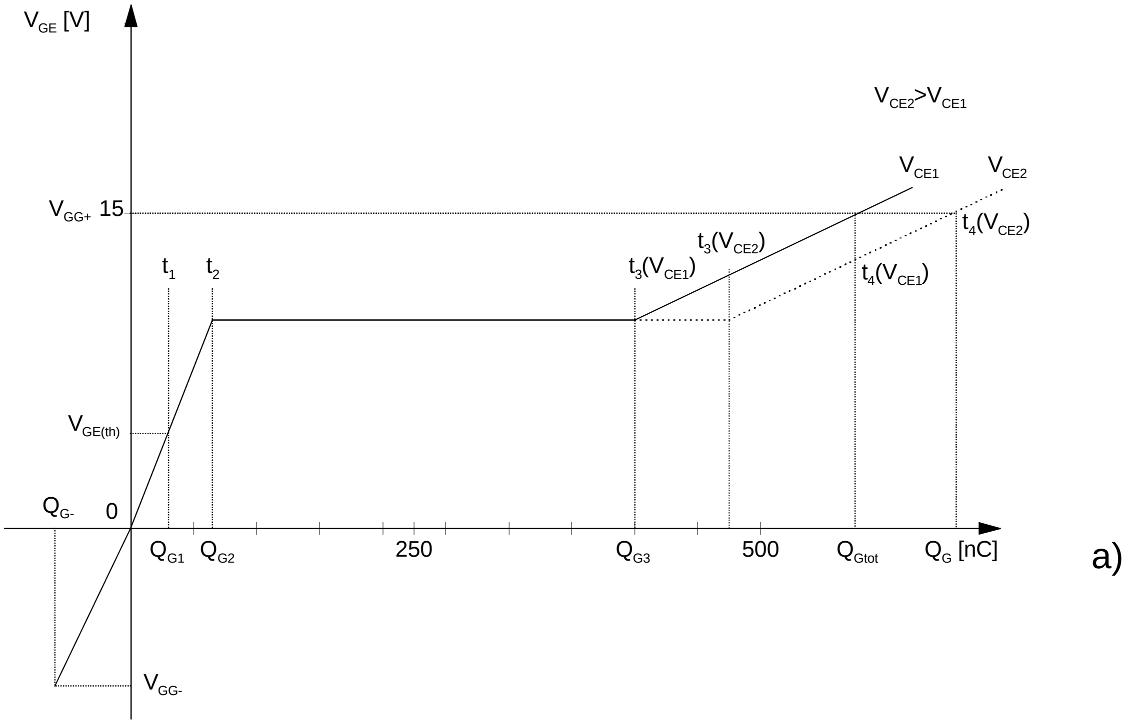

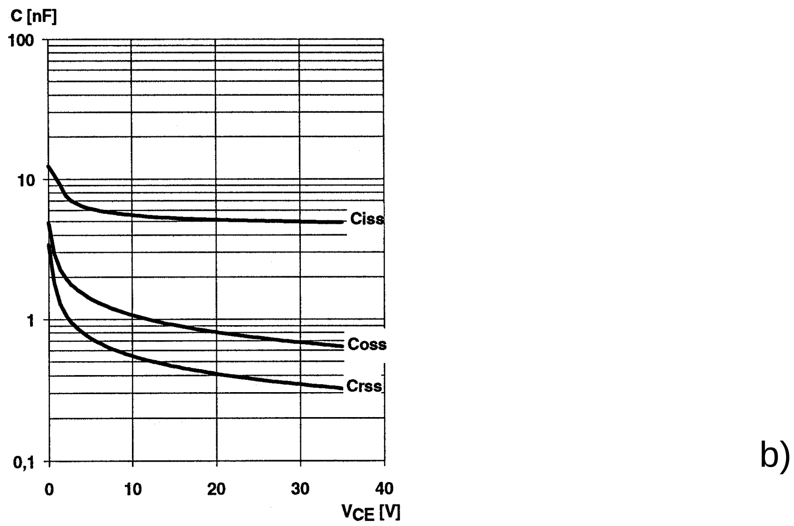

Figure 1.13 a) Extended IGBT gate charge characteristic for gate control between V_{GG+} and V_{GG-}
b) IGBT low-signal capacitances

