Time Resolved In Situ T_{vj} Measurements of 6.5kV IGBTs during Inverter Operation

Waleri Brekel, Thomas Duetemeyer, Gunnar Puk, Oliver Schilling

Infineon Technologies AG, Max-Planck-Straße 5, D-59581 Warstein, Germany

Abstract

Although the device temperature is one of the most critical parameters in the dimensioning of an inverter, experimental studies focusing on the virtual junction temperature (T_{vj}) in running inverter are scarcely found. In this work the feasibility of four different practical methods is compared. Special focus is set on routines with a high time resolution that enables tracking of the time-dependent-temperature during one period of the sinusoidal output current. Details of the procedures are explained and compared with simulations.

1. Introduction

The dimensioning of an inverter application requires qualified knowledge of the stress imposed on the semiconductor devices. All electrical parameters are easily accessible by modern current and voltage probes and standard oscilloscope data recording. The chip temperature during inverter operation at the moment is seldom experimentally determined. The thermal dimensioning is normally done using typical or worst case values specified by the supplier (e.g. thermal resistance of IGBT module and cooler) in combination with simulations of the generated losses. Also the simulation of the temperature ripple shows a typical curve [1]. In this work theoretical predictions for the junction temperature are compared with experimental findings. The following four different methods are used to measure the T_{vj} during inverter operation:

- Infrared Camera (IR-Camera)
- Thermocouple
- Infrared Sensor (IR-Sensor) [2]
- Internal Gate Resistor of an IGBT as a sensor (R_{GINT})

The investigations are done on three IGBT chips in a 6.5kV module.

2. Test conditions of the inverter

The temperature measurements are performed in a 3-phase pulse-controlled inverter with water cooling. Each of the 3 phases consists of two single switch 6.5kV IGBT modules with 600A nominal rating. One module is on the low side and one module on the high side, i.e. no paralleling of the devices. Due to accessibility, the device under test (DUT) is mounted on the low side position in the inverter. To measure the temperature with the IR-Sensor and the Infrared Camera requires the surface of the IGBT to be uncovered. Therefore an open 6.5kV-Module is used without the dielectric that is necessary to assure high insulation capability of the module. To avoid a flashover at high voltage due to the absence of an additional dielectric, the applied DC-Link voltage for those measurements is limited to V_{CC}=2kV, i.e. lower as the usual condition of ~3.6kV. The following conditions are applied: I_{Cmax}=980A; f_0=20Hz; f_{SW}=400Hz; cosφ=0.01; T_a=30°C.
Fig. 1 shows a black coated DUT whose IGBT chips are investigated by different methods. IGBT a) is measured with thermocouple, b) with IR-Sensor and c) with R_{GINT} method.

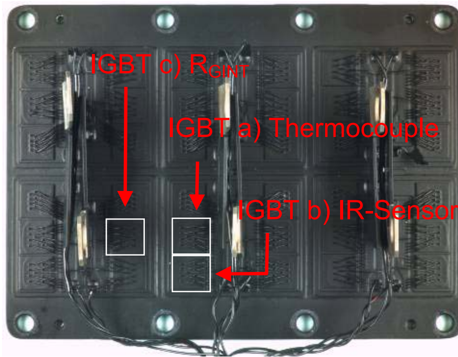

Fig. 1. Black coated 6.5kV module (DUT) with marked IGBTs measured by different methods

3. Temperature calculation with IPOSIM

IPOSIM is a simulation tool for power loss and thermal calculations of Infineon IGBT modules. It provides switching and conduction losses of IGBTs and free-wheeling diodes operated in a three-phase inverter configuration with sinusoidal output current. The corresponding T_{vj} under defined operating condition which can be set by user (e. g. V_{CC}; I_C; f_{SW}; f_0;…) is calculated as well. The details of IPOSIM simulation are described separately [3]. For best comparison, thermal values Z_{th} acquired by experiment are used for the calculation. Fig. 2 illustrates the time depended power losses p(t) within one period and the according junction temperature of the IGBT.

