Wide Temperature Operating Range of High Isolation HV-IGBT Modules

Mitsubishi Electric has developed new High Voltage Insulated Gate Bipolar Transistor (HV-IGBT) modules called the 'R-Series' with a high isolation package, which can be used with a wide operating temperature range from -50°C up to 150°C. The newly developed chip set achieves stable operation and high SOA capability over a wide temperature range. In addition the new package design is optimized for high isolation. The new HV-IGBT R-series has been developed to meet the requirements of high reliability applications for cold latitudes and to increase the inverter output power without increasing the equipment size. **Kenji Hatori, Shuichi Kitamura, Shigeru Hasegawa, Shinichi Iura, Power Device Works, Mitsubishi Electric Corporation, Japan; Masuo Koga, Fukuryo Semicon Engineering Corporation, Fukuoka, Japan; Eugen Stumpf, Mitsubishi Electric Europe B.V., Germany**

High-voltage IGBT modules are widely installed in high power applications, such as railway and large industrial drives. High reliability of the modules is requested for these applications. Recently, lower temperature operation has been requested for applications in cold latitudes. Also, higher temperature operation is requested for increasing the inverter output power. Therefore, the newly developed high isolation package module of HV-IGBT is able to operate from -50°C to 150°C.

Several issues had to be addressed for achieving the wide temperature operation. At first, a chip set with high SOA capability at T_j=150°C was achieved without thermal destruction. It has been already reported that the new planar IGBT structure for 3.3kV IGBT module has a high SOA capability at T_j=150°C [1, 2]. The second point was the optimization of package design. The optimization of the layout of the power terminals and chips is done by current sharing analysis in order to satisfy Short Circuit Safe Operating Area (SCSOA) at T_j=150°C. The excellent SCSOA robustness at T_j=150°C could be achieved by optimizing the current sharing. The third issue is the operation at T_j=-50°C. Stable operation is achieved by optimized lifetime control. The last item is the silicone gel for wide temperature operation, which has the same isolation capability as conventional modules even at very low temperatures.

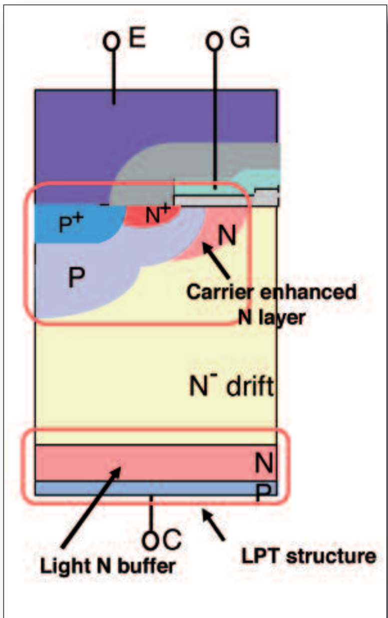

Figure 1: The structure of R-Series IGBT

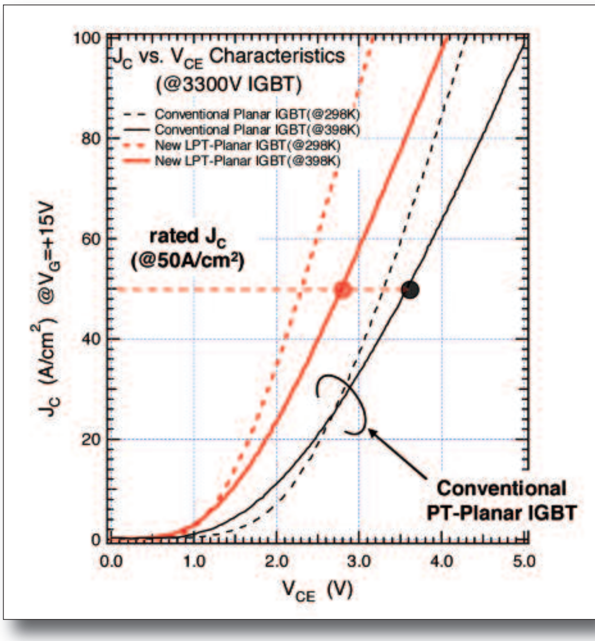

Figure 2: Output characteristics (3.3kV class)

R-Series chip set

The new HV-IGBT module called the R-Series (Figure 1) achieves larger current rating with wide safe operating area (SOA).

