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Power semiconductor and packaging trends in vehicle electrification

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Abstract

Since road traffic currently contributes 23% to CO₂ emission, the European Union forces car makers to reduce the average CO₂ emission of their fleet to 95g CO₂/km by 2021. This can only be achieved by electrification of vehicles. It is obvious that the market requires electrified vehicles to be comparable to combustion engine cars in price, driving range, maintenance effort, lifetime and safety.

The main inverter, also called HPCU (hybrid control unit), with the power module as its core component plays a key role because it is a major lever for CO₂ reduction. The strict rules of the EC requires future power modules with highest power density, high voltage and high current rating, high temperature capability and cooling, sufficient lifetime, low weight and small size.

The article describes how Infineon will meet the requirements of power modules for the coming years. On the power semiconductor technology side, a new IGBT generation will be introduced as well as a very thin IGBT technology. On the packaging side, two new packages will be introduced: a very compact low-cost generator module, and a high power motor module with significant improvements in power density and size, cost, stray inductance and efficiency. It will also be discussed how to further increase the robustness of such packages to allow operation at even higher operating temperatures. An insight into wide bandgap power semiconductor switches will also be given. The new technologies will reduce V_{ce} and switching losses at the same time and thereby increase inverter efficiency and power density.

Keywords: (Hybrid) Electric vehicle, IGBT module, HybridPACK, power density, SiC, GaN

1 Introduction

A white paper of the European Commission defines its vision of a sustainable, environmentally-friendly roadmap for the economy until 2050 [1]. A central lever for the measures is the reduction of CO₂ emissions because it contributes to global warming. Road traffic currently produces around 23% (14% passenger and 9% freight traffic) of all CO₂ emissions in the European Union [2].

In 2010, the CO₂ fleet emissions were recorded for the first time by the European Environmental Agency and determined to 141g CO₂/km. The CO₂ limits for passenger cars started to gradually come into effect on January 1, 2012. By 2015, the average CO₂ emission levels for the new passenger car fleet in Europe must be reduced to 130g CO₂/km. 95g CO₂/km must be achieved by 2020 for 95% of the car manufacturer's fleet and by 2012 for 100% of the fleet. The actual target values a car manufacturer has to keep is related to

the average weight of the fleet. If a manufacturer exceeds the mass specific limits, penalties are imposed due to the level of overrun. Large, heavy and highly motorized vehicles cause the highest pressure to take measures to reduce CO₂ emission.

There are a lot of measures car manufacturers can take to reduce CO₂ emission (see figure 1 CO₂ reduction measures). However, as a study of the IKA shows, the only way to achieve the emission goals is to electrify the vehicle fleet. Other measures such as downsizing, aerodynamic optimization or gearbox optimization are comparably cheap but will reduce the emission level only by very few percent [2].

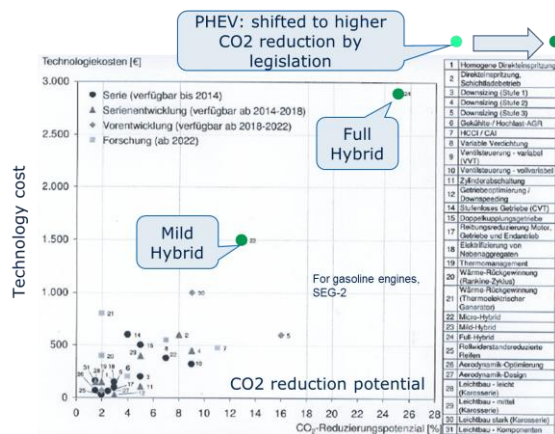


Figure 1: CO₂ reduction potentials of passenger cars [2].

The car manufacturers need a portfolio of mild hybrids, full hybrids, plug-in hybrids and electric vehicles. Up to today, only mild hybrids can be produced with costs still comparable to cars with combustion engine. Unlike a full hybrid system, a mild hybrid system cannot propel a vehicle on electric power alone. The electric motor is used to start the combustion engine (start stop function), to offer a boost function during acceleration or to enable for regenerative braking to recuperate energy. Such a system offers a highly cost-effective way to increase fuel efficiency. Some models show 15 to 20% better fuel economy with a cost adder of only a couple hundred dollars more than similar conventional models

Electrified vehicles have a total new architecture with new power electronic systems. The presence of a high voltage battery will allow driving current applications (i.e. air conditioning compressor or water/oil pump) with higher voltage in order to reduce costs and increase

effectiveness. Figure 2 shows a standard (H)EV architecture [3].

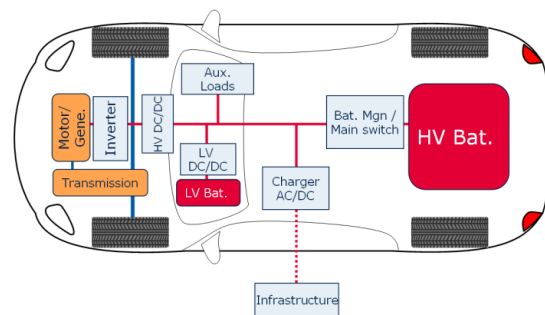


Figure 2: An EV requires a new vehicle architecture [3].