1.2.4 New developments in MOSFET and IGBT technology

For the time being, the most important goals in research and development of MOSFET- and IGBT chips are:

a) Reduction of the on-state voltage
b) Reduction of switching power losses
c) Improved ruggedness (overcurrent-, overvoltage-behaviour, switching performance)
d) Increased off-state voltage for high-volt transistors
e) Consequent to a)...c): increased current density (shrinking)
f) Provided that e) is complied with, increase of current per chip or decrease of chip surface and costs
g) Optimized *low saturation* and *high speed*-IGBTs

h) Integration of monitoring, protection and driver functions or power electronic circuits (monolithic, chip-on-chip or silicon-on-insulator)

Especially during the past years a rapid development progress is to be noted concerning mainly the optimization of the horizontal and vertical cell design, the refinement of the cell structure and the successful handling of ultra-thin silicon wafers.
With mastery of the thin-wafer technology (wafer thickness 100µm), for example, the production of extremenly low-loss 600V-IGBTs in NPT-technology had been possible [164].

For the time being, the principal improvement potential for MOSFETs and IGBTs lies in optimizing the cell design.
Firstly, there are new superfine structures, such as the S-FET product range by SIEMENS, thanks to the latest self-adjusting processes realizing an on-state resistance that is a fifth of that of conventional MOSFETs and a clearly improved switching and avalanche stability [216]. These structures, which are applied in similar forms also in modern high-density IGBTs, contain double-implantation gates with spacers in the margin region (Figure 1.14).

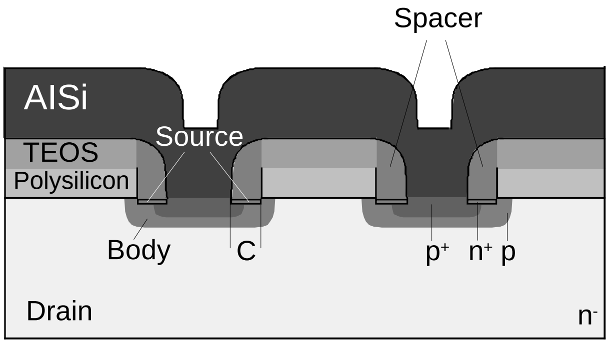

Figure 1.14 Double-implantation gate structure (Siemens S-FET) [298]

A lately developed gate structure for MOSFETs and IGBTs which will replace the conventional gate structure is the *trench-gate*, which allows for a vertical passage of the channel in the p-well (Figure 1.15). Since this structure provides for more active silicon surface, control of the channel cross-section becomes easier and a smaller channel resistance may be realized. The on-state losses can be reduced by about 30 %.
Furthermore, the cell surface can again be reduced, allowing higher current density, reduced on-state losses, improved latch-up stability, reduced switching losses and a higher breakdown voltage compared to planar MOSFETs and IGBTs.
The disadvantages, however, are a decreased short-circuit stability and an approximately three times higher gate capacitance compared to that of planar elements.

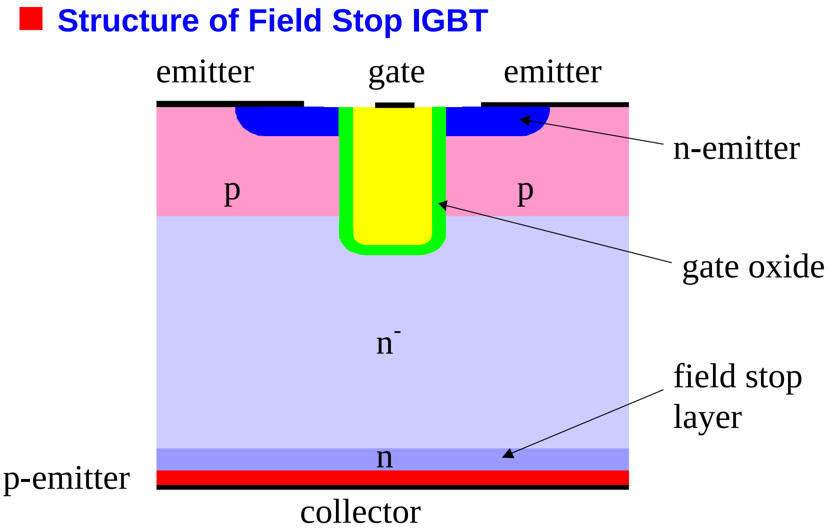

Figure 1.15 IGBT-cell with trench-gate and field stop layer

Also the so-called IEGTs (**I**njection **E**nhaced **G**ated **T**ransistors) for extremely high voltage applications (4.5...6.5 kV) have been designed in trench technology; due to the cathode emitter structure, the leak-off process of the holes is impeded, causing a charge carrier density similar to that of thyristors during on-state [194].

