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# 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.

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1 Characteristics of a smart switch

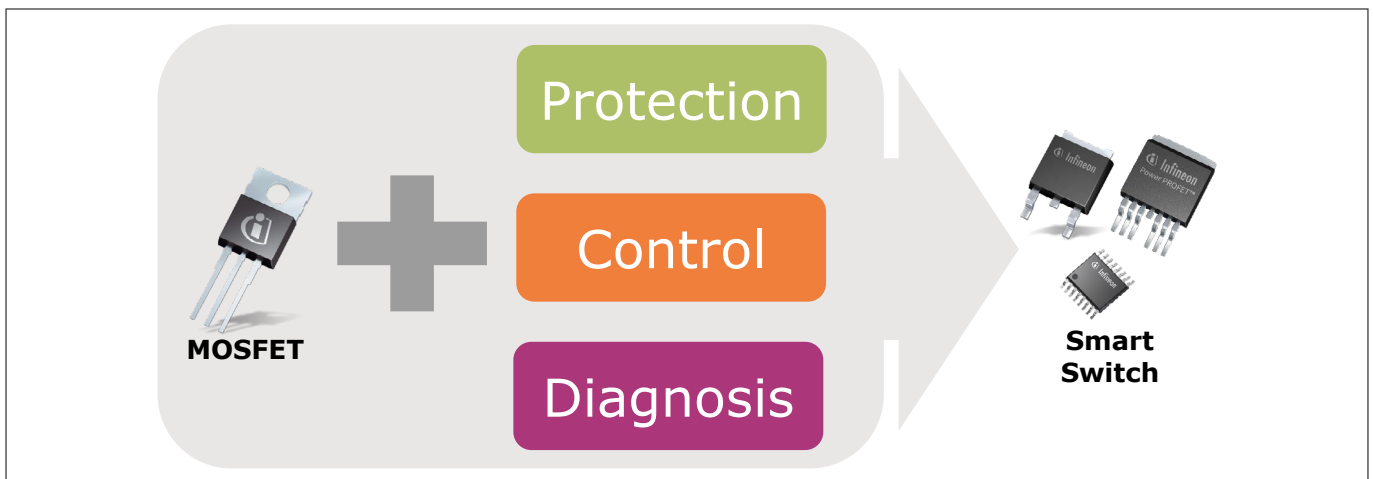
# 1 Characteristics of a smart switch

## 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.



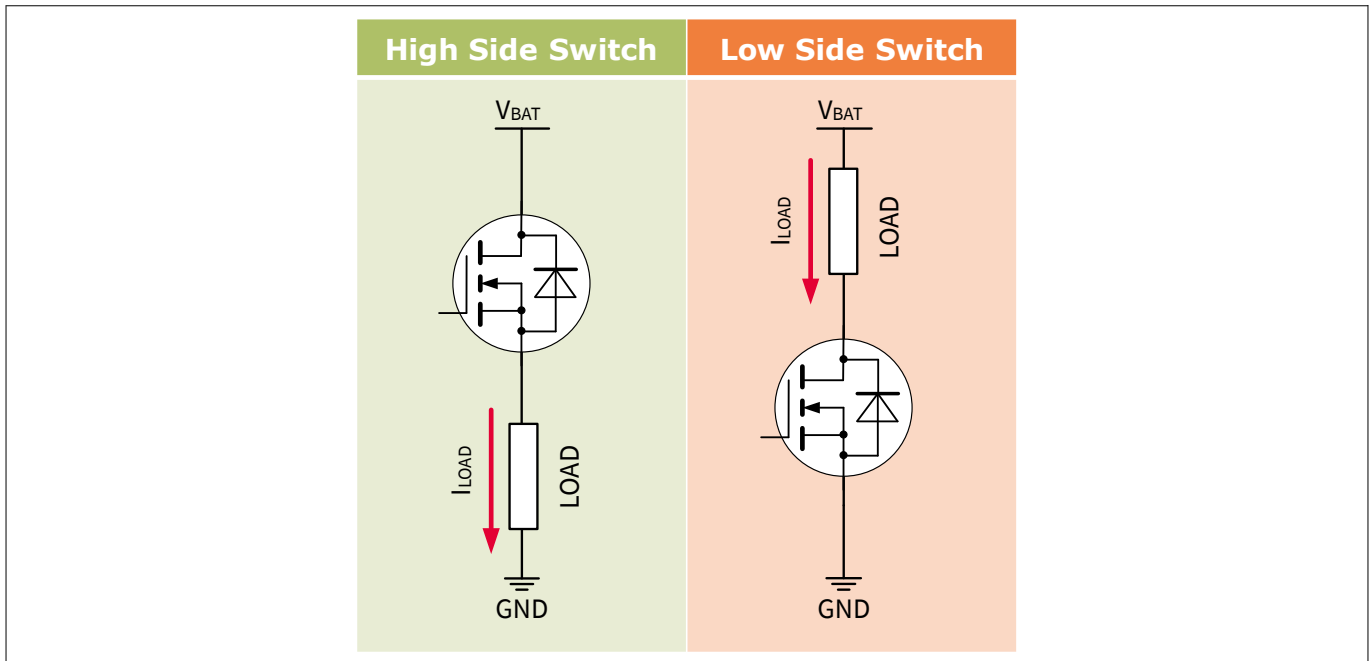
**Figure 1 Smart switch derived from a standalone MOSFET**

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.

