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 devices 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 EP2 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 (EP3) in the previous generation technologies (See Chapter 4 for more detail). The new rating IGBTs can contribute to miniaturization of power conversion systems and reduction of total system cost.

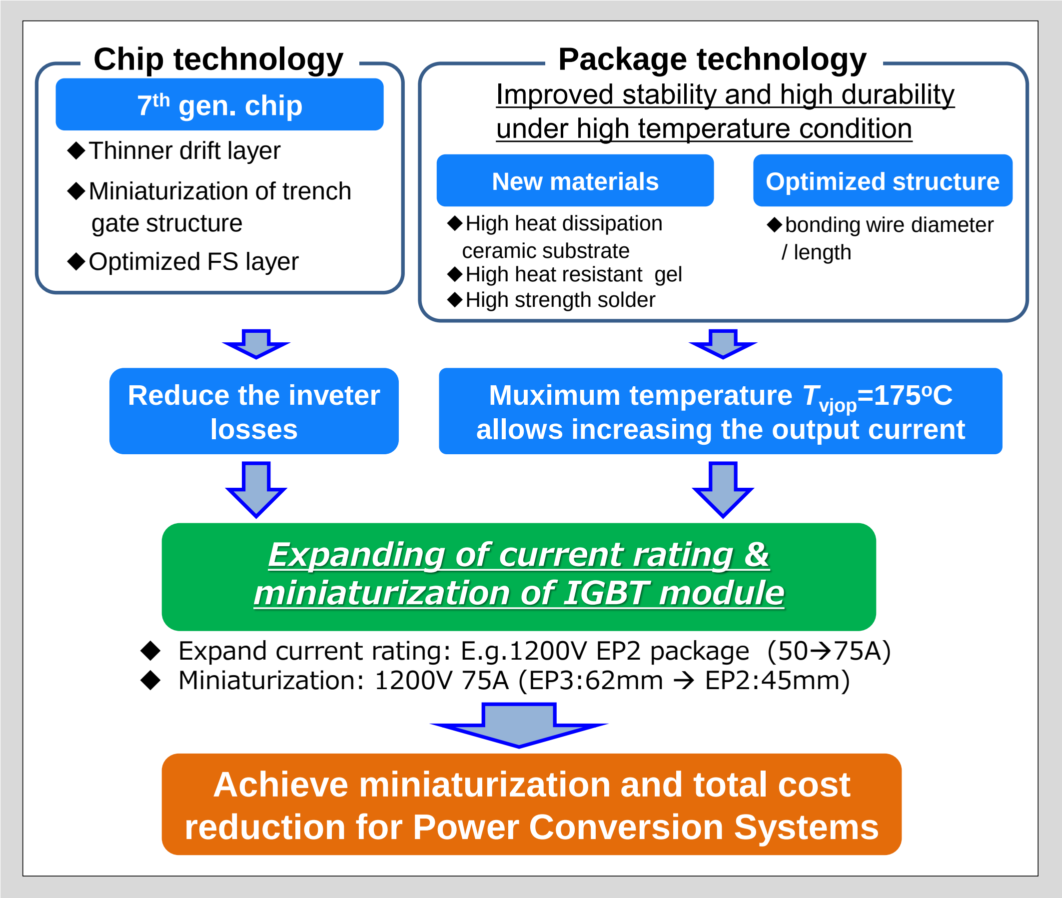
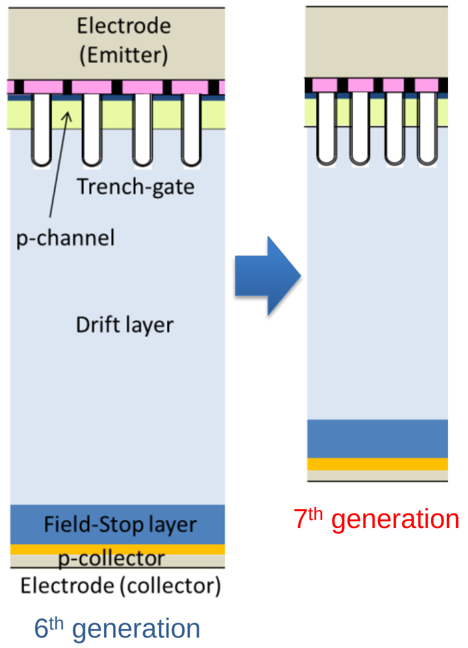


Figure 1-1 The basic concept of 7th generation X-series IGBT modules

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 new field stop structure of 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 voltage spikes 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 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

Figure 1-2 IGBT cross section comparison

<u>Main features of X-series chip</u>

1. Thinner drift layer
   - Reduced on-state voltage drop
   - Reduced switching energy
2. Fine trench gate structure
   - Reduced on-state voltage drop
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.