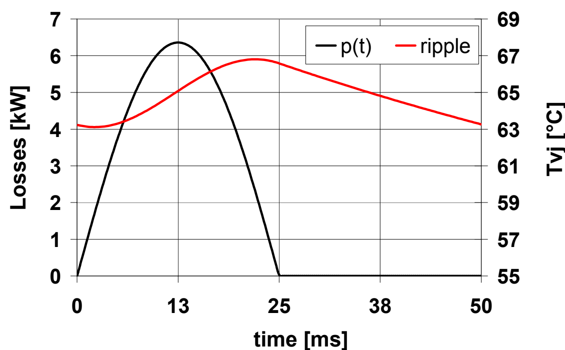

Fig. 2. Power losses and T_{vj} as calculated with IPOSIM. Conditions see chapter 2 (T_{vjmax}=66.8°C; $\Delta T_{vjRipple}$=3.7°K; T_{vjav}=65°C)

4. Infrared camera

The temperature dependent intensity of the emitted electromagnetic radiation of a body is given by Planck's equation. This can be used to determine the surface temperature of an IGBT chip. To achieve an emissivity close to one, the surface has to be coated with a suited material. The respective wavelength maximum of the emitted radiation is in the infrared spectral region (IR). The availability of infrared cameras makes it possible to determine spatial resolved infrared emission of a coated module. Thus it is possible to get the temperature distribution of the module and measure the temperature of all IGBT chips in parallel. A picture of the temperature distribution is shown in Fig. 3.

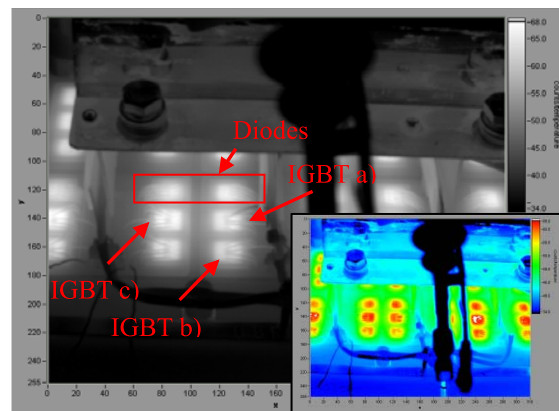

Fig. 3. Temperature distribution in a module measured with IR–Camera and appropriate methods as aforementioned (scale: 34°C – 68°C)

The prerequisite for high time resolution with IR- Camera is its low integration time of the focal pane area. Here a compromise has to be made between required time resolution and the necessary intensity to measure the temperature itself [5]. For this measurement an integration time with 0.6ms is chosen to achieve a fine resolution of the 50ms period of the output current. The sample rate of the IR-Camera is set to 19.5Hz in contrast to f_0=20Hz load current. The small difference of the two frequencies leads to sequentially sampling of the temperature over many periods at the steady state conditions. In this case the time between two sampling point is 1.28ms and there are 39 sampling points for a 50ms temperature period.

The temperature of IGTB a) and b) is analyzed over their chip area, whereas IGBT c) is investigated in the middle of the die where the R_{GINT} is positioned. That result is presented in Fig. 4 below.

