Relay replacement within automotive power distribution

Smart switch basics

About this document

Scope and purpose

This document intends to give a better understanding of semiconductor-based power distribution in automotive applications. It lists first the key characteristics of smart switches and then gives a detailed comparison of a smart switch versus an electromechanical relay.

Intended audience

People familiar with electromechanical relay- and fuse-based power distribution systems, who want a better understanding of smart power distribution systems based on semiconductor smart switches.

Table of contents

1 Characteristics of a smart switch

1.1 What is a smart switch?

Smart switches are an alternative solution to relays when it comes to remotely control the supply of a load.

A smart switch is a standard power switch (MOSFET) with additional features that have been integrated to enhance its performance as shown in ***Figure 1***.

Firstly, a MOSFET driver is included to turn the switch on/off. In addition, several protection features are integrated. For example, short circuit protection can protect the MOSFET if a short to ground/battery occurs. The overvoltage protection ensures the MOSFET will not be damaged during load dump transients or other high voltage events (assuming the transient pulse energy is within specified limits). The reverse battery protection keeps the smart switch safe if the battery polarity is reversed (current may flow, but the device will not be damaged). The current limit feature limits the maximum current which the MOSFET switch can source. This again helps to protect the switch from short to ground/battery conditions. The overtemperature protection is enabled if the temperature of the MOSFET junction reaches unsafe levels: the switch is turned off stopping the current flow completely *[1]*.

Finally, diagnostics are included so the smart switch can provide feedback to a microcontroller if a fault condition is detected.

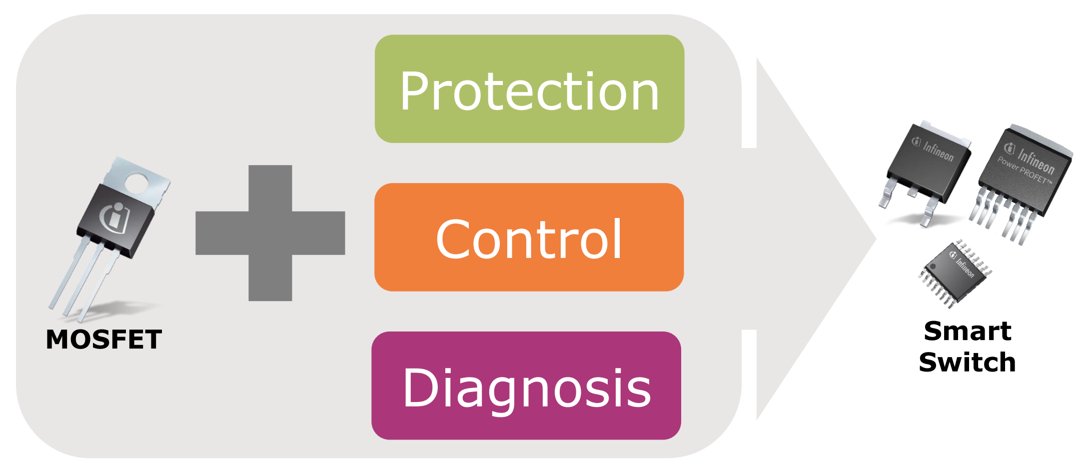


Figure 1 **Smart switch derived from a standalone MOSFET**

There are two configurations to energize a load, whatever the type of switch used (relay or smart switch): high-side switch and low-side switch.

In a low-side driver configuration, the switch is located between the load and ground as shown in ***Figure 2***. The MOSFET is on the low side of the load, therefore it is called low-side switch.

In a high-side driver configuration, the switch is now connected between the supply voltage and the load - the switch is on the high side of the load.

