1200V CoolSiC™ MOSFET in TO-247 3/4pin Evaluation Board

User Manual

About this document

Scope and purpose

This application note is a user guide for the 1200V CoolSiC™ MOSFET in TO-247 3pin/4pin evaluation board. It explains the board's hardware and provides detailed instructions on how to use it for addressing various measurement tasks. Finally, practical examples demonstrate the performance of the MOSFET.

Intended audience

This document is intended for owners and users of the evaluation board.

Table of Contents

About this document **1**
Table of Contents **1**
1 Introduction **3**
1.1 Purpose of the board 3
1.2 Scope of delivery 4
2 Hardware **5**
2.1 Circuit and main components 5
2.2 Recommended accessories 6
3 Usage **8**
3.1 Settings 8
3.1.1 Replacing switches or diodes 8
3.1.2 Changing between 3pin and 4pin packages 9
3.1.3 Tuning gate voltages and resistors 10
3.1.4 Adjusting and monitoring the heat sink temperature 11
3.2 Operation 11
3.2.1 Configurations 11
3.2.2 Switching loss measurements 13
3.2.3 Efficiency or temperature measurements 14
4 Examples **15**
4.1 Turn-on loss reduction with a 4pin package 15
4.2 Substituting an IGBT with a MOSFETs in a boost circuit 16
5 Appendix **18**
5.1 Schematic drawing 18
5.2 Board layout 19
5.3 Bill of materials 21
References **24**
Revision History **25**

Dangerous Equipment!

High Voltage

Do NOT touch the board during operation.

Depending on the configuration of the board and the chosen supply-voltage, life-threatening voltages might be present!

Even brief accidental contact during operation might result in severe injury or death!

Always make sure that the capacitors are discharged before touching the board.

Only qualified personnel are allowed to handle this board!

Read the instructions provided in this application note before putting the evaluation board into operation

The board described is an evaluation board dedicated for laboratory environment only. It operates at high voltages and must only be operated by qualified and skilled personnel familiar with all applicable safety standards.

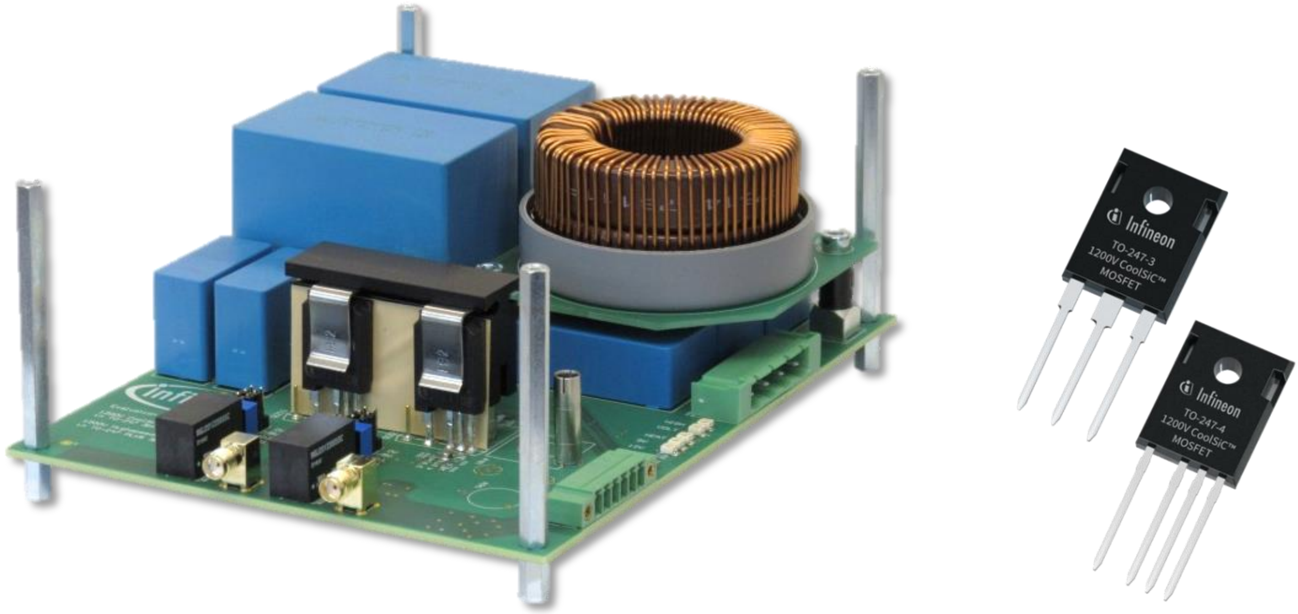
1 Introduction

The evaluation board EVAL-COOLSIC-MOSFET-1200V-TO247-4 was developed as a test platform for 1200V CoolSiC™ MOSFETs in TO-247 and TO-247 4pin packages but is also compatible with IGBTs and other TO-247-like packages such as TO-247PLUS and TO-247PLUS 4pin.

This introductory section provides an overview of the potential applications of the evaluation board and lists the components included in the delivery.

1.1 Purpose of the board

The main motivation to develop the evaluation board shown in Figure 1 was to have one universal test platform for 1200V Silicon Carbide MOSFETs in TO-247 and TO-247 4pin packages. It allows evaluating the features offered by the CoolSiC™ MOSFET technology as well as the performance improvement given by the Kelvin source connection of the TO-247 4pin package. For detailed information on the CoolSiC™ MOSFET and the TO-247 4pin package refer to the application notes [1] and [2], respectively.



(a) (b)

Figure 1 Evaluation board and devices under test: (a) 1200V CoolSiC™ MOSFET in TO-247 3pin and 4pin Evaluation Board, (b) TO-247 and TO-247 4pin package

Two different modes of operation can be implemented with this board. First, it can be used to investigate the switching behavior and measure the switching losses of MOSFETs, diodes or IGBTs at different conditions. Parameters like the DC link voltage, the load current, the device temperature as well as the gate voltages and resistors are easily adjustable. If desired, snubbers can be assembled as well. Second, the board can be operated as a step-up or step-down DC/DC converter. Thus, it is possible to characterize and run devices in a continuous mode of operation in the same setup.

Care was taken to minimize the parasitic inductances and capacitances of this board wherever possible. If needed, board users can tune the parasitic circuit elements by simply adding small capacitances and inductances.

1.2 Scope of delivery

The evaluation board is delivered together with spare parts and complete documentation in an environmentally friendly carton box as illustrated in Figure 2. As depicted, the carton box contains:

- Evaluation board EVAL-COOLSIC-MOSFET-1200V-TO247-4 (172mm x 133mm x 72mm; LxWxH)
- 1200V CoolSiC™ MOSFETs IMW120R045M1 and IMZ120R045M1
- 1ED Compact isolated gate-driver ICs 1EDI20H12AH in a 300mil wide-body package
- USB flash drive containing all related application notes and data sheets
- Wire-to-board plugs for connecting the evaluation board to sources and loads

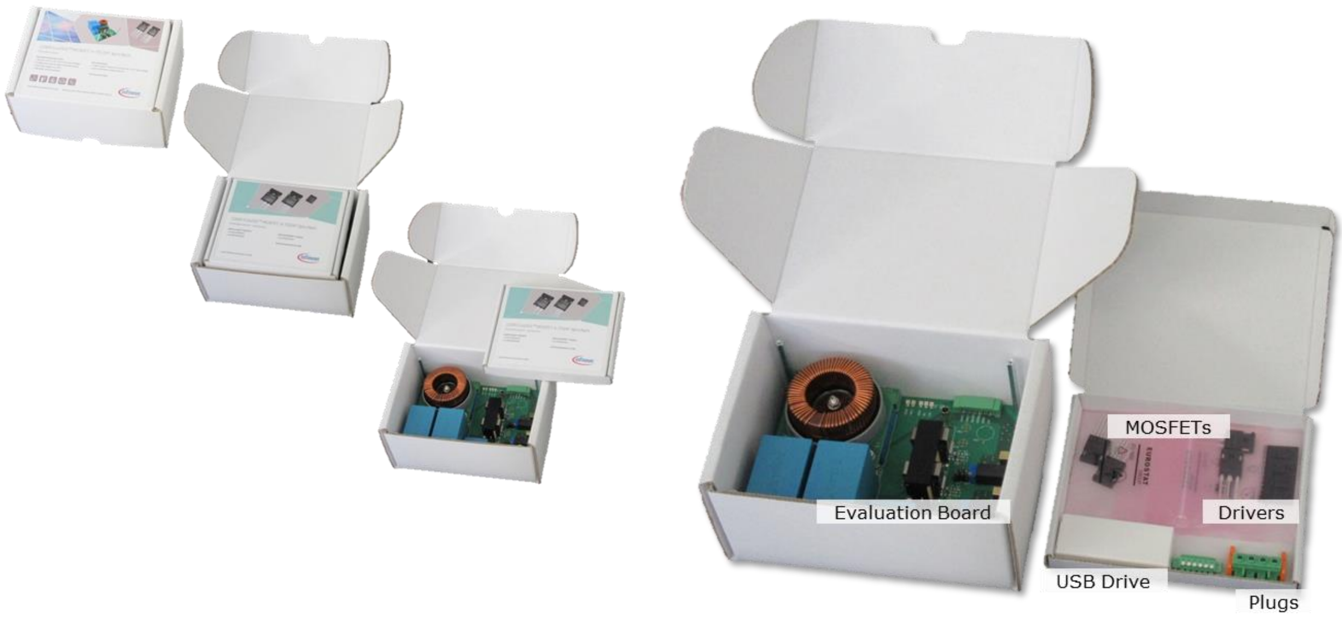


Figure 2 Scope of delivery: evaluation board, spare parts and USB drive with documentation

For high accuracy switching loss measurements, it is highly recommended to use these additional components which are not included in the delivery:

- Coaxial shunt SDN-414-xxx (IB Billmann) for high accuracy current measurements
- Probe adapter A-PCB-5,0-L (PMK) for connecting a passive high voltage oscilloscope probe
- Probe adapters PK106-4 (LeCroy) for connecting passive low voltage oscilloscope probes

2 Hardware

This section provides a short description of the board hardware. First, it explains the power circuitry, the main components and the connectors. Then, the application of the recommended accessories is discussed.