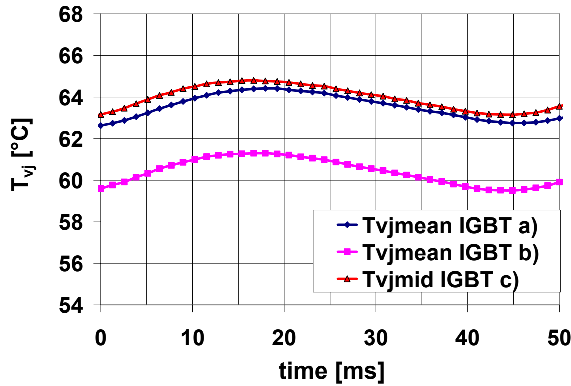

Fig. 4. Time resolved temperature ripple measured with IR- Camera

The mean temperature of IGBT a) with ~64°C fits very well to the simulated value of 65°C. It is also noticeable that T_{vjav} of chip a) which is located near the centre of the module is higher about 3°K than the chip b) with T_{vjav}~61°C. This is well known effect caused by lateral temperature spreading in the module and taken into account in the module characteristics and specification.
Fig. 5 shows a spatial temperature distribution of the IGBT c). It is identifiable that the middle of the die, where R_{GINT} measurement is done is not a hot spot. It averages to 64°C with a $\Delta T_{vjRipple}$~2°K.

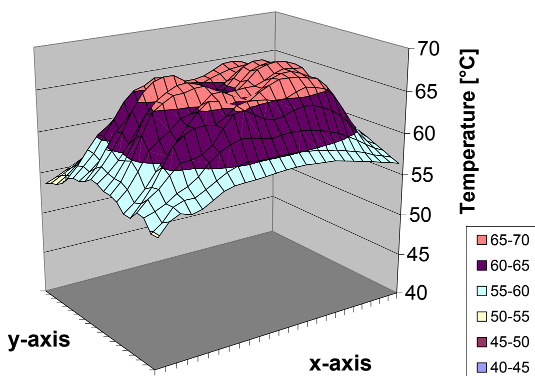

Fig. 5. Spatial resolved temperature of IGBT c)

5. Thermocouple

A common way to measure the temperature is given by the thermo electric effect. To record T_{vj} a thermocouple of type K is glued on the surface of a single IGBT chip position a). The glue which is used is characterized by low thermal impedance. The picture of an IGBT chip with a glued thermocouple close to the center of the emitter area is shown in Fig. 6.

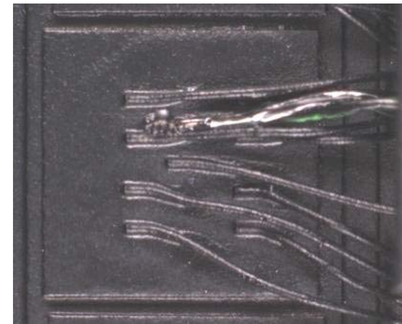

Fig. 6. Glued thermocouple on top of the IGBT

The advantage of the thermocouple is its linearity in the usual chip temperature range. To use the thermo voltage as a temperature proportional signal, it needs to be amplified. The calibrated characteristic line of the thermo voltage amplified by a transducer [4] is shown in Fig. 7. Furthermore a commercial data acquisition board is used for signal processing.

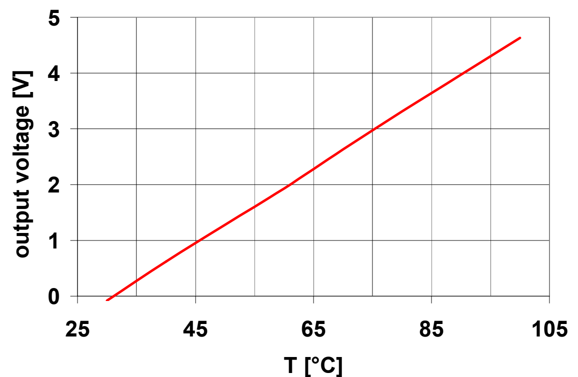

Fig. 7. Characteristic line of amplified thermo voltage with respect to temperature

As the time constant of the thermocouple is in the range of ~200ms the temperature ripple during of the output period of the inverter

load current (20Hz frequency) can not be resolved. In Fig. 8 the measured temperature of ~65 °C matches also very well with the T_{vjav} of the simulation and IR-Camera.

