Optimizing Power Modules by Enhancing Power Density, Ease of Implementation and Supporting Automotive Reliability Requirements

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Abstract

Increasing power density, enabling compact systems and a high vehicle range are key success factors for power semiconductor solutions within electric vehicles. At the same time, it is necessary to fulfill their lifetime requirements and ensure the respective level of reliability and safety across high production volumes. With the second generation of the HybridPACK^{TM} Drive Infineon Technology AG has developed an automotive power module meeting all these targets. Performances up to 300 kW are possible within the HybridPACK^{TM} Drive footprint thanks to an increased operating temperature in combination with the latest generations of SiC MOSFETs and Si IGBTs. To ensure vehicle lifetime despite the resulting increased temperature stress within the modules, its power cycling robustness was improved accordingly. In this paper, the benefits of new functionalities, like the integration option for a next-generation phase current sensor, on-chip temperature sensors for IGBT products and single chip temperature diodes for SiC products, are presented. Furthermore, new materials (frame, isolation gel) and interconnection technologies and their impact on reliability are introduced.
In detail we'll demonstrate:

- Infineon has elaborated a solution that allows significant Power Cycling improvements with Aluminium based bond wires of more than 100 k Cycles @dT =100 K at T_{vj}=175°C (PC_{sec})
- The introduction of new materials allows operation at higher temperature up to 200°C without sacrificing reliability
- Press-fit pin are qualified in an automotive power module according to IPC-9797 for the first time
- The reliable implementation of an integrated hall based current sensor together with our partner Swoboda into the power module’s frame

1 Introduction to HybridPACK^{TM} Drive Generation 1 + 2

1.1 HybridPACK^{TM} Drive Generation 1

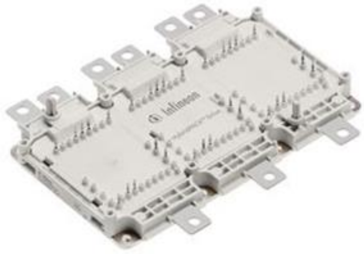


Figure 1 HybridPACK^{TM} Drive Generation 1

HybridPACK™ Drive (Figure 1) is a very compact power module optimized for hybrid and electric vehicles traction applications offering a scalable power range of 100 kW to 200 kW within the 750 V and 1200 V class.

	SiC-MOSFET	Si-IGBT
750 V		FS660R08A6P2FB FS770R08A6P2x FS820R08A6P2x FS950R08A8P2x
1200 V	FS03MR12A6MA1x FS05MR12A6MA1x	FS380R12A8P1x

The first version of HybridPACK™ Drive Generation 1 was introduced in 2017, using Infineon’s silicon EDT2 technology, specifically optimized to deliver the best efficiency on a real-world driving cycle [1]. It was followed by several additional product versions enabling scalable inverter platforms. In 2021, Infineon introduced the first trench based SiC-MOSFET technology dedicated for Automotive, called Automotive CoolSiC™, and complemented the HybridPACK^{TM} Drive portfolio with it [2]. Compared to planar structures, the trench enables a higher cell density, resulting in the best-in-class figure of merit. Therefore, trench MOSFETs can be operated at lower gate-oxide field strengths, resulting in increased reliability.

1.2 HybridPACK^{TM} Drive Generation 2

Based on the success of the HybridPACK^{TM} Drive's first generation, the second generation is introduced now (**Figure 2**). It significantly increases the power density and further enhances the degree of integration. This portfolio extension allows now addressing the complete range of power required in tomorrow's electric drivetrains with one footprint.

Figure 2 HybridPACK^{TM} Drive Generation 2 (G2)

This is reached by extensive "three-dimensional (3D) scaling" relying on Infineon's broad set of field-proven process technologies:

- Package Scaling (first dimension): already at the introduction of the family, two different assembly technologies allow performance scaling of a given chipset. In the "Standard" version, the package comes with a thermal stack implementing Al_2O_3 substrate, complemented with Al bond wires for chips' top-side assembly (e.g. FS1000R08A7P1x, FS410R12A8P1x). The "Enhanced" version offers an improved thermal stack performance with Si_3N_4 substrate, the chips' top-side assembly is realized by Al bond wires and bondfoot sealing (e.g. FS1150R08A8P1x, FS01MR12A8MA2B, FS02MR12A8MA2B, FS03MR12A8MA2B, FS01MR08MA2x).
- Chip technology scaling SiC / Si (second dimension): The available package process technologies of the HybridPACK^{TM} Drive Gen2 enable the usage of SiC MOS chips and Si IGBT within the same package footprint, each time optimizing the assembly by respecting the specifics of each chip technology. For the SiC versions, the second generation of trench based CoolSiC^{TM} MOSFETs is implemented. The Si versions are realized with the second and the third generations of the well-known EDT technology [3], all implementing fast-reacting on-chip temperature sensors. All used technologies are specifically developed for the use in automotive inverter systems.
- Voltage scaling (third dimension): for both chip technologies, versions are available for both system voltage classes 470V and 850V. To support the trend of batteries with raised nominal voltage and resulting higher end-of-charge voltage at 850V systems, the packages creepage distance was increased to 10.6mm. Sufficient headroom for switching operation is reached by implementing chip breakdown voltages of at least 1200V for the 850V class, and 750V for the 470V class.

