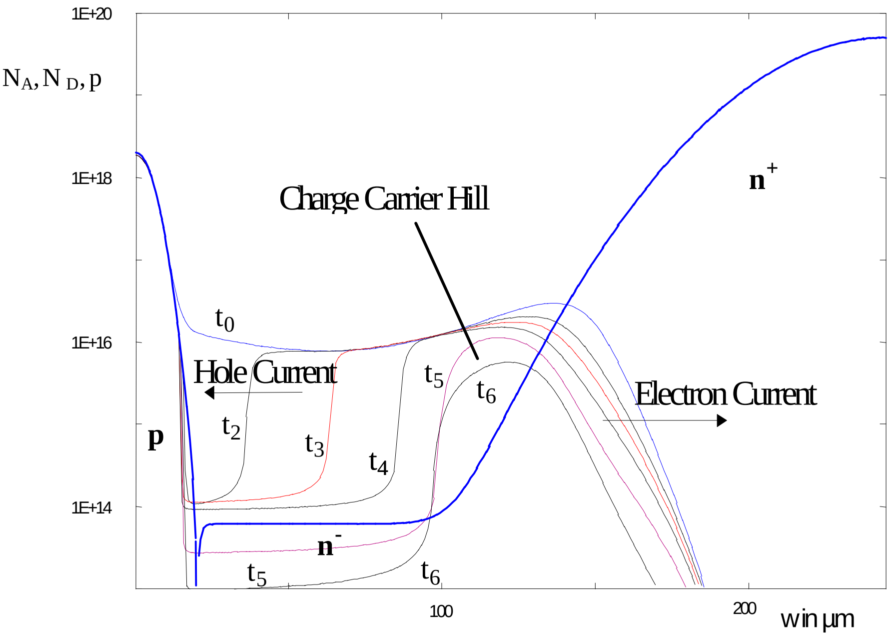

Figure 1.31 Diffusion profile and decline of charge carriers (density of holes) in a soft-recovery diode (ADIOS-simulation)

The following measures will effect a softer recovery behaviour:

1. The basis width w_B of the n^--zone is enlarged, NPT-dimensioning is applied (see equation (1.9)), an additional zone is generated in the diode, which is not reached by the field at rated voltage. But this will lead to extreme increase of the on-state voltage (see equation (1.7)) or the V_F/Q_{RR}-ratio. Nevertheless, this inconvenience is accepted even in lately developed solutions (as mentioned e.g. in [286]).
2. In order to slightly neutralize the w_B-increase, a two-phase n^--zone may be applied [287] showing a highly doped area near to the nn^+-junction. In Figure 1.30 and 1.31 a similar effect is realized by a flat gradient at the nn^+-junction. This measure on its own will not be sufficient in order to reach soft-recovery behaviour.
3. Inversion of the charge carrier distribution by a low-efficiency p-emitter (see chapter 1.3.4.1).
4. An axial charge carrier lifetime profile, providing for a low charge carrier life at the pn-junction, and a longer charge carrier life at the nn^+-junction (see chapter 1.3.4.2).

To guarantee for soft-recovery behaviour on any condition, usually several of those measures have to be taken at the same time. Progress in this respect has always to be assessed on consideration of the acceptance of a high on-state voltage drop or a higher Q_{RR}.

1.3.3.4 Dynamic ruggedness

While the space charge zone is increasing, a hole current, carrying I_R, is flowing through the empty area of the n^--zone. Therefore, the density p of the holes is:

$$p = \frac{I_R}{q v_d A} \tag{1.12}$$

In this equation, v_d stands for the drift velocity ($7.57 \cdot 10^6$ cm/s) and A for the area of the diode.

