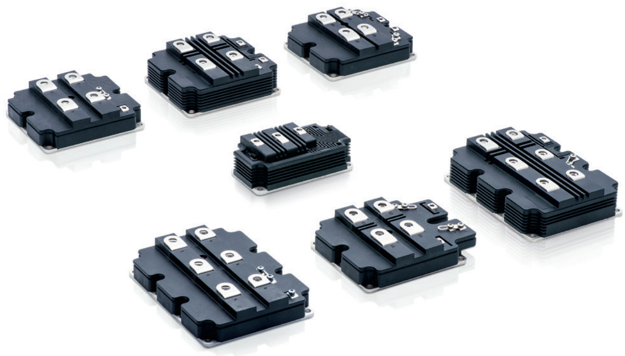
Application note 5SYA 2057-01

IGBT diode safe operating area (SOA)

The majority of IGBT applications require a reverse conduction mode, ie the IGBT should be accompanied by an antiparallel diode for bi-directional conduction, also called a freewheeling diode (FWD) or fast recovery diode (FRD). The rapid development of IGBTs in recent years led to the expansion of reverse blocking SOA, which also increased the demand for complementary robust diodes. Complementary means that the diode has to match the active switching component and must fulfill the same or even higher SOA boundaries.



Contents

1 Introduction

Traditionally, the diode area in IGBT modules is approximately half of the IGBT area and the diodes have to accomplish low conduction and switching losses with high SOA, because accordingly the thermal conductivity is also half of the IGBT. Therefore, diode demands are contradictive and the freewheeling diode design is not less but even more complicated than for the IGBT in many aspects.
The purpose of this application note is to outline the safe operation principles, which should be considered during the circuit design and verification phase, which are mandatory to achieve safe and reliable operation.

1.1 Data sheet parameters

An explanation of the main data sheet parameters can be found in the application note 5SYA2053 “Applying IGBT” [2]. Here we will concentrate on the diode parameters. The FWD part in the data sheet of 5SNA 1500E330305 is taken as an example.

Maximum rated values [1]

Parameter	Symbol	Conditions	Min	Max	Unit
Collector-emitter voltage	V_{CES}	V_{GE} = 0 V, T_{vj} ≥ 25 °C		3300	V
DC collector current	I_C	T_C = 100 °C, T_{vj} = 150 °C		1500	A
Peak collector current	I_{CM}	t_p = 1 ms		3000	A
Gate-emitter voltage	V_{GES}		-20	20	V
Total power dissipation	P_{tot}	T_C = 25 °C, T_{vj} = 150 °C		14700	W
DC forward current	I_F			1500	A
Peak forward current	I_{FRM}	t_p = 1 ms		3000	A
Surge current	I_{FSM}	V_R = 0 V, T_{vj} = 150 °C, t_p = 10 ms, half-sinewave		13500	A
IGBT short circuit SOA	t_{psc}	V_{CC} = 2500 V, $V_{CEM\ CHIP}$ ≤ 3300 V V_{GE} ≤ 15 V, T_{vj} ≤ 150 °C		10	µs
Isolation voltage	V_{isol}	1 min, f = 50 Hz		6000	V
Junction temperature	T_{vj}			175	°C
Junction operating temperature	$T_{vj(op)}$		-50	150	°C
Case temperature	T_C		-50	150	°C
Storage temperature	T_{stg}		-50	125	°C
Mounting torques [2]	M_s	Base-heatsink, M6 screws	4	6	Nm
	M_{t1}	Main terminals, M8 screws	8	10	
	M_{t2}	Auxiliary terminals, M4 screws	2	3	

[1] Maximum rated values indicate limits beyond which damage to the device may occur per IEC 60747

[2] For detailed mounting instructions refer to ABB Document No. 5SYA 2039

V_{CES}: Collector-emitter voltage: The maximum voltage that could be applied between the collector and the emitter. Applying voltages to the module in excess of this limit, even for a short duration, can lead to device failure.
The collector – emitter voltage has a strong temperature dependency. Most ABB IGBT modules have been designed to have full blocking voltage within the total operating temperature range but there are a few exceptions where the temperature range, across which the rated voltage is valid, is reduced. This is shown in the data sheet at conditions where the temperature range for the rated blocking voltage is specified.
High DC voltages applied to any semiconductor will provoke high failure rates due to cosmic radiation. For this reason, the operating DC voltage is much lower than the peak repetitive voltage V_{CES} defined above. This is explained and specified in the application note 5SYA 2042, “Failure rates of HiPak modules due to cosmic rays” [4]. For voltage design recommendations see the application note 5SYA 2051, “Voltage ratings of high power semiconductors” [5].