	SiC-MOSFET	**Si-IGBT**
750 V	FS01MR08A8MA2x	FS1000R08A7P3x FS1150R08A8P3x
1200 V	FS01MR12A8MA2x FS02MR12A8MA2x FS03MR12A8MA2x	FS410R12A8P1x FS520R12A8P1x

The combination of the latest generation CoolSiC^{TM} chip technology with the "Enhanced" package allows an overall power density increase by 50% up to 300 kW. Thereof 30% result of the new chip technology and 20 % originate from the "Enhanced" package as shown in chapter 3.

Further versions will be introduced soon, following the 3D logic and further upgrading it.

All the products can be evaluated by using the corresponding HybridPACK^{TM} Drive Gen2 Evaluation kits (**Figure 3**).

Figure 3 HybridPACK^{TM} Drive G2 Evaluation kit

2 Integrated current sensor

Nowadays core based hall-effect integrated circuits are the standard current sensor solution for automotive power modules based on the HybridPACK^{TM} Drive footprint **(Figure 4** right).

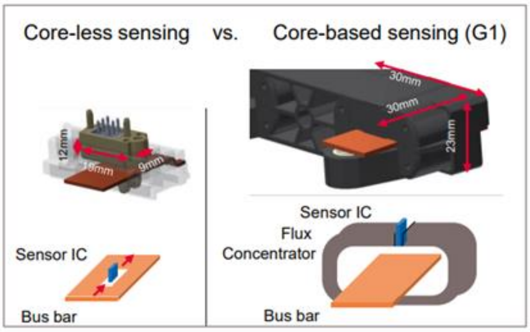


Figure 4 Core-less sensing of the HybridPACK^{TM} Drive G2 versus the Core-based sensing of G1

Due to the trend of higher volumetric and gravimetric power density and cost pressure in automotive (inverter) applications and to enable for example X-in 1 electric drivetrains, were inverter, DC-DC, power distribution unit, on-board charger, battery management system; electric motor and reducer are combined in one-part, Infineon

Technologies AG together with its partner Swoboda [4] developed a solution where the sensors can be directly pressed into the frame. This solution works without a bulky and heavy external core and the sensor is positioned in a slot of the bus bar of the module (figure 4, left).

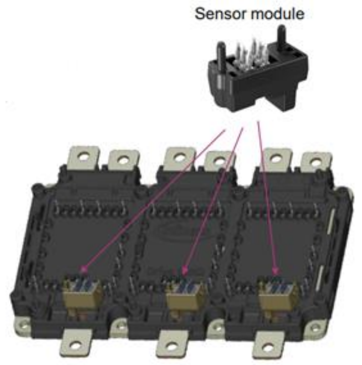


Figure 5 Three Swoboda current sensors in the corresponding slots

The current sensors can first be placed into the three slots (**Figure 5**) and then pressed into the PCB with the other pins. The sensors will self-align due to a poke-joke. A second option is to first press in the sensors into the PCB and to afterwards mount the hole PCB with current sensors to the power module.

The sensor with the two hall-cells are mounted in the slot of the busbar, so that the flux surrounding the busbar can be sensed.

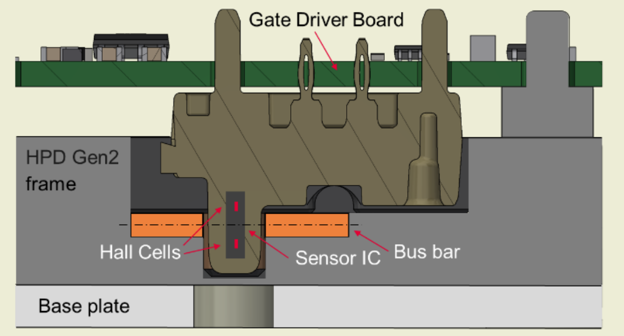


Figure 6 Core-less sensing of the HybridPACK™ Drive G2 versus the Core-based sensing of G1

