Solar Inverter Performance Improvement Utilizing 650 V HighSpeed 3 IGBT Power Modules

For applications which require an output filter or have a boost/buck choke, higher switching frequencies can lead to advantages on system level. One application where both can be found is a solar inverter. At the state-of-the-art efficiency and power density, high cost pressure can be observed for solar inverters. In this article, the difference between the 650 V IGBT3, 650 V IGBT4 and the 650 V HighSpeed 3 (HS3) IGBT from Infineon Technologies used in power modules will be described. It will be shown that due to the device design, the 650 V HS3 IGBT provides a superior performance and can be used as a highly efficient switch. **Jens De Bock and Christian R. Müller, Infineon Technologies AG, Warstein, Germany**

The trench-field-stop technology is the most common concept for modern IGBTs with blocking voltages in the range of 600 V to 1200 V. This technology allows implementing devices with low on-state voltages and soft switching on the one hand and low switching losses and a MOSFET-like switching performance for high-frequency applications on the other hand. Within this technology, the device performance is mainly controlled by design parameters like cell geometry, chip thickness, and doping profile. For instance, by adjusting these parameters, devices with a high carrier density in the drift region can be implemented. Such devices provide a low $V_{CE\,sat}$ and achieve low static losses. During the turn-off, a high carrier density leads to a slower clear out of the device and the dynamic losses are increased. Therefore, the performance of an IGBT can be either optimized for high-frequency applications like solar inverters or boosters, which need devices with low dynamic losses, or for low-frequency applications, which benefit from low static losses.

The HighSpeed IGBT is optimized for high-frequency hard-switching applications [1]. Therefore, this device is an ideal choice for power modules which are used in solar applications.

Electrical setup

For the measurements, a 650 V IGBT3, a 650 V IGBT4, and a 650 V HS3 IGBT with a nominal collector current of 50 A were used. The electrical performance of the chips is determined by measuring the switching losses. For the measurement each chip was integrated in an EasyPACK 2B power module with an identical electrical circuit and a stray inductance of 17 nH. Due to the fact that the turn-on losses E_{ON} are mainly dominated by the free-wheeling diode used, all chips were operated with a 650 V emitter-controlled diode with a nominal current $I_F = 30$ A.

A setup with an integrated current probe and a stray inductance $L_{\sigma} = 25$ nH was used. The DC-link voltage was set to $V_{DC} = 400$ V, which is a typical voltage in the application and the chips were operated at nominal collector current $I_C = 50$ A. To drive the IGBT, a gate-emitter voltage $V_{GE} = \pm 15$ V was used. All measurements were performed at $T_{vj} = 25$ °C.

Switching behavior and chip comparison

The switching behavior of the chips is measured with the setup described. The corresponding energies and the characteristic switching parameters are extracted from the turn-on and turn-off waveforms.

Figure 1 displays the switching losses for HS3 IGBT, IGBT3 and IGBT4 for identical switching parameters. R_G was modified in the way that di/dt = 1.5 kA/μs and dv/dt

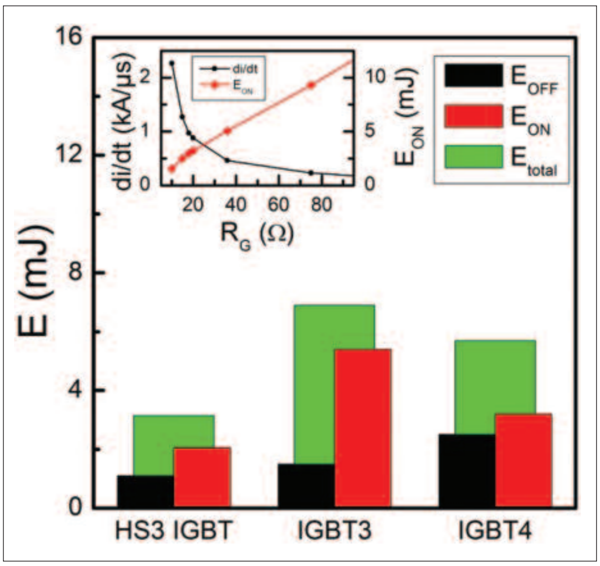

Figure 1: Comparison of the switching energies E_{ON}, E_{OFF}, and E_{total} with identical di/dt during turn-on and dv/dt during turn-off for HS3 IGBT, IGBT3, and IGBT4 (Inset: E_{ON} and di/dt of the HS3 IGBT versus R_G)

