

Automotive MOSFETs

Reverse Battery Protection

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Automotive Power



Never stop thinking

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1 Abstract

This Application Note is intended to provide an overview of reverse battery protection in automotive applications. The pros and cons of each solution will be discussed.

2 Introduction

By changing the battery of a car or during maintenance work on the electronic system of a car, the battery has to be reconnected. During this event, it is possible that the polarity of the battery could be applied in reverse direction. Today's battery terminals are marked with colours and the terminal post itself are mechanically different, nevertheless the possibility for reverse battery is still present, at least for short connection duration.

With reverse applied voltage, a short circuit via diodes or transistors could occur, leading to fatal errors of the electronics of the car. This means, that the ECUs (Electronic Control Unit) have to be protected against reverse battery polarity.

3 Possible Solutions

In this chapter three most common reverse battery protection circuits will be discussed. A solution with relay is not taken into account.

3.1 Reverse Battery Protection with Diode

The easiest way for reverse battery protection would be a series diode in the positive supply line to the ECU accordingly the load. By applying the battery in the wrong polarity the pn junction of the diode blocks the battery voltage and the electronics are protected.

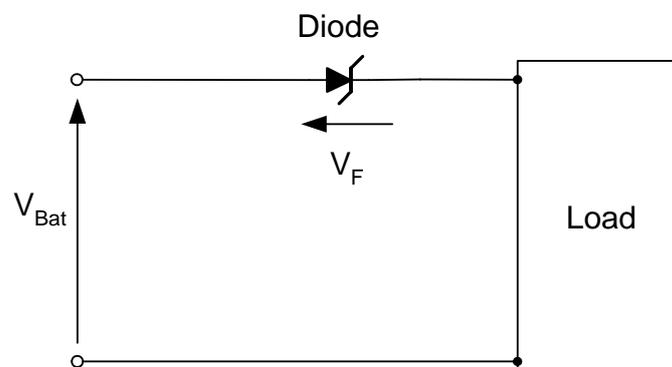


Figure 1 Solution with diode

From a correctly installed battery the supply current is flowing in forward direction through the diode to the load.

Power losses of the diode can be calculated easily with its forward voltage drop characteristic.

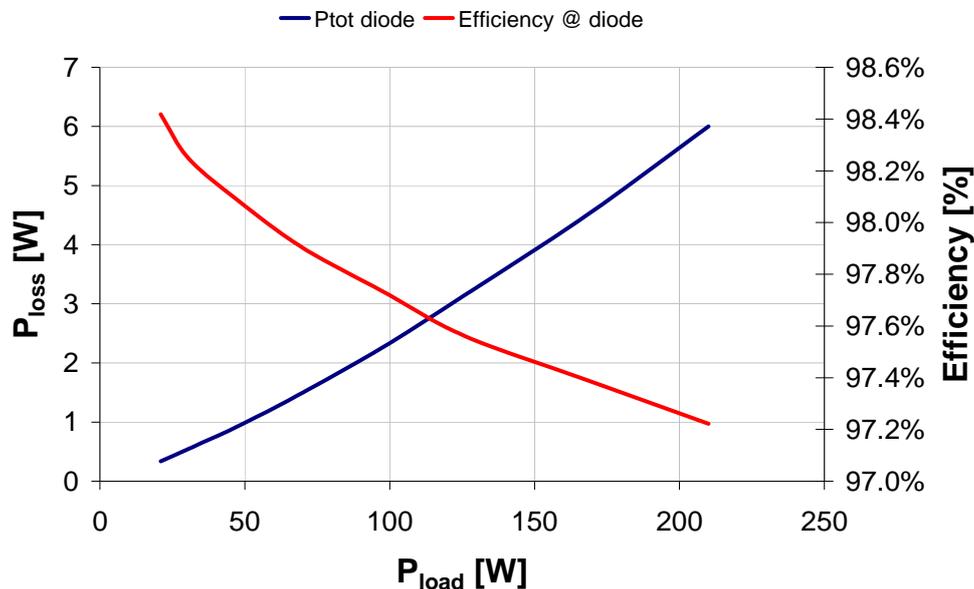


Figure 2 $P_{tot} = f(P_{load})$ for diode solution

Figure 1 shows an example of a solution using 45V rated Schottky diode(s). The total power losses as a function of the power rating of the load with the assumption of a battery voltage of 14V are shown. If the power losses at high output powers can not be handled by one diode, several devices have to be connected in parallel. Due to the diode threshold, which is a constant, switching the devices in parallel the total power losses will stay more or less at the same level. They will be distributed only according to the amount of used diodes.

