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# TRENCHSTOP™: IGBT and Diode Optimization

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# 1 Short Description

This Application Note describes the possible trade-offs for the design of the antiparallel diode in DuoPack-like devices, which influences the cost and the performance of the overall IGBT-diode-system. The smaller the diode the lower the switching losses are and the cost. Then the thermal resistance $R_{thJC}$ of the diode gets worse and the conduction losses increase additionally. The balance of the power losses between IGBT and diode in combination with the individual $R_{th}$ is therefore an important measure to get correctly sized diodes. This application note discusses the main aspects of the design of antiparallel diodes and shows the loss balance at an example for a 1kW drive with an estimation of the junction temperatures.

# 2 Introduction

The discussion about the right design of antiparallel diodes considers various factors. Some of them are technology related, others are application related. However, it is the magic triangle between forward voltage drop $V_F$, the reverse recovery charge $Q_{rr}$ and the thermal capabilities with $R_{th}$ and $Z_{th}$ as shown in Figure 2.1, which is important in the end.

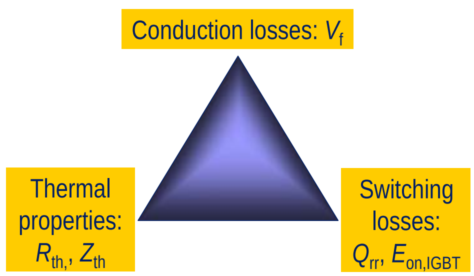


**Figure 2.1: Triangle of Diode Design**

It is easy to see, that even the cost aspect is left out, because the diode chips themselves have been shrinked so small with the current diode technologies that the electrical performance is in the view of diode designers again. This paper now concentrates on the trade-off and considerations for diodes used in drive applications. Nevertheless, the basic considerations are the same for all applications: Is it useful to have lower absolute static diode losses or does the total system including the IGBT benefit from a diode which offers slightly higher static losses, but also less switching losses?

# 3 The Diode Trade-off

The trade-off curve of the reverse recovery charge $Q_{rr}$ over the forward voltage $V_F$ of a diode characterizes a given diode technology. This means, that in principle every single point on this curve can be targeted. Figure 3.1 shows an example of such a tradeoff curve. It is therefore possible to design diodes either with rather low $Q_{rr}$ but increased $V_F$ or diodes with low $V_F$ and high $Q_{rr}$. The trade-off curve can be either achieved by varying the current density or by variation of the lifetime killing.

A larger chip size results generally in a lower forward voltage $V_F$, because the current density is lowered. This additionally improves the thermal capabilities of the chip and is therefore an advantage. But simultaneously the switching losses increase and the cost aspect has its comeback.

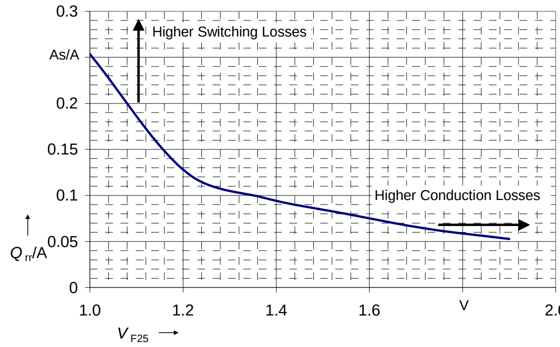


**Figure 3.1: Tradeoff curve of a diode technology**

Reducing the carrier lifetime either locally (e.g. by irradiation with He-ions) or globally (e.g. by electron irradiation or doping with recombination centers such as gold or platinum) has a similar effect for a given current density and die size: A shorter life time will reduce the stored charge $Q_{rr}$ in the device, but also reduce conductivity and increase forward voltage drop $V_F$, where a longer carrier life time will give lower $V_F$ but increased switching losses. Most commercially available diodes use one or more methods of lifetime engineering with the exception of rectifier diodes. A reduction of carrier lifetime is not always necessary for this kind of diodes, because of the very low frequency and the strong need for low conduction losses.
For the investigated diode technology both methods - the variation of current density and the variation of die size - lead to very similar curves. Therefore, the variation of the current density was chosen for the calculations in this paper. This method results in smaller diode chips and hence in a higher number of chips per wafer which will reduce the price of the chip.

On the other hand, smaller chips have a higher thermal resistance from junction to case $R_{thJC}$, so that at first sight a larger heatsink is necessary. This conclusion will be shown to be premature.