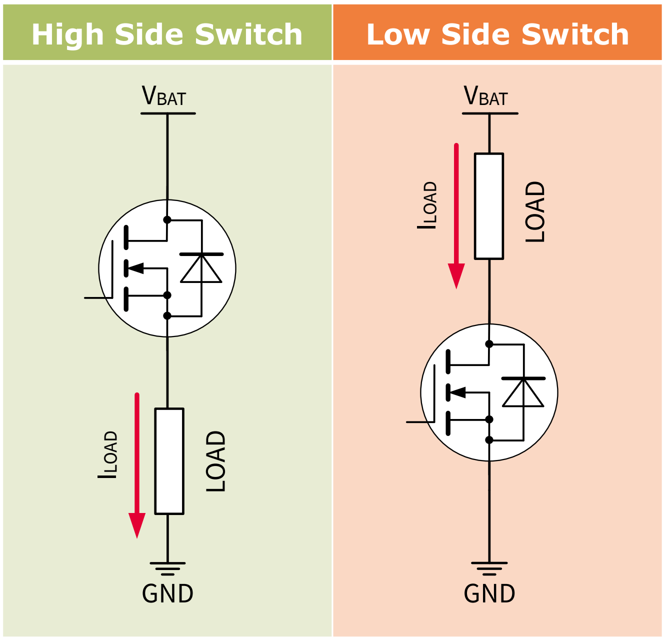


Figure 2 High-side and low-side switch configurations

There are two main technology categories within smart switches devices, depending on the number of silicon dies used: chip-on/by-chip design and monolithic design as shown in ***Figure 3***.

The chip-on-chip (chip-by-chip) design is based on two technologies, one for the base chip and one for the top chip. The base chip is the power MOSFET with current sensor and temperature sensor and the top chip is the logic. The combination of different technologies offers optimized solution for each functions.

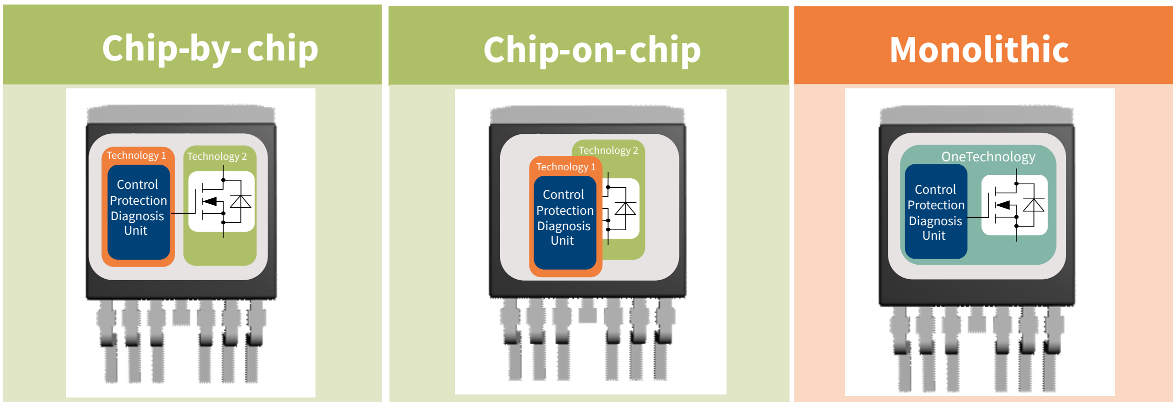


Figure 3 Comparison between smart switches based on chip-on/by-chip and monolithic technology

The monolithic design is based on the same chip and the same technology for the logic and the power die.

Having these features inside a smart switch is the cheapest and the best solution to ensure that the MOSFET is optimally protected: the sensors and control/logic circuitries can be tuned exactly to the MOSFET characteristics. An equivalent level of protection is hardly achieved for a discrete MOSFET driven by a separate/ external gate driver chip and separate/external sensors.

1.2 Introduction to the MOSFET

MOSFETs are electronic components manufactured in a semiconductor material. In the scope of this document, silicon is the only semiconductor considered, although there are other materials which also exist for specific applications (SiC and SiGe for instance).

The MOS transistor is a voltage controlled device: the conductivity of the component varies with the voltage applied on the control electrode (gate). This allows a simple control circuitry compared to a current-controlled transistor, which is an advantage especially with regard to transistors for power applications.

An important characteristic of semiconductor materials is that it is possible to change their properties in a controlled manner through the introduction of impurities (or dopant). The process through which this introduction takes place is called doping of the material *[2]* .

Depending on the dopant, there are two types of semiconductors:

- **N**-channel MOSFET (NMOS), which presents an excess/abundance of conducting electrons. A common **N** -type dopant for silicon is phosphorus or arsenic
- **P**-channel MOSFET (PMOS), which presents a lack of conducting electrons. A common **P**-type dopant for silicon is boron or gallium

In this document only N-type channel are analyzed.

1.2.1 NMOS internal structure

This introduction is based on the **N**MOS. The source and drain terminals are **N**-type semiconductor regions, which are implanted into a **P**-type semiconductor (usually called either the substrate, the bulk or the body).