Low on-state losses are achieved by three technologies: Carrier enhanced N layer, thinner N- drift layer and LPT (Light Punch Through) structure (as shown in Figure 1). Because of reducing the on-state losses, increased current rating by 25 - 33% is achieved (see Figure 2).

The LPT structure with optimized lifetime control achieves low leakage current and positive temperature

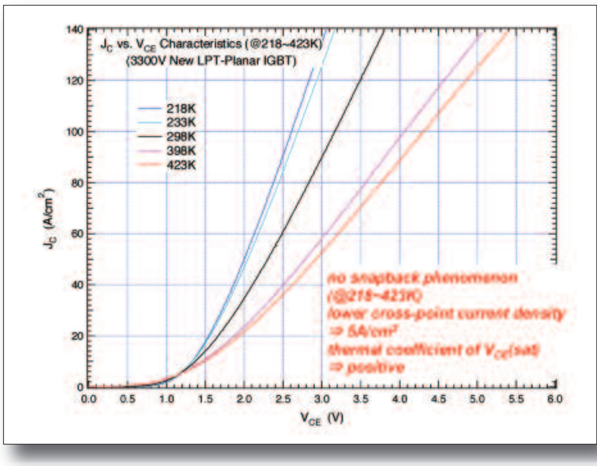

Figure 3: Output characteristic at T_j=-55-150°C (3.3kV class)

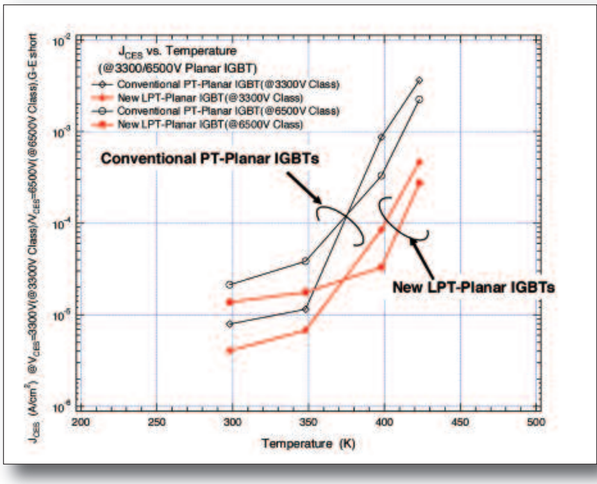

Figure 4: Leakage current characteristics of IGBT chips as function of temperature (3.3kV and 6.5kV class)

coefficient of the on-state voltage characteristic. Therefore, this structure is so rugged against thermal runaway and a safe operation at T_j=150°C is achieved. The positive temperature coefficient characteristic of on-state voltage has a big advantage in parallel operation. The new HV-IGBT R-series has higher SOA capability at a wider temperature range than the conventional module. The LPT structure also safely avoids the snap-back phenomenon at T_j=-50°C and ensures stable operation at T_j=-50°C (as shown in Figure 3). Figure 4 shows leakage current characteristics of IGBT chips as function of temperature (3.3kV and 6.5kV class).

The new diode (Figure 5) achieves reduction of reverse recovery current. Reduction of the reverse recovery current is achieved by the following three technologies: light anode by low concentration P layer, thinner N-drift layer and LPT structure, shown in Figure 5. The benefit of reduced reverse recovery current is low peak power during reverse recovery and low turn-on switching energy of the IGBT part. As shown in Figure 6, the reverse recovery current is significantly reduced. The LPT structure with optimized lifetime control achieves a positive temperature coefficient of on-state voltage characteristic and low leakage current, as well as high reverse recovery SOA capability.

High isolation package

The newly developed package is suitable for a wide temperature operation range. The wide temperature operation at -50°C