Figure 3.2 shows the relationship between the chip size and the thermal resistance $R_{thJC}$. It can be seen that the hyperbolic curve approximates in a value which is defined by the solder thickness of the die bond.

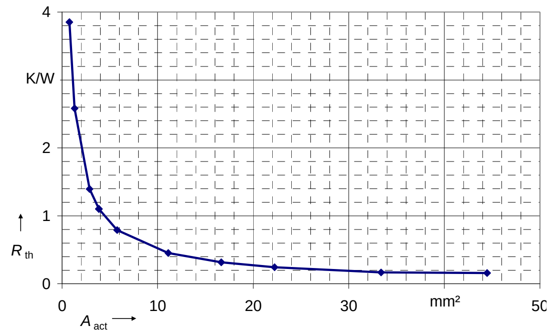


**Figure 3.2: Thermal Resistance dependent on chip size**

For a final evaluation, however, a closer look at the total losses and the different contributions of IGBT and diode is necessary.

An analysis of the commutation process shows that the reverse recovery charge of diodes stresses not only the diode itself, but also the IGBT to which the current is commutated on according to Figure 3.3. The shaded area under the collector current waveform represents the reverse recovery behavior of the diode and the additional charge which is superimposed by the discharge of the parasitic output capacitance. The portion of the output capacitance is usually neglectable because of the very small capacitance of IGBT. Therefore we assume the area to be caused entirely by the reverse recovery. It can be seen, that firstly the reverse recovery current is already flowing when the voltage over the transistor is still high and that secondly the diode current tail extends over some 100ns. It is obvious, that the reverse recovery behavior of the diode is very important for the switching losses in the IGBT.

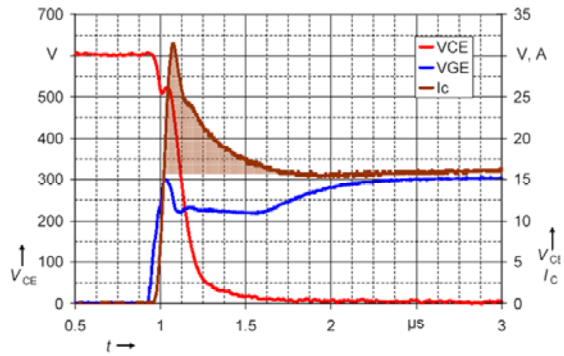


**Figure 3.3: Commutation Process with current transition from the diode to the IGBT**

Looking at the distribution of the power losses, the main power loss contributor is usually the IGBT, so that the diode chip is heated from the IGBT. If the diode itself would have higher losses, then this would not change the situation unless the self-heating of the diode would be higher than the heating effect of the IGBT losses. From the product point of view it can be therefore advantageous to actually increase the diode temperature, thereby decreasing total losses and IGBT junction temperature. The optimal loss distribution is reached, when the junction temperature of the IGBT equals the junction temperature of the diode at rated conditions.

This means, that even though an optimized diode might have a higher $R_{thJC}$ due to smaller chip size of an optimized technology, this does not influence the performance of the IGBT-diode combination, because the overall power dissipation is reduced. Therefore, the optimization of the new antiparallel diode of the new 3rd generation Emitter-Controlled-Diode-technology [1] shows a higher forward voltage drop, but also an improved reverse recovery behavior for lower switching losses compared to 2nd generation of the Emitter Controlled-Diode-technology.

This conclusion is contradictory to the widespread understanding that diodes for drives applications mandatorily must be optimized for low conduction losses. Especially in the consumer drives area such as washing machines low switching losses are also vital, because the switching frequencies can go up to 15 kHz or even higher there. Then the switching losses form a considerable portion of the overall losses in the drive and must not be neglected. This optimization now opens a large door for a wide range of applications - not only in the drives segment, but also in the so-called "High Speed"-area.

# 4 Benchmark of the Emitter Controlled Diode Technologies

Figure 4.1 shows the balance of power losses per rated ampere of two IGBT-diode combinations. The left set of bars results from the combination of 3rd generation diode-technology and the TRENCHSTOP-IGBT IGBT3-technology. As mentioned above, the 3rd generation diode-technology is optimized for lower switching losses and slightly higher forward voltage. The right set of bars results from the combination of a