The main inverter with the IGBT power module as the central component is the most expensive power electronics application in the car after the high-voltage battery and the electric motor. As part of the powertrain system it controls the energy flow between the energy storage and the electric motor. Its efficiency is important because it influences fuel economy and driving range. Failure of the main inverter may not only result in an immobilized vehicle, but a safety risk. During the operational lifetime of an electrified car, the power modules in the main inverter are exposed to harsh environmental conditions such as severe temperature cycles as well as to moisture or mechanical stress through vibration or shock. Consequently, reliability, highest power density, and low cost are top requirements to such IGBT modules. High voltage and high current rating, high temperature capability, low weight and small size are also important, pending on the detailed requirement capturing.

2 Levers to increase power density and efficiency

In order to make the best use of battery's available energy and at the same time to minimize costs, it is necessary to maximize the efficiency of the main inverter. Reduced power losses enable smaller inverter size and reduced cooling effort. The way to go is through both the front-end (power semiconductor) and back-end (power module) technology, which has to be optimized to the requirements. Most improvements in power modules can be traced back to an increase of power density by loss reduction, thermal improvements and integration (Figure 3)

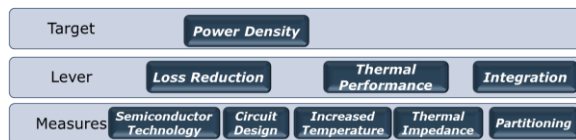


Figure 3: Levers to increase power density

3 Packaging trends

Power module manufacturers have developed dedicated products to meet automotive requirements, especially with respect to traceability, life cycle management, high quality customer service. One example is the HybridPACK power module family of Infineon for electrical power conversion in electrified vehicles.

Figure 4 shows the development of indirectly cooled IGBT power module for a power range up to 20–30kW and a maximum junction operation temperature of 150°C. The modules accommodate a 3-phase Six-Pack configuration of Trench-Field-Stop IGBT3 and matching emitter controlled diodes (for 200A and 400A nominal current, both with 650V maximum voltage).

Figure 5 shows the power modules for applications from a power range up to 100kW continuous power. Designed for a 150°C junction operation temperature, also these modules accommodate a 3-phase Six-Pack configuration of Trench-Field-Stop IGBT3 and matching emitter controlled diodes. Maximum chip ratings are 600A/650V and 800A/650V. The direct cooling concept with pin-fins significantly improves the thermal cycle capability and extends the lifetime of the power module.

Both IGBT modules are already in the field with high volume for many years. How can these modules be improved to meet future requirements of the car manufacturers?

3.1 Size and cost reduction

The strong need of OEMs to reduce cost and size of the main inverter has led Infineon to develop the HybridPACK™ Light (figure 4). It is a very compact six-pack module (705V/200A) targeting automotive inverter applications with power levels up to 20kW. The module is based on established solder and screw interconnections known from HybridPACK™ 1. The package design has been optimized for highest compactness and low stray inductance thereby allowing a reduction of power losses, especially at inverter maximum ratings. Furthermore, the blocking voltage of the IGBT was increased by

50V through an optimization of the termination edge of the chip. The system assembly concept is the same as for the other HybridPACKs. Automotive qualification will be completed in Q2/2015.

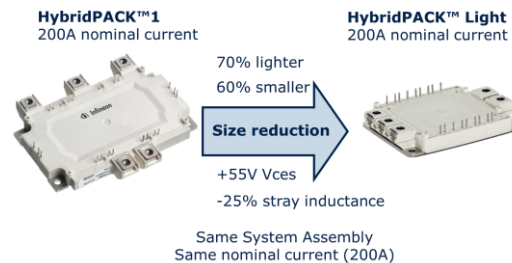


Figure 4: Power module size reduction at the same nominal current (200A) by compact design

3.2 Increase of power density

The need to further improve power density and efficiency, led to the development of the HybridPACK™ Drive. This is a more compact six-pack module (750V/660A) for the range of 50kW – 100kW. The direct cooling concept with pin-fins as well as the material stack have been carried over from HybridPACK 2.

Equipped with the new EDT2 technology, power losses will be reduced especially for applications with switching frequencies in the range of 10kHz. This allows a 10% higher rated current (660A) as compared to predecessor module. Furthermore, the blocking voltage is now 750V, 100V higher as in the HybridPACK2 with the previous IGBT technology.

While most power modules are equipped with screw-mounted power connections, the HybridPACK Drive has multi-function tabs that for faster installation. Such multi-purpose power terminals furthermore allow the inverter manufacturer to choose the preferred mounting method to the busbar. As screwing is still most common by today, welding is attractive for high volume manufacturing at low cost. For the connection of the signal pins it was decided to use the PressFit technology. By mechanically pressing the the gate driver board on the module's PressFit pins the electrical contact is achieved by a gas tight contact zone which is very robust against corrosive environments and mechanical stress such as vibration. Compared to a standard selective soldering process the PressFit mounting technology is 10 to 20 times faster. The interconnection technology furthermore allows a flexible signal pin configuration. Hence, features

like on-chip temperature or current sensing features can be integrated easily.