The MOSFET is a symmetrical device: drain and source are made in exactly the same way. In an N-channel MOS it is convention to call the drain the terminal with the higher potential. The circuit symbol in ***Figure 4*** highlights the direction of the drain current I_D (direct from the drain to the source).

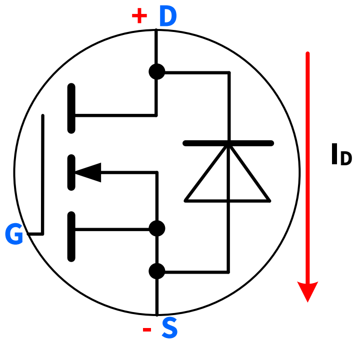


Figure 4 **NMOS symbol**

MOSFET is an acronym for Metal Oxide Semiconductor Field Effect Transistor. The gate of the MOSFET is either metal or a polycrystalline silicon material which behaves like a metallic material.

Silicon dioxide (Oxide) is used to insulate the gate from the underlying semiconductor. It is the electric field created by the gate-to-source bias voltage which actually turns the MOSFET on and off.

In ***Figure 5*** it is possible to notice:

- the N + regions of source and drain
- the so-called vias that serve to contact these regions
- the thin oxide below the doped polysilicon gate
- the channel region

- the B-S diodes (body-source) and B-D (body-drain) intrinsic parasitics of the structure
- the layer of protective oxide/passivation covering the entire top.

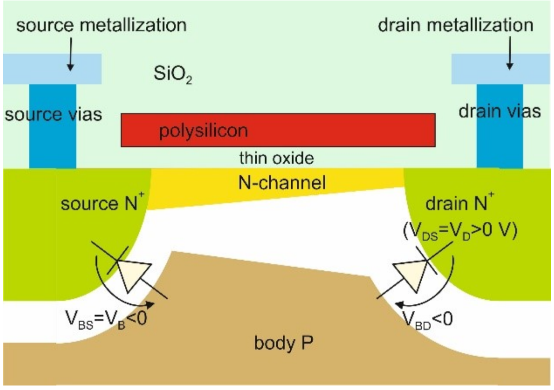
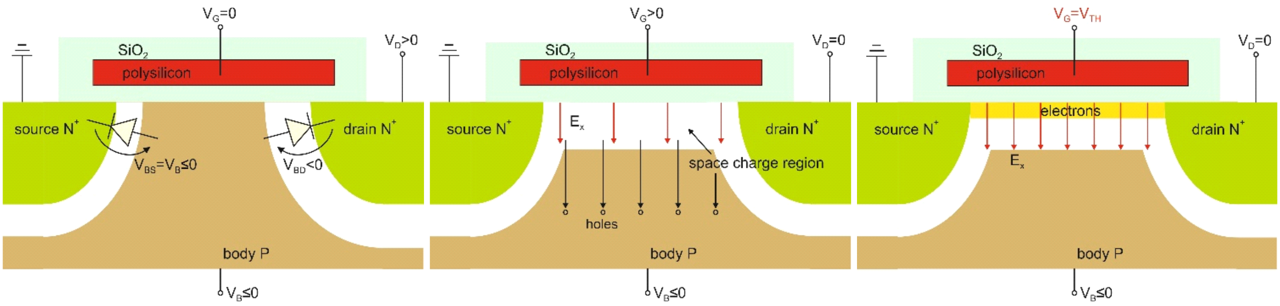


Figure 5 **NMOS cross-section**

Applying a voltage on the gate terminal ($V_G > 0$ V) creates an electrical field under the gate oxide (SiO_2), as shown in ***Figure 6***.

A further increase of V_G (and therefore of the vertical electric field E_x) has the effect of attracting electrons to the silicon-oxide interface (***Figure 6***, b)). At a certain point, when $V_G = V_{TH}$ (gate threshold voltage) the concentration of free electrons becomes dense enough to form a conductive channel between the source and drain regions, as shown in ***Figure 6***, c). The higher V_{GS} is, compared to V_{TH}, the wider the channel is, resulting in a higher current flowing from drain to source.



