

# IGBT with higher operation temperature - Power density, lifetime and impact on inverter design

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## Abstract:

The development of IGBT power modules has always been characterized by the continuous increase of the power density for cost reduction and design optimization of the complete frequency converter system [1]. The requirement of higher power density is directly associated with increased current per chip area and therefore an increase of the junction temperature during the operation is expected.

The cooling conditions related to applications like hybrid vehicle are further important drivers for the need of an increase of the junction temperature [2]. The reason for this is that for cost improvement the cooling of the IGBT module is combined with the combustion engine's cooling system, which reaches temperatures in the range of 120°C.

This paper focuses on the most important questions for the application of power modules with increased junction temperature:

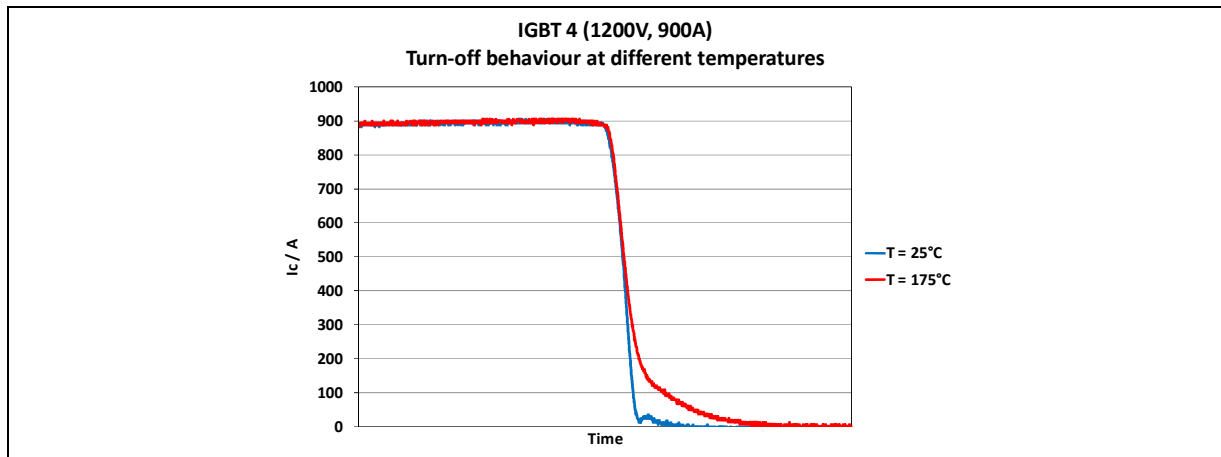
- How much more inverter output current can be achieved per chip area?
- How much can the cooling effort be reduced?
- How does the temperature rise influence further inverter components and what are the consequences?
- How is the influence to IGBT module's lifetime expectation?

## 1. Introduction

From physical principles the effect of a higher temperature on silicon devices is well known. For a unipolar MOSFET the carrier concentration is given by the doping level. With increasing temperature the mobility of the carriers is reduced by enhanced phonon scattering leading to increased on-resistances, i.e. a positive temperature coefficient [3].

In order to achieve a better on state performance an IGBT has an additional p-emitter at the back side of the die. This p-emitter additionally injects positive charge carriers and changes the device characteristic from unipolar to bipolar. The IGBT front cell design also aims to accumulate charges in the device for conductivity enhancement. In a bipolar device a so-called electron hole plasma with a concentration far above the base doping concentration carries the current. With increasing temperature the carrier's mobility is reduced as for a unipolar device. This effect is partly compensated by an increased carrier injection from the back side p-emitter. As a result, the temperature coefficient at nominal current is usually still positive but at a much smaller value as compared to a unipolar MOSFET device.

The temperature not only influences the static properties but also the dynamic behavior. The increased number of charge carriers, so called plasma, is visible by investigating the tail current during the turn-off of the IGBT. The turn-off waveforms of an IGBT at different temperatures and the effect of increased number of charge carriers are visible in Figure 1. The comparison is done by adjusting the turn-off speed of the IGBT in order to minimize dynamic effects such as different removal rates of the charge carriers. The turn-off energy is of course similarly affected. In [2] an increase of the operation temperature from 150°C to 200°C results into a 10% increased IGBT turn-off energy.