The new HybridPACK Drive package technology allows operation of the chips up to $T_{vj}=175^{\circ}\text{C}$ for 10 consecutive seconds. Consequently, the module can cover short-term power peaks which would otherwise require a larger module. An enhanced power cycling capability ensures that the higher temperature variations have no negative impact on the module's lifetime. By new solder techniques and material the module can survive 60.000 power cycles (so-called PCsec test with 100K temperature change). Due to this, utilizing the 660A HybridPACK Drive, an 800A HybridPACK2 can be matched.

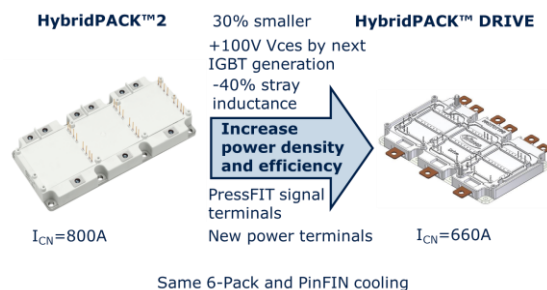


Figure 5: 10% increase of nominal current and 30% size reduction by new chip and package technology

3.3 Advances in reliability

Higher power density with shrunk chip sizes requires the IGBT and the power module working at higher temperatures. Such higher temperature swings reduce the lifetime of the power module because of the increased thermo-mechanical stress at interconnects (wire bonds, chip solder, system solder) Figure 6 shows the schematic cross section of a HybridPACK power module.

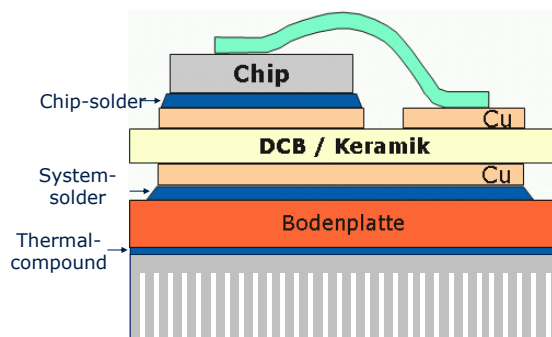


Figure 6: Schematic cross section of a HybridPACK power module

For chip solder and aluminium wire bond the PC (power cycling) lifetime in an IGBT module depends exponentially on the temperature swings (ΔT_j). Also maximum junction temperature T_{jmax} has an influence (figure 7). For this reason, there is a lot of research on alternative packaging technologies with improved PC and TC (thermal cycling) capability.

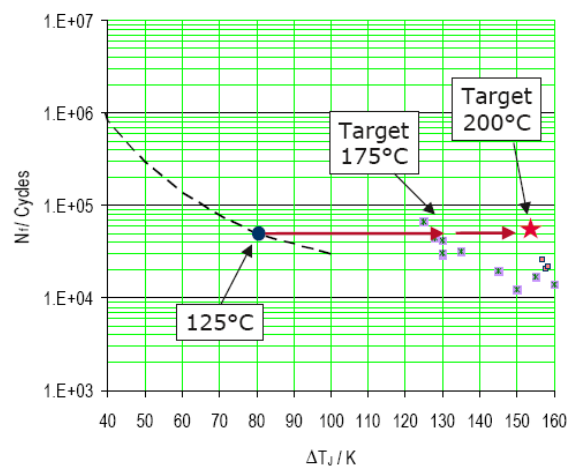


Figure 7: Reliability at higher junction temperatures

The HybridPACKs use soft solder process for the die attach and system interconnect (DCB to base plate). Infineon has improved the system solder process several years ago to prevent potential solder cracks from propagating by formation of Cu-Sn precipitations within a standard SnAg solder matrix [4].

These interconnect technologies are sufficient for today's requirements of the main inverter with T_{jmax} up to 150°C or even up to 175°C occasionally (few hours only over lifetime) with improved soft solder material and process. Several HybridPACK 1 modules were analysed optically and electrically after having driven 200.000km on public roads in a full hybrid passenger car with a 30kW e-motor. None of the typical failure modes (such as solder degradation, wire bond lift off) could be detected on these field-tested power modules after the quality analysis. Lifetime simulation of the modules revealed no significant active lifetime consumption. To confirm this, the modules were subjected to a standard power cycling test until end of life after the 200,000km test drive. As a result, the field stressed modules showed the same active lifetime as a new module from the factory. End of life failures were as expected wire bond lift off caused by chip solder degradation. The system solder did not show any degradation. The 95% Weibull criteria was passed (Figure 8). Very recently, a HybridPACK 1 was

investigated after having driven 300.000km on public roads in the same full hybrid car. Again, there were no signs of any significant degradation after optical inspection and after electrical correlation measurements. The results will be published soon.

