The first modules that contained hybrid diodes were introduced to the market the beginning of 1996. They have been applied preferably as free-wheeling diodes in chopper circuits with 100V- or 200V-MOSFET switches. Here, an epitaxial diode designed for 400V is used as snappy diode D_E. The part of the soft-recovery diode D_S is taken over by a modified CAL-diode. The basic recombination centre density in it is kept on low-level, which results in a forward voltage of about 1.1 V at 150 A/cm².

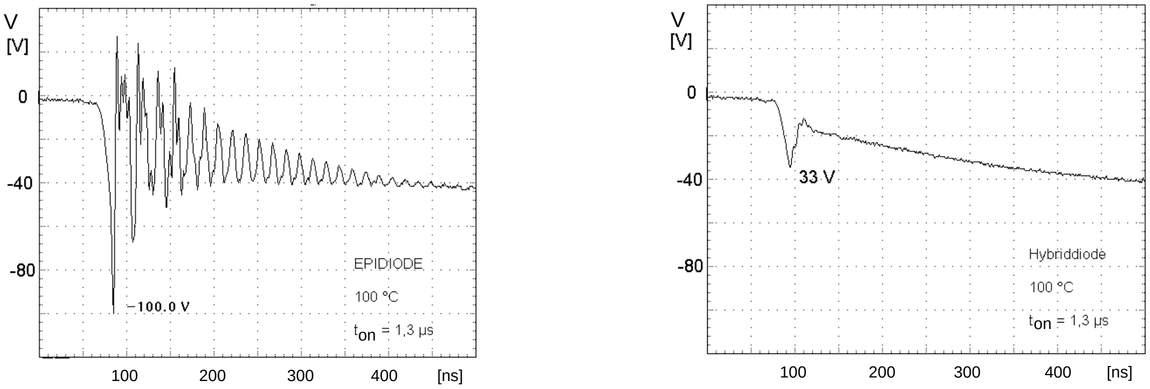

Figure 1.39 Voltage characteristic in a 350 A, 100 V chopper module,
on the left: with epitaxial diodes, on the right: with a hybrid diode

Figure 1.39 shows the voltage taken at turn-on of the MOSFET in a 350 A/100 V chopper module.

The diagram to the left shows the voltage characteristic for the free-wheeling diode being realized by parallelling of 7 epitaxial diodes.

The diagram to the right shows the voltage characteristic, if one of the 7 epitaxial diodes has been replaced by the soft-recovery diode D_S. The induced peak voltage will decrease from 100 V to 33 V, the interfering oscillations will disappear. By application of a like free-wheeling diode, the MOSFET can be turned on with a high dI/dt. If the turn-on time of the MOSFET is reduced from 1.3 µs to 0.3 µs by decreasing the gate resistance, the voltage characteristic will still be acceptable. Total losses of the circuit will drop to 48 % (= sum of line- and switching losses of all components).

Hybrid diodes are of special advantage in a voltage range of ≤ 600 V. In this range, diodes with a minimum w_B may be applied, if they are integrated as part of a hybrid diode. On the other hand, hybrid diodes will not offer decisive advantages to high-voltage applications, since differences in w_B between soft-recovery CAL-diodes and PT-diodes are not that serious.

1.3.5 Series and parallel connection of fast power diodes

1.3.5.1 Series connection

In series connections, attention must be paid to the symmetry of circuits with respect to static reverse voltage and with respect to the dynamic reverse voltage.

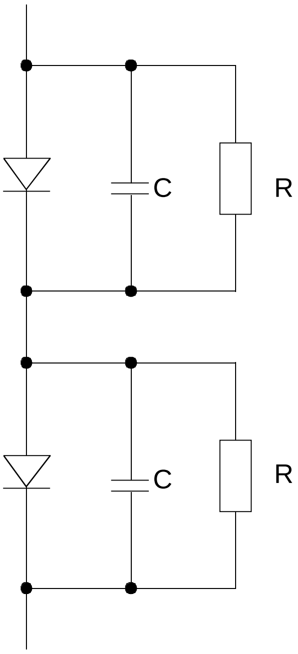

Figure 1.40 RC-circuit for series connection of fast diodes

With reference to the **static** reverse voltage, the variation of leakage current due to production processes will drive the components with the lowest leakage current to avalanche mode. As long as the avalanche stability of the components can be relied on, no resistors will have to be connected. If, however, components with a blocking capability of > 1200 V are connected in series, it is common practice to parallel a resistor.

This parallel resistor has to be dimensioned with respect to the fact that voltage distribution is always determined by its resistance.

