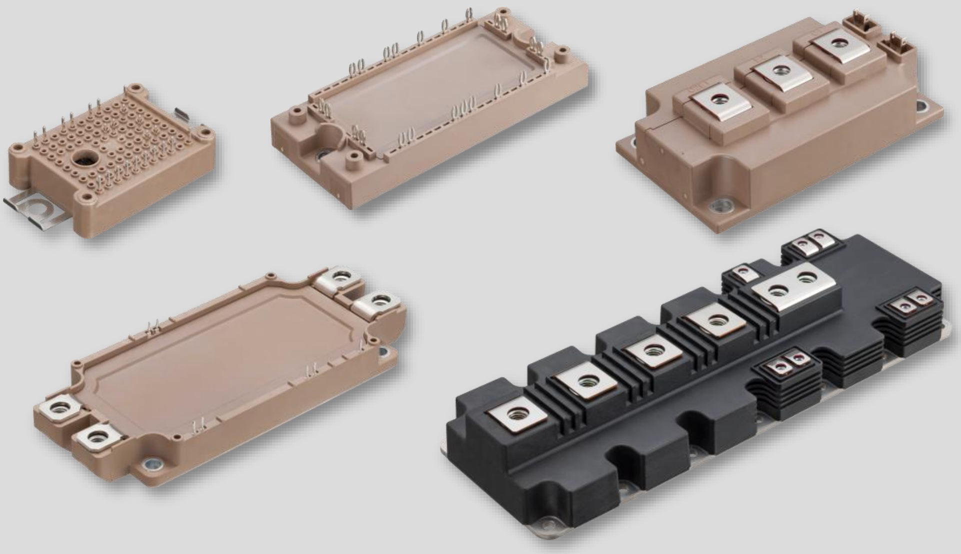

Fuji 7th Generation IGBT Module
X Series

Application Manual

June 2021 Rev.2.0

Fuji Electric Co., Ltd.

Warning:

This manual contains the product specifications, characteristics, data, materials, and structures as of June 2021.

The contents are subject to change without notice for specification changes or other reasons. When using a product listed in this manual, be sure to obtain the latest specifications.

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⚠ Cautions

(1) During transportation and storage

Keep locating the shipping carton boxes to suitable side up. Otherwise, unexpected stress might affect to the boxes. For example, bend the terminal pins, deform the inner resin case, and so on.

When you throw or drop the product, it gives the product damage.
If the product is wet with water, that it may be broken or malfunctions, please subjected to sufficient measures to rain or condensation.

Temperature and humidity of an environment during transportation are described in the specification sheet. There conditions shall be kept under the specification.

(2)Assembly environment

Since this power module device is very weak against electro static discharge, the ESD countermeasure in the assembly environment shall be suitable within the specification described in specification sheet. Especially, when the conducting pad is removed from control pins, the product is most likely to get electrical damage.

(3)Operating environment

If the product had been used in the environment with acid, organic matter, and corrosive gas (hydrogen sulfide, sulfurous acid gas), the product's performance and appearance can not be ensured easily.

CONTEXTS

Chapter 1 Basic Concepts and Features of X-series

Chapter 2 Precaution for Use

Chapter 3 7th Generation X Series RC-IGBT Module

Chapter 1 Basic Concepts and Features of X-series

This chapter explains basic concepts and features of the 7th generation X-series IGBT modules.

1. Basic Concepts of X-series

In recent years, efforts have been made to improve energy efficiency and to reduce carbon dioxide emissions from the viewpoint of global warming and the exhaustion of fossil fuel. Therefore, it is necessary to provide highly efficient power conversion equipment which are based on high effective power semiconductors. These can be used in various fields like industrial applications of motor drive and consumer products, power supplies, renewable energy as well as electrical vehicles and railway applications. Among power semiconductor devices, IGBT (Insulated Gate Bipolar Transistor) modules are characterized by high-speed switching, high efficiency at high power and by easy handling.

This leads to a steady expansion of their application fields. Since the emergence of IGBT modules in the market, technological innovations realize lower power dissipation and achieve a substantial miniaturization. These innovations contribute higher efficiency, smaller size and higher cost performance of power conversion systems. However, the miniaturization of IGBT modules causes an increase of IGBT junction temperature and a decrease of reliability in consequence of higher power density. In order to realize further miniaturization and higher efficiency, it is inalienable to improve, besides chip characteristics, also heat dissipation by innovative package technology. In response to this market demand, Fuji Electric has released the 7th generation X-series IGBT modules with innovative chip and package technologies.

- **Reduction of power dissipation (chip technology)**

7th generation X-series IGBT power dissipation performance has been improved dramatically compared to the previous IGBT generation realized by ultra-thinner wafer fabrication technology and fine trench gate structure. Innovative technologies can realize further benefit for power conversion systems such as higher output power or miniaturization.

- **Enhancement of continuous operating temperature T_{vjop} = 175°C (package technology)**

Maximum continuous operation temperature (T_{vjop}) of X-series is expanded by using newly developed package technologies. The enhanced stability and durability against high temperature operation is achieved by high heat insulating substrate and high heat resistant Si-gel, high strength solder and optimization of wire bonding technology on Si-chips. Due to these efforts by Fuji Electric, the X-series can guarantee maximum T_{vjop} of 175°C (previous generation is T_{vjop}=150°C). The upgrading of T_{vjop} allows higher output power without increasing package size.

- **Expansion of rated current and downsizing of package**

Rated current of X-series has been increased with the same package size as for the previous generation. For example, the maximum rated current of 1200V EconoPIM™2 package for X-series is increased to 75A from 50A of the previous generation. That means 50% expansion of rated current can be achieved by X-series technologies. From another point of view, the expansion of maximum rated current allows downsizing of the package. The rating of 75A/1200V could only be realized by bigger size package (EconoPIM™3) in the previous generation technologies. The new rating IGBTs can contribute to miniaturization of power conversion systems and reduction of total system cost.

Note) EconoPIM™ is a registered trademark of Infineon Technologies.

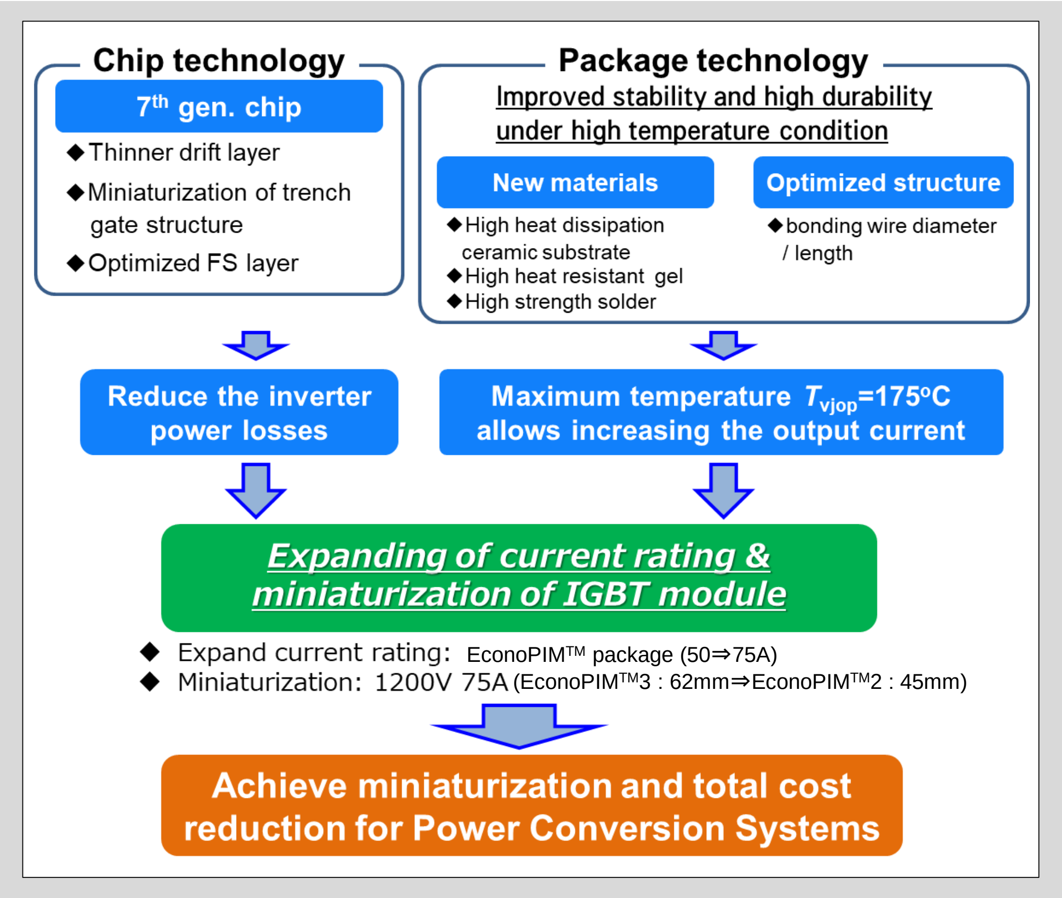
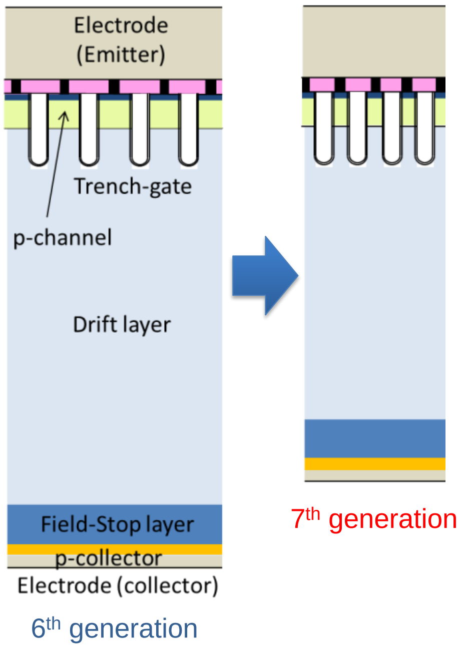


Fig.1-1 The basic concept of 7th generation X-series IGBT modules

Note) EconoPIM™ is registered trademark of Infineon Technologies.

2. Chip Features of X-series

Fig.1-2 shows a cross-section diagram of 6th generation V-series and 7th generation X-series IGBT chip. The structure of X-series IGBT has field stop and trench gate structure basically just like V-series. However, the X-series can realize a thinner drift layer than the previous IGBT generation which can achieve a breakthrough of trade-off relationship between on-state voltage and turn-off switching energy. In general, thinner drift layers cause voltage oscillations and high overvoltage at turn-off as well as voltage withstand capability degradation. To overcome the negative effects, the new field stop structure is reinforced with newly developed technology. Moreover, the optimized fine trench gate structure has been well-considered and designed to adjust hole ejection and carrier density on the surface area for utilizing Injection Enhanced effect sufficiently. The combination of ultra-thinner drift layer and higher carrier concentration brings significant improvement of trade-off between on-state voltage drop and turn-off energy.



Generation	6th	7th
Series	V	X
Wafer	FZ	FZ
Gate structure	Trench	Fine Trench
Bulk	FS	FS
Lifetime control	None	None
Thickness	Thin	Thinner

Fig.1-2 IGBT cross section comparison

Main features of X-series chip

1. Thinner drift layer
   - Reduced on-state voltage drop
   - Reduced switching energy
2. Fine trench gate structure
   - Reduced on-state voltage drop
   - Reduced switching energy
3. Optimization of field stop layer
   - Suppression of voltage oscillations
   - Reduced leakage current at high temperature

2.1 Trade-off improvement between turn-off energy and on-state voltage drop

Fig.1-3 shows a comparison of IGBT output characteristics between the 7th generation X-series and the 6th generation V-series. As shown in this figure, the on-state voltage drop of X-series is reduced by 0.25V. As direct consequence the conduction power dissipation decreases and the power conversion system efficiency improves.