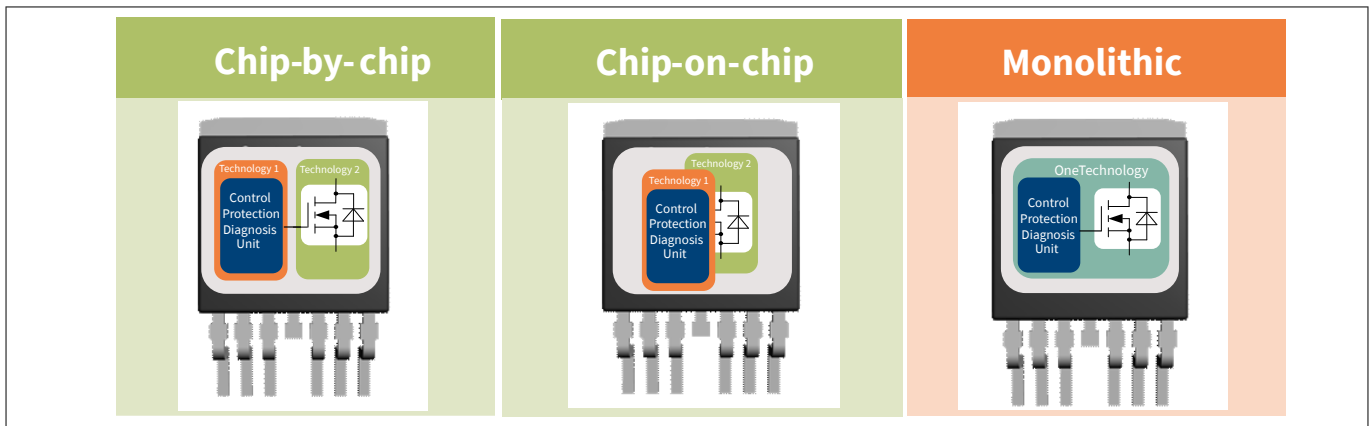
1 Characteristics of a smart switch



**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 Characteristics of a smart switch

#### 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:

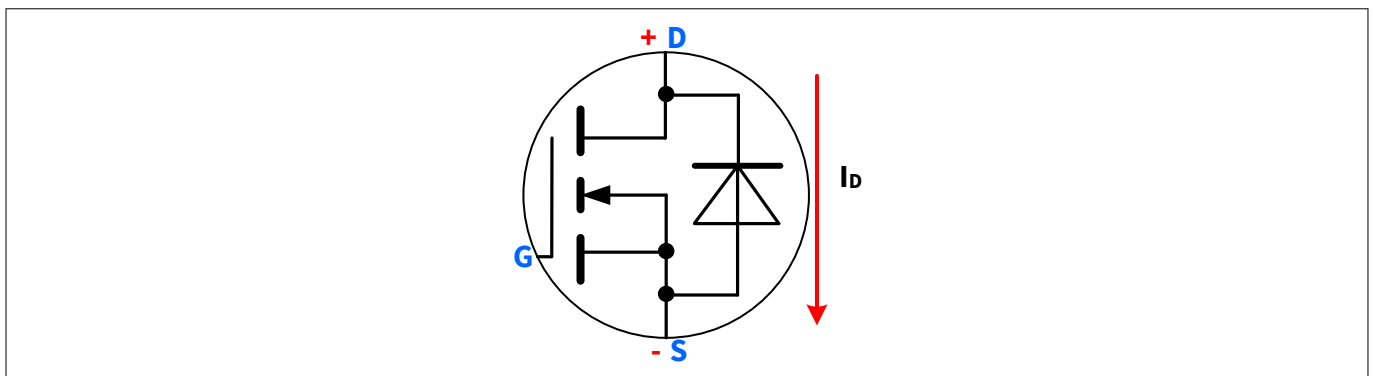
- **N**-channel MOSFET (NMOS), which presents an excess/abundance of conducting electrons. A common **N**-type dopant for silicon is phosphorus or arsenic
- **P**-channel MOSFET (PMOS), which presents a lack of conducting electrons. A common **P**-type dopant for silicon is boron or gallium

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.

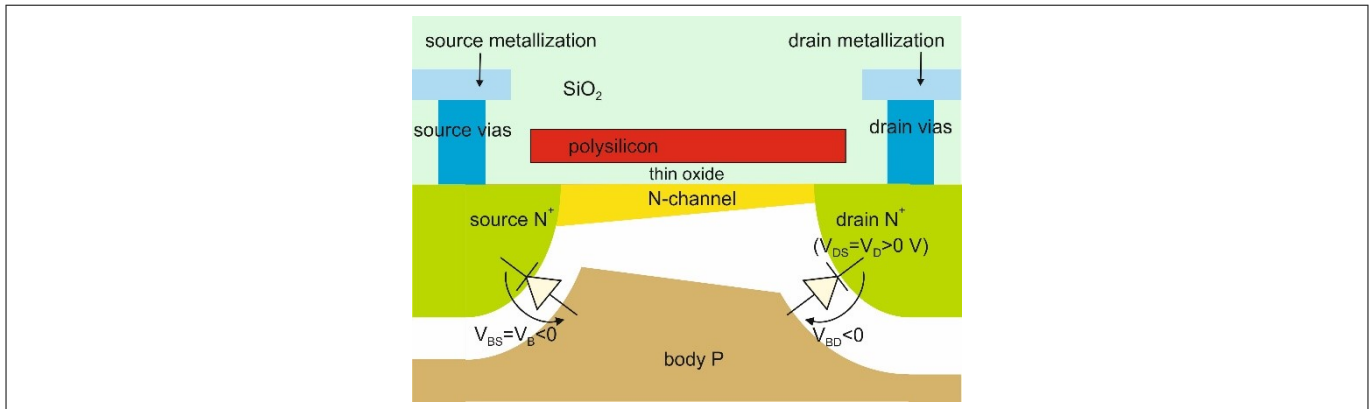
Silicon dioxide (Oxide) is used to insulate the gate from the underlying semiconductor. It is the electric field created by the gate-to-source bias voltage which actually turns the MOSFET on and off.