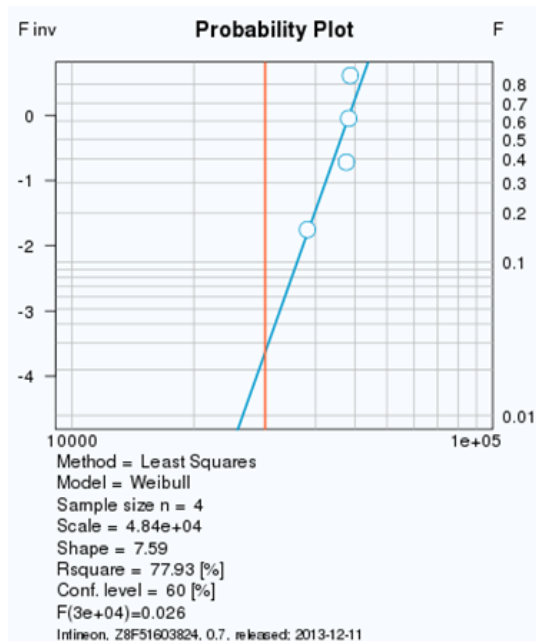


Figure 8: The 95% Weibull criteria of the standard power cycling test was still passed after the main inverter modules were 200.000km on the road.

In light of these positive results it has to be reconsidered, if future power modules with even smaller chips and operating temperatures beyond 150°C for longer times require new technologies. Two die attach technologies, sintered silver and diffusion soldering are today both qualified to meet significantly higher requirements. Compared with today's power cycling limit for $T_{jmax}=150^{\circ}\text{C}$, a 30-60 fold increase of the power cycling capability even for an increased T_{jmax} could be achieved [5]. Sintered silver system joints significantly improve the passive thermal stress resistance.

New wire bonding materials like pure copper, aluminum clad copper have shown to increase operational lifetime as well. However one must as well consider the fact that the external body or package consisting of polymeric substances is temperature hindered. As a result frame wire bonds must be replaced by alternative connection technologies like ultrasonic welded terminals to withstand higher operating temperatures as well. The main limitation of the process involved for higher operating temperature is the optimization

of process repeatability and reproducibility. Both sintering and wire bonding processes using new materials are still in technological development phase [5].

The engineering and technological solutions presented in this section would eventually lead to enhanced lifetime of the IGBT module. However the reference operating lifetime of a failed electrical inverter still remains open. There is a growing demand for higher power and thermal cycling of IGBT module, however it would incur additional process and material costs which would eventually lead to a higher cost of the end product. One of the basic needs at this moment is to perform harsh stress tests to identify the eventual failure conditions for the inverter in EV/HEV. This would facilitate proper technological and engineering selection process [6].

4 Power semiconductor trends

The IGBT's contribution to losses in the main inverter is dominating. Improving electrical behaviour in terms of conducting and switching of IGBT's will thus have a major impact to the power losses.

At Infineon we explore two ways to reduce power losses (figure 9):

- (a) by reducing the chip thickness: power losses of the IGBT are roughly quadratically proportional to the wafer thickness.
 - (b) by introducing a new cell structure which is optimized to achieve a significant reduction of conduction losses (V_{CEsat})
- (a) is realized in the 400V version of the Trenchstop (IGBT3) generation [7]. (a) and (b) are realized in the EDT2 IGBT [8].

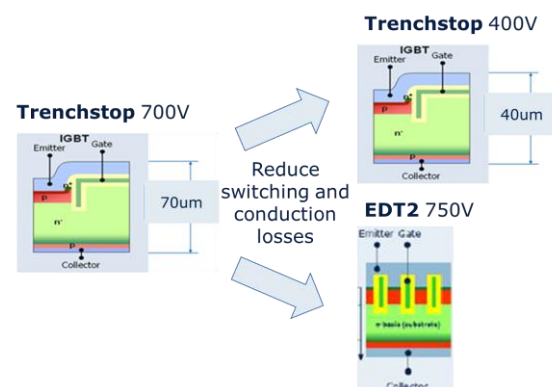


Figure 9: Reduce power losses by improved IGBT concept and process technology

Automotive applications require sufficient short circuit strength. However, reduced conduction

losses cause in most IGBT technologies a reduced short circuit withstand time. For this reason, a compromise between conduction losses and short circuit capability has to be done such that the IGBT is optimized for the application.

