Automotive

Power Input Protection

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Contents

1. Introduction

Every automotive application can be divided into functional blocks in terms of the electronics that they contain. First of all, there are electronic blocks that deal with power and electronic blocks that deal with information. Bot of them have an interface to the surrounding environment and a main hub for processing the information or power.
In this respect the power electronics blocks are:

- Power Input Protection
- Power Management

While the signal electronics blocs are

- Communication Interface
- Signal Processing

These four blocks define a basic automotive Electronic Control Unit (ECU). However, there is no use of having an Automotive ECU without its main functionality. A fift block is therefore necessary in order to provide the means for controlling the main functionality of the application:

- Load Management

Therefore, the Load Management block is specific for every application: LED drivers for lighting units; MOSFET inverters for BLDC drivers; radar transmitters; camera lenses; lasers for lidars; amplifiers for audio and antennas for wireless communications.

The first four blocks are universal for most applications in their nature. However, there might be a difference in their scales. A central computer or ADAS control unit might have a large Signal Processing requirement that would require fast Communication Interface and substantial power requirements for the Power Management and Input Protection blocks. Compared to a lighting module that would still require substantial power but much less signal processing and communication bandwidth.

The interconnections of these blocks within the application of a Zone Control Unit are displayed below in Fig. 1.

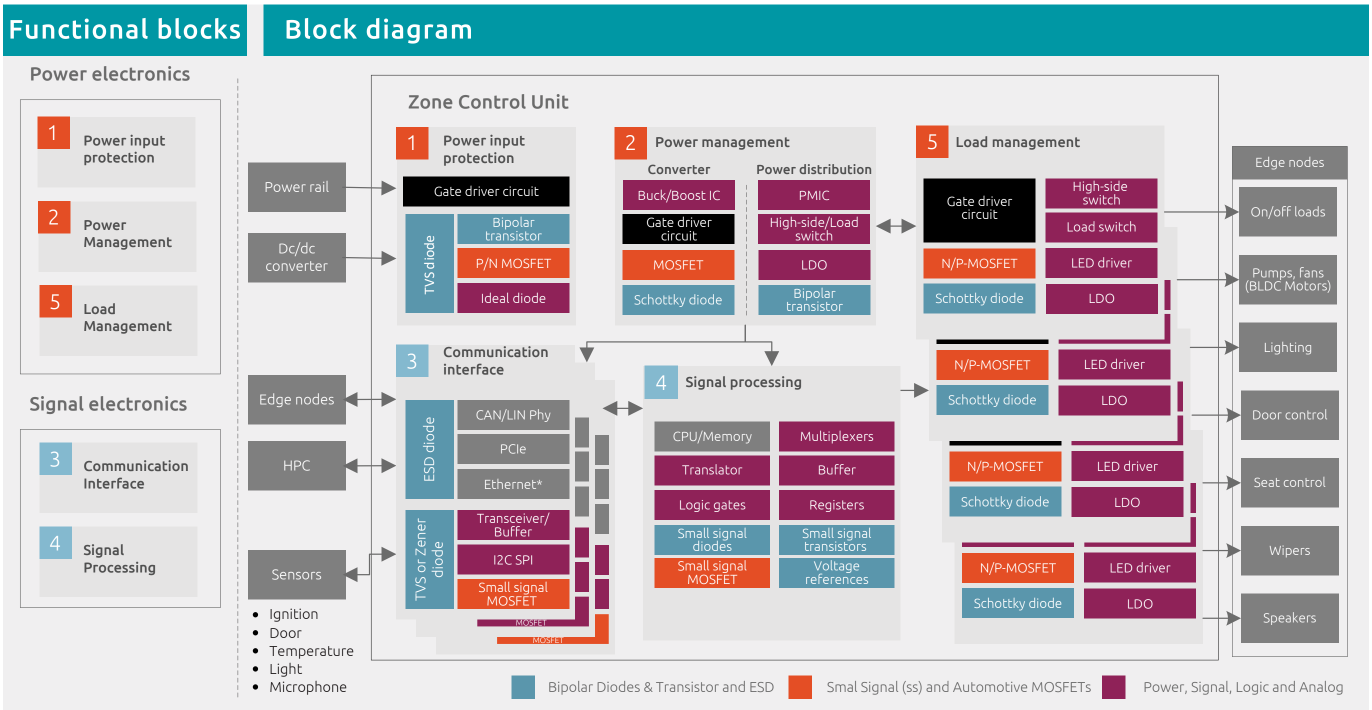


Fig. 1 Zone Control Unit internal electronics block diagram

As the main function is distribution of power and communications to the local actuators, the corresponding blocks appear multiple times.

1 The Power Input Protection block can take up substantial size and large power devices. Besides protecting the rest of the circuit from power surges it can also interconnect various energy supply sources like the batteries and dc/dc converter. It is important to protect the supplies in case the other collapses. It can also appear in several voltage levels like 12 V and 48 V in case the vehicle contains both power nets.

