decrease of overvoltage. In contrast to that, there will be no substantial overvoltage on any of those conditions with CAL-diodes.

All further explanations in this manual are based on the following definition:

*A diode shows soft-recovery behaviour, if, in all conditions relevant to the application in an application-related circuit, no overvoltage occurs, caused by reverse current snap-off due to the diode.*

Relevant conditions being the total current range, all commutation velocities useful for the application and the temperature range of -50°C up to +150°C. This definition is valid as long as dI/dt is not too high (> 6 kA/µs) or high parasitic inductances (> 50 nH) are applied, which might lead to circuit-dependent voltage peaks also with soft-recovery diodes.

An equally important requirement for free-wheeling diodes with a voltage from 100V upwards (apart from soft switching behaviour) is **dynamic ruggedness**. Figure 1.24b shows that nearly the whole DC-link voltage is taken up by the diode, while it is still conducting a substantial tail current. If the IGBT is switched very steeply (small gate resistance $R_G$), reverse current and tail current will rise, at the same time causing a decrease of $V_{CE}$ at the IGBT, which switches over to the diode with a respectively higher dV/dt. The density of the current-carrying charge carriers (holes) will then be above the original doping density, the consequence of which will be an inevitable avalanche breakdown in the semiconductor at applied voltages far below reverse voltage level (dynamic avalanche). To manage these operating conditions is characteristic of the dynamic ruggedness of a free-wheeling diode. The dynamic ruggedness may be defined as follows:

*The dynamic ruggedness is the ability of a diode to manage high rates of rise of commutating di/dt and a high DC-link voltage at the same time.*

If the diode shows no sufficient dynamic ruggedness, manufactures limit the dI/dt of the IGBT or admit only a maximum reverse recovery peak current of the diode thus accepting increased switching losses.

#### 1.3.1.4 Demands on free-wheeling diodes used in the rectifier and inverter mode of voltage source converters

Free-wheeling diodes in IGBT- or MOSFET-converters have to cope with different requirements depending on whether they are used in rectifiers or inverters with the same power regarding the power losses occurring.

Typically, the average energy flow in inverter mode is directed from the DC-link to the AC-side, i.e. a consumer is connected to and supplied by the AC-side (e.g. three-phase motor).

On the other hand, the average energy flow in rectifier mode is directed from the AC-side to the DC-link. In this case the converter works as a pulse rectifier connected to an AC-mains or generator.

Although the power performance in both cases is the same, the power semiconductors are subject to different power losses basically due to the opposite phase shift between voltage and current on the AC-side, when in rectifier or inverter operation.

This can be explained using to the basic circuit in Figure 1.26.

