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Fast IGBT based on TRENCHSTOP^{TM}5 technology for industrial applications

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1 Introduction

Historically fast IGBTs have been proposed as the replacement of conventional or Superjunction MOSFETs due to higher power density, however because of technology limitations there are only limited areas where IGBTs can reach both commercial and technical advantages.
The new TRENCHSTOP™5 IGBT overcomes many of those technical limitations providing an interesting solution for high speed applications to be found in application like solar, UPS and welding.
This application note was designed to provide engineers information and advice on how to design-in the new TRENCHSTOP™5 IGBT into standard IGBT applications.
After providing an introduction of the new technology, measurements on bipolar H4 solar inverter are provided with more technical details.

2 Description of Technology and Product Family

The TRENCHSTOP™5 technology is an optimization of Infineon's TRENCHSTOP™ concept combining Trench gate and Field Stop structures. In order to minimize total power losses, the chip thickness is reduced to 50µm, an optimization of the carrier profile has been carried out to provide a reduction of charge carriers within the drift zone that have to be removed during the turn-off phase. These two measures allow for a significant reduction in conduction losses (V_{CEsat}) and turn-off switching loses (E_{off}).
Additionally, the gate charge Q_g is reduced thanks to a new transistor stripe cell structure, which also offers a significantly increased MOS-Channel width, as illustrated in Figure 1.
The combination of new cell design and vertical doping profile results in lower $V_{CE(sat)}$ and E_{ts} at even increased current density.

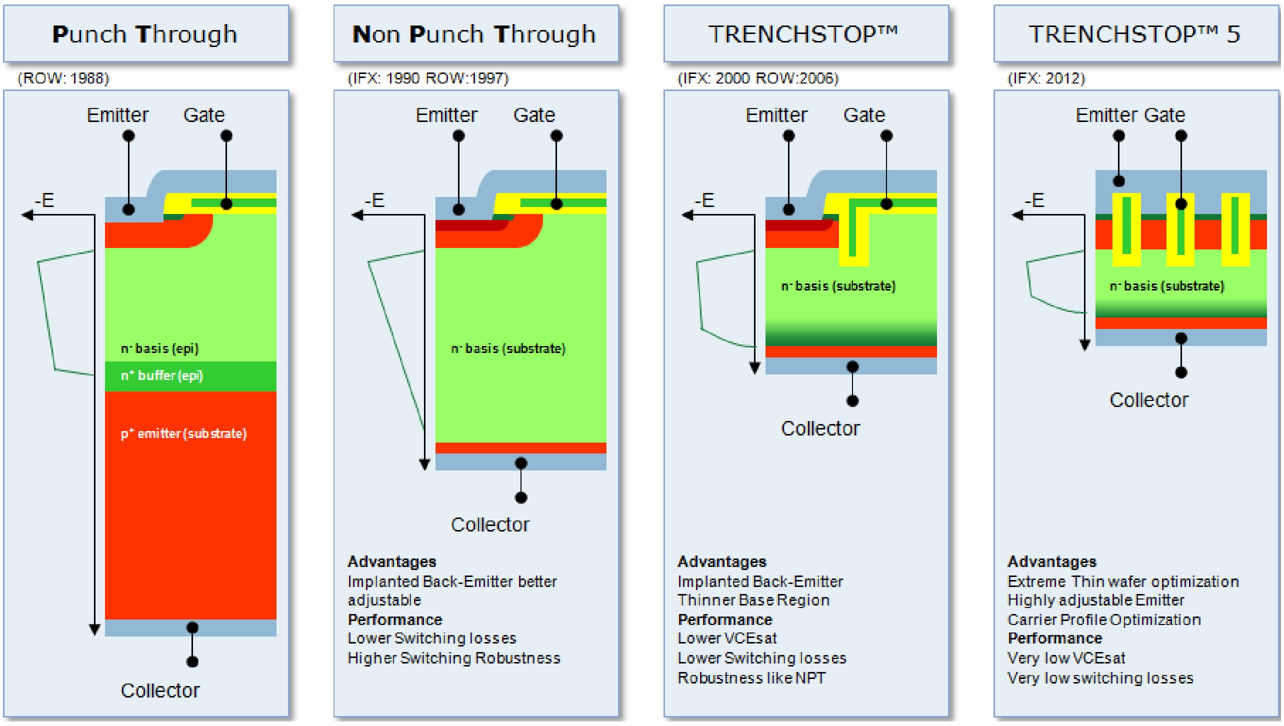

Figure 1: Infineon IGBT generations

Despite the chip thickness reduction, a 650V blocking capability is achieved, which is 50V higher than the previous generation.

Two different device versions of the TRENCHSTOP™5 are being released to address different application requirements and fulfill designers' needs.