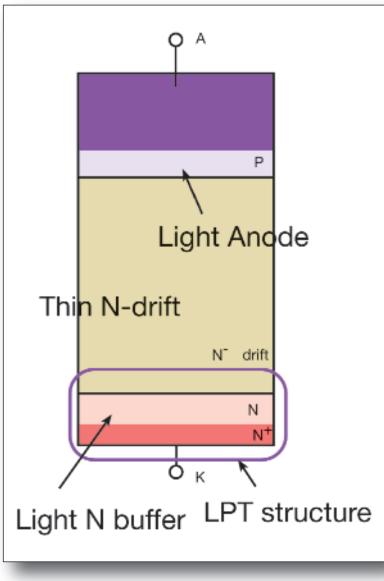

Figure 5: The structure of R-Series diode

to 150°C is achieved by adopting the newly designed components, especially the silicone gel material for maintaining high isolation voltage 10.2kVrms at 1 minute in spite of the extended operation temperature. For better utilization of the improved chip performance, the package of HV IGBT R-series is designed to optimize the inside current sharing among parallel chips, especially by newly designed chip layout, gate wiring and electrode structure. Figure 7 shows the new R-series package, which has compatibility of terminals and mounting position with the existing modules.

Optimized current sharing

Electromagnetic influence on the gate circuit is increased by a large current at

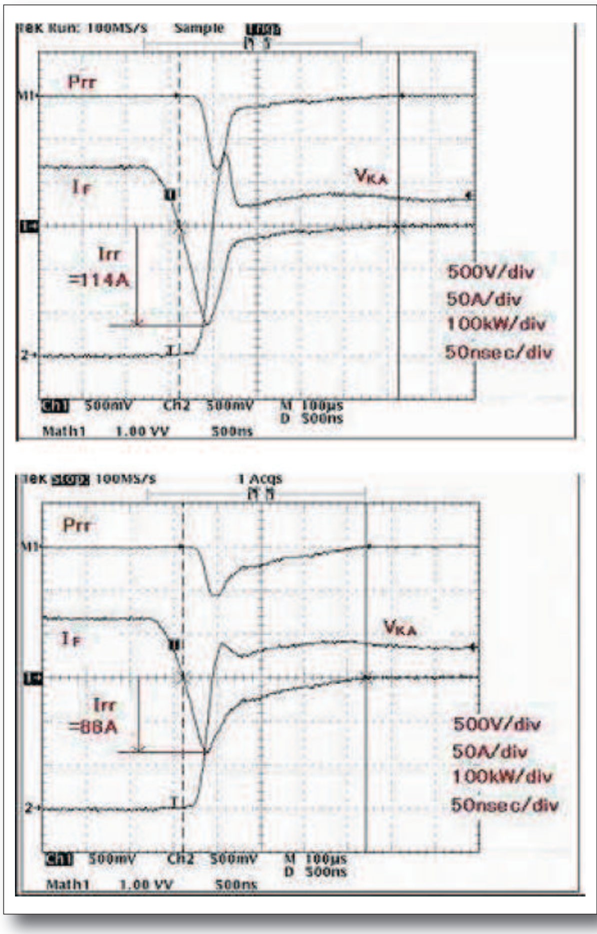

Figure 6: Reverse recovery waveforms of R-Series 3.3kV-diode (top: conventional chip, bottom: new chip, V_{CC}=1800V, I_F=67A, di/dt=290A/µs)

short circuit operation. Therefore, it is important to evaluate the influence of mutual inductance and also design a module to keep the current sharing balanced.

The calculation result of current sharing in new high isolation package under short circuit operation is shown in Figure 8. The electromagnetic influence on the gate circuit is avoided and excellent current sharing is achieved. The waveform of the high isolation package with 3.3kV IGBT is measured under short circuit condition (V_{CC}=2800V, T_j=150°C, V_{GE}=16.5 V), shown in Figure 9. It is confirmed that the new module can turn off at such harsh conditions without destruction.

Silicone gel

The silicone gel material is one of the key components for insulated modules. The characteristics of new silicone gel are less dependent on the temperature than the conventional one. Therefore, the new silicone gel has tougher characteristics even at the wider temperature range of -50°C up to 150°C. Of course, the new silicone gel has a good adhesive capability that achieves stable isolation at 10.2kVrms for 1 minute and partial