All current carrying conductors generate a magnetic field around them. Therefore, by measuring this flux density, the current flowing can be measured. The Infineon XENSIV™ TLE4973 current sensor embedded in the module consists of two hall cells separated by a gap of approximately 2.3 mm, as shown above (**Figure 6**). The difference between the flux densities measured by the two sensitive elements (**Figure 7**) is filtered and amplified. Subsequently, an analog output voltage that is proportional to the measured flux density is given out. As this flux density is proportional to the current flowing, the chip measures the current flowing in the bus bar. This system by design inherently offers the following advantages over traditional core based single ended sensors [4]:

- Immunity to uniform stray magnetic flux densities because of the differential measurement principle.
- High linearity and negligible hysteresis due to the absence of a ferromagnetic core.
- Very fast over current detection (1.3µs) due to the coreless sensing principle and separate over current signal and output path.
- High linearity and low phase error over frequency (**Figure 8**)
- The sensor module can be programmed for current classes from 300A to 950A. One sensor module fits all HybridPACK™ Drive G2 derivates. No separate modules required

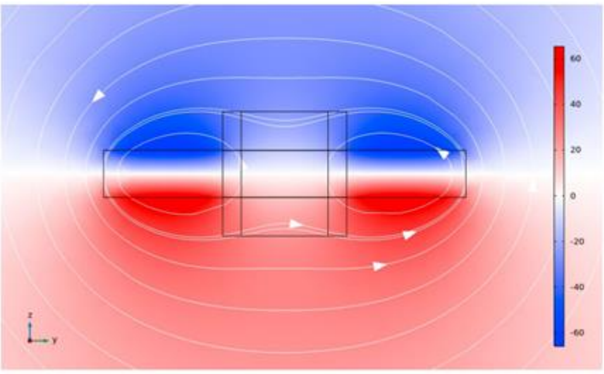


Figure 7 Flux lines based on finite element analysis [4]

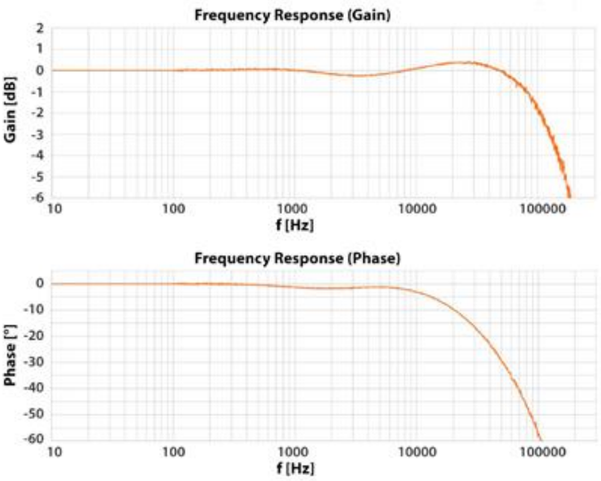


Figure 8 Frequency response, Gain vs. Phase error [4]

To guarantee the quality of the combination of power module and current sensor the following qualification tests of the AQG 324 [5] and beyond were conducted and passed:

- High Voltage- High-humidity, high-temperature reverse bias test (HV-H^{3}TRB)
- High temperature reverse bias test (HTRB)
- Thermal shock test (TST)
- HV Leakage Test
- HV MMCI Test
- Vibration Test
- Vibration Test Extended

A special focus for the investigation is placed on the vibration test, due to the importance in automotive applications. The vibration profiles B [5] for transmission mounted parts were applied on the shacker (**Figure 9**).

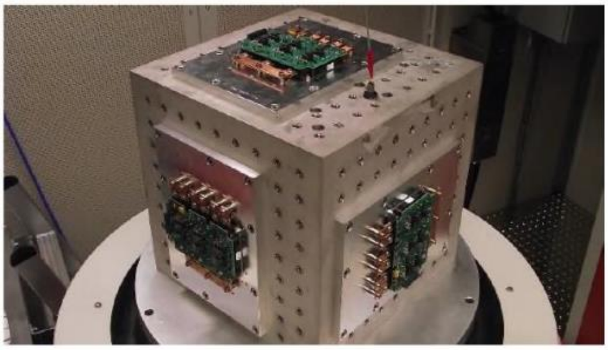


Figure 9 Test setup overview

The profiles are applied for each spatial axis. A detailed view on the shaker with the assembled module with current sensor, heat staking domes and screwed busbars can be observed for the y-Axis in **figure 10**.

