Technical Explanation
CAL Freewheeling Diodes

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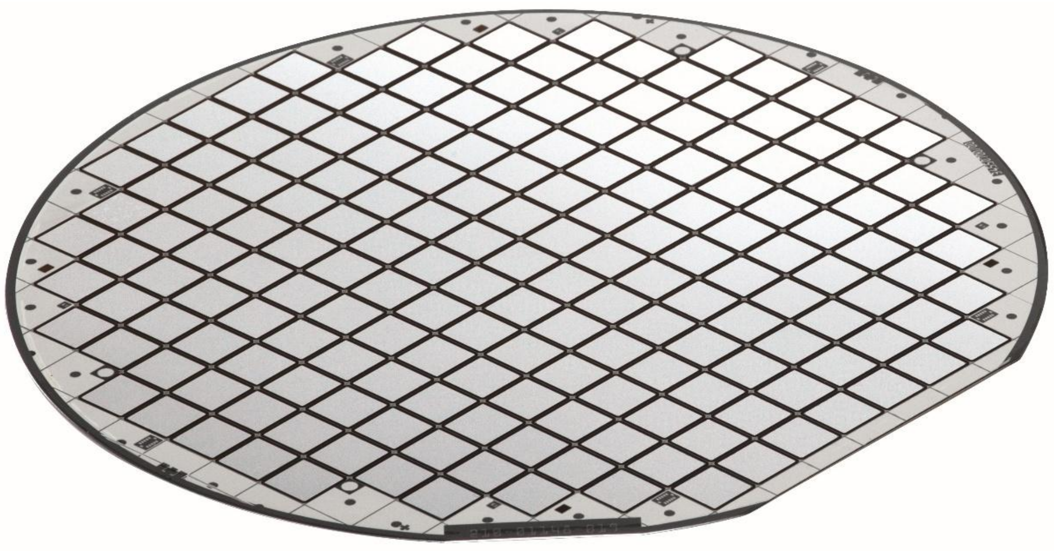
1. Introduction and Technology Overview

CAL diodes represent a family of soft and fast recovery diodes used in conjunction with an Insulating Gate Bipolar Transistor (IGBT). The SEMIKRON DANFOSS CAL portfolio consist of three major technology generations, CAL3 (suitable for T_{jmax}=150°C), CAL4 and CAL7 with a state-of-the-art performance up to T_{jmax}=175°C. The latest technology generation CAL7 utilizes the so-called thin-wafer-technology.
CAL diodes are available in different voltage classes from 600 V up to 1700 V, and current ratings from 6 A to 300 A. Figure 1 shows a typically, fully processed CAL diode wafer.
The diodes are primarily developed for use in power modules but could also be packaged as discrete devices.

Figure 1: CAL Diode Wafer



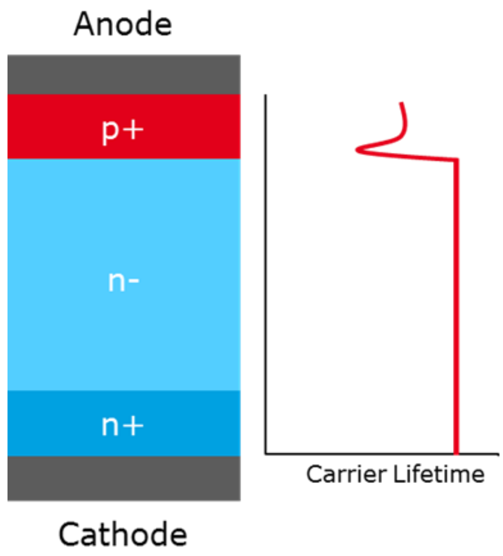
1.1 Controlled Axial Lifetime (CAL) Technology

A freewheeling diode for an IGBT must exhibit a soft recovery behavior during switch-off of the diode in order to avoid high overvoltages caused by stray inductances and a high rate of fall of the diode current di/dt. Overvoltages could lead to damage or destruction of semiconductor devices in the circuitry.

The softness and low reverse recovery charge of the CAL diode is achieved by locally influencing the carrier lifetime along the current path between anode and cathode (i.e. the z axis) [2], intentionally lowering it at the p-n junction (cf. Figure 2). This non-uniform behavior is reflected in the naming of the diode: Controlled Axial Lifetime (CAL).