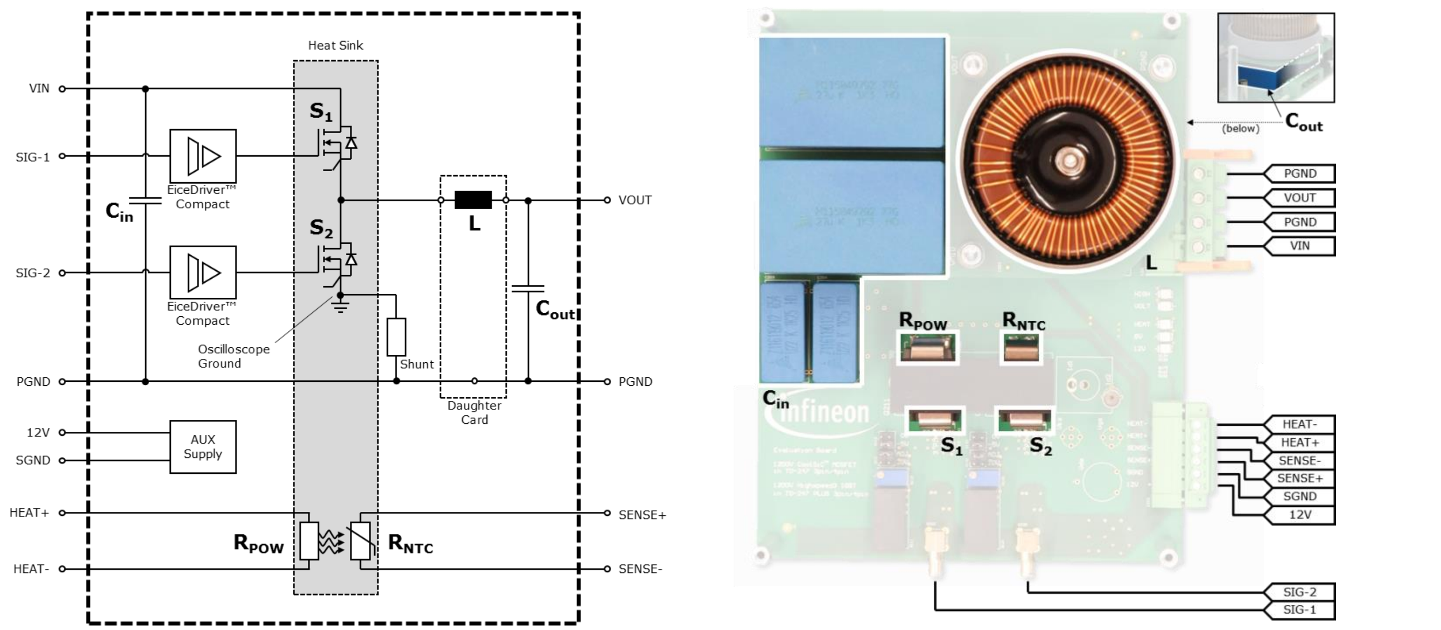
2.1 Circuit and main components

As shown in the block diagram of Figure 3, the evaluation board essentially is a half bridge converter consisting of two MOSFETs, S_1 and S_2. Due to the clip-based heat sink mounting and the universal socket on the PCB it is possible to assemble standard TO-247 and TO-247PLUS packages with three as well as four leads.

The switches are driven using EiceDriver™ 1ED Compact driver ICs. Due to the robust nature of the coreless transformer technology combined with the 300mil wide-body package, these drivers are well suited for applications that require high voltages, frequencies and switching speeds. Both drivers are controlled with independent PWM signals on the connectors SIG-HS and SIG-LS. The driving voltages are provided using the 12V auxiliary supply and isolated DC/DC converters.

For versatility reasons, the evaluation board was equipped with input and output capacitors C_{in} and C_{out} as well as a load inductor L. While the input capacitor and the load inductor where designed having mainly switching loss measurements in mind, the output capacitor is required for continuous operation, for instance as a buck converter. The provided filter inductor might not meet the requirements for the latter case but it is straightforward to replace it with a custom solution.

The same applies to the heat sink: its size and shape reveals that it cannot provide the cooling performance required for continuous operation. Rather, it is intended to serve as a heating element for performing high temperature switching loss measurements. Using the power resistor R_{POW} and the thermistor R_{NTC}, the heat sink temperature can be adjusted and monitored, respectively. Again, it is easily possible to replace the provided heat sink with a high performance solution.



(a) (b)

Figure 3 Overview of the board schematics (a) and components (b)

An experimental analysis of a device's switching behavior requires oscilloscope measurements of the gate voltage, the drain-source voltage as well as the drain current. While voltage measurements are straightforward, current measurements are more difficult to do, particularly in the presence of steep current slopes. This evaluation board contains a basic SMD shunt resistor solution. It gives an impression of the drain current waveform but is not considered an ideal solution for high accuracy measurements.

2.2 Recommended accessories

The introductory section already clarified which components are delivered with the evaluation board and which are not. Although the board can be used for switching loss measurements right away, it is strongly recommended to use additional components for the highest accuracy and signal quality.

Coaxial shunt

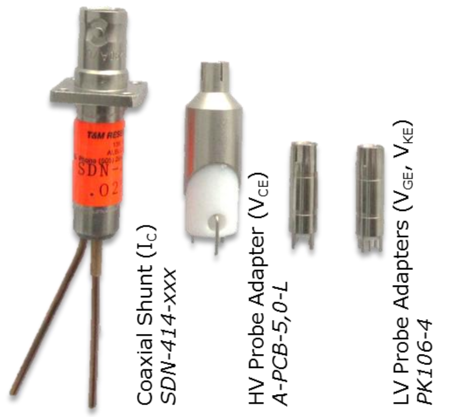
Performing oscilloscope measurements of a MOSFET's drain current waveform is typically a non-trivial task, particularly during switching events where extremely steep current slopes of several Amperes per nanosecond are reached. An ideal current measurement for this purpose would be non-invasive – at least it should not require significant changes of the circuit – and have a very high bandwidth.

By default, this evaluation board contains a 50mΩ metal foil SMD shunt resistor and an RC low-pass filter in order to suppress disturbances caused by parasitic circuit elements. Due to the substantial filtering, this approach might be considered a current estimation rather than a measurement. For high accuracy measurements it is recommended to use a coaxial shunt SDN-414-xxx.[3] It has a bandwidth in the gigahertz range and can be connected to any oscilloscope with a standard BNC cable.

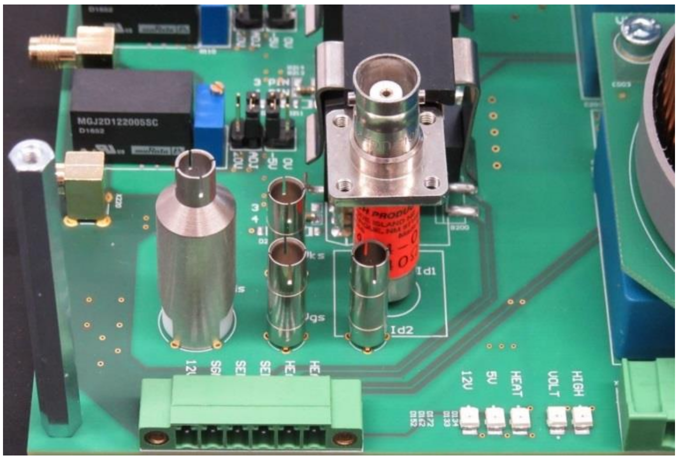
To assemble the coaxial shunt:

1. Unsolder the 50mΩ metal foil resistor R201 and the 100Ω thin film resistor R200 on the bottom side of the board.
2. Optionally, remove the capacitor C201 and the probe adapter Id2 as they are inoperable.
3. Strip the isolation at the central terminal of the shunt and solder it to the PCB.

As visible in Figure 4, the shunt should be positioned as close to the PCB as possible to minimize parasitic inductances.



(a)

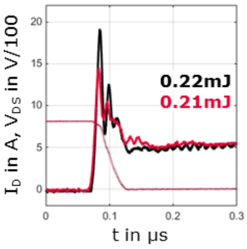
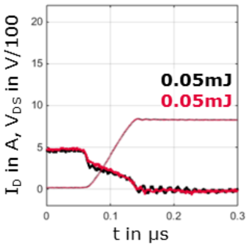
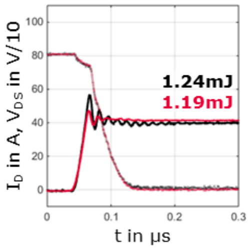
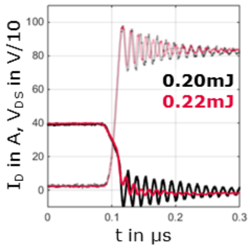


(b)

Figure 4 Recommended accessories for switching loss measurements: (a) pictures of the components, (b) assembly of the components on the board

Table 1 compares waveforms as well as switching losses measured with the metal foil SMD resistor and the coaxial shunt at different conditions. As all measurements are done with exactly the same semiconductor devices, the differences can be attributed to the different current sensors. It is clearly visible that the SMD solution estimates the basic waveform of the drain current relatively well. However, the exact determination of switching slopes and losses requires a coaxial shunt.

Table 1 Comparison of the coaxial (black) and the SMD shunt (red): the double pulse tests were performed with IMZ120R045M1 at 800V and 25°C.

5A		40A	
Turn-On	**Turn-Off**	**Turn-On**	**Turn-Off**
			

Oscilloscope probe adapters

In contrast to current measurements, the acquisition of voltage waveforms is straightforward. By selecting the source potential of the low side MOSFET S_2 as common ground, the gate voltage, the drain-source voltage and the drain current can be measured with ordinary passive probes.

While voltage probes can be connected using grounding wires and clips, the use of PCB adapters is considered advantageous for several reasons. First and foremost, the grounding of the probe is improved which leads to a proper and reproducible signal quality, especially in the presence of disturbances caused by switching transients. Additionally, connecting the probes becomes more convenient and less error-prone.

The evaluation board was designed to accommodate one PMK high voltage probe adapter A-PCB-5,0-L and two LeCroy low voltage probe adapters PK106-4 [4][5]. They share the source of the low-side switch as common ground and measure the voltage on the drain, on the gate and on the Kelvin connection terminal, respectively. Assembling the probe adapters can be done as depicted in Figure 4.b.

3 Usage

Due to its flexibility, the evaluation board can address a variety of measurement problems. While the previous sections explained the basic purpose as well as the hardware of the board, this section provides detailed instructions on how to set it up and operate it. Section 3.1 describes how to modify certain board settings, section 3.2 deals with the preparation and execution of different experiments.

3.1 Settings

The evaluation board is capable of testing TO-247 and TO-247PLUS packages with three as well as four leads under many different conditions. This section provides exemplary instructions on how to assemble different package variants and make the most important adjustments, particularly in the driving circuitry.