2 The Power Management block contains the means for transforming the incoming voltage to a level that is suitable for the rest of the components. The resulting voltage rails are used to fuel the signal processing and communication blocks. In vehicles with 48 V board nets, this is the place to transform the 48 V to 12 V or 16 V to supply legacy actuators. This is done via high power resonant converters, such as the Switched Tank Converter.

3 The Communication Interface block consists of a variety of communication protocols. Some of these could be analog and slow digital inputs towards sensors. Somewhat faster like IVN and ESD towards information rich peripherals such as ADAS cameras and radars. Audio signals can be transmitted to local speakers and received from microphones. Finally, the received information is translated and packed in a fast Ethernet protocol to communicate with other ZCUs and the central High-performance computer. All these information feeds need to have appropriate protection via ESD or TVS diodes, according to the speed and strength of the signal.

4 Finally, the Signal Processing block contains the Controller and Memory blocks. From the Nexperia arsenal logic gates and registers can be used to establish additional layers of logic and safety that are independent of the main controller; small signal discrete devices can be used for conditioning signals from nearby sensors; and multiplexers and analog switches to increase the digital and analog input channels of the controller.

In this Techbook the Power Input protection block is described in more detail. The challenges a designer might face are addressed with a proposal of appropriate devices and their design in procedures.

2. Design challenges and solutions

The sizing of the power input protection block depends on the amount of power the ECU itself needs to operate. ECU like ZCU or central computers have large power requirements due to their power-hungry signal processing units. Applications that drive BLDC motors, such as fans and pumps also use a large amount of power, however the power to the actuators is connected directly to their load management system and only a restricted amount of power goes through the Power Input protection block towards Signal processing and Communication interface blocks. There are further low power applications as well, such as cameras or radars that only require a few Watts of power and are mostly powered by Power over Coax and therefore do not need much of protection on the power input.

2.1. Protecting the electronics from negative overvoltages caused by reverse battery connection

To protect from these, a switch can be used. The realization of the switch can be with a recovery rectifier, Schottky rectifier, single N-channel MOSFETs or a P-channel MOSFET [AN50001]. For guidance on which one to opt with see Table I.

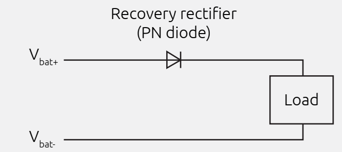
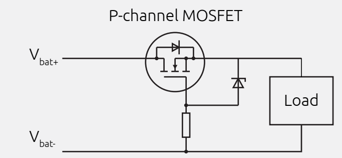
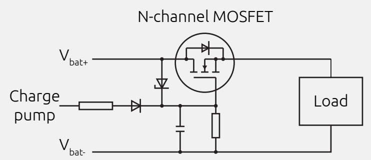
Recovery rectifier (PN diode) e.g. PNE20030EP in CPF5		› Low power ~ 1 A supply › Low cost › Device rating: 200 V; 3 A › High conduction loss
Schottky rectifier e.g. PMEG045T150EPD in CFP15		› Low - Medium power ~ 3 A supply › Slightly higher cost › Device rating: 45 V; 15 A › High leakage current, especially at high temperature
P-channel MOSFET e.g. BUK6Y14-40P in LFPAK56E		› Medium - High power ~ 5.7 A supply › Device specifications: 14 mΩ; 40 V; 110 W › High-side: very cost effective due to simple gate drive
N-channel MOSFET e.g. BUK7J1R4-40H in LFPAK56E		› High power ~ 25 A supply › Device specifications: 1.4 mΩ; 40 V; 395 W › High-side: requires charge pump circuitry, low-side is more cost effective

Table I Solutions for reverse battery protection

Automotive power rails experience high energy negative voltage spikes when inductive loads are disconnected. The ISO 7637 2 Pulse 1 transient is defined as –75 V to –150 V pulse of ~2 ms duration. A reverse battery protection diode must survive these negative spikes without entering breakdown or avalanche, and therefore 200 V rated recovery rectifiers are selected. Extra margin is required since ISO 16750 2 considers reverse battery connections for extended periods, and the transients stack up to these negative voltages. In case the real transient exceeds these values, recovery rectifiers offer strong avalanche capability, improving reliability and confidence in the design.