CAL technology has been introduced by SEMIKRON DANFOSS in 1992 and further optimized ever since. It is one of the softest and best performing diodes on the market, especially in its latest CAL4 and CAL7 generations.
Besides the soft recovery, CAL diodes are characterized by a high dynamic robustness. Most CAL families exhibit an only slightly negative or even positive temperature coefficient above the nominal current (cf. section 2.2). This property is beneficial in case of parallel operation of diodes which is common in power module layouts.

Figure 2: CAL Diode Principle (Schematic)



1.2 Portfolio

1.2.1 General Considerations Regarding Choice of Diode

In order to achieve the optimum performance of a freewheeling diode, it is important to use it with a fitting IGBT. SEMIKRON DANFOSS freewheeling diodes have been developed and used with a large range of IGBTs by different vendors. The fitness for use can be checked initially by comparing some basic parameters: voltage class, junction temperature and nominal current. An overview of the currently available choices are given in Table 1. An overview of currently available diodes, voltage classes, current ratings and die sizes can be found on our website [1]. Please contact us in case for support or a special product request.

Table 1: CAL Diodes Portfolio Overview (status Q4/2024)

Voltage Class	Available T_{jmax}	I_{Fnom}	Chip Area
600 V	150°C and 175°C	10 … 210 A	4 … 121 mm²
650 V	175°C	30 … 200 A	10 … 81 mm²
1200 V	150°C and 175°C	6 … 300 A	6 … 121 mm²
1700 V	150°C and 175°C	40 … 200 A	28 … 120 mm²

One of these basic parameters is the voltage class describing, i.e. the maximum repetitive reverse voltage (V_{RRM}) which can be applied to the diode at room temperature. It should be chosen according to application needs, e.g. DC link voltage.

The second important factor is the junction temperature T_j. The (electrical) power P_v created during operation of a semiconductor device (i.e. heat) needs to be dissipated by means of cooling:

$$P_v = V \times I = \frac{\Delta T}{R_{th}};\ \Delta T = T_j - T_s$$

For a given setup with a fixed heatsink temperature T_s and thermal resistance R_{th}, the ampacity is limited by the maximum allowable temperature of the device known as maximum junction temperature T_{jmax}. The higher the maximum junction temperature, the higher the current density/performance of a device is.
It is important to understand that T_{jmax} describes the maximum allowable local temperature of any part of the semiconductor device under all conditions which means that a safety margin is required in real-world applications. This safety margin is typically 25°C, and sometimes described as maximum operation

temperature T_{jop}. It is also the reason why in the datasheets, dynamic and static parameters required for loss calculations are given at 25°C below T_{jmax}.
In a module assembly, thermal coupling between adjacent chips must be taken into account. It is therefore not recommended to combine an IGBT with a CAL diode designed for a different T_{jmax} because the chip with the lower T_{jmax} will limit the operation of the chip with the higher T_{jmax} due to the coupling.

The nominal current of a freewheeling diode is more difficult to interpret. In a given chip design, the ampacity is scaled by means of the chip size (more accurately, the active area of the chip at a given current density A/mm^2).
To calculate the required chip size for a given power rating, some boundary conditions have to be taken into account.
This is rather straight forward for a grid-side rectifier application where dynamic losses can be neglected: only R_{th} and T_s have to be given to calculate a mean forward current of a sinusoidal or DC signal, $I_{F(AV)}$ and $I_{F(DC)}$, respectively [2].
However, it gets more complicated in case of freewheeling diodes with typical switching frequencies in the kHz regime. In that case, the dynamic losses are often the dominant energy loss factor. Optimizing operation of IGBT and freewheeling diodes requires the assumption of a couple of parameters:

- dynamic and static losses of diode under operation conditions
- dynamic and static losses of IGBT under operation conditions
- switching frequency
- thermal assembly (R_{th}, case and sink temperature)
- mode of operation of converter (e.g. described by current-voltage phase shift φ)

Based on these assumptions, it is possible to simulate and find a diode chip size best suited to an IGBT with a given current rating. This approach has been followed at the latest chip generations CAL4 and CAL7. Therefore, the nominal current given in the data sheets of CAL4 and CAL7 diodes is identical to the nominal current of the IGBT it is used with.
The nominal currents of the earlier generation CAL3 have been calculated based on the purely static consideration described above, and reflect an $I_{F(DC)}$ value.

Since there is no rule or standard how a nominal current has to be defined (and taking the vast parameter space into account), it is very difficult to compare nominal values of soft recovery diodes between different manufacturers. Hence, it can be useful to check the chip area as another indicator of the actual current performance of a device. However, design differences can lead to differences in the required chip size for a given rating.