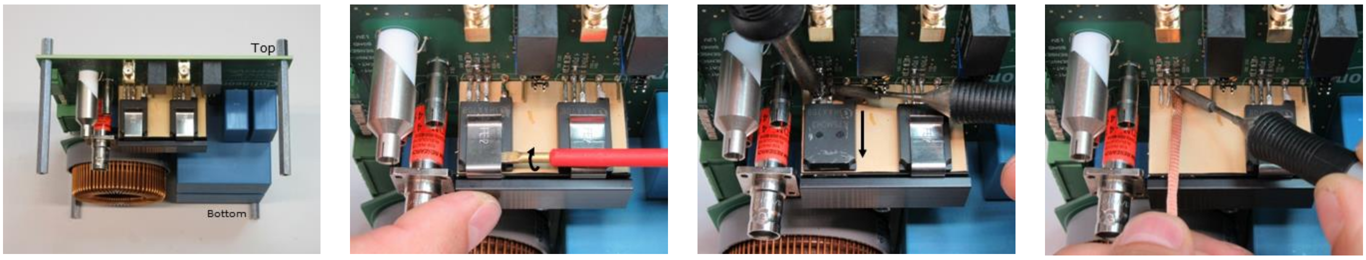
Attention: Prevent potential exposure to hazardous voltages by turning off all power supplies and discharging the DC link capacitors before undertaking any of the modifications described in the remainder of this section.

3.1.1 Replacing switches or diodes

A PCB is subject to severe thermomechanical stress when soldering and unsoldering components. As a consequence, the adhesion between the copper layers and the core material gets weaker and eventually, copper pads or traces may lift off and break. In order to allow a large number of switch and diode replacements, this evaluation board uses press fit pins for connecting the TO packages and the PCB. As the device is not soldered directly to the board but to the pins, the stress to the PCB is limited.

There are several ways of removing the TO packages from the heat sink and the board. A simple approach is to cut the package leads, remove the package body from the heat sink and unsolder one lead after another from the press fit pins. Figure 5 illustrates a different strategy where the semiconductor device remains intact.

1. Put the board in an upright position so that the semiconductor packages face upwards (a).
2. Push a flat screw driver between the clip and the package body and twist it to pull the clip out of the heat sink’s groove (b).
3. Use two soldering irons to heat up all leads at the same time. When the solder melts on all leads, gently pull the package away from the board (c).
4. Finally, clean the press fit pins using solder wick (d).



(a) (b) (c) (d)

Figure 5 Disassembling a device from the heat sink and the PCB

The assembly of a new device is easier. Figure 6 presents a possible sequence of steps.

1. Prepare the TO package by cutting the leads to a length of around 5mm (a).
2. Place the package freely and perfectly flat on the heat sink (b).
3. Put the spring clip on the package and the heat sink groove and fasten it using pliers (c).
4. Solder one lead after the other to the press fit pins (d).

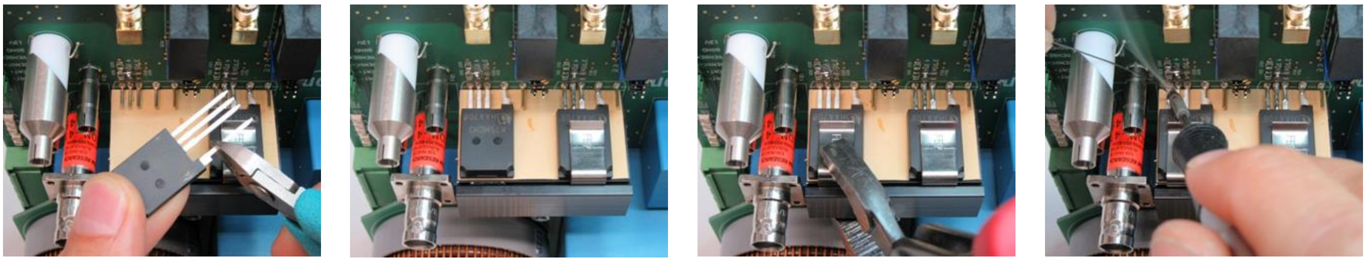

(a) (b) (c) (d)

Figure 6 Assembling a device onto the heat sink and the PCB

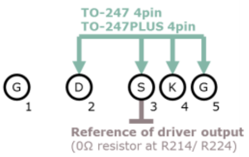
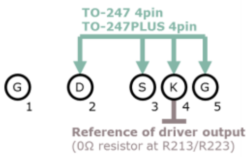
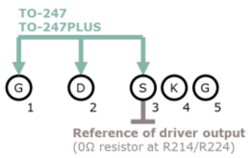
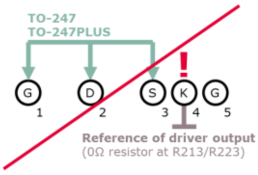
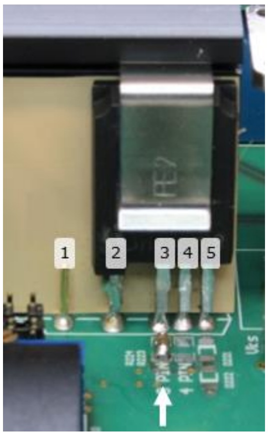
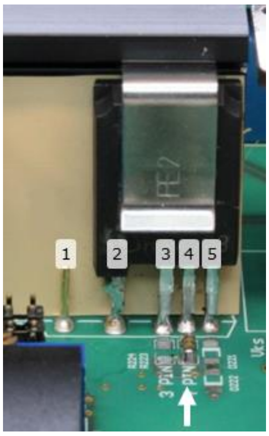
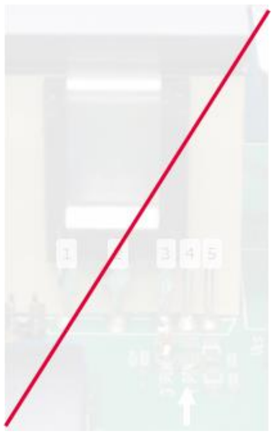
3.1.2 Changing between 3pin and 4pin packages

Since the evaluation board has to serve as a universal test platform for TO-247-like packages with three as well as four leads, it contains special five pin sockets which can accommodate all package variants.

The connection schemes for switches and drivers are described in Table 2.

1. Solder the discrete semiconductor package to the proper socket pins: four lead packages to pins 2-5, three lead packages to pins 1-3.
2. Ensure that the reference of the driver output is connected to the proper source lead using a 0Ω resistor: assemble R214/R224 for a three-pin, R213/R223 for a four pin configuration.

Table 2 Assembly of TO-247-like packages with three and four pins

Package	**TO-247 4pin TO-247PLUS 4pin**		**TO-247 TO-247PLUS**	
Connected press fit pins	Pins 2-5		Pins 1-3	
Reference of driver output	Pin 3 (0Ω resistor at R2_4)	Pin 4 (0Ω resistor at R2_3)	Pin 3 (0Ω resistor at R2_4)	Pin 4 (0Ω resistor at R2_3)
Connection Scheme				
Picture				
Comment	Operation of the 4pin package as a 3pin package	Intended operation of the 4pin package	Intended operation of the 3pin package	**Attention:** floating gate; setting can cause device and circuit destruction

3.1.3 Tuning gate voltages and resistors

Figure 7.a illustrates the schematics of the driving circuitry implemented for both, the high side and the low side switch. It includes the relevant components of the circuitry and highlights the most important part labels which consist of a letter and a three-digit number. The second digit is replaced by a wildcard underscore in the picture but would normally indicate whether the component belongs to the high side (“1”) or the low side (“2”).

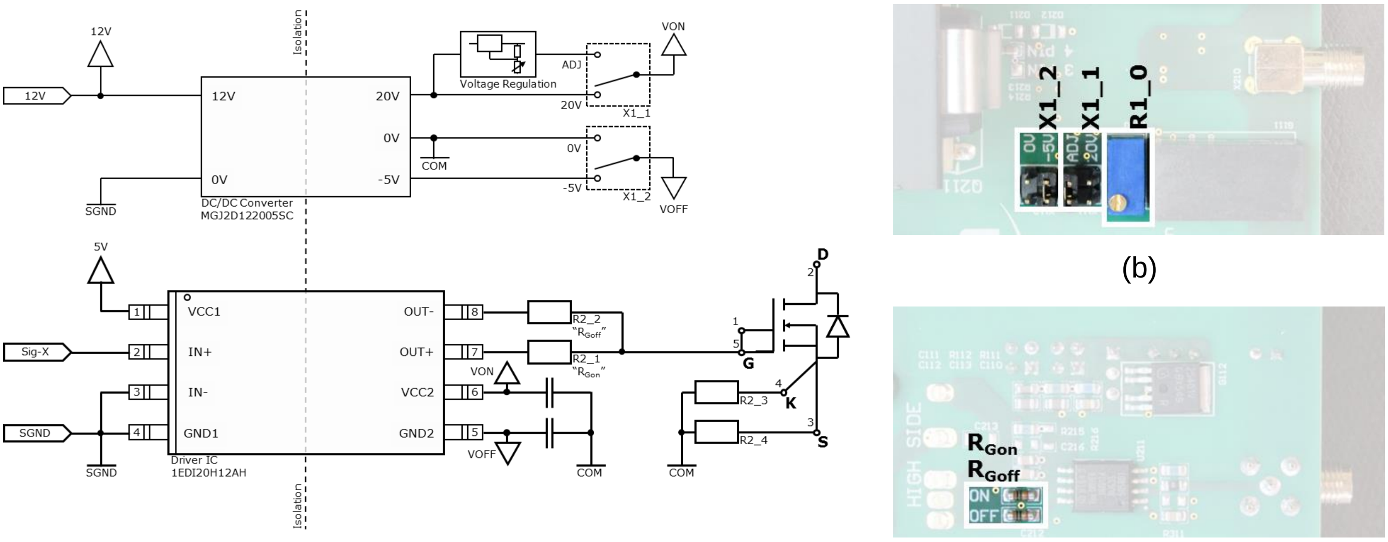
A galvanically isolated EiceDriver™ 1ED Compact IC with a nominal current of 2A, separate source and sink outputs and a wide-body package forms the core of the driving circuitry. The input or primary side of the driver is powered with a voltage of 5V referring to SGND – this voltage is generated based on the 12V auxiliary input using a linear regulator – and controlled with a PWM signal on the input Sig-X. Please note that since the driver already contains high accuracy input filters, there is no need to use an external RC low-pass on the signal path. Such a filter would require additional components, introduces a higher propagation delay tolerance and is thus not recommended.

The driving voltages on the output or secondary side of the driver are provided by an isolated DC/DC converter and adjusted using the jumpers X1_1, X1_2 as well as the potentiometer R1_0. These components are assembled on the top side of the board and highlighted in Figure 7.b.