3.2 Reverse Battery Protection with n-channel MOSFET

To lower the power losses of the reverse battery protection, a MOSFET can be used. Inserting such a device in the right direction in the positive supply line can protect the load against reversal battery as well. Note that a MOSFET has always an intrinsic anti parallel body diode.

The MOSFET is fully turned on when applying the battery in the right direction. Due to the fact that the Source is at high potential, the MOSFET is a high side switch not referenced to ground. A charge pump circuit (or something equivalent) is needed to boost the Gate-voltage over the Source-voltage to turn the MOSFET on.

During reverse polarity of the battery, the diode in the ground line of the charge pump blocks the voltage. No voltage supplies the Gate and the MOSFET will be switched off. The diode protects as well the charge pump against reverse battery. Otherwise a short via the two transistors would occur.

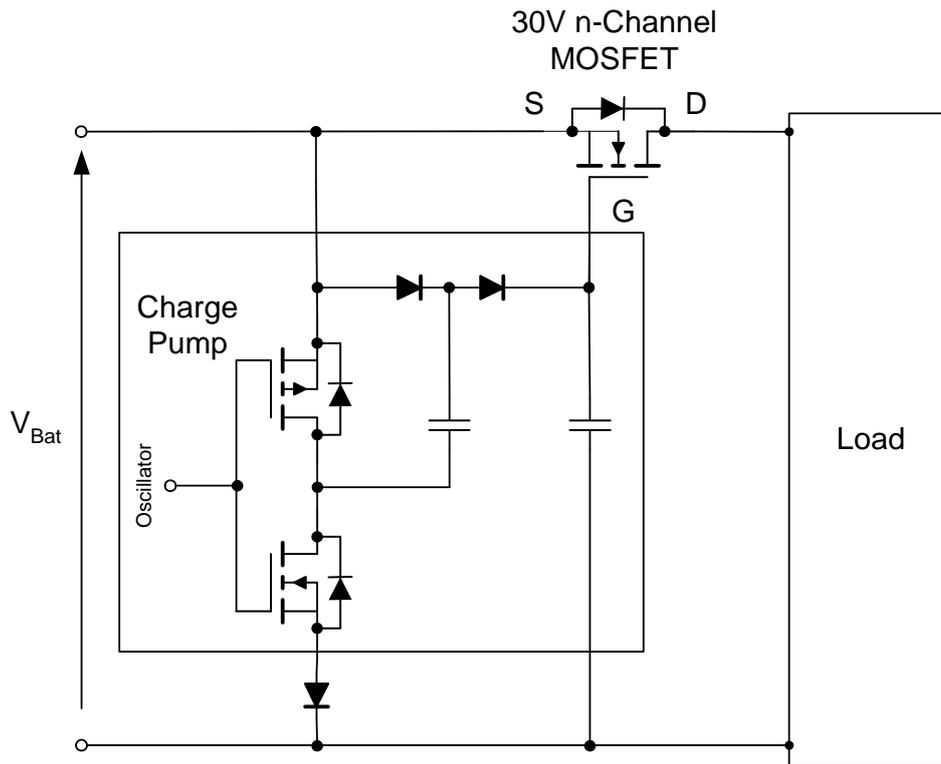


Figure 3 Solution with n-channel MOSFET

Figure 3 shows a typical solution for reverse battery protection with an n-channel MOSFET.

The power losses of an n-channel MOSFET for a reverse battery protection are determined by the $R_{DS(on)}$ of the device and the load current. Switching losses can be neglected because the device will be switched on once when the battery is applied and stays in on state during normal operation. The power losses and ratio of power losses versus output power are shown in Figure 4 with an example of a 30V, 3.3mOhm MOSFET (SPP100N03S2-03).