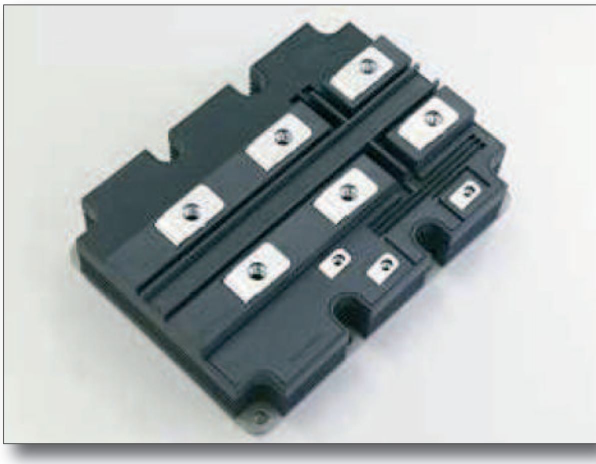

Figure 7: **R-series package (size: 190mm x 140mm x 48mm)**

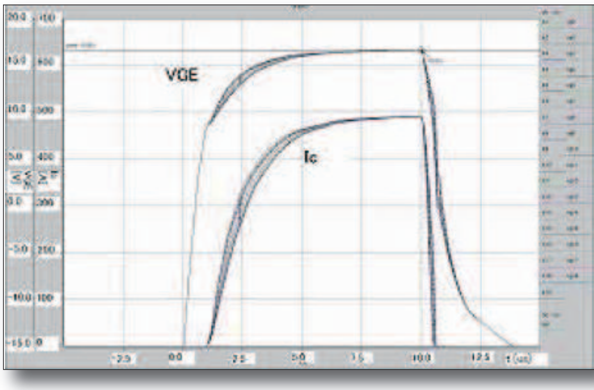

Figure 8: **Calculation result of new high isolation package with 3.3kV IGBT (V_{CC}=2800V, T_j=150°C, V_{GE}=16.5V, L_s=80nH)**

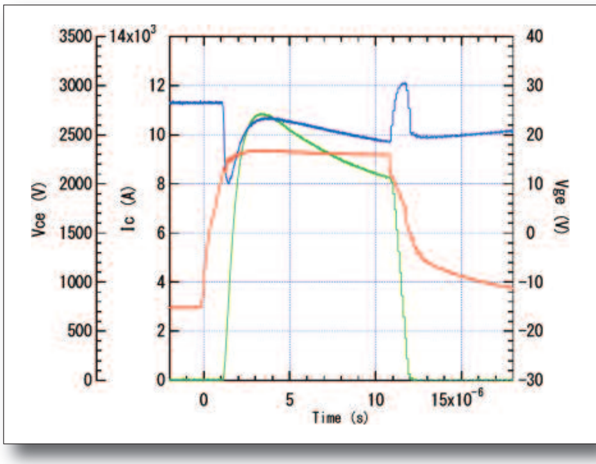

Figure 9: **Measurement of the new high isolation package with 3.3kV IGBT under short circuit condition (V_{cc}=2800 V, T_j=150°C, V_{ge}=16.5V, L_s=80 nH)**