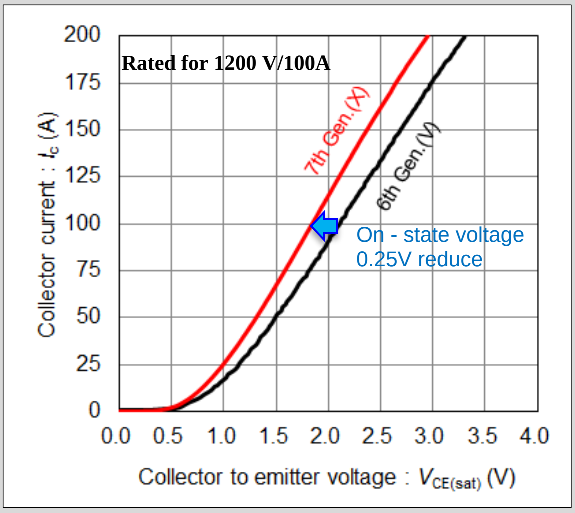


Figure 1-3 Improvement of IGBT output characteristics

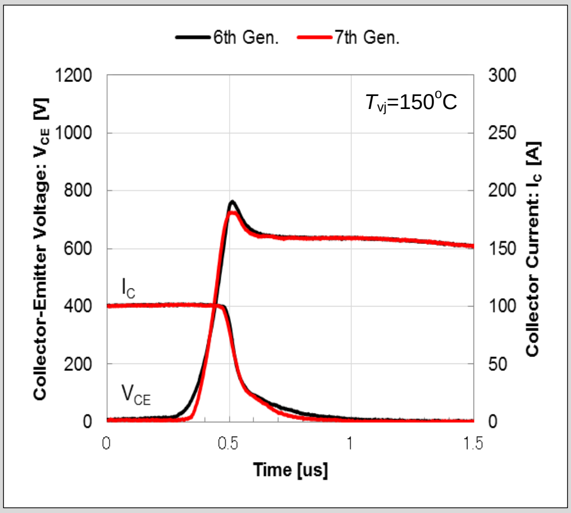


Figure 1-4 Turn-off waveforms comparison

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 loss reduction, despite the fact that the chip size has been shrunken.