I_F: DC forward current: The maximum DC-current that the diode part of the module can conduct at the given conditions. Exceeding this limit will lead to over-heating of the device.

I_{FRM}: Peak forward current: The maximum peak current that the diode part of the module can conduct.

I_{FSM}: Surge current: Maximum non-repetitive surge current is the maximum allowed pulse-width-dependent peak value of a half-sinusoidal surge current, applied at an instant when the diode is operating at its maximum junction temperature. Though a single surge at the given conditions does not cause any irreversible damage to the module, it should not occur too frequently due to the thermal stress applied to the module during the surge.
During a surge, the junction heats up to a temperature well above its rated maximum value such that the diode is no longer able to block the rated voltage; the surge current values are therefore only valid when no voltage is reapplied after the surge.
Please refer to the application note 5SYA 2058, “Surge currents for IGBT diodes” [3].

Diode characteristic values [5]

Parameter	Symbol	Conditions		Min	Typ	Max	Unit
Forward voltage [6]	V_F	I_F = 1500 A	T_{vj} = 25 °C		2.05	2.5	V
			T_{vj} = 125 °C		2.25	2.6	V
			T_{vj} = 150 °C		2.20		V
Reverse recovery current	I_{rr}	V_{CC} = 1800 V, I_F = 1500 A, V_{GE} = ±15 V, R_G = 1.0 W, C_{GE} = 330 nF, di/dt = 6 kA/µs L_σ = 100 nH, inductive load	T_{vj} = 25 °C		1700		A
			T_{vj} = 125 °C		1850		A
			T_{vj} = 150 °C		1900		A
Recovered charge	Q_{rr}		T_{vj} = 25 °C		950		µC
			T_{vj} = 125 °C		1550		µC
			T_{vj} = 150 °C		1800		µC
Reverse recovery time	t_{rr}		T_{vj} = 25 °C		1050		ns
			T_{vj} = 125 °C		1350		ns
			T_{vj} = 150 °C		1500		ns
Reverse recovery energy	E_{rec}		T_{vj} = 25 °C		1150		mJ
			T_{vj} = 125 °C		1900		mJ
			T_{vj} = 150 °C		2250		mJ

[5] Characteristic values according to IEC 60747 – 2r halves blocking in forward direction
[6] Forward voltage is given at chip level

V_F: Forward voltage: The anode-cathode on-state voltage of the diode at the specified conditions. It is given at chip level and includes the bond-wire resistance but not the terminal resistance which is separately specified.
All switching parameters are defined in a phase-leg connection using an auxiliary component of the same type as the device under test (DUT), see figure 1. For the definitions of the different switching parameters see figure 2. All switching parameters in the ABB data sheet are specified for inductive load.
Note that other manufacturers may use different definitions for diode turn-off parameters. This must be taken into consideration when comparing modules from different suppliers.