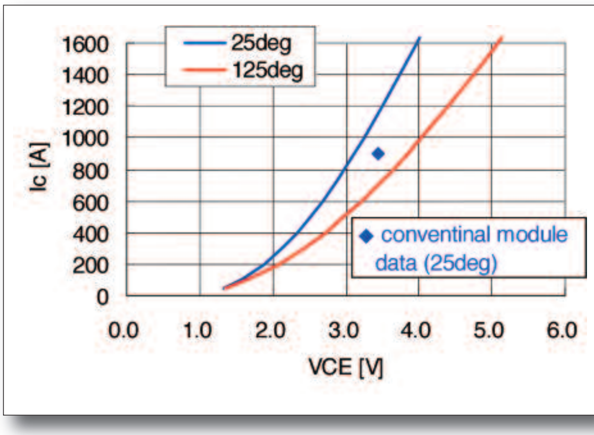

Figure 10: **Output Characteristic of new 4.5kV IGBT ($I_{C(nom)}$=1200A)**

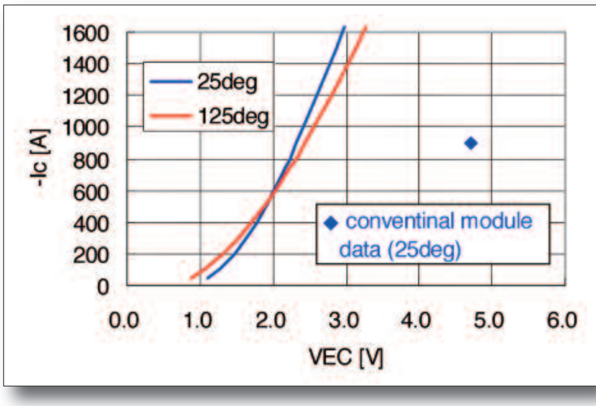

Figure 11: **Output Characteristic of new 4.5kV diode ($I_{C(nom)}$=1200A)**

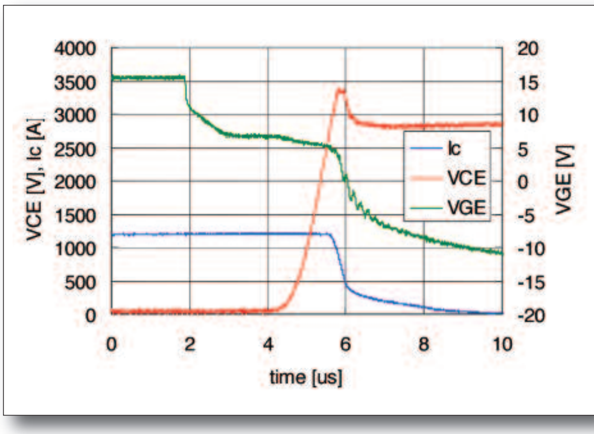

Figure 12: **Turn-off switching waveform of 4.5kV IGBT at nominal condition at T_j=125°C**

discharge characteristics according to IEC 61287-1.

The new HV-IGBT R-series has been qualified for the storage temperature test at -55°C and 150°C. In addition, in spite of the expansion of operational temperature, the new module achieves the same lifetime as the conventional module at the same temperature cycling condition.

Characteristics of HVIGBT

The characteristics for three different voltage classes are shown in Table 1.

Figures 10 and 11 show output characteristic of the 4.5kV / 1.2kA modules. It can be seen that both collector-emitter saturation voltage and diode forward voltage at nominal current are reduced. A positive temperature

	3.3kV Module	4.5kV Module	6.5kV Module
$I_{C(nom)}$	1500A	1200A	750A
$T_{j(op)}$	-50 to 150°C	-50 to 125°C	-50 to 125°C
$V_{CE(sat)}$	3.10V	4.40V	4.90V
V_{EC} (V_F)	2.30V	2.80V	3.40V

Table 1: **Characteristics comparison table of HVIGBT R-Series with high isolation (measured at Tj=125°C and IC(nom))**

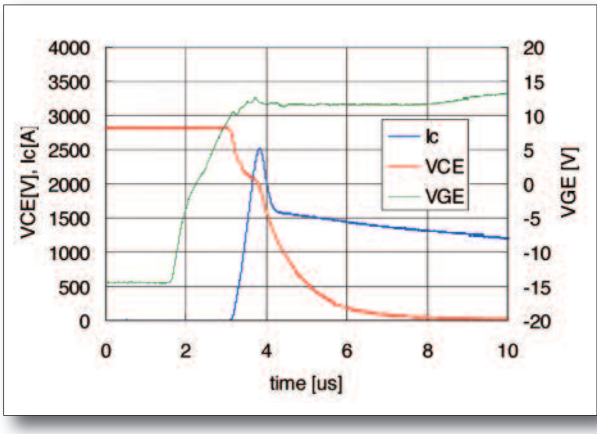

Figure 13: **Turn-on switching waveform of 4.5kV IGBT at nominal condition at T_j=125°C**

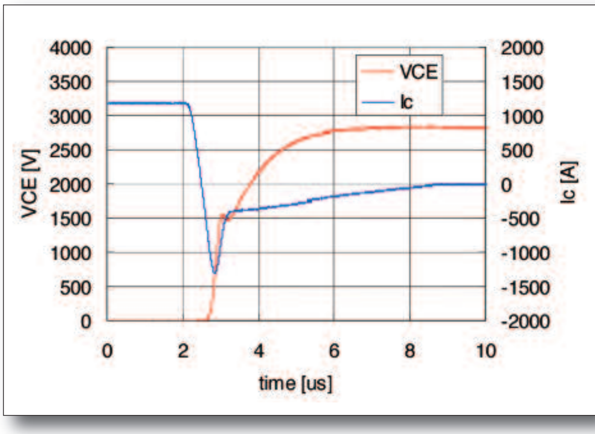

Figure 14: **Reverse recovery waveform of 4.5kV IGBT at nominal condition at T_j=125 °C**