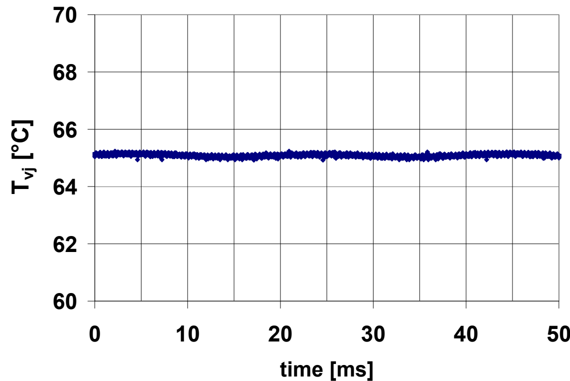

Fig. 8. IGBT temperature measured with thermocouple during inverter operation

6. Infrared sensor

Infrared sensors covering a defined solid angle are commercially available. The infrared sensor allows a contact free determination of the chip temperature at the surface. Fig. 9 shows the mounted infrared sensor on top of a 6.5kV IGBT chip.

Fig. 9. IR- Sensor over covered IGBT chip

The used IR-sensor has a ratio of 1:2 between the distance to the surface and the diameter of the measured area [2]. The distance is chosen to limit the investigated area to the active area of the chip. The sensor generates a voltage that corresponds to a thermocouple of type K. This allows of using the similar transducer and data acquisition as mentioned in chapter 5. The according amplified calibration line is shown in Fig. 10.

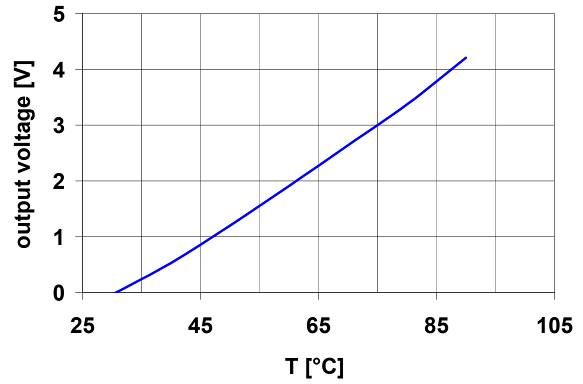

Fig. 10. Characteristic line of IR- Sensor amplified by a transducer

The output of the sensor is fairly linear correlated to the temperature in the relevant range. Due to the time constant of the sensor (~50ms) only an averaged temperature of the chip can be determined. Fig. 11 below shows the result with average temperature over two periods of load current.

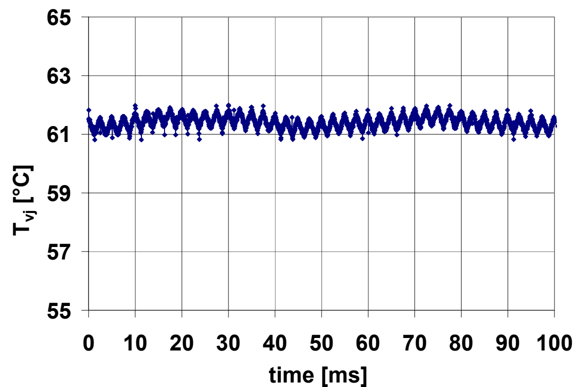

Fig. 11. Surface temperature of the IGBT as a function of time recorded with IR- Sensor

The measured mean temperature is ~61.4 °C. The observed small waviness with a frequency of 20Hz corresponds to the load current. Due to high time constant of the measurement the amplitude of the temperature swing is expected to be damped to a large extent. The measured high frequency rate correlates to the switching frequency of 400Hz. As this frequency is far too high to be recorded with this method it is obviously due to interference between the thermoelectric voltage and the module switching operation.

7. Internal Gate Resistor

The 6.5kV IGBT chip under investigation contains an internal gate resistor (R_{GINT}) in the centre of the die. As this resistance has a well known temperature dependence it can also be used to determine the chip temperature. A major advantage is the absence of an additional heat capacitance to the chip. Furthermore the resistor is in immediate vicinity of the relevant semiconductor junction inside the same die. The accurate measurement of the resistance in presence of transient high voltage and current in the IGBT module is a major challenge. A sophisticated circuitry is developed for data recognition and safe data transfer from the measurement point inside of the inverter to the external laboratory periphery. A sketch of the measurement system is shown in Fig. 12.