The hole density (shown in Figure 1.30 and 1.31 from t_2 to t_4 each) must no longer be neglected with respect to the basic doping level [288]. P is added to the positively charged donators N_D, the effective doping N_{eff} at that moment is

$$N_{eff} = N_D + p \tag{1.13}$$

This will cause premature avalanche breakdown. Electrons and holes will be generated at the pn-junction by **dynamic avalanche**. The holes will move through the highly doped p-zone. On the other hand, the electrons will move through the n^--zone, causing an effective doping

$$N_{eff} = N_D + p - n_{av} \tag{1.14}$$

Here, n_{av} stands for the density of the electrons generated by dynamic avalanche, which move from the pn-junction through the space charge zone, partly compensating the hole density and thus counteracting the avalanche effect. In [289] dynamic avalanche is designated as a self-limiting effect: it is limited to a degree which is just sufficient to manage the field intensity resulting from the reduced effective doping. Consequently, the diode is not likely to be destroyed by dynamic avalanche.

Reduced forward current will cause reduced reverse current, and consequently reduced density of holes p (according to (1.12)). But, since the switching devices have a higher dV/dt at smaller currents, stress caused by dynamic avalanche may be higher, if small currents are applied.

For diodes dimensioned for higher blocking voltages, τ has to be increased due to the enlarged w_B. This will cause higher reverse currents, leading to increased hole density and to dynamic avalanche according to (1.12). But dynamic ruggedness is especially important for the application in this case.

1.3.4 Modern diodes with optimized recovery behaviour

1.3.4.1 Emitter conception

In the conventional pin-diode the pn-junction is flooded by more charge carriers than the nn^+-junction (Figure 1.30). The idea of the emitter conception is to invert the charge carrier distribution: the nn^+-junction is to be flooded by more charge carriers than the pn-junction. This is achieved by reducing the injection quantity at the p-emitter.

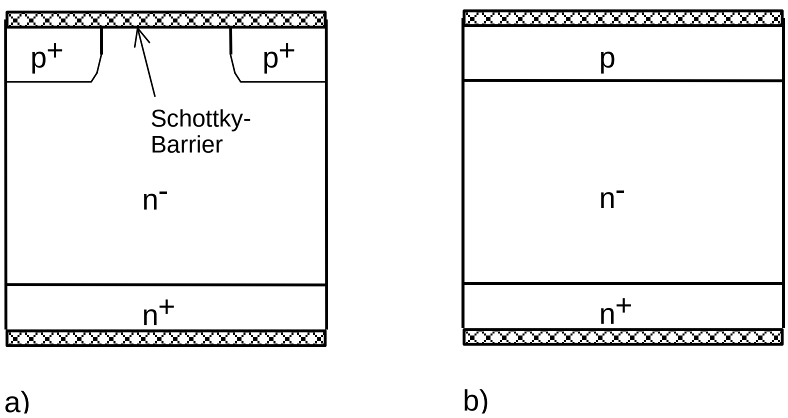

Figure 1.32 P-emitter for improvement of soft-recovery behaviour:
a) Emitter structures, e.g. the merged PiN/ Schottky diode
b) Reduced p-doping

Various emitter structures had been considered, which, in summary, would meet this effect by their functions. One example is the ”merged PiN/Schottky-diode”, consisting of a sequence of p^+-zones and Schottky-areas [290] (Figure 1.32a). There is a number of structures similar to that, comprising also structures with diffused p- and n-zones.
The advantages of Schottky or similar zones, however, are restricted to voltages below 600V. As for blocking voltages of 1000 V and more, the ohmic potential drop will prevail. Only the reduced injection area at the p-zone remains. The same effect as with emitter structures is achieved by a continuous low-doped p-zone (Figure 1.32b). On balance the result of the application of these structures is that they have not lived up to the set expectations.
Also the latest developments are aiming at the reduction of the emitter doping quantity and, thus, the improvement of recovery behaviour. [132], [291]. Further progress can be made by reducing the depth of penetration.
However, with a dI/dt-rate of more than 1000 A/µs, some diodes with reduced p-doping do not show sufficient dynamic ruggedness. Figure 1.33 shows a failure statistics considering more than 16 production lots with 25642 free-wheeling diodes altogether. The failure results in a hole within the active area of the diode. This points to filamentation.
According to statistics, the number of failures caused by low-doped diodes and therefore higher resistance in the p-zone (Figure 1.33, 160 Ω/squ) was higher than that of diodes with re-increased doping (Figure 1.33, 60 Ω/squ), but those had shown impaired soft switching behaviour. This demonstrates the contrast of both requirements to this technology: soft switching behaviour on the one hand, and dynamic robustness on the other hand. Even accepting the restriction of soft switching behaviour could not completely avoid failures. In order to guarantee safe field application, all modules had to be subjected to a full load test in a chopper circuit under field conditions.