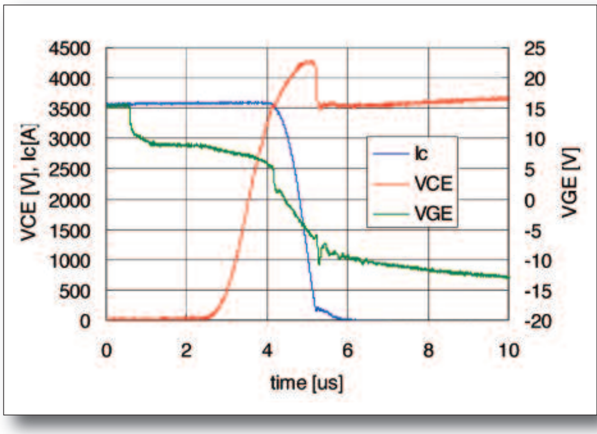

Figure 15: **Turn-off switching waveform at 3 x $I_{c(nom)}$ condition at 125°C.**

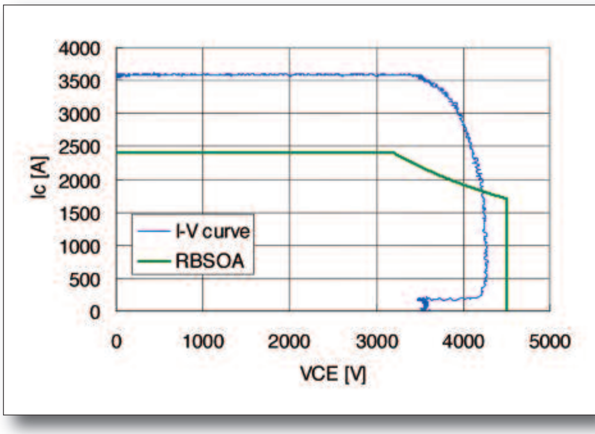

Figure 16: **RBSOA and V-I curve from Figure 15**

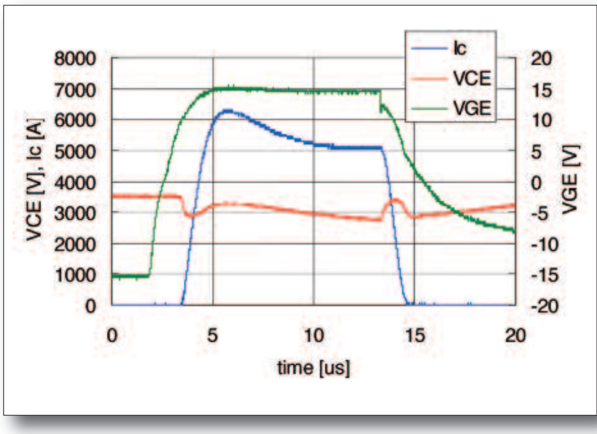

Figure 17: **Short circuit waveform at 125°C**

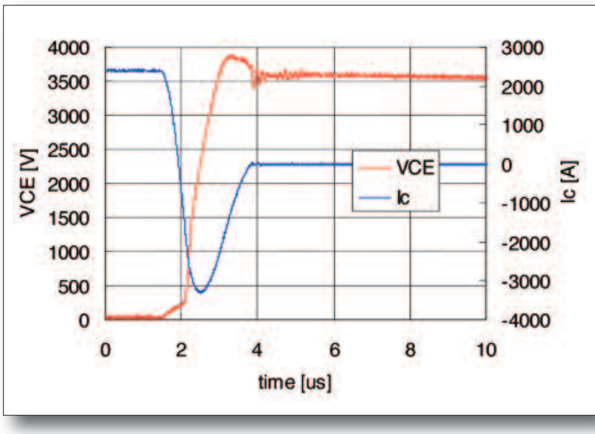

Figure 18: **Reverse recovery waveform at reached P_{rr}=9MW at 125°C**

coefficient has been obtained.

The waveform during turn-off switching of the 4.5kV module at nominal condition at T_j=125°C is shown in Figure 12. It operates smoothly without oscillation. A significantly low switching energy E_{off}=4.30J/P is achieved with $R_{g(off)}$=10Ω.