The only solution to this dilemma is assembling and testing diodes under the required application conditions allowing a real-world comparison of different diode technologies.

1.2.2 Differences between CAL3, CAL4 and CAL7 Generation

CAL3 technology has two sub-families I3 and I HD. In general, the I HD ("High Density") is optimized for low static losses in terms of V_F with a trade-off regarding switching losses.
CAL3 diodes are generally rated at T_{jmax}=150°C. Only 600 V CAL_IHD diode has been qualified for T_{jmax}=175°C.
In 1700 V voltage class, the I3 sub-family is named "I", indicating a special life-time tuning process.
For new designs SEMIKRON DANFOSS recommends to use available CAL4 and CAL7 generation.

In 2008, SEMIKRON DANFOSS entered the market with the CAL4 [3] and later on the enhanced CAL4F [4] generation of soft recovery diodes. The main feature is the higher maximum junction temperature of T_{jmax}=175°C. This is possible by means of a new passivation scheme. The higher junction temperature increases the current density on the active area by approximately 25%, therefore allowing smaller chip outline or higher performance at same dimensions, respectively.
Moreover, CAL4F technology provides an enhanced humidity protection enabling operation of modules in challenging environments.

In 2024, SEMIKRON DANFOSS made another major technology step with the introduction of CAL7. CAL7 is the first freewheeling diode at SEMIKRON DANFOSS which utilizes the so-called thin-wafer-technology. In comparison to CAL3 or CAL4 with standard wafer thicknesses between 220 µm to 300 µm, CAL7 shows wafer thicknesses between 80 µm to 200 µm.
Because of the thinner wafer, the current density on the active area is approximately 20% higher in comparison to a CAL4 diode.

Maximum junction temperature is rated to T_{jmax}=175°C.
Passivation scheme and enhanced humidity protection is taken over from the well-established and proven CAL4 technology generation.

1.2.3 Naming Convention

Typical product name looks like this: SKCD 81 C 120 I4F. For explanation of the naming, please refer to Table 2.

Table 2: Naming Convention

Name	SKCD	81	C	120	I4F	
Meaning	**S**emi**k**ron Danfoss **C**AL **D**iode	Chip size in mm^2	Separator	Voltage class	CAL family	Optional
Variants	-	Various	-	060: 600 V	I: fast	R: rectangular chip
				065: 650 V	I3: fast (CAL3)	Default: square chip
				120: 1200 V	I HD: high density (CAL3)	
				170: 1700 V	I4F: fast (CAL4)	
					I4U: ultra fast (CAL4)	
					IN: CAL7	

2. Data Sheets

The latest version of data sheets are available on the internet [1]. They typically comprise of different paragraphs which are described in more detail in the sections below. The layout of the data sheet might vary slightly from chip generation to chip generation.
It is important to note that the specification given in the data sheet is only valid for a properly assembled chip, i.e. with suitable thermal and electrical connections as well as die protection (e.g. soft mould).

2.1 Absolute Maximum Ratings

In this paragraph, the basic limitations of the device are given.
One parameter is the voltage class, represented by the maximum repetitive reverse voltage (V_{RRM}) at room temperature. The break-down voltage $V_{(BR)}$ is temperature dependent and will decrease by lowering the temperature.

The second one is surge current rating for a half sine wave signal of 10 ms at room temperature and T_{jmax}. Please note that surge current is not only dependent on the die properties itself but can also be influenced by the interconnection technology (e.g. bonding layout). The value given in the data sheet is based on a typical assembly type which is a common standard in power semiconductor industry. The i^2t value is calculated from the maximum surge current.

The maximum junction temperature T_{jmax} describes the temperature not to be exceeded at any time and point of the semiconductor device. Running the die above T_{jmax} might lead to degradation of the device's functionality and reliability.

2.2 Electrical Characteristics

This section specifies the static behavior of the device in forward and reverse direction. Typically, the elevated temperature characterization is done at the recommended operation temperature for application simulation purposes.
The maximum and sometimes the typical reverse current is given at the defined V_{RRM} voltage and at different temperatures.

The forward I-V characteristics are specified by the V_F typical and maximum value at a certain current level. For most CAL families, this is at or close to the current level which is tested at wafer test. For some diodes, it is given at the nominal current level. Since the wafer test does not allow a current density testing close to the nominal current in most cases, the first variant allows a more accurate V_F rating than the later one.
The temperature dependence of the forward characteristics can be approximated by calculating the temperature coefficient using T_1=25°C and T_2=T_{jmax}-25°C.
Most CAL diode families are characterized by a positive temperature coefficient (for T_1=25°C and T_2=T_{jmax}-25°C) above the nominal current rating. The crossing point is typically close to the nominal current point. An example of a 650 V CAL4F diode can be found in Figure 3.
The temperature dependence at intermediate temperatures needs to be determined according to application needs.