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

### 1 Characteristics of a smart switch

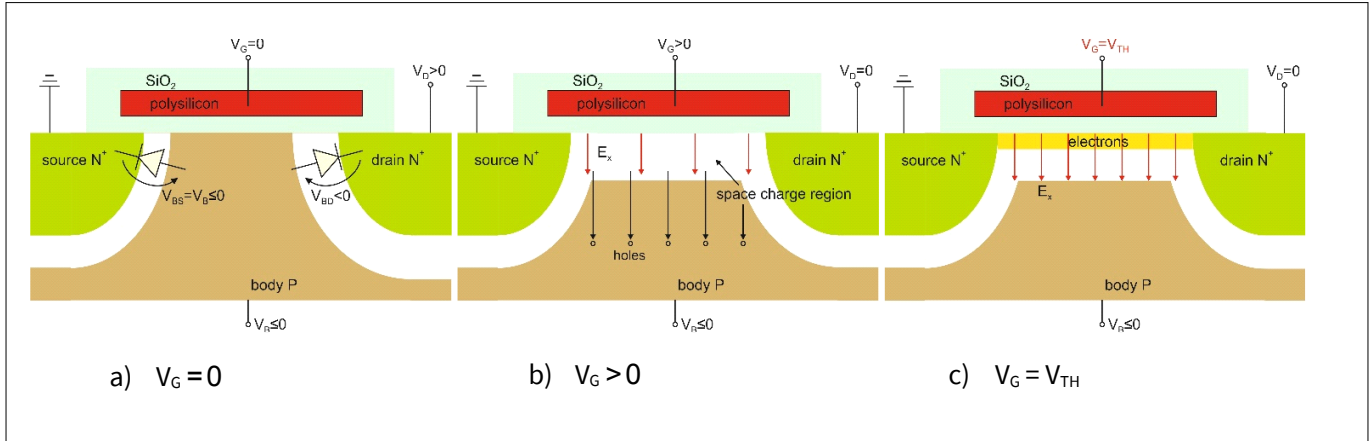
- the B-S diodes (body-source) and B-D (body-drain) intrinsic parasitics of the structure
- the layer of protective oxide/passivation covering the entire top.



**Figure 5 NMOS cross-section**

Applying a voltage on the gate terminal ( $V_G > 0$  V) creates an electrical field under the gate oxide ( $\text{SiO}_2$ ), 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.



**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*).

1 Characteristics of a smart switch

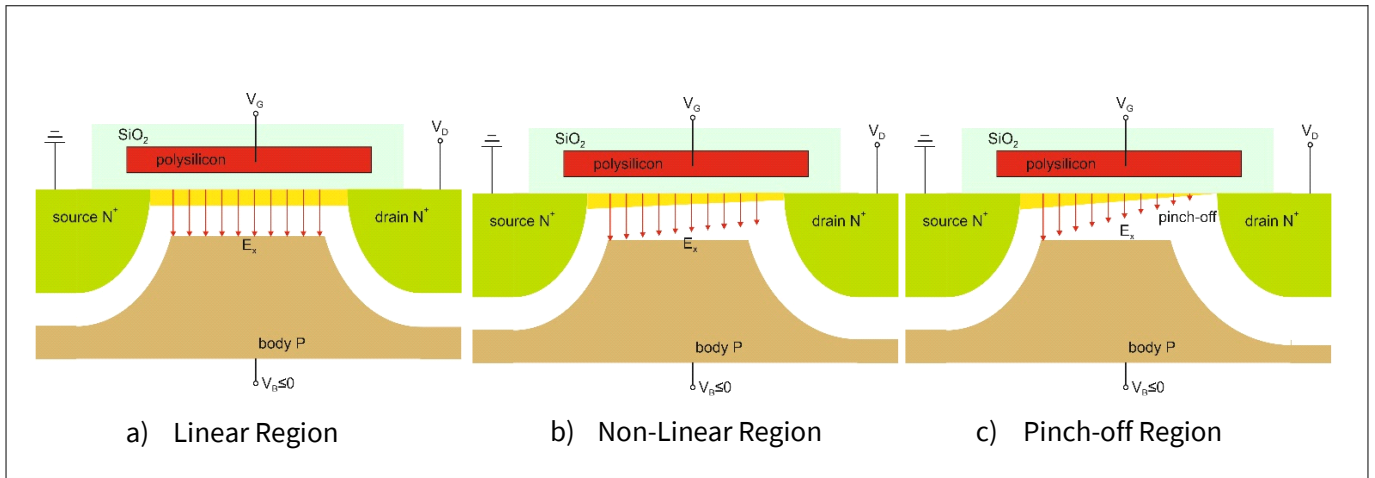


Figure 7 Regions of operation

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].