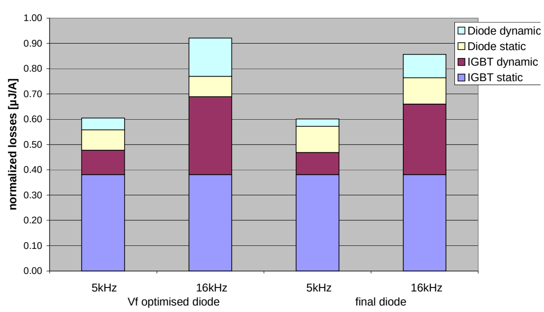


**Figure 4.1: Normalized switching losses for TRENCHSTOP-IGBT in combination with $V_F$-optimized diode (left bars) and the diode of the final design (right bars)**

2nd generation diode-technology and a TRENCHSTOP-IGBT. The 2nd generation-diode-technology used in this benchmark is also the antiparallel diode of the well known Fast-IGBT family from Infineon. This diode is optimized for low forward voltage. The benchmark is conducted using IGP10N60T Infineon Technologies. The heatsink with a thermal resistance of $R_{thHS}$ = 4.2 K/W is designed in order to achieve an elevated junction temperature of approximately 125°C at an ambient temperature $T_A$ = 50°C. This is shown later on. The switching frequency $f_P$ is 16 kHz, which proves the capabilities of the combination containing IGP10N60T and 3rd generation-diode-technology. It can be seen in Figure 4.4, that as expected the conduction losses of the IGBT are not affected by the diode at all. The increased $Q_{rr}$ of the $V_F$-optimized

diode heavily influences the dynamic losses $P_{vsI}$ of both the IGBT and $P_{vsD}$ of the diode. Both effects together, the increased dynamic loss of the diode itself and its influence on the IGBT overcome the advantages during conduction of the $V_F$-optimized diode. This behavior is already visible at a switching frequency of approximately 5 kHz and the effect increases for higher switching frequencies.

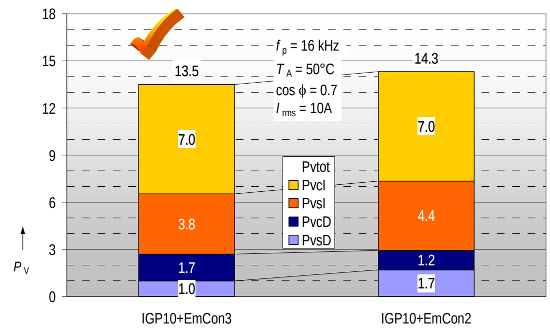


**Figure 4.2: Losses balance for optimizations of diodes ($R_{thHS}$ = 4.2 K/W, $T_A$ = 50°C, cos f = 0.7)**

Of course one can not easily determine the individual portions of the balance of losses shown in Figure 4.2 for a given hardware circuit design. Usually engineers measure the temperature at the case or the leadframe. The thermal capabilities of both diodes in terms of $R_{thJC}$ are considered to be the same. The thermal equivalent circuit of the combination is shown in Figure 4.3. The constant ambient temperature results in a common case temperature $T_C$ defined by the thermal resistance heatsink-ambient and the sum of the losses of IGBT and diode. Then the different junction-case resistances $R_{thJCD}$ and $R_{thJCI}$ of the diode and the IGBT lead to different junction temperatures $T_{JD}$ and $T_{JI}$.

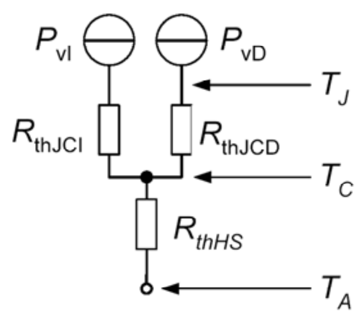


**Figure 4.3: Thermal Equivalent Circuit for temperature calculation**

Figure 4.4 shows now the resulting junction temperatures of both combinations. The junction temperatures are close to 125°C. The combination of IGP10N60T with the $Q_{rr}$-optimized 3rd generation diode results in a lower junction temperature than the combination of IGP10N60T and the $V_F$-optimized 2nd generation diode. Both the diode and the IGBT stay cooler by 4 K in the left pair of bars. Please note here, that the advantage in power loss is 0.7 W for the IGBT and 0.2 W for the diode. Due to the lower $R_{thJC}$ of the IGBT the larger reduction of losses has smaller impact on the junction temperature then the comparably smaller loss reduction for the diode. Therefore, the difference in temperature is the same.