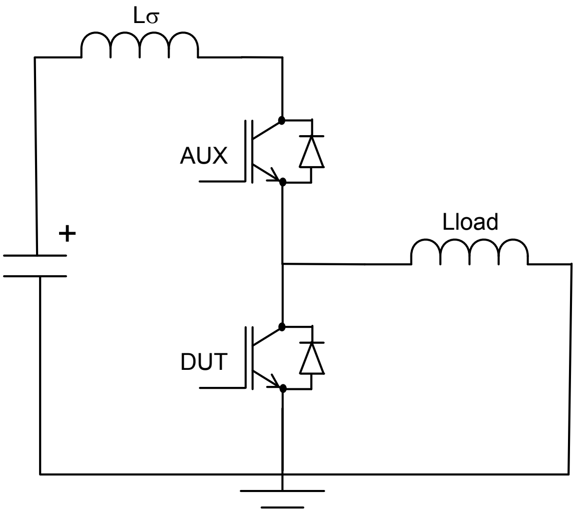


Figure 1 Test circuit for the dynamic performance of the diode

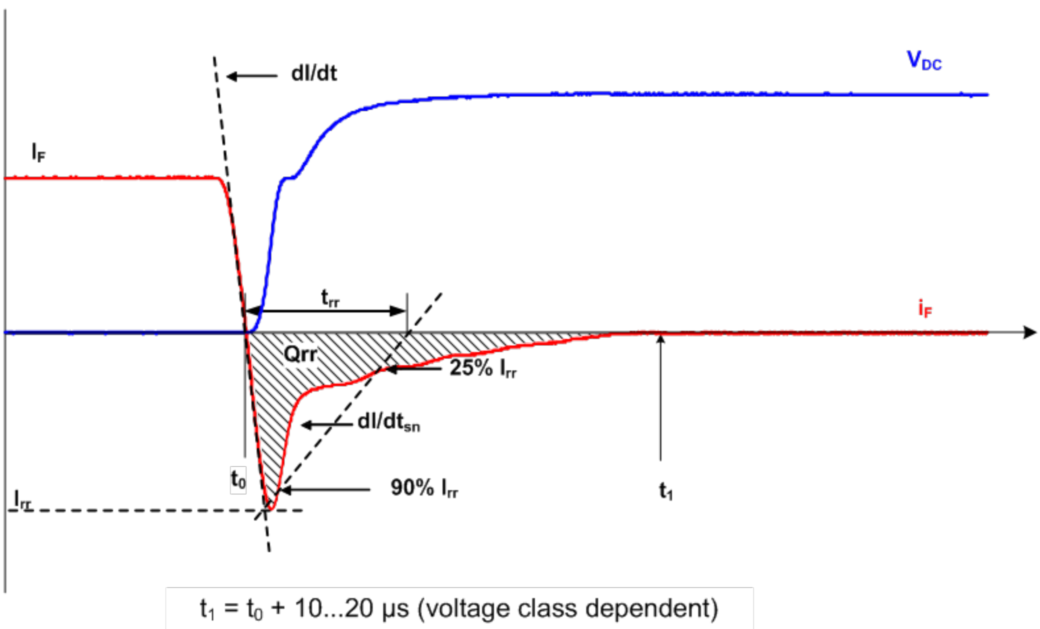


Figure 2 Definitions for the diode turn-off parameters

I_{rr}: Reverse recovery current: The peak value of the reverse current during commutation at the specified conditions.

Q_{rr}: Reverse recovery charge: The integral over time of the reverse current during commutation at the specified conditions starting at the zero-crossing of the current and ending when the reverse current has decayed to zero after the tail-current phase.

t_{rr}: Reverse recovery time: The commutation time of the diode at the specified conditions. It is measured between the current zero-crossing and the zero-crossing of a straight line drawn between 90% of the reverse current peak on the rising flank and 25 % of peak (on the falling flank).

E_{rec}: Reverse recovery energy: The energy dissipated during a single reverse recovery event. It is the integration of the product of the reverse current and voltage from t_0 to t_1 (see figure 2) as expressed by equation 1.

$$E_{rec} = \int_{t_0}^{t_1} (i_R(t) \times v_R(t))dt \qquad \text{Equation 1}$$

In "conditions", the nominal operation conditions are specified as the gate resistor and the driving voltage, which define the speed of the commutation (di/dt).

2 Diode design

2.1 On-state – Turn-off loss trade-off, parameter deviation

The IGBT freewheeling diodes have to combine low on-state losses with high immunity to dynamic stresses. Semiconductor devices are often characterized with a so-called technology curve – the trade-off curve of the reverse recovery energy E_{rr} or reverse recovery charge Q_{rr} versus the forward voltage V_F. This means, that in principle every single point on this curve can be targeted. Figure 3 shows an example of such a trade-off curve. It is, therefore, possible to design diodes either with a rather low E_{rr} but increased V_F or diodes with a low V_F and high E_{rr}. The trade-off curve can be achieved either by varying the current density or by variation of the carrier lifetime. A larger chip size results generally in a lower forward voltage V_F, because the current density is lowered which additionally improves the thermal capabilities of the chip and is therefore an advantage. But simultaneously the switching losses increase and the cost aspect has its drawback. The tendency to make a very "soft" diode through silicon thickness also results in a poor technology curve. Soft diodes through local lifetime killing can be achieved with a very competitive technology curve, but to the cost of increased leakage current. [8] The ABB diodes are designed in a way that they can suite the majority of known applications.

2.2 Paralleling of chips

Single diode dies are limited in current capability by the specific current density per voltage class. To overcome this limitation, single dies are connected in parallel, as many as necessary, for a given module current capability. The dies have though a parameter spread which in some limiting cases can lead to an overload of particular dies. To overcome that problem design measures are taken, but some derating of single die parameters is necessary.