4.1 Thin chips

Electric motors used in mild hybrid vehicles have a limited power rating (less than 20kW). For this reason, the required voltage from the battery can be reduced as compared to full hybrid or electric vehicles in order to reduce costs of the different components (battery, switches, capacitors...). Mostly, mild hybrid vehicles are designed with battery voltages up to 200V while only full hybrids or electric vehicles work up to 450V battery voltage (or even higher with a booster). A new IGBT technology with a blocking voltage capability of 400V was developed in order to further increase the improvements of hybrid vehicles in terms of fuel efficiency. Conduction and switching losses are significantly reduced by means of using an ultra-thin wafer technology (approximately 40 μ m thickness) having a direct impact on the overall efficiency. For today's 650V IGBT class, Infineon uses ~70 μ m ultra-thin wafers, which is approximately 30% less thickness than state-of-the-art. Reducing the voltage to 400V means a ~40 μ m ultra-thin wafer and therefore a significant technological challenge as many processes are done when the wafers are already thinned. A sophisticated wafer handling, including very special equipment for ultra-thin wafers in combination with a controlled wafer bow by an optimized backside metallization is essential.

A complete inverter prototype was designed and used to compare the performance of state-of-the-art 650V IGBTs and the new 400V technology. The results showed a significant decrease of the power losses using 400V IGBTs, which could be used to increase the efficiency (less fuel consumption), reduce cost (less chip area or cooling efforts) or/and increase the power density of the system (under same conditions, higher output power possible). Figure 10 shows that, compared to the state-of-the-art 650V IGBT3, V_{cesat} of the 400V IGBT is reduced by 200mV at nominal current. It could be furthermore shown with a demonstrator 2-phase inverter that the inverter efficiency could be increased by 1.4% [7]

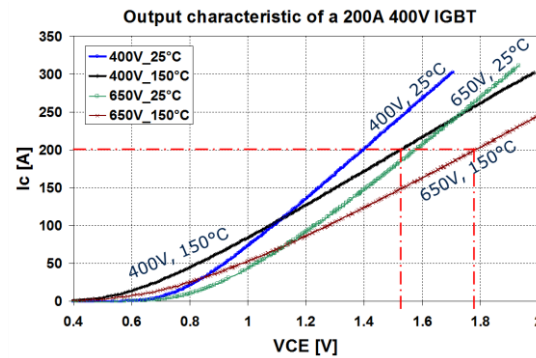


Figure 10: V_{cesat} reduced by about 200mV in comparison to standard 650V IGBT

4.2 EDT2

EDT2 is advancing Trench gate and Field Stop structures to a new level. Thanks to a new cell structure the gate charge (Q_g) is reduced and current density is increased. In order to minimize total power losses, the chip thickness is reduced and 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 (tail current). These two measures allow for a significant reduction in conduction losses (V_{cesat}) and turn-off switching losses (E_{off}). Figure 11 shows a comparison of the collector current of IGBT3 (Trenchstop) and EDT2 with a similar size of the active area. The current density can be significantly increased.

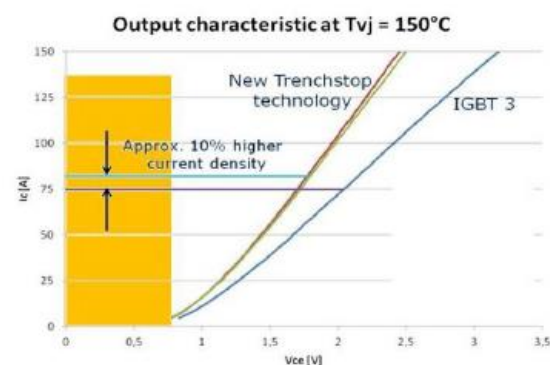


Figure 11: V_{ce} and I_c comparison of IGBT3 and new Trenchstop technology (EDT2)

In addition, break down voltage has been increased to 750 V blocking capability, 100 V higher than the previous IGBT3 generation

4.3 Integration

One option to cover the increasing demand for higher power density of the (H)EV main inverter systems is higher integration of functionality in the power semiconductor, such as on-chip temperature and current sensing. Infineon so far sees a trend towards IGBTs with on-chip sensors only for a minority of OEMs. Depending on the detailed requirements of the application, there are certain limitations to be considered for over-current and over-temperature protection.

4.3.1 Temperature sensing

HybridPACK modules up to now all use several NTC resistors on the ceramic substrate for temperature sensing. The drawback is that such temperature sensors are relatively far away from the power semiconductor chips (figure 12). To set the over-temperature protection trip point accurately, the designer needs to know the worst case losses at all operation modes, device to device fluctuations, and the thermal impedance between the NTC resistor and the power semiconductor's pn junction. In addition to this, thermal impedance fluctuations from module to module, e.g. because of mounting conditions, thermal grease application, have to be taken into account. After all worst case variations are considered when setting the protection trip point, the protection will work effectively. However, in case the typical losses and effective thermal impedance are significantly lower than the worst case, then the device may be under-utilized in maximum operation conditions.

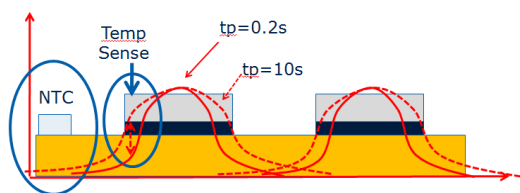


Figure 12: Temperature distribution across IGBT and ceramic substrate

The car manufacturer may decide to use a thermal software model to calculate the IGBT's junction temperature T_{vj} during operation by monitoring the operation conditions such as V , I , switching frequency, cooling water temperature etc. and de-rate the current if the T_{vj} exceeds a certain limit. A second protection level for abnormal over temperature condition (which triggers a shut-down) is set just below the datasheet limit of T_{vj} . For this situation the NTC temperature is read and T_{vj} is calculated [9].