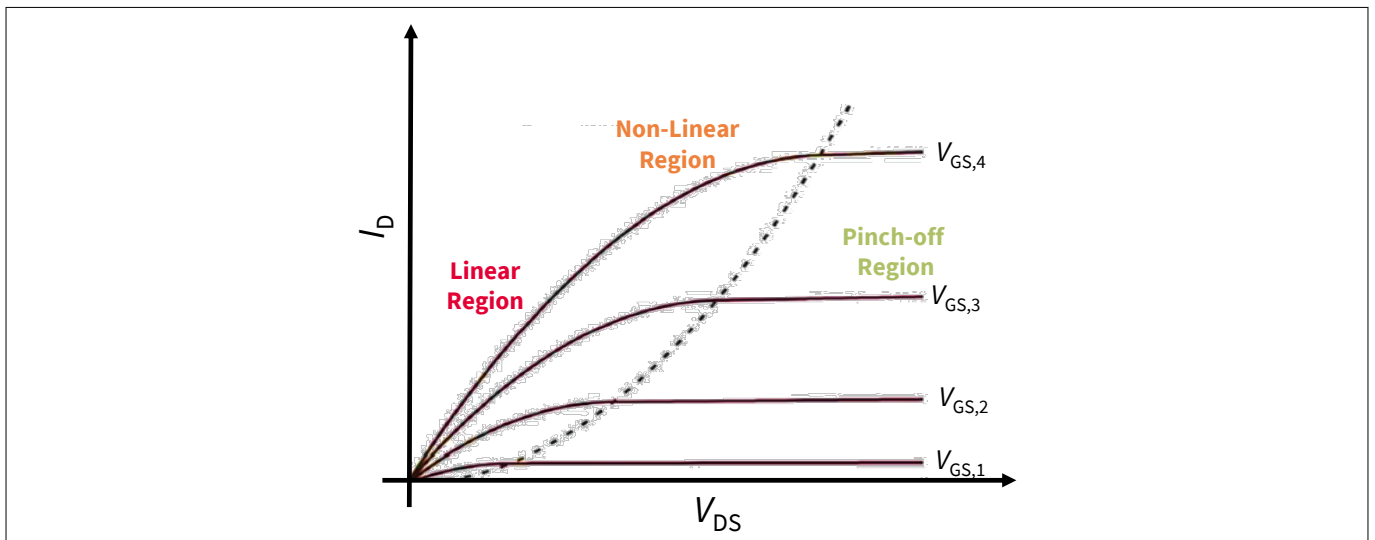


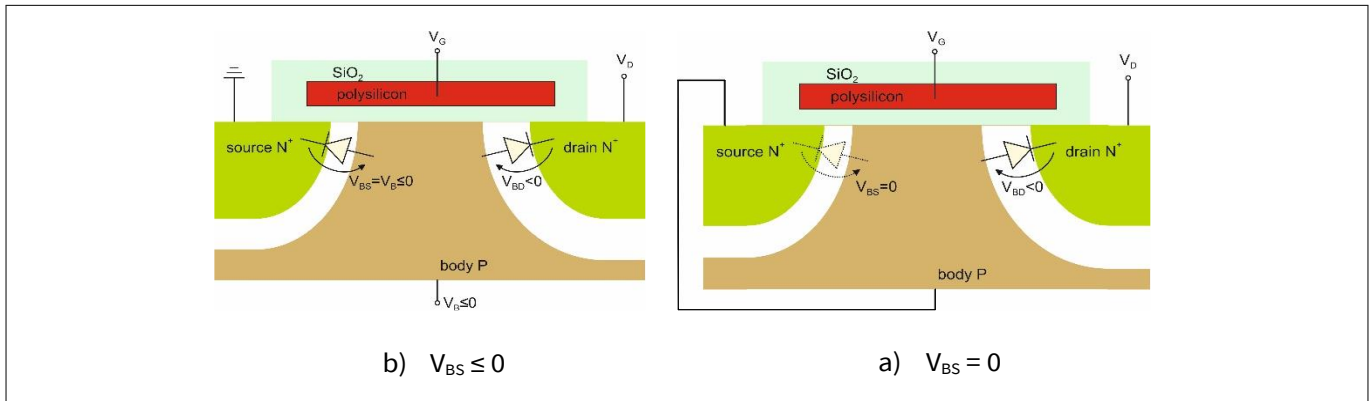
Figure 8 MOSFET characteristics

1 Characteristics of a smart switch

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).

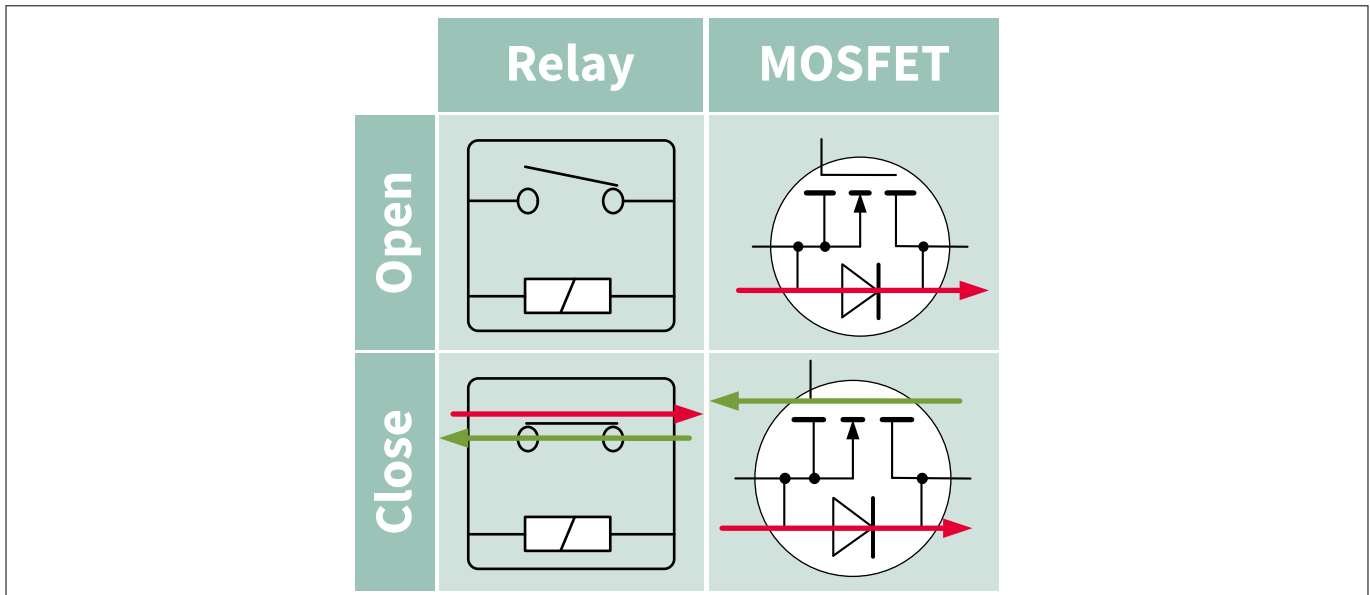
This can be explained from the structure of the MOSFET already introduced. Due to the doping of the semiconductor material used to build source, drain and body terminals, there are two intrinsic PN junction diodes present as shown in **Figure 9, a)**.