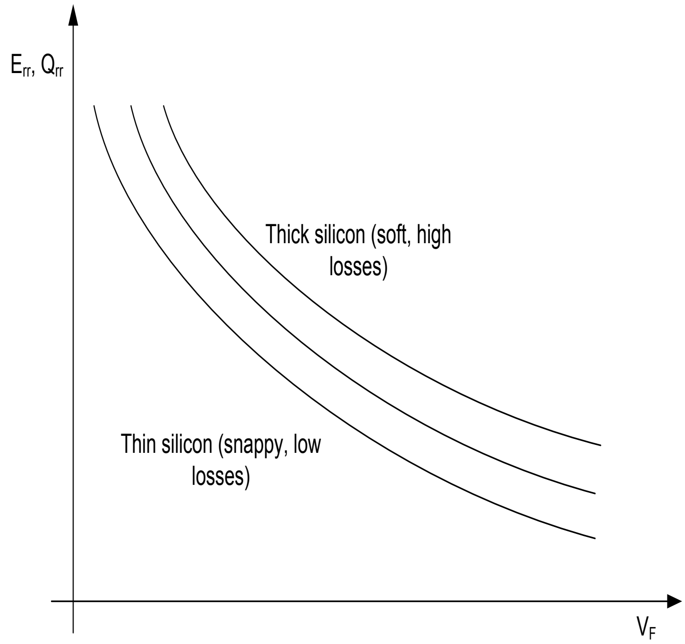


Figure 3 Technology curves

ABB diodes are specially designed for parallel operation, with a positive temperature coefficient of the forward voltage drop V_F already around nominal current.
The stray inductance of the circuit is mainly given by the converter construction. With an increased number of modules switched in parallel, the effective overvoltage $V = L_\sigma$*di/dt is also increased if di/dt per module stays the same as in a single module operation. It can be illustrated as L_σ increase per module see figure 4.

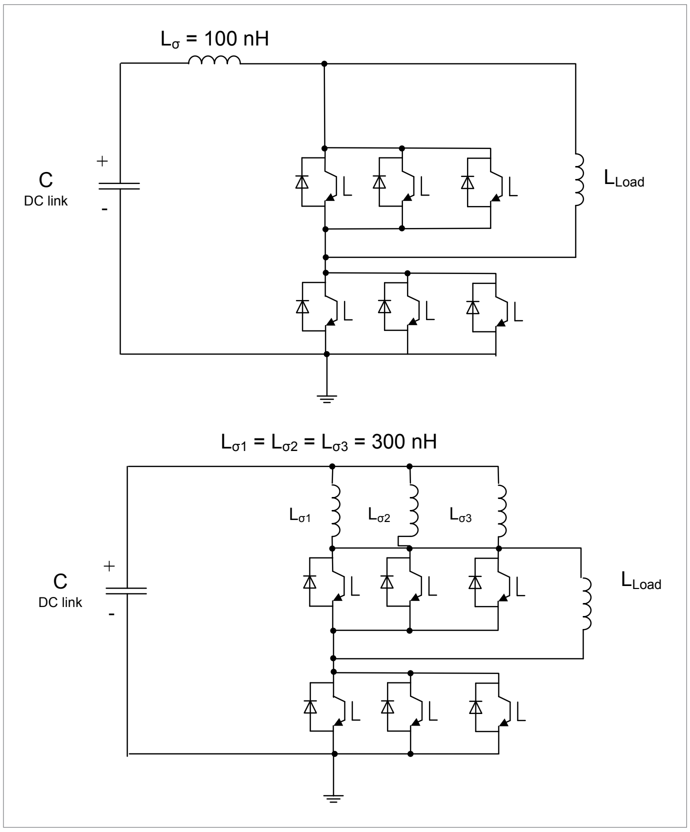


Figure 4 Inductances at different configurations to achieve the same di/dt.

The peak power during diode turn-off as a product of voltage and current will also increase proportionally to the overvoltage. A high overvoltage can lead to strong dynamic avalanche (additional carrier generation) and further increase the peak power. A design utilizing parallel module operation has a higher demand on the total stray inductance and the gate drive should be adjusted to keep the diode within the specified limits, which is explained in section 3.

2.3 Forward recovery

One other known phenomenon of the high voltage diode is the so-called forward recovery. When a current is applied in the forward direction the diode voltage does not rise smoothly and monotonically from its initial blocking value to a steady-state forward bias value of a few volts. The diode in its blocking phase behaves as a charged capacitor (space charge capacitor) which has to be discharged when the voltage changes polarity across the diode. The stored charge is proportional to the diode voltage class. (figure 5) Another part of the voltage builds across the diode due to ohmic resistance of the drift region and the inductance of the silicon chip and of the bond wires attached to it. As the forward current grows in time, there is no conductivity modulation of the region until the space charge layer is discharged to its thermal equilibrium value. The circuit stray inductance also adds a significant voltage drop at a higher di/dt. The combined effect of these two facts is a voltage overshoot that can be as large as several hundred volts. This voltage is applied to the antiparallel IGBT and because it exceeds the reverse blocking capability of the IGBT, the IGBT is driven into reverse avalanche. Some charge is generated in the IGBT, which recombines during diode conduction, but with a short diode conduction time some remaining charge will be added to the diode reverse recovery charge. In addition, the gate drive circuitry which measures the collector voltage or acts as an active clamp has to be designed accordingly to withstand the full forward voltage.