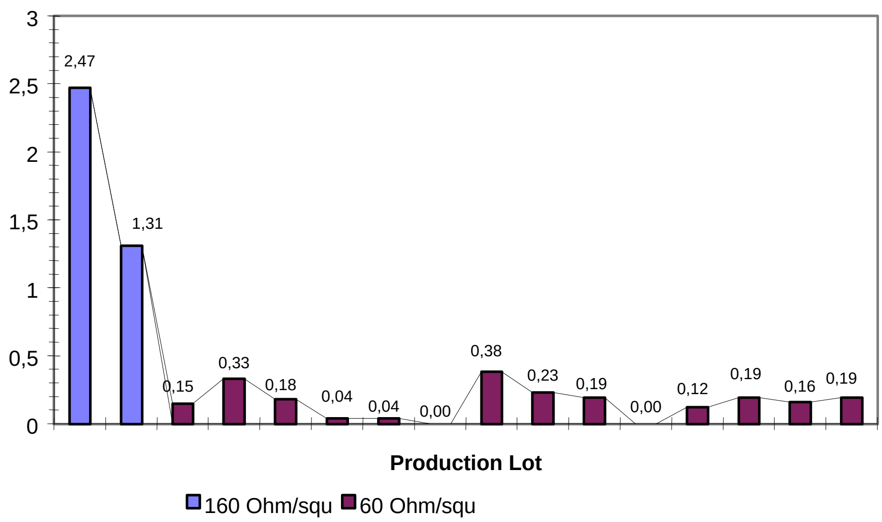

Figure 1.33 Proportion of failures of diodes with reduced p-doping for several production lots (at very high dI/dt)

It seems possible that the failures in Figure 1.33 may be reduced by technological optimization. However, it remains doubtful whether they can be completely avoided.
SEMIKRON has, at least, stopped any developments related to the emitter conception for free-wheeling diodes in fast switches.

1.3.4.2 *Controlled Axial Lifetime (CAL) - conception*

Recombination centre profiles similar to those shown in Figure 1.34a and 1.34b can be generated by implantation of protons or He^{++}-ions in silicon. Some time ago, this technology which required accelerators performing up to 10 MeV, had been exclusively reserved for research purposes, but the situation has changed. Basic research is interested more and more in the GeV-range, and medium energy accelerators are available for other fields of application.

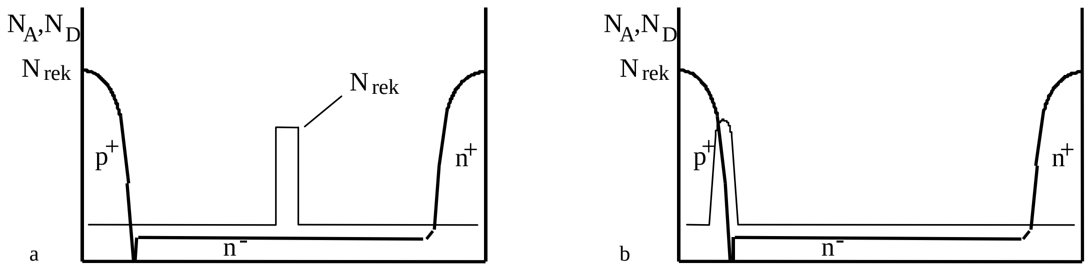

Figure 1.34 Axial profile of recombination centres generated by light ion radiation
a) Narrow partial zone with higher concentration of recombination centres in the middle of the n^--zone
b) Narrow zone with high concentration at pn-junction