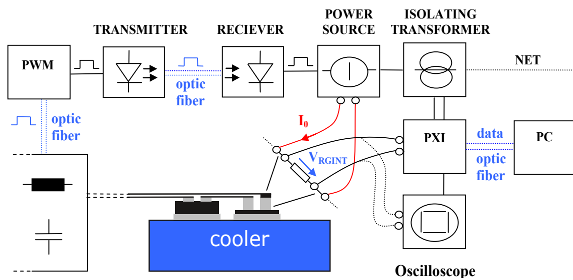

Fig. 12. Sketch of the temperature measuring system at the inverter with the R_{GINT} method

The evaluations show that it is possible to achieve high temperature and time resolution at the same time. A principle of the temperature measurement within IGBT with R_{GINT} is sketched in Fig. 13.

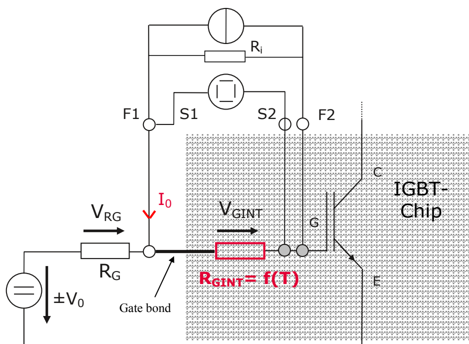

Fig. 13. Principle circuit for R_{GINT} measurement with additional force and sense contacts

A constant test current of I_0=500mA is applied at the force connections (F1 and F2) and makes a voltage drop over R_{GINT}, which depends on temperature inside the die. This voltage is used as temperature indicator and is measured by sense contacts (S1 and S2). The temperature dependence of the resistor is determined to be $\Delta R_{GINT}/\Delta T$ ~ 1.5mΩ/K. In order to resolve temperature variations down to ~1K accuracy, the requirement for voltage resolution is given by 500mA·1.5mΩ/K= 0.75mV/K. In addition the internal gate resistor of each IGBT chip varies in specified tolerance. Therefore using R_{GINT} as a sensor, the exact calibration line is needed. Fig. 14 shows a period of the output current of the DUT with a switching frequency of 400Hz. The test current I_0 is applied while the IGBT is in conducting operation.

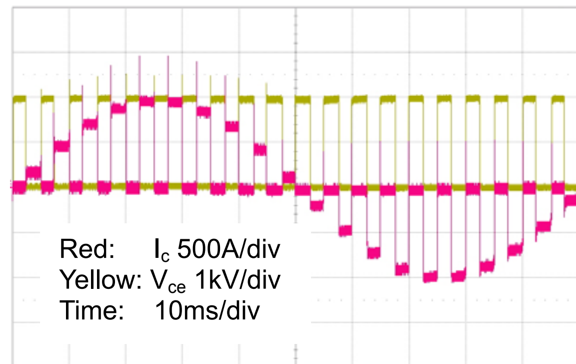

Fig. 14. Waveform of the DUT

In order to avoid an influence on the switching losses due to the voltage drop in the internal resistor induced by I_0, the test current is pulsed with delay to the IGBT switching pulses. According to Fig. 13 additional connectors (Force: F2 and Sense: S2) are needed to realize the measurements. Therefore a special substrate with modified layout is used to enable separate bonds for F2 and S2 without changing the thermal characteristic of the substrate. The connection of the standard gate bond to IGBT is used for F1 and S1 (Fig. 13). The temperature measured by R_{GINT} method is presented in Fig. 15. The maximum of temperature is about 67.3°C with a ripple of 5.8°K and average value of ~64°C. Thus the characteristic of the temperature ripple of an IGBT at inverter operation during the period of the output current could be resolved and the course over time

is in excellent agreement to the simulated results. The $\Delta T_{vjRipple}$ is about 2°K higher than expected by simulation. As shown in chapter 4 the average temperature of IGBT c) measured with IR-Camera matches perfectly to the R_{GINT} value.