**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.

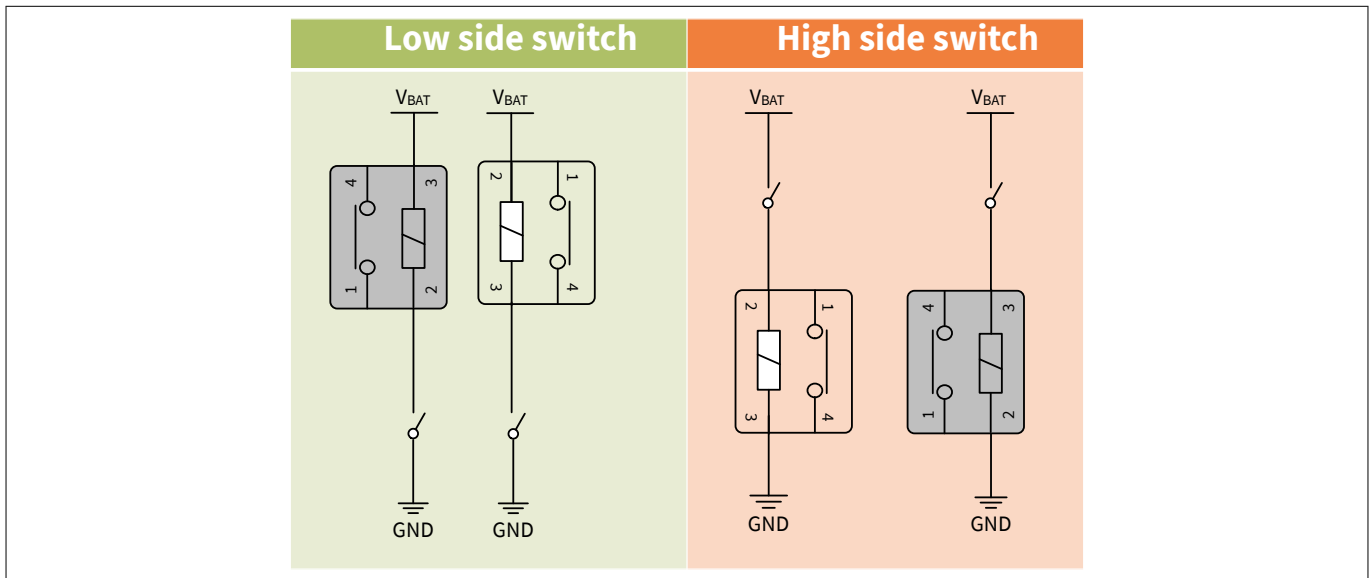
1 Characteristics of a smart switch

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.