The designer has the opportunity to select between the **H5** and **F5** versions. The **H5** family is characterized by an optimized Field Stop design and is aimed to complement Infineon's HighSpeed3 IGBT family in standard IGBT applications; it allows for the "plug-and-play" replacement of IGBTs without any special effort in adjusting the board design. It provides very soft voltage rise during hard commutation at turn-off even with low R_g values and very high di/dt.

The **F5** meanwhile is the higher performance solution. It provides higher efficiency, but more design effort is required to harvest the high efficiency. The driver stage should be equipped with split $R_{g,on}$ / $R_{g,off}$ gate resistor to maximize efficiency and to control voltage overshoot during turn-off. It is the best fit for optimized PCB design with low stray inductance both in the commutation loop and packages.

2.1 TRENCHSTOP™5 Static and Dynamic Characterization

This section will guide the reader towards a comparison between the two versions of the new TRENCHSTOP™5 and Infineon's HighSpeed 3 family. Both static and dynamic characteristcs will be presented.

2.1.1 Comparison with Previous Generation

As can be seen in Table 1, compared to the HighSpeed 3 family, the TRENCHSTOP™5 shows significant improvement in all static and dynamic parameters. It provides 50V higher blocking voltage, up to 250mV lower V_{cesat}, drastic reduction of C_{oss}, C_{res} and Q_g, faster rise and fall times during current transition, and a factor of 2 lower E_{on} and E_{off}.

Improving the device performances in terms of loss reduction often translates in a snappier behavior during switching off. This is also one of the reasons why, especially for the F5, the blocking voltage has been increased to 650 in order to allow a higher margin to handle voltage spikes generated during turn-off of high currents with low Ohmic gate resistor. The increased breakdown rating is also beneficial in solar applications when the open circuit voltage of solar panel could be as high as 580V or even in special cases 600V. In this case the 650V rating provides higher cosmic radiation hardness.

As indicated in Figure 2, the TRENCHSTOP™5 allows a new $V_{CE(sat)}$ vs. E_{off} trade-off not achievable by previous generations, resulting in an improvement in performances of both conduction and switching losses during operation.

Table 1: Electrical parameter comparison between TRENCHSTOP^{TM}5 and HighSpeed 3

		IKx40N60H3	IKx40N65F5	IKx40N65H5	Unit
Static Char.	$V_{CE(sat)}$ Typ@40A, U_g=15V, T_c=25°C	1,95	1,7	1,75	V
	$V_{CE(sat)}$ Typ@40A, U_g=15V, T_c=175°C	2,4	2,1	2,15	V
	DC collector current, T_c=25°C	80	80	80	A
	DC collector current, T_c=100°C	40	40	40	A
	G_{fs}@V_{ce}=20V, I_c=40A	24	50	50	S
	V_{geth}@0,4mA, V_{ce}=V_{ge}	5,1	4,0	4,0	V
	$V_{(br)ces}$, V_{ge}=0V, I_c=2mA	600	650	650	V
Cap. & Charges	C_{ies}@V_{CE}=25V, f=1MHz	2190	2100	2100	pF
	C_{oes}@V_{CE}=25V, f=1MHz	112	43	47	pF
	C_{res}@V_{CE}=25V, f=1MHz	64	9	9	pF
	Q_g@V_{cc}=480V, I_c=40A, V_{ge}=15V	223	84	90	nC
Switching @ 25°C **Ls=45nH/Cs=40pF**	$t_{d(on)}$)@V_{cc}=400V, I_c=20A	19	21	21	Ns
	t_r@V_{cc}=400V, I_c=20A	33	10	11	Ns
	$t_{d(off)}$@V_{cc}0400V, I_c=20A	197	140	140	Ns
	t_f@V_{cc}=400V, I_c=20A	21	8	8	Ns
	E_{on}@V_{cc}=400V, I_c=20A	0,61	0,3	0,27	mJ
	E_{off}@V_cc=400V, I_c=20A	0,29	0,13	0,16	mJ