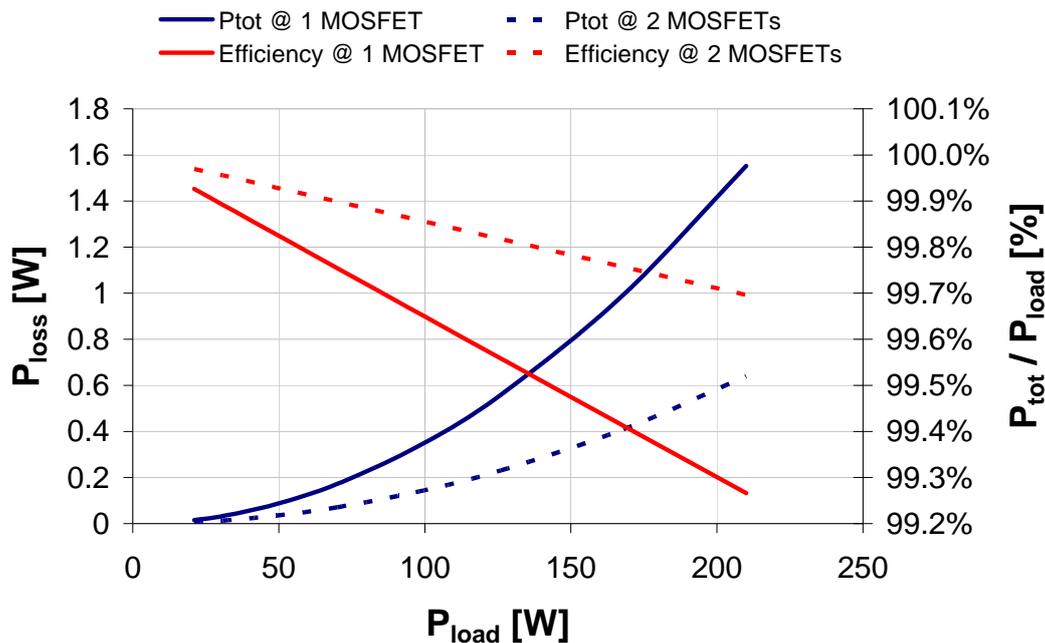


Figure 4 $P_{tot} = f(P_{load})$ for n-channel MOSFET (1 and 2 in parallel) solution

The power losses of the MOSFET are increasing by the power of two over the output power and decreasing linearly by the size of the MOSFET. Meaning by switching two MOSFETs in parallel the power losses will be reduced by a factor of two. This means by switching n MOSFETs in parallel, the total power losses will be reduced by a factor of n and the power losses which has to be handled by each MOSFET will be reduced by n^2 .

Such a solution would be feasible for high output power requirements.

The drawback of this solution is the additional circuit effort which has to be spent to drive the n-channel MOSFET during normal operation. A charge pump circuit is needed to create the required offset on the Gate pin over the battery line.

EMI is an issue because the oscillator of the charge pump circuit is switching the two MOSFETs. But the power which will be handled by the charge pump is not significant because the power MOSFET is switched on only once. This means that the EMI is not as high as it is normally by dealing with such circuits.

It is not always possible in automotive applications to insert the MOSFET in the ground line to eliminate the need for the high side driver. The voltage drop over such a MOSFET connected to a ground line would result in a shift of the ground level. For sensitive loads this can lead to malfunction.

3.3 Reverse Battery protection with p-channel MOSFET

The third solution to achieve reverse battery protection would be to connect a p-channel MOSFET in the positive supply line of the load. It is again important to insert the transistor in the right direction, because the p-channel MOSFET has as well an intrinsic anti parallel body diode. Note: For a p-channel MOSFET the diode is in forward direction from Drain to Source.

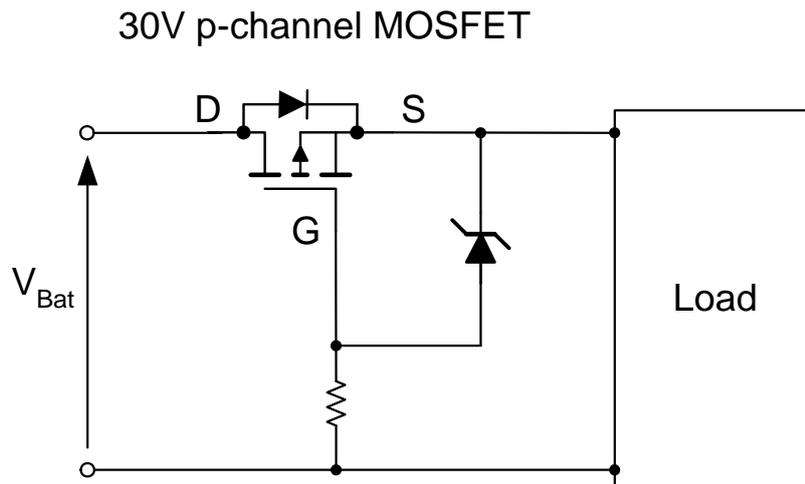


Figure 5 Solution with p-channel MOSFET

The huge benefit by using a p-channel MOSFET belongs to the fact, that no additional high side driver circuit is needed. Compared to an n-channel MOSFET the device will be turned on by applying a negative Gate Source voltage. By referring the Gate signal to the ground line, the device is fully turned on when the battery is applied in the right polarity. For the first start up, the intrinsic body diode of the MOSFET will conduct, until the channel is switched on in parallel. The Zener diode will clamp the Gate of the MOSFET to its Zener voltage and protecting it against over voltage.

By reverse polarity, the MOSFET will be switched off, because the Gate Source voltage for this case will be positive (voltage drop over the Zener diode).