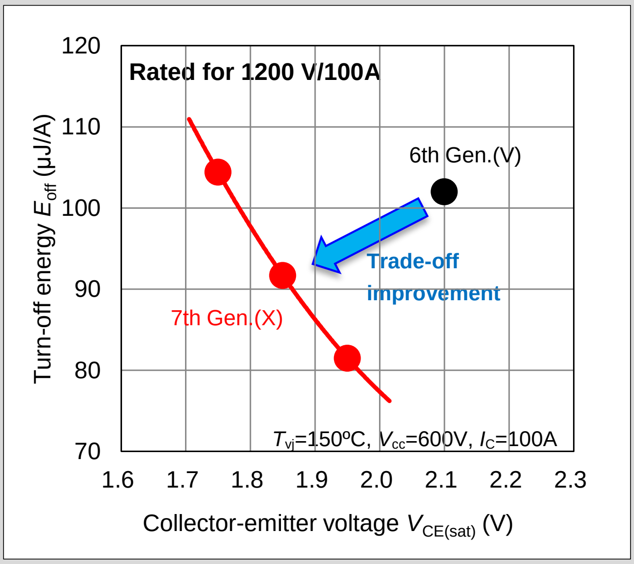


Figure 1-5 Improvement of turn-off energy vs. on-state voltage

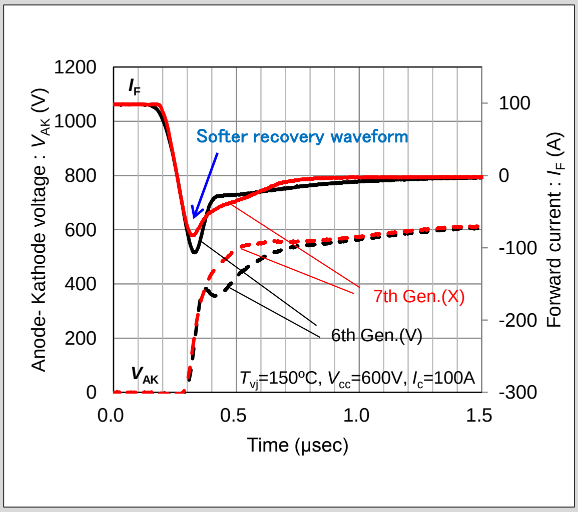
2.2 Improvement of leakage current

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 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.

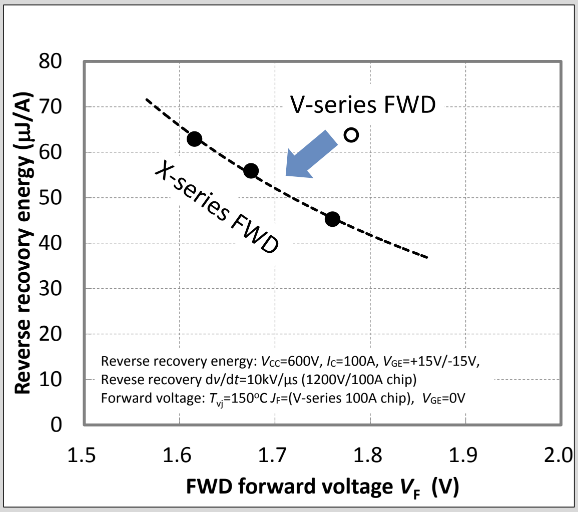
2.3 Improvement of FWD characteristics

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 surge voltage 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 loss 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 d*v*/d*t*. Softening the reverse recovery waveform is aiming to improve the emitted noise by reducing the d*v*/d*t* slope.



(a) Example of FWD reverse recovery waveform



(b) Reverse recovery loss vs. forward voltage

Figure 1-6 Improvement of X-series FWD characteristics

3. Package Technology Characteristics of X-Series

The 7th generation X-series has a guaranteed junction temperature for continuous operation of 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 within the module. The ceramic insulating substrate has the biggest influence on the thermal resistance between chip and heat sink. Reasonable priced alumnia (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 case temperature (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.

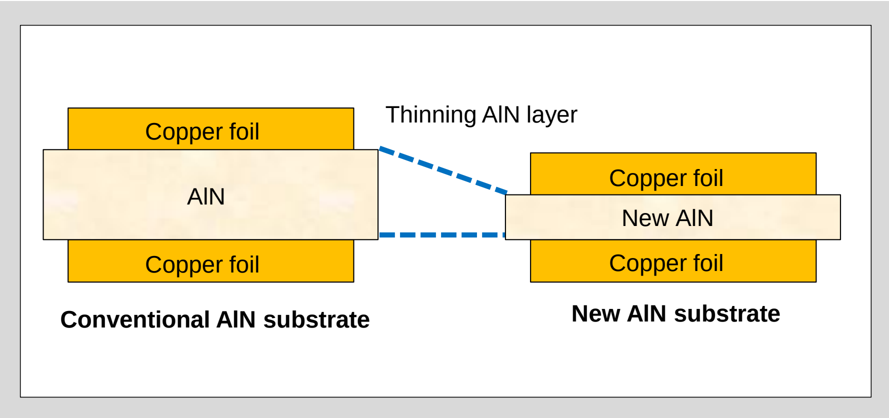


Figure 1-7 Cross-sectional structure of the AlN substrate

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 can be seen in this figure, the heat dissipation of the AlN substrate has a 45% lower thermal resistance compared to the conventional Al_2O_3 (comparison for an identical chip size). By applying this new AlN insulating substrate 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.