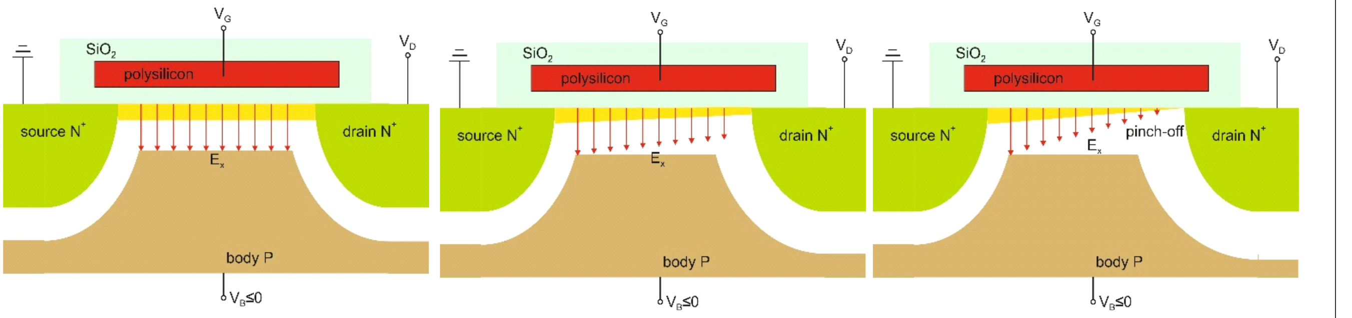
a) $V_G = 0$ b) $V_G > 0$ c) $V_G = V_{TH}$

Figure 6 **Gate voltage biasing**

If $V_{GS} > V_{TH}$ and a drain voltage V_D (= V_{DS}) > 0 V between drain and source is applied, a horizontal electric field (or channel) E_y is induced, which promotes the passage of electrons from the source to the drain (***Figure 7***, a)). The current increases linearly increasing V_{DS}, therefore this behavior is known as *linear region*.

As the applied V_{DS} increases, the longitudinal electric field continues to increase, and so also the drain current. However the voltage drop $V_{(y)}$ becomes significant in the region of the drain, where the vertical field E_x is reduced and the channel begins to assume the typical triangular shape, which involves a reduction of the conductivity (***Figure 7***, b)). This effect tends to counteract the increase in current due to the increase of E_y, and results in a decrease in the slope of the I_D-V_{DS} curve with increasing V_{DS}, this is known as *non-linear region*.

Due to the E_y increase, the current increases, until the time when V_{DS} pinches off the availability of free electrons at the region of body-drain transition (***Figure 7***, c)). In this situation the drain current I_D is independent of further increases of the drain voltage V_{DS}. This region is known as *pinch-off region* (or *saturation*).



a) Linear Region b) Non-Linear Region c) Pinch-off Region

Figure 7 Regions of operation

A typical set of IV curves (MOSFET characteristic) are shown in ***Figure 8***. The initial slope of the output IV curves is the *linear region*, then further increasing the V_{DS} the *non-linear region* is reached. When V_{DS} reaches the pinch-off condition, the *pinch-off region* can be observed ***[2]***.

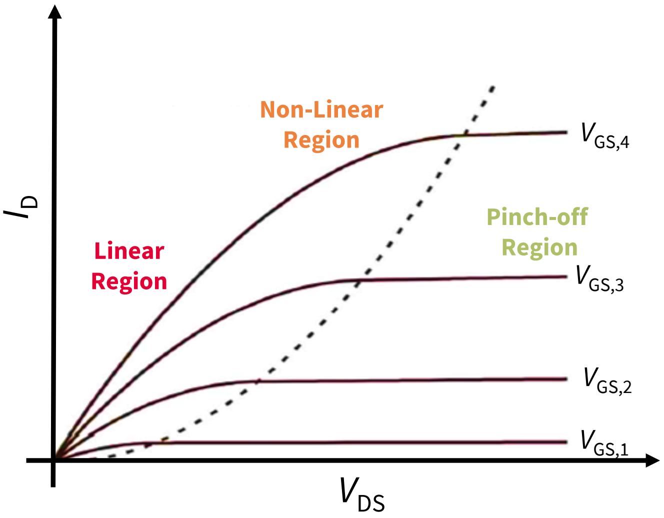
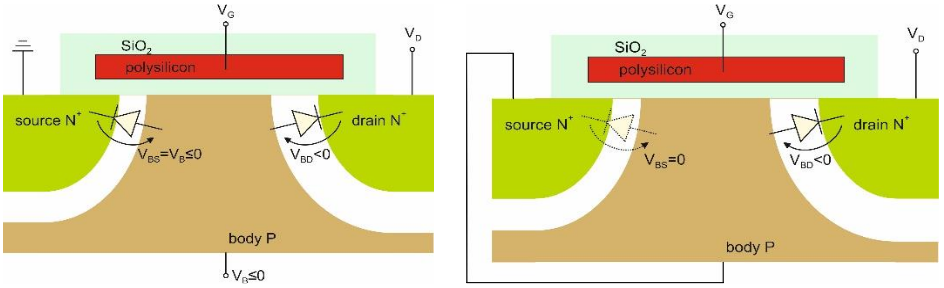


Figure 8 MOSFET characteristics

1.2.2 MOSFET body diode

The MOSFET comes with a characteristic which makes it quite different from a relay: it behaves as a switch in one current direction (drain to source), and as a diode in the other direction (source to drain).