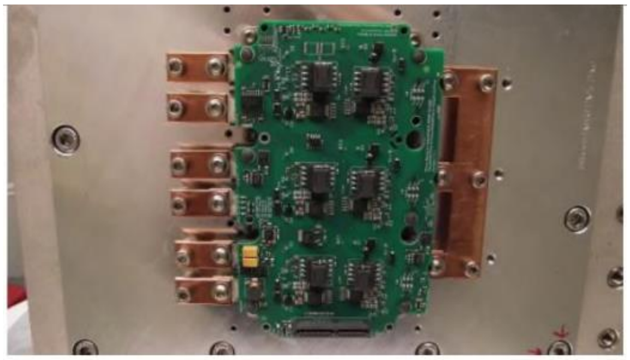


Figure 10 Test setup: HybridPACK^{TM} Drive G2 Module assembled on shaker with PCB, current sensor, heat staking and busbar

The sinusoidal and random noise vibration profiles in table 3 were applied to three modules from three different production lots for 22 h for each spatial axis.

Vibration excitation	**Sinusoidal**	
Test duration for each spatial axis	22 h	
Vibration profile	Frequency in Hz	Amplitude of the acceleration in m/s²
	100	30
	200	60
	440	60
Vibration excitation	**Wide-band random vibration**	
Test duration for each spatial axis	22 h	
RMS value of acceleration	96.6 m/s²	
Vibration profile	Frequency in Hz	Power density spectrum (m/s²)²/Hz
	10	10
	100	10
	300	0.51
	500	5
	2000	5

Furthermore, also an extended vibration test was carried out. Therefore, one frequency sweep was executed in x, y and z direction. For the sweep frequencies between 5 Hz to 440 Hz 20g were applied between 440 Hz to 2 kHz 10g were applied.

During the sweep a test current of 100 A was applied (**Figure 11**) and the sensor values were permanently read out with a 20 kHz sampling rate. A laser vibrometer was used for checking the acceleration in all directions. The sensor output signal was checked for a modulation of the vibration.

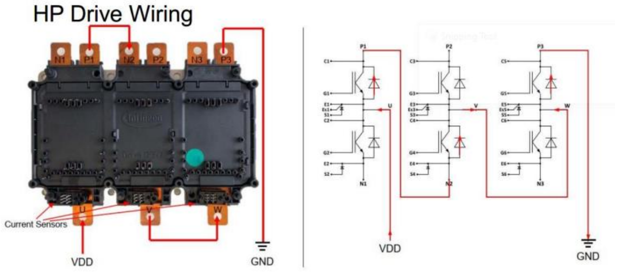


Figure 11 Wiring for application of test current

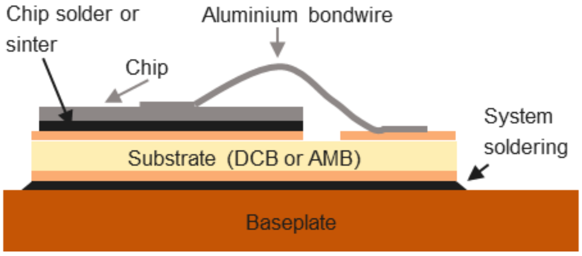
As a result, there was no vibration of the sensor module detected and also no interference on the sensor output signal detected.

3 Power cycling

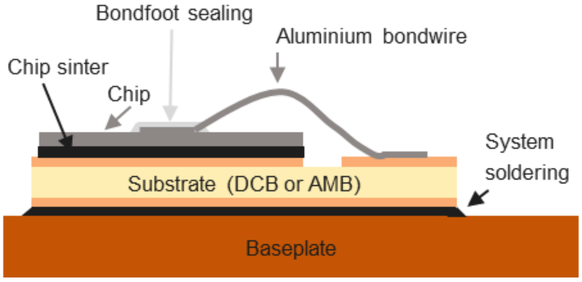
A major improvement between the HybridPACK^{TM} Drive Gen1 and Gen2 is the qualification of a continuous virtual junction temperature (T_{vj}) of 175°C or even 185°C instead of 150°C.

One of the most important parameters to use the full temperature range is a sufficient number of power cycles or an appropriate power cycling curve of the power module.

The HybridPACK^{TM} Drive Gen2 family uses a set of different assembly and connection technology for the individual modules to suit the respective requirements (**Figure 12**).



a)FS1000R08A7P3x, FS410R12A7P1x and FS520R12A8P1x IGBT modules



b) FS1150R08A8P3x IGBT module and SiC power modules

Figure 12 Interconnection technologies of the HybridPACK^{TM} Drive Gen2 modules

ISBN: 978-3-8007-6288-0

A special focus of this paper should be put on all of the HybridPACK^{TM} Drive G2 products with SiC MOSFETs, were the chips are sintered at the backside of the chip and on the frontside aluminium bondwires with a new bondfoot sealing are introduced (**Figure 12** b).