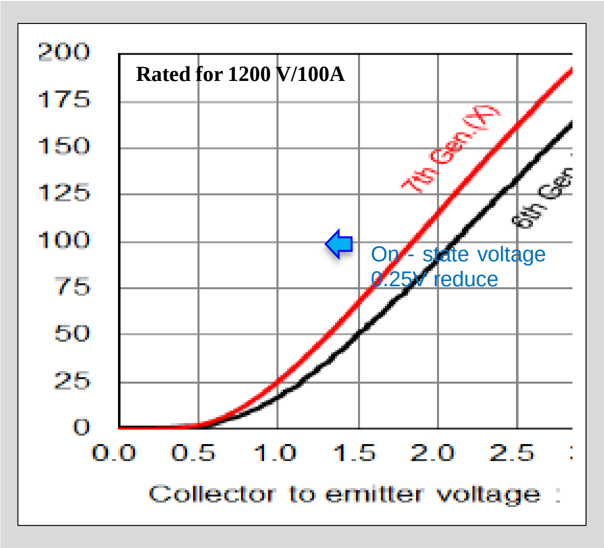


Fig.1-3 Improvement of IGBT output characteristics

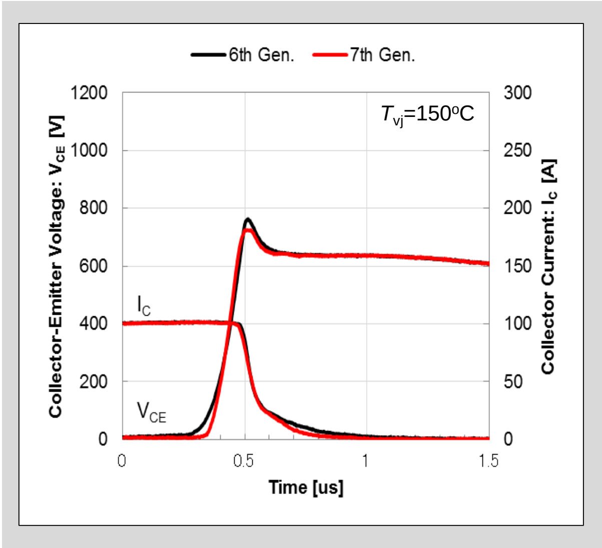


Fig.1-4 Turn-off waveforms comparison

Fig.1-4 shows a turn-off switching waveforms comparison of the X-series and the V-series. The turn-off energy of the X-series has been reduced by 10% by reducing significantly the tail current. The energy reduction is achieved by the thinner drift layer as described above.

Fig.1-5 shows a trade-off relation between on-state voltage and turn-off energy. Compared to the V-series the collector emitter voltage is reduced by 0.25V for the X-series.

With the improvements introduced, the X-series IGBT chip realizes a power loss reduction, despite the fact that the chip size has been shrunken.

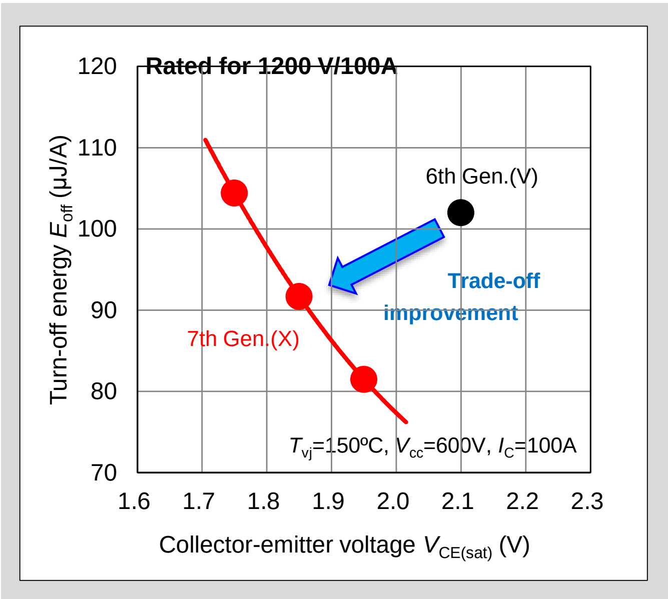


Fig.1-5 Improvement of turn-off energy vs. on-state voltage

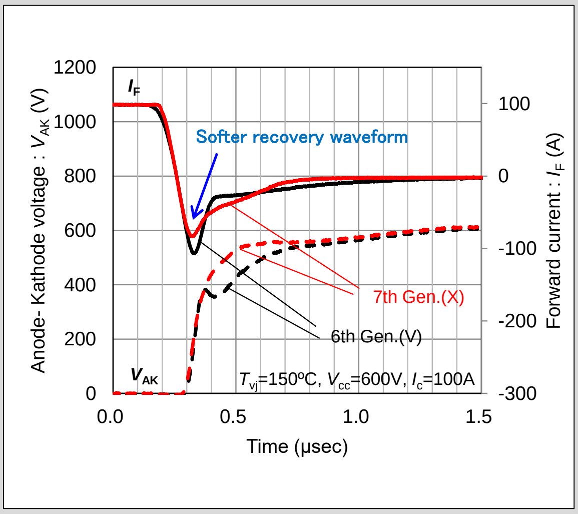
2.2 Improvement of leakage current

IGBT devices allow a leakage current to flow with reverse biased voltage between collector and emitter. This current increases for higher temperatures of the IGBT. The power losses caused by the leakage current lead to a further rise of the junction temperature. This relation is possibly leading to a thermal runaway breakdown. The optimization of the field stop layer for the X-series reduces the leakage current at high temperatures by 28% compared to the previous generation. Therefore, the risk of a thermal runaway is reduced and a junction temperature of 175°C for a continuous operation can be guaranteed.

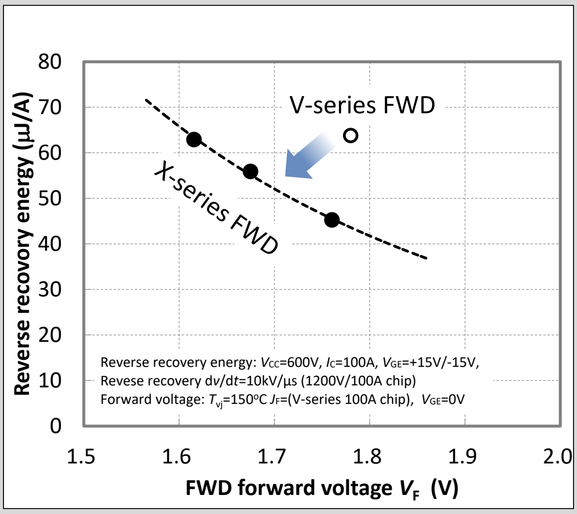
2.3 Improvement of FWD characteristics

In the 7th generation X-series IGBT module, not only the IGBT chip characteristics but also the characteristics of the diode (FWD: Free Wheeling Diode) which is connected anti parallel to the IGBT has been improved. The forward voltage (V_F) could be reduced due to a thinner drift layer. While reducing the thickness of a FWD drift layer, the depletion layer is likely to reach the back surface during reverse recovery. This can cause voltage oscillation. In the X-series FWD device the expansion of the depletion layer during reverse recovery is suppressed by optimizing the back surface structure. As the depletion layer will not reach the back surface, voltage oscillation and overvoltage can be suppressed. Fig.1-6 shows a comparison of the FWD characteristics between the X-series and the V-series. As shown in Fig.1-6 (a) the reverse recovery peak as well as the tail current are reduced. A soft reverse recovery waveform is realized. The improved trade-off relation between reverse recovery energy and forward voltage drop is shown in Fig.1-6 (b). A loss reduction of around 30% for the same V_F condition could be achieved compared to the V-series.

In general, it is known that EMI noise (Electromagnetic Interference noise) which is emitted from a module during switching, depends on the voltage slope dv/dt. Softening the reverse recovery waveform is aiming to improve the emitted noise by reducing the dv/dt slope.



(a) Example of FWD reverse recovery waveform



(b) Reverse recovery energy vs. forward voltage

Fig.1-6 Improvement of X-series FWD characteristics

3. Package Technology Characteristics of X-Series

The 7th generation X-series has a guaranteed T_{vjop}=175°C. In order to realize this, it is indispensable to increase the efficiency and to reduce the size of IGBT and FWD chips. However, the increased power density due to miniaturization of the chips causes an increase of chip temperature and therefore may reduce the reliability of the device. An optimized module structure as well as a newly developed high temperature and high reliability package has solved this trade-off issue for the X-series.

- Development of new materials
  - High heat dissipation ceramic substrate → Improved heat dissipation and reliability
  - High heat resistant silicone gel → Long term insulation at 175°C
  - High strength solder → Improved ΔT_{vj} power cycle capability

- Optimization of module structure
  - Optimized bond wire diameter and length → Improved ΔT_{vj} power cycle capability

3.1 High heat dissipating ceramic insulating substrate

In order to improve the heat dissipation of the 7th generation IGBT and FWD chips, the thermal resistance has been decreased by improving the ceramic insulating substrate inside of the module. The ceramic insulating substrate has the biggest influence on the thermal resistance between chip and heat sink. Reasonable costed alumina (Al_2O_3) and aluminum nitride (AlN), the latter with a high thermal conductivity and a low thermal resistance, are widely used as ceramic insulating substrate material. In order to fulfill the requirements for high output operation and miniaturization, the application of an AlN insulating ceramic with low thermal resistance is desirable. However, the conventional AlN insulating substrate has a high rigidity due to the large substrate thickness. The thermal stress to the solder layer under the substrate will increase if the T_C rises. This will have a negative impact to reliability.

Therefore, as shown in Fig.1-7, the AlN ceramic layer for the 7th generation X-series is thinner than for the previous series. This high heat dissipating, low thermal resistance and long-term reliability ceramic substrate was especially developed. The reduction of the insulation layer thickness comes always together with a concern regarding a reduction of the insulation resistance and a limitation of the initial strength. These problems have been solved by optimizing the ceramic sintering conditions.

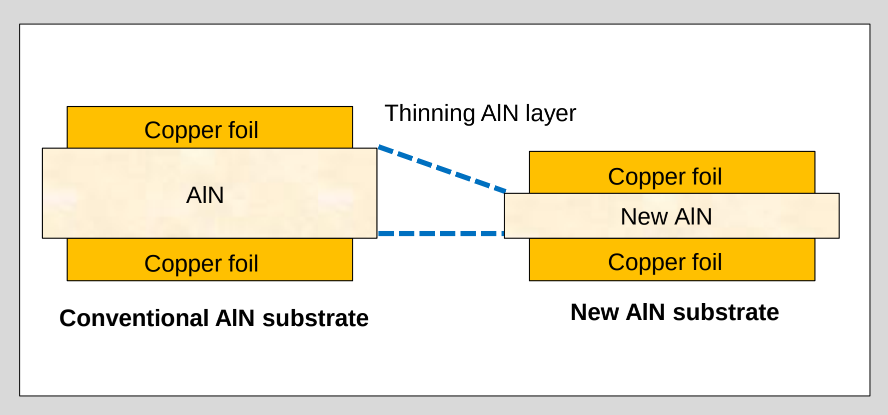


Fig.1-7 Cross-sectional structure of the AlN substrate

Fig.1-8 shows the thermal impedance ($Z_{th(j-c)}$) between the junction of chip and case for the conventional Al_2O_3 substrate and the newly developed high heat dissipation AlN substrate. As shown in this fig., the heat dissipation of the AlN substrate makes thermal resistance 45% lower compared to the conventional Al_2O_3 (comparison for an identical chip size). By applying this new AlN one to modules where power density and therefore chip temperature are particularly crucial, all issues of reliability and temperature rise have been solved, and the miniaturization as well as the high temperature operation of the module have been realized.