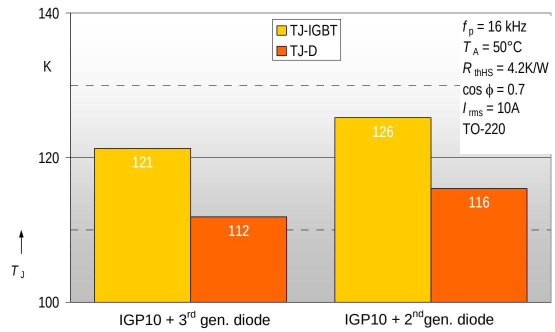


**Figure 4.4: Junction temperature for the above example**

The advantage in losses is of course partially sacrificed for a little poorer $R_{thJC}$. But calculations show, that the junction temperature of the final diode result approximately 4 °C lower at an ambient temperature $T_A$ of 50 °C in combination with the 10A-IGBT IGP10N60T. It can also be seen, that the junction temperature of the IGBT is also lower by 4°C. The system therefore gains generally from the chosen diode optimization. In order to achieve the same junction temperature with the final diode, one can gain more current out of the inverter and therefore more output power for free. This is shown in Figure 4.5. On the other hand it is possible to even reduce the heatsink for a given output current which reduces the cost of the total drive. However which way the designer can use, in total the system shows higher efficiency.

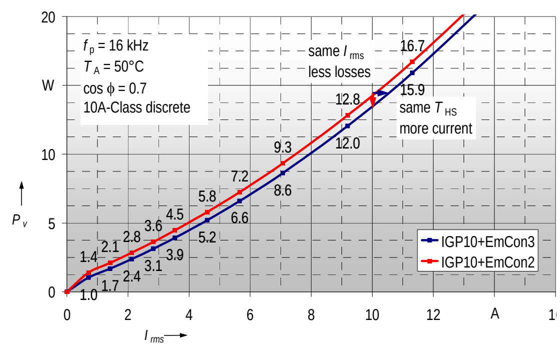


**Figure 4.5: RMS output current of a half bridge leg of an inverter**

# 5 Conclusion

The optimization of a diode is not sufficient, if one is looking to the forward voltage only. Considerations on the used IGBT technology and application related design conditions must be taken into account. It is shown in the paper, that the diodes used in combination with Infineon´s latest TRENCHSTOP-IGBT technology are designed according to those technology and application conditions. The diodes have a smaller chip size, but they achieve even a lower resulting junction temperature than larger, $V_F$-optimized chips. This enables engineers to go for a higher utilization of the combination of IGBT and diode. It can either reduce the size of the heatsink or increase the output power of a given system. But in the end it always reduces the system cost.

# 6 Summary of Used Nomenclature

**Physics:**

General identifiers:

*A* ......... cross area
*b*, *B* ..... magnetic inductance
*d*, *D* ..... duty cycle
*f* .......... frequency
*i*, *I*........ current
*N*......... number of turns
*p*, *P* ..... power
*t*, *T* ...... time, time-intervals
*v*, *V* ..... voltage
*W*........ energy
h ......... efficiency

Special identifiers:

$A_L$............inductance factor
$V_{(BR)CES}$...collector-emitter breakdown voltage of IGBT
$V_F$ ...........forward voltage of diodes
$V_{rrm}$ .........maximum reverse voltage of diodes

big letters: constant values and time intervals
small letters: time variant values

**Components:**

*C*......... capacitance
D......... diode
IC........ integrated circuit
*L* ......... inductance
*R*......... resistor
TR ...... transformer

**Indices:**

AC ...... alternating current value
DC ...... direct current value
BE....... basis-emitter value
C......... collector value
CS ...... current sense value
E ......... emitter value
G......... gate value
OPTO . optocoupler value
P ......... primary side value
Pk ....... peak value
R......... reflected from secondary to primary side
S ......... secondary side value
Sh ....... shunt value
UVLO.. undervoltage lockout value
Z ......... zener value

fmin ........value at minimum pulse frequency
i ..............running variable
in ............input value
max ........maximum value
min .........minimum value
off ...........turn-off value
on ...........turn-on value
out ..........output value
p .............pulsed
rip ...........ripple value

1, 2, 3 .....on-going designator

# 7 References

[1] T. Laska, L. Lorenz, T. Mauder: The New IGBT Generation - A Great Improvement Potential for Motor Drive Systems; IAS Conference 2000; Rome; Italy, 2000

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[3] W. Frank: TrenchStop-IGBT - Next Generation IGBT for Motor Drive Application; Application Note; Infineon Technologies; Germany; Oct. 2004

[4] Infineon Technologies: IGP10N60T; datasheet; Infineon Technologies ; Germany ; 2004