1 Characteristics of a smart switch

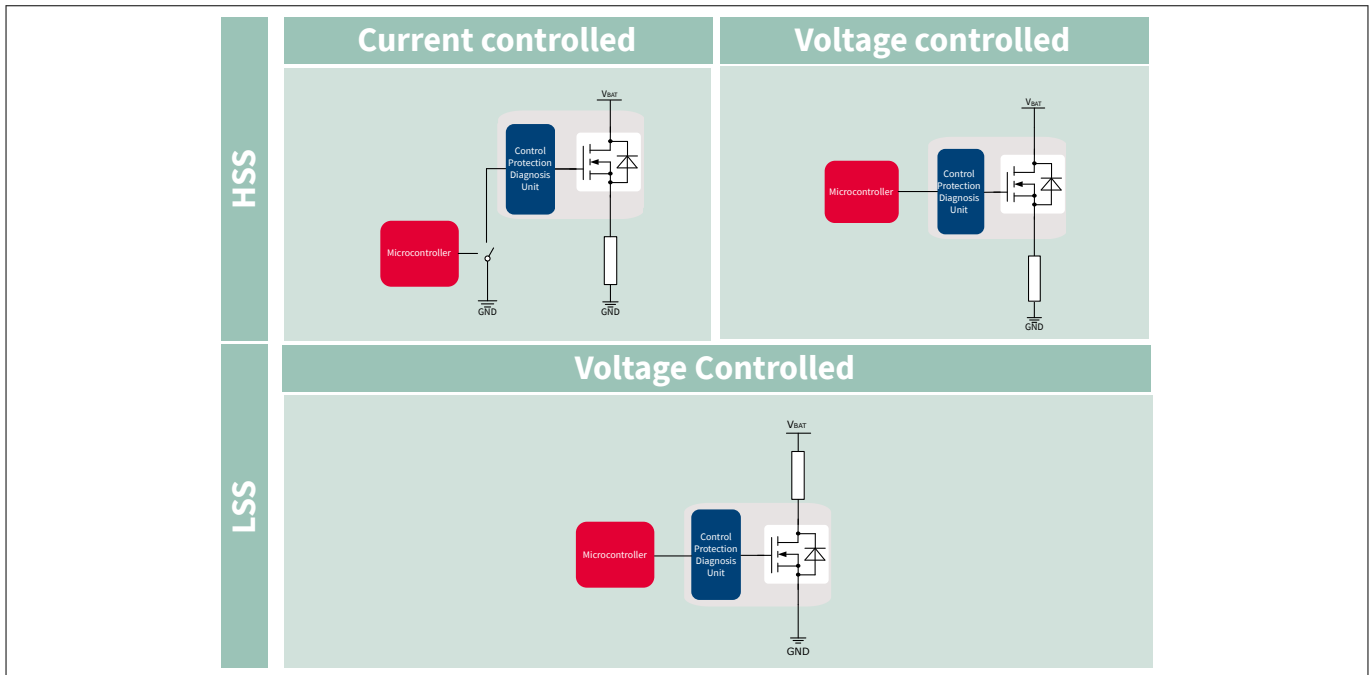


Figure 12 Control schemes for high-side and low-side switches

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<sub>RMS</sub> 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.

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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](#).

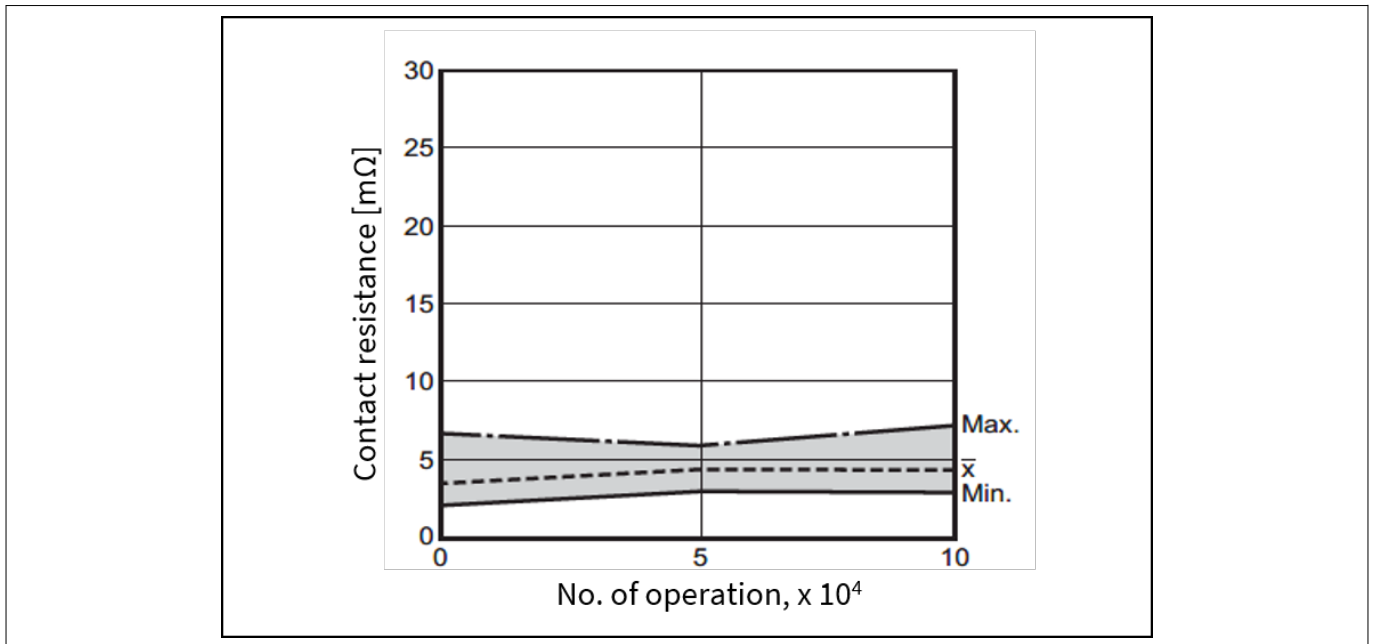


Figure 13 Relay contact resistance variations

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](#).