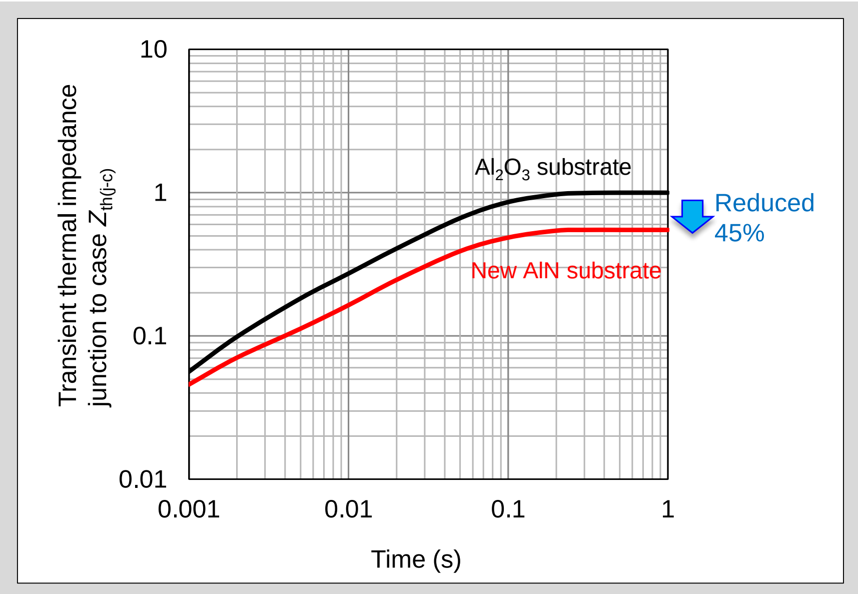


Fig.1-8 Comparison of thermal resistance between Al_2O_3 and AlN ceramic

3.2 Development of high heat resistant silicone gel

The T_{vjop} during continuous operation is 150°C for the 6th generation V-series modules. The 7th generation X-series guarantees an operating temperature of 175°C. One crucial aspect to guarantee the long-term reliability of an IGBT module is the degradation at high temperature of the silicone gel which is used inside the module.

Silicone gel is used to secure the withstand voltage of an IGBT module. In general, silicone gel becomes harder for higher temperatures. This may lead to cracks causing a reduction of voltage withstand capability. This problem becomes more serious for the increased continuous junction temperature. In order to solve this issue, a new high heat resistant silicone gel has been developed. The curing effect for high temperatures could be suppressed for this new silicone gel by optimizing the material's composition. It has been confirmed that no any cracks occurred, even at very high temperatures (215°C, 2000hours).

Fig.1-9 shows the relation between ambient temperature and silicone gel lifetime. The lifetime of the high heat resistant gel at 175°C is about five times higher, compared to the conventionally used gel, and it has an equivalent lifetime to the conventional gel at 150°C. As a result, the insulation performance of the 7th generation X-series ensures the same reliability at 175°C as the conventional product at 150°C junction temperature.

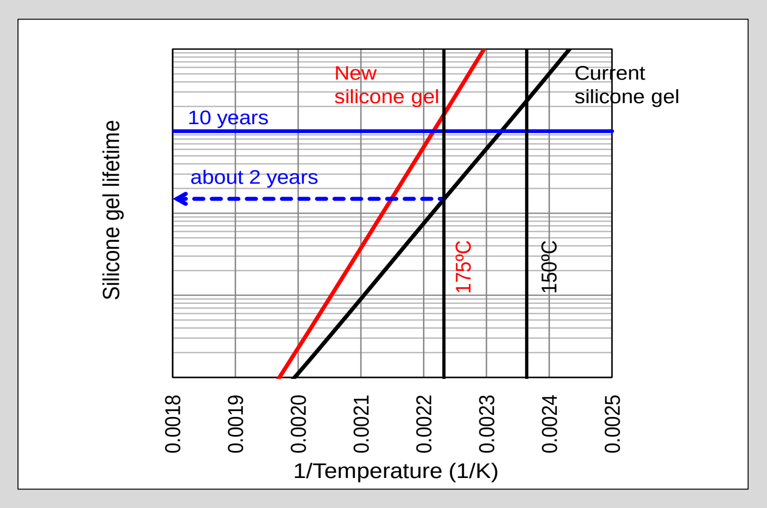


Fig.1-9 Silicone gel lifetime vs. temperature

3.3 Development of high strength solder and optimization of wire diameter/length

In order to ensure the long-term reliability of an IGBT module, it is necessary to improve the withstand capability (ΔT_{vj} power cycle capability) against repeated thermal stress.

Fig.1-10 shows the cross-sectional structure of an IGBT module in general. An IGBT module consists of a ceramic substrate for insulation which is soldered to a base plate most often out of copper. At the topside of the ceramic is a copper wiring pattern on which the IGBT or FWD chips are soldered. The connection between the chips' top surface and the copper pattern is building the circuit and is realized by wires that are made of aluminum or copper. During operating the power conversion equipment, the temperature of the IGBT module will rise. Because every used material (copper, ceramic, semiconductor chip, solder) has a different thermal expansion coefficient, mechanical stress will arise at the joint area. During normal conditions of use, the T_{vj} of the semiconductor chip repeatedly goes up and down. This leads to an oscillating mechanical stress which mainly occurs at the solder joint under the chip and the connected wire on the chips' surface and will cause deterioration. The progress speed of this degradation is accelerated for a higher T_{vj}.

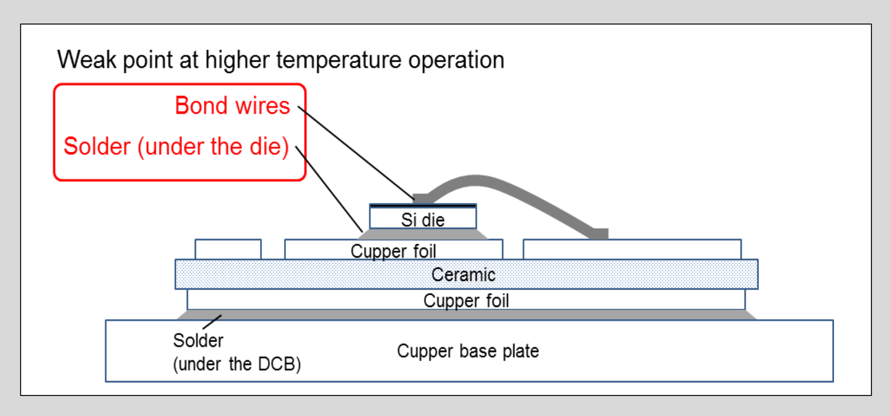


Fig.1-10 module structure diagram

For the 7th generation X-series the on-chip wires have been optimized in terms of diameter and length. This ensures a sufficient power cycle withstand capability even for a continuous operation of T_{vj}=175°C. In addition, the soldering material under the chip has been replaced by an improved, new developed, high strength soldering material.

Fig.1-11 shows the comparison of the ΔT_{vj} power cycle capability for X-series and V-series modules. The X-series achieves about twice the withstand capability of the V-series ($T_{vj,max}$ = 150°C, ΔT_{vj} = 50°C). Even at the increased junction temperature $T_{vj,max}$ = 175°C, the power cycle capability of X-series is equal or higher compared to the V-series at $T_{vj,max}$ = 150°C.

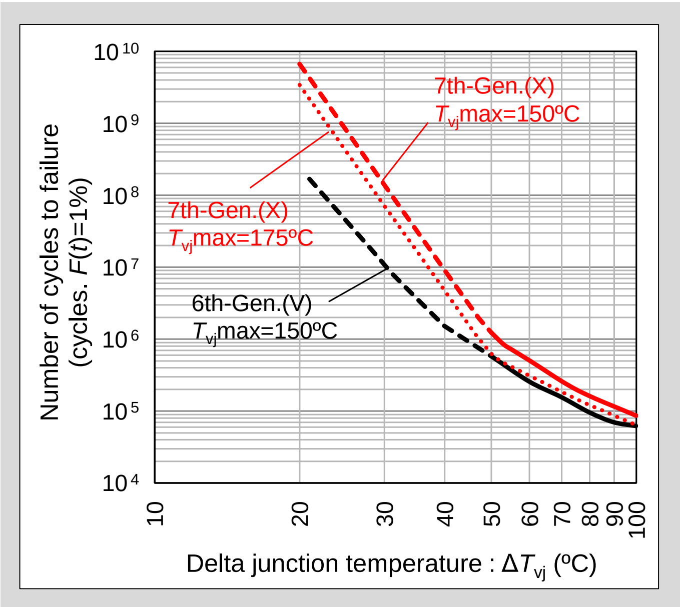


Fig.1-11 ΔT_{vj} power cycle capability curve

4. Expansion of Current Rating and Downsizing of IGBT Modules

As mentioned above, power losses in the 7th generation X-series have been reduced by improving the chip technology of IGBT and FWD chip to offer a more user-friendly device. Moreover, due to the innovation of the packaging technology a great improvement in terms of reliability and heat dissipation has been achieved. These technologies enable modules to achieve a high efficiency, small size, high power density as well as high reliability at high temperature.

Fig.1-12 shows the comparison of the inverter power losses and the junction temperatures (calculated values) for modules of X-series and V-series using the example of a 75A/1200V rated module. In the X-series the conduction losses of IGBT and FWD (P_{sat}, P_f) are reduced compared to the V-series because of lower on-state voltages. In addition, switching characteristics of IGBT and FWD are improved resulting in a lower turn-off energy (E_{off}) as well as in a lower reverse recovery energy (E_{rr}). These improvements lead to a power loss reduction of about 10% for the inverter operation. In combination with the new package technology and its improved insulating ceramic the junction temperature could be reduced by about 10°C by reducing the above mentioned power losses.

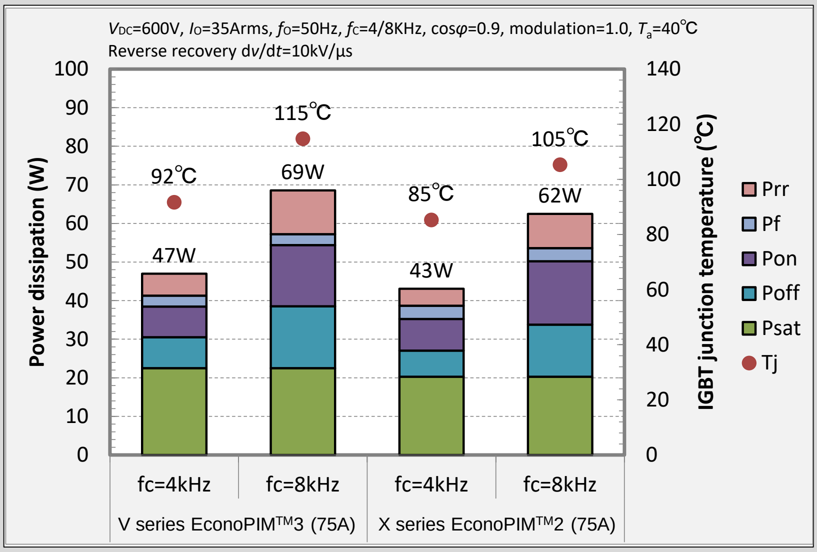


Fig.1-12 generated power losses and junction temperature for inverter operation

In the X-series a continuous operation at a junction temperature of 175°C is guaranteed. This can be realized by the improved silicone gel and reduced leakage current at high temperatures. As displayed in Fig.1-13, the operation range of the inverter is expanded compared to the V-series due to power loss reduction and the operating temperature increase. The output current for inverters of the same size can be increased by about 35%.

Note) EconoPIM™ is registered trademark of Infineon technologies

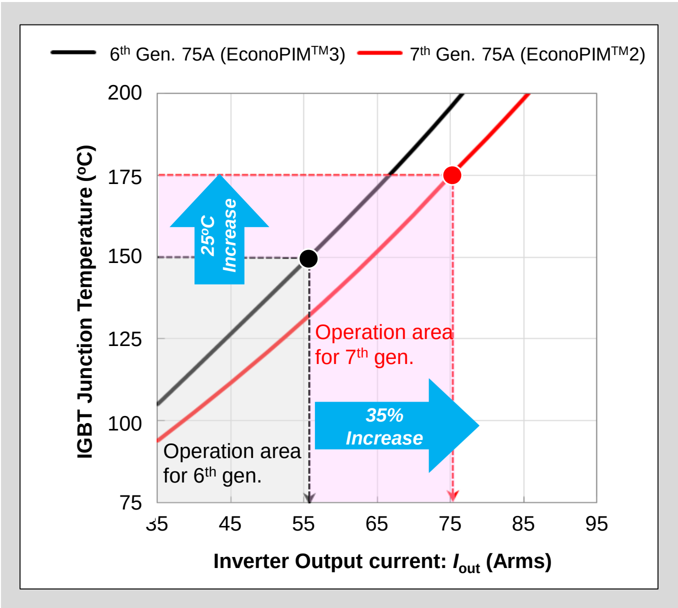


Fig.1-13 Inverter output current vs. junction temperature

Furthermore, the reduced power losses, the high temperature operation and the high power density in the 7th generation X-series allow to increase the current rating in the same package. For example, the 6th generation V-series enables a configuration of up to 50A/1200V in an EconoPIM™2 package, while the X-series achieves 75A of current rating (Fig.1-14). This fact allows to increase the output power of a power conversion system without changing the frame size.