The first assumption, that the best results could be achieved by implantation of a zone of highly concentrated recombination centres in the middle of the n^--zone as depicted in Figure 1.34a, had proven wrong. The arrangement of such a zone at the pn-junction as in Figure 1.34b turned out to be more favourable [292] [293].

Reference [147] explains that the relation between peak reverse current and forward on-state voltage is improved with approximation of the recombination centre peak to the pn-junction.

If the recombination centre peaks are arranged directly at the pn-junction, the charge carrier distribution will be inverted during on-state. The charge carrier distribution shown in Figure 1.31 results from a calculation based on the recombination centre profile according to Figure 1.35.

As for the CAL-diode, the recombination center peak (generated by He^{++}-implantation) has been arranged in the p-zone close to the pn-junction as in Figure 1.35, since this will lead to reduction of leakage currents. He^{++}-implantation has been combined with an adjustment of the basic charge carrier lifetime, preferably achieved by electron beam radiation.

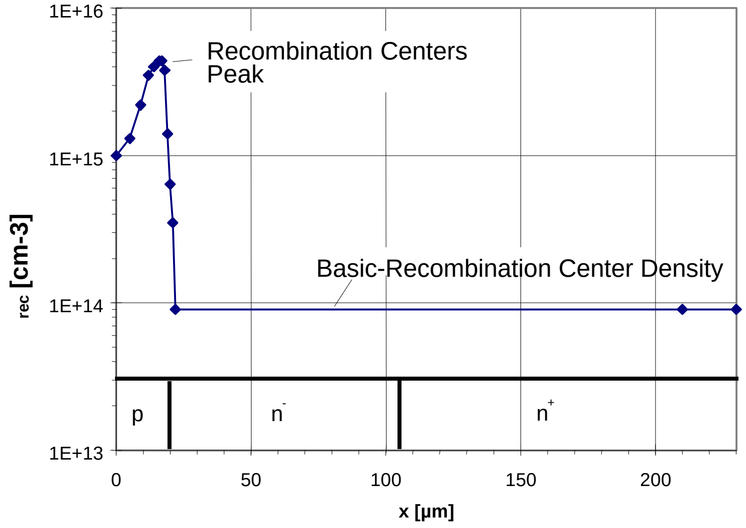

Figure 1.35 Recombination centre profile in the CAL-diode (scheme)

The characteristics of a CAL-diode in combination with an IGBT have already been referred to in Figure 1.24. The reverse peak current can be decreased by the recombination centre peak level, which is to be adjusted by the He^{++}-implantation dose. The biggest share of the storage charge of the CAL-diode occurs in the tail current, which, on the other hand, can be controlled by the basic recombination centre density. Reduction of the basic charge carrier lifetime will reduce tail current duration, however at increase of the on-state voltage of the diode. Recovery behaviour can be greatly controlled by both parameters, basic charge carrier lifetime and He^{++}-implantation dose. So the diode will show soft-recovery behaviour under any operating conditions, especially when low currents are applied.

CAL-diodes manufactured this way are proving a high **dynamic ruggedness**. CAL-diodes dimensioned for 1200 V and 1700 V have been tested under lab conditions at dI/dts up to 15 kA/cm²µs without destruction of the diode.

CAL-diodes are especially not likely to fail under the operating conditions shown in Figure 1.33. This fact is based on the production of over 26 million CAL-diodes up to now.

A ruggedness test of a 3,3 kV CAL-diode is shown in Figure 1.36. In the measurements in Figure 1.35 stress on the diode is still intensified by an additional parasitic inductance of 0.5 µH, generating a peak voltage of 1500 V directly subsequent to the commutation.