A remarkable progress within the high-volt power MOSFET has been made with the CoolMOS introduced by SIEMENS in 1998 [216]. As shown in Figure 1.16, the MOSFET-cell structure of the CoolMOS has been equipped with p-conducting areas in the drift zone which are connected to the p-wells.

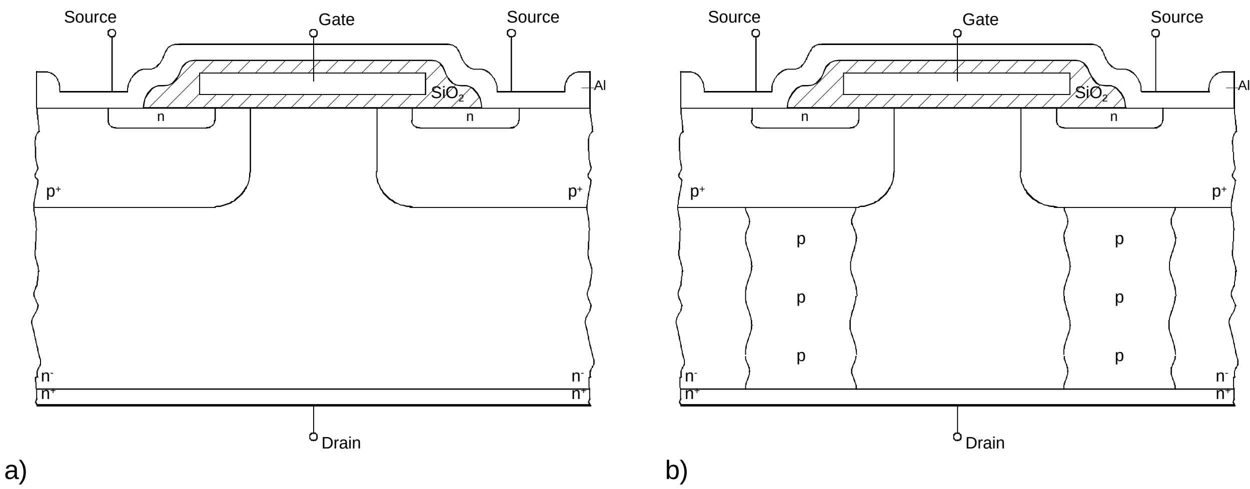

Figure 1.16 MOS- cell structures
a) Conventional structure
b) CoolMOS-structure (principle)

Since, during forward off-state, the electrical field is not only handled in vertical, but also in horizontal direction, the n^--drift area may be drastically reduced in size compared to conventional MOSFETs, by increasing its conductivity at the same time.
The turn-on resistance $R_{DS(on)}$ will then not increase in the exponential way described under chapter 1.2.1 anymore (exponent 2.4...2.6), but only linearly to the breakdown voltage $V_{(BR)DS}$.

By this, the forward on-state losses of a 600V-CoolMOS, for example, will be reduced by the factor 5 in contrast to a conventional MOSFET with the same chip surface. Only 1/3 of the previous chip surface is required to manage the same current. Switching losses will be halved and on-state losses will be reduced to about 35 %; due to the reduced chip surface, also gate capacitance and gate charge will decrease to about a third of the previous value [216].
However, the bad dynamic behaviour of the inverse diodes inside the CoolMOS-structure is disadvantageous. This restricts the application in hard switching topologies with inductive commutation.
Further progress will be achieved with the use of other semiconductor materials, such as silicon carbide (SiC).
Compared to Si, SiC shows an almost 10 times higher breakdown field intensity.
In spite of restricted mobility of the electrons, on-state resistances reduced by the factor 1/300 are realizeable in unipolar components, which guarantees for a high-voltage application range far beyond 1000V. As for bipolar SiC-components, the smaller drift area results in a scaled down storage charge. On the one hand, the energy gap, which is three times as big as that of Si, allows operating temperatures up to 500°C; on the other hand the threshold voltage of bipolar components is increased to 2.5V.
Other unfavourable effects lie in the considerably higher junction capacitances compared to Si-components and in today's still tremendous technological problems: diffusion of impurity centers is almost impossible, non-defective big surfaces are currently not realizeable and today's fundamental technologies for the margin design are not applicable to SiC. [282], [124], [130].