Suggested Nexperia 200V recovery rectifiers in CFP packages

CFP2-HP (SOD323HP)
2.2 X 1.3 X 0.68 mm*
$R_{th(j-sp)}$ = 6 K/W

CFP3 (SOD123W)
2.6 X 1.7 X 1.0 mm*
$R_{th(j-sp)}$ = 18 K/W

CFP5 (SOD128)
2.8 X 2.5 X 1.0 mm*
$R_{th(j-sp)}$ = 12 K/W

CFP15B (SOT1289B)
5.8 X 4.3 X 0.95 mm*
$R_{th(j-sp)}$ = 18 K/W

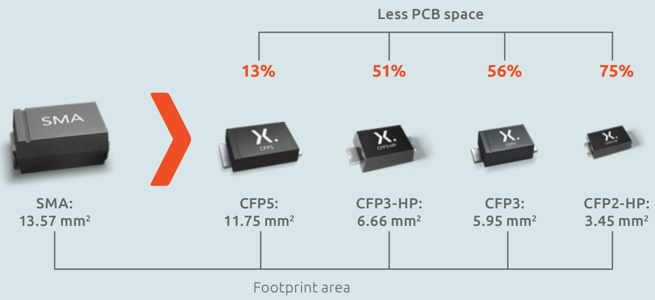
- 200 V – 650 V Ultra- and Hyperfast switching
- Optimized recovery time (t_{rr}) of up to < 30 ns
- Low voltage drop
- Low leakage current, also at high temperature
- High current pulse capability due to solid copper clip-bond (CFP packages)
- High power density / high efficiency planar technology
- Low magnetic inductance optimizes switching behavior

The decision on what device should be employed depends on how much it will heat up. Initial simulations and estimates can provide a ballpark figure, but experimental measurements are there to ensure the design is valid. A suggested measurement method has been proposed in Nexperia Technical Note TN90007. Even for the initial simulations, the designer needs information about the thermal resistance of the medium the device is connected to. These can also be measured via the virtual junction measurement method of TN90007.

If an appropriate TVS diode protection is provided for the large negative transient pulses Schottky diodes of 40-60 V rating can be employed to provide lower heat dissipation and therefore higher current capability, due to their inherently lower forward voltage drops compared to standard diode rectifiers. Nexperia offers Schottky diode technology with very low forward drop voltage. The Clip-bonded FlatPower (CFP) packages the devices are offered in enable miniaturization, and the copper clip employed ensures good thermal conductivity towards the PCB. This, in turn, ensures a large surge in current capability and high board-level reliability of the devices.

For more information on power diodes and their applications as well as the benefits of the CFP packages, have a look at Nexperias Power Rectifier webinars.

Suggested Nexperia Schottky diodes



- Solid copper clip for high thermal performance and power dissipation
- Reduced package inductance for improved switching behavior
- High reliability (2 x AEC-Q101, Board Level Reliability compliance)
- Free from delamination
- Junction temperature up to 175 °C
- Small, thin and light design
- Optimized lead form ensuring uniform solder joints for maximum flexibility in AOI

Recommended MOSFET packages for higher power reverse battery protection are Nexperia's range of LFPAK33 (3x3mm leaded, copper clip, BUK9Mxxx, BUK7Mxxx) and LFPAK56D (5x6mm dual, leaded, copper clip, BUK9Kxxx, BUK7Kxxx) packages and the newly introduced MLPAK33 (3x3mm micro-leaded, BUK9Qxxx, BUK9Qxxx) and MLPAK56 (5x6mm micro-leaded, BUK9Rxxx, BUK7Rxxx) packages. The dual packages can be convenient in case back-to-back protection is required, incorporating both reverse polarity protection and load switch in the same package. For even smaller designs, DFN2020MD-6 (2x2mm leadless, BUK6Dxxx or PMPBxxx) packages can be considered because of their good thermal performance. All these packages have a copper frame that allows for a good heat transfer from the device die to the PCB, yielding high gains in the thermal performance of the devices as shown in Application Note AN90003. This further opens the possibilities of cooling the device via copper plating of the PCB or just providing high copper content in all the PCB layers to allow for better heat distribution across the PCB and, thus, better heat convection and radiation into the environment [AN50019]. Nexperia's precision electrothermal models allow for making thermal considerations easier [AN90034]. All of the packages discussed allow for automatic optical inspection, which is enabled by the side wettable flanks (SWF) in the case of the micro-leaded and leadless package types.

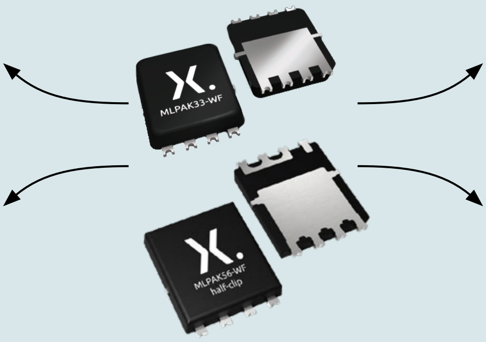
Suggested Nexperia micro-leaded MOSFETs

Automotive quality

- Automotive Qualified to AEC-Q101 standard

System level savings

- Ultra compact footprint
  - MLPAK33-WF = 10.9 mm²
  - MLPAK56-WF = 31.9 mm²
- Footprint compatible with industry standard packages



High manufacturing reliability

- Micro-leaded design
- Side wettable flanks for Automated Optical Inspection (AOI)

High power density

- Low $R_{DS(on)}$
  - ≥ 1mΩ in MLPAK56-WF
  - ≥ 2mΩ in MLPAK33-WF
- High current capability
  - ID max < 71A
- Low thermal resistance
  - Rch (j-mb) max > 1.54 K/W for MLPAK56-WF
  - Rch (j-mb) max > 2.5 K/W for MLPAK33-WF

MLPAK devices are micro-leaded and can host a larger die. Although their board level reliability is lower than of the LFPAK devices they are still automotive qualified and can be used in applications with high thermal fatigue. The relationship between different devices board level reliability is illustrated in Fig. 2 and a detailed account of the comparison is provided a Nexperia conference paper from APEC 2025.