In contrast to other diodes, CAL-diodes may also be operated in this voltage range at a high dI/dt (here 2000 A/cm²µs).

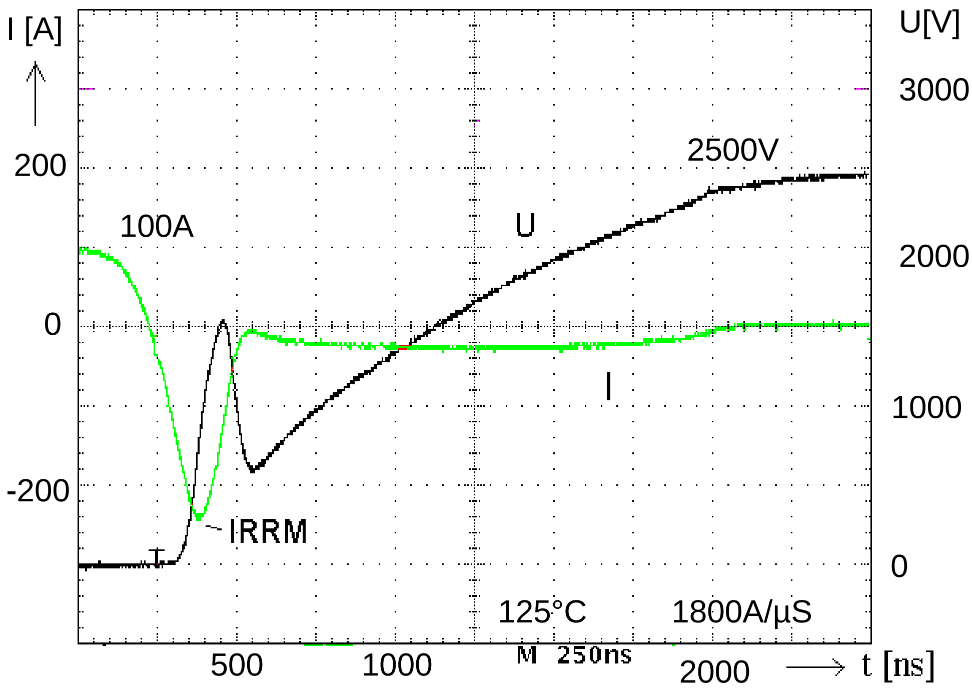

Figure 1.36 Ruggedness test of a 3300 V-CAL-diode

The base width w_B can be dimensioned comparatively narrowly for CAL-diodes, similar to the PT-dimensioning indicated in equations 1.10 and 1.11. This provides for a comparatively low on-state voltage or a better compromise between switching behaviour and on-state voltage, respectively. The base width is also of special importance to the turn-on behaviour of the diode. The forward recovery voltage V_{FR} increases proportionally to w_B; components designed for 1700V and more are likely to generate some 100 V V_{FR} in the free-wheeling diode due to high dI/dt during turn-off of the IGBT. In contrast to conventional diodes, V_{FR} can be reduced by more than 50 % in 1700 V-CAL-diodes. [106].

Recently developed free-wheeling diodes for IGCTs as well as snubber-diodes [294] are being produced according to the CAL-conception, because

1. dynamic robustness is one of the most important demands,
2. dimensioning similar to PT-dimensioning results in an improved cosmic ray stability,
3. a favourable trade-off between on-state voltage and switching characteristics of the diode may be adjusted by the measure mentioned above,
4. minimum V_{FR} can be achieved in snubber-diodes,
5. a low leakage current can be realized compared to the conventional gold-diffusion process.

1.3.4.3 The concept of hybrid diodes

The concept of the hybrid diode was invented in 1991 [295], [296]. This conception is based on the idea that a soft-recovery diode is connected in parallel to a PT-diode with a low on-state voltage, but a snappy recovery behaviour, as shown in Figure 1.37.