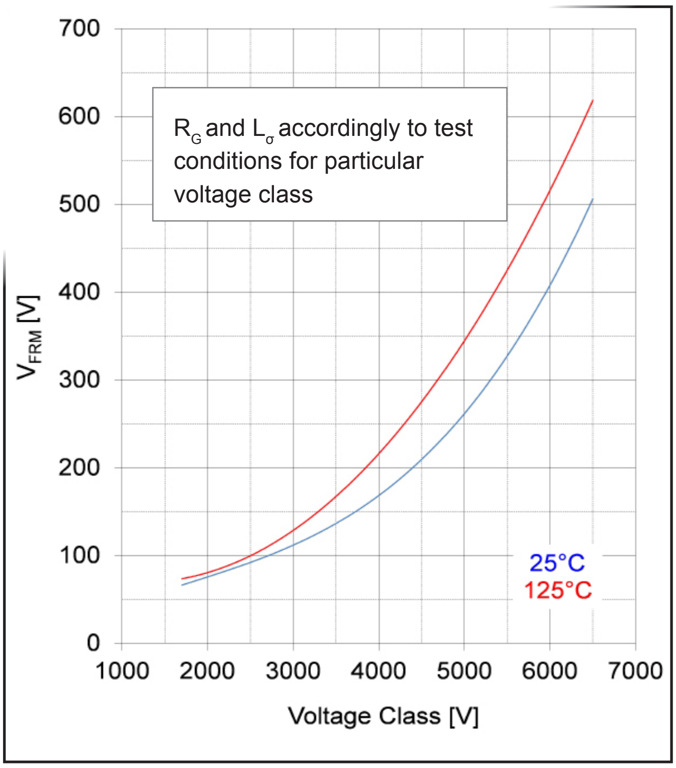


Figure 5 Forward voltage dependence of blocking voltage.

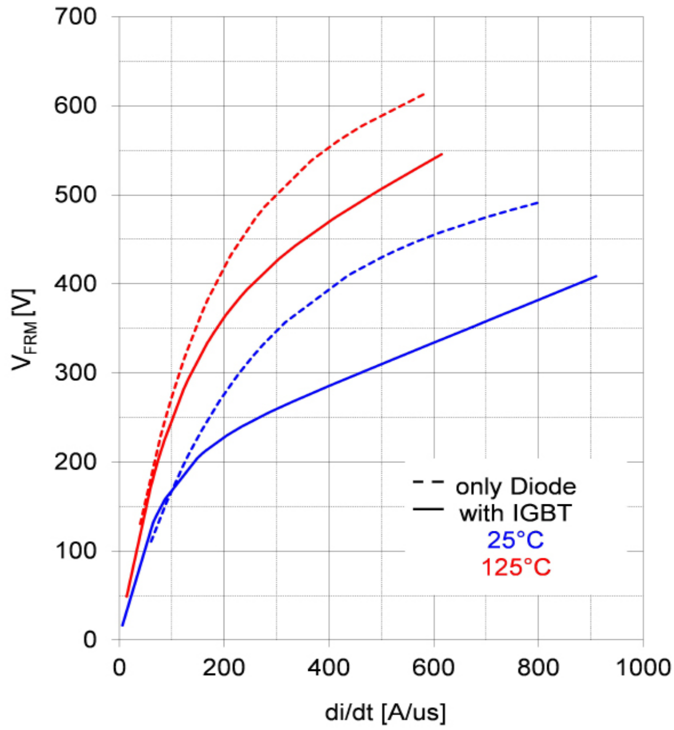


Figure 6 Forward voltage di/dt dependence, with and witout antiparallel IGBT

3 SOA

3.1 Data sheet SOA

The safe operating area (SOA) diagram (figure 7) shows the diode reverse voltage vs. the recovery current limits of the diode at the specified conditions. The specified SOA must not be exceeded at any instant of the recovery process under rated conditions. The SOA diagram has the following areas:

1. High value of forward current and as a consequence - high $I_{rr:}$ reverse recovery current often limited by the value of maximum forward current. A maximum recommended negative di/dt value (mainly defined by recommended gate driving and stray inductance) is given in the diagram.
2. Peak power limitation - higher L_σ as stated above with given di/dt will contribute to higher overvoltage and peak power. By tracing the curves of $v_R(t)$ and $i_R(t)$ the peak power at any instant can be calculated, in case of the 1,500 A module their product should not exceed the peak power of 3 MW, see figure 7.
3. Low current – high overvoltage, higher L_σ and di/dt will lead to exceeding the allowed voltage.