**Figure 1:** Turn-off wave form at different temperatures,  $V_{CE} = 600 \text{ V}$ ,  $V_{GE} = \pm 15 \text{ V}$ ,

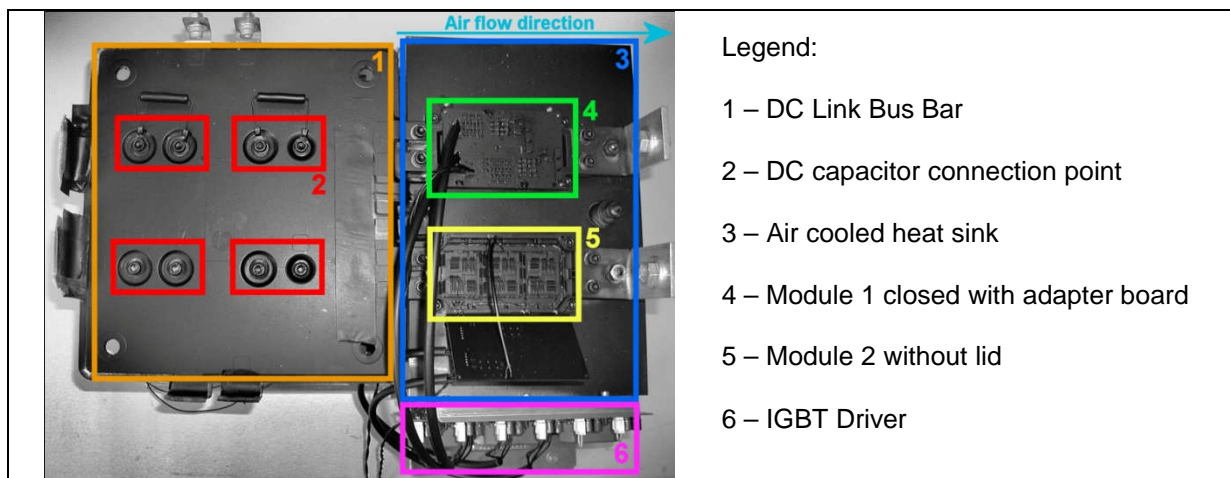
The benefit of the increased operation temperature becomes apparent when the total power dissipation of a device is observed. This maximum power dissipation is defined by the ratio of the temperature difference between junction and case and the according thermal resistance. Assuming a constant resistance, the maximum transferable total power is depending on the temperature difference between junction and case. With an adjusting of the thermal resistance a further step in the reduction of the device size is possible.

The impact of the improved power density and temperature level in a power module is discussed in the next chapters.

## 2. Relation between output current and IGBT temperature

As already mentioned above, one of the benefits of increased junction temperature is a higher power density of the frequency converter system. To find out how much more output current can be achieved, a calculation of the junction temperature at different output currents was performed with IPOSIM [4] and, based on this data, a metrological investigation was carried out.

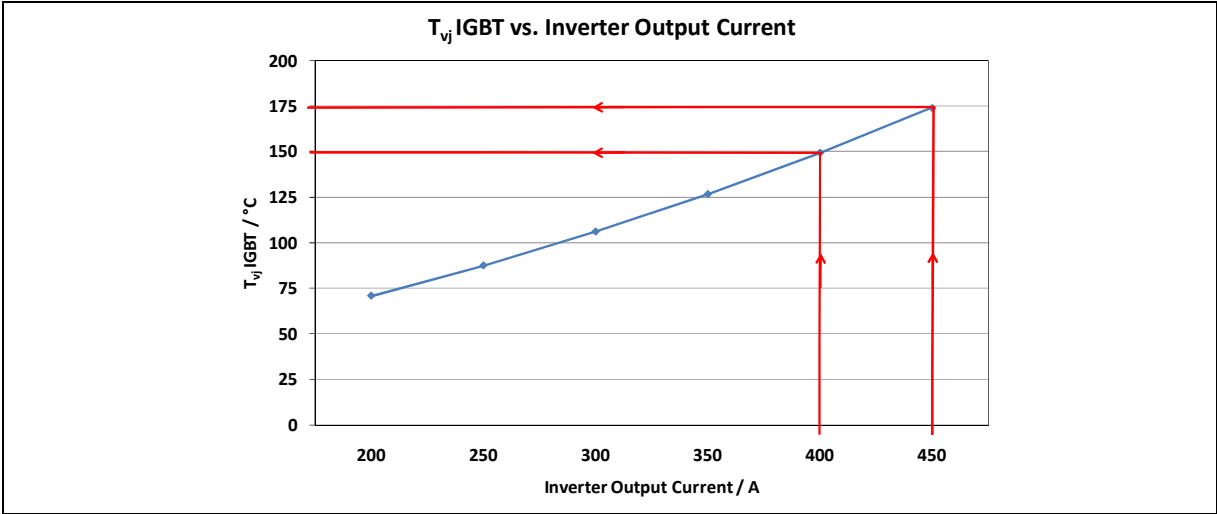
A power converter configured as H-bridge was used for the practical validation and is shown in Figure 2. The FF450R12ME4 modules from Infineon's EconoDUAL™ family were mounted on an air cooled heat sink. The complete setup was covered with black paint as preparation for the temperature measurement utilizing an infrared camera.