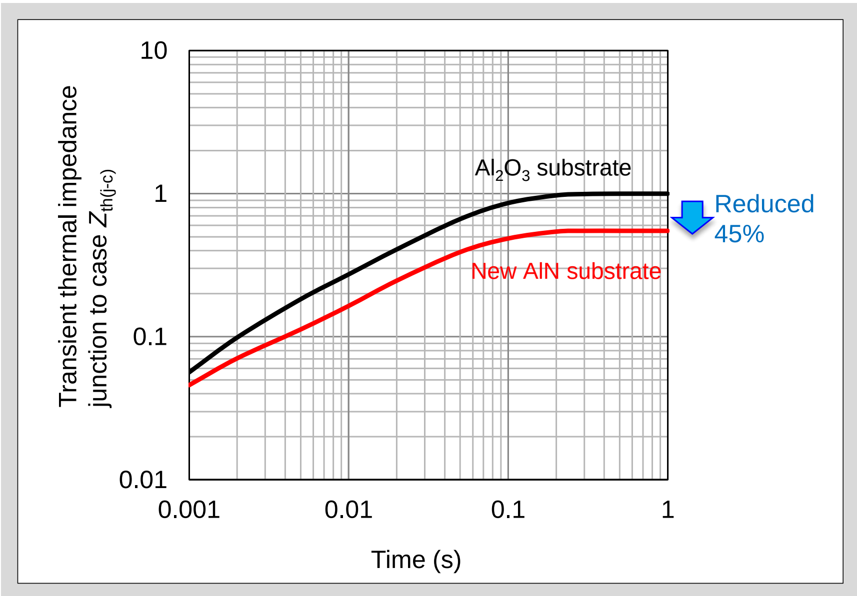


Figure 1-8 Comparison of thermal resistance between Al_2O_3 and AlN ceramic

3.2 Development of high heat resistant silicone gel

The maximum junction temperature (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 not 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 conventional 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.

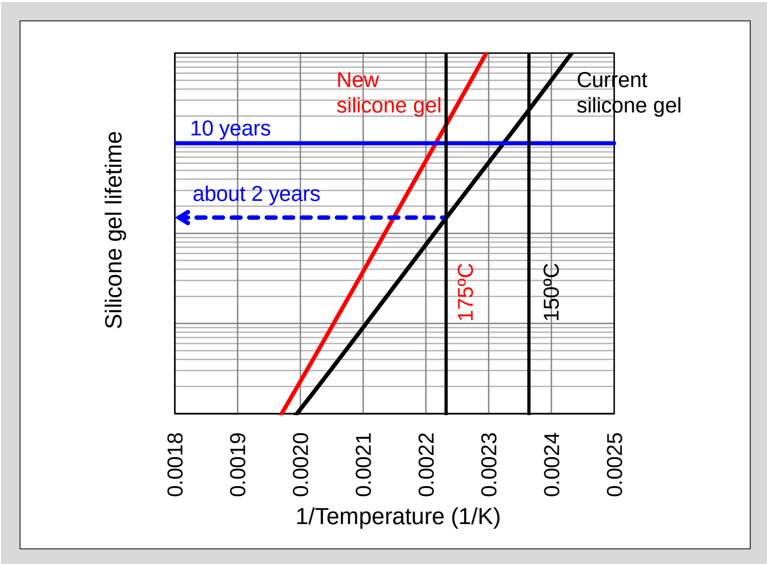


Figure 1-9 Silicone gel lifetime vs. temperature

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 device, 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 junction temperature 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}.

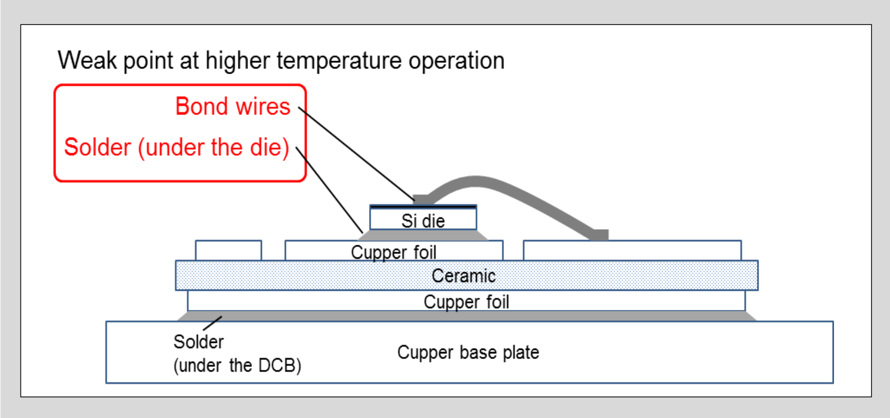


Figure 1-10 module structure diagram

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.