If the leakage current is supposed to be independent of the voltage and if resistance tolerances are neglected, the simplified rule for dimensioning the resistance for series connection of n diodes of a specified reverse voltage V_r will be [297] :

$$R < \frac{nV_r - V_m}{(n-1) \cdot \Delta I_r} \tag{1.15}$$

V_m stands for the maximum series voltage and ΔI_r for the maximum spread of leakage current in the diode, based on the maximum operating temperature. According to [297] it may be supposed with high confidence that

$$\Delta I_r = 0.85\ I_{rm}, \tag{1.16}$$

with I_{rm} being specified by the manufacturer. According to this estimation, the current conducted through the resistor is approximately 6-times the leakage current in the diode.

Considering existing experiences, it will be sufficient for modern free-wheeling diodes to dimension the resistor in such a way that it will carry a current three times as high as the maximum leakage current of the diode. However, even then considerable power losses are generated within the resistor.

Dynamic voltage distribution may differ basically from static voltage distribution. If the pn-junction in one diode is free of charge carriers earlier than in another one, this diode will also take on voltage earlier.

If capacitor tolerances are neglected, a simple dimensioning rule can be used for this capacitor paralleled to a series connection of n diodes of a specified reverse voltage V_r:

$$C > \frac{(n-1)\cdot \Delta Q_{RR}}{n\cdot V_r - V_m} \tag{1.17}$$

ΔQ_{RR} stands for the maximum variation of storage charge of the diodes. In all probability, it can be supposed that

$$\Delta Q_{RR} = 0.3 Q_{RR} \tag{1.18}$$

if all diodes used are taken from the same production lot. Q_{RR} is specified by the semiconductor manufacturer. The charge stored in this capacitance is maintained in addition to the storage charge generated when the free-wheeling diode is turned off and has also to be taken up by the IGBT during turn-on. Based on these dimensioning rules, the occuring charge will be up to twice the storage charge of a single diode.

Free-wheeling diodes are usually not connected in series, due to the following additional sources of power dissipation:

- n-fold diffusion voltage of the pn-junction,
- power losses in the parallel resistor,
- increased storage charge to be taken up by the IGBT,
- more components necessary for the RC-circuit.

This holds, if a freewheeling diode for the required voltage range is available.

Series connection may however be made exceptionally, if the on-state power losses are not of considerable importance and if the application is dependent on short switching times and low storage charge, which is typical for low-voltage diodes.

1.3.5.2 Connection in parallel

Connection in parallel does not require any additional RC-circuit. It is important for parallel connection that the variation of the on-state voltage is kept as low as possible.

A decisive parameter to assess the parallelling capability is the temperature dependency of the on-state voltage. If the on-state voltage drops due to increasing temperature, the temperature dependency of the on-state voltage will be negative, the only advantage of which can be noticed in the power loss balance.

If the on-state voltage rises due to increasing temperature, the temperature dependency will be positive.

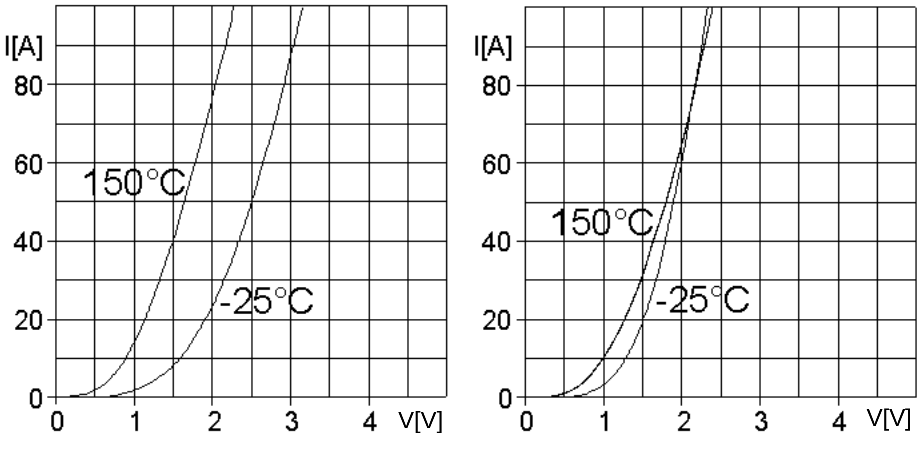

Figure 1.41 Temperature dependency of the forward on-state voltage for different types of diodes
Left side: extremely negative temperature dependency
Right side: positive temperature dependency above rated current (75 A)

A positive temperature dependency is of advantage for the application-specific parallelling, since a heated diode carries less current and the system stabilizes. An extremely negative temperature coefficient (> 2 mV/K) involves the risk of thermal instability for parallel connection of diodes, which always show spreading of the forward on-state voltage due to production processes.