**Figure 2:** Power converter with forced air cooling and components covered with black paint

The module 1 was equipped with Infineon's adapter board MA200E12 to observe the thermal behavior of the PCB components under real field conditions. Module 2 was mounted without lid and gel to measure the chip temperature and thus to crosscheck the results of the calculation. The air flow direction is given by the blue arrow. The IGBTs were driven by Infineon's 2ED300C17-S driver.

The result of the measurement is hinted out in Figure 3:



**Figure 3:** IGBT junction temperature as a function of the inverter output current

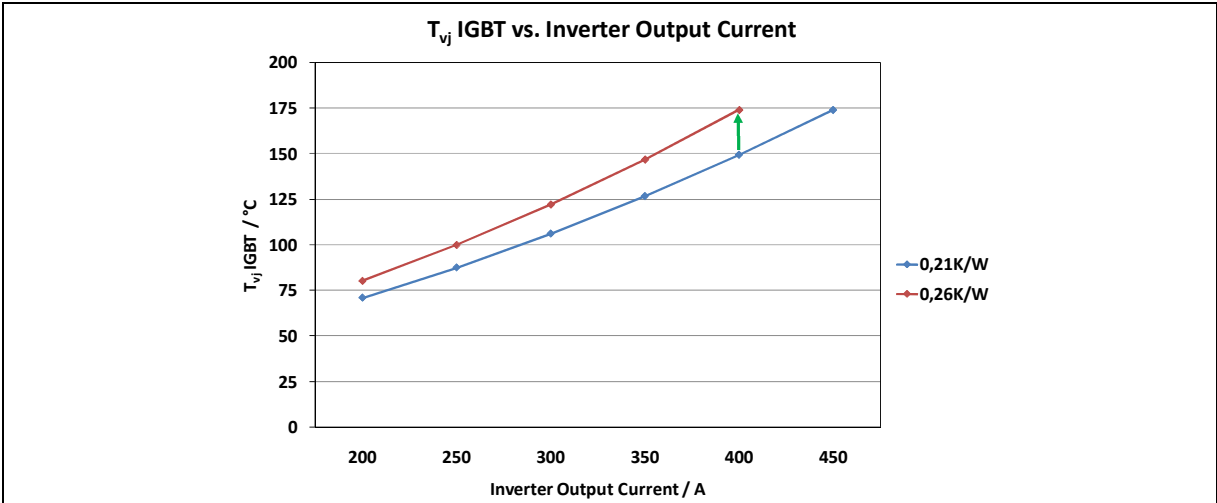
The operation of the IGBT at a junction temperature of 175°C allows an increased output current, respectively output power, of 12,5% in comparison to an operation of the IGBT at 150°C.

### 3. Relation between inverter cooling and IGBT temperature

Another advantage for applications using modules with higher junction temperature is the possibility to increase the thermal resistance  $R_{thha}$ . This leads to lower cost for the heat sink with lower performance respectively or in the case of hybrid vehicles mentioned above, a heat sink with higher cooling fluid temperature can be used.

The same measurement setup as displayed in Figure 2 was used to find out how much the heat sink performance can be decreased. The air flow through the heat sink was reduced by about 10%. This was done by reducing of the supply voltage of the fan. Due to this change, the  $R_{thha}$  was increased by approximately 23%.