3.1 PC$_{sec}$ results

The usage of an innovative solution of using Al bond wires with a special process and sintering the SiC chip instead of soldering them allows Infineon to extend the power cycling capability of our HybridPACK^{TM} Drive G2 with CoolSiC^{TM} Gen2 by factor five in comparison to our HybridPACK^{TM} Drive G1 with CoolSiC^{TM} Gen1.

For the executed power cycling tests an increase of V_{DS} by 5 % and/or the increase of the R_{th} by 20 % according the AQG 324 are considered as failure criteria. The test method used was with a constant load current and cycling time, a power derating during the test was not allowed [6].

Looking into the test results, as predominant failure mechanism an increase of V_{DS} (**Figure 13**), mainly caused by bondwire lift-off, was observed. In the tested module lots no devices reached end of life due to a backside die attach degradation and an associated increase of the R_{th} (**Figure 14**).

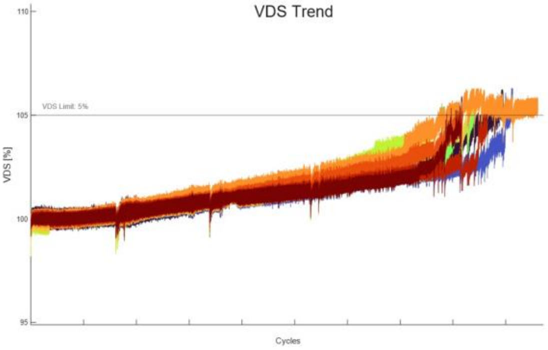


Figure 13 V_{DS} Trend

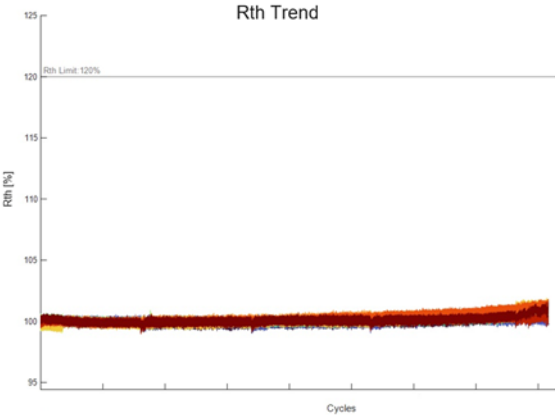


Figure 14 R_{th} Trend

Considering all the PC$_{sec}$ results at different dT with a temperature difference of at least 40 % required from the AQG 324, the conversion from raw to normalized values, considering a safety margin and a confidence interval of 95 % of the Weibull distribution, the power cycling curve in **Figure 15** with 100 k Cycles at dT= 100 K at T_{vj}=175°C can be summarized.

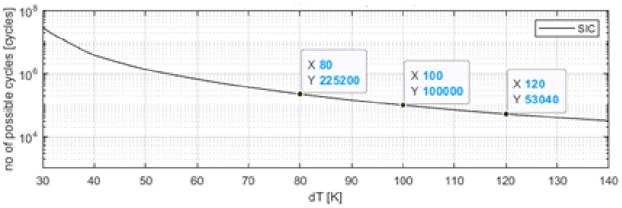


Figure 15 Released PC$_{sec}$ curve

3.2 PC$_{min}$ results

Having a look into the results of the PC$_{min}$ tests at different dT with a temperature difference of at least 40 % required from the AQG 324, the conversion from raw to normalized values, considering a safety margin and a confidence interval of 95 % of the Weibull distribution the power cycling curve in **Figure 16** with 33 k Cycles at dT= 100 K at T_{vj}=175°C can be summarized.

Also, for the power cycling with cycling of minutes an increase of V_{DS} by 5 % and/or the increase of the R_{th} by 20 % according the AQG 324 are considered as failure criteria.

An increase in V_{DS} was detected as the predominant failure mechanism in the PC$_{min}$ test, too. As with PC$_{sec}$, an increase in R_{th} is not the cause of PC$_{min}$ reaching end of life.