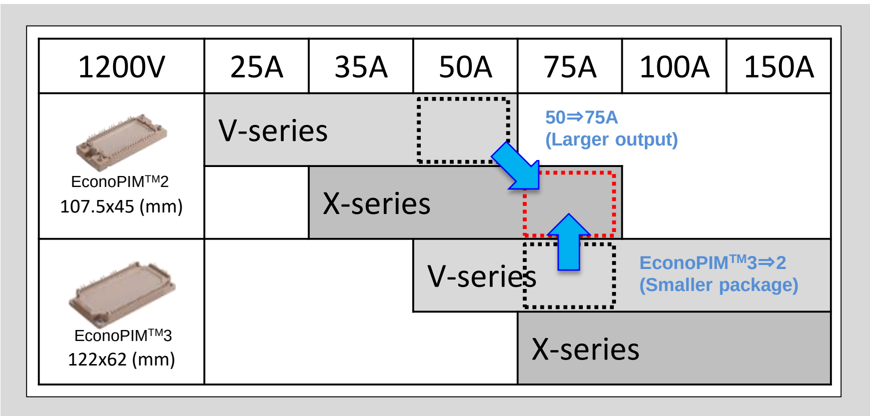
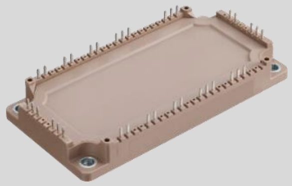
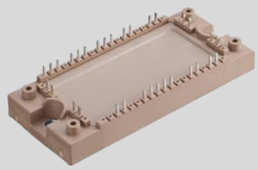


Fig.1-14 EconoPIM™ Series (1200V rating)

On the other hand, expanding the current rating of the IGBT module can also contribute to the miniaturization of a power converter (Fig.1-14). For example, as shown in Table 1-1, the IGBT module rated for 75A/1200V has to use an EconoPIM™3 package (122mm x 62mm) in the V-series. The X-series can fit the same rating into the EconoPIM™2 package (107.5mm x 45mm). The module footprint size can be reduced by 36%.

Note) EconoPIM™ is a registered trademark of Infineon Technologies.

Table 1-1

	6th generation V-series	7th generation X-series
Package	 EconoPIM™3 package	 EconoPIM™2 package
Voltage rating / current rating	1200V / 75A	1200V / 75A
Current density	100%	160%
Footprint size	122mm x 62mm 7564mm² (100%)	107.5mm x 45mm 4836mm² (64%)
Module weight	310g (100%)	200g (65%)

Note) EconoPIM™ is a registered trademark of Infineon Technologies.

As described above, the 7th generation X-series achieves a reduction in module size for the same power rating or an increased power rating for the same package size. This is due to reduced power losses for IGBT and FWD, increased operating temperature and new package technologies. These improvements support the pursuit of a more efficient and cost effective power conversion system by allowing a system size reduction and a higher output current.

5. Module Type Name

Table 1-2 shows the structure of the product names for the 7th generation X-series modules and how to interpret them.

Table 1-2 How to read a module name using the example of 6MBI100XBA120-50

6	MB	I	100	X	B	A	120	-50
IGBT Switch number	Type of module	Internal configuration	Current rating	IGBT Chip generation	Package		Voltage rating	Suffix
	MB: IGBT module	I: Standard module	I_C x 1 (A)	X: X-series (7th Gen.)			V_{CES} x1/10 (V)	< 50: RoHS inconsistent
		R: Power integrated module (PIM)						≥ 50: RoHS consistent
		P: Intelligent power module (IPM)						

6. Terms and symbols

The terms and symbols of the characteristics used in the data sheets and specifications for the 7th generation X-series modules may differ from those of older generation modules. Table 1-3 shows a comparison of the major terms and symbols between the 7th generation X-series and the 6th generation V-series. Please use this table as a reference when comparing to products of the 6th generation V-series or older generations. Basically the notification changes to follow the IEC standard (IEC 60747). For some modules the same notification like for the V-series is used.

Table 1-3 Symbols and terms

V-series and older generation		X-series	
Term	Symbol	Term	Symbol
Collector current	I_C	Collector current	I_C
	I_C pulse	Repetitive peak collector current	I_{CRM}
	- I_C	FWD forward current	I_F
	- I_C pulse	FWD Repetitive peak forward current	I_{FRM}
Collector Power dissipation	P_c	Total Power dissipation	P_{tot}
Junction temperature	T_j	Virtual junction operating temperature	T_{vj}
Junction temperature (Switching condition)	T_{jop}	Operating virtual junction temperature	T_{vjop}
Isolation voltage	V_{iso}	Isolation voltage	V_{isol}
Screw torque	-	Mounting torque of screws to heat sink	M_s
		Mounting torque of screws to terminals	M_t
Thermal resistance (case to heat sink)	$R_{th(c-f)}$	Thermal resistance (case to heat sink)	$R_{th(c-s)}$

Regarding the maximum rating / electrical characteristics used in the datasheets and specifications of X-series RC-IGBT module products, the terms and symbols related to FWD are different from those of X-series IGBT module products due to the integration of IGBT and FWD. For different reasons, IEC defines the direction of current flow as forward. For this reason, the FWD integrated with the RC-IGBT has the opposite definition of the forward direction from the conventional FWD (see Fig.1-15). Table 1-4 shows the comparison of terms and symbols related to FWD for X-series IGBT module products and X-series RC-IGBT module products, so please refer to them when comparing with IGBT module products. Basically, the notation conforms to the IEC standard (IEC60747).

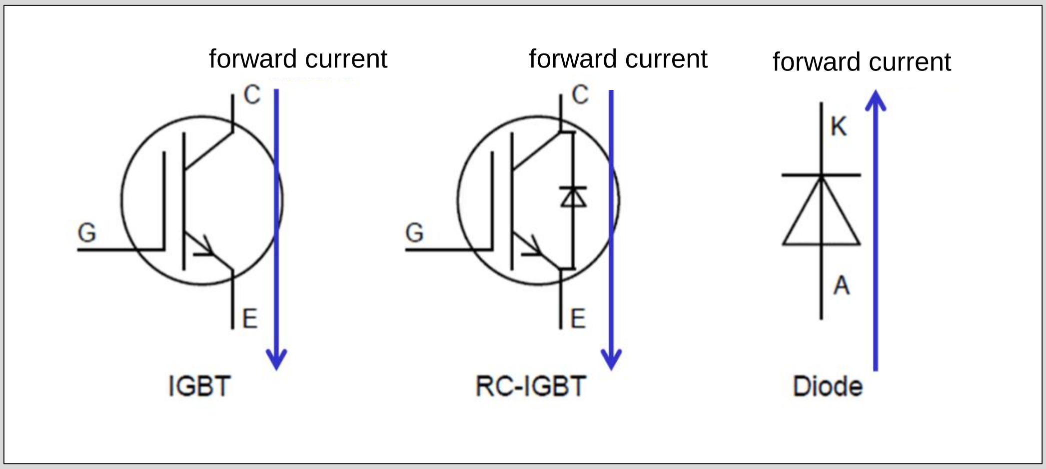


Fig.1-15 Definition of forward current

Table 1-4 Symbols and term comparisons between X-series IGBT modules and X-series RC-IGBT modules

X series IGBT module		X series RC-IGBT module	
Term	Symbol	Term	Symbol
Forward current	I_F	Reverse-conducting current	I_{RC}
Repetitive peak forward current	I_{FRM}	Repetitive peak reverse-conducting current	I_{RCRM}
Forward voltage	V_F	Reverse-conducting voltage	V_{RC}
Reverse recovery time	t_{rr}	Forward recovery time	t_{fr}
Reverse recovery energy	E_{rr}	Forward recovery energy	E_{fr}

Chapter 2 Precaution for Use

The 7th generation X-series IGBT modules contains the same Field Stop (FS) and trench gate structure that had been introduced for the 5th generation U-series and 6th generation V-series, respectively. Beside that the overall characteristics have been improved by thinning the wafer thickness and optimizing the trench structure.

This chapter explains how to use the 7th generation X-series IGBT modules.

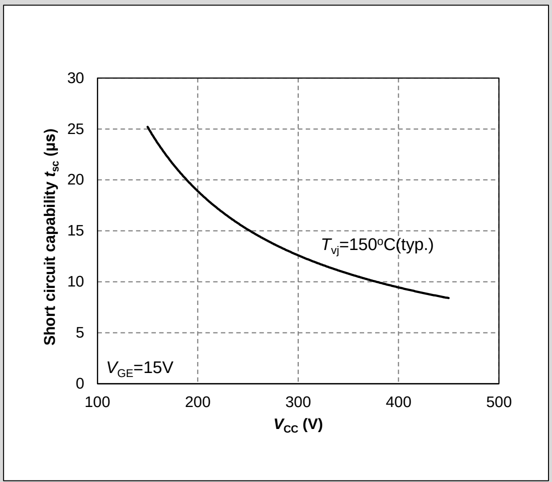
1. Maximum Junction Temperature T_{vj}, T_{vjop}

The characteristics of the 7th generation X-series modules have been improved to provide a continuous operation junction temperature T_{vjop} of maximum 175℃. Operating conditions must never be defined to exceed the maximum junction temperature. Please be aware using these products beyond the maximum temperature may result in a reduction of the product life time, such as power cycle endurance.

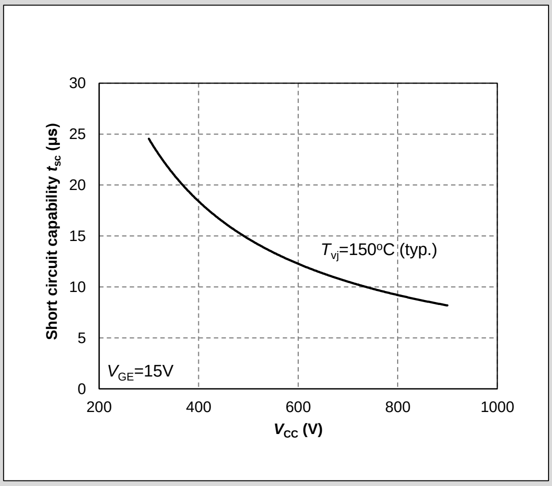
2. Short-Circuit (Overcurrent) Protection

If a short-circuit occurs, the IGBT collector current I_C will increase. If I_C reaches a saturated value, the voltage between collector and emitter (V_{CE}) will rapidly increase. Because of this behavior the collector current during short circuit is suppressed to a certain level. The short circuit condition has to be removed immediately as high voltage and high current is applied to the IGBT at the same time.

Fig. 2-1 shows the relation between the applied voltage V_{CC} and the short-circuit withstand capability (short circuit time) for the 650V and 1200V X-series modules. Please define the short circuit detection time and protection intervention time in order to not exceed the withstand capability. This has to be applied according to the operating requirements of the application.



(a) 650V module



(b) 1200V module

Fig.2-1 Short circuit capability of X-series IGBT modules as function of the applied voltage V_{CC} (V_{GE}=15V)

3. Overvoltage Protection and Safe Operating Area

3.1 Overvoltage protection

Due to fast switching speed of IGBTs, a high d*i*/d*t* is generated during the IGBT turn-off and the IGBT turn-on / FWD reverse recovery. This high d*i*/d*t* causes a high overvoltage due to the external wiring stray inductance. If the overvoltage exceeds the module's maximum rated voltage (V_{CES}), it can lead to the destruction of the module. There are several methods to avoid high overvoltage like adding a snubber circuit, adjusting the gate resistance R_G, or reducing the inductance of the main circuit.

Fig.2-2 shows a schematic diagram of turn-off and reverse recovery waveforms as well as the specific definition of overvoltage. The overvoltage which arises between collector and emitter during the IGBT turn-off is called V_{CEP}. V_{AKP} defines the overvoltage which occurs between the anode and the cathode of the FWD during the reverse recovery phase.