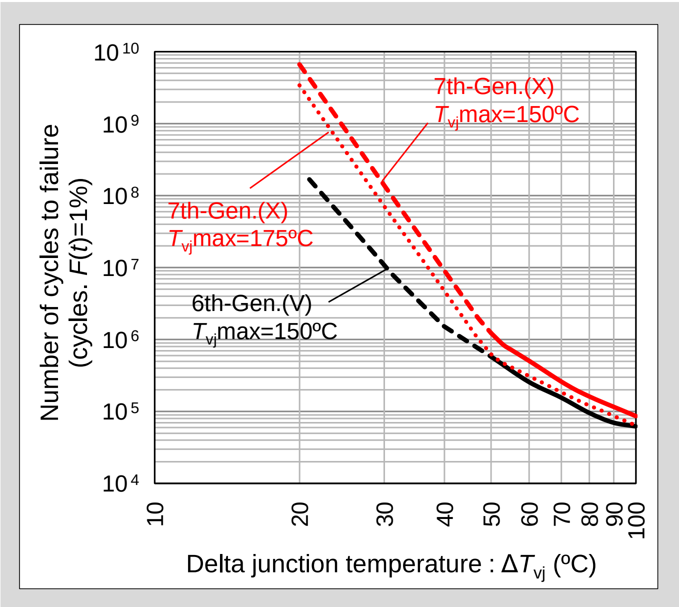


Figure 1-11 ΔT_{vj} power cycle capability curve

4. Expansion of Current Rating and Miniaturization of IGBT Modules

As mentioned above, 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 smaller on-state voltages. In addition, switching characteristics of IGBT and FWD are improved resulting in a lower turn-off loss (E_{off}) as well as in a lower reverse recovery loss (E_{rr}). These improvements lead to a 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 losses.

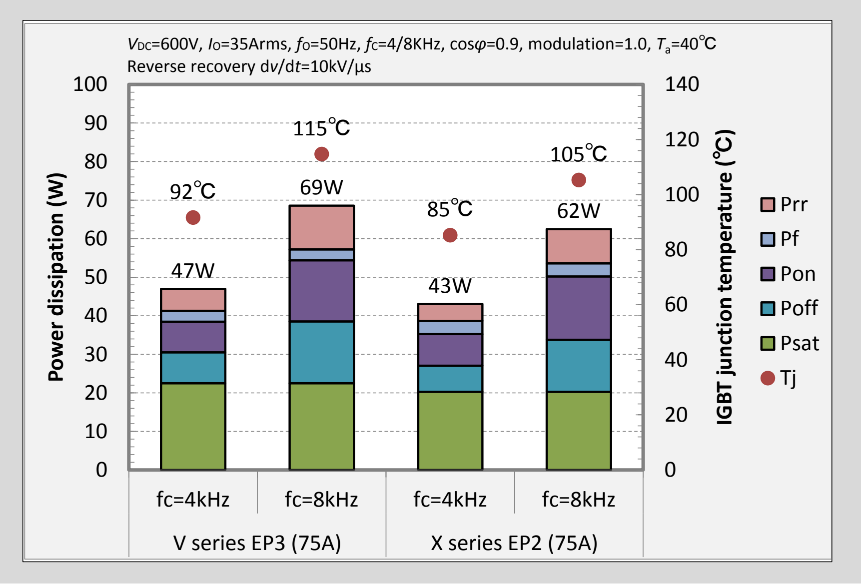


Figure 1-12 generated losses and junction temperature for inverter operation

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 loss reduction and the operating temperature increase. The output current for inverters of the same size can be increased by about 35%.