Three real waveforms illustrate where the limitations occur. As described in [6] there are two major failure mechanisms in diodes during reverse recovery: low current snap-off and peak power failure.

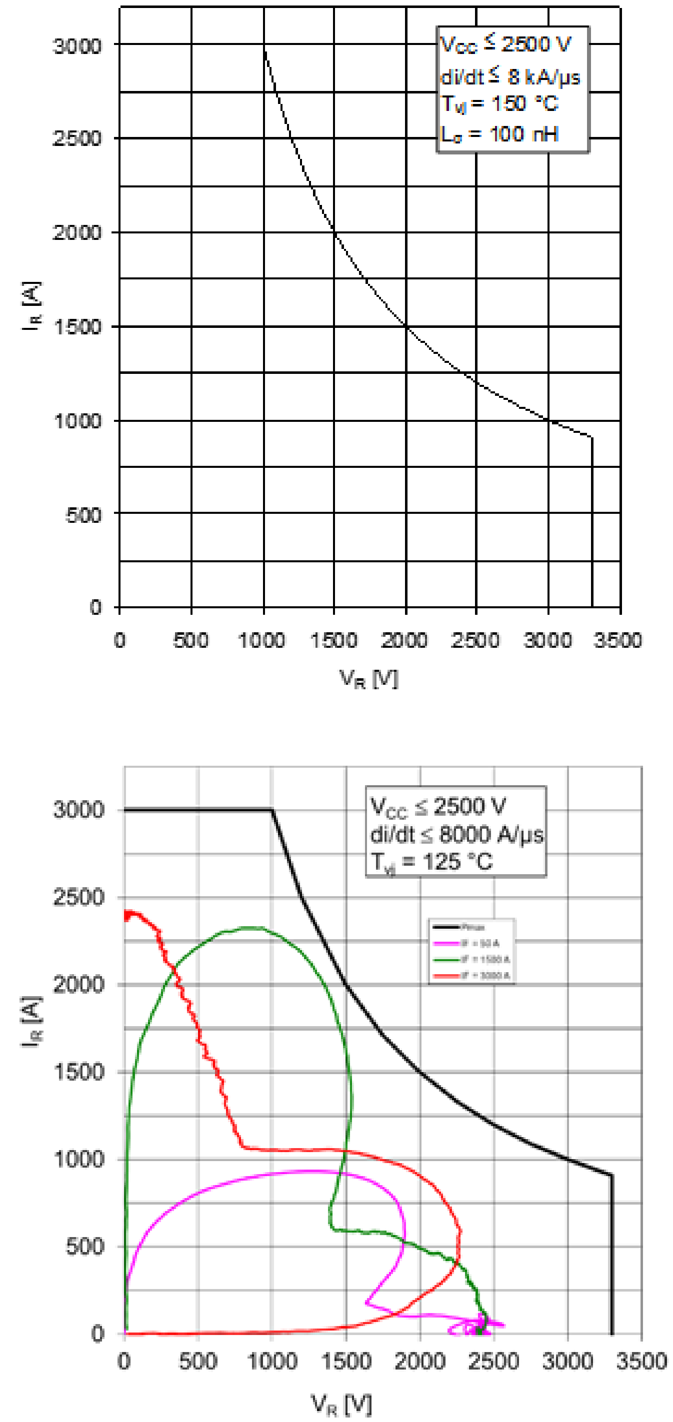


Figure 7 Safe operating area diagrams for the diode

3.2 High di/dt limitation

Even with low L_σ very high di/dt can provoke diode destruction, so the recommended di/dt should not be exceeded.

3.3 Peak power failure, I_F, V_{CC}, R_G, C_{GE}, clamp

The second type of failure mode, termed as reverse-recovery dynamic avalanching or peak power occurs at high di/dt switching speeds. Normally, the process itself is safe if the device does not exhibit any non-uniformity in the recovery current. However, dynamic avalanching can result in the generation of a hot spot in the silicon die due to non-uniform current distribution leading to the destruction of the device. The causes of these hot spots can range from process to material variations in a single diode and silicon chip to non-uniform cooling of the module. To prevent this failure mode, certain design/process considerations must be taken into account to minimize the effects of any current filamentation. One of the major factors of this failure is also the circuit stray inductance. Higher stray inductance produces higher voltage stress and drives the diode into dynamic avalanche directly after the beginning of current decay, when non-uniformities in the recovery current are most possible. The forward current defines how much energy is stored in the stray inductance, but at higher currents the IGBT switching velocity is also lower, and it reduces stress on the diode.