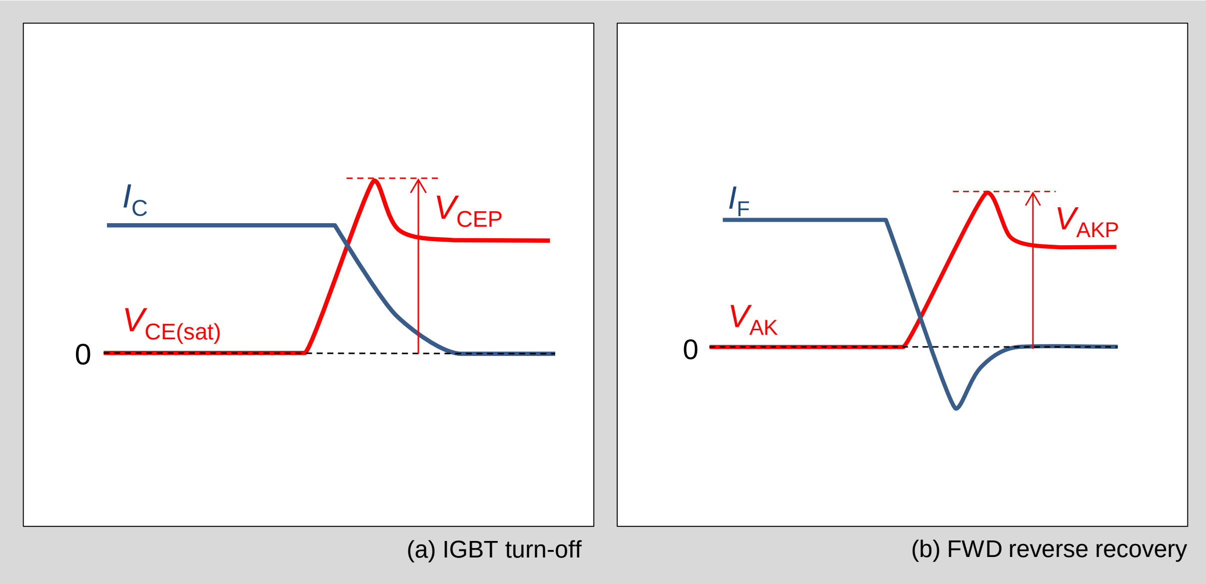
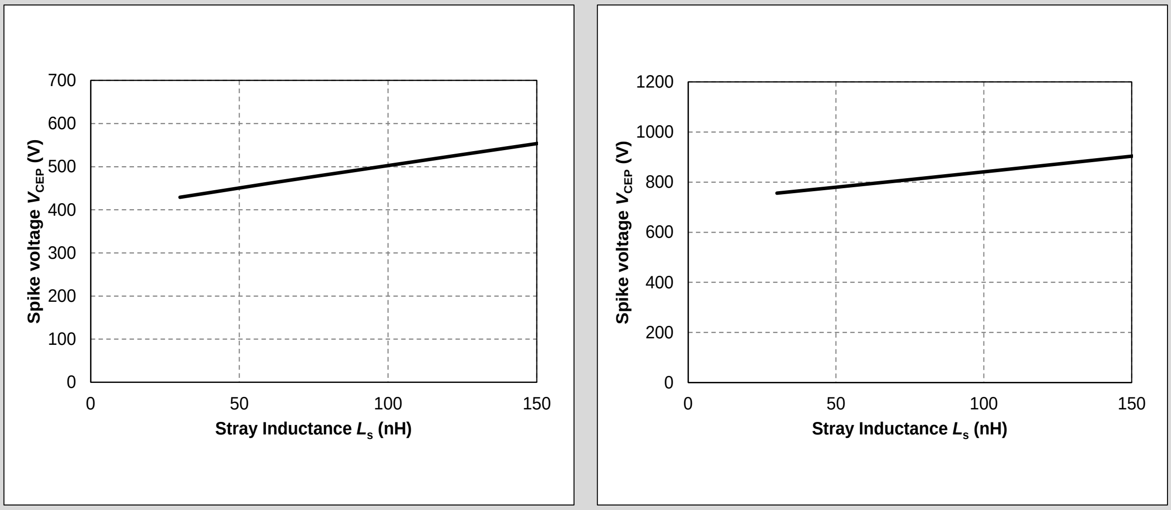


Fig.2-2 Schematic diagram of waveforms and overvoltages for (a) IGBT turn-off and (b) FWD reverse recovery

The overvoltage characteristics are described below using the following two modules serving as example: 7MBR100XRA065-50 (650V/100A) X-series and 7MBR100XNA120-50 (1200V/100A) X-series.

Fig.2-3 shows an example of the relation between the main circuit stray inductance (L_s) and the overvoltage V_{CEP} when the IGBT is switched off. It is obvious that V_{CEP} increases with increasing L_s. Due to this coherence, the main circuit has to be designed with the lowest possible inductance. Fuji recommends the use of laminated bus bars for reducing the external inductance value.

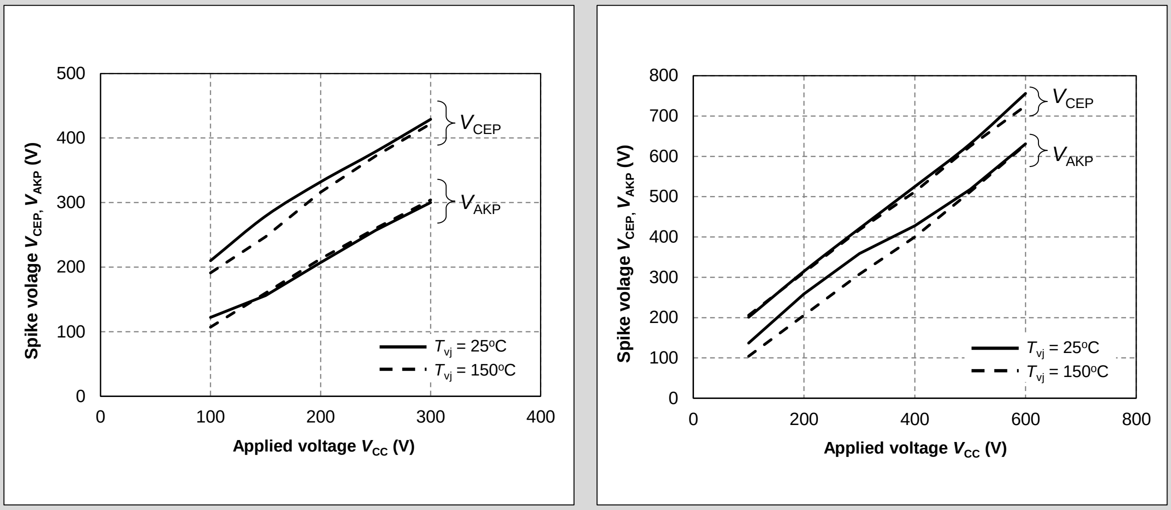
Fig.2-4 shows an example of the relation between the applied voltage V_{CC} and the overvoltage V_{AKP} and V_{CEP}. As one can easily see from this figure, by increasing V_{CC} the overvoltage V_{CEP} and V_{AKP} will increase as well.



(a) 7MBR100XRA065-50 (650V/100A)
V_{CC}=300V, I_C=100A, R_G=27Ω

(b) 7MBR100XNA120-50 (1200V/100A)
V_{CC}=600V, I_C=100A, R_G=5.1Ω

Fig.2-3 Example of the relation between stray inductance L_s and IGBT turn-off overvoltage



(a) 7MBR100XRA065-50 (650V/100A)
V_{CC}=300V, I_C,I_F=100A, R_G=27Ω

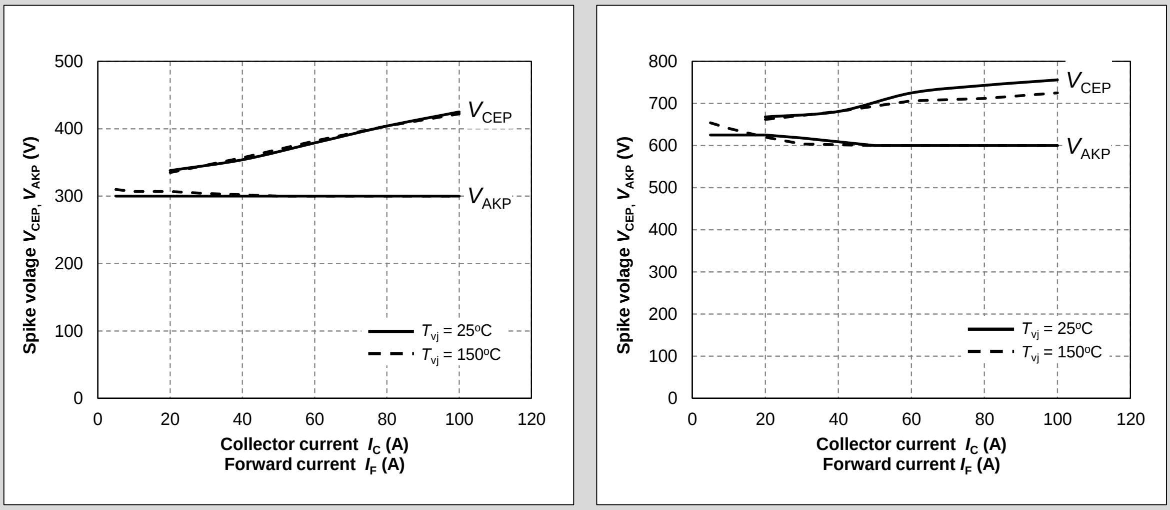
(b)7MBR100XNA120-50 (1200V/100A)
V_{CC}=600V, I_C,I_F=100A, R_G=5.1Ω

Fig.2-4 Example of the relation between the applied voltage V_{CC} and the overvoltage in IGBT turn-off and FWD reverse recovery

Fig.2-5 shows an example of the relation between the I_C and the overvoltage V_{CEP} and relation between I_F and V_{AKP}, respectively. V_{CEP} is increasing with increasing I_C. On the other hand, V_{AKP} tends to be larger for smaller values of the I_F currents. The largest value for V_{AKP} occurs for values smaller than one tenth of the rated current. During design phase it is therefore necessary to evaluate and take into account the overvoltage for the actual used current.

Fig.2-6 shows an example of the relation between the gate resistance R_G and the overvoltage V_{AKP}.

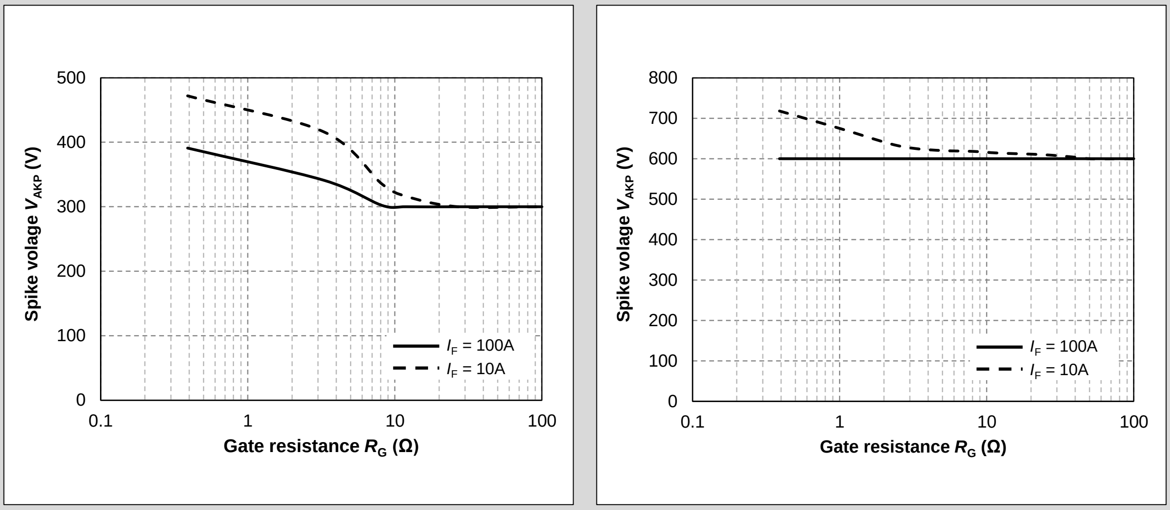
In each subfigure two curves are displayed. One represents the rated current 100A and the other one represents one tenth of the rated current, 10A. It has to be highlighted that V_{AKP} is increasing with decreasing R_G and I_F values.