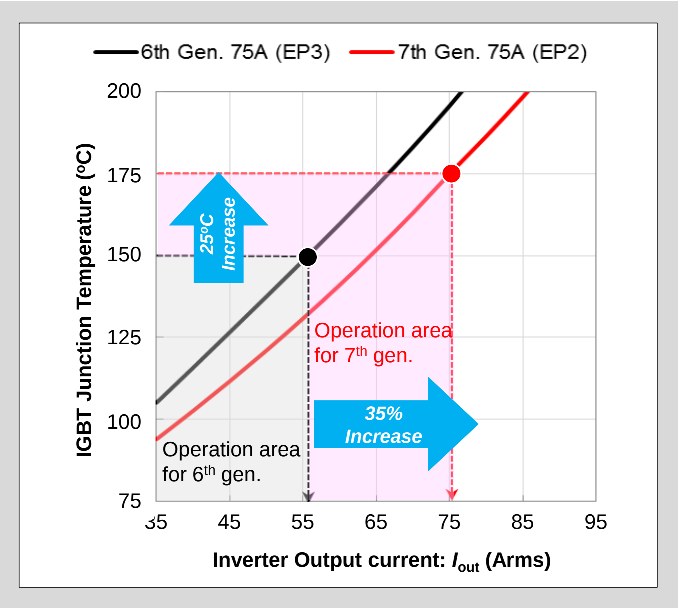


Figure 1-13 Inverter output current vs. junction temperature

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 EP2 package, while the X-series achieves an output current of 75A (Fig. 1-14). This fact allows to increase the output power of a power conversion system without changing the frame size.

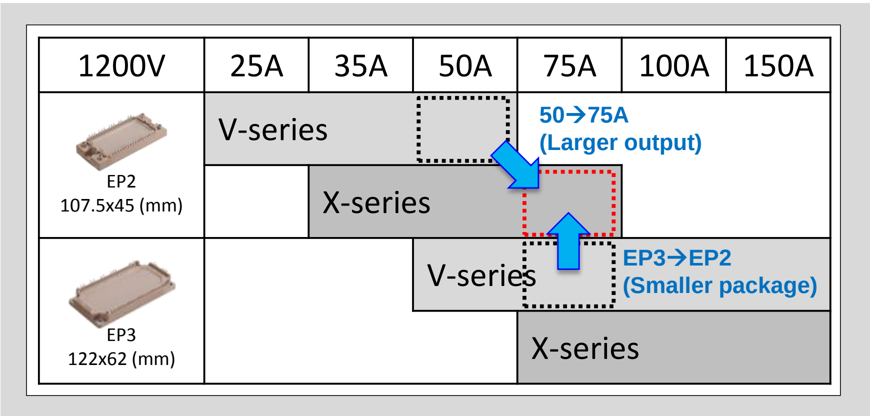
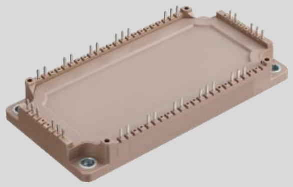
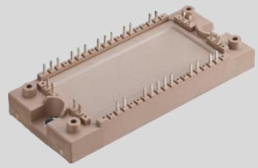


Figure 1-14 EP Series (1200V rating)

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 EP3 package (122mm x 62mm) in the V-series. The X-series can fit the same rating into the EP2 package (107.5mm x 45mm). The module footprint size can be reduced by 36%.

Table 1-1

	6th generation V-series	7th generation X-series
Package	 EP3 package	 EP2 package
Voltage rating / current rating	1200V / 75A	1200V / 75A
Current density	100%	160%
Footprint size	122mm x 62mm 7564mm^2 (100%)	107.5mm x 45mm 4836mm^2 (64%)
Module weight	310g (100%)	200g (65%)

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}
Operation junction temperature Junction temperature (Switching condition)	T_{jop}	Operating virtual junction temperature	T_{vjop}
Isolation voltage	V_{iso}	Isolation voltage	V_{isol}
Tightening torque 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)	$R_{th(c-s)}$
		Thermal resistance (case to heat sink per IGBT)	$R_{th(c-s)I}$
		Thermal resistance (case to heat sink per FWD)	$R_{th(c-s)D}$