To adjust the gate voltages levels:

1. Set the jumper X1_1 to ADJ and tune the potentiometer with a flat screw driver until the recommended value of 15V is reached.
2. Select a turn-off voltage of either -5V or 0V using the jumper X1_2.
3. Monitor or check the gate voltage levels on an oscilloscope or multimeter.

Separate turn-on and –off resistors R2_1 and R2_2 are assembled on the bottom side of the board. As depicted in Figure 7.c, resistors in a Mini-MELF mounting form were selected and highlighted with the labels ON and OFF. The gate resistance values can be adapted using a soldering iron.



(a) (b) (c)

Figure 7 Explanation of the driving settings: (a) schematics of the driving circuitry, (b) gate voltage settings, (c) gate resistors

3.1.4 Adjusting and monitoring the heat sink temperature

Switching losses are not only measured at room temperature but also at temperatures of 100°C and above. Consequently, a measurement setup must offer the possibility to adjust and monitor the case temperature of the devices under test.

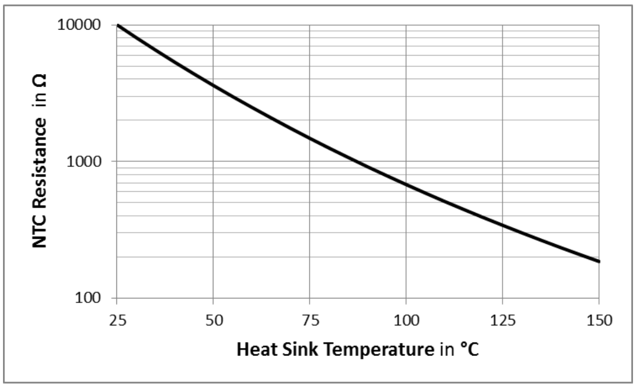
This evaluation board contains a small heat sink that has been designed to serve as a small heating element. The temperature of this element can be set and measured using the power resistor E200 and the NTC B200, respectively. Both devices are assembled on the back of the heat sink, on the opposite side of the devices under test.

In order to adjust the heat sink temperature:

1. Connect a laboratory power supply to the HEAT+/HEAT- terminals of the power resistor.
2. Connect an ohmmeter to the SENSE+/SENSE- terminals of the NTC thermistor.
3. Use the power supply to adjust the heat sink temperature. A rough guide is provided by Figure 8.a.
4. Monitor the actual temperature value using the ohmmeter and the NTC characteristic in Figure 8.b.

The heat sink behavior can be approximated with a thermal resistance of around 6 K/W to the ambient and a thermal time constant of approximately 7 minutes. This analytic description is valid if the heat sink is facing upwards and not exposed to a forced air cooling.

(a)



(b)

Figure 8 Characteristics for temperature adjustments: (a) heat sink temperature as a function of power, (b) NTC value as a function of the heat sink temperature

3.2 Operation

As described in section 2.1 the evaluation board implements a half bridge circuit with independent driver stages for the high side and the low side semiconductor device. Due to the universal nature of this topology, the board can be operated in various modes of operation. The remainder of this section explains the possible measurement configurations and procedures.

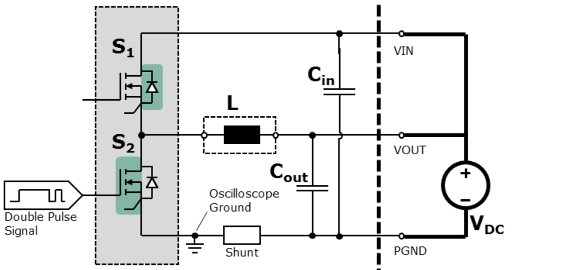
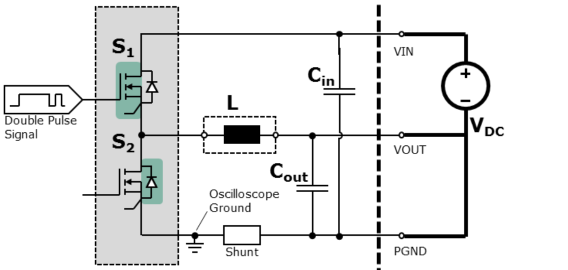
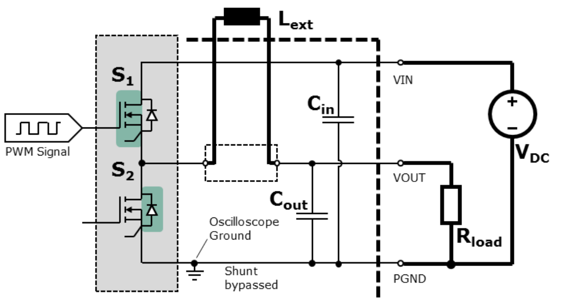
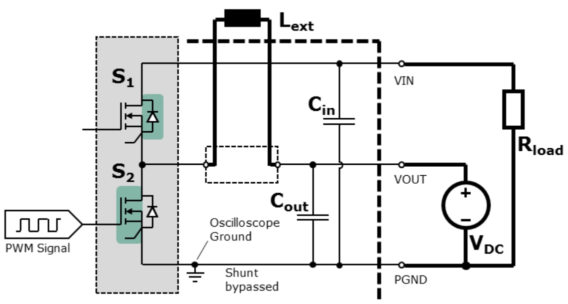
Attention: Prior to starting measurements ensure that the board settings are correct. Take special care that no physical short circuits or floating gates are present. Increase the input voltages slowly and monitor that the circuit behaves as expected.

3.2.1 Configurations

Table 3 provides a summary of the main board configurations. The first two lines illustrate how to study the switching behavior of a certain MOSFET and diode combination. By switching the MOSFET according to a double pulse signal it is possible to generate a turn-off as well as a turn-on event with a specific voltage and current. Measuring the current and voltage waveforms of the devices on the oscilloscope gives an impression of the switching behavior and allows a calculation of the switching losses. In order to maximize the accuracy and minimize the effort, it is recommended to make oscilloscope measurements on the low side device S_2: use configuration (1) to study the switch and configuration (2) to study the diode behavior. More detailed information on this mode of operation can be found in section 3.2.2.

Configuration (3) and (4) correspond to a buck and a boost converter, respectively. Since these configurations are actually processing power in a continuous manner, both the heat sink and the inductor need to meet the individual voltage, power and switching frequency requirements. It is straightforward to replace those components with appropriate custom solutions. Refer to section 3.2.3 for more detailed information on how to use the board in this mode of operation.

Table 3 Board configurations for switching loss measurements and continuous operation

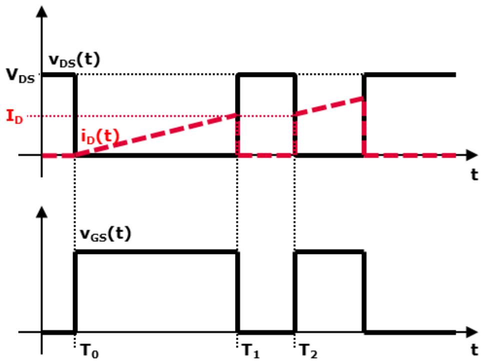
Conf.	DUTs	Results	Parameters and limits		Simplified circuit drawing
(1) Switching Cell (Switch characterization)	Switch S2 Diode S1	V_{DS}, I_D and V_{GS} waveforms, E_{on}, E_{off}, Q_{rr}, I_{rrm}, $V_{DS(peak)}$ dv/dt, di/dt, …	V_{DS} I_D T_C $V_{GS(on)}$ $V_{GS(off)}$ R_G Package	< 900V [1] < 150A [2] < 150°C [3] 0/-5V 12- 20V - TO-247x-3/4 [4]	
(2) Switching Cell (Diode characterization)	Diode S2 Switch S1	V_{DS}, I_D and V_{GS} waveforms, E_{rec} Q_{rr}, I_{rrm}, dv/dt, di/dt, …	V_{DS} I_D T_C $V_{GS(on)}$ $V_{GS(off)}$ R_G Package	< 900V [1] < 150A [2] < 150°C [3] 0/-5V 12- 20V - TO-247x-3/4 [4]	
(3) Buck Converter	Switch S1 Diode S2	T_{S1}, T_{S2}, $T_{heatsink}$, η, V_{DS} and V_{GS} waveforms, …	V_{DC} f_{sw} P_{out} $V_{GS(on)}$ $V_{GS(off)}$ R_G Package	< 900V [1] - - [5] 0/-5V 12- 20V - TO-247x-3/4 [4]	
(4) Boost Converter	Switch S2 Diode S1	T_{S1}, T_{S2}, $T_{heatsink}$, η, V_{DS} and V_{GS} waveforms, …	V_{DC} / (1-d) f_{sw} P_{out} $V_{GS(on)}$ $V_{GS(off)}$ R_G Package	< 900V [1] - - [5] 0/-5V 12- 20V - TO-247x-3/4 [4]	
	Do not operate a boost converter without a load! **Ensure that the DC link voltage does not exceed 900V!**				

[1] Limited by the ceramic DC link capacitors C201 and C202 on the bottom side of the PCB.
[2] Not a hard limit due to the soft saturation behavior of the inductor core.
[3] Limited by the maximum temperature of the power resistor.
[4] TO-247x-3/4 refers to TO-247 and TO-247PLUS as well as TO-247 4pin and TO-247PLUS 4pin packages.
[5] Limit depends on the device selection and the cooling performance.

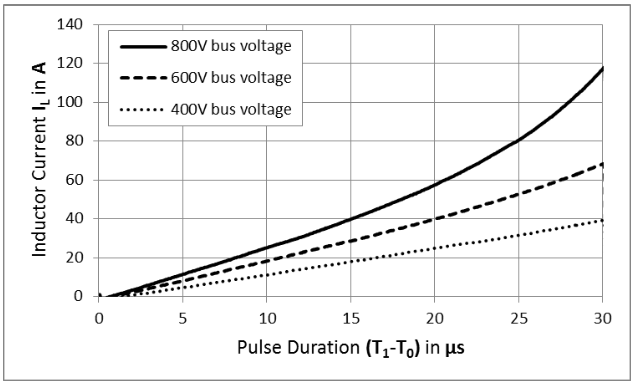
3.2.2 Switching loss measurements

Switching losses can be determined using a double pulse test. It generates both a turn-off and a turn-on event by applying two consecutive pulses on the gate of the switch – hence the expression double pulse. Due to the fact that the circuit is not operated in a continuous fashion the self-heating of the semiconductors and the inductor is negligible. This is particularly convenient since the junction temperatures of S_1 and S_2 correspond to the heat sink temperature and are therefore well known.