The diagram of the IGBT's junction temperature as a function of the measured inverter output current for the two different cooling conditions is shown in Figure 4.



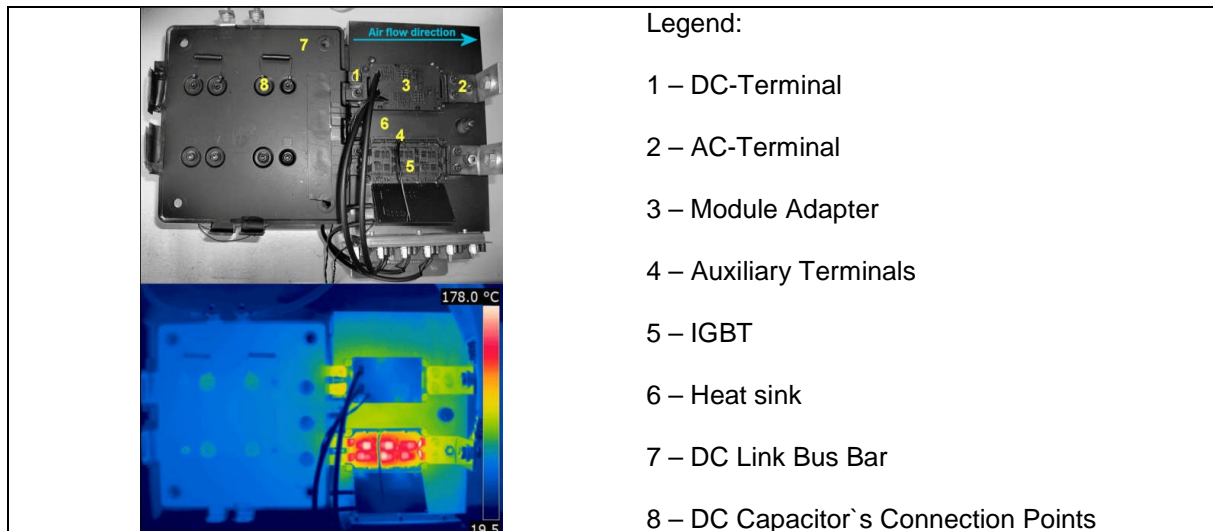
**Figure 4:** IGBT junction temperature as a function of inverter output current with different cooling conditions

The green arrow shows that for an inverter output current of 400A it will be possible to increase the  $R_{thha}$  from 0.21K/W to 0.26KW if an increase of the IGBT's junction temperature from 150°C to 175°C is tolerable.

## 4. Influence of the IGBT temperature on the inverter components

The aim in this part of the investigation was to find out the temperature rise and distribution on surrounding inverter components as a function of the inverter output current and of the dies` junction temperature.

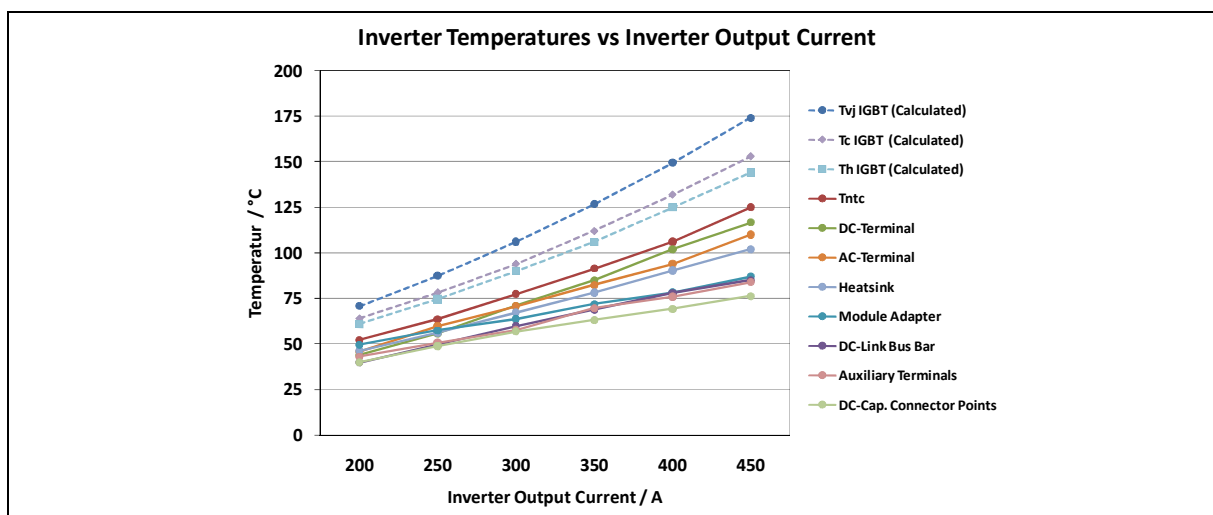
The setup depicted in Figure 2 together with the infrared image of the power converter under load conditions and at 175°C junction temperature can be seen in Figure 5. The legend on the right side of the picture lists the selected points that were evaluated concerning the maximum temperatures.