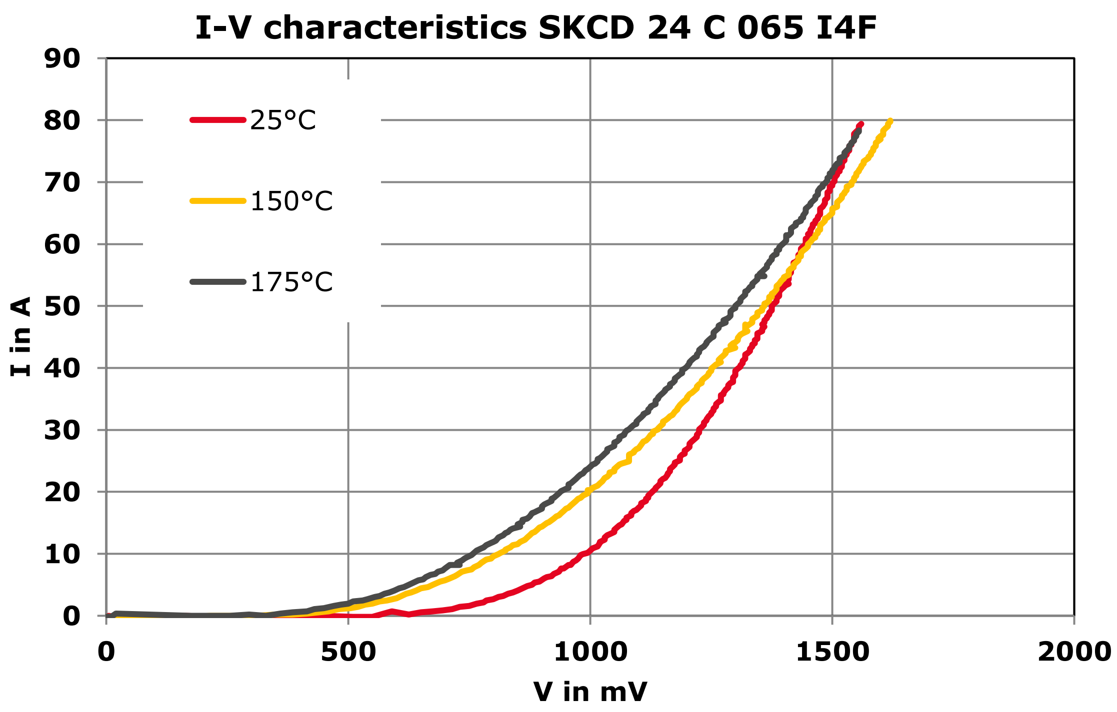
For simulation purposes, a linear approximation of the I-V forward characteristics is also given in the data sheets. Is follows the formula

$$V_{F\,(approximation)} = V_{(T0)} + r_T I_F$$

The two points of the I-V curve used for the linear approximation are typically close to I_{Fnom} and 2/3 of I_{Fnom}. The maximum values of the two parameters $V_{(T0)}$ and r_T include adequate safety margins.

With this linear approximation, another parameter can be calculated, $I_{F(AV)}$. This includes certain assumptions regarding thermal resistance, case temperature, wave form, etc. It is intended only as a guidance since the dynamic boundary conditions are completely ignored. Please refer to section 1.2.1 of this document regarding the discussion of nominal current ratings.

Figure 3: Temperature Dependence of VF for 50 A CAL4F 650 V diode (typical values)



2.3 Dynamic Characteristics

In many application cases for a freewheeling diode, the dominant loss factor is the energy loss during switch-off. It is therefore important to describe this operation mode.
This is done by testing the diode under lab conditions using e.g. the double-pulse method (for reference, see [5]). For characterization purposes in the data sheet, realistic switching conditions are used which are close to typical application cases.
Input parameters to be defined for the characterization are:

- temperature
- current prior to switch-off
- DC link voltage
- rate of fall of the diode current di/dt (which can be controlled by the IGBT gate resistor)

The IGBT used as a switch is another influencing factor.
The diode is driven at about nominal current prior to switch-off, and the DC link voltage is chosen to be approx. 0.5*V_{RRM}. The rate of fall of the diode current di/dt is also selected to be at a real-life value, and I_F/(di/dt) is kept constant throughout a CAL family.
As output parameters, the energy dissipation during reverse recovery E_{rr} (also called E_{off}), the reverse recovery charge Q_{rr}, the peak reverse recovery current I_{rrm} and the reverse recovery time t_{rr} can be determined. The meaning of these parameters can be seen in the switching diagram in Figure 4.
Most significant are E_{rr} and/or Q_{rr} – describing the loss contribution of the diode – as well as I_{rrm} which represent real characteristics of the switch-off behavior.