The remainder of this section describes how to perform double pulse tests based on configuration (1). It is worth noting, however, that configuration (2) is operated in an analogous manner. Figure 9.a shows the principle current and voltage waveforms of S_2 during the double pulse test. Initially, S_2 is blocking the full DC link voltage, thus V_{CE}=V_{DC}. At T_0 the switch is turning on and the current I_C(t) rises with a rate V_{BUS}/L. When the switch is turned off at T_1, the load current commutates from S_2 to the diode of S_1 where it is freewheeling until T_2. Then, the switch S_2 is turning on and taking over the current again. After a few microseconds S_2 is turned off again. The load current is commutating to the diode one last time and slowly decaying to zero in tens or hundreds of milliseconds. Using this approach it is simple to produce defined turn-off and turn-on events at T_1 and T_2, respectively: while the voltage level is set directly with the DC link voltage V_{DC} the current value is adjusted with the width of the first pulse (T_1-T_0). Figure 9.b shows the current value as a function of the pulse width for the provided inductor and different DC link voltages.



(a)



(b)

Figure 9 Double pulse testing: (a) schematic drawing of the current and voltage waveforms during a double pulse test, (b) saturation behavior of the provided inductor

To perform a double pulse test on the evaluation board

1. Assemble the devices under test S_1 and S_2 as described in section 3.1.1.
2. Connect the driver to the proper source pin according to section 3.1.2.
   a) Solder 0Ω resistors to R214/R224 when using three pin packages.
   b) Solder 0Ω resistors to R213/R223 when using four pin packages.
3. Adjust the driving circuitry for S_2 and, if necessary, also for S_1 according to section 3.1.3.
   a) Set the jumper X111/X121 to ADJ.
   b) Use the jumper X112/X122 to set the turn-off voltage to 0V or -5V.
   c) Adjust the turn-on and turn-off gate resistors R211/R221 and R212/R222, respectively.
4. Connect oscilloscope probes in order to measure V_{DS}, V_{GS} and I_D of S_2.
   a) Measure V_{DS} and V_{GS} with ordinary voltage probes and grounding clips on the package. If possible use the probe adapters introduced in section 2.2.
   b) Measure I_D using the probe adapter Id2. If possible use a coaxial shunt as recommended in 2.2.
5. Connect an auxiliary supply to the 12V/SGND terminals of the board and provide a voltage of 12V.
6. Connect a signal generator to X220 and provide a double pulse pattern with 5V amplitude. Please note that this signal is referenced to SGND.
7. Check the gate voltage waveform on the oscilloscope and adjust it according to section 3.1.3.

8. If required, connect a power supply to the HEAT+/HEAT- terminals and set the voltage level according to 3.1.4. Monitor the temperature using an ohmmeter connected to SENSE+/SENSE-.
9. Connect a high voltage source to VIN and PGND and short VIN and VOUT.
10. Slowly increase the voltage and monitor the current and voltage waveforms on the oscilloscope.

3.2.3 Efficiency or temperature measurements

Testing a particular semiconductor device inside a switching cell is essential for understanding its switching behavior. However, it requires some calculation or simulation effort to translate the acquired switching loss data into quantities that are more relevant for an application, such as the efficiency of the converter, the temperature of the devices or the required cooling effort. By operating the evaluation board in a continuous manner these values can be determined in a purely experimental and thus straightforward way. The remainder of this section explains how to configure and run the board as a buck converter as sketched in configuration (3) of Table 3.

Prior to running the evaluation board as a buck converter, some preparations are required:

1. Short circuit the shunt resistor R201 in order to avoid unnecessary power dissipation.
2. Disable the LEDs that indicate the presence of the DC link voltage by removing R134, R138 and R142. Otherwise consider the power dissipation of this block: 1.6W at 800V.
3. Replace the heat sink
   a) Unfasten the M3 screws that fix the heat sink to the board.
   b) Pull the heat sink away from the board so that the spring clips fall off.
   c) Unsolder the power resistor E200 and the NTC B200.
   d) Remove the probe adapter Id2 from the board.
   e) If necessary, solder the film capacitors C203 and C204 to the other side of the board.
   f) Mount a reasonable heat sink. If possible put an insulation sheet between heat sink and board.
4. Replace the filter inductor
   a) Disconnect the daughter card containing the inductor by unfastening the M4 screws.
   b) Connect a custom inductor between the VMID and the VOUT potential.

After the preparation steps, the efficiency measurements can be performed.

1. Assemble the devices under test S_1 and S_2 as described in section 3.1.1.
2. Connect the driver to the proper source pin according to section 3.1.2.
   a) Solder 0Ω resistors to R214/R224 when using three pin packages
   b) Solder 0Ω resistors to R213/R223 when using four pin packages
3. Adjust the driving circuitry for S_1 and, if necessary, also for S_2 according to section 3.1.3.
   a) Set the jumper X111/X121 to ADJ.
   b) Use the jumper X112/X122 to set the turn-off voltage to 0V or -5V.
   c) Adjust the turn-on and turn-off gate resistors R211/R221 and R212/R222, respectively.
4. Connect isolated voltage probes to measure the gate as well as the drain-source voltage of S_1 and use a current probe to measure the inductor current.
5. Connect an auxiliary power supply to the 12V/SGND terminals of the board and provide a supply voltage of 12V.
6. Connect a signal generator to X210 and provide a PWM signal with 5V amplitude. Please note that this signal is referenced to SGND.
7. Check the gate voltage signal on the oscilloscope and adjust the turn-on voltage level to +15V using the potentiometer R110.
8. Connect a high voltage source to VIN and PGND.
9. Connect an Ohmic load to VOUT and PGND.
10. If possible, measure the input and output power using a power meter and the device temperatures using an infrared camera.
11. Slowly increase the input voltage while monitoring the waveforms and device temperatures.

4 Examples

After the in-depth explanation of possible test settings and procedures that were provided in the previous section, this section shows two practical examples: a switching loss and a temperature measurement.

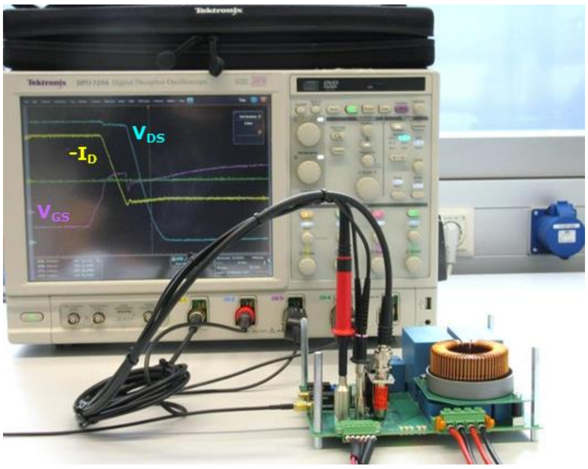
4.1 Turn-on loss reduction with a 4pin package

As extensively explained in [2] on the basis of TRENCHSTOP™ 5 IGBTs, the main advantage of four-pin packages over three-pin packages is the reduction of turn-on losses, particularly at higher current levels. The reason for that is the virtual elimination of the inductive coupling between the gate and the commutation loop. This section demonstrates the positive impact of the Kelvin source connection, i.e. the fourth pin, on 1200V/45mΩ CoolSiC™ MOSFETs. Table 4 summarizes the test cases.

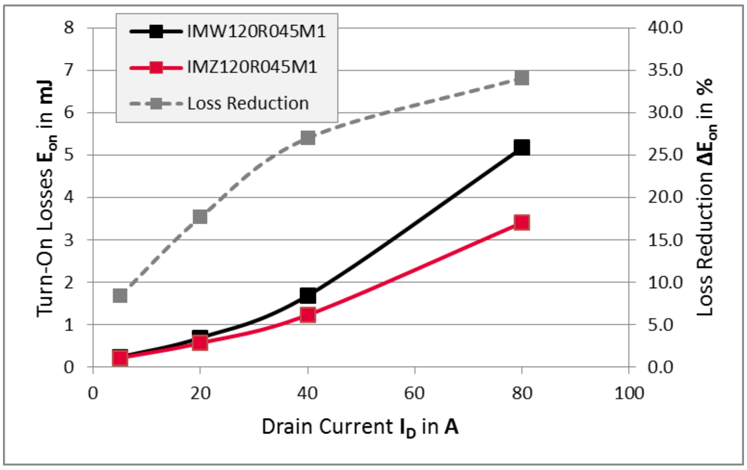
Table 4 Turn-on loss comparison of TO-247 3pin and 4pin: test conditions

	Solution 1	**Solution 2**
Part number (switch and diode)	IMW120R045M1	IMZ120R045M1
Package	TO-247	TO-247 4pin
Junction temperature T_j=T_c	25°C	25°C
Switched voltage V_{DS}	800V	800V
Switched current I_D	5A-80A	5A-80A
Gate voltages $V_{GS(on)}$	+15V	+15V
Gate resistors $R_{G(on)}$	10Ω	10Ω
Driver Ground Connection	0Ω at R214 and R224	0Ω at R213 and R223

The evaluation board was set up as explained in section 3.2.2. Following the recommendations in section 2.2, current measurements were made using a coaxial shunt and voltage probes were connected via PCB adapters. Figure 10.a shows the evaluation board and the measurement hardware as the main part of the setup – power supplies and the signal generator are not included in the picture.



(a)



(b)

Figure 10 Turn-on loss comparison of TO-247 3pin and 4pin: (a) main parts of the test setup, (b) absolute and relative comparison of the measured losses

By multiplying V_{DS} and I_D on the oscilloscope the waveform of the momentary power dissipation was calculated. Integration of this power waveform resulted in the turn-on energy values E_{on} which are shown in Figure 10.b for different current levels and for both package variants. It is clearly visible that the switching losses can be significantly reduced by going to a 4pin package. Since the Kelvin source is increasing di/dt, this is particularly true for higher current levels.

4.2 Substituting an IGBT with a MOSFETs in a boost circuit

The unique material properties of Silicon Carbide – high break through field strength combined with good bulk mobility – are the key to produce high voltage MOSFETs with a reasonable low R_{DSon}·A. Compared to an IGBT the unipolar nature of such a high voltage MOSFET allows a drastic reduction of switching losses. This section demonstrates the advantages of a 1200V/45mΩ CoolSiC™ MOSFET over a 1200V/40A HighSpeed 3 IGBT in a boost converter. For comparison purposes switches with a similar DC current rating where selected.

Note: In a boost converter, Silicon Carbide MOSFETs might replace IGBTs with considerably higher DC current ratings and, at the same time, allow a significant increase of the switching frequency. This is particularly true when using Silicon Carbide Schottky barrier diodes: these diodes are fully exploited with high speed transistors operating at high switching frequencies.