Operating at DC-link voltages above the nominal levels leads to an increase of dv/dt and peak power. If the gate unit does not have a voltage feedback loop, operation with high di/dt and forward currents can lead to failure.

The gate resistor defines the switching velocity of the IGBT, and the turn-off di/dt of the diode. The data sheet shows the value of R_{gon} which guarantees safe operation at the described conditions. For some modules a gate emitter capacitor C_{GE} is also recommended. The utilization of C_{GE} helps the user to keep a lower E_{on} due to the possibility of using lower R_{gon} values, and still operate the diode inside SOA boundaries. During turn-on additional capacitance between the gate-emitter helps to accelerate the voltage fall, which helps to reduce turn–on loss up to 50%. It is important to mount the recommended gate emitter capacitor C_{GE} directly onto the module's auxiliary connections to obtain the best results.

3.4 Low current snap-off

One of the most common and catastrophic failure modes in fast diodes is snappiness during diode reverse recovery. It is known that under adverse combinations of high commutating di/dt, large circuit stray inductance, low forward current and low junction temperature it is likely that all fast power diodes produce excessive voltage spikes due to snappy recovery [8]. The depletion of the remaining stored charge during the recovery period results in a current discontinuity (chop-off). This produces a very high di/dt and, hence, large voltage overshoot which may result in the destruction of the device.

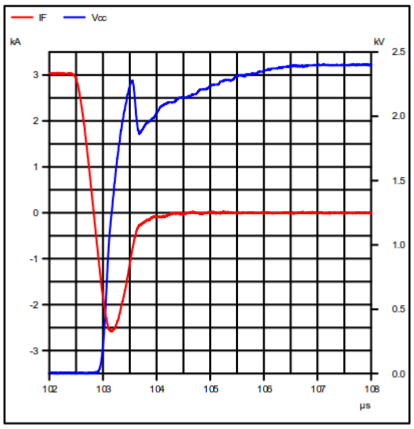
In pulse width modulation (PWM) operation very short conduction times can occur. The diode due to short conduction will not be fully filled with carriers, so current discontinuity as described above is possible not only at low forward currents. Hence, short turn-on time can also result in the destruction of the device.

The temperature dependency of the above described phenomena can be critical for different diode technologies. Reliable design needs careful verification of critical parameters within the complete operation temperature range.

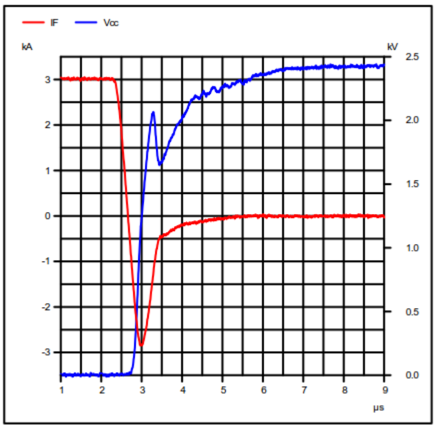
In some cases, when the circuit inductance is too high (the need

to slow down the switching speed to avoid excessive overvoltages leads to unacceptable switching losses), it is advantageous to use an active voltage clamp to dissipate energy stored in the stray inductance. The name “active” comes from the use of the IGBT in a linear “active” mode. The IGBT will be driven in the active region when the voltage across it exceeds the avalanche voltage of the Zehner diode network connected between the collector and the gate. The use of this method has to be combined with a careful thermal load calculation of the IGBT, because additional losses are generated.
Sample waveforms below show the diode turn-off behavior at specified SOA conditions over an operation temperature range.