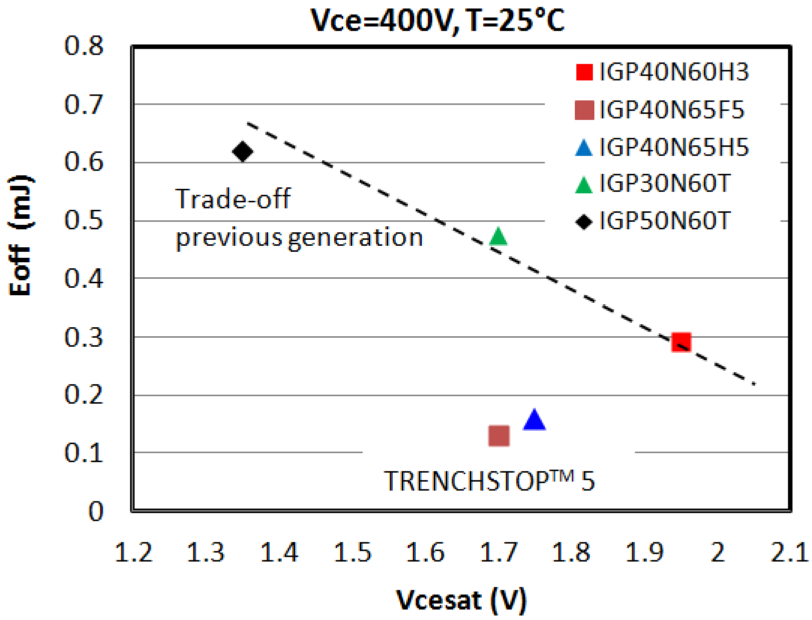

Figure 2: Trade-off V_{CEsat}-E_{off} comparing with previous generation

2.1.2 Dynamic Characterization

In order to complete the new technology assessment it's important to focus on the R_g dependency of the switching behavior. On the left hand side of Fig 3, the turn-off controllability as function of R_g during a standard double pulse test circuit is highlighted, with stray inductance of 45 nH in the commutation loop. The E_{off} curve of both H5 and F5 are drastically lower compared to traditional fast IGBTs, and in the same range of Superjunction MOSFETs at low R_g of 5Ohm.

The right hand plot Figure 3 shows the collector-emitter voltage at turn off as function of R_g. The plot helps to underline once again the difference in between H5 and F5, thus the need for the two families. The H5 shows a smooth switching behavior, with voltage overshoot of the same order as the HighSpeed 3. The F5 meanwhile is characterized by higher voltage overshoot at turn off, but exhibits higher efficiency. The typical waveforms are also shown in Figure 4, where the F5 shows much faster current drop during turn off, translating unavoidably in higher voltage overshoot (L*di/dt).

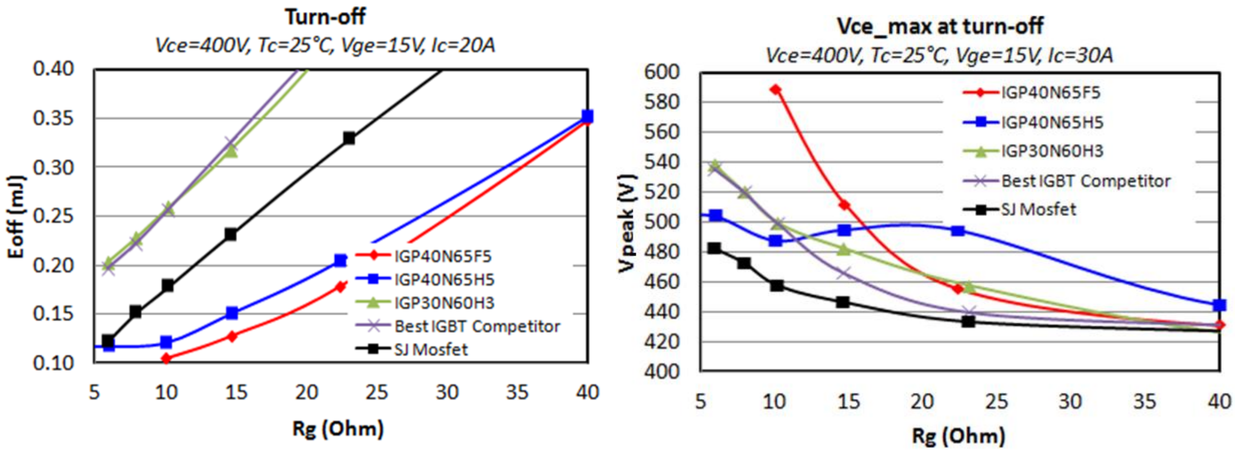

Figure 3: Turn-off dependence of gate resistor: turn-off Energy (left) and voltage overshoot (right)