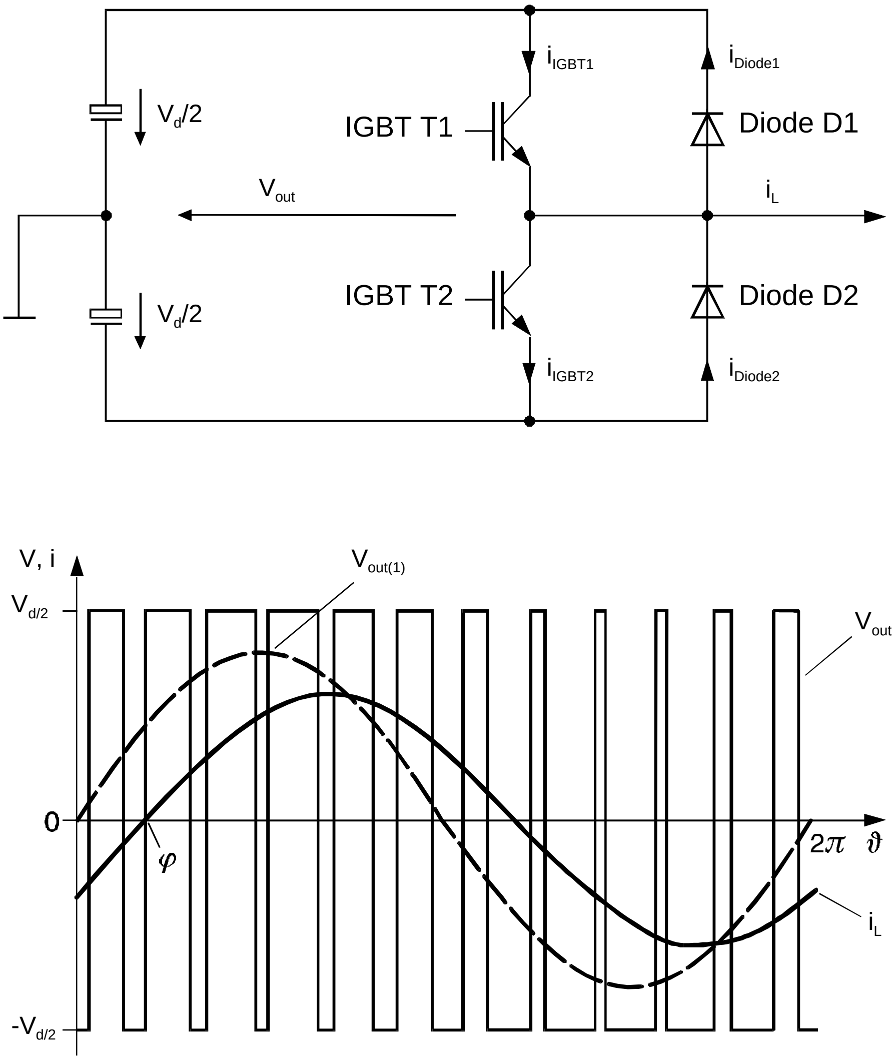


Figure 1.26 Basic circuit of a converter phase with IGBTs and free-wheeling diodes

It shows:

| | |
|---|---|
| - if $v_{out}$ = positive and $i_L > 0$: | current flow over IGBT 1, |
| - if $v_{out}$ = negative and $i_L > 0$: | current flow over diode 2, |
| | |
| - if $v_{out}$ = positive and $i_L < 0$: | current flow over diode 1, |
| - if $v_{out}$ = negative and $i_L < 0$: | current flow over IGBT 2. |

Consequently, the IGBT- and FWD- on-state power losses occurring at a given RMS-current value are dependent on the cos phi between voltage and current fundamental frequency as well as on the modulation factor m of the converter (determines duty cycles).

In the case of inverter-operation $0 \leq m*\cos \text{phi} \leq 1$. Power losses in semiconductors reach their limits, if $m*\cos \text{phi} = 1$. In this case maximum on-state losses and, therefore, total losses in the IGBTs have been reached, whereas losses in the free-wheeling diodes are at their minimum.

In the case of rectifier operation $0 \geq m*\cos \text{phi} \geq -1$. Power losses in semiconductors reach their limits, if $m*\cos \text{phi} = -1$. In this case, minimum on-state losses and, therefore, total losses in the IGBTs have been reached, whereas losses in the free-wheeling diodes are at their maximum. Applied to the characteristics in Figure 1.26, this situation is given when the fundamental frequency of the pulse rectifier converts pure active power from the line and the neutral point of the line is connected to the centre point of the DC-link voltage.

This is illustrated with the graphs in Figure 1.27 with an example.