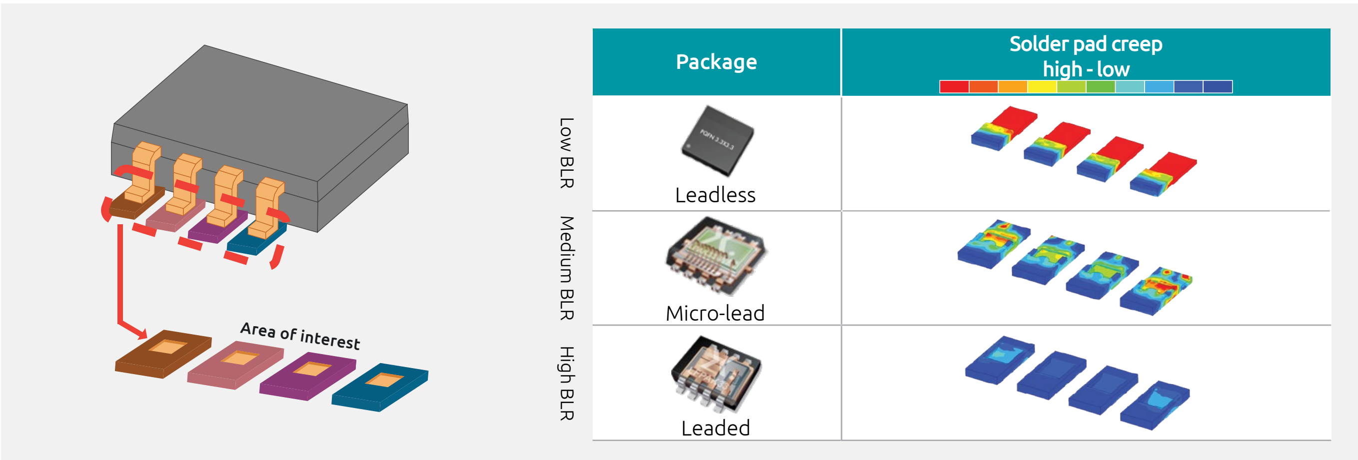


Fig. 2 3x3mm packages solder pad creep strain comparison

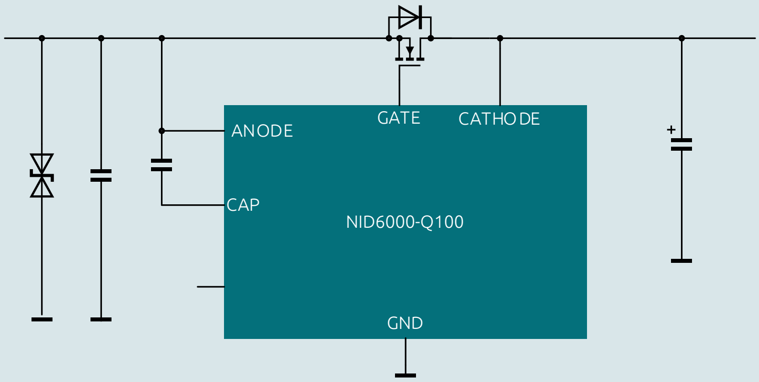
In case the supply structure of the vehicle is 48 V, Nexperia offers a range of 80 V and 100 V devices in small packages that have a good conduction and switching performance as well:

V_{DS}	 LFPAK56D/ HB	 LFPAK33	 MLPAK33-WF	 DFN2020MD-6
80 V	12-49 mΩ	12-48 mΩ	14-45 mΩ	81-230 mΩ
100 V	24-134 mΩ	34-156 mΩ	16-50 mΩ	385 mΩ

Table II Overview of Nexperia 80 V and 100 V MOSFETs

For controlling the N-channel MOSFETs ideal diode controllers can be used. The controllers ease the design in process of a discrete circuit and have added functionality. The precision of these controllers provides the possibility to rely on their protection without designing in the tolerances of the discrete counterparts. They also control the devices to a precise voltage drop (they are not fully on) maintaining the operating point on the knee of the device output characteristics for very rapid transition to a blocking state in case of need.

Suggested Nexperia Ideal Diode Controller: NID6000-Q100



- Automotive AEC-Q100 Qualified
- Operating Supply 3.2 V – 65 V, for 12 V and 24 V applications
- 20 mV regulated Anode to Cathode forward voltage drop
- 2.3 A peak gate turnoff current
- Reverse Current Blocking & Reverse Polarity Protection
- -65 V input reverse voltage rating
- Meets ISO 7637-2 transient requirement with TVS diode
- Functional safety capable (ISO 26262 and IEC 61508)

Another discrete realisation can be established with power P-channel MOSFETs. In the case of P-channel MOSFET, a single signal MOSFET is needed to control the power MOSFET

Nexperia's portfolio of P-channel devices covers applications on all automotive distribution voltage levels from 12 to 48 V as well as in a range of power levels as seen in the table below.