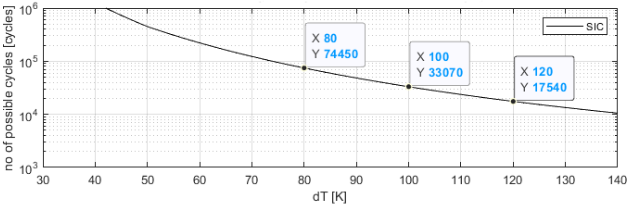


Figure 16 Released PC$_{min}$ curve

3.3 Comparison between the two generations of HybridPACK^{TM} Drive CoolSiC^{TM} power cycling performances

To show the benefit of the introduction of the improved interconnection technology used in our HybridPACK^{TM} Drive of the second generation in an automotive inverter application the HybridPACK^{TM} Drive CoolSiC^{TM} Gen1 with an HybridPACK^{TM} Drive G2 CoolSiC^{TM} Gen2 are compared.

The SiC-MOSFET module of the first Generation fullfills the PC$_{sec}$ lifetime curve with 20 k cycles at dT = 100 K at T_{vj} = 175°C.

In the next step we are applying a real-world driving profile to each power module, with the corresponding interconnection technologies, and by scaling the driving profile, via the phase current the maximum permitted temperature curve for the module, under consideration of lifetime is investigated [7]. The respective power losses are calculated by using the AutoSIM simulation environment [8].

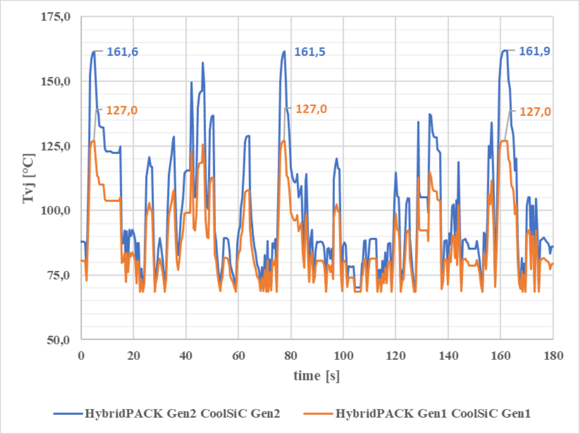


Figure 17 Maximum permissible temperature profile for the two different interconnection technologies

As a result, for a module with the equal chip area and chip technology but different, improved interconnection technologies it is possible to drive the module to a higher T_{vj} than with the less sophisticated interconnection technology. The maximum temperature difference can be more than 34°C higher with the applied mission profiles using the HybridPACK^{TM} Drive G2 CoolSiC^{TM} Gen 2 than with the previous version of the interconnection technology (**Figure 17**). This results in a 20 % higher phase current for the same chip area. So, the power density of the module can be increased and SiC-chip content can be saved. Another possibility to use the higher power cycling performance is to extend the lifetime of the vehicle. The extension of lifetime enables the usage of the HybridPACK^{TM} Drive Gen2 in other applications besides passenger cars like commercial and agricultural vehicles (CAV) i.e. e-trucks and e-buses [9].

4 Release of a short-time extended temperature of 200°C for the HybridPACK^{TM} Drive Gen2 CoolSiC^{TM} Gen2 modules

To extend the temperature range up to T_{vj} = 175°C continuously and T_{vj} = 200°C for a short time for the HybridPACK^{TM} Drive Gen2 CoolSiC^{TM} Gen2 modules, Infineon changed materials of the frame, power tabs, isolation gel, pin and pin rivet, as well as the corresponding processes.
The short time extended temperature of up to T_{vj} = 200°C is ensured by a qualification where the following tests are performed:

- High temperature reverse bias test (HTRB) with a test duration of 100h, test temperature of T_{vj} = 200°C and $V_{DS} >= 0.8\ V_{DS,max} =$ 960 V and V_{GS} = 0 V,
- High temperature gate stress test (HTGS) with a test duration of 100 h, test temperature of T_{vj} = 200°C and V_{GS} = ±20V (DC),
- PC_{min} at dT = 120 K, ton = 30 s, T_{vj} = 200°C Reduced cycles to ensure overload, not part of the QPAC.

5 Press-fit pin qualification according to IPC-9797

In the year 2020 the IPC-9797 Press-Fit Standard for Automotive Requirements and Other High-Reliability Applications was released [10]. The standard prescribes practices for the characterization, qualification and acceptance requirements of compliant press-fit technology for printed boards that cover the manufacturability and reliability needs for high-reliability applications intended for use in harsh environments such as automotive and aerospace.
The qualification was divided in a qualification of (just) the pin (**Figure 18**) and where it had benefits for the application, the qualification of the pin was performed in the HybridPACK^{TM} Drive Gen2 product (Error! Reference source not found.).