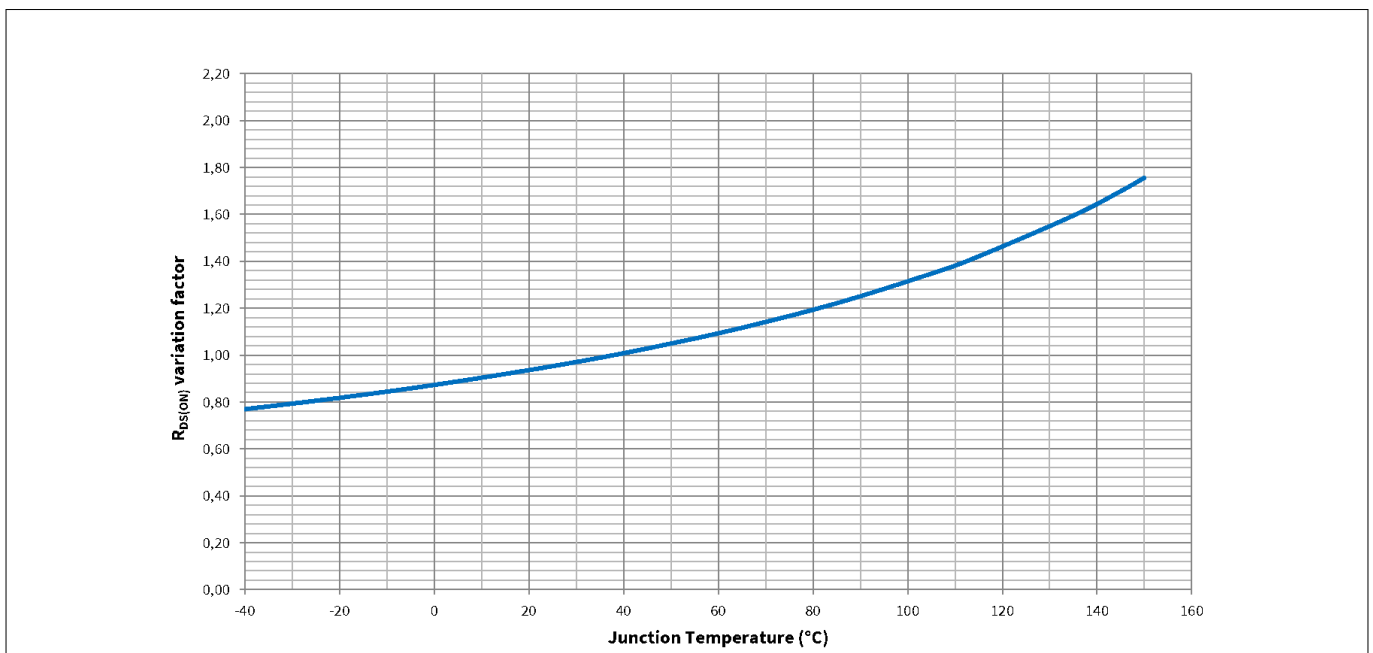


Figure 14  $R_{DS(ON)}$  variation overtemperature

### 1 Characteristics of a smart switch

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 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

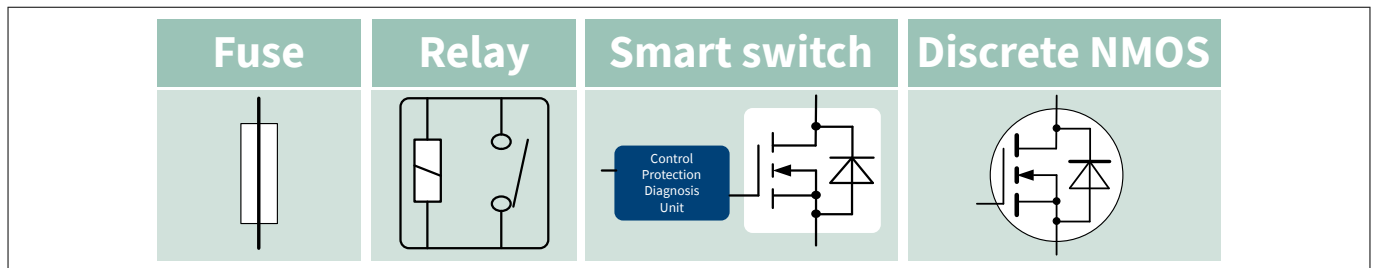


Figure 15 Main symbols used in this document

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4 Revision history

## 4 Revision history

**Table 1** Revision history

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

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**Email: [erratum@infineon.com](mailto:erratum@infineon.com)**

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## EBV European Headquarters

EBV Elektronik GmbH & Co. KG | DE-85586 Poing | Im Technologiepark 2-8 | Phone: +49 8121 774 0

## EBV Regional Offices | Status June 2021

### AUSTRIA

1120 Wien  
Grünbergstraße 15/1, 4. Stock  
Phone: +43 1 89152 0  
Fax: +43 1 89152 30

### BELGIUM

1831 Diegem  
De Kleetlaan 3  
Phone: +32 2 716001 0  
Fax: +32 2 72081 52

### BULGARIA

1505 Sofia  
48 Sitnyakovo Blvd., Serdika  
offices,10th floor, Unit 1006  
Phone: +359 2 9264 337  
Fax: +359 2 9264 133

### CZECH REPUBLIC

18600 Prague  
Amazon Court, Karolinska 661/4  
Phone: +420 2 34091 011  
Fax: +420 2 34091 010

### DENMARK

8230 Åbyhøj  
Ved Lunden 10-12, 1. sal  
Phone: +45 8 6250 466  
Fax: +45 8 6250 660

### ESTONIA

80042 Pärnu  
Suur-Jõe 63  
Phone: +372 5 8864 446

### FINLAND

02180 Espoo  
Klovinpellontie 1-3, 6<sup>th</sup> floor  
Phone: +358 9 2705279 0  
Fax: +358 9 27095498

### FRANCE

91300 Massy Cedex (Paris)  
Le Copernic bât B  
12 rue Jean Bart  
Phone: +33 1 644729 29

35700 Rennes  
16, Rue de Jouanet  
Phone: +33 2 998300 51  
Fax: +33 2 998300 60

67400 Illkirch Graffenstaden  
35 Rue Gruninger  
Phone: +33 3 904005 92  
Fax: +33 3 886511 25

31500 Toulouse  
8 chemin de la terrasse  
Parc de la plaine  
Phone: +33 5 610084 61  
Fax: +33 5 610084 74

69693 Venissieux (Lyon)  
Parc Club du Moulin à Vent  
33, Av. du Dr. Georges Lévy  
Phone: +33 4 727802 78  
Fax: +33 4 780080 81