As listed in Table 5, three boost converter solutions processing a power of 4kW were compared. Solution 1 was considered as reference and used a 40A IGBT together with a 20A diode operating at 16kHz. Solution 2 and 3 used a 45mΩ MOSFET instead of the IGBT. While the latter solutions used identical devices, they differed in the switching frequency: solution 2 was operated at 16kHz, solution 3 at 64kHz. In order to maintain the ripple current of the inductor constant, the inductance value was adjusted according to the switching frequency.

Table 5 Comparison of 40A IGBTs and 45mΩ MOSFETs in a boost converter: test conditions

	Solution 1	Solution 2	Solution 3
Part number switch	IKW40N120H3	IMW120R045M1	IMW120R045M1
Part number diode	IDW40G120C5B (1 leg)	IDW40G120C5B (1 leg)	IDW40G120C5B (1 leg)
Package	TO-247	TO-247	TO-247
Electrical isolation	Insulation sheet Kapton, 1.3W/mK, 150µm	Insulation sheet Kapton, 1.3W/mK, 150µm	Insulation sheet Kapton, 1.3W/mK, 150µm
Thermal grease	None	None	None
Heat sink assembly	Clip 60N	Clip 60N	Clip 60N
Gate voltages V_{GE}	+15V/-5V	+15V/-5V	+15V/-5V
Gate resistors R_G	10Ω	10Ω	10Ω
Topology	Boost	Boost	Boost
Sw. frequency f_{sw}	16kHz	16kHz	64kHz
Voltages V_{in}/V_{out}	400V/800V	400V/800V	400V/800V
Output power P_{out}	4kW	4kW	4kW
Heat sink perf. $R_{th(HA)}$	0.93K/W	0.93K/W	0.93K/W
Inductance L	1mH	1mH	250µH

The evaluation board was set up as explained in section 3.2.3 with one exception: a boost converter was implemented instead of a buck converter. Figure 11 shows the test setup including the custom inductor and the custom heat sink. While the inductor was handmade, a LAM 3 K miniature cooling aggregate from Fischerelektronik was used as heat sink. By using a constant supply voltage of 12V the fan of this aggregate was operated at constant speed throughout all tests. The thermal performance was characterized using calibration measurements and described as thermal resistance $R_{th(HA)}$ = 0.93K/W towards the ambient. An infrared-camera was used to monitor the heat sink and device temperatures, an oscilloscope to acquire the most relevant waveforms. Due to the boost converter configuration, the gate and drain-source voltages could be measured with simple passive probes. The inductor current was measured using a caliper-style current probe.

Examples

The picture of the setup does not show the sources and loads. Besides the auxiliary supply which provides the driving voltages, a high voltage DC source and an active DC load were utilized to provide the required testing power of up to 4kW.

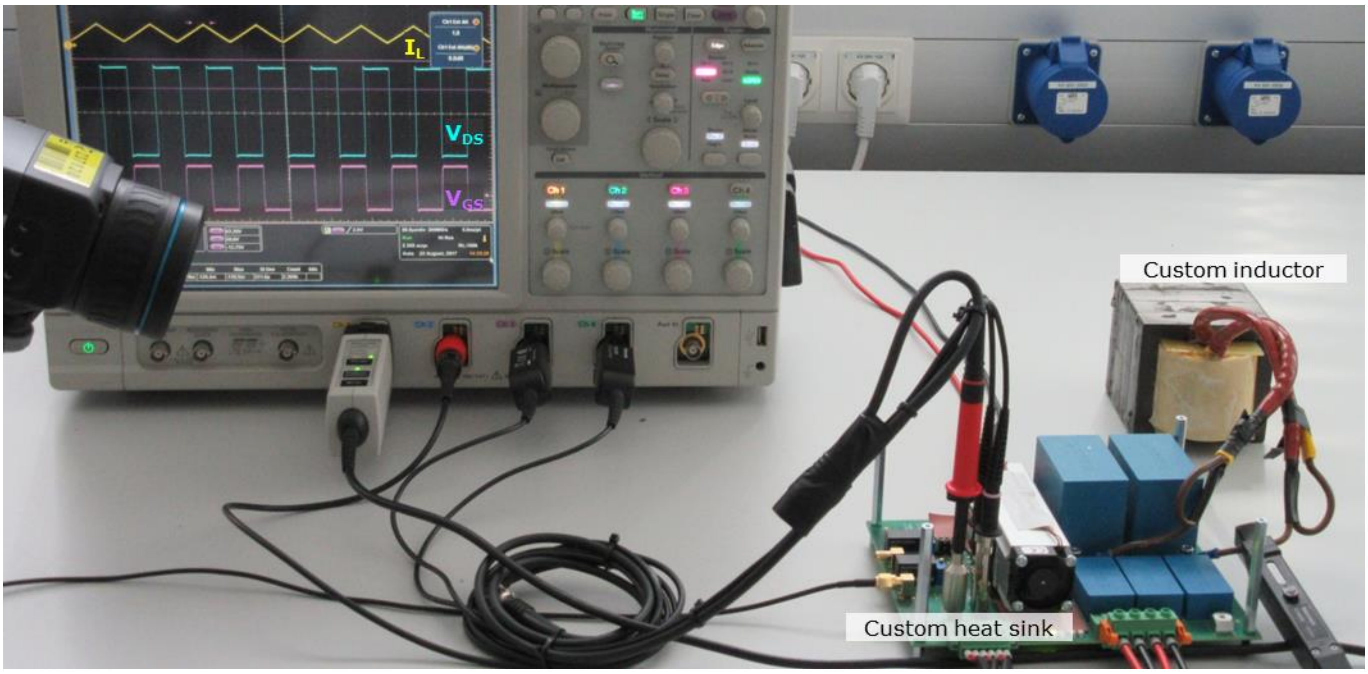
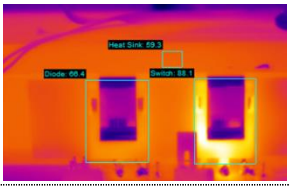
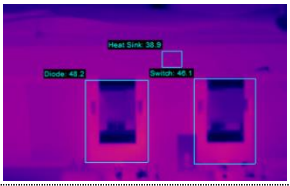
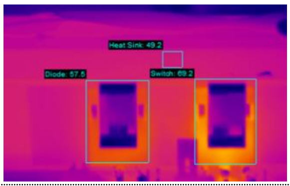


Figure 11 Comparison of 40A IGBTs and 45mΩ MOSFETs in a boost converter: test setup

Table 6 shows the resulting device and heat sink temperatures for all tested solutions. Knowing the heat sink and the ambient temperature as well as the thermal performance of the heat sink it is easily possible to estimate the power dissipation of all devices assembled on the same heat sink. Please note that the scale of the IR camera is kept the same throughout all cases. Thus not only the numeric values but also the color shades are comparable.

Table 6 Results of the temperature measurement: temperature and losses of the solutions 1-3

	Solution 1	Solution 2	Solution 3
IR camera picture (same scale for all pictures)			
Heat sink temperature T_{HS}	59.3°C	38.9°C	49.2°C
Ambient temperature T_A	24.0°C	24.0°C	24.0°C
Temperature difference ΔT_{HA}	35.3°C	14.9°C	25.2°C
Tot. semiconductor losses P_{SC}	38.0W	16.1W	27.2W

Comparing the temperatures and semiconductor losses of solution 1 and solution 2 indicates that replacing the 1200V IGBT with a MOSFET of a similar DC current rating would be possible but does not take full advantage of the Silicon Carbide technology. Apparently, one could increase the switching frequency or reduce the Silicon Carbide chip size. In fact, both might be done at the same time. Solution 3 demonstrates that even when operating the MOSFET-based solution at four times the switching frequency of the reference solution – this would lead to a significant reduction of the magnetics size and cost –, the semiconductor losses remain around 30% lower compared to the reference solution. A further optimization step which is not shown here could be to reduce the MOSFET chip area.