The integration of monitoring, protection and driver functions or power electronic circuits (monolithic, chip-on-chip or silicon-on-insulator) to the chip is more and more gaining importance in low-voltage (e.g. car electronics) or low-current (e.g. consumer products) batch applications.
For example, driver-, protection-, system- and diagnostic functions have been integrated on one chip in the „intelligent" SMARTPOWER-transistors, leading to a reduction of power losses and to an improvement of the system reliability apart from the advantages of system miniaturization [277], [213], [232].

The simplest method is to generate e.g. protection- and sensor units to manage currents, voltages or temperatures on control supply potential by diffusion to the MOSFET- or IGBT-chip surface.
Popular designs to be mentioned are the *SENSFET* and the *Sense-IGBT*, where source- or emitter current, respectively, are separated into a main circuit conducting the main current share and a parallelled measuring circuit. By inverse feedback of the measuring signal to the control circuit, the measuring current is reduced by increase of the sense-resistance [194]. Sense-IGBTs are integrated in many IPMs.
The *TEMPFET* is equipped with an integrated temperature sensor, which is used as overcurrent indicator at the same time and which will short-circuit the gate-source-connection, in case a certain temperature limit has been exceeded.

*PROFET*s and *HITFET*s, for example, contain a complete driver circuit with overcurrent-/short-circuit-protection, overvoltage- and overtemperature-protection, gate-protection, load indicator, polarity protection, over- and undervoltage turn-off and a charge pump for generation of the gate voltage, e.g. [4], [277].
The *PROFET* is being produced as single- and multi-channel high-side switch up to a break-over voltage of 60V.
In contrast to the high-side switch, there is not sufficient supply voltage generated for the protection logic during on-state of a MOSFET for a low-side switch. Therefore, an integrated

temperature sensor in the *HITFET* will reduce the gate voltage at a high chip temperature that the drain voltage is able to increase to the minimum supply voltage-value of 3V and the protection circuit may react.
With reference to [232], *monolithic integration* of whole inverters with power semiconductors, high-voltage ICs for driver/ protection and micro-electronic system control circuits is limited to 1A/ 600V (soon up to approx. 2A) and 5A/75V for the time being, the disadvantages compared to hybrid system integration of chips (currently up to 30A/ 1200V and up to 150A towards the year 2002) being the limitation of the blocking voltage to 600 V, restricted ruggedness reffering to short-circuit- and pulse-currents and tripled losses in the used lateral transistors in contrast to vertical transistors.

1.3 Free-wheeling- and snubber-diodes

1.3.1 Demands to free-wheeling and snubber-diodes

Modern fast switching devices require fast diodes as free-wheeling diodes. With every turn-on of the switch, the free-wheeling diode is commutated from conductive to blocking state. At this process, it has to show soft-recovery behaviour. For a long time, the importance of fast diodes had been underestimated. The performance of the switch had been impaired by the free-wheeling diodes. During the past few years, however, free-wheeling diodes had regained importance, and significant progress could be made by improving the reverse-recovery behaviour.

1.3.1.1 Reverse voltage and forward voltage drop

The *reverse voltage* V_R indicates that, at a specified voltage, the leakage current must not exceed the limit current I_R.
The specifications in the databooks are indicated for an operating temperature of 25°C. In the case of lower temperatures, the blocking capability will decrease, e.g. by approximately 1.5 V/K for a 1200V-diode. For components which are operated at temperatures below the ambient temperature, this has to be considered in the circuit layout.