An alternative method for temperature measurement is to have the sensor integrated on the chip. Such an on-chip temperature sensor can be realized by an additional poly diode integrated either in the active cell area or outside the active area at the edge of the chip (e.g. near the bond pad of the gate). The temperature dependency of its forward voltage drop V_F at a given measuring current I_{meas} is used to determine the temperature.

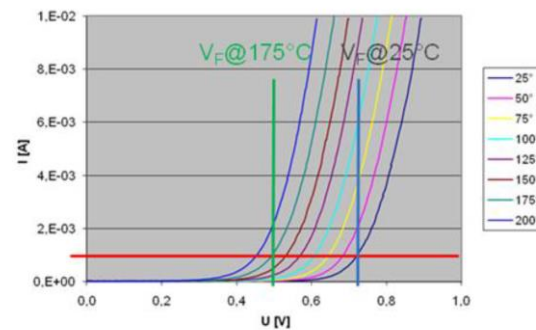


Figure 13: Forward characteristic of a temperature diode.

For our 200A IGBTs, approximately 15% of the active chip area is used to form a temperature diode with three additional lithographic layers, thereby adding complexity and cost to the chip production. Moreover, if the central active area of the chip is not accessible by wire bonding (e.g. if the top side of the chip is soldered to a metal spacer, ribbon bonds or a power lead), a diode in the covered central area requires to sacrifice another small part of the active region for routing the temperature signal to bond pads outside the active area.

The advantage of on-chip temperature sensing is that the comparably fast response of the poly diode enables a higher level of protection. Hence, effective protection in case of transient events in normal operation (e.g. acceleration), in hill-hold condition or in case of specific malfunctions such as sudden loss of coolant seems to be possible. However, an on-chip temperature sensor is not fast enough to protect the chip from short circuits or overvoltage events. In such events the IGBT temperature rises significantly within only a few milliseconds.

The IGBT process practically allows only poly silicon to be used for the sensor. For such integrated diodes however, the overall system accuracy including current source, ADC jitter, and typical forward voltage variations is typically $\pm 15K$ without calibration of each single diode.

If the on-chip poly diode should be placed at the edge of the IGBT or rather in the central area in the active region depends on the specific application conditions and preferences of the OEM. A position of the sensor near the chip edge (especially in the corner) allows early detection of any chip solder degradation (such as solder cracks) caused by thermos-mechanical stress. Such solder cracks start at the chip edges where the stress is highest. Such a partial interruption of the thermal path to the DCB can be detected earlier if the on-chip sensor is located above the degraded chip solder area.

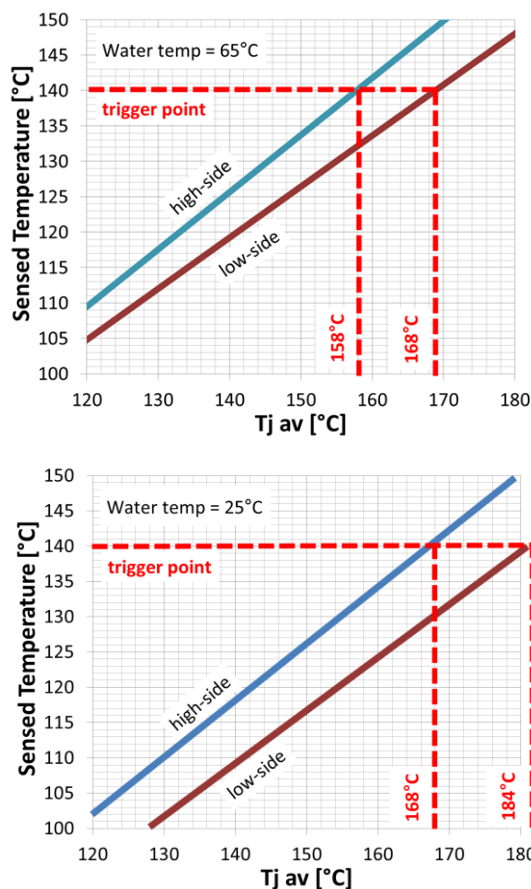


Figure 14: Insufficient over-temperature protection in case of low cooling water temperature

The drawback on the other hand is that the temperature gradient is very high in the chip corner, depending on the duration of the transient event (figure 12). This can make over-temperature protection difficult. We have shown that for a hybrid vehicle application under hill hold conditions an over-temperature protection is difficult under low cooling water conditions (figure 14). This is because a high uncertainty of the measured temperature has been taken into account, caused by the poly silicon process

variations (as explained above) and by the high temperature transient at the chip corner. Table 1 shows an example how much T_{vj} minus T_{sense} depends on the cooling water temperature for an IGBT sandwiched between a DCB at the bottom side and a metal spacer on the top side. In contrast to this, if the on-chip temperature sensor is placed roughly in the center of the active area, $T_{vj} - T_{sense}$ is much lower, making over temperature protection at different cooling water temperatures easier (table 2). It should be noted that the I_c and T_{vj} values in table 1 and 2 cannot be compared because they are for IGBTs of different voltage class, however, it still provides a good insight on the impact of the location of the on-chip temperature sensor.