(a) 7MBR100XRA065-50 (650V/100A)
V_{CC}=300V, R_G=27Ω

(b) 7MBR100XNA120-50 (1200V/100A)
V_{CC}=600V, R_G=5.1Ω

Fig.2-5 Example of the relation between I_C and overvoltage V_{CEP} and I_F and overvoltage V_{AKP}



(a)7MBR100XRA065-50 (650V/100A)
V_{CC}=300V, T_{vj}=25°C

(b)7MBR100XNA120-50 (1200V/100A)
V_{CC}=600V, T_{vj}=25°C

Fig.2-6 Example of the relation between gate resistance and overvoltage V_{AKP} of FWD reverse recovery

As described above, the value of the overvoltage generated in IGBT modules varies greatly depending on the used driving conditions, main circuit stray inductance L_s and the switching conditions.

Besides this, external parts like snubber circuits, capacitor values and gate drive capability also have an influence on the overvoltage.

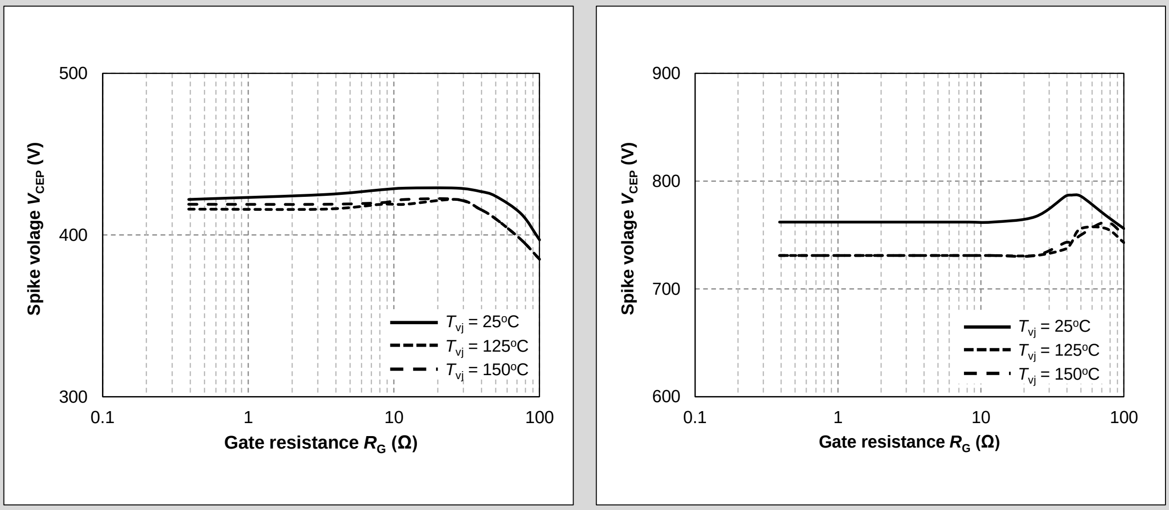
When using IGBT modules, please make sure that the overvoltage will stay within the Reverse Bias Safety Operating Area (RBSOA) for all operating conditions in all various equipment such as inverter systems where the IGBT will be used in. If the overvoltage exceeds the guaranteed RBSOA, please take countermeasures like changing the gate resistance, reducing the stray inductance or adding a snubber circuit. In addition, it could be appropriate to use different gate resistances for turn-on and turn-off in order to optimize the driving condition.

3.2 Gate resistance influence on overvoltage during turn-off

In order to properly design the overvoltage protection, Fig.2-7 shows the relation between the gate resistance R_G value and the turn-off overvoltage V_{CEP} for X-series 1200V IGBT module.

Be aware that the IGBT modules belonging to the 4th generation (S-series) or even older ones show a different relation. In order to suppress the overvoltage usually an increase of R_G has been a suitable countermeasure. Now, since the carrier injection efficiency has been improved starting with 5th generation (U-series) the general relation between R_G and the overvoltage has been changed.

Due to this change increasing R_G value may cause now increasing overvoltage V_{CEP} values in contrary to the behavior of old generation products. Therefore, please select the gate resistance value carefully during the design phase to match the requirements and parameters of the actual device where the IGBT module will be used in.



(a)7MBR100XRA065-50 (650V/100A) V_{CC}=300V (b)7MBR100XNA120-50 (1200V/100A) V_{CC}=600V

Fig.2-7 Example of the relation between gate resistance R_G and turn-off overvoltage V_{CEP}

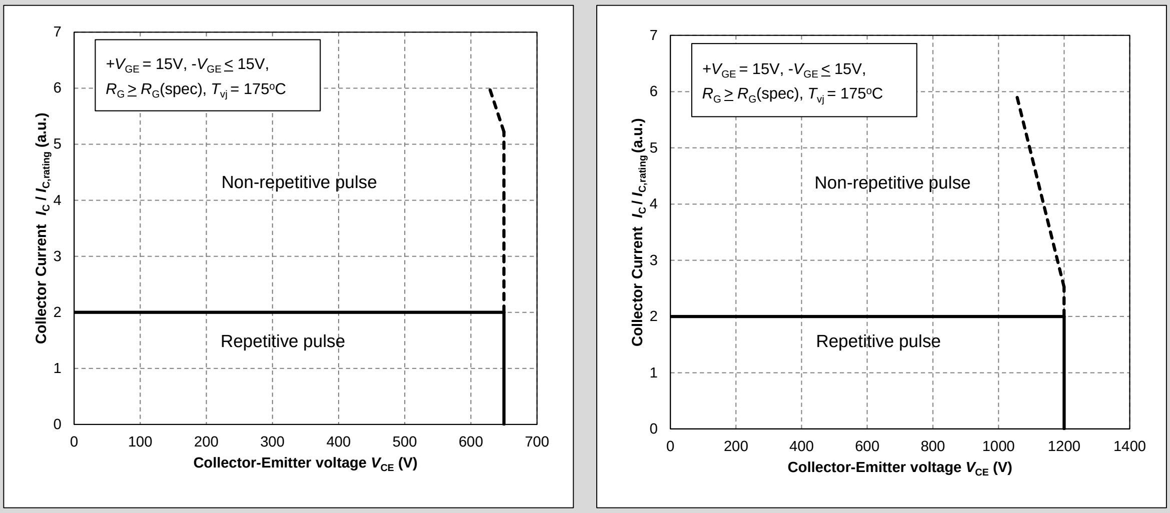
Reference

1) Y. Onozawa et al., "Investigation of carrier streaming effect for the low spike fast IGBT turn-off", Proc. ISPSD, pp. 173-176, 2006.

3.3 Overvoltage Protection under short circuit condition

When a short circuit occurs, the I_C sharply increases. In this case a larger I_C has to be cut off compared to a normal operation during turn-off. Thus, there is an additional RBSOA (Reverse Bias Safe Operating Area) for non-repetitive pulse is defined for the short circuit condition.

Fig.2-8 shows RBSOA (repetitive pulse) and RBSOA (non-repetitive pulse) for the 650V and 1200V 7th generation X-series modules. The V_{CE}-I_C locus has to stay within the RBSOA (non-repetitive pulse) during a short circuit condition until it will be turned off. Unless stated otherwise the voltage V_{CE} of RBSOA is the voltage measured at the main terminals of the module.



(b) 650V rated module

(b) 1200V rated module

Fig.2-8 RBSOA for IGBT

3.4 Safe Operating Area for FWD

In the design phase, SOA (Safe Operating Area) for FWD, which exists similar to RBSOA for IGBT, has to be carefully considered. As shown in Fig.2-9 the SOA for FWD is indicated as the area which is limited by the maximum power (P_{max}) during reverse recovery. The maximum power is defined as the product of current I_F and voltage V_{AK}. Therefore, it is mandatory to ensure that the V_{AK}-I_F locus of the FWD always stays within the SOA. Unless stated otherwise the voltage V_{AK} of SOA is the voltage measured at the main terminals of the module.

Fig.2-9 shows an example of SOA for the FWD for 2MBI600XNE120-50 (600A/1200V). In this case, P_{max} is given as 420 kW.

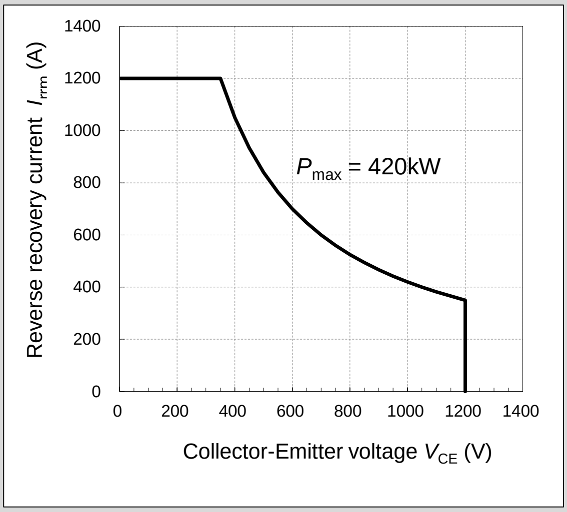
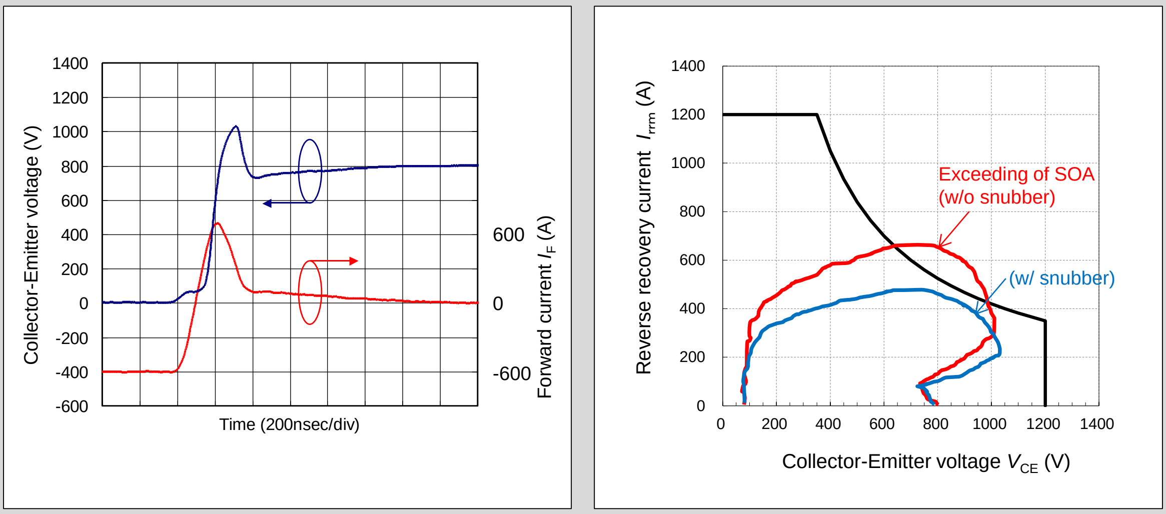


Fig.2-9 Example of Safe Operating Area (SOA) for FWD

An example of the reverse recovery waveform is shown in Fig.2-10(a) whereas in Fig.2-10(b) SOA for FWD including V_{AK}-I_F locus for the reverse recovery waveforms from Fig 2-10(a) are displayed. The blue line in the latter figure represents the V_{AK}-I_F locus resulting from a circuit using a snubber circuit. The locus is within the SOA for FWD and the circuit will not cause any problem. The red line in the same figure represents a V_{AK}-I_F locus which is exceeding the SOA for the FWD. Hence, the used circuit may lead to the destruction of the FWD. In consequence it is mandatory to take appropriate action for keeping the locus within the SOA. For instance, this might be achieved by using a larger gate resistance for the IGBT.

The gate driving condition must be defined and chosen in order to keep the V_{AK}-I_F locus within the SOA for FWD for all operating conditions and all used devices.



(a) Waveform example of FWD reverse recovery

(b) V_{AK}-I_F and SOA for FWD reverse recovery

Fig.2-10 Reverse recovery waveform and V_{AK}-I_F locus for FWD reverse recovery

4. Parallel Connection

IGBT modules can be connected in parallel for increasing the current capability. This chapter describes the parameters which have to be taken into account when X-series IGBT modules are going to be connected in parallel.