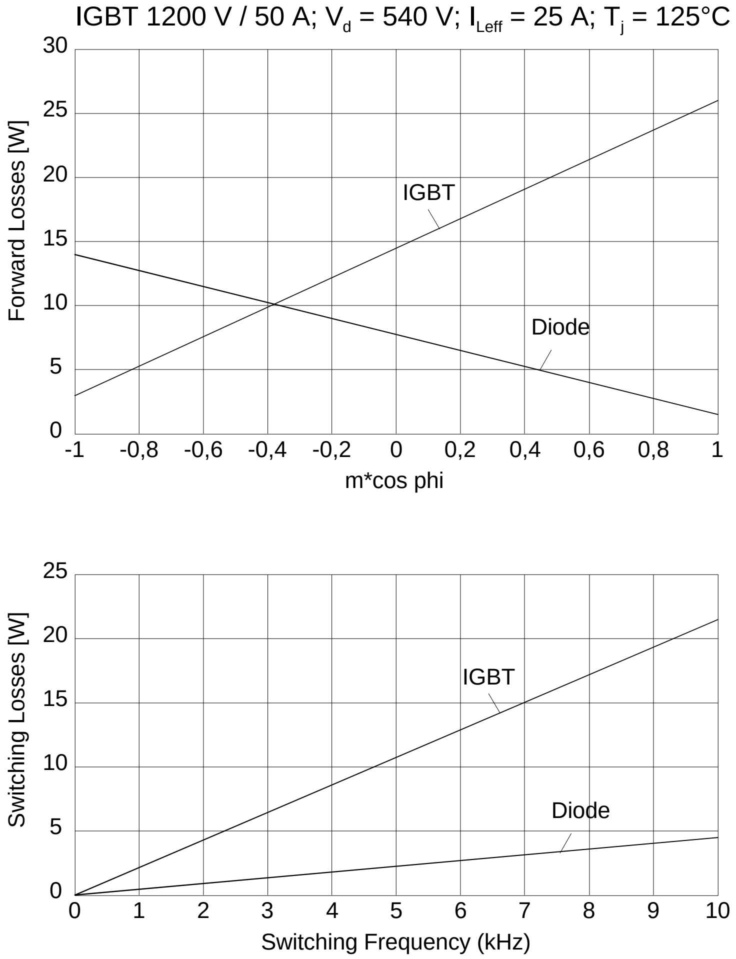


Figure 1.27 Switching and forward on-state losses of IGBT and free-wheeling diode in a VSI

At given DC-link voltage and RMS-AC-current values the switching losses of the components are merely dependent (linear) on the switching frequency (Figure 1.27).

A large number of the available IGBT and MOSFET modules with integrated free-wheeling diodes are dimensioned for being applied in inverters regarding the power losses that may be dissipated at rated current (e.g. cos phi = 0.6...1). Due to their reduced on-state and total losses, diodes have been designed for a considerably lower dissipation of power losses compared to IGBTs (ratio IGBT : diode ≈ 2..3:1).
Therefore, the use of power modules with higher rated current is recommended when dimensioning pulse rectifiers with the same converter power as a corresponding pulse inverter.

***Example:***
Driving system:

* Power supply (400 V/50 Hz) – pulse rectifier ($f_s$ = 10..12 kHz) – DC-link – pulse inverter ($f_s$ = 10..12 kHz) – three-phase motor (400 V/50 Hz/22 kW)

* <u>Pulse rectifier</u> with standard IGBT-modules (phase leg) ≥ <u>1200 V/100 A</u> ($T_c$ = 80°C)
* <u>Pulse inverter</u> with standard IGBT-modules (phase leg) ≥ <u>1200 V/75 A</u> ($T_c$ = 80°C)

This difference is not required for power modules with higher rated diodes.

### 1.3.2 Structure of fast power diodes

We have to distinguish between two basic types: Schottky-diodes and pin-diodes.
In Schottky-diodes, the metal-semiconductor junction serves as blocking junction. There is no diffusion voltage at the pn-junction as in pin-diodes; this guarantees a lower on-state voltage as with any pin-diode, provided the n$^-$-zone is very thin. When passing over from conductive to blocking state, ideally only the space charge zone has to be charged. Due to this, the component is suitable for very high frequencies (> 100 kHz). This advantage is, however, restricted to voltages < ~ 100 V. In this range, the Schottky-diode is the appropriate free-wheeling diode for a MOS-transistor. If, on the other hand, the component is dimensioned for higher voltages,

- the on-state voltage will rise considerably, since $w_B$ increases and only one sort of charge carriers is available (unipolar) and
- the leakage current will rise considerably, which will cause thermal instability.