### GERMANY

85609 Aschheim-Dornach  
Einsteinerweg 1  
Phone: +49 89 388 882 0  
Fax: +49 89 388 882 020

10553 Berlin  
Kaiserin-Augusta-Allee 14  
Phone: +49 30 747005 0  
Fax: +49 30 747005 55

30938 Burgwedel  
Burgdorfer Straße 2  
Phone: +49 5139 8087 0  
Fax: +49 5139 8087 70

59439 Holzwickede  
Wilhelmstraße 1  
Phone: +49 2301 94390 0  
Fax: +49 2301 94390 30

41564 Kaarst  
An der Gumpgesbrücke 7  
Phone: +49 2131 9677 0  
Fax: +49 2131 9677 30

71229 Leonberg  
Neue Ramtelstraße 4  
Phone: +49 7152 3009 0  
Fax: +49 7152 759 58

90471 Nürnberg  
Lina-Ammon-Straße 19B  
Phone: +49 911 817669 0  
Fax: +49 911 817669 20

04435 Schkeuditz  
Frankfurter Straße 2  
Phone: +49 34204 4511 0  
Fax: +49 34204 4511 99

78048 VS-Villingen  
Marie-Curie-Straße 14  
Phone: +49 7721 99857 0  
Fax: +49 7721 99857 70

65205 Wiesbaden  
Borsigstraße 36  
Phone: +49 6122 8088 0  
Fax: +49 6122 8088 99

### HUNGARY

1117 Budapest  
Budafoki út 91-93, West Irodaház  
Phone: +36 1 43672 29  
Fax: +36 1 43672 20

### ISRAEL

4581500 Bnei Dror  
Tirosh 1  
Phone: +972 9 77802 60  
Fax: +972 3 76011 15

### ITALY

20095 Cusano Milanino (MI)  
Via Alessandro Manzoni, 44  
Phone: +39 02 660962 90  
Fax: +39 02 660170 20

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Phone: +39 05 543693 07  
Fax: +39 05 542652 40

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Phone: +39 059 292 4211  
Fax: +39 059 292 9486

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Via de Settebagni, 390  
Phone: +39 06 4063 665/789  
Fax: +39 06 4063 777

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Phone: +39 049 89747 01  
Fax: +39 049 89747 26

10144 Torino (TO)  
Via Treviso, 16  
Phone: +39 011 26256 90  
Fax: +39 011 26256 91

### IRELAND

Fitzwilliam Hall  
Fitzwilliam Place  
Dublin 2  
D02 T292  
Phone: +353 1 4097 802  
Fax: +353 1 4568 544

### NETHERLANDS

Zonnebaan 9  
3542 EA Utrecht  
Phone: +31 346 5830 10  
Fax: +31 346 5830 25

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1181 Oslo  
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Phone: +47 22 67 17 80  
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80-838 Gdansk  
Targ Rybny 11/12  
Phone: +48 58 30781 00

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Postepu 14  
Phone: + 48 22 209 88 05

50-062 Wrocław  
Pl. Solny 16  
Phone: +48 71 34229 44  
Fax: +48 71 34229 10

### PORTUGAL

4400-676 Vila Nova de Gaia Unipessoal  
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Rotunda Eng. Edgar Cardoso, 23 - 14<sup>o</sup>G  
Phone: +351 22 092026 0  
Fax: +351 22 092026 1

### ROMANIA

020334 Bucharest  
4C Gara Herastrau Street  
Building B, 2nd Floor - 2nd District  
Phone: +40 21 52816 12  
Fax: +40 21 52816 01

### RUSSIA

620028 Ekaterinburg  
Tatischeva Street 49A  
Phone: +7 343 31140 4  
Fax: +7 343 31140 46

127486 Moscow  
Korovinskoye Shosse 10,  
Build 2, Off. 28  
Phone: +7 495 730317 0  
Fax: +7 495 730317 1

197374 St. Petersburg  
Atlantic City, Savushkina str 126,  
lit B, premises59-H, office 17-2  
Phone: +7 812 635706 3  
Fax: +7 812 635706 4

### SERBIA

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Milentija Popovica 5B  
Phone: +381 11 40499 01  
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### SPAIN

08014 Barcelona  
c/ Tarragona 149 - 157 Planta 19 1<sup>o</sup>  
Phone: +34 93 47332 00  
Fax: +34 93 47363 89

39005 Santander (Cantabria)  
Racing n° 5 bajo  
Phone: +34 94 22367 55  
Phone: +34 94 23745 81

28760 Tres Cantos (Madrid)  
c/Ronda de Poniente 14 - 2<sup>a</sup> planta  
Phone: +34 91 80432 56  
Fax: +34 91 80441 03

### SWEDEN

16440 Kista  
Isafjordsgatan 32B, Floor 6  
Phone: +46 859 47023 0  
Fax: +46 859 47023 1

### SWITZERLAND

8953 Dietikon  
Bernstrasse 394  
Phone: +41 44 74561 61  
Fax: +41 44 74561 00

### TURKEY

06520 Ankara  
Armada Is Merkezi  
Eskisehir Yolu No: 6, Kat: 14  
Ofis No: 1406, Sogutozu  
Phone: +90 312 2956 361  
Fax: +90 216 528831 1

34774 Ümraniye / Istanbul  
Tatlısu Mahallesi Pakdil Sokak 7  
Phone: +90 216 528831 0  
Fax: +90 216 528831 1

35580 Izmir  
Folkart Towers  
Manas Blv. No 39 B Blok  
Kat: 31 Ofis: 3121  
Phone: +90 232 390 9196  
Fax: +90 216 528831 1

### UKRAINE

03040 Kiev  
Vasilovskaya str. 14  
off. 422-423  
Phone: +380 44 496222 6  
Fax: +380 44 496222 7

### UNITED KINGDOM

Maidenhead (South)  
Berkshire, SL6 7RJ  
2, The Switchback  
Gardner Road  
Phone: +44 16 28778556  
Fax: +44 16 28783811

Manchester (North)  
M22 5WB  
Manchester International Office Centre  
Suite 3E (MIOC) Styal Road  
Phone: +44 16 149934 34  
Fax: +44 16 149934 74