Table 1: Difference of T_{vj} and T_{sense} for the temperature sensor placed at the chip corner (700V IGBT, simulated values)

I_c [Arms]	T_{water} [°C]	T_{vj} [°C]	T_{sense} [°C]	$T_{vj}-T_{sense}$ [°C]
400	65	140	121	19
507	30	140	112	28
583	0	139	104	35
simulated values, water cooling				

Table 2: Difference of T_{vj} and T_{sense} for the temperature sensor placed in the center (1200V IGBT, measured values)

I_c [Arms]	T_{water} [°C]	T_{vj} [°C]	T_{sense} [°C]	$T_{vj}-T_{sense}$ [°C]
120	25	83.6	90.8	7.2
140	25	101.4	109.0	7.6
160	25	123.2	131.0	7.8
180	25	152.8	160.0	7.2
10LPM, 50% water, 50% ethylen glycol				

The commercial success of on-chip temperature sensing will depend on how an added value on inverter level can be created which compensates for the added system complexity and cost.

4.3.2 Load current sensing

An on-chip current sensor can be realized by current mirroring (figure 15) [10]. A defined small fraction of the IGBT cells (T_S) is separated from the power emitter metallization. The major parts of the IGBT cells (T_L) carry the load current I_L . A sense resistor R_S is placed at the emitter side of the sense IGBT cells to measure the voltage drop caused by the sense current I_S .

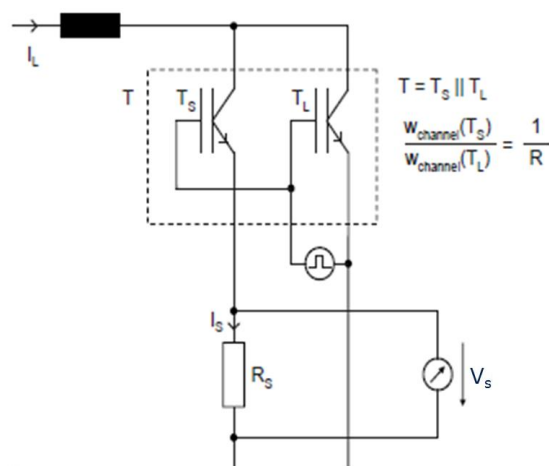


Figure 15: Current-Sense-IGBT device (inside dashed line) with low ohmic sense resistor R_S

On-chip current sensing can be used for over-current protection instead or in addition to desaturation detection. The definition of over-current condition depends on the application conditions and is set by the OEM. The temperature dependency of V_S has to be considered carefully. Figure 16 shows the temperature dependency of V_S measured at Infineon's 200A Trenchstop IGBT for $R_S=3.9\Omega$.

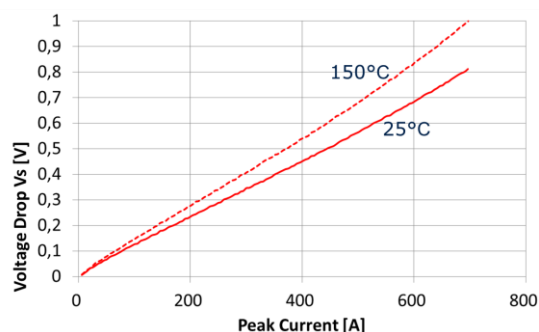


Figure 16: temperature dependency of V_S measured at Infineon's 200A Trenchstop IGBT for $R_S=3.9\Omega$

Similar to on-chip temperature sensing, the signal processing and galvanic isolation of the current sense signals increases the routing efforts on both, PCB and DCB. Especially an increase of the DCB size and thereby the module size due to the routing of the signal lines makes the power module significantly more expensive.

In contrast to on-chip temperature sensing the integrated current sense consumes only a very small amount of active cell area on a single IGBT and may thus be considered as additional protection feature if the functional safety

consideration shows an improvement of the system safety if a reasonable number of IGBT chips with current sense feature e.g. one per switch is seen as sufficient.

4.4 Wide bandgap semiconductors

Since the 1950s wide bandgap semiconductors have been forecasted to be the next step as soon as Si reaches its limits [11]. The advantages for power devices are obvious: Low conduction and switching losses, high temperature operation, low thermal resistance and high breakdown field (table 3). However, it took almost half a century until the first power device, a SiC Schottky diode, became commercially available in 2001. Since then, SiC switches entered the industrial market as well [12], and GaN emerged as another alternative wide bandgap material for power devices. How can SiC and GaN help reduce losses and thereby improve the efficiency of electrified vehicles.