As opposed to that, the reverse recovery time t_{rr} is an extrapolated value: a line is drawn through I_{rrm} and 25% I_{rrm} values to define the fall time of the reverse recovery peak. It essentially assumes a triangular shape of the reverse recovery peak. However, most soft recovery diodes are characterized by an initial peak and a long tail current to avoid critical overvoltages in the circuitry.
This raises some concerns regarding the determination of t_{rr}. The first one is a measurement concern: since the 25% I_{rrm} point typically lies in the flat (tail) part of the reverse current curve, small variations from measurement to measurement lead to big variations of the extrapolated t_{rr} value. The second one is a more general one: t_{rr} will not give any information on how the current depletion over time looks like in the actual

tail curve since the shape of the tail can be different between different technologies. Due to these concerns, t_{rr} is no longer part of the more recent data sheets.

In general, dynamic specifications depend heavily on the input parameters chosen. Figure 5 shows an example of the dependence of dynamic characteristics on di/dt for two different temperatures.
Hence, it is extremely difficult to compare different diode technologies just by data sheets because the input parameters are not standardized. Actually, it can be quite misleading to compare e.g. measurements under real-life conditions (like in SEMIKRON DANFOSS data sheets) with small-signal measurements.

Figure 4: Testing Method and Parameter Definition for Dynamic Characterization

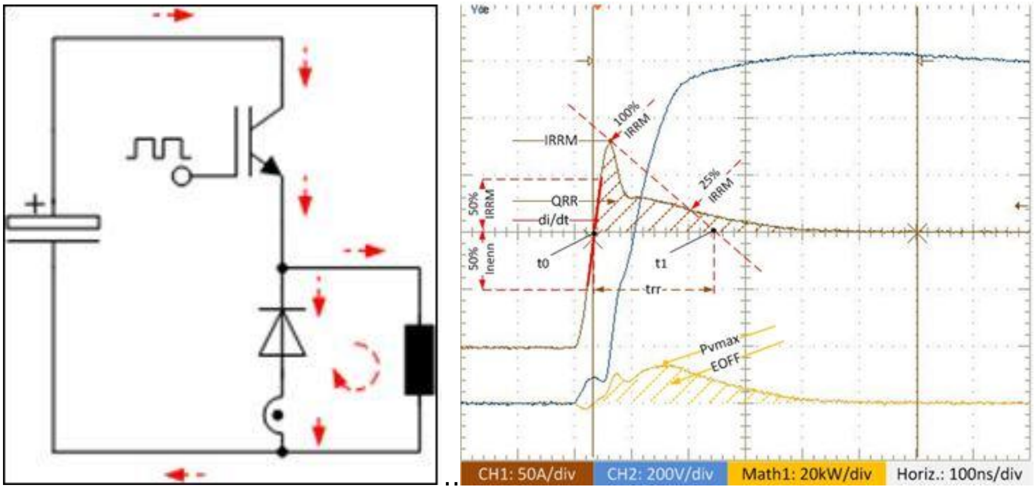
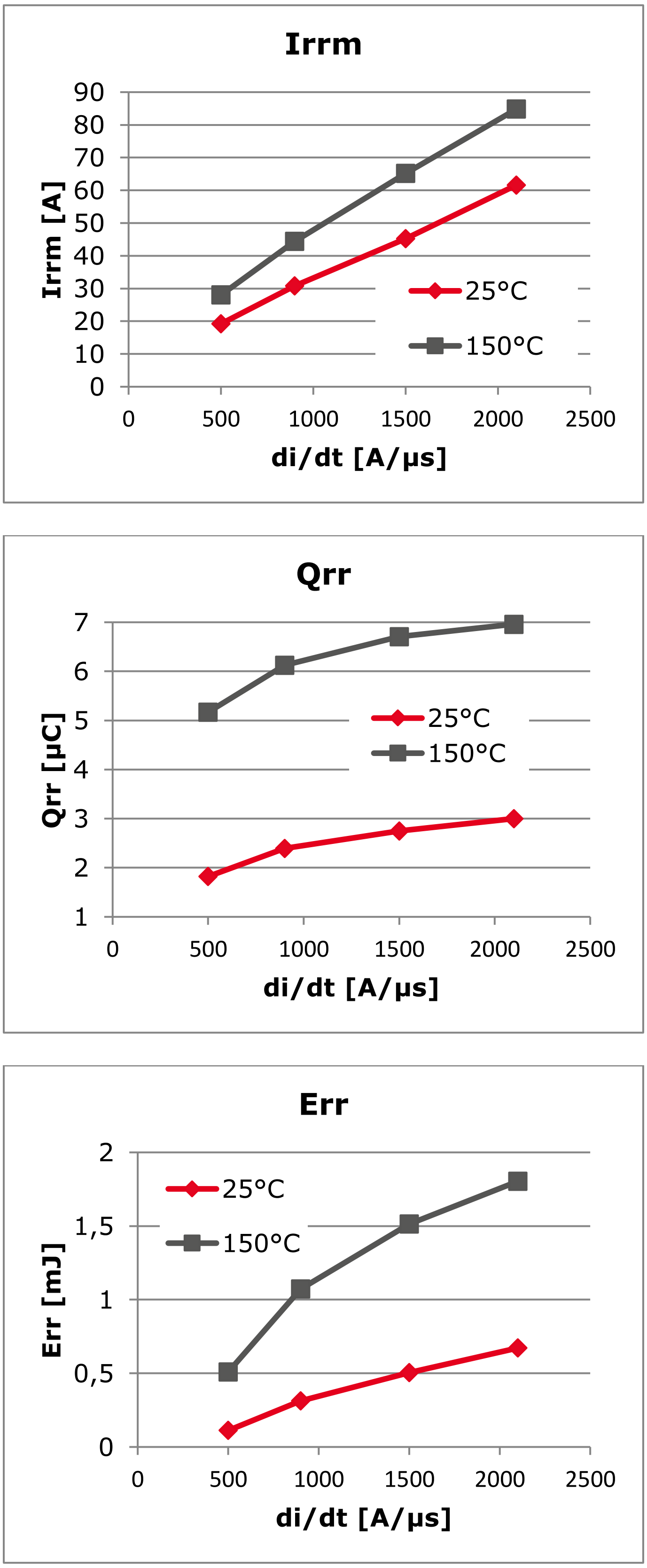