5 Appendix

5.1 Schematic drawing

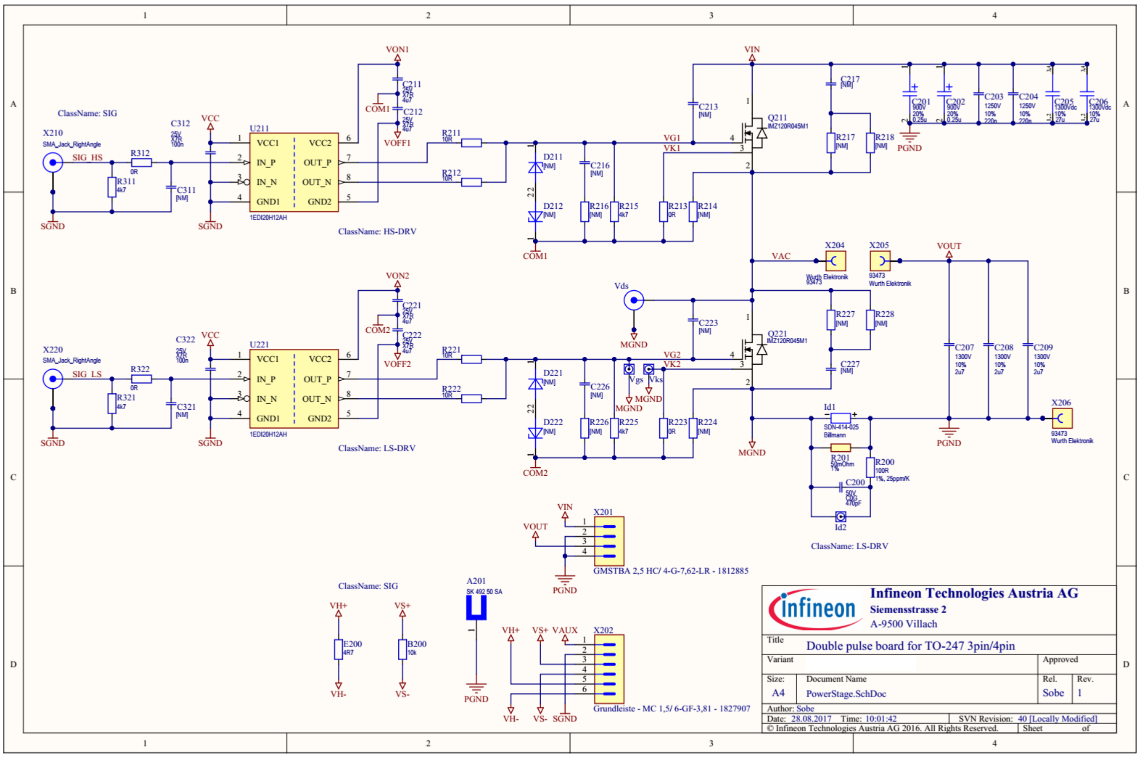


Figure 12 Power and driving circuitry

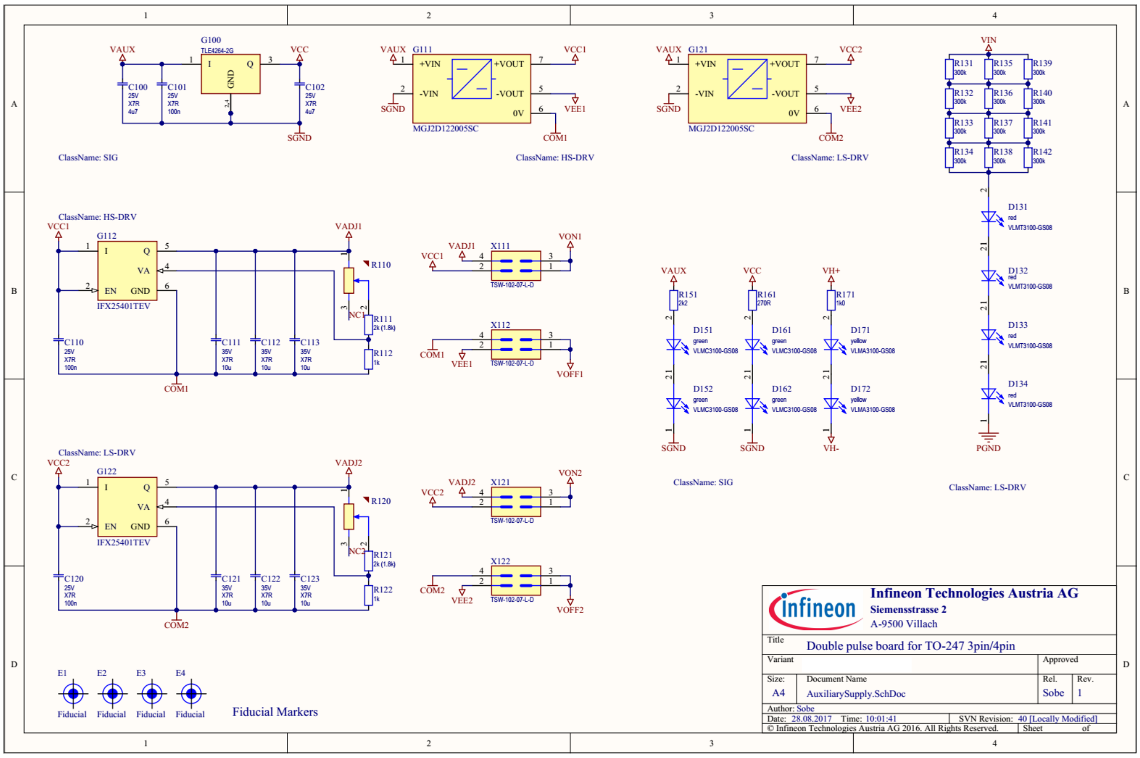


Figure 13 Auxiliary supply and LED indicators

5.2 Board layout

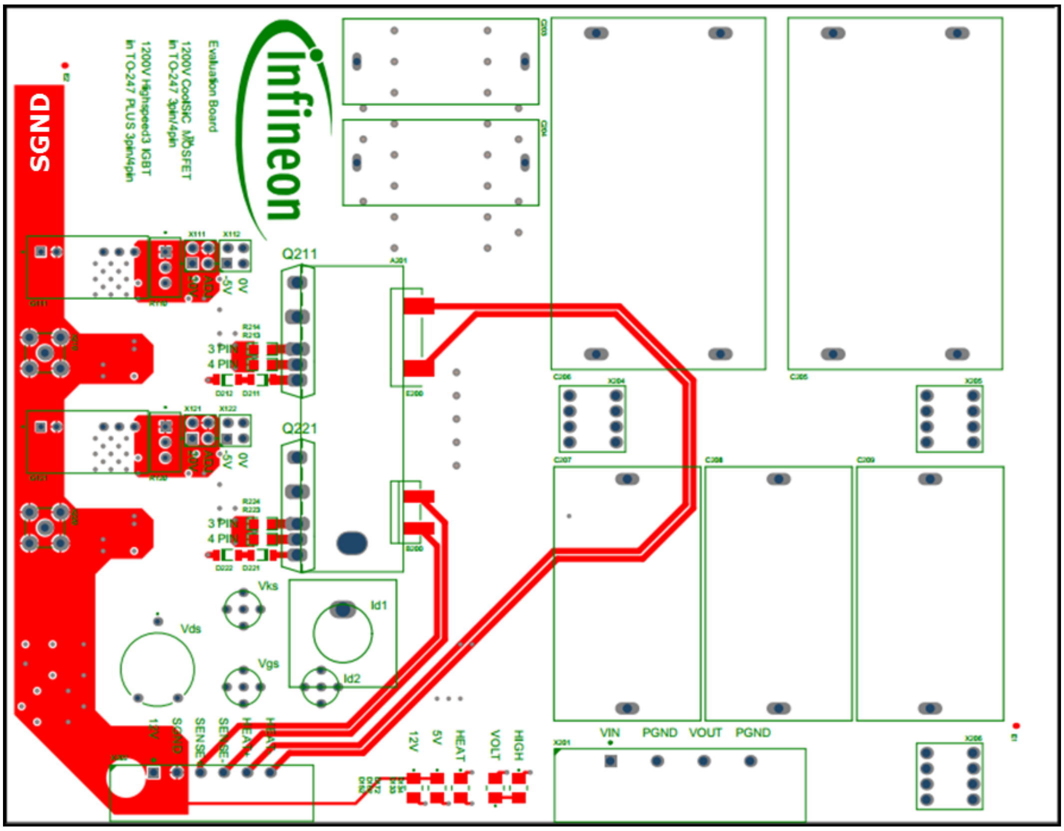


Figure 14 Layer 1 (top layer)