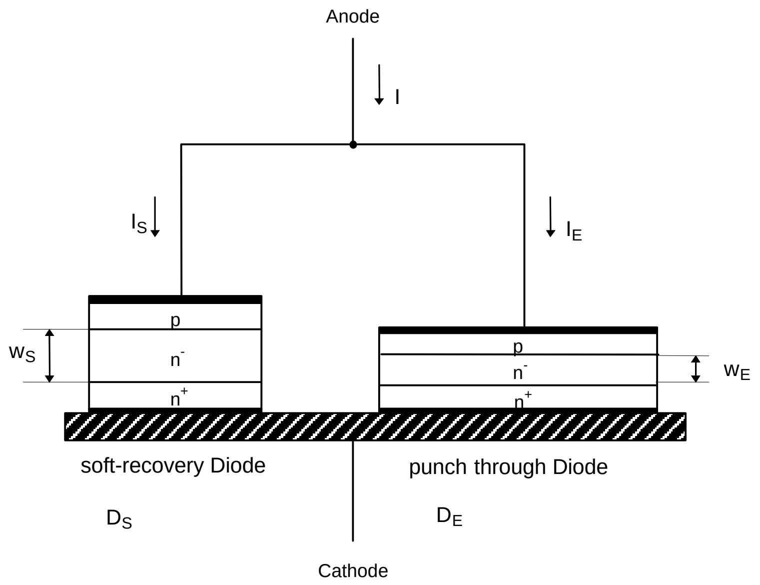

Figure 1.37 Structure of a hybrid diode

The function principle is shown in Figure 1.38. The main part of the on-state current is conducted by the snappy diode D_E. The rest is conducted by diode D_S. Current I_S is conducted through diode D_S and is the first to drop to zero passage, reaching its reverse current peak at t_1. At this time, diode D_E is still carrying forward current. At t_1 the pn-junction of diode D_S is free of charge carriers. Now, diode D_E is commutated with increased dI/dt. The total current is still determined by the outer circuit.

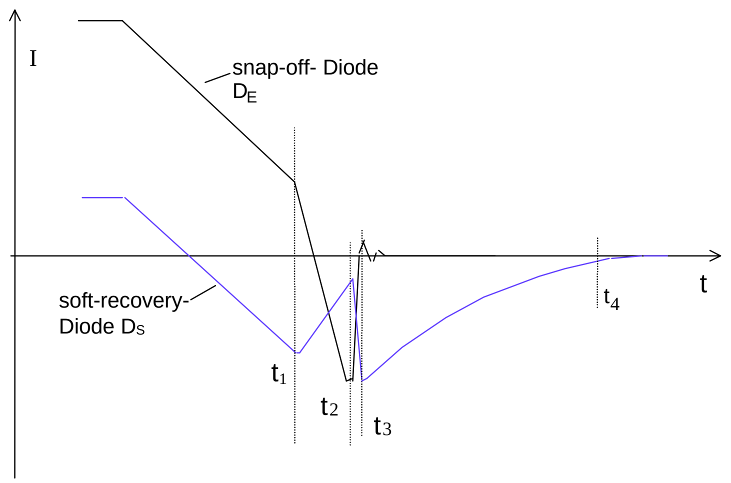

Figure 1.38 Current flow in the components of a hybrid diode

At t_2 the pn-junction of D_E is free of charge carriers. Between t_2 and t_3 the reverse current in D_E will snap off. It will then rise accordingly in diode D_S, which is not completely free of charge at that moment. The total current does not show a reverse current snap-off. Consequently, there will be no induced overvoltage. The charge carrier density in diode D_S is reduced between t_3 and t_4. The combination behaves soft.

To achieve efficient function of the hybrid diode, D_S has to supply sufficient charge even after the reverse current snap-off of D_E. To manage this, the soft diode D_S has to take on between 10 % and 25 % of the forward current. Therefore, the forward voltages have to be attuned.