= 4.5 kV/µs were achieved during turn-on and turn-off respectively. The HS3 IGBT has the lowest switching losses E_{ON} and E_{OFF} and, in sum, E_{total} is less than half compared to the IGBT3. The inset shows E_{ON} and di/dt of the HS3 IGBT versus R_G. E_{ON} increases and, in turn, di/dt decreases with increasing R_G. Especially for $R_G <$ 20 Ω, di/dt > 1 kA/µs can be achieved whereas larger R_G lead to di/dt below 0.5 kA/µs.

The low turn-off losses indicate the superior switching performance of the HS3. Therefore, the HS3 IGBT is optimized for high-frequency applications and, with respect to the trade-off between E_{OFF} and $V_{CE\ sat}$, provides low dynamic losses. With a high gate resistor the turn-on losses of the HS3 IGBT are quiet high and, in turn, are attributed to the very low di/dt. To compensate for this, it is necessary to significantly decrease the turn-on gate resistor. One possible way for implementation is to use a more sophisticated gate-driver design which allows operating the HS3 IGBT as a very efficient switch.

HS3 IGBT under operating conditions

Above it was shown, that the HS3 IGBT outperforms IGBT3 and IGBT4 in high-frequency applications. The upcoming question is how the HS3 IGBT performs under operating conditions. Under typical operating conditions in a solar inverter, the HS3 IGBT will mainly be operated with collector currents lower than the nominal chip current. In addition, the DC-link voltage may vary over a mentioned wide voltage range. Therefore, the switching losses of the HS3 IGBT are analyzed for DC-link voltages in the range of 150 V to 450 V and for collector currents up to the nominal chip current.

For the measurement, R_G = 15 Ω was used in the gate-driver circuit. Figure 2 shows the switching losses of the HS3 IGBT versus the DC-link voltage. For low V_{DC}, E_{OFF} is low and increases linearly with increasing V_{DC}, higher collector currents result in higher turn-off losses. In contrast to this, it is found that E_{ON} increases disproportionally with V_{DC} and I_C as well. For I_C = 10 A, the slope of E_{ON} versus V_{DC} is almost constant. At I_C = 30 and 50 A, a steeper slope for $V_{DC} \geq 300$ V is observed. In the inset, this disproportional increase is also identified for E_{total}.

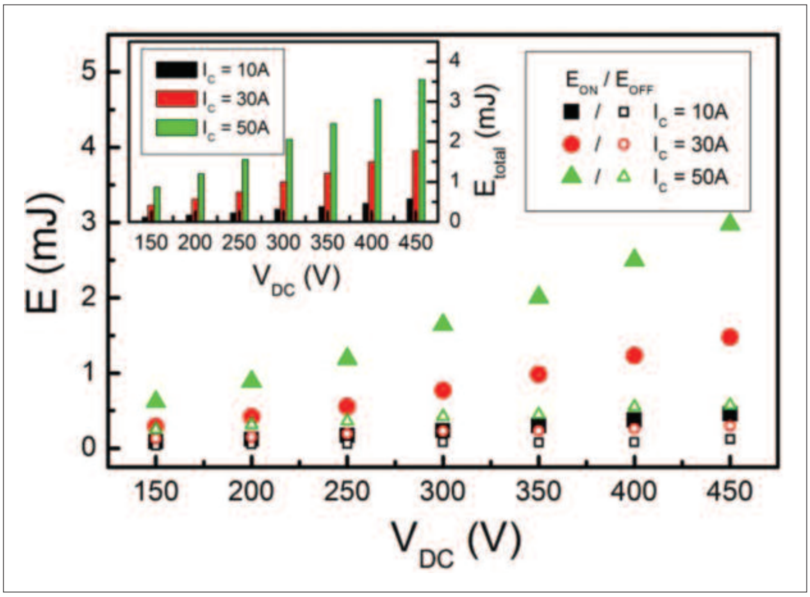

Figure 2: Switching energies E_{ON} and E_{OFF} of the HS3 IGBT versus the DC-link voltage for IC = 10, 30, and 50 A (Inset: E_{total} of the HS3 IGBT versus the DC-link voltage for I_c = 10, 30, and 50 A)