The main difference in terms of technology between an n-channel MOSFET and a p-channel MOSFET is the inverse doping profile over the whole device as it can be seen in Figure 6.

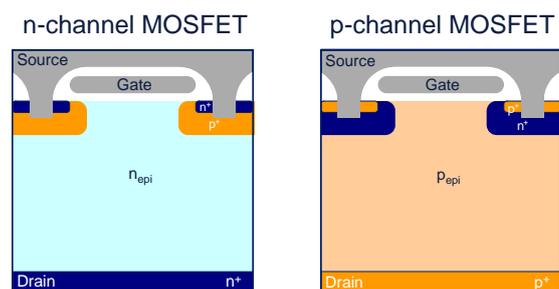


Figure 6 Cross section of a planar n-channel and p-channel MOSFET

To switch on a p-channel MOSFET a negative Gate Source voltage has to be applied. The electrical field will push the electrons in the channel region back and will attract the holes, the “p-channel” is created and a load current can flow through the device. But this current is a hole current and not an electron current as for an n-channel MOSFET. Holes do not have the same mobility of electrons. It is much harder to push them through the device, resulting in a higher area specific on state resistance. In the past this was a blocking point for the use of a p-channel MOSFET because you have to replace an n-channel MOSFET with a two to three times larger p-channel. With today’s technologies it is possible to shrink the p-FET and the price is going down accordingly.

The power losses of a p-channel MOSFET versus the output power and the efficiency are shown in Figure 7. By switching several MOSFETs in parallel the same effect is valid as for n-channel MOSFETs. The power losses of each device are decreasing with a dependency of n^2 .

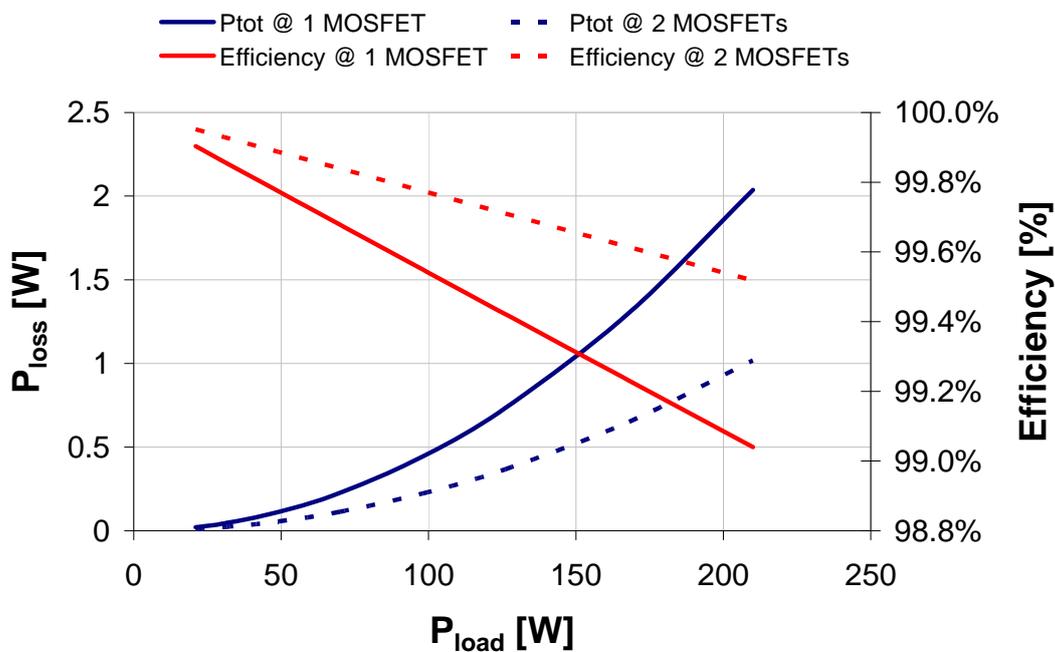


Figure 7 $P_{tot} = f(P_{load})$ for p-channel MOSFET solution

4 MOSFETs and ISO pulses

One common point of uncertainty for the development of the application using MOSFETs as reverse polarity protection is related to the ISO pulses.

Basis for most OEM or TIER 1 is the ISO 7637-1 plus some tailored add-on tests.