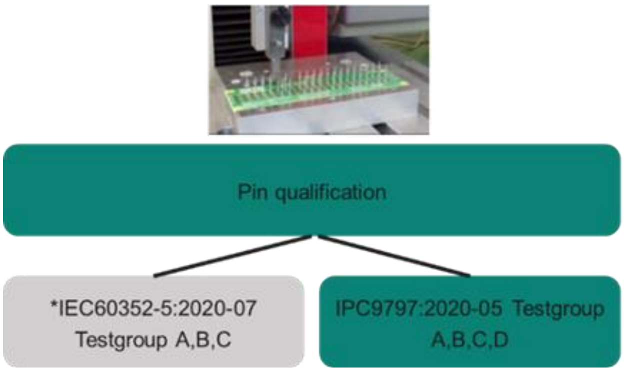
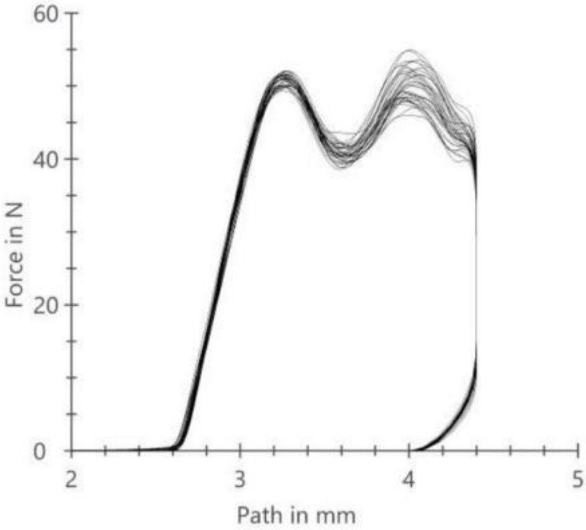
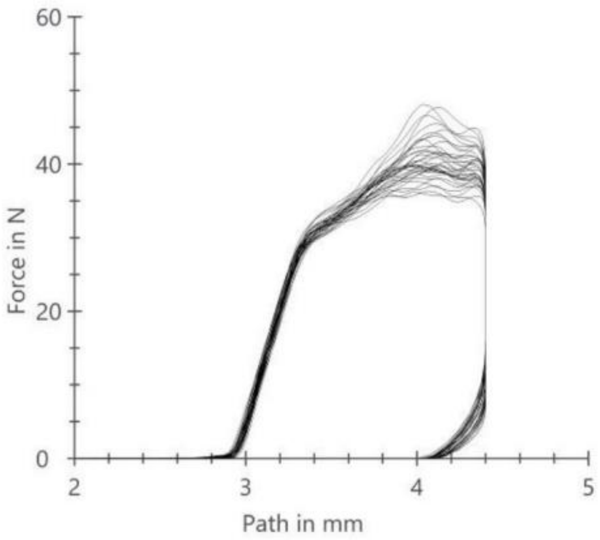


Figure 18 (Single) Pin qualification

The tests are clustered in different test groups. In test group A “unassembled, investigations on pin & printed circuit board level” the unassembled single pins were mechanically characterized, bending and elasticity tests of the pins are performed. PCB holes are characterized and cross section of PCBs are optical measured in detail.
In test group B “forces and cross sections”, the focus is on the pin forces, contact resistances and cross sections. The push in forces during push in are documented.



a) F_{in} minimum-hole for test group B



b) F_{in} maximum-hole for test group B

Figure 19 F_{in} for different PCB hole sizes

Afterwards the PCBs are stored for 24 to 168 h at room temperature. Afterwards an optical inspection took place and the contact resistances are measured. In the next step the push out forces during push out are measured. Vertical and horizontal cross sections of the pins are taken in different positions. For the pressfit pin used in the HybridPACK^{TM} Drive Gen2 from the the result of the push-in forces there is no major difference of pushing in the pins of the module in a PCB with minimal holes or in a PCB with maximal holes (**Figure 19**).

In test group C "Temperature Cycling" the rationale is the Single Pin Temperature Cycle. The test conditions are the following: The push in forces during push in are documented. Afterwards the PCBs are stored for 24 to 168 h at room temperature. Following an optical inspection takes place and the contact resistances are measured. Next 250 temperature cycles with each 15 min at -40°C and 125°C are performed the temperature cycles are performed with a change time < 10 s.

Afterwards an optical inspection took place and the contact resistances are measured. In the next step the push out forces during push out are measured. Vertical and horizontal cross sections of the pins are taken in different positions.

In test group D "climatic incl. corrosion" the pins are exposed to temperature cycles, humidity (changes) and gases. The push in forces are documented. Afterwards the PCBs are stored for 24 to 168 h at room temperature. Afterwards an optical inspection of top and bottom side of the pins took place and the contact resistances are measured. Next 250 temperature cycles with each 15 min at -40°C and 125°C are performed the temperature cycles are performed with a change time < 10 s.