Parallelled diodes are thermally coupled

- via the substrate in case of parallelling within the module,
- normally via the heatsink in case of parallelling of modules.

Principally, at a slightly negative temperature coefficient, this coupling effect will be sufficient to avoid thermal runaway of the diode with minimum on-state voltage. For diodes with a negative temperature coefficient of > 2 mV/K we recommend selecting a lower total rating than the current of the single diodes would add up to (derating).

1.4 Power modules: special features of multi-chip structures

1.4.1 Structure of power modules

In a power module *several power semiconductors* (MOSFET or IGBT chips and diode chips) which are *electrically isolated* from the mounting surface (heatsink) are integrated into a case on a common base plate.

The chips are soldered (or glued) to the metallized surface of an *isolation substrate*, which electrically isolates the chips from the module base plate, and at the same time creates good thermal conductivity.

The chip top sides are connected to the structured areas of the metallized surface by thin Al-bond wires.

In addition to that, passive elements such as gate resistors, shunts/ current sensors or temperature sensors (e.g. PTC-resistors) may be integrated into the module (hybrid) and also partly into the transistor chips (monolithic).

Moreover, “intelligent” power modules contain additional protection and driver circuits, see chapter 1.6.

The currently used isolation substrates for power modules are listed in the table below:

Isolation material

ceramic:	aluminum oxide Al_2O_3	*organic:*	epoxy
	aluminum nitride AlN		polyimide (Kapton)
	(beryllia oxide BeO)		
	(silicon carbide Si_3N_4)		

Substrates

Metal sheets:	(**D**irect **C**opper **B**onding)	*Metal sheets:*	IMS (**I**nsulated **M**etal **S**ubstrate)
	AMB (**A**ctive **M**etal **B**razing)		Multilayer-IMS
Thick film layers:	TFC (**T**hick **F**ilm **C**opper)		

*DCB (**D**irect **C**opper **B**onding)*

Figure 1.42 shows the structure of a power module with IGBTs and free-wheeling diodes in the most common current technology with substrates made of *DCB*-ceramics with Al_2O_3 or AlN isolation, combining good thermal conductivity and high isolation voltage.

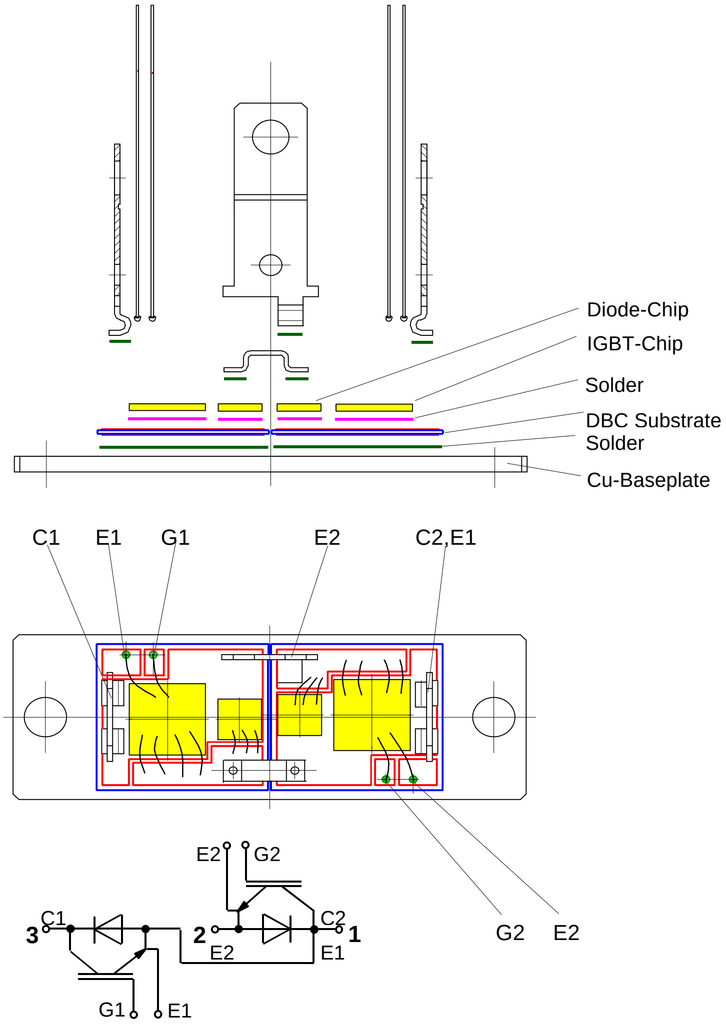

Figure 1.42 Structure of an IGBT module SKM100GB123D in a SEMITRANS 2 case

For production of a DCB-substrate, copper surfaces with a thickness of e.g. 300 µm are applied to the top and bottom areas of the isolation material (thickness 0.38...0.63 mm) by means of eutectic melting over 1000°C. After the necessary track structure for the module circuitry has been etched into the top side copper surface, the chips are soldered on, and the connection to the contacts on the chip top side is effected by bonding. The bottom side of the DCB-ceramic substrate is fixed to the module base plate (thickness e.g. 3 mm) mainly by soldering, see Figure 1.42.