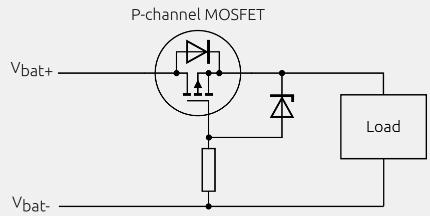


Fig. 3 Reverse battery protection with P-channel MOSFETs.

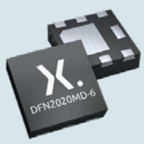
V_{DS}	 LFPAK56	 LFPAK33	 MLPAK33	 DFN2020MD-6
20 V				19-122 mΩ
28 V / 30 V	10-19 mΩ		7.5 & 21 mΩ	24, 40, 50 mΩ
40 V	14-24 mΩ		12 & 26 mΩ	43 mΩ
60 V	33-61 mΩ	61 mΩ	66 mΩ	120 mΩ
80 V	55 mΩ			120 & 220 mΩ

Table III Nexperia's P-channel MOSFET portfolio

2.2. Maintaining power supply integrity with multiple power supplies

The Power Input Protection plays an especially important role in power-distributing applications like ZCU, electronic power distribution board or domain control units. It replaces the blade fuses with electronic, intelligent ones and connects the various power supplies. On a new BEV or HEV it is not uncommon to have 12 V or 48 V and high-voltage (HV) battery as well.

The interconnection of the various sources is enabled by appropriate Power Input Protection block design. For example, there can be a connection to the 48 V battery, 48 V side of the HV/LV dc/dc and a 12 V battery, with a 48 V to 12 V converter within the application (for example ZCU), as shown in Fig. 4. As the batteries are directly connected to the Power input protection via short and thick conductors, the potential currents flowing can reach several hundred Amperes. Additionally, there might be requirements to obtain a certain voltage level for a brief time period at a fault occurrence on either supply side to enable safe shutdown of critical loads. This means that the MOSFETs would need to survive high currents in linear mode operation for substantial intervals (from the MOSFET robustness perspective).

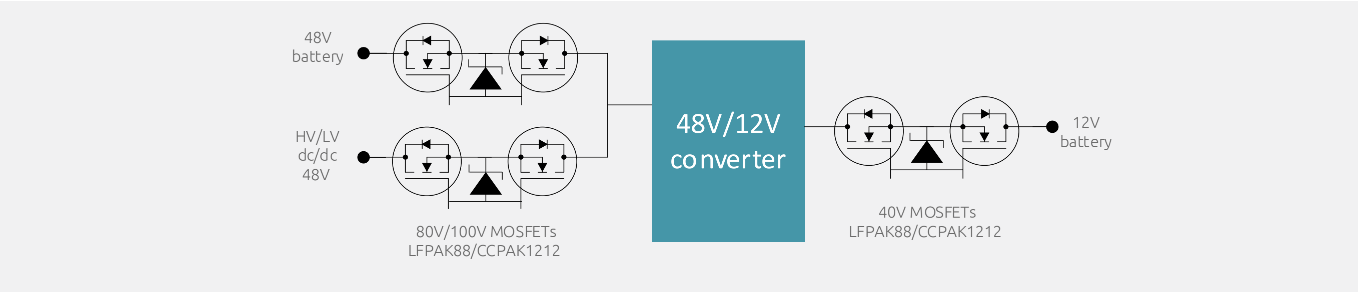


Fig. 4 Example of Front ZCU power inputs

Nexperia Solution

For this reason, the MOSFETs selected for this application are of the largest die and package and can be stacked in parallel. Their switching behaviour is not of great significance, but parameters important for paralleling should be tightly regulated (e.g. R_{dson}, V_{gsth} and Q_{gtot}). The effect of the spread of these parameters can be counteracted by splitting the gate resistor between one close to the MOSFETs gate and a common one at the driver side. This modification will improve the sharing with huge benefits during switching as shown in Fig. 5. For more details and other techniques as PCB routing, cooling recommendations and advice on simulations see Nexperia Application Note AN50005.