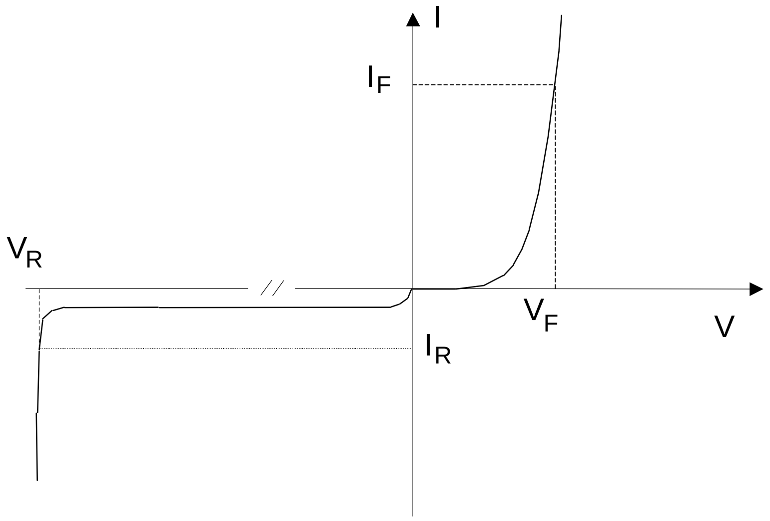

Figure 1.17 Definition of reverse and forward voltage of a diode

At temperatures above the ambient temperature the reverse voltage will increase accordingly, however affecting an simultaneous increase of the leakage current. Therefore, a leakage current value is specified also for high temperatures (125°C or 150°C). In case of gold-diffused devices the leakage current can rise very steeply, which might cause thermal instability in circuits, where the whole system is operated at high temperatures due to the losses of the switching devices.

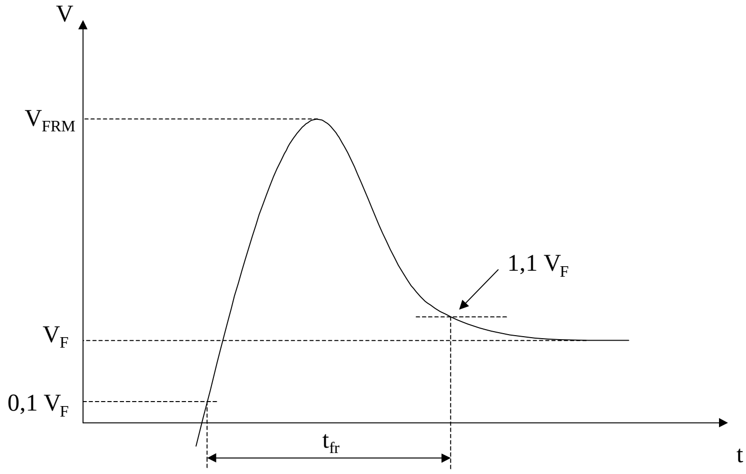

Figure 1.18 Turn-on behaviour of power diodes

The *continuous forward voltage* V_F indicates that, at a specified current, the forward voltage drop over the diode must not exceed the specified limit value. Typically, these limit values are specified at ambient temperature. A decisive factor in the power loss balance, however, is the forward voltage at higher temperatures. All datasheets of free-wheeling diodes should contain a note of this temperature dependency.

1.3.1.2 Turn-on behaviour

When the diode passes over to conductive state, the voltage will at first increase to the repetitive peak forward voltage V_{FRM}, before it drops to forward voltage level again. Figure 1.18 shows the currently valid definition of V_{FRM} and the turn-on time t_{fr}.
This definition, however, does not give much information on the behaviour of free-wheeling and snubber-diodes for IGBTs, because

- the rise of the on-state current di/dt is so high that e.g. V_{FRM} may increase to 200V or even 300V for an unsuitable 1700V-diode, which is more than 100 times V_F,
- the diode is normally turned on f run the blocking state, generating a considerably higher V_{FRM} than if it is turned on from its neutral state.

A low V_{FRM}-value is one of the most important requirements to snubber-diodes, since the snubber-circuit becomes effective only after turn-on of the diode.
The repetitive peak forward voltage is also of importance for free-wheeling diodes, which are designed for a reverse voltage of > 1200V. When the IGBT is turned off, a peak voltage is generated over the parasitic inductances, which is still superimposed by V_{FRM} of the free-wheeling diode. The sum of both components may lead to critical voltage peaks.
However, this measurement is not trivial, since the inductive component and V_{FRM} cannot be told apart in the application conform chopper circuit. Measurements may only be made with the open construction directly at the bonding wires of the diode.