Other module types (e.g. SEMITOP, SKiiPPACK, MiniSKiiP) do not necessarily require a base plate and the previous soldering procedure may be avoided. In these modules, the DCB-substrate is pressed on to the heatsink by means of suitable case constructions (see chapter 1.5).

Advantages of the DCB-technology compared to other structures are mainly the high current conductivity due to the copper thickness, good cooling features due to the ceramic material, the high adhesive strength of copper to the ceramic (reliability) and the optimal thermal conductivity of the ceramic material [52].

*AMB (**A**ctive **M**etal **B**razing)*

The AMB process (“brazing” of metal foil to substrate) has been developed on the basis of DCB technology. The advantages of AMB-substrates with AlN-ceramic materials compared to

substrates with Al_2O_3-ceramic materials are e.g. lower thermal resistance, lower coefficient of expansion and improved partial discharge capability.
Figure 1.43 explains the differences between DCB and AMB.

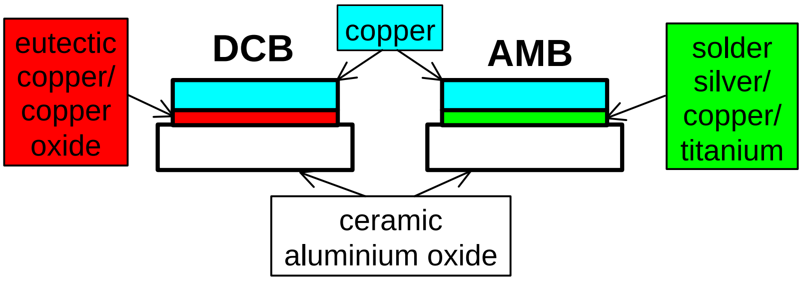

Figure 1.43 Direct Copper Bonding (DCB) and Active Metal Brazing (AMB)

*IMS (**I**nsulated **M**etal **S**ubstrate)*

IMS is mainly applied in the low cost/ low power range and is characterized by direct connection of the isolation material to the module base plate. For insulation, polymers (such as epoxies, polyamides) are usually applied to an aluminum base plate. The upper copper layer is produced in foil form and glued on the isolation substrate (similar to PCB production) and is structured by etching (Figure 1.44).

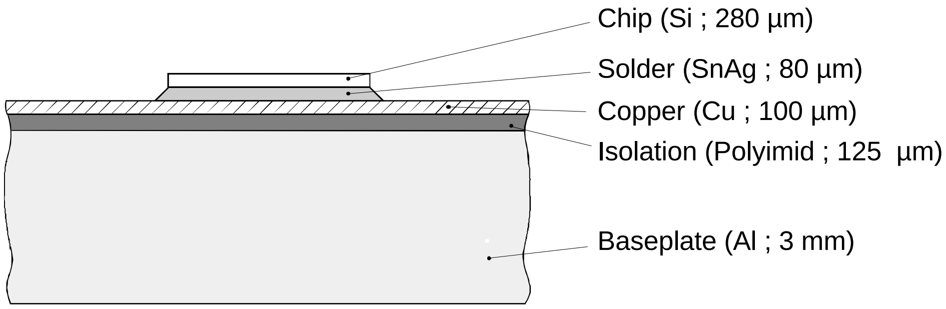

Figure 1.44 Basic structure of an IMS power module [194]

Advantages of IMS are low costs, filigree structure of tracks (possible integration of driver and protection facilities), high mechanical robustness of substrate and relatively wide substrate areas, compared to DCB.
The very thin isolation layer, however, leads to comparably high coupling capacitances against the mounting surface (see chapter 1.4.2.6). Furthermore, the thin upper copper layer only provides a comparably low spread of heat, which is improved by additional metallized heat spreading layers under the chips or by adding Al-particles to the isolation layer.

*TFC (**T**hick-**F**ilm-**C**opper)-thick film substrates*

Just as with DCB, the basic material for thick film substrates is an isolation ceramic, which is glued directly on to the base plate or a heatsink by means of silicone or applied by soldering (Figure 1.45).
The tracks on the top side of the ceramic substrate are made of copper and are applied by screen printing. The power semiconductor chips or other components are soldered or glued on to the tracks.