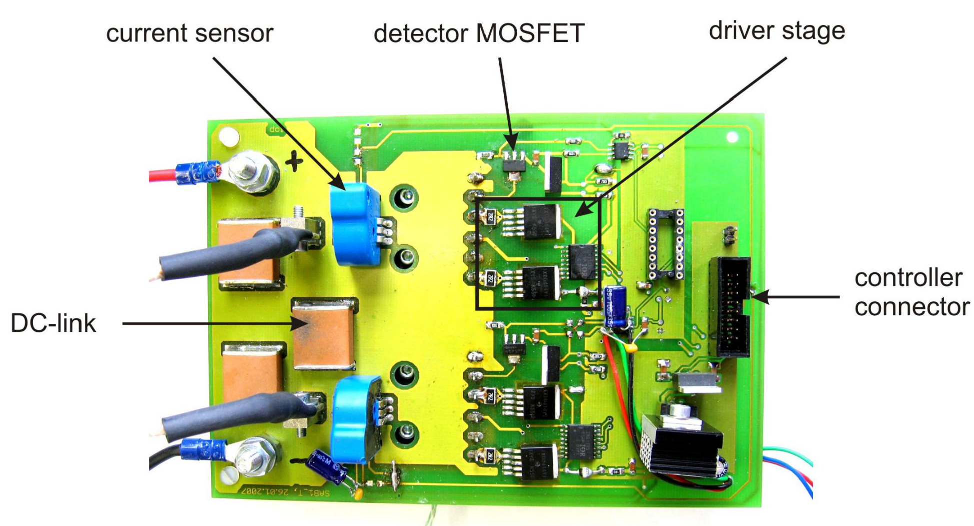

Fig. 5. Inverter section with sensing electronics

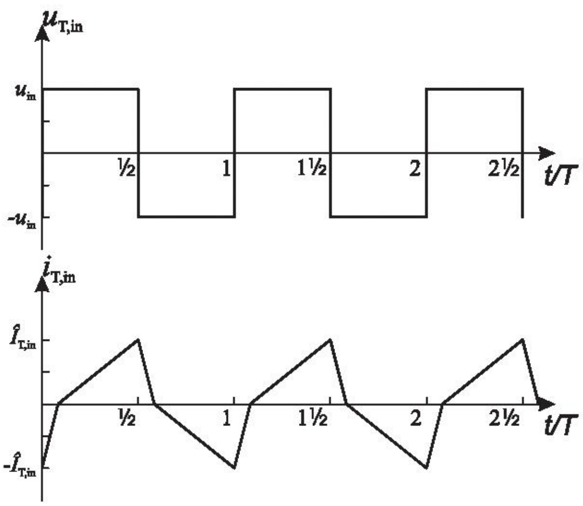

Fig. 3. DC/DC-converter (SAB1) waveforms

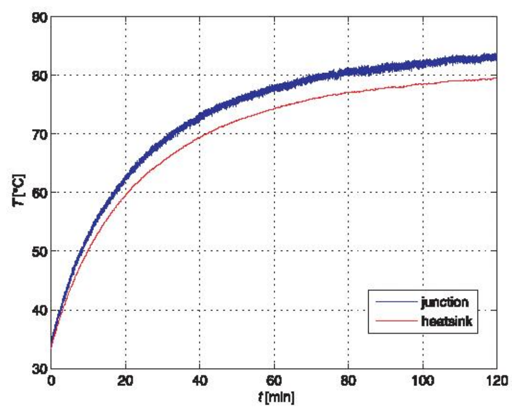

Fig. 6. Junction temperature during operation of DC/DC-converter

comparison to the switching frequency, an averaging of ten values for instance is tolerable.

VII. Conclusion

With this method, an accurate measurement of the junction temperature can be established, where no thermal model and other thermal resistances have to be regarded. This method can be employed either in applications where the devices are operated at their thermal boundaries to ensure a safe operation at any time. Furthermore, this method could be used in order to compare different topologies with each other in terms of semiconductor losses (e.g. resonant and non-resonant converters).

VIII. Future Work

As mentioned before the dependency of the on-state resistance from the drain current is not regarded since the influence of the channel resistance is neglected. Figure 8 shows the dependency of the on-state resistance on the drain current. In this figure the drain current I_{D} is plotted on the x-axis and the corresponding resistance R_{DS} on

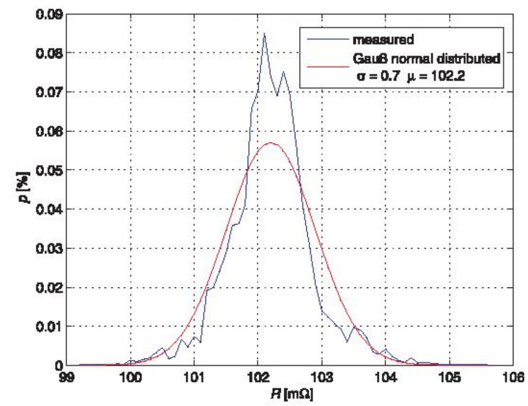

Fig. 7. Gaussian distribution

the y-axis for two temperatures (25°C and 150°C). It can be clearly seen that the gradient of the curve depends on the temperature. For lower temperatures the gradient is almost negligible. In contrast to this, the gradient for higher temperatures is significant.

In the approach presented in this paper the effect can be neglected because the system is calibrated at the same current level (e.g. 5 A) which occurs at the sampling point during operation of the converter. In this case the dependency of the on-state resistance on the current does not effect the measurement.

If a temperature measurement is desired which can measure the temperature over the entire current range of a device, the dependency of the on-state resistance depending on the drain current also has to be entered in the look-up table.

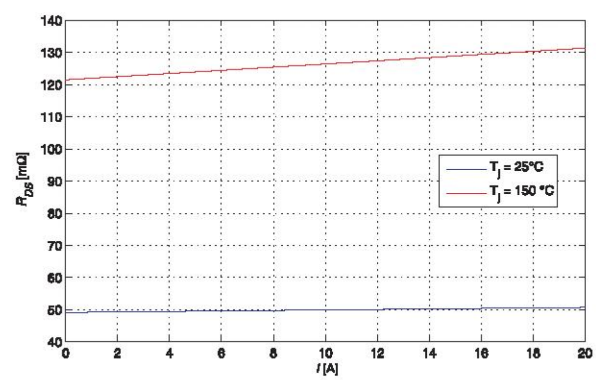

Fig. 8. Influence of temperature on channel resistance

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