4.1 Junction temperature dependency of output characteristics and current imbalance

The T_{vj} dependence of output characteristics influences the current imbalance of modules which are connected in parallel significantly. Fig.2-11 shows typical output characteristic of 7th generation X-series IGBT modules ($V_{CE(sat)}$-I_C relation). As shown in Fig.2-11, the X-series IGBT has a positive temperature coefficient which means that increasing T_{vj} leads to larger $V_{CE(sat)}$ values. Due to the positive temperature coefficient the current imbalance will be automatically regulated because the collector current I_C will decrease when T_{vj} increases.

As all output characteristics have a positive junction temperature coefficient, the X-series IGBT modules have suitable characteristics for parallel operation. According to historical data the positive temperature coefficient has been achieved by Fuji Electric starting from the 4th IGBT generation (S-series).

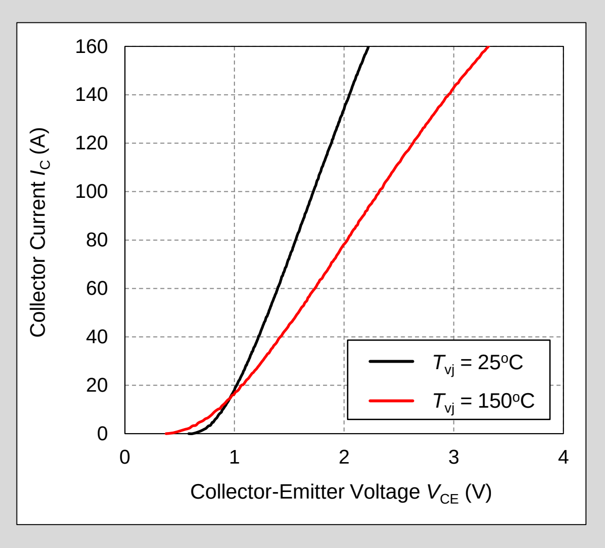


Fig.2-11 Relation between T_{vj} (1200V/100A) and IGBT output characteristics

4.2 $V_{CE(sat)}$ variation and current imbalance

The ratio of current sharing between IGBT modules in parallel connection is called current imbalance ratio α. This ratio is determined by the variation of $V_{CE(sat)}$ of the IGBT itself and the junction temperature dependency of the output characteristics.

The relation between the current imbalance ratio α and variation $\Delta V_{CE(sat)}$ of $V_{CE(sat)}$ for two X-series IGBT modules connected in parallel are shown in Fig.2-12. The current imbalance ratio α is obtained by applying Equation 2-1 with I_{C1} as current value and $I_{C(ave)}$ (=$I_{C1}/2+I_{C2}/2$) as the average current of the two paralleled modules.

As shown in Fig.2-12, an increase of $\Delta V_{CE(sat)}$ results in a larger current imbalance α. Hence, parallel connection of modules requires a combination of modules which have only slightly different $V_{CE(sat)}$ values.

$$\alpha = \left(\frac{I_{C1}}{I_{C(ave)}} - 1 \right) \times 100 \qquad \text{Equation 2-1}$$

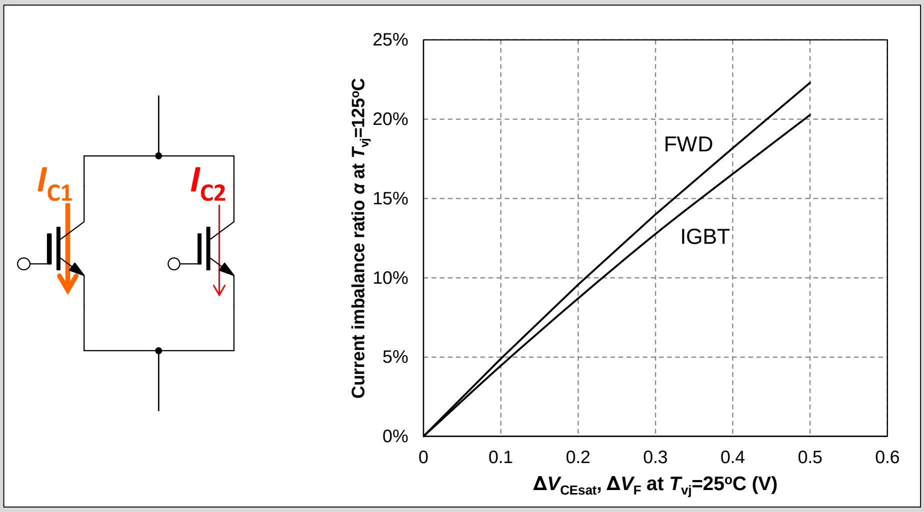


Fig.2-12 $V_{CE(sat)}$ and V_F variation and current imbalance ratio (1200V)

5. Mounting Instruction

Please refer to the WEB site (see URL below) and download the suggested mounting instruction for the concerned package of X-series module.

Fuji Electric Power Semiconductor - Design Support
http://www.fujielectric.com/products/semiconductor/model/igbt/mounting/index.html

Chapter 3 7th Generation X Series RC-IGBT Module

This chapter describes the 7th Generation X series RC-IGBT.

1. Basic Concepts and Features of 7th Generation X Series RC-IGBT Module

●Further miniaturization and higher power density (RC-IGBT technology)

The X-series RC-IGBT module uses our 7th generation X-series chip technology and packaging technology to achieve low power loss and 175 ℃ continuous operation guarantee. Furthermore, the chip area can be expanded compared with each of the IGBT or FWD, and the $R_{th(j\text{-}c)}$ has been reduced by integrating the functions of the IGBT and FWD into a single chip using RC-IGBT technology. In addition, the total number of chips and chip area have been reduced by applying RC-IGBT.

Through these technological innovations, the X-series RC-IGBT modules contribute to further miniaturization and total cost reduction of power conversion systems by achieving high power density with the same package size as before.

●Features of X series RC-IGBT chips

Fig.3-1 shows a schematic diagram and equivalent circuit of the X series RC-IGBT chip. The RC-IGBT integrates the IGBT and FWD into a single chip, so that during switching operation, the IGBT operation and FWD operation are repeated alternately on the same chip. Since the IGBT / FWD operations are continuous on the same chip, the junction temperature swing (ΔT_{vj}) is smaller than the case of the IGBT / FWD operating alternately on different chips. In addition, since the IGBT and FWD are integrated into a single chip, the thermal resistance has been reduced by increasing the chip area of each of the conventional IGBT and FWD.

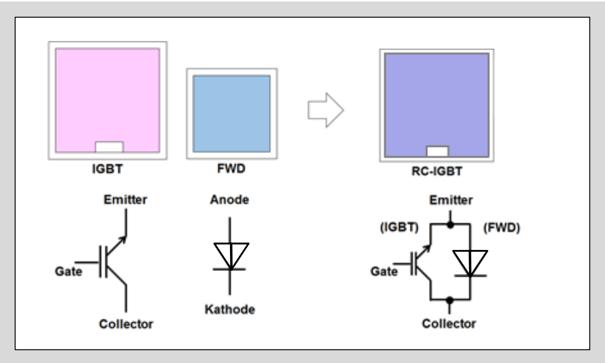


Fig.3-1 Schematic diagram and equivalent circuit of the X series RC-IGBT chip

Fig.3-2 shows the output characteristics of the 1200V X-series RC-IGBT. The X-series RC-IGBT chip can output current in both the forward direction (IGBT) and the reverse direction (FWD) with one chip. In the forward direction, the application of X-series chip technology has achieved a lower saturation voltage than V-series IGBT chips. The characteristics of the X-series RC-IGBT chips have been improved by applying the thin wafer technology, which is the X-series chip technology. There is a concern of oscillation and lower breakdown voltage during turn-off due to the use of thin wafers, however, the X-series RC-IGBT chips suppress oscillation and breakdown voltage reduction by optimizing the wafer resistivity and each structure. As shown in Fig.3-3, the overvoltage of the X-series RC-IGBT is equivalent to that of the V-series IGBT, and the E_{off} is reduced by 23% by reducing the tail current compared to the V-series IGBT. The turn-on and reverse recovery operation are shown in Fig.3-4 and Fig.3-5 respectively. While the combination of V series IGBT and FWD has a steep current waveform, the X series RC-IGBT realizes a soft recovery current waveform by optimizing the structural parameters. In addition, the I_{frm} and the forward recovery charge have been reduced to reduce the forward recovery energy E_{fr} by 20%.

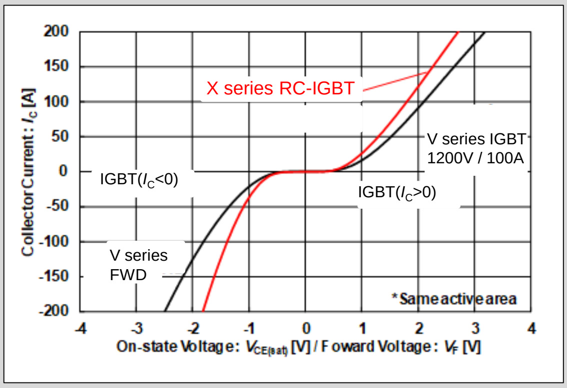


Fig.3-2 Output characteristics of X series RC-IGBT

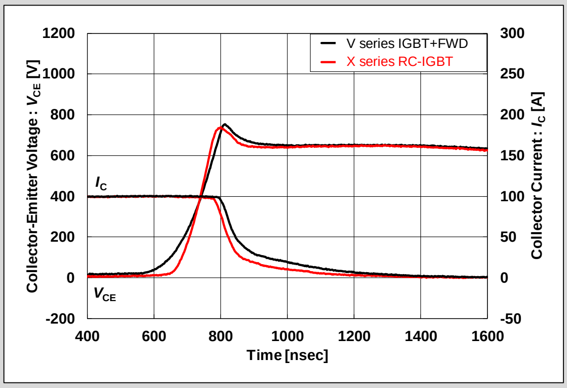


Fig.3-3 Turn off waveform of X series RC-IGBT

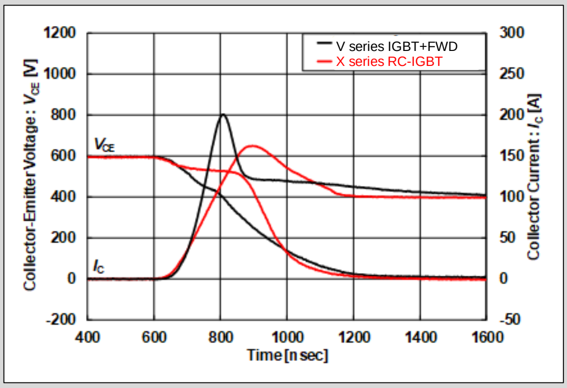


Fig.3-4 Turn on waveform of X series RC-IGBT

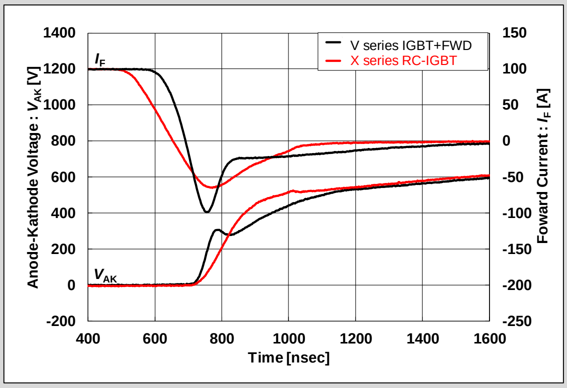
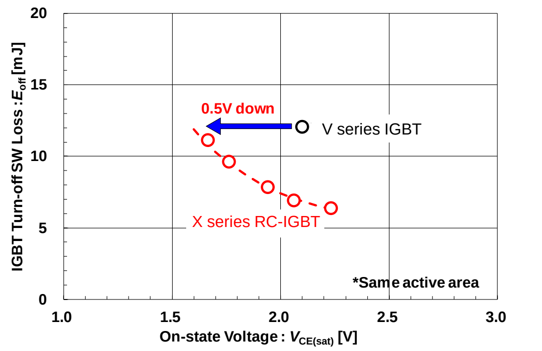


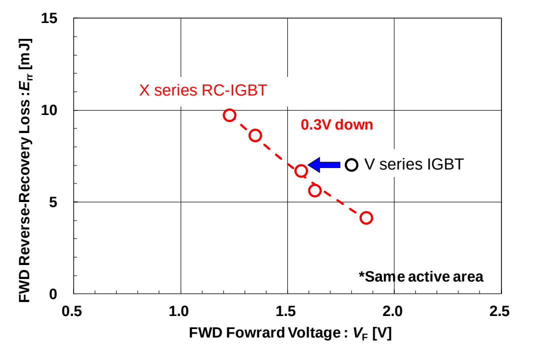
Fig.3-5 Reverse recovery waveform of X series RC-IGBT

Fig.3-6 shows the trade-off relationship of IGBTs compared with the same active area. In case of the turn off energy is the same, the X-series RC-IGBT has an improved saturation voltage of 0.5V compared with the V-series IGBT. Fig.3-7 shows the trade-off relationship of FWD compared with the same active area. In case of the forward recovery (reverse recovery) energy is the same, the X-series RC-IGBT improves V_{RC} (V_F) by 0.3V compared with the V-series FWD.