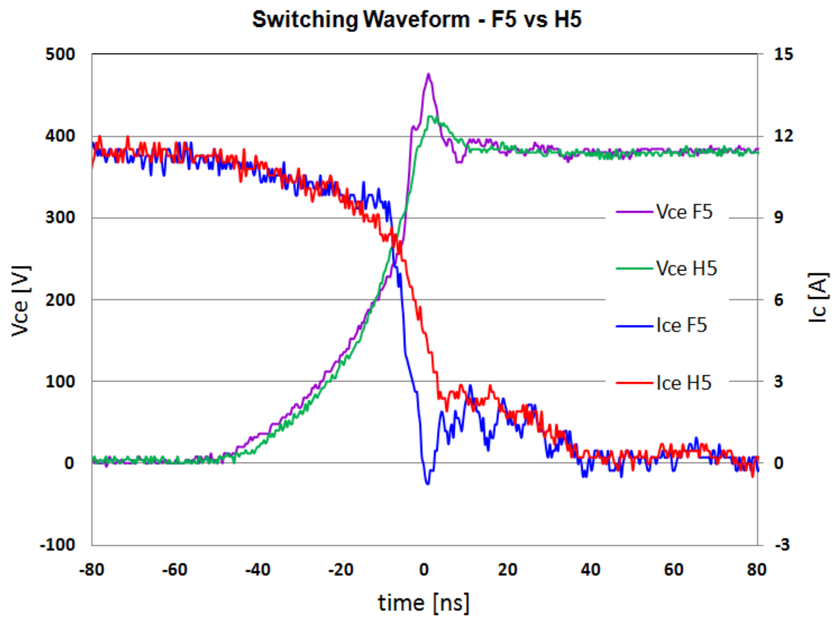

Figure 4: Typical turn-off waveform H5 vs F5

Figure 5 shows the relationship between the turn-on losses (E_{on}) and turn-on gate resistor value ($R_{g.on}$) for both F5 and H5. Form figure 5, it can be seen that the TRENCHSTOP™5 shows very similar behaviour to a Superjunction MOSFET of equivalent rating, and significantly lower losses compared to previous IGBTs. It can also be concluded that the turn-on behavior of the F5 and H5 is controllable via the turn on gate resistor ($R_{g.on}$) over a wide range.

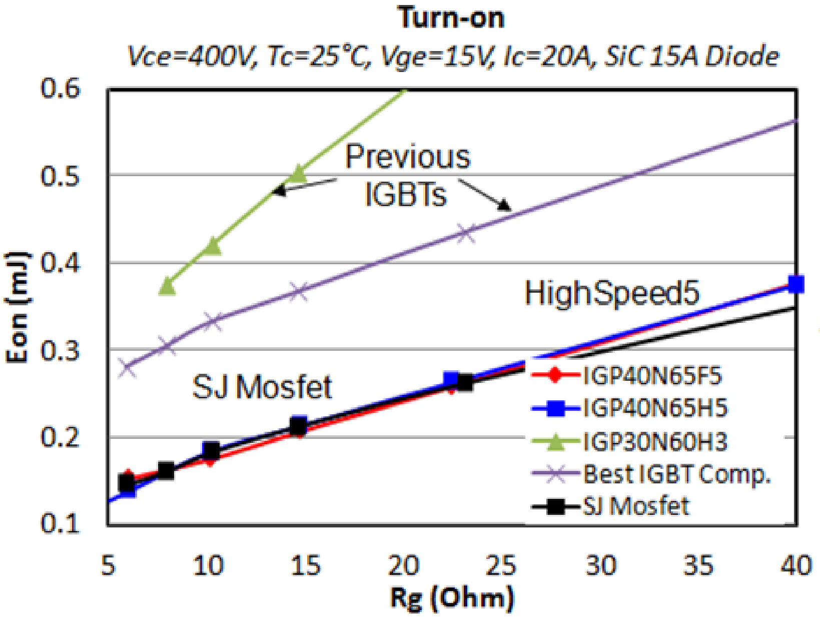

Figure 5: Effect of $R_{g,on}$ on turn-on energy

What can be concluded from figures 3, 4 and 5 is as follows:

a. Two families are required to provide designers with either an IGBT that is easy to handle and thus can be easily implemented (H5) or an IGBT that is snappy, needs care during implementation to reduce commutation loop inductance, but offers even higher efficiency (F5).
b. Turn-off controllability of the voltage overshoot and the switching losses is possible
c. Turn-on controllability is possible and turn-on switching losses are on par with super-junction MOSFETs
d. Ultimately there is a trade-off between switching losses and voltage overshoot. F5 needs to be driven with higher Ohmic gate resistors compared to the H5, to limit the voltage overshoot
e. F5 has the highest efficiency due to the higher di/dt and is recommended for low inductance commutation loops and in combination with silicon carbide diodes
f. H5 can be driven with gate resistors down to 5Ω due to the softer turn off behavior compared to F5

3 Industrial Application Measurements – Solar Inverter DC/AC stage

3.1 Power loss calculation

For this industrial application measurement example, the H5 has been analyzed compared to the HighSpeed3 equivalent products.
With high load currents as well as high speed switching (di/dt), the H5 is seen as an easy to use solution which is recommended to test first to get a feeling of how efficient the TRENCHSTOP™5 technology actually is. Once this is done, the F5 can be used, with optimized PCB layout, driver designs, and system switching frequency to examine the extended efficiency improvement.