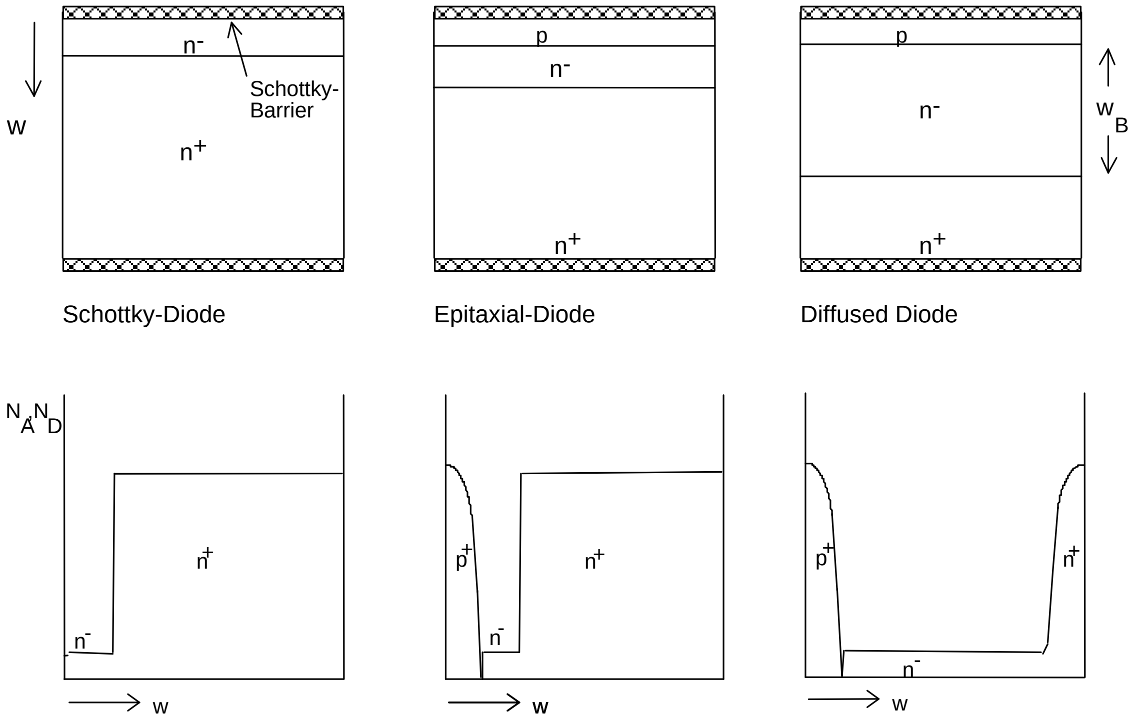


Figure 1.28 Schottky-, pin-epitaxial - and pin-diffused diode structures
Top: structure
Bottom: doping profile (scheme)

The advantages of pin-diodes become effective in the range of more than 100V. In diodes produced today, the middle zone is not „i“ (intrinsic), but of n-type with a very low doping level (n$^-$) compared to the marginal zones. In pin-epitaxial-diodes (Figure 1.28, mid) a n$^-$-zone is separated from the highly-doped n$^+$-substrate (epitaxy). Then, the p-zone is diffused. By this technology, a very small base width $w_B$ down to some µm may be produced, the silicon wafer being thick enough to manage high production yields. By diffusion of recombination centres (mainly gold-diffusion) very fast diodes can nevertheless be produced with a low forward on-state voltage due to the small $w_B$. However, the on-state voltage will always be above the diffusion voltage of the pn-junction of 0.6 to 0.8 V. The main applications of epitaxial (epi-) diodes are within the range of 100 V and 600 V, some manufacturers are even producing epi-diodes for 1200 V.

From 600 V upwards the $n^-$-zone will be enlarged to such an extent that a diffused pin-diode (right Figure) may be produced. The p- and $n^+$-zones are diffused into the $n^-$-wafer. Similar, recombination centres are necessary to adjust the dynamical characteristic.

As the major applications of power modules are within the range above 100 V, pin-diodes will be explained in more detail in the following.

### 1.3.3 Characteristics of fast power diodes

As for free-wheeling diodes, a compromise has to be found for optimizing the contrasting requirements. Therefore, we have to come up against the physical limits of the material, which makes the design of excellent free-wheeling diodes very sophisticated.

#### *1.3.3.1 Forward and blocking behaviour*

In forward direction, there is the pn-junction and the resistance of the adjacent $n^-$-zone. The voltage drop is composed of

$$V_f = V_{diff} + V_{ohm} \tag{1.6}$$

The pn-junction diffusion voltage $V_{diff}$ is dependent on the doping of both pn-junction sides and is, typically, between 0.6...0.8V. For fast diodes with a blocking voltage of 600V and more, the ohmic part prevails. Charge carrier lifetime of free-wheeling diodes has to be kept very low so that the on-state voltage will depend exponentially on the base width $w_B$ and the charge carrier lifetime $\tau$ [283]:

$$V_{Ohm} = \frac{3\pi kT}{8q} e^{\frac{w_B}{2L_A}} \tag{1.7}$$

$L_A$ is the ambipolar diffusion length

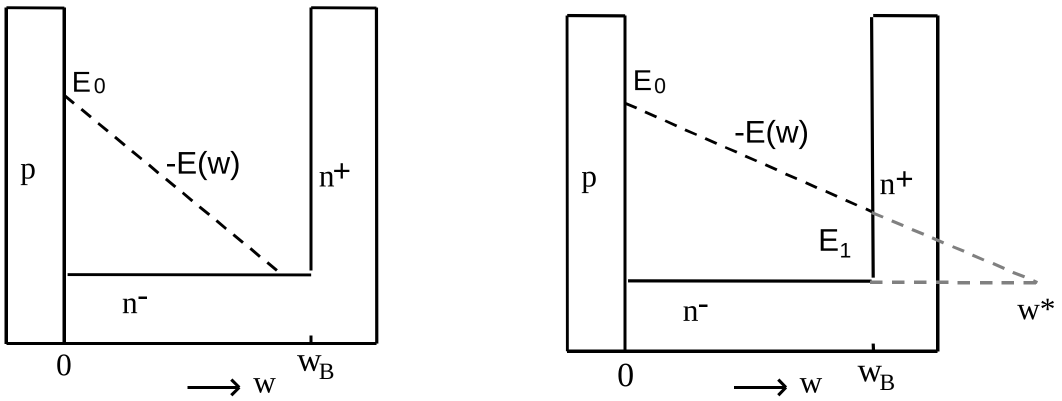
$L_A = \sqrt{D_A \tau}$, with the ambipolar diffusion constant $D_A = 2\frac{\mu_n \mu_p}{\mu_n + \mu_p}\frac{kT}{q}$.

k: Boltzmann-constant; $1.38066 \cdot 10^{-23}$ J/K
q: electronic charge; $1.60218 \cdot 10^{-19}$ C

$\mu_n$ and $\mu_p$ stands for the mobility of the electrons and holes on condition of a $n^-$-zone flooded by free electrons and holes [284]. Due to this exponential correlation, the smallest possible $w_B$ should be selected.

In spite of this, the base width $w_B$ has a definite influence on the blocking voltage. Two different cases may occur (see Figure 1.29):

If $w_B$ has been dimensioned in such a way that the space charge zone cannot protrude into the $n^+$-zone (triangular characteristic), this is called non-punch-through structure [285]. If $w_B$ has been dimensioned in such a way that the space charge zone will protrude into the $n^+$-zone, the characteristic will be trapezoidal, which will be called punch-through-diode. However, a real punch-through, where the space charge zone would reach the area of another doping type, is not realized in this case. Nevertheless, the designation has generally been accepted.



non-punch-through (NPT) -Diode
a)

punch-through (PT) -Diode
b)

Figure 1.29 Dimensioning of a diode for triangular (a) and trapezoidal (b) characteristic

For an ideal **NPT-diode** $w_B$ is dimensioned so that it is located at the end of the triangular characteristic. If the doping is optimal, the minimum width for $w_B$ would then be

$$w_B = 2^{\frac{2}{3}} C^{\frac{1}{6}} V_R^{\frac{7}{6}} \tag{1.8}$$

with C = $1.8 \cdot 10^{-35}$ $cm^6V^{-7}$

Minimum doping necessary for PT-diodes can be calculated similarly. As a extreme, the characteristic would be rectangular, $E_1 = E_0$ (see Figure 1.29). Consequently,

$$w_B(\mathrm{PT, extreme}) = C^{\frac{1}{6}}\ V_{BD}^{\frac{7}{6}} \tag{1.9}$$

Compared to $w_B$ of the NPT dimensioning (1.8):

$$w_B(\mathrm{PT, extreme}) = 2^{-\frac{2}{3}} w_B(\mathrm{NPT}) \cong 0.63 w_B(\mathrm{NPT}) \tag{1.10}$$

This extreme case, however, may not be achieved, but with the existing technology it may be approximated by

$$w_B(\mathrm{PT}) \cong 0.66 \cdot w_B(\mathrm{NPT}) \tag{1.11}$$

The difference between PT-structure according to (1.11) and NPT-structure according to (1.8) adds up to about 0.8 V on-state voltage, considering the necessary low charge carrier lifetime. Therefore, PT-structure should be preferred.