Figure 5: di/dt Dependence of Dynamic Parameters. SKCD 24 C 065 I4F (50 A); conditions: V_{DC}=400 V, I_F=60 A. Typical values shown.



2.4 Thermal Characteristics

Thermal characteristics given in the data sheets are the range of junction temperature T_j and storage temperature T_{stg}, respectively.
Solder temperature T_{solder} recommendations are given for two different time intervals. Exceeding the thermal budget as described in the data sheet might lead to an altering of chip properties including reliability. More details on assembly processes can be found in section 3.3. In some data sheets, also a thermal resistance junction to case $R_{th(j-c)}$ is given. This is valid only for a specific assembly and is not a generic chip property. It is used to calculate $I_{F(av)}$ as described in section 2.2.

2.5 Mechanical Characteristics

Mechanical characteristics include the die dimensions and area. The dimensions are given as the raster size of the die on the wafer which is in fact an upper limit for the actual chip outline since some material will be consumed during the dicing process.

Moreover, the chip metallization's are described. The anode (upper) metallization is an Al contact suitable for wire bonding. The cathode (backside) metallization is a multilayer contact system whose main components are nickel and a terminating Ag layer. This contact is compatible with a wide range of assembly processes.

CAL diodes are delivered as sawn-on-frame dies. The "Chips/Package" information therefore defines the number of chips per wafer. This is also the maximum number of good dies per wafer which might vary due to variation in yield.

2.6 Reliability Tests

During qualification, each CAL sub-family has been subject to reliability testing. An (non-exclusive) example of reliability tests applied to CAL diodes can be found in Table 3. Test conditions depend e.g. on voltage class or maximum junction temperature.
All chip related reliability tests must be performed in an assembled state (e.g. standard module). Interaction between the chip itself and the assembly might influence the results of the reliability testing. Hence, reliability performance needs to be verified on the customer side in the specific assembly used.