The next test are 5 cycles of damp heat with frost of each 24 h: first within 3 hours at a rel. humidity of >=95 % the temperature is increased from 25°C to 55°C. The 55 °C are hold for 9 h at a rel. humidity of >= 90%. Afterwards the temperature is decreased to 25°C at a rel. humidity of >=80 % within 3 to 6 hours. The temperature is hold there for 6-9 hours at a relative humidity of >95 %. Afterwards it is exposed to -40°C for 2 h.

As a next test the pins and PCBs are exposed to dry heat for 24 h at a temperature of 125°C +/-5K. Following the pins exposed to a flowing mixed gas with 0.1 ppm H_2S and 0.5 ppm of SO_2 for 10 days at 25°C and 75 % humidity.

Afterwards an optical inspection and whisker inspection took place and the contact resistances are measured. In the next step the push out forces during push out are measured. Vertical and horizontal cross sections of the pins are taken in different positions.

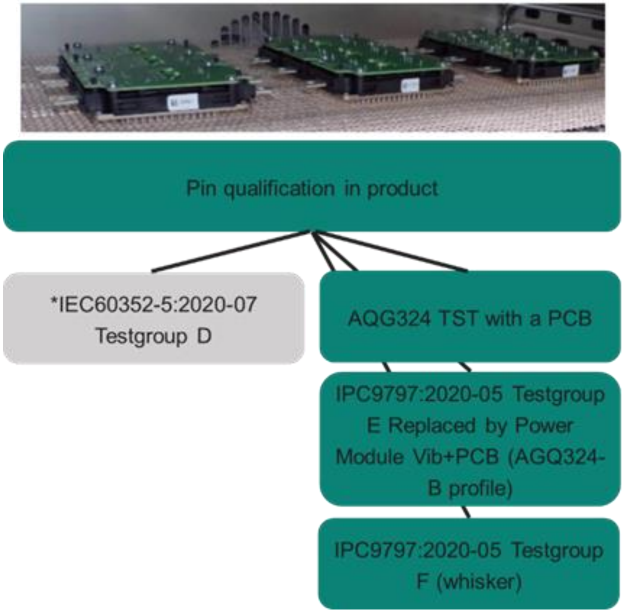


Figure 20 Pin qualification in the module

The test group E "Vibration" was replaced by a vibration test with PCB and thermal shock test with PCB on power module level. The reason for replacing test group E was that a single pin test does not include the mechanical stress conditions from the package in vibration and temperature cycling which are important stress mechanisms in an automotive power module. In a first step the force curves during press in are documented. The power tabs are mounted by screws to a small busbar with same material as the power tabs. The busbars are fixated at the heatsink. Before the test and (after press-in) the Pin/PCB connection has to be inspected and documented by high resolution pictures Before test: Press-fit Connection Resistance. After the test a whisker investigation at PCB and power tabs is performed

The Pin/PCB connection has to be inspected and documented and the press-fit Connection Resistance need to be documented. Vertical and horizontal cross sections of the pins are taken in different positions for one DUT.

For test group F "whisker" push in forces at room temperature and at a push in speed of 1mm/s were measured and afterwards the module was stored for over 2000 h at 25°C +/-10K. After the test whisker were tried to be investigated from top and bottom side of the PCB.

All the tests and test groups were successfully passed with the pin used in the HybridPACK^{TM} Drive Generation 2. It's the first module family in the HybridPACK^{TM} Drive format fulfilling the new IPC-9797 standard.

6 Summary

Infineon Technology AG introduces the second generation of the HybridPACK^{TM} Drive automotive power modules, increasing the power density by 50 % and significantly extending the scalability of the HybridPACK^{TM} Drive family in the three dimensions output current, system voltage class and chip technology Si/SiC. It was shown that this is reached by enabling continuous $T_{vj,max}$ of up to 185°C and short term operation at $T_{vj,max}$ at 200°C, in combination with the latest generations of EDTx Si IGBT and the latest CoolSiC^{TM} SiC MOSFETs. In addition, the shown AC current sensor integration concept further optimizes the power density and simplifies AC sensor mounting by supporting one single press-in step. On-chip temperature sensors complement the chip technologies and help to reach fast detection of potential failures in the inverter system. Furthermore, thanks to the introduced new set of different connection and assembly technologies like chip sintering and bond foot sealing, lifetime requirements of tomorrow's electrified drivetrains can be reached even at fully exploiting the modules temperature capability.

7 Literature

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