Impulstyp	Anzahl	U_s (V)	t_d (μ s)	t_r (μ s)	Generator		Bemerkung
					R_1 (Ω)		
					12 V	42 V	
Impuls 1	5 000 Impulse	-100	2 000	1	4	10	Spannungsabschaltung für 200 ms
Impuls 2	5 000 Impulse	+75	50	1	4	10	
Impuls 3a	2 h 10 Hz	-150	0,1	0,005	50		Burstimpuls
Impuls 3b	2 h 10 Hz	+100	0,1	0,005	50		Burstimpuls
Impuls 6	1 000 Impulse	-50	200 bis 500	1	4	10	Einstellung im Leerlauf, dann erst Parallel zur Bordnetznachbildung an-klemmen

Table 1 ISO pulses VW standard puls 1 – 3 and 6 (12V and 42V)

Typical IC products are commonly protected against the high voltage transients with special protection circuits. The MOSFET however is not protected against these transients as a stand alone component. How should these transients be considered during the selection of the right reverse polarity protection concept?

First: The only critical pulses for the MOSFETs used as reverse polarity protection are the negative transients. The positive ISO pulses will pass the MOSFET via its intrinsic body diode or the parallel connection of the MOS-channel and the diode.

Second: the first point is valid as well for n-channel MOSFET as for p-channel MOSFETs (and finally as well for a diode solution).

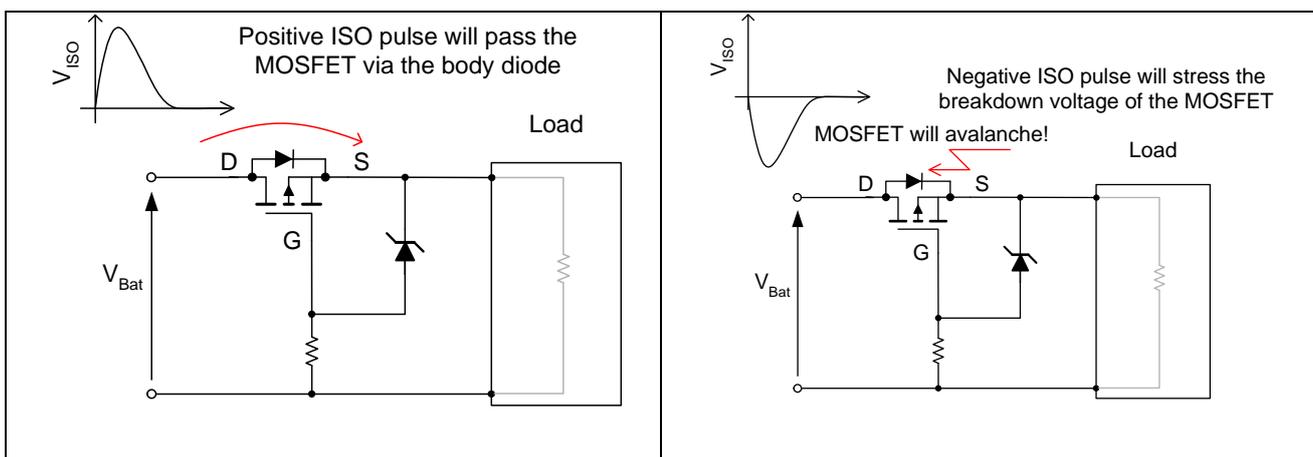


Figure 8 Reverse polarity MOSFET pass the positive and block or avalanche the negative ISO pulse

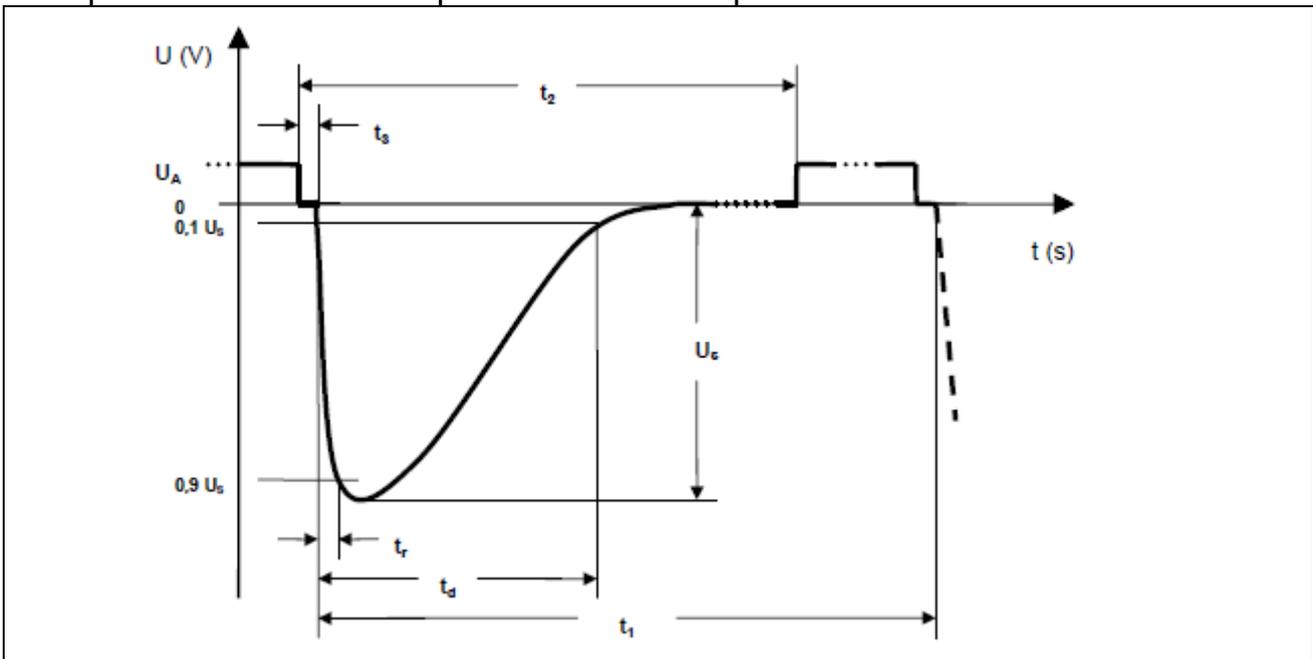
If the negative pulses (e.g. Impulse 1 or 3a or 6 out of Table 1) will reach the MOSFET, the device will go to avalanche mode if the breakdown voltage of the MOSFET is significantly exceeded (as a rule of thumb: avalanche occurs at 1.4 times the rated min breakdown voltage of a low voltage MOSFET up to 100V).