Table 3: Reliability Tests for CAL Diodes

Test	Reference
High temperature storage (HTS)	IEC 60068-2-2
Low temperature storage (LTS)	IEC 60068-2-1
Steady-state temperature humidity bias life test (H^3TRB)	IEC 60068-2-67 or IEC 60749-5
High temperature reverse bias (HTRB)	IEC 60749-23
Power cycling (PC)	IEC 60749-34
Temperature cycling (TC)	IEC 60068-2-14

3. Instructions and Recommendations for Use

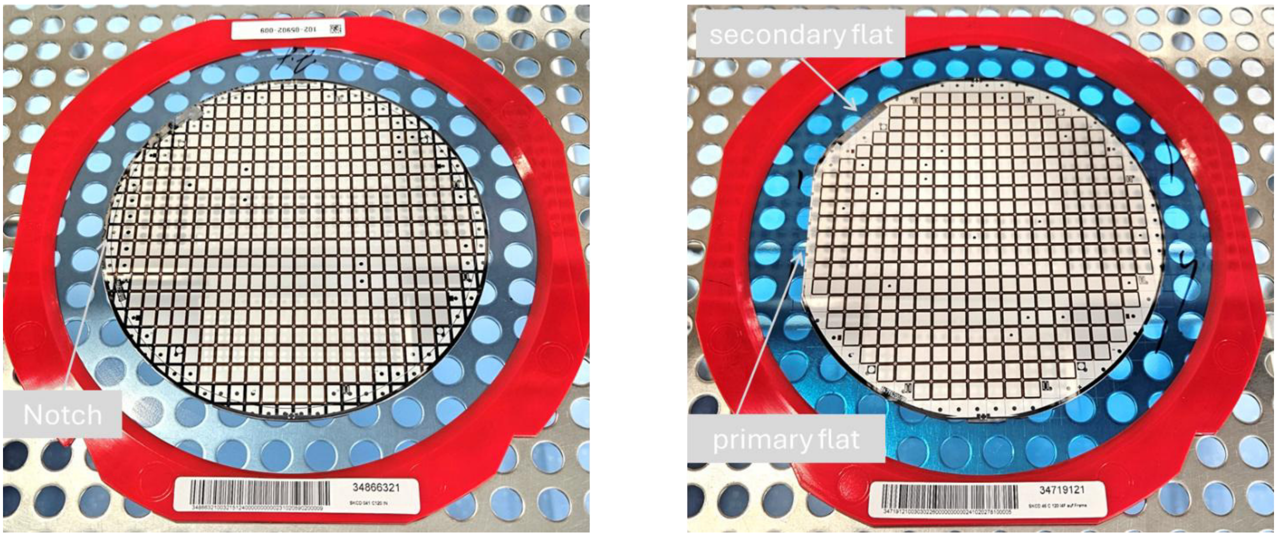
The following chapter deals with packaging, labeling, and handling of SEMIKRON DANFOSS CAL diodes when shipped to the customer. Moreover, some general considerations regarding assembly of CAL diodes are given. Mishandling of semiconductor devices might compromise their electrical or mechanical properties.

3.1 Delivery Format and Packaging

The standard delivery format for CAL diodes is a 150 mm wafer mounted and diced on an adhesive tape with the aid of a fitting wafer frame (format: sawn-on-frame; Figure 6).
CAL4 or CAL3 wafer shows a primary and secondary flat, laser lot marking as well as various aligning marks. CAL7 wafer shows a Notch (no flats), laser lot marking as well as various aligning marks. Additionally, the wafer shows on the edge a TAIKO dicing line, which is a typical feature originate from thin-wafer process flow. At bottom of the wafer frame is a frame label used for traceability matters (see section 3.2).

Figure 6: CAL Wafer Images

CAL7 | CAL4 or CAL3



Each wafer is packaged in an evacuated bag with protective inlays (cf. Figure 7). Prior to customer shipment, up to 25 wafers of one lot are placed into a cardbox for transport. If less than 25 wafers are shipped, filling material is used.
Chips can only be shipped as multiples of wafers. Due to the varying yield on the wafer, the exact number of good dies might be different per wafer. Orders have thus to be placed with an appropriate delivery tolerance of typically +/-10%.

Figure 7: Wafer Packaging

3.2 Product Labeling

There exist three different labels to allow customers identifying SEMIKRON DANFOSS hardware at the different stages of the assembly process. The first one is on the outer cardbox packaging, the second one on the bag around the wafer, and the third one ("frame label") on the red wafer frame which is readable when all surrounding packing material has been removed. The barcodes used on these labels are according to the Code 128 standard.

