Sixth-Generation V-Series IGBT Module Application Note Chapter 1 – Basic Concept and Features –

Table of contents		Page

Introduction

The sixth-generation V-series IGBT module adopts the field stop (FS) structure and the trench gate structure developed for the fifth-generation U-series and has a thinner wafer, optimizes the trench structure and so has improved characteristics.

This chapter describes the basic concept and characteristics of the sixth-generation V-series IGBT module.

e-Front runners

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1 Basic concept of V series

There is an increasing call for reduction of carbon dioxide in the world for conservation of the environment. It is imperative to reduce use of energy to decrease emission of carbon dioxide. It is also important to reduce the number of parts used for equipment and devices and the number of materials used for parts because the energy used for production is reduced. Therefore, the market requires manufactures to improve the energy conversion efficiency of equipment and devices and to downsize them. IGBT modules are the main components especially for a power converter and so downsizing of the modules directly leads to downsizing of the converter.

In this background, the latest-generation V-series IGBT module was developed based on the concept of "downsizing".

Figure 1-1 shows the basic requirements for IGBT modules by the market. The basic requirements are the improvement of performance and reliability and the reduction of environmental load. The characteristics for performance, environment and reliability are mutually related and so it is important to improve those characteristics in a good balance to "downsize" the IGBT module.

The sixth-generation V-IGBT developed this time materialized the basic concept of "downsizing" by optimizing the respective characteristics for performance, environment and reliability. In addition to "downsizing", the maximum current rating was extended in the same package.

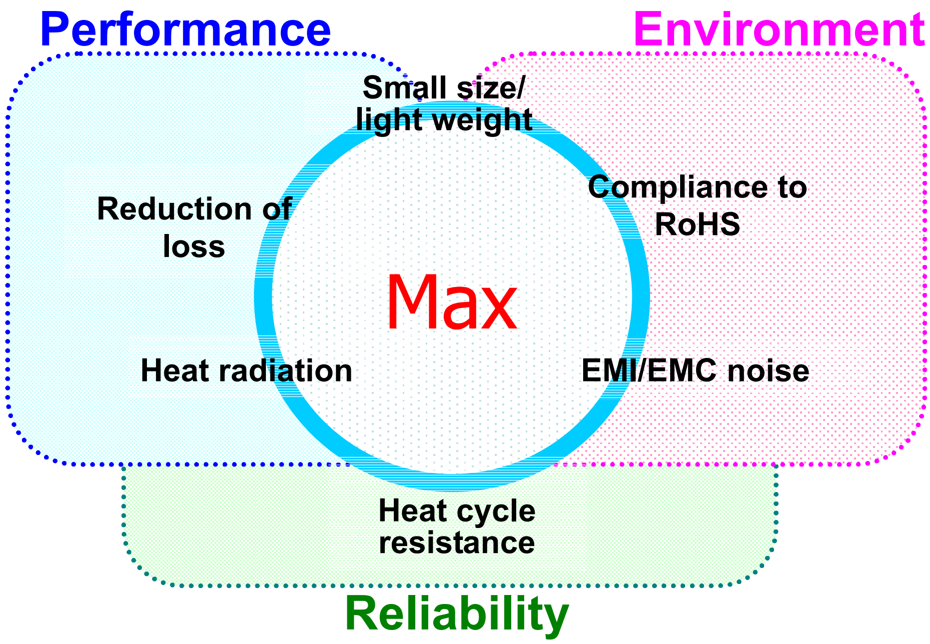


Fig. 1-1 Image of IGBT module development targeted by Fuji Electric

2 Transition of device structure

Figure 2-1 shows the cross-section views of the respective IGBT chips for 1200V series in Fuji Electric. Table 2-1 shows a list of technologies applied to the IGBTs of respective generations.

For the third-generation IGBT and before, the planar-gate punch-through IGBT was mainly used. The punch-through IGBT at that time used the Epitaxial wafer, and the low ON-state voltage was materialized by high injection of carrier from the collector side. At the same time, it was necessary to quickly remove the carrier, which was high-injected into the n base layer, at turnoff and so the lifetime control technology was used. The low ON-state voltage and the low turn-off switching loss (Eoff) were materialized in this way.

However, when the lifetime control technology was used, the improvement of characteristic was limited because the high-injected carriers were controlled by the lifetime control technology. In addition, the restriction of current unbalance when IGBTs were used in parallel was a problem because the ON-state voltage characteristics varied significantly.

To solve these problems, the fourth-generation S-series non-punch-through IGBT, which did not need the lifetime control technology, was developed. In the non-punch-through IGBT, the carrier injection efficiency was suppressed by controlling the impurity concentration in the collector (P+ layer) and the transport efficiency was increased by making the n base layer thinner. The non-punch-through IGBT used the float zone (FZ) wafer instead of the Epitaxial wafer and so had the advantage that it was less affected by crystal defect. On the other hand, it was necessary to improve the transport efficiency and have the n base layer thinner, namely make the chip thickness smaller, in order to have low ON-state voltage. Fuji Electric has developed new technologies for production of thinner wafers and improved the characteristics. It is necessary to produce an IGBT, which has thinner chip, to further improve the characteristics. However, the thickness of the n-base layer accounts for most of the chip thickness, and if its thickness is made smaller, the element withstand voltage is decreased significantly. The filed stop (FS) structure solved this problem for improvement of characteristics and element withstand voltage. In the FS structure, high concentration FS layer is provided in the n-base layer, enabling the improvement of characteristics.

Fuji Electric has also advanced the miniaturization of surface structure that is imperative to improve the characteristics of IGBT. The IGBT element consists of many arranged basic structures called cells. The more IGBT cells are provided, the lower ON-state voltage can be obtained. Therefore, the surface structure has changed