As the pulses are all repetitive (up to 72,000 pulses for 3a and 3b) and repetitive avalanche is not specified in today's data sheets, the device will operate in a grey

area. However for a single pulse the avalanche energy could be calculated and the according increase of the junction temperature of the MOSFET defined.

4.1 Calculation example

MOSFET: IPD80P03P4L-07
 OptiMOS P2 technology
 Min breakdown voltage = 30V
 Typ avalanche voltage = 1.4 x 30V = 42V
 ISO pulse to asses: Impulse 1 with -150V peak



$t_r = 1\mu s$
 $t_d = 200\mu s$
 $t_1 = 0.5s \dots 5s$
 $t_2 = 200\mu s$

- please note that the attached conditions might vary from OEM to OEM

To simplify the calculation lets assume a triangular voltage shape with a peak voltage of -150V and a time duration of the pulse of 200 μs .

For the given MOSFET the typical avalanche voltage is 42V. The time duration in avalanche is according to the voltage wave form:

$$t_{avalanch} = t_d - \left(\frac{V_{avalanche} \cdot t_d}{150V} \right)$$

$$t_{avalanch} = 200\mu s - \left(\frac{42V \cdot 200\mu s}{150V} \right)$$

$$t_{avalanch} = 144\mu s$$

During that time the MOSFET will clamp the Drain Source voltage to 42V. The current flowing through the device can be determined using internal resistance of the load dump generator (40Ω for 12V bord net) and the rest of the voltage pulse (150V – 42V with a triangular shape).

The peak avalanche current is therefore:

$$I_{avalanch_peak} = \frac{150V - 42V}{40\Omega}$$

$$I_{avalanch_peak} = 27A$$

The according avalanche energy can be calculated:

$$E_{avalanche} = 0.5 \cdot V_{avalanche} \cdot I_{avalanche} \cdot t_{avalanche}$$

$$E_{avalanche} = 0.5 \cdot 42V \cdot 27A \cdot 144\mu s$$

$$E_{avalanche} = 82mJ$$

According to the data sheet the single pulse avalanche ruggedness is defined as 135mJ at Drain current of -40A and and case temperature of 25°C. The dependency of the avalanche energy to the drain current is indirectly proporsional; ½ Drain current would result in double avalanche energy.

At 27A the device can sustain single pulse avalanche energy of:

$$(40A/27A) \times 135mJ = 200mJ.$$

This value is well above the required 82mJ due to the ISO pulse.

For that example the device should withstand the ISO pulse without degradation or destruction, but there might be effects reducing the life time of the device due to repetitive avalanche events which are not considered in that application note.

4.2 Simulation example

To assess the junction temperature of the MOSFET for the calculated example and to prove the result out of the calculation, a PSpice simulation has been performed. Asumption was again a triangular voltage pulse (based on ISO pulse 1), accordingly a triangular current shape in case of avalanche.