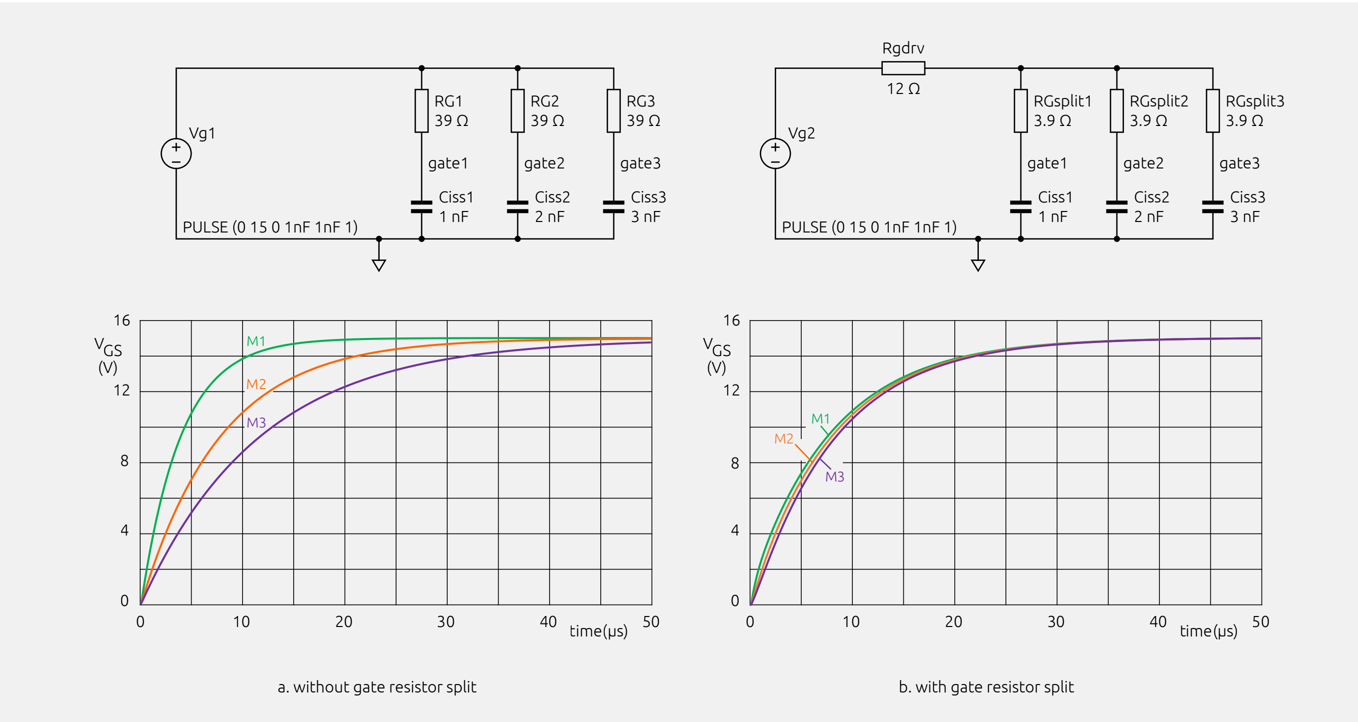


Fig. 5 Gate resistor split effect on parallelled MOSFET switching performance

Additionally, it's worth noting that the waveforms of the MOSFET currents and voltages have a great impact on their linear mode capabilities. They can be compared in the Fig. 5 and more information can be obtained in the Nexperia article published on APEC 2025. This effectively means that triangular pulses allow for doubling the SOA area from the device datasheets.

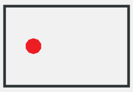
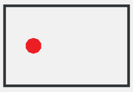
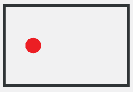
Pulse (20V, 10ms)	Max current	Peak Temp	Hotspot location
Square pulse	1.02A	83.0 °C	
Triangular pulse (Active clamp)	2.27A	77.7 °C	
Triangular pulse (Inrush current)	2.34A	81.1 °C	

Table IV Comparison of MOSFET behaviour in triangular and square wave pulses in linear region.

The paralleling issues are smaller if less MOSFETs are paralleled. For this reason, Nexperia has released worlds biggest package and die area MOSFETs in its CCPAK1212 package. A comparison with TOLT packages can be seen in Fig. 6 and Fig. 7.

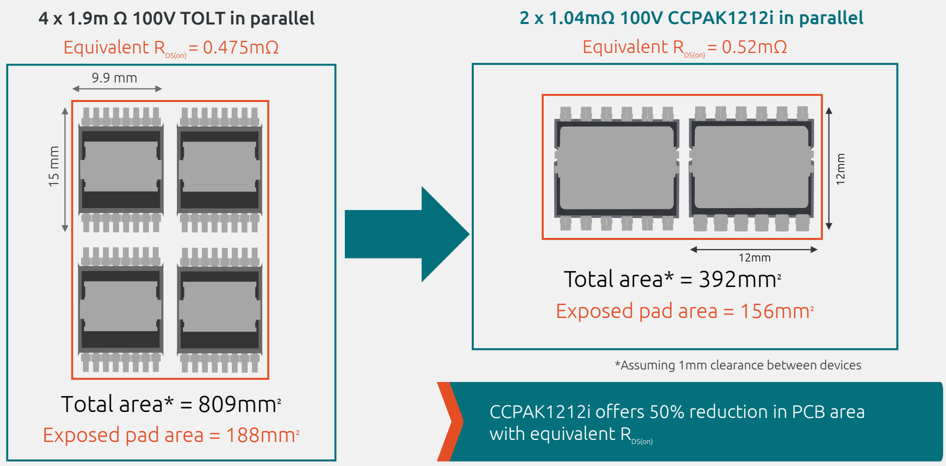


Fig. 6 Comparison parallel MOSFET design with TOLT and CCPAKi packages.