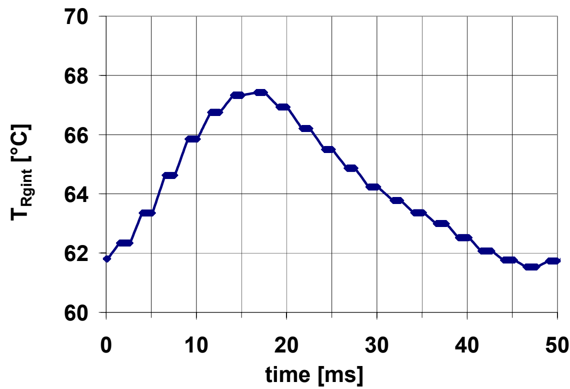

Fig. 15. Time resolved temperature measured with R_{GINT} method over one period of the inverter output current (T_{vjav}=64.5°C; $\Delta T_{vjRipple}$=5.85°K) .

It is especially remarkable that the time dependent temperature has not a sinusoidal shape but is characterized by steep increase and a significantly slower decrease after the maximum temperature has been reached. This is in accordance to IPOSIM simulation given in Fig. 2 and to results presented in ref. [1].
As mentioned before the resistor position is in the middle of the die at the gate pad. According to IR measurement presented in chapter 4 there is not a hot spot at the gate pad. Therefore this measurement method provides local temperature which is approximately the mean chip temperature of the IGBT.

8. Conclusion

Four different measurement methods (Thermocouple, IR-Sensor, R_{GINT}, IR-Camera) to determine the junction temperature of an IGBT during inverter operation are applied and compared. It is shown that two of those methods (R_{GINT} and IR-Camera) are capable to resolve the temperature ripple of the IGBT caused by the periodic alternating output current in inverter application. With the other methods it is not possible to resolve the temperature ripple due to high time constants. Nevertheless those methods (thermocouple and IR-Sensor) achieve a mean temperature over the time.
The measurements are most valuable as a complimentary method to check simulation results. This can help to improve the careful design of an inverter application. Table. 1 gives an overview of all measurement methods in comparison with simulation.

method	IGBT a)		IGBT b)		IGBT c)	
	T_{vjav} [°C]	$\Delta T_{vjRipple}$ [°C]	T_{vjav} [°C]	$\Delta T_{vjRipple}$ [°C]	T_{vjav} [°C]	$\Delta T_{vjRipple}$ [°C]
IR-Camera	63.7	1.7	60.4	1.8	64.3	1.7
Thermocouple	65.0	-	-	-	-	-
IR-Sensor	-	-	61.3	-	-	-
R_{GINT}	-	-	-	-	64.5	5.9

Table. 1. Overview of all measurement methods. Comparison with simulated temperatures: T_{vjav}=65°C and $\Delta T_{vjRipple}$=3.7°K.

The measurement with the IR-camera is best choice for temperature measurements at lower voltages. But the investigation shows the R_{GINT} method is a reliable method to achieve time resolved temperature information when no optical access to the module is possible or measurements at high voltages are requested.

9. Literature

[1] Th. Hunger; O. Schilling: Proc. 2008, Numerical investigation on thermal crosstalk of silicon dies in high voltage IGBT modules
[2] www.omega.de
[3] www.inifineon.com: IPOSIM Technical Documentation
[4] www.asm-sensor.com
[5] Phoenix Camera Systems, User's Guide 420.00000.10 Version 1.1
[6] Hering, E., Martin, R., Stohrer, M.: Physik für Ingeniere, 8. Aufl.: Aalen, Esslingen und Stuttgart 2002
[7] www.ni.com