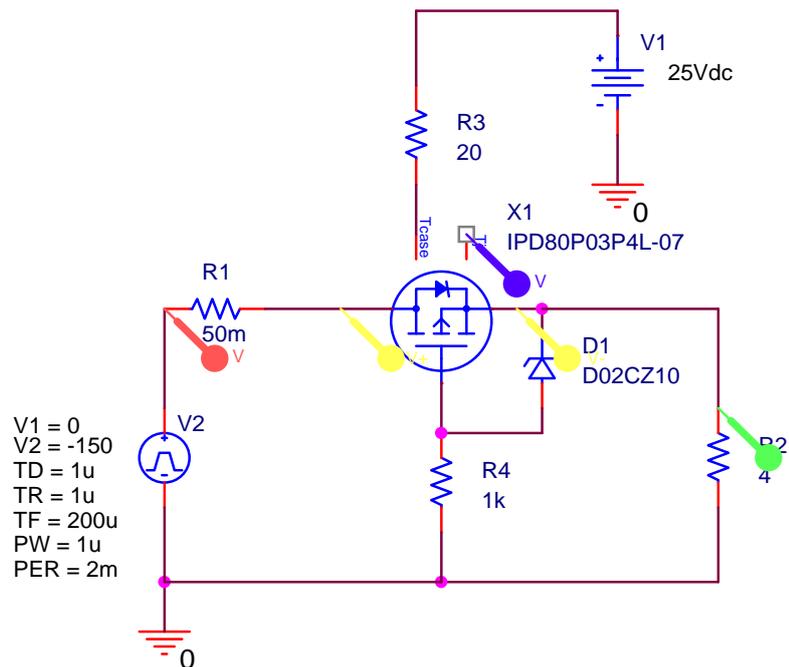


Figure 9 Schematic of ISO pulse simulation

In Figure 9 the schematic for the simulation is shown. With a level three model of the PFET (coupling between electrical and thermal properties of the device), the junction temperature can be observed.

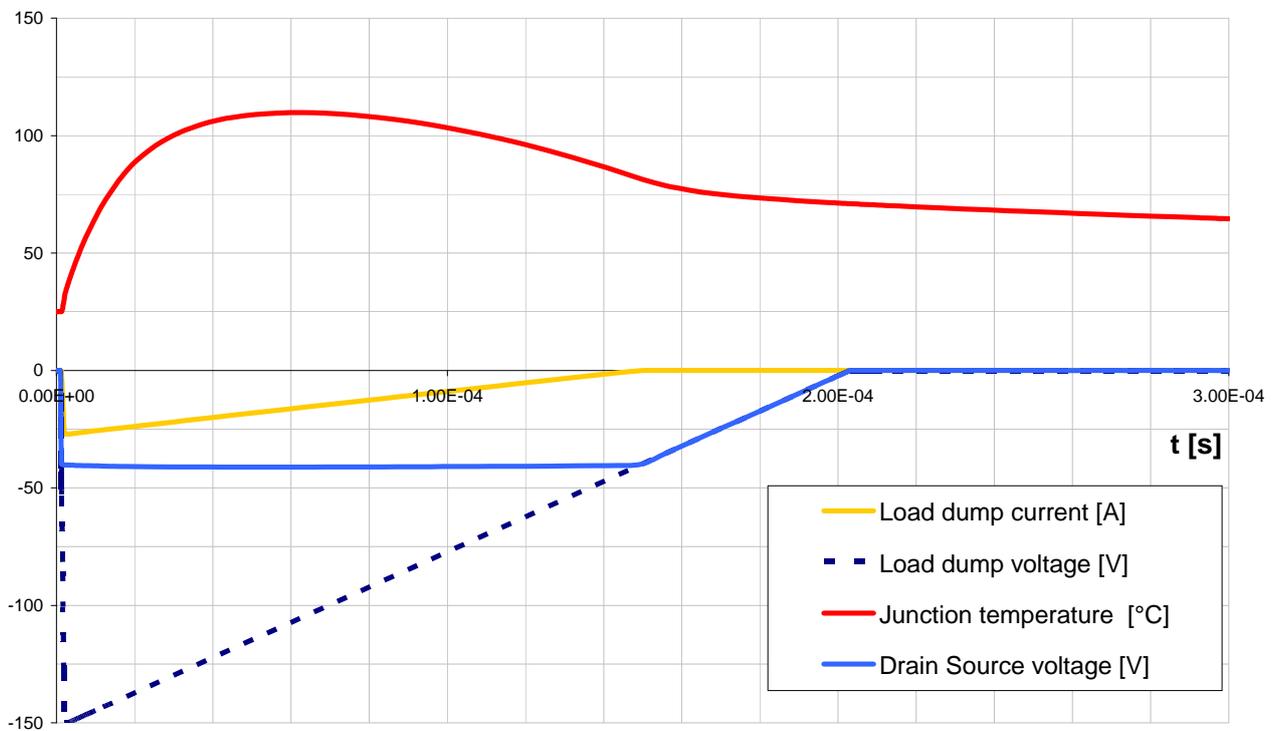


Figure 10 Simulation results

The result of the simulation is showing the Drain to Source voltage, the Drain current, the Junction temperature and the ISO pulse voltage. As soon as the load dump voltage reaches the avalanche voltage of the MOSFET, the device starts to conduct and a current is flowing till the load dump voltage goes below the avalanche voltage.