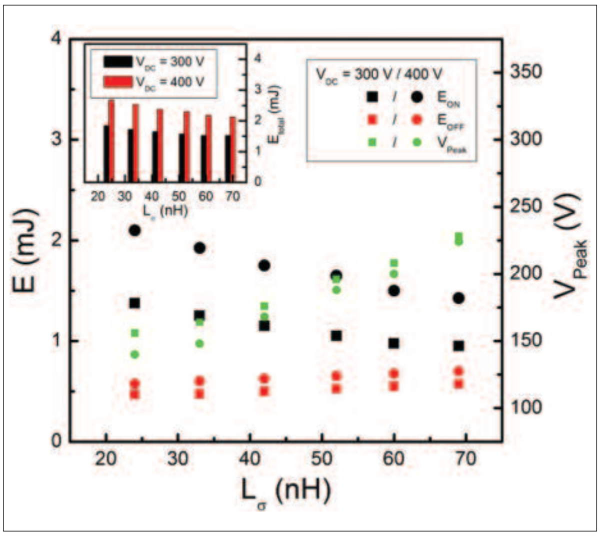

Figure 3: Switching energies E_{ON} and E_{OFF} and V_{Peak} of the HS3 IGBT versus the stray inductance for VDC = 300 and 400 V (Inset: E_{total} of the HS3 IGBT versus the stray inductance for V_{DC} = 300 and 400 V)

These measurements show that, compared to the turn-on losses, the turn-off losses of the HS3 IGBT have minor impact on the device performance. Due to the disproportional increase of the turn-on losses for $V_{DC} \geq 300$ V at $I_C \geq 30$ A, the highest efficiency can be achieved at low collector currents. The high turn-on losses for larger V_{DC} and I_C are attributed to a reduction of the di/dt. This effect is characteristic for the HS3 IGBT and is related to the device design. One way to compensate this effect is the reduction of R_G which, in turn, leads to a decrease of the softness.

When fast-switching devices are used, an upcoming requirement for the application is the reduction of the stray inductances in the setup [2, 3]. Hence both, module and setup must provide a low inductance to avoid parasitic effects. Two of the most common effects, closely related to stray inductances, are the over-voltage peak V_{Peak} on the collector-emitter voltage and the reduced switching losses due to the collector-emitter voltage drop during turn-off and turn-on, respectively.

Figure 3 displays the switching losses and the over-voltage peak of the HS3 IGBT versus the stray inductance of the setup for identical switching parameters, di/dt = 1.5 kA/µs and dv/dt = 7.2 kV/µs for V_{DC} = 400 V and di/dt = 1.6 kA/µs and dv/dt = 6.0 kV/µs for V_{DC} = 300 V. With increasing L_σ, the turn-off energy increases slightly whereas the turn-on energy decreases significantly. As a result, the total switching energy is reduced for larger L_σ. This general trend is independent of the applied DC-link voltage. On the other hand, large L_σ leads to a raise of V_{Peak}. As a consequence, the DC-link voltage in the application becomes limited. A countermeasure for this is to reduce the switching speed by increasing R_G, which in turn, results in higher switching losses.