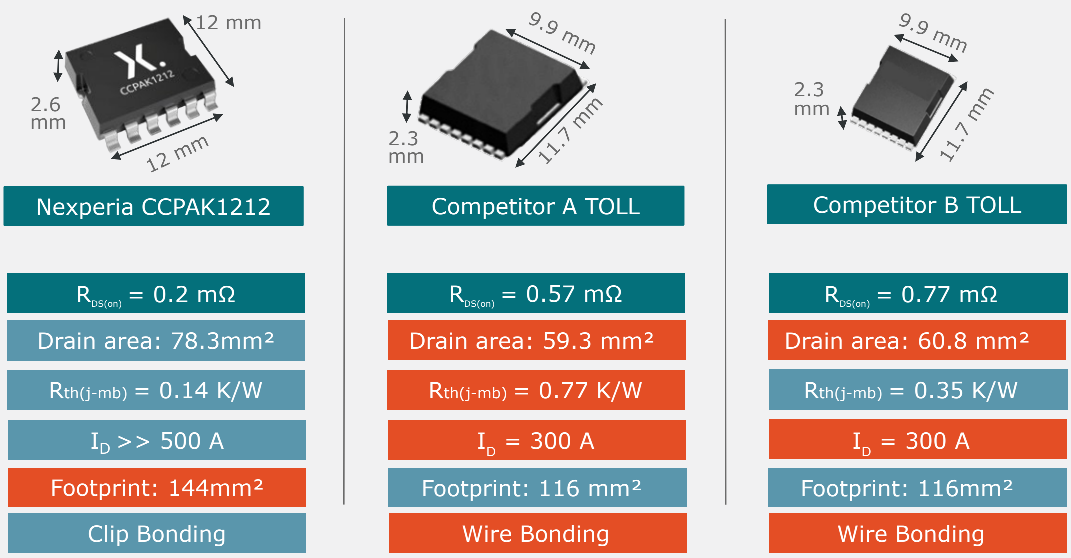


Fig. 7 Comparison of CCPAK1212 and TOLL MOSFET devices in 40V technology.

All these packages have a copper frame that allows for a good heat transfer from the device die to the PCB, yielding high gains in the thermal performance of the devices as shown in Application Note AN90003. This further opens the possibilities of cooling the device via copper plating of the PCB or just providing high copper content in all the PCB layers to allow for better heat distribution across the PCB and, thus, better heat convection and radiation into the environment [AN50019]. Nexperia's precision electrothermal models allow for making thermal considerations easier [AN90034].

2.3. Protecting ECU electronics from surges and disturbances on the power signal lines

The protection from overvoltage events can be realised with TVS diodes. Unidirectional TVS diodes can be used in twos or in combination with reverse polarity protection diode or the protection switches described above, to replace bidirectional functionality as shown in Fig. 8.

How to choose the right solution: Choosing a TVS solution starts with context. Engineers need to distinguish requirements between board-level protection and primary design protection. Further, the types of transients expected to impact the circuit have to be considered – for example a lightning strike differs from voltage overshoots created by load change and non-perfect voltage relation. Temperature also plays a role in finding the right device: as temperature increases, the power rating of a TVS diode decreases.

With our product selector, simply start by looking at the Reverse Standoff Voltage or Reverse Working Voltage (V_{RWM} or V_{WWM}), which is the peak of normal DC operation in a circuit. Typically 15% higher than this value, the Reverse Breakdown Voltage (V_{BR}) is the point where a TVS diode enters low-impedance mode thanks to avalanche breakdown. Once these two parameters are defined, review the Peak Pulse Current (I_{PP}) of the TVS for typical waveforms at 8/20 µs acc. to IEC 61000-4-5 and/or 10/1000 µs acc. to IEC 41643-21 pulse testing. Clamping Voltage (V_{CL}) requirements are derived from these values. When the voltage on the protected line reaches the TVS breakdown voltage, it will start conducting current to ground, resulting in the voltage being clamped to V_{CL}. To select a suitable solution, make sure the V_{RWM} is equal to or higher than V_{Bus}, but never surpass the V_{CC} limits of any of the circuit's components.

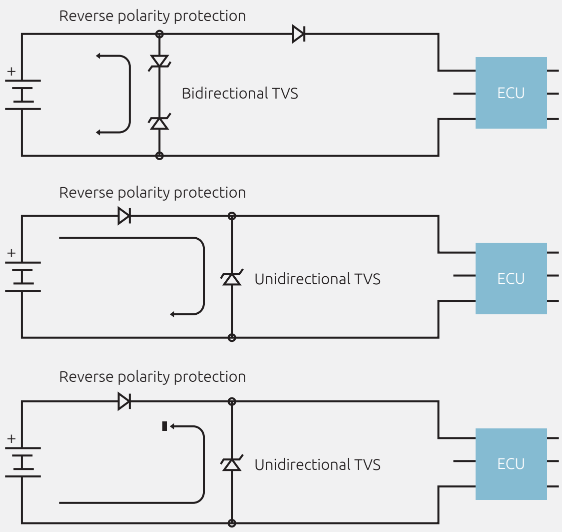


Fig. 8 Current flow for positive and negative pulses with bidirectional and unidirectional TVS