For this application investigation, only the H5 was used to indicate, just by implementing a plug and play approach, the system efficiency improvement.
Before looking into the real application of solar inverter, let's firstly get a feeling of the power loss improvement the H5 offers compared to Infineon's HighSpeed 3. Based on a very simple condition of a 20A square wave with 50% duty cycle, junction temperature 100°C, the curves of total power loss per IGBT vs switching frequency are shown in figure 6 below:

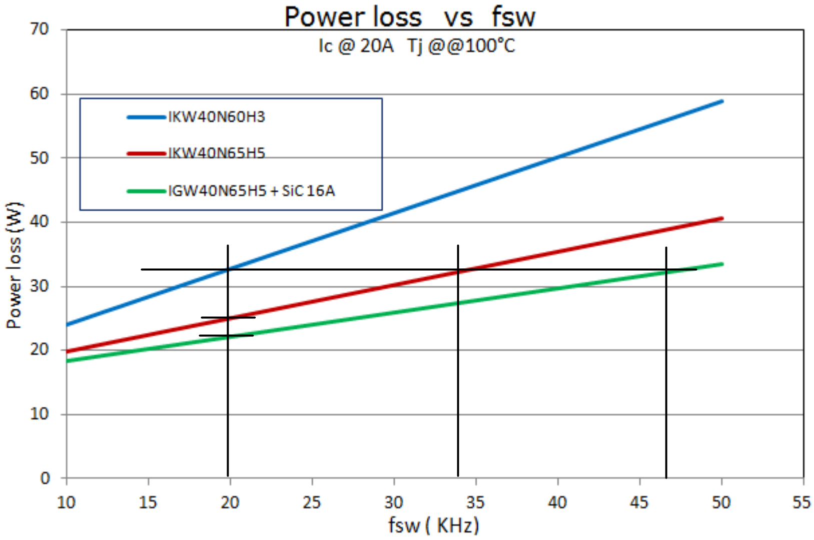

Figure 6: Ptot vs switching frequency

At 20 kHz, which is a commonly used frequency in state-of-the-art photovoltaic inverter designs, the total power loss per IGBT dropped from 32.80 W, when the HighSpeed 3 was used, to 25.04 W, when the H5 was implemented.
What the results show is that just by implementing the new H5 (with no changes to driver circuit or board layout), power losses were reduced by approximately 24%. Furthermore, when the IKW40N65H5 was replaced, which has the Rapid silicon diode as the free-wheeling diode, with the IGW40N65H5 in combination with Infineon's 2nd generation silicon carbide (SiC) diode, a further 11% power loss reduction was achieved.
When considering the affects of switching frequency on the power losses, the application tests highlighted that the H5 was able to attain the same level of switching losses compared to the H3 at 33 kHz. The switching frequency could be extended to 46 kHz when the H5 was used in combination with a silicon carbide diode. Having the chance to increase switching frequency gives designers the change to reduce passive component sizes, thus allowing for system cost and size reduction.

Device selection is critical to ensure designs adhere to a thermal design specification. The maximum allowable loss and junction temperature are defined according to heatsink condition, ventilation as well as the configuration of power devices, magnetic components etc. Therefore, one of the major tasks for electrical design engineers is to ensure the junction temperature of all the power devices fulfill the derating requirement e.g. 80% of the T_{jmax}. That means that the maximum allowable power loss per device is defined.
Taking a practical example to demonstrate the performance of the H5, assume the specification of the maximum junction temperature is 100°C. Taking the same load condition mentioned above (20A square wave,

50% duty cycle) for a 40A device, the maximum power-losses for a standard TO-247 package would be 40W. At 40W, the maximum operating frequency of HighSpeed 3, with respect to max junction temperature 100°C, is around 28 kHz. The new H5 could however be driven up to 50 kHz, which represents nearly a 50% increase in switching frequency, whilst maintaining the same junction temperature.
Having the opportunity to increase the frequency, whilst maintaining the same thermal performance, brings about a cost and reliability benefit. This can be realized by using smaller and lighter magnetic components, and reducing or even eliminating the use of electrolytic capacitors. Although increasing the switching frequency increases the design complexity, clear benefits can be achieved for applications like Solar and UPS, where the costs of the passive components dominate the bill of material.
Below is an example on a HERIC topology which was measured at Fraunhofer Institute ISE. The H5 allows for the switching frequency to be tripled from 16 to 48kHz compared to corresponding TRENCHSTOP™ device by keeping the same efficiency over the entire load range.
Conversely, by maintaining the switching frequency at 16kHz, overall system efficiency has been increased. A clear design strategy is necessary to get the best out of the new TRENCHSTOP™5 IGBTs.