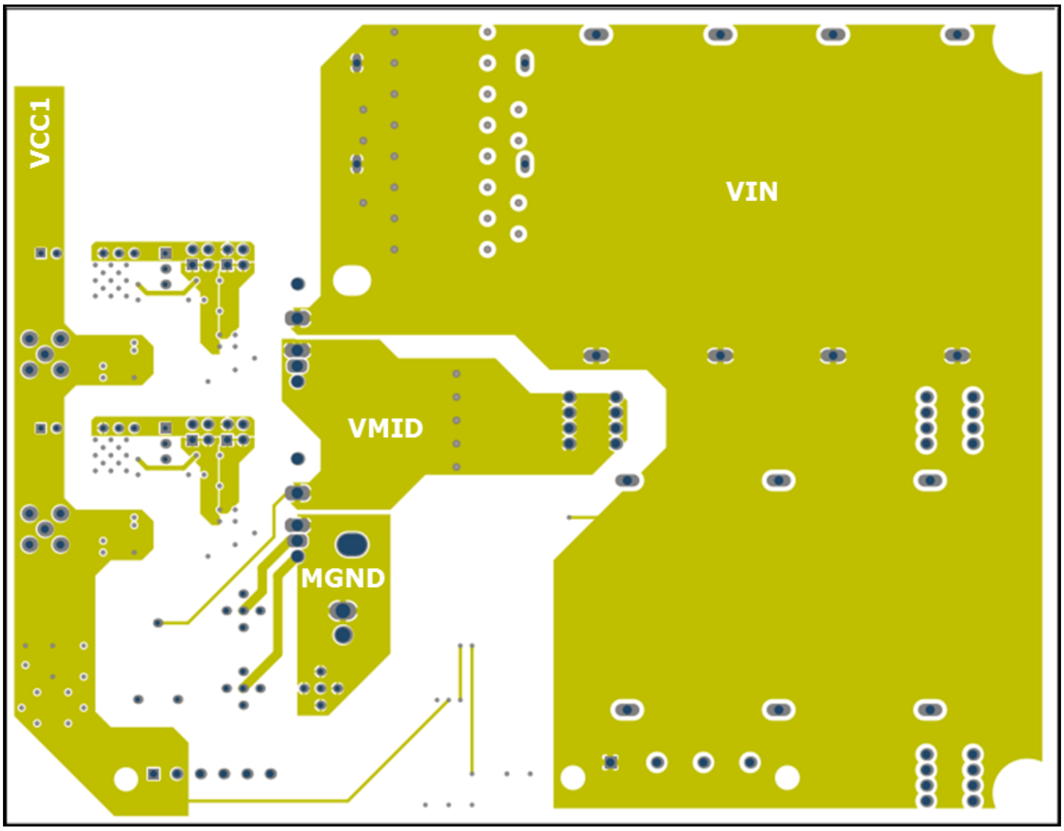


Figure 15 Layer 2

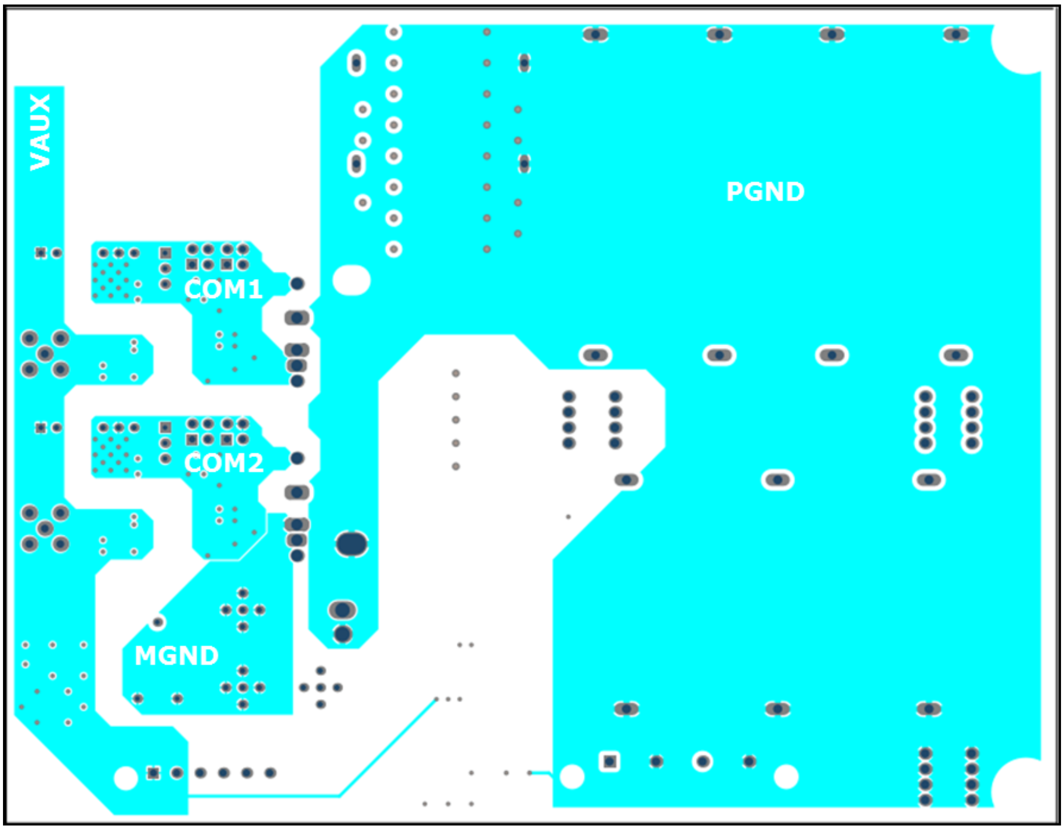


Figure 16 Layer 3

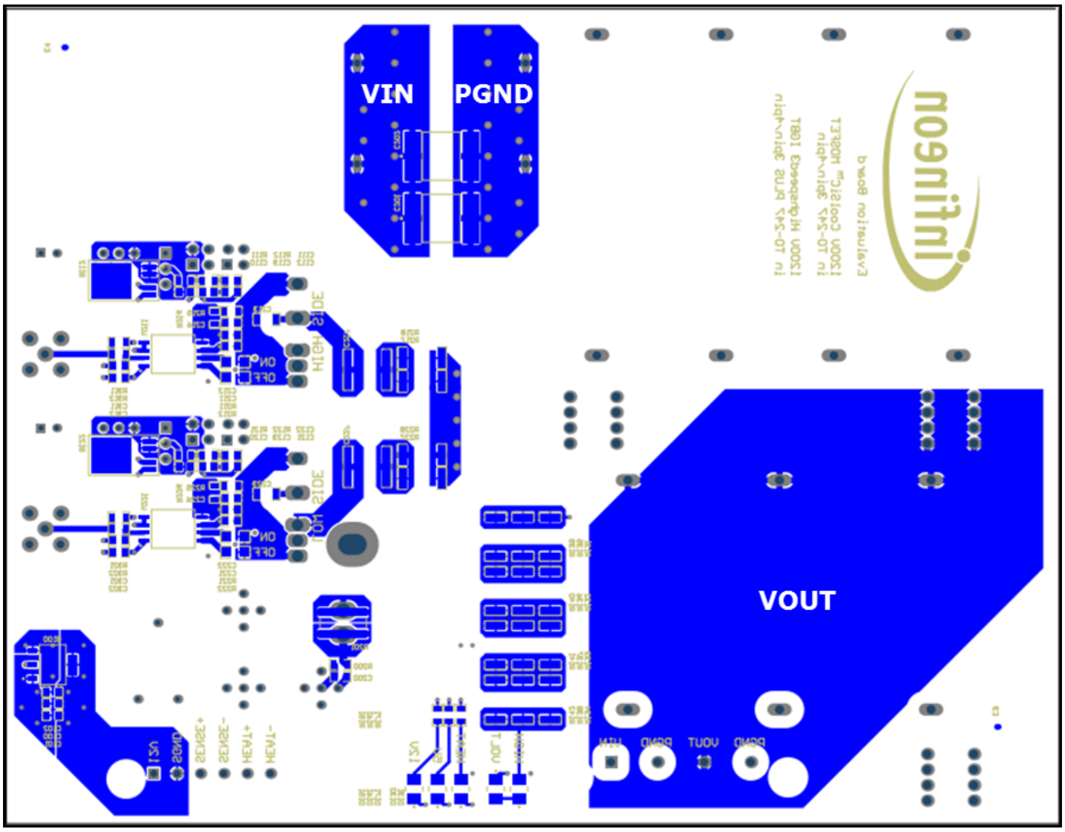


Figure 17 Layer 4 (bottom layer)

5.3 Bill of materials

Designator	Description	Value	Package
Power Semiconductors			
Q211	Power Semiconductor Switch	Infineon IMZ120R045M1	TO-247PLUS 4pin
Q221	Power Semiconductor Switch	Infineon IMZ120R045M1	TO-247PLUS 4pin
U211	Isolated Single Channel Driver	Infineon Technologies 1EDI20H12AH	PG-DSO-8-59
U221	Isolated Single Channel Driver	Infineon Technologies 1EDI20H12AH	PG-DSO-8-59
Ceramic Capacitors			
C100		4u7 X7R 25V	C 0805
C101		100n X7R 25V	C 0805
C102		4u7 X7R 25V	C 0805
C110		100n X7R 25V	C 0805
C111		10u X7R 35V	C 0805
C112		10u X7R 35V	C 0805
C113		10u X7R 35V	C 0805
C120		100n X7R 25V	C 0805
C121		10u X7R 35V	C 0805
C122		10u X7R 35V	C 0805
C123		10u X7R 35V	C 0805
C200		470pF C0G 50V	C 0805
C201		TDK Z63000Z2910Z 1 Z21	
C202		TDK Z63000Z2910Z 1 Z21	
C211		4u7 X7R 25V	C 0805
C212		4u7 X7R 25V	C 0805
C221		4u7 X7R 25V	C 0805
C222		4u7 X7R 25V	C 0805
C312		100n X7R 25V	C 0805
C322		100n X7R 25V	C 0805
Film Capacitors			
C203		EPCOS TDK B32654A7224	
C204		EPCOS TDK B32654A7224	
C205		EPCOS B32778G1276	
C206		EPCOS B32778G1276	
C207		EPCOS B32776T1275	
C208		EPCOS B32776T1275	
C209		EPCOS B32776T1275	
Light Emitting Diodes			
D131		Vishay VLMT3100-GS08	
D132		Vishay VLMT3100-GS08	
D133		Vishay VLMT3100-GS08	
D134		Vishay VLMT3100-GS08	
D151		Vishay VLMC3100-GS08	
D152		Vishay VLMC3100-GS08	
D161		Vishay VLMC3100-GS08	
D162		Vishay VLMC3100-GS08	
D171		Vishay VLMA3100-GS08	
D172		Vishay VLMA3100-GS08	
Thick Film Resistors			
R111		2k (1.8k) 1%	R 0805
R112		1k 1%	R 0805
R121		2k (1.8k) 1%	R 0805
R122		1k 1%	R 0805
R131		300k	R 2512
R132		300k	R 2512
R133		300k	R 2512
R134		300k	R 2512
R135		300k	R 2512
R136		300k	R 2512

Appendix

R137		300k	R 2512
R138		300k	R 2512
R139		300k	R 2512
R140		300k	R 2512
R141		300k	R 2512
R142		300k	R 2512
R151		2k2	R 0805
R161		270R	R 0805
R171		1k0	R 0805
R200		100R 1%, 25ppm/K	R 0805
R215		4k7	R 0805
R225		4k7	R 0805
R311		4k7	R 0805
R312		0R	R 0805
R321		4k7	R 0805
R322		0R	R 0805
Metal Foil Resistors			
R201		Ohmite FCSL76R050FER	
MiniMELF Resistors			
R211		10R 1%	R MMA 0204
R212		10R 1%	R MMA 0204
R213		0R 1%	R MMA 0204
R221		10R 1%	R MMA 0204
R222		10R 1%	R MMA 0204
R223		0R 1%	R MMA 0204
Connectors			
X111		Samtec TSW-102-07-L-D	
X112		Samtec TSW-102-07-L-D	
X121		Samtec TSW-102-07-L-D	
X122		Samtec TSW-102-07-L-D	
X201		Phoenix Contact 1812885	
X202		Phoenix Contact 1827907	
X204		Wurth Elektronik 93473	
X205		Wurth Elektronik 93473	
X206		Wurth Elektronik 93473	
X210		TE Connectivity 5-1814400-1	
X220		TE Connectivity 5-1814400-1	
X801		Phoenix Contact GMSTB 2,5 HCV/ 4-ST-7,62-LR - 1812775	
X802		Phoenix Contact MC 1,5/ 6-STF-3,81 - 1827745	
Mechanical			
A201	Heat Sink	Fischer Elektronik SK 492 50 SA	
MC821	Screw	M3 x 15mm, metal	
MC822	Screw	M3 x 15mm, metal	
MP801	Spacer bolt, hexagon	M3 x 60mm	
MP802	Spacer bolt, hexagon	M3 x 60mm	
MP803	Spacer bolt, hexagon	M3 x 60mm	
MP804	Spacer bolt, hexagon	M3 x 60mm	
MP805	Spacer bolt, hexagon	M3 x 10mm	
MP806	Spacer bolt, hexagon	M3 x 10mm	
MP807	Spacer bolt, hexagon	M3 x 10mm	
MP808	Spacer bolt, hexagon	M3 x 10mm	
MP811	Metal tube	ETTINGER 05.53.053	
MP812	Metal tube	ETTINGER 05.53.053	
MP813	Metal tube	ETTINGER 05.53.053	
MP814	Metal tube	ETTINGER 05.53.053	
MP831	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0	
MP832	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0	
MP833	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0	
MP834	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0	

Appendix

MP835	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0
MP836	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0
MP837	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0
MP838	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0
MP839	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0
MP840	Press Fit Pin	Mill-Max 8979-0-00-15-00-00-03-0
MP841	Isolation Foil	Bergquist Sil-Pad K10
MP842	Isolation Foil	Bergquist Sil-Pad K10
MP851	Spring Clip for TO-247	Fischerelektronik THFU 2
MP852	Spring Clip for TO-247	Fischerelektronik THFU 2
MP853	Spring Clip for TO-247	Fischerelektronik THFU 2
MP854	Spring Clip for TO-220	Fischerelektronik THFU 3
Others		
B200	NTC Resistor	US Sensor TO103J2F
E200	Power Resistor	Vishay LTO100F4R700FTE3
G100	Voltage Regulator	Infineon Technologies TLE4264-2G
G111	Isolated DC/DC	MuRata MGJ2D122005SC
G112	Voltage Regulator	Infineon Technologies IFX25401TEV
G121	Isolated DC/DC	MuRata MGJ2D122005SC
G122	Voltage Regulator	Infineon Technologies IFX25401TEV
Id2	Oscilloscope Probe Adapter	LeCroy PK106-4
R110	Potentiometer	Vishay T93YA502KT20
R120	Potentiometer	Vishay T93YA502KT20

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Major changes since the last revision

Page or Reference	Description of change
--	Revision 1.0 – First Release – Klaus Sobe

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