Conditions :
$V_{CE(sat)}$: I_C=100A、V_{GE}=+15V、
E_{off} : V_{CC}=600V、I_C=100A、V_{GE}=+15/-15V、
Reverse recovery dv/dt=10kV/usec

Fig.3-6 Trade-off relationship of X series RC-IGBT (IGBT)



Conditions :
V_F : I_F=100A、V_{GE}=-15V(X series RC-IGBT)
E_{rr} : V_{CC}=600V、I_F=100A、V_{GE}=+15/-15V、
Reverse recovery dv/dt=10kV/usec

Fig.3-6 Trade-off relationship of X series RC-IGBT (FWD)

●Features of X series RC-IGBT package

The X-series RC-IGBT module uses an AlN (aluminum nitride) insulating substrate same as the X-series IGBT module in order to take advantage of features such as miniaturization and high power density by integrating the functions of the IGBT and FWD into a single chip. As a result, the thermal resistance has been further reduced. Fig.3-8 shows the junction-case thermal resistance. The AlN insulating substrate has lower thermal resistance than the Al_2O_3 (alumina) insulating substrate. It has been greatly improved to about 45% (same chip size ratio), and the issue of temperature rise due to the miniaturization of the IGBT module has been overcome. Furthermore, high reliability is ensured and continuous operation at 175 ℃ is guaranteed by optimizing wire bonding and adopting high-strength solder and high-heat-resistant silicone gel.

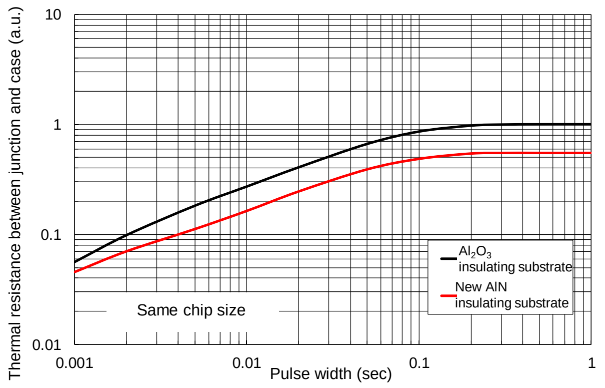


Fig.3-8 Thermal resistance between junction and case

●Features of X series RC-IGBT modules

Fig.3-9 shows the inverter output current I_o and the maximum IGBT virtual junction temperature $T_{vj,max}$ assuming that the 1200V / 1000A X series RC-IGBT DualXT module in the same package as the 1200V / 600A V series DualXT module is mounted on the inverter drive equipment. The X-series RC-IGBT module have reduced power loss and junction-case thermal resistance compared with V-series IGBT module. Furthermore, by applying the 7th generation X series packaging technology, the guaranteed continuous operation temperature has been expanded from 150 ℃ to 175 ℃ for X series IGBT modules. As a result, a higher current density is possible in the same package compared with the V series IGBT module, and the IGBT module has achieved even higher power density and miniaturization.

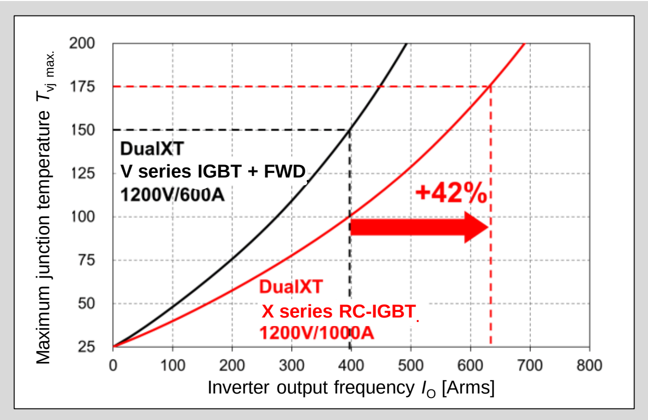


Fig.3-9 Maximum IGBT junction temperature and maximum inverter output current

Fig.3-10 shows the T_{vj} simulation results when the inverter operates at low frequencies, such as when accelerating or decelerating a motor. In the conventional IGBT + FWD structure, the IGBT and FWD repeatedly generate heat and dissipate heat, respectively. On the other hand, in RC-IGBT, the IGBT region and FWD region generate heat alternately. As a result, in RC-IGBT, the heat generated in the IGBT is also transferred to the FWD region, and the heat generated in the FWD is also transferred to the IGBT region, so the heat dissipation area is expanded compared to the IGBT + FWD structure. Therefore, the thermal resistance is reduced and the temperature swing ΔT_{vj} is significantly reduced. From the above, the thermal stress on the aluminum wire bonding and the solder under the silicon chip is relieved.

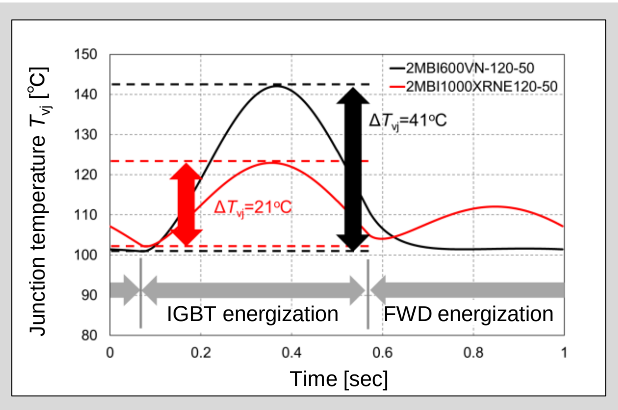


Fig.3-10 ΔT_{vj} simulation result

The X-series RC-IGBT modules have significantly improved ΔT_{vj} power cycle by significantly reducing ΔT_{vj} during low-frequency operation. As a result, higher output can be expected for the same power cycle compared with the conventional IGBT + FWD structure. On the other hand, high reliability can be expected in the case of the same ΔT_{vj}. As a result, the X-series IGBT modules can meet the demands for miniaturization, low power loss, and high reliability required for IGBT modules.

2. 7th Generation X Series RC-IGBT Module Family

Increasing the rated current of the IGBT module can contribute to the increase in output power of power conversion systems. For example, as shown in Fig.3-11, in the 1200V series DualXT package, the maximum rated current of the V series was 600A. In the X series IGBT module, the maximum rated current has been expanded to 800A by applying the X series technology, and the maximum rated current of 1000A has been achieved by applying the RC-IGBT technology. By expanding the rated current in the same package, it is possible to increase the output power without changing the housing size of the power conversion systems. The expansion of the rated current of the IGBT module can also contribute to the miniaturization of the power conversion systems. For example, as shown in Fig.3-11, the 1200V / 900-1000A rated current module was realized in the PrimePACK™ 2 package (172mm x 89mm) in the V series, however, in the DualXT package (150mm x 62mm) in the X series RC-IGBT module. This has reduced the module installation area (footprint size) by 39%.

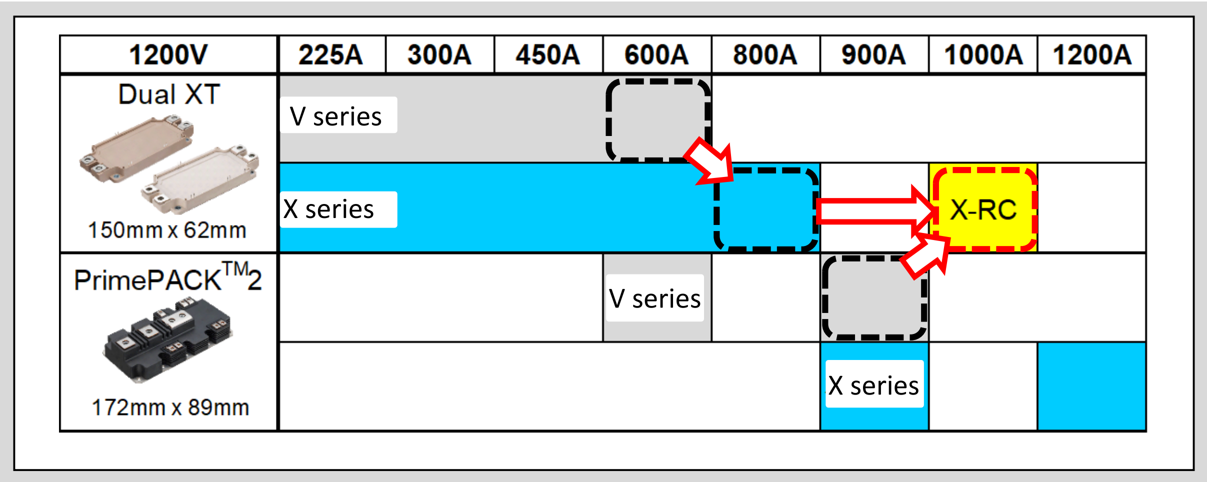


Fig.3-11 Fuji X series RC-IGBT module expansion

Note) PrimePACK™ is a registered trademark of Infineon Technologies.

Fig.3-12 shows our X-series RC-IGBT module family. The expansion of the rated current, which was difficult with the conventional combination of IGBT and FWD, has been achieved by combining the X series technology and RC-IGBT technology.

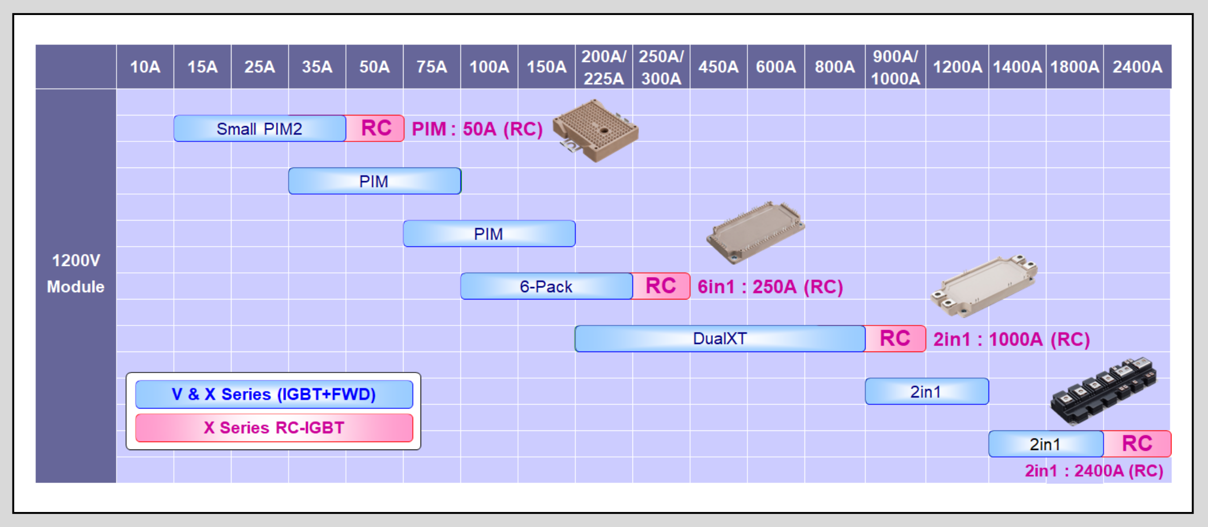


Fig.3-12 Fuji X series RC-IGBT module series