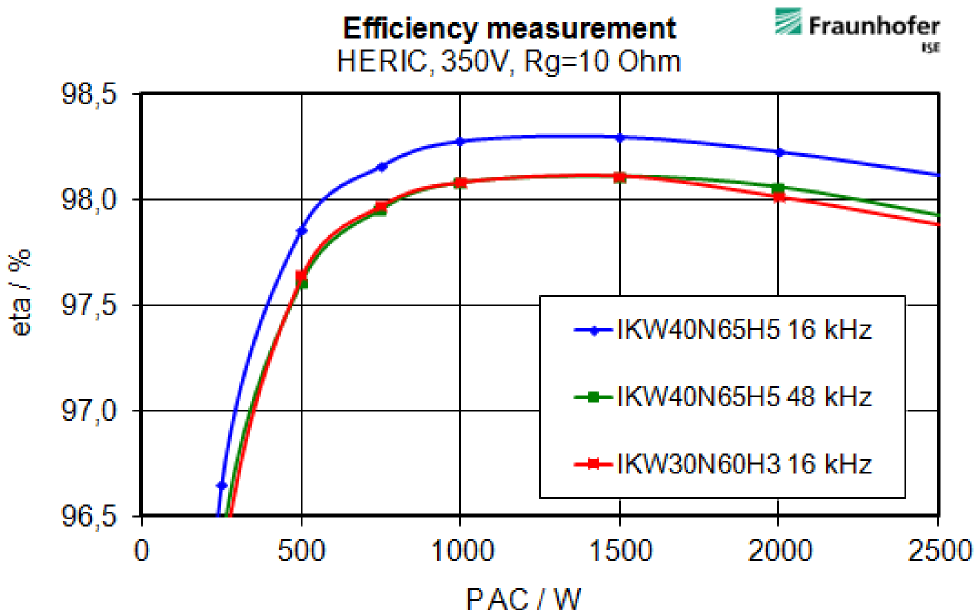

Fig 7: Efficiency at different switching frequencies

Figure 7 shows the efficiency of the H3 and H5 IGBTs. Further improvements in efficiency can be attained when a silicon carbide diode is used as the free-wheeling diode or the F5 IGBT is used.

It will be those designers and companies who are able to deal with this increase complexity that will be able to offer differentiated systems to their end customers and increase their own market share.

3.2 Benchmarking on a bipolar H4 platform

Based on Infineon's in-house 3 kW inverter board, which consists of a bipolar H4 topology as shown in figure 8. A direct comparison has been carried out between the H5 and the equivalent HighSpeed 3 with different combinations of diodes (e.g. SiC vs Si). Measurements were carried at a switching frequency of 20kHz, which is typically adopted by solar designers today. From measurements, the efficiency and temperature curves were recorded and are presented in figures 9 and 10.