This can be explained from the structure of the MOSFET already introduced. Due to the doping of the semiconductor material used to build source, drain and body terminals, there are two intrinsic PN junction diodes present as shown in ***Figure 9***, a).



b) $V_{BS} \leq 0$ a) $V_{BS} = 0$

Figure 9 **Intrinsic body diode in an NMOS**

The body-to-source diode cannot be biased because the source and body contacts are in general short-circuited during design, in order to avoid this body effect. The body-to-drain diode is still present, and thus there is always a diode between source and drain as shown in ***Figure 9***, b). This diode is called *body diode* and it is an intrinsic part of the MOS structure *[2]*.

Due to this diode, the MOSFET is not a symmetrical switch: when it is switched off, it blocks the drain-source current in one direction only as shown in ***Figure 10***.

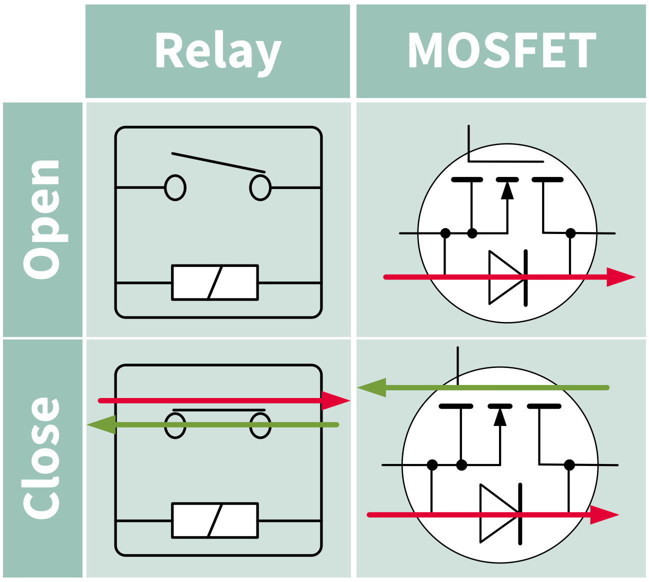


Figure 10 **Current direction in a relay and a MOSFET**

The consequence is that the polarity of the connection on drain and source in the MOSFET is not flexible. The connections to drain and source must ensure that the parasitic body diode is reverse biased so that it does not disturb the switching functionality.

1.3 Smart switch vs relay: overview

In this chapter the differences between a smart switch and a relay are reviewed.

1.3.1 Control polarity

Relays are very versatile devices on the control side: the control coil can be connected in four different configurations because the current direction in the control coil is not critical. In addition, the relay coil driver can either be a high-side switch (HSS) or a low-side switch (LSS) as shown in ***Figure 11***.