Table 3: Properties of power semiconductor materials

Parameter	Si	GaAs	SiC
Bandgap (eV)	1.1	3.39	3.26
Saturation velocity (10^7 cm/s)	1.0	2.7	2
Thermal conductivity (W/cmK)	1.3	2.0	4.9
Breakdown field (MV/cm)	0.3	3.3	2
Relative dielectric constant	11.8	9	10
Electron mobility (cm^2/Vs)	1350	2000	900

4.4.1 SiC

SiC based power semiconductor devices are state of the art in high efficiency and high frequency applications. While cost for such devices have decreased significantly over the last year, SiC cost per area will stay by factors higher than Si cost per area due to wafer size, defect density and process complexity. In its 2014 market research report IHS states that SiC prices will fall less fast as expected in 2013 [13]. This price disadvantage has to be overcome by either a significant reduction of area for a given application, system cost savings for instance reduction of cooling effort or sellable customer value like fuel economy.

Figure 17 shows that in an application using SiC with equal thermal performance (reduced semiconductor area for SiC) especially the switching losses are reduced [6]. This improvement is linked to an increase of switching speed and the related challenges. An alternative approach for introduction of SiC is to utilize high temperature capability of the material. A limiting factor for this approach is the absence of a capable packaging technology. In addition, the oxide quality of the MOSFET structure has to be

improved to meet lifetime requirements in an automotive environment.

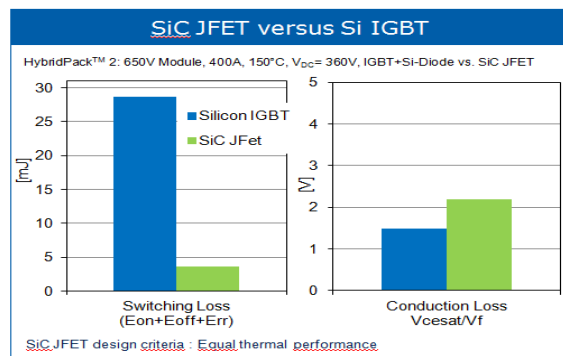


Figure 17: Comparison of power losses, SiC vs Si

4.4.2 GaN

The demand for improved efficiency at no additional cost has put GaN-devices on silicon into focus. In general, material properties are indicating an on state loss reduction for the same die size of a factor of more than five versus super junction MOSFETs. At nominal current a factor of more than 3 still seems feasible in comparison to IGBT technologies. In addition, very low switching losses could be demonstrated. The challenges which arise from the natural device structure being a normally on HEMT (High Electron Mobility Transistor) can be managed by a cascode circuit design. The excellent technical performance along with the cost benefit potential assigned to GaN on Si has steered a lot of interest towards development of future power semiconductor devices up to 600V in GaN.

While the possibility to grow AlGaN/GaN-devices on silicon wafers is key to commercial success, it is at the same time root cause for the challenges. To avoid reaction between Gallium and Silicon a nucleation layer (typically AlN) is needed. Additional buffer layers below the GaN device layers are required to manage stress compensation and wafer bow due to the material mismatch in CTE (coefficient of thermal expansion). During the epitaxial growth of the GaN layers a 5 magnitudes higher defect density is generated than typical of SiC due to the material mismatch in the lattice constant (dislocation defect density [cm⁻²]: SiC 10³-10⁴ vs. GaN on Si 10⁸-10⁹). Significant research is spent these days to reduce the defect density, but it has to be assumed that GaN on Si will not be free of defects for decades to come. For the application of GaN on Si this leads to the point, that the effect of those defects on the devices needs to be properly evaluated. A known result of defects in

a HEMT is a dynamic R_{dson} increase for a short period of time after turn on. Another impact of the defect density is the achievable yield especially for the bigger dies needed for high current applications. The resulting yield impact could be limited by reducing the individual die size. Finally, new screening concepts are necessary to prevent shipping of defect dies. For such screened devices it has to be ensured that undetected defects do not influence quality and lifetime. The characteristic and limitations of GaN today suggest that there is still significant work to be done until it is ready for automotive applications. To balance risks and chances of GaN choosing the right application within the automotive context is recommended (e.g. low power – small devices; high frequency – switching performance; low voltage – growth of bulk material; non safety critical – technology maturity) [6].

Ga₂O₃ is another promising new semiconductor material for high-breakdown and low-loss power Mosfet devices. Its excellent material properties, such as wide bandgap, can reduce the cost and energy consumption of power conversion. Ga₂O₃ power devices can be fabricated on native melt-grown single-crystal substrates, leading to a great advantage of Ga₂O₃ over other widegap semiconductors such as SiC, GaN for low-cost mass production. The Ga₂O₃ MOSFETs have a structure and characteristics applicable for actual use as is. A Japanese consortia headed by the National Institute of Information and Communications Technology has first demonstrated such a device in 2013 [14].

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