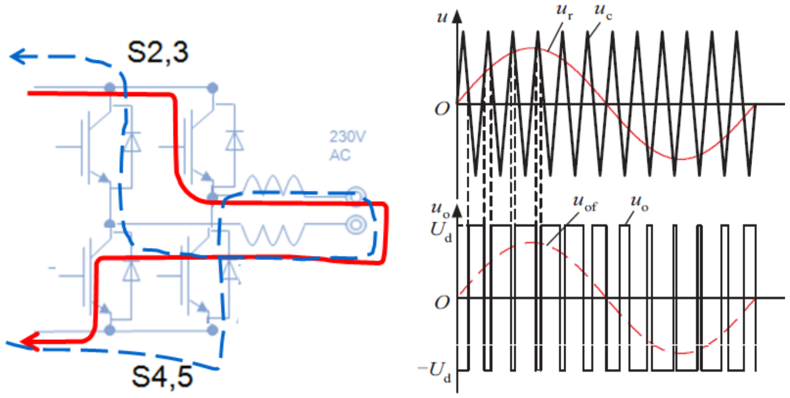

Figure 8: Topology and modulation method of bipolar H4

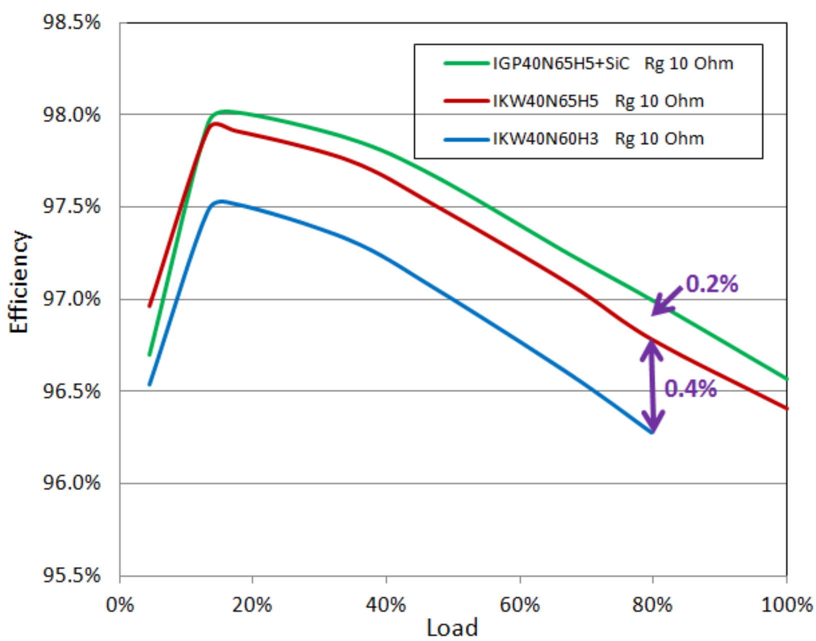

Figure 9: Efficiency vs load

The efficiency of the test board, when using the duo-pack H5 IGBTs as switching devices, starts from 97% at light load and reaches peak value 97.9% at around 15% of the total load. Due to the design of output filter, which for these measurements was not fully optimized, the efficiency declines beyond 600W and finally reaches 96.4% at 3kW. Comparing the efficiency behavior with the equivalent HighSpeed 3 IGBT, the efficiency improvement, by simply plug and play approach, is around 0.4% over the whole range!
Additional measurements were carried out; where a SiC diode was used instead of an anti-parallel Rapid diode as hard commutation diode and these measurements are indicated by the green line in figure 9. As can be seen, an additional 0.2% efficiency could be gained, which takes the peak efficiency above 98%! This is the first time 98% system efficiency has been reached when using IGBTs in a H4 bridge.

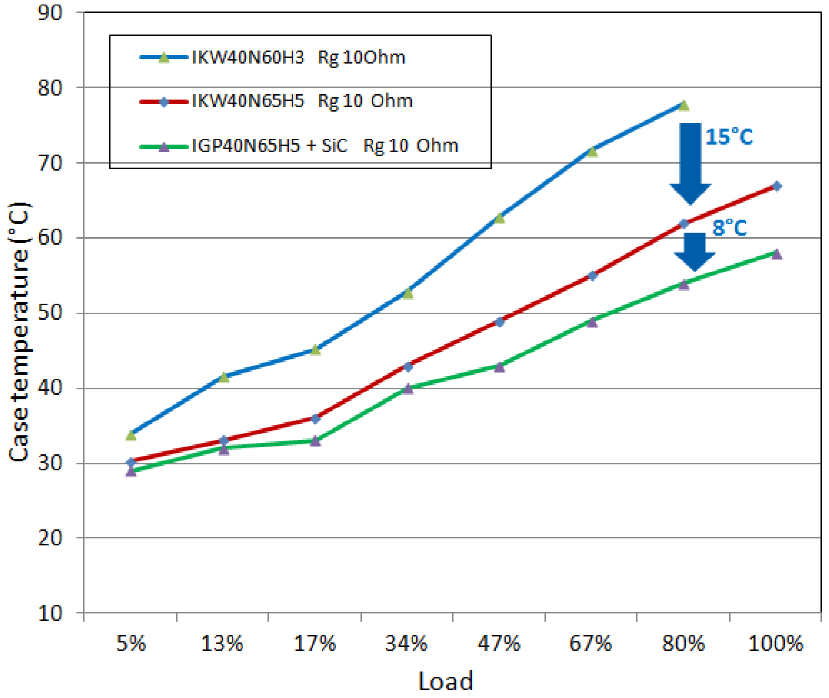

Figure 10: Case temperature vs load

Figure 10, meanwhile indicates the case temperature versus load. Figure 10 demonstrates an outstanding feature of the new TRENCHSTOP™5 technology compared to the HighSpeed 3. During high-load conditions, the temperature difference on the surface of the package mold-compound was seen to be 15°C lower, which corresponds to 0.4% efficiency improvement. And, once again when a SiC diode was used the gap was enlarged by another 8°C temperature reduction.
So, as clearly illustrated above, H5 IGBT can achieve higher efficiency as well as much better thermal performance than the HighSpeed 3. The major reason behind is due to the fast switching capability which came from the optimised carrier profile.
Figure 11 shows the switching waveform behaviour of the H3 and H5 families. The waveforms show the turn-off behaviour to get a visual impression of the voltage over-shoot and the speed of the current turn off. Please note the scale on the x-axis – these are seriously fast IGBTs and the traditional “tail-currents” are no longer present on Infineon’s high speed IGBTs.