Suggested Nexperia TVS Portfolio

Package	Voltage	10/1000 µs Power Rating
SOD123W	3.5 – 64 V	400W
SOD128	3.5 – 64 V	600W

- Small plastic packages with very low height
- Up to 50% board space saving compared to SMA/SMB packages
- Wide range of voltage choices from 3.3 to 64 V
- Automotive qualified up to junction temperature of 185 °C

3. Recommended products

3.1 Power electronics

Product	Description	Key part numbers
Power input protection		
TVS and ESD protection devices		
TVS Diodes	SOD128, 600 W Transient Voltage Suppressor, Reverse standoff voltage range: 3.3-64 V	PTVS16VP1UP-Q
	SOD128, 600 W Transient Voltage Suppressor, Reverse standoff voltage range: 3.3-64 V, <185°C Temperature stability	PTVS16VP1UTP-Q
	SOD123 W, 400 W Transient Voltage Suppressor, Reverse standoff voltage range: 3.3-64V	PTVS33VS1UR-Q
	SOD123 W, 400 W Transient Voltage Suppressor, Reverse standoff voltage range: 3.3-64 V, <185°C Temperature stability	PTVS33VS1UTR-Q
	DFN1006-2, Ultra Compact Transient Voltage Suppressor	PTVS4V5D1BL, Q PTVS5V5D1BL-Q
Load switch and reverse battery protection		
Schottky Diodes	40 V, medium power, low V_F Schottky barrier rectifier in CFP package	PMEG4050E(T)P-Q, PMEG4030E(T)P-Q
	30 V, medium power, low V_F Schottky barrier rectifier in CFP package	PMEG3050(B)EP-Q, PMEG3030(B)EP-Q
P-channel MOS	LFPAK56, LFPAK33, MLPAK33 and DFN2020MD, 20-80 V, P-channel devices	BUK6Y14-40P, BUK6Y24-40P, BUK6Q12-40P
N-channel MOS	LFPAK33, 40 V, N-channel device, R_{DSon} 3-15 mOhm	BUK9M3R3-40H, BUK9M4R3-40H, BUK9M7R2-40E BUK9M9R1-40E, BUK7M8R0-40E, BUK7M10-40E, BUK7M12-40E
	LFPAK56D, 40 V, Dual N-channel device, R_{DSon} 3-30 mOhm	BUK9K13-40H, BUK9K6R2-40E, BUK9K6R8-40E, BUK9K8R7-40E, BUK7K6R2-40E, BUK7K6R8-40E, BUK7K8R7-40E
	DFN2020MD-6, 40 V, N-channel device, R_{DSon} 10-30 mOhm	BUK9D23-40E, BUK6D23-40E, BUK7D25-40E, BUK6D30-40E
	MLPAK33, 40 V, N-channel devices, 4.6-7.5mOhm, Logic Level gate threshold	BUK9Q4R6-40H, BUK9Q7R0-40H, BUK7Q4R9-40H, BUK7Q6R0-40H, BUK7Q7R5-40H
	SOT457, 40 V, N-channel device	PMN20ENA, PMN30ENEA
Bipolar transistors	Low voltage, leadless package, linear mode low V_{CEsat} devices	PBSS4310PAS-Q, PBSS4620PA-Q
Integrated load switch	5.5 V, load switch with precision current limit	NPS4053-Q100, NPS4001-Q100, NPS4069-Q100
Ideal diodes	1.5 A Ideal Diode with Reverse Polarity Protection	NID5100-Q100

4. References

Nexperia handbooks

MOSFET and GaN FET application handbook

ESD Application Handbook

Bipolar Junction Transistor (BJT) Application Handbook

Diode fundamentals, characteristics and applications

Logic product features and application insights

Application notes

AN50001 | Reverse battery protection in automotive applications -

AN50005 | Paralleling power MOSFETs in high power applications -

AN50019 | Thermal boundary condition study on MOSFET packages and PCB substrates -

AN90003 | LFPAK MOSFET thermal design guide -

AN90034 | Nexperia Precision Electrothermal models in SPICE and VHDL-AMS for Power MOSFETs -

TN90007 | Evaluation of junction temperature and thermal stacks using the virtual junction -

Other collaterals

Whitepaper | Side-WettableFlanks -

Brochure | CFP_Schottky_rectifier -

Leaflet | LFPAK56D_factsheet -

Leaflet | DFN2020MD-6 -

Webinar | Power Rectifier Webinar Series -

2025 IEEE Applied Power Electronics Conference and Exposition (APEC) | Board Level Reliability of Gull-wing, Micro-leaded and Lead-less Packaged MOSFETs in Automotive Environments

2024 IEEE Applied Power Electronics Conference and Exposition (APEC) | Triangular and Rectangular Power Pulses in Automotive MOSFETs Applications for Thermally Unstable Linear Mode

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