Figure 13 shows the waveform during turn-on switching of the 4.5kV module at nominal condition. The new module can increase di/dt to reduce turn-on switching energy by a smaller $R_{g(on)}$ compared to conventional one. This significant improvement is achieved by installing new diode chips. Turn-on switching energy is E_{on} = 5.50J/P with $R_{g(on)}$ = 2.7Ω and no capacitance between gate and emitter.

The waveform during diode reverse recovery is shown in Figure 14. The behavior is very soft and the reverse recovery current is low resulting in low reverse recovery peak power P_{rr}. The reverse recovery energy is $Erec_{= 2.50J/P}$ with di/dt = 3.6kA/µs.

It is important to have a wide Safe Operating Area (SOA) for HV-IGBT modules. Figure 15 shows the turn-off switching waveform of 4.5kVIGBT under over-current conditions at V_{cc}=3500V and T_j=125°C. Three times nominal current (I_c = 3600A) is successfully turned off (Figure 16). Figure 17 shows typical short circuit waveform of 4.5kV IGBT at V_{cc}=3500V, T_j=125°C and pulse time = 10µs.

A wide Reverse Recovery Safe Operating Area (RRSOA) was the objective for R-series diode design. Figures 18 and 19 are showing the reverse recovery waveform of 4.5kV

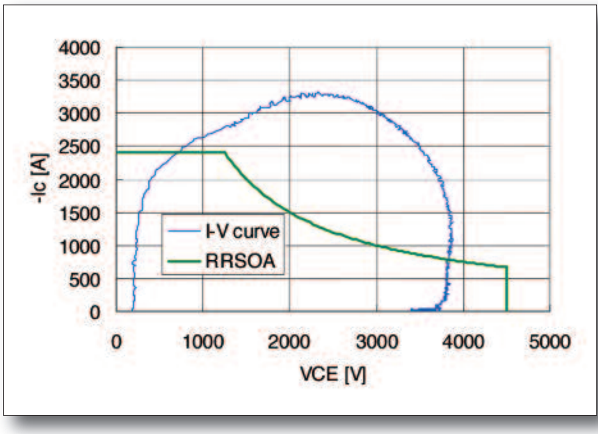

Figure 19: RRSOA and V-I curve from Figure 18

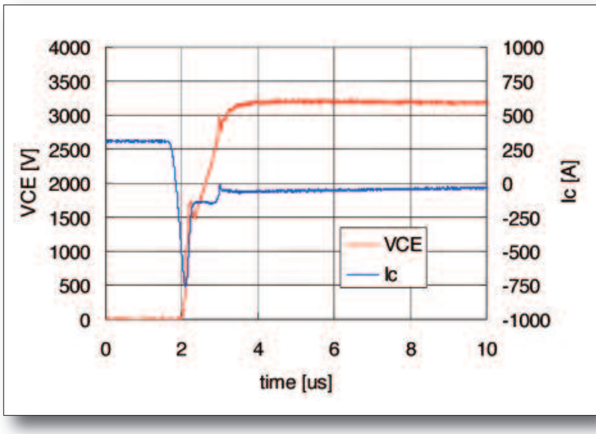

Figure 20: Reverse recovery waveform at 1/4 nominal current and T_j=-40°C.

diode at V_{CC}=3500V, T_j=125°C, I_F=2400A and di/dt ≥ 6kA/µs. The resulting P_{rr} reached 9MW without destruction. This is 3 times the RRSOA-limit and an indication for very robust diode design.

In general high-voltage diodes have a tendency to oscillation during reverse recovery at low temperature, low current and high DC-link voltage conditions. The new 4.5kV diode has no oscillation as shown in Figure 20 at the critical condition T_j=-40°C, V_{CC} = 3200V, I_C=300A (1/4 nominal current). A stable reverse recovery operation over the whole temperature range is achieved.

Conclusions

Mitsubishi has developed the new HV-IGBT R-Series module with high isolation. It has been confirmed that the new module is able to operate safely within a wide temperature range. The new module has an excellent robustness of SOA both for the IGBT and diode part without sacrificing performance. This high performance has been achieved by an optimized design combination of both the chip and the package. The new HV-IGBT R-Series with high isolation completely satisfies the extended needs, such as increasing current rating and operation in cold latitudes.

Literature

[1] K. Nakamura, et al. "The Next Generation of HV-IGBTs with Low Loss and High SOA Capability" ISPSD2008

[2] S. Iura, et al., "Development of New Generation 3.3kV IGBT module", PCIM 2006