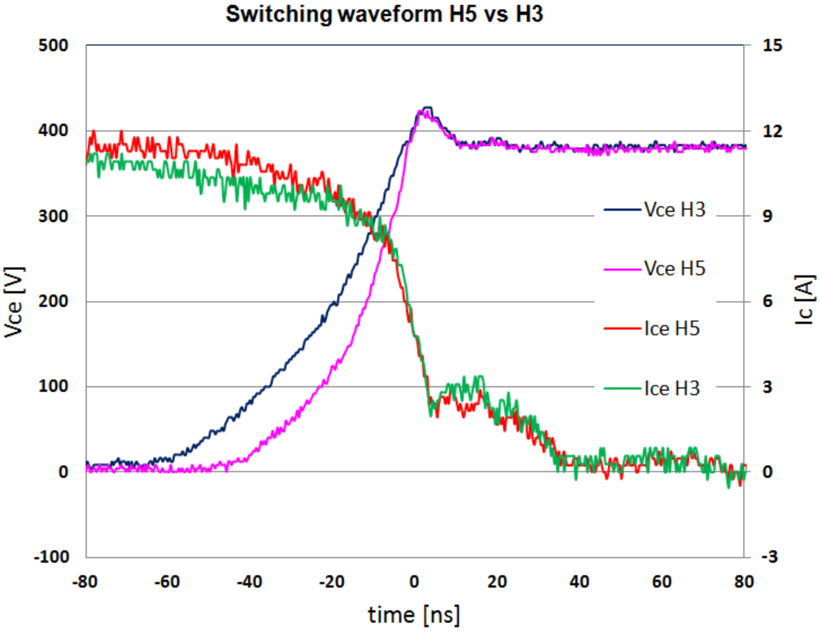

Figure 11: Switching waveform H5 vs HighSpeed 3

When examining the waveforms of Figure 11, the current slope of H5 is the same as the HighSpeed 3. The higher efficiency of the H5 comes from the faster voltage build-up between collector and emitter compared to the HighSpeed 3, resulting in drastically reduced E_{off}.
Furthermore, the overshoot behavior of the H5, as indicated by Figure 12, is similar to the HighSpeed 3 over the entire load range. This translates into excellent EMI behaviour and a well-controlled absolute value of the maximum voltage spike.
The additional 50V on the breakthrough voltage of the H5 over the HighSpeed 3 is a clear benefit for designers.

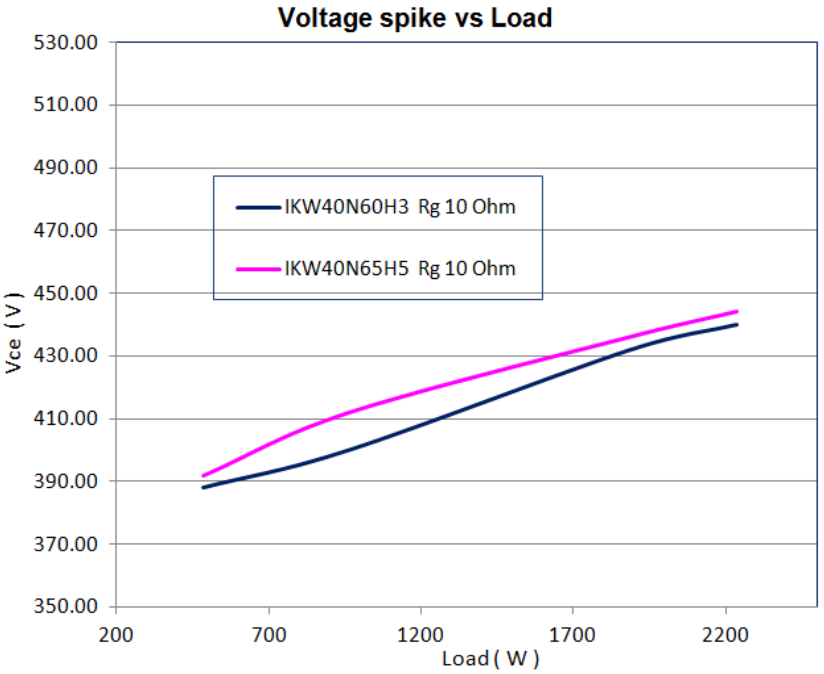

Figure 12: Voltage spike H5 vs HighSpeed 3

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4 Summary

Through application measurements it has been proven that the TRENCHTOP™5 sets a new benchmark on the market for fast switching IGBT performance. As a result of the best optimization of carrier profile in combination with Infineon's further advancement of thin wafer technology, a dramatic reduction in both turn-off and turn-on losses in hard switching applications, along with a low V_{cesat} value provide an IGBT that can achieve more than 98% system efficiency, as seen with the H4 platform.

Furthermore, the overshoot and EMI behavior is well controlled and is on the same level as the well-known HighSpeed 3 series,

The H5 with the Rapid diode as the free-wheeling diode offers an ease-of-use solution for high performance industrial applications like solar, UPS and Welding.

The H5 in combination with silicon carbide further increases this efficiency range, while further optimisation is available when using the F5 version.

The TRENCHSTOP™5 offers designers many advancements in IGBT performance. It is now up to designers to harness the full capability.

5 References

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