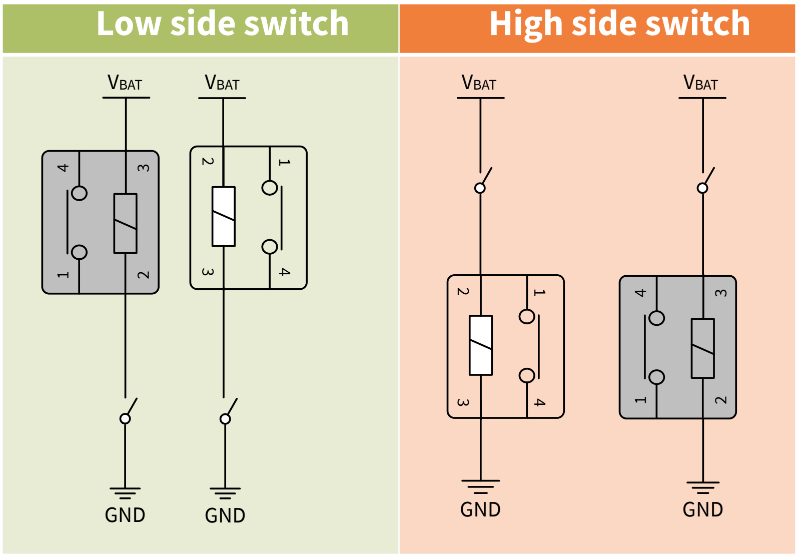


Figure 11 **Different control schemes for a relay**

Relays for automotive applications are designed to be driven using the battery voltage for the control of the coil. This is not compatible with the capabilities of a typical microcontroller, therefore a relay driver is then necessary between the MCU and the relay coil. In addition, this relay driver has to be dimensioned to tolerate the high demagnetization energy of the control coil and it also must apply a high clamping voltage during demagnetization. This is critical to safeguard the lifetime of the relay contacts since it ensures a fast disconnection of the relay contacts to limit arcing. Whatever the relay driver configuration (HSS or LSS), it is a quite specialized component which adds cost to the overall relay solution.

Unlike relays, smart switches come with a lower control solution cost: most of them can be directly interfaced to an MCU. The HSSs can be either *current controlled* or *voltage controlled*: the current controlled ones require an external switch for control operation, the voltage controlled ones can be directly interfaced with an MCU, as shown in ***Figure 12***.

The external switch used to control the current is usually a simple NPN transistor, low cost and low power.

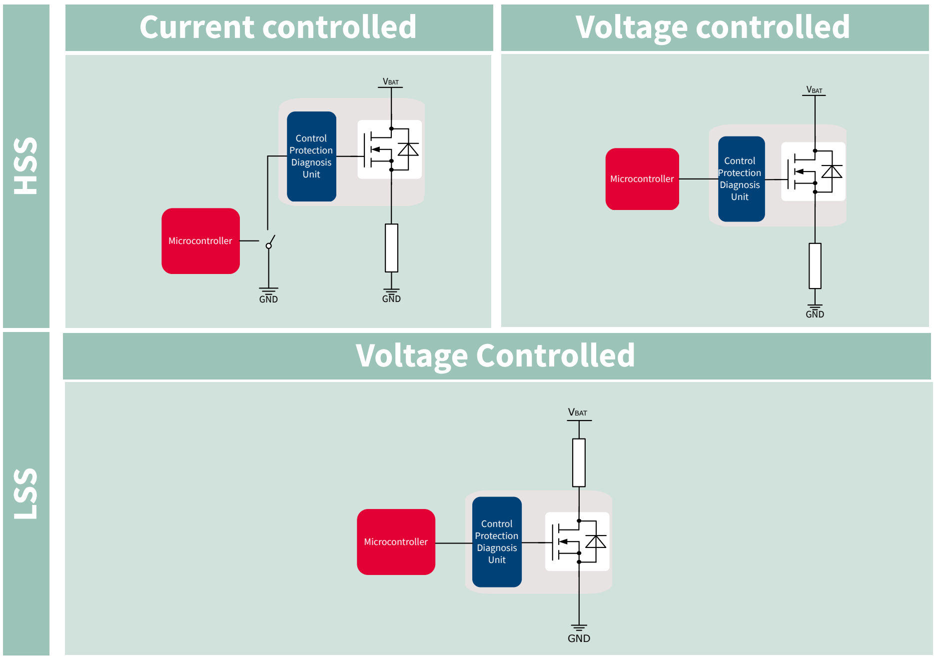


Figure 12 **Control schemes for high-side and low-side switches**

1.3.2 Voltage limitation

While the distance between contacts inside a relay is in the range of 1 mm, the distance between the drain and source inside a MOSFET is in the range of a few micrometers. This very small distance has a direct impact on the maximum stand-off voltage of the MOSFET which is called the *breakdown voltage*. It also has a direct impact on the size of the MOSFET and consequently on its cost.

Manufacturers define specific semiconductor technologies with the optimum drain-to-source distance, tuned for the targeted applications.

For 12 V supply applications in the car, various transient stress conditions are defined, such as *jump start* and *load dump* for instance. They have a direct influence on the maximum battery voltage the smart switch has to survive. To safely pass these stress tests, the required breakdown voltage is typically around 40 V.

Looking at relays datasheets, they can withstand in the range of 500 V_{RMS} between contacts. It is then clear that smart switches are more sensitive to overvoltage conditions compared to relays: there are usually several protections mechanisms integrated within the smart switch, but there might be a need in some applications to add external protection such as freewheeling diodes or Transient Voltage Suppressors (TVS). This information is available in every Infineon datasheet.