### *1.3.3.2 Turn-on behaviour*

When the diode is turned on, it has to overcome the resistance of the low-doped base. Therefore, the turn-on peak voltage will increase proportionally to $w_B$. The turn-on peak voltage becomes critical, especially if a significant base width $w_B$ has to be chosen due to a high blocking voltage over 1200V. In this respect, PT-diodes will show optimized turn-on behaviour.

Free-wheeling diodes always contain recombination centres. For free-wheeling diodes dimensioned for applications of 1200V and more, recombination centres that cause increase of the base resistance have to be avoided. A like recombination centre would be one that had been generated by gold-diffusion. Recombination centres generated by platinum-diffusion, electron beam radiation or light ions will only slightly increase the turn-on overvoltage in comparison to diodes without recombination centres.

### *1.3.3.3 Turn-off behaviour*

The turn-off behaviour of fast diodes is determined by the way in which the charge declines to zero. Figure 1.30 shows the procedure for a snappy diode, Figure 1.31 for a soft-recovery diode.

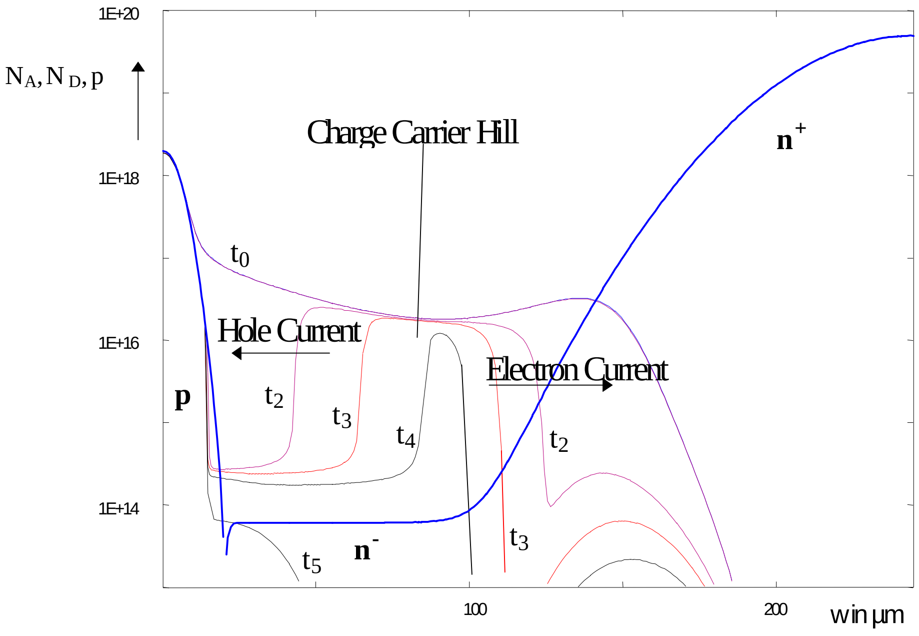


Figure 1.30 Diffusion profile and decline of charge carriers (density of holes) in a snappy diode (ADIOS-simulation)

During on-state, the n$^-$-zone is flooded by > $10^{16}$ cm$^{-3}$ electrons and holes, the concentration of electrons n and holes p presumably being the same. After commutation the charge carrier hill is within the n$^-$-zone between $t_2$ and $t_4$, provided $n \approx p$. The decline of charge carriers towards the cathode is effected by the flow of electrons, that move towards the anode by the flow of holes, which flow as reverse current in the outer circuit. In case of the snappy diode in Figure 1.30 the charge carrier hill declines to zero shortly after $t_4$. Between $t_4$ and $t_5$ the diode will suddenly turn from its state with charge carrier hill to a state without charge carrier hill, the reverse current snaps off. The switching behaviour of the diode is snappy.

Figure 1.31 shows the same procedure for a soft-recovery diode. A charge carrier hill feeding the reverse current is kept during the whole procedure. At $t_5$ the diode has already taken on the applied voltage. The procedure described in Figure 1.31 will lead to a tail current as shown in Figure 1.24.

Whether soft-recovery behaviour is reached or not, depends on the successful reduction of charge carriers. This is difficult to achieve by microstructures on the surface, a technology where the semiconductor industry has made an enormous progress in the past. Therefore, it has taken a relatively long period of time until the reverse recovery behaviour could be controlled.