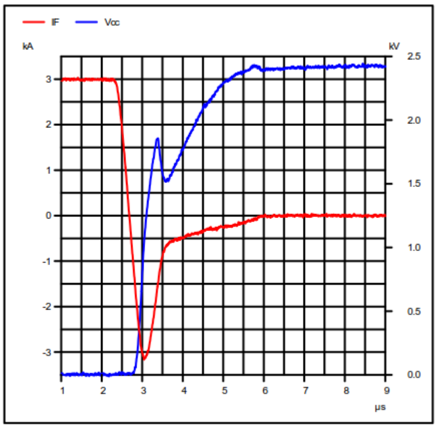
SOA measurements on 5SNA 1500E330305 IGBT module I_c = 3000 A, V_{cc} = 2400 V



Tj = -40 °C

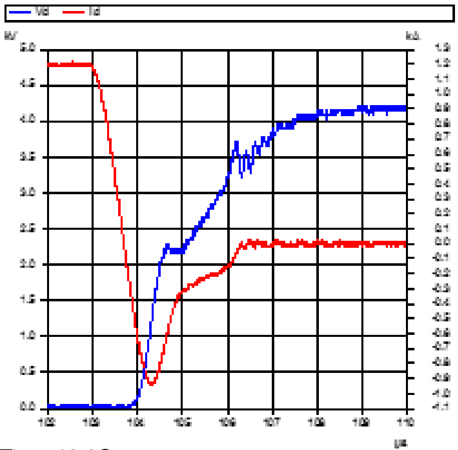


Tj = 25 °C

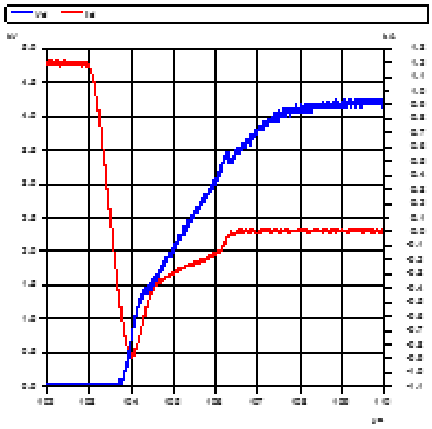


Tj = 125 °C

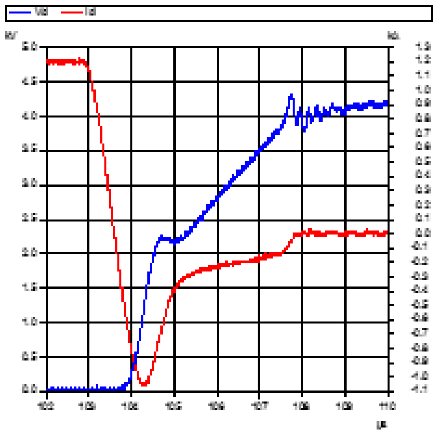
SOA measurements on 5SNA 0600G650100 IGBT module I_c = 1200 A, V_{cc} = 4200 V



Tj = -40 °C



Tj = 25 °C



Tj = 125 °C

4 References

[1] IEC Standard 60747 “Semiconductor Devices”
[2] 5SYA 5023 “ Appling IGBT”
[3] 5SYA 2058 “Surge currents for IGBT Diodes”
[4] 5SYA 2042 “Thermal Runaway”
[5] 5SYA 2051 “Voltage dimensioning of high power semiconductors”
[6] M.T. Rahimo, N.Y.A. Shammas, “Freewheeling Diode Reverse Recovery Failure Modes in IGBT Applications“ IEEE Transactions on Industrial Application, Vol. 37, No. 2, March/April 2001, pp 661 - 670.
[7] Stefan Linder “Power Semiconductors” ISBN: 2-940222-09-6, EPFL-Press 2006, 280 pp, (US ISBN 0-8427-2569-7).
[8] M.T. Rahimo, A. Kopta, S. Eicher , N. Kaminski, F. Bauer, U. Schlapbach, S. Linder, “Extending the Boundary Limits of High Voltage IGBTs and Diodes to above 8kV”, Proc. ISPSD’02, pp. 41-44, Santa Fe, New Mexico, USA, June 2002.
[9] M.T. Rahimo, A. Kopta, S. Eicher, U. Schlapbach, S. Linder, “Switching-Self-Clamping-Mode “SSCM”, a breakthrough in SOA performance for high voltage IGBTs and Diodes” Proc. ISPSD’04, pp. 437 440, Kitakyushu, Japan, May 2004.
[10] A. Kopta, M.T. Rahimo “The Field Charge Extraction (FCE) Diode A Novel Technology for Soft Recovery High Voltage Diodes” Proc. ISPSD’05, pp. 83-86, Santa Barbara, USA, May 2005.

5 Revision history

Version	Change	Authors
01		Evgeny Tsyplakov

Contact us

ABB Switzerland Ltd
Semiconductors
Fabrikstrasse 3
CH-5600 Lenzburg
Switzerland
Tel: +41 58 586 14 19
Fax: +41 58 586 13 06
E-Mail: abbsem@ch.abb.com
www.abb.com/semiconductors

Application Note 5SYA2057-01 January 2015