Increasing the stray inductance of the setup reduces E_{total} of the IGBT due to the fact that the reduction of E_{ON} is more pronounced than the increase of E_{OFF}. However, parasitic effects like oscillations caused by resonance frequencies of the setup or the diode snap-off will lead to

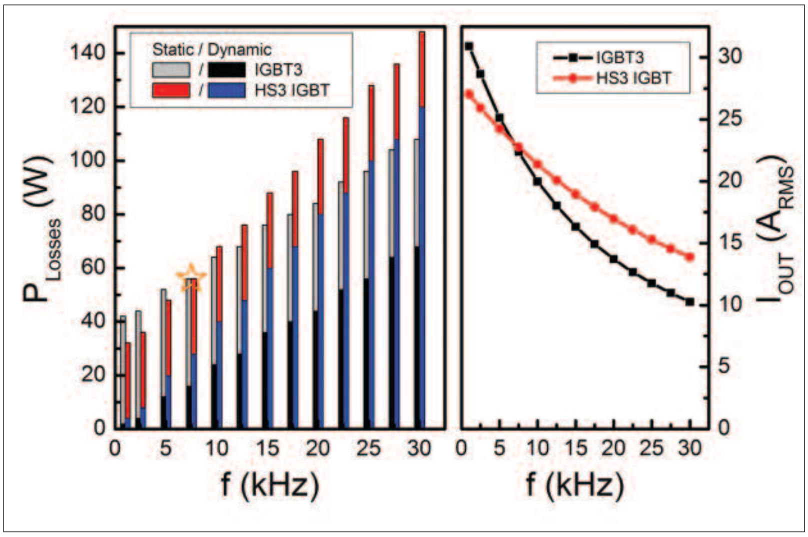

Figure 4: Simulated semiconductor power losses of HS3 IGBT and IGBT3 in an H-bridge inverter topology versus switching frequency (left). The simulated power losses are the power losses of the H-bridge inverter and not of a single chip. Maximum achievable output current versus switching frequency for HS3 IGBT and IGBT3 (right)

electromagnetic interference, which has to be considered in the application [4].

Simulated device performance

To analyze the device performance for different switching frequencies, the inverter performance was simulated using IPOSIM [5]. To ensure comparability, the dynamic losses of HS3 IGBT and IGBT3 shown in Figure 1 are considered. In the simulation, the output current of a single-phase H-bridge with an output power of 4 kVA was calculated under the following operating conditions: The output current IOUT was set to 17.4 A RMS and a power factor of 1.0. The modulation index was 0.8 and the DC-link voltage was 400 V. For both devices, an identical thermal situation with a fixed heat-sink temperature of 80°C was used.

Figure 4 shows the simulated semiconductor power losses P_{Losses} in an H-bridge inverter under the operating conditions mentioned above. The analysis of the H-bridge inverter shows that the static losses of the IGBT3 are only about 70 % of the static losses of the HS3 IGBT. With increasing switching frequency f the dynamic losses become dominant. For f = 7.5 kHz, the overall losses of the HS3 IGBT are equal to the overall losses of the IGBT3 as highlighted in Figure 4. A further increase of the switching frequency amplifies this effect and it can be clearly seen that the advantage of the HS3 IGBT comes to the fore at higher switching frequency. On the right-hand side, the maximum achievable output current is displayed. For the calculation, the above mentioned operation conditions were used, whereas I_{OUT} was not fixed but limited by the maximum junction temperature of the devices.

With increasing frequency I_{OUT} decreases. At low switching frequencies, the IGBT3 provides higher maximum output current than the HS3 IGBT. For $f \geq 7.5$ kHz, the output current of the HS3 IGBT is higher than the output current of the IGBT3. The difference between I_{OUT} of HS3 IGBT and IGBT3 increases at higher switching frequencies.

Conclusion

In this article, a comparison of HS3 IGBT, IGBT3 and IGBT4 is presented. It is shown that the HS3 IGBT outperforms IGBT3 and IGBT4 in high-frequency applications by providing up to a factor of 2 lower switching losses. To take advantage of the superior switching performance of the HS3 IGBT, an application-optimized operation mode is needed. Therefore, the operating current and the gate resistor have to be considered carefully. For the latter, one possible way is to use a more sophisticated gate-driver design.

The HS3 IGBT is a cost optimized highly efficient switch for high-frequency hard-switching applications like solar inverters or UPS. The results of the simulation support these findings and show that the HS3 IGBT should be considered as state-of-the-art switch for applications which are operated with switching frequencies exceeding 7.5 kHz.

Literature

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