**Figure 5:** Measurement setup with evaluated temperature points and corresponding infrared image

Due to the air flow direction and the different distances from the DC-Link to the parallel IGBTs the thermal situation of the single dies is slightly different.

The temperatures in the frequency converter as a function of the inverter output current are indicated in the diagram in Figure 6.

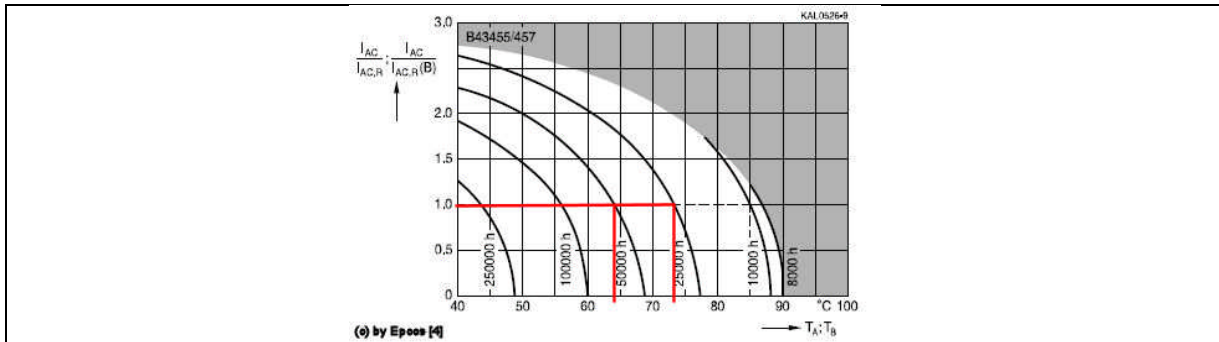


**Figure 6:** Frequency converter temperature as a function of the inverter output current

The values of the IGBT`s virtual junction temperature  $T_{vj}$ , the case temperature  $T_c$  and the heat sink temperature below the chips  $T_h$  were calculated with IPOSIM. The NTC temperature results from the NTC`s resistance measured during the experiment. All other temperatures were evaluated with the infrared picture of the measurement setup.

At  $T_{vj}=175^\circ\text{C}$  the base plate temperature of  $153^\circ\text{C}$  and the heat sink temperature of  $144^\circ\text{C}$  represent a challenge for the thermal interface material. The usually used materials today are not necessarily suitable for such high temperatures and further investigations concerning this topic are necessary.

Due to the fact that the lifetime of capacitors is strongly temperature dependent, it is important to take care of the maximum temperature achieved in its vicinity and on the connectors to the DC-link. In the setup used, the DC-Terminals of the module heated up by 15K through the step of 400A to 450A output current. Figure 7 [5] provides the useful life time curves for the electrolytic capacitors in use.



**Figure 7:** Electrolytic capacitor useful life time depending on ambient temperature  $T_A$  for natural cooling under ripple current operating conditions [5]

An increase of the ambient temperature by 9K from 64°C to 73°C reduces the lifetime of the electrolytic capacitor by half. Research and solutions for capacitors intended for high temperature applications were discussed in [6], [7], and [8].