The label on the cardbox consists of the SEMIKRON DANFOSS logo and the product name as well as 4 different barcodes (refer to Figure 8):

(1) barcode/text: **P** customizable material no. (not always applicable)
(2) barcode/text: **H** SEMIKRON DANFOSS lot no. (10 digits)
(3) barcode/text: **Q** wafer qty/good die qty/country code ("D")/SK lot no.
(4) barcode/text: **X** SEMIKRON DANFOSS article no.

Figure 8: Label on Cardbox Packaging

The bar code on the foil bag label and the frame label has the same structure. However, the outer label has some more information given in plain text. The outer label (foil bag) contains:

- Type of chip
- SEMIKRON DANFOSS article number
- Lot number
- Chip Quantity
- Delivery date
- Signature field for "QC pass" (quality conformity)
- Bar code field
- "process until" date for wafer

The frame label contains the following information:

- SEMIKRON DANFOSS article number
- Type of chip
- Bar code field

Pictures of the two different labels can be found in Figure 9.
As mentioned above, the barcode of the two labels on the two wafer packaging labels has the same structure:

- digits 1- 8: SEMIKRON DANFOSS article number
- digits 9-13: good dies per wafer
- digits 14-17: "use-by date" given by the calendar week and year (wwyy)
- digits 18-27: customizable (0 by default)
- digits 28-37: lot number
- digits 38-40: split number
- digits 41-42: wafer number

The barcode is also given as text underneath the code.

Figure 9: Labels on single wafer packaging

3.3 Storage Conditions

SEMIKRON DANFOSS guarantees a shelf life of 12 months after shipment from production line to SEMIKRON DANFOSS stock for the unopened package if handled appropriately.
For handling and storage recommendations, please refer to IEC 62258-3 [6].
Required storage conditions for unopened package at the customer site:

- temperature 20-26°C
- relative humidity rH < 60%

Dies in opened packages are intended for immediate use.

3.4 Assembly Process

CAL diodes have been tested to be compatible with different industry standard assembly processes. It can be used in a reflow or preform solder process. A second soldering process is possible.
The thermal budget given in the data sheet (i.e. T_{solder} for 10 min at 250°C or T_{solder} for 5 min at 320°C) shall not be exceeded. The appropriate temperature profile used during soldering depends on the process as well as the materials (e.g. solder paste) used.

The anode Al metallization is comparably thick and allows thick-wire bonding connections. A typical wire diameter is about 300 µm.

4. Summary

SEMIKRON DANFOSS freewheeling diodes employ the Controlled Axial Lifetime (CAL) technology in order to achieve an excellent soft and fast recovery behavior required when used with an IGBT.
There are different generations available, which are designed for T_{jmax}= 150°C and 175°C, respectively. Moreover, CAL diodes are characterized by a high dynamic robustness and can be used in parallel operation mode.
The specifications given in the data sheet are explained in this document.
CAL diodes provide outstanding usability in industry standard assembly technologies like thick-wire bonding or different solder techniques.

5. List of Figures and Tables

6. Symbols and Terms

Letter Symbol	Term
di/dt	rate of fall of the diode current
E_{rr}	energy dissipation during reverse recovery
i^2t	permitted limit integral
I_F	forward current
$I_{F(AV)}$	mean forward current (sine signal)
$I_{F(DC)}$	mean forward current (DC signal)
I_{Fnom}	nominal forward current of diode/IGBT
I_{FSM}	maximum forward surge current
I_{RRM}	peak reverse recovery current
P_v	power dissipation
Q_{rr}	reverse recovery charge
r_T	forward slope resistance (linear approximation)
R_{th}	thermal resistance
T_j	junction temperature
T_{jmax}	maximum junction temperature
T_{jop}	maximum operation junction temperature
T_s	(heat) sink temperature
T_{solder}	soldering temperature
T_{stg}	storage temperature
t_{rr}	reverse recovery time
V_F	forward voltage
$V_{(BR)}$	avalanche break-down voltage
V_{RRM}	maximum repetitive reverse voltage
$V_{(T0)}$	forward threshold voltage (linear approximation)

A detailed explanation of the terms and symbols can be found in the *Application Manual Power Semiconductors* [2].

7. References

[1] www.semikron-danfoss.com
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[5] SEMIKRON DANFOSS Application Note AN-7006, *IGBT Peak Voltage Measurement and Snubber Capacitor Specification*, 2008
[6] IEC/TR 62258-3: *Semiconductor die products – Part 3: Recommendations for good practice in handling, packing and storage*, Ed. 2, Geneva 2010

IMPORTANT INFORMATION AND WARNINGS

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