The current flow through the device in combination with the Drain to Source voltage leads to power losses, accordingly a rise in the junction temperature. For the selected MOSFET and ISO pulse 1, the Junction temperature reaches 110°C.

5 Conclusion

This application note points out the three most common ways to achieve reverse battery protection which are:

- solution with a diode
- solution with an n-channel MOSFET
- solution with a p-channel MOSFET

Each solution has its advantages and drawbacks.

	diode	n-channel MOSFET	p-channel MOSFET
Parts	+	-	0
EMI	+	-	+
Power losses	--	++	+
Efficiency	--	++	+
High power	--	++	+

The table is summarizing the pros and cons of the three described solutions. For high power applications the diode is not feasible for reverse battery protection, since power losses are much too high.

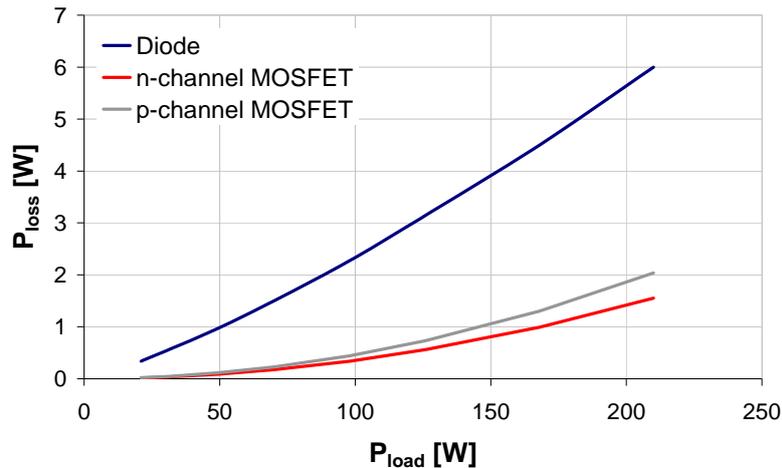


Figure 11 Comparison of power losses for the three solutions

For such applications, the n-channel MOSFET solution offers the highest efficiency with the drawback of additional circuit requirements such as a charge pump circuit and EMI filter.

A very simple solution still with an excellent efficiency would be the p-channel approach. Nearly no additional circuit effort compared to the diode and only a slightly worse efficiency in comparison to the n-channel MOSFET makes this solution very attractive.

With the introduction of p-channel MOSFETs in a trench technology the performance of the device increased dramatically and compensates the disadvantage of the hole mobility significantly.

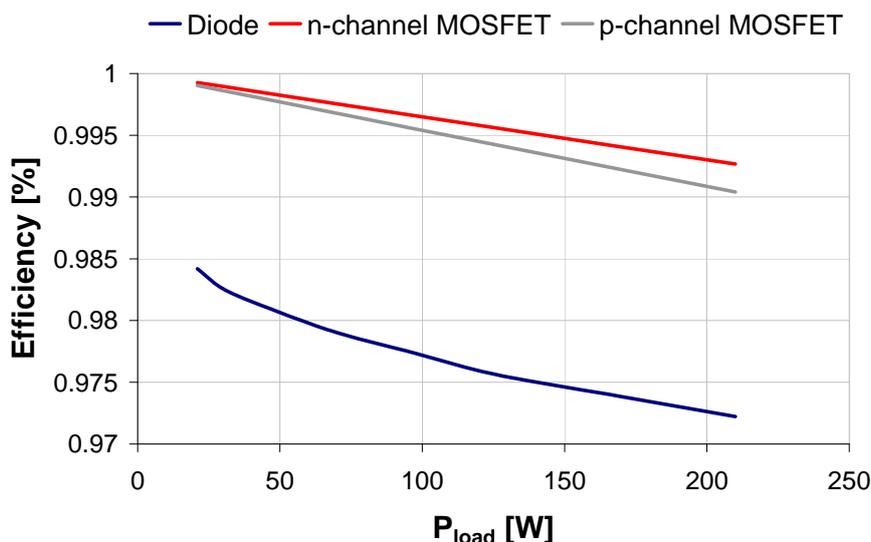


Figure 12 Comparison of efficiency for the three solutions

The best solution for reverse battery will be determined by the requirements of the application. The designer will have to find the trade off between power losses and the effort to spend on the reverse battery protection schematic itself.

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