The maximum temperature achieved on the adapter board of 87°C and on the auxiliary terminals of 84°C is not critical taking into account the maximum recommended temperature of FR4 material of 105°C to 140°C. On a printed circuit board (PCB) that conducted the load current, an elevated temperature is expected. Details about the thermal effects on PCBs are described in [9] and [10]. Table 1 [11] indicates a rough guide concerning cost ratio and maximum operating temperature at different PCBs material. Further information concerning alternative PCB materials is described in [11].

Resin-reinforcement	Phenolic-paper	Epoxy-glass (FR-4)	Polyimide-glass	Polyester-glass	Silicone-glass	PTFE-glass	Unit
Relative cost	0.5	1.0	5.0	0.75	5.0	8.0	
Max. operating temp.	100	120	250	110	200	300	°C

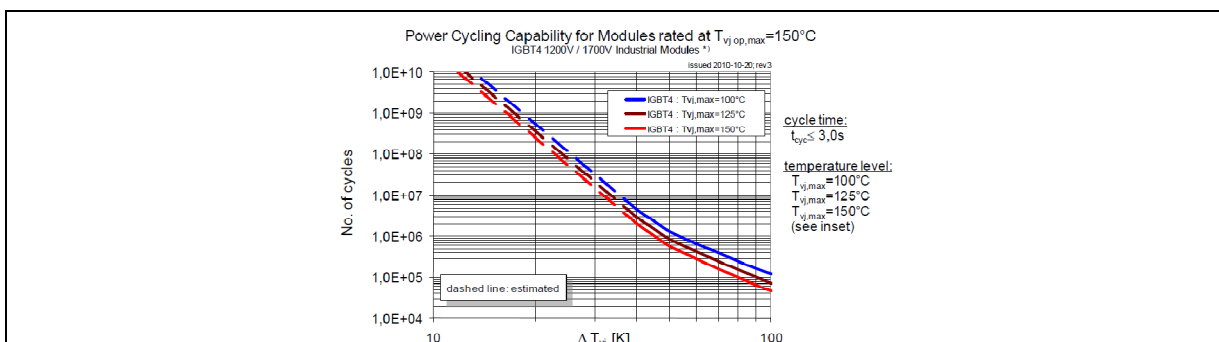
**Table 1:** Relative cost and temperature performance of common PCB laminate materials [11]

A temperature rise on the PCB also increases the mechanical stress on its solder joints, causing an accelerated degradation of these interconnections [12].

The increased temperature of the components surrounding the module demands an adjusted design of the converter to enable all components to work without reduction of the lifetime. The more compact the inverters, the more attention to the temperature rise of the passives devices has to be paid and the thermal management becomes more important.

## 5. How is the IGBT module's lifetime expectation?

To define the lifetime expectation of a certain IGBT module, the power cycling capability of this device has to be used as basis. The Power Cycling curves for the used module FF450R12ME4 is depicted in Figure 8.



**Figure 8:** Power Cycling Capability for the module FF450R12ME4

The higher the maximum junction temperature  $T_{vjmax}$ , the higher is the stress to the device which results in a reduced number of cycles [13]. Therefore, the expected lifetime of the module decreases with the increase of the junction temperature. The lifetime is limited mainly by the packaging technologies, such as wire bonding and soft soldering. Infineon introduced a new integrated set of interconnection technologies which overcomes today's limitations for wire bonding as well as chip and substrate soldering. The so called .XT technology increases the lifetime of IGBT modules by a factor of 10 compared to existing technologies. Alternatively the output power can be increased by 25% [14][15]. The realization of an application with higher junction temperature is only reasonable with Infineon's new .XT technology.

## 6. Conclusion

With an increasing IGBT operating temperature the user will have the choice to raise the output current or to decrease the cooling costs. The investigations on this paper proved that an IGBT module can handle 12.5% more output power if the maximum junction temperature rises from 150°C to 175°C. Alternatively, lower cost cooling systems can be considered to benefit from the high temperature capabilities. Beside this, care must be taken regarding the temperature raise seen at other system components to guarantee that the frequency inverter's lifetime does not suffer from an elevated temperature. A good thermal management also considering the surrounding area of the module becomes mandatory. At module level the frequency inverter will work at  $T_{vj} = 175^\circ\text{C}$  without additional lifetime restrictions compared to state-of-the-art designs if devices utilizing Infineon's new .XT technology were used.

## 7. Literature

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