1.3.3 On resistance

The mechanical contact inside a relay is sensitive to various parameters which can influence its resistance when it is closed. These include dust and contamination, usage, mechanical aging and mechanical stress, oxidation, etc. Along the lifetime of the relay, the contact resistance varies, even if the environmental conditions remain constant. The usual trend is that this resistance increases over time, together with the number of switching cycles: however, this is not predictable and depends on the sample measured and on the load driven by the relay as shown in ***Figure 13***.

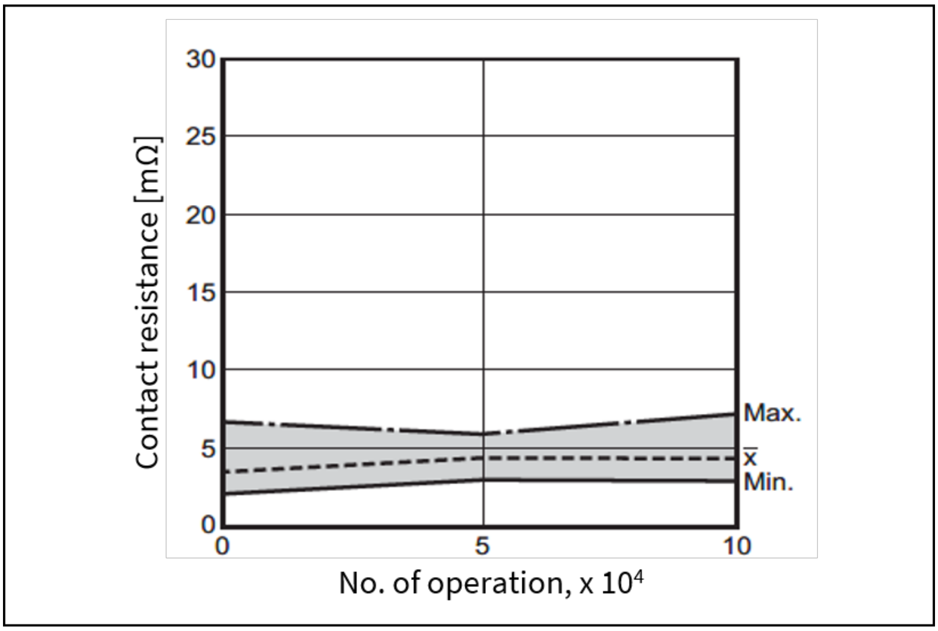


Figure 13 **Relay contact resistance variations**

The resistance of a MOSFET behaves quite differently: it is very stable and repeatable for constant environmental conditions. The main parameter which influences the $R_{DS(ON)}$ is the temperature as shown in ***Figure 14***.

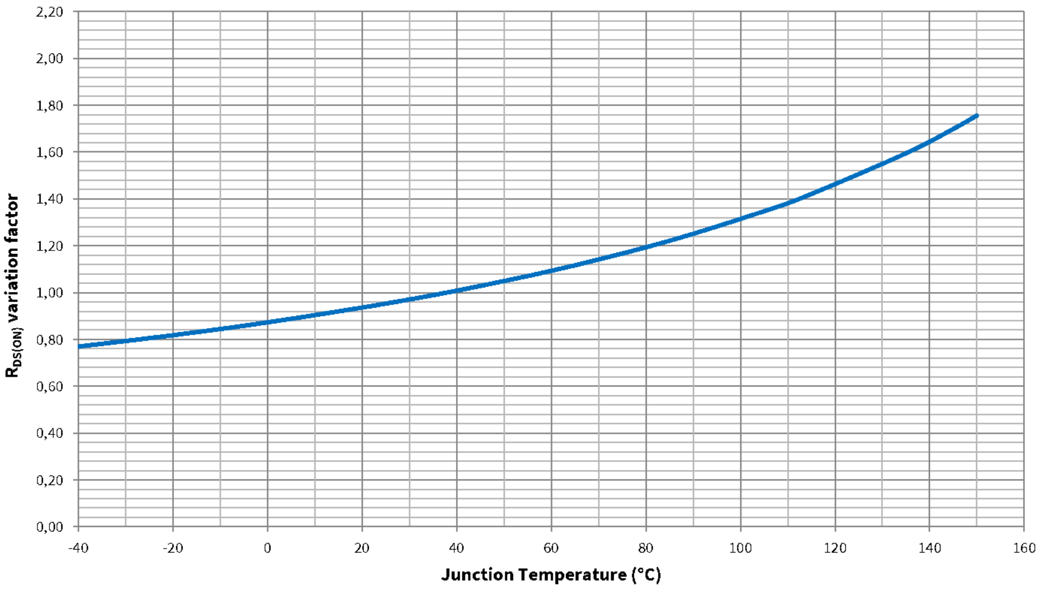


Figure 14 **$R_{DS(ON)}$ variation overtemperature**

Over the lifetime of the switch, the variation of the $R_{DS(ON)}$ is negligible. With a resistive load, the resistance shift over lifetime is lower than a few percent up to 10^{15} ON/OFF switching cycles. It is worth mentioning that relays survive in the range of 10^5 switching cycles only. There are however some conditions where the stress on the MOSFET can lead to a slight shift of its $R_{DS(ON)}$:

- Repetitive switch-off on an inductive load (such as valves or motors)
- Repetitive short-circuit conditions

Under such conditions, MOSFETs drive high currents and work under thermal stresses, which can generate a shift in electrical parameters if they repeat over a large number of times. Infineon performs intensive tests to qualify this drift for specific conditions (repetitive short circuit and repetitive switch-off on an inductive load mainly). The residual drift which may appear is included in the datasheet limits for the $R_{DS(ON)}$.

2 References

1. *Infineon Technologies AG, "Bridging Theory into Practice," 2008*
2. *V. D'Alessandro, "Slides del corso di Circuiti Digitali", Napoli, 2014*

3 Glossary and symbols

3.1 Definition of acronyms

Here are the definitions of the main acronyms used in this document:

- ADC: **A**nalog to **D**igital **C**onverter
- HSS: **H**igh-**S**ide **S**witch
- LSS: **L**ow-**S**ide **S**witch
- MOSFET: **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor.

3.2 Symbols

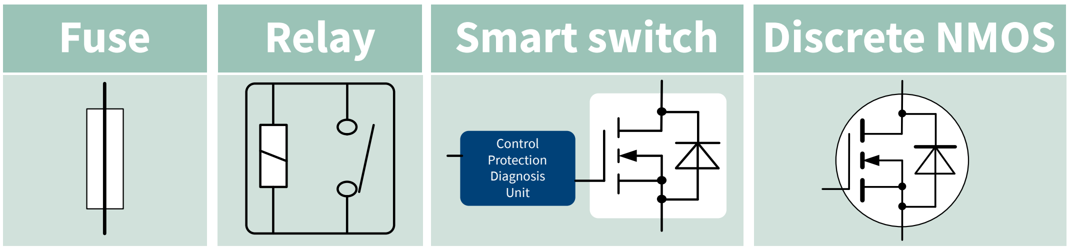


Figure 15 Main symbols used in this document

4 Revision history

Table 1 **Revision history**

Document version	Date of release	Description of changes
Rev. 1.00	2019-04-29	Initial application note

Trademarks

All referenced product or service names and trademarks are the property of their respective owners.

Edition 2019-04-30
Published by
Infineon Technologies AG
81726 Munich, Germany

© 2019 Infineon Technologies AG
All Rights Reserved.

Do you have a question about any aspect of this document?

Email: erratum@infineon.com

Document reference
IFX-yjo1554291936958

IMPORTANT NOTICE

The information contained in this application note is given as a hint for the implementation of the product only and shall in no event be regarded as a description or warranty of a certain functionality, condition or quality of the product. Before implementation of the product, the recipient of this application note must verify any function and other technical information given herein in the real application. Infineon Technologies hereby disclaims any and all warranties and liabilities of any kind (including without limitation warranties of non-infringement of intellectual property rights of any third party) with respect to any and all information given in this application note.

The data contained in this document is exclusively intended for technically trained staff. It is the responsibility of customer's technical departments to evaluate the suitability of the product for the intended application and the completeness of the product information given in this document with respect to such application.

WARNINGS

Due to technical requirements products may contain dangerous substances. For information on the types in question please contact your nearest Infineon Technologies office.

Except as otherwise explicitly approved by Infineon Technologies in a written document signed by authorized representatives of Infineon Technologies, Infineon Technologies' products may not be used in any applications where a failure of the product or any consequences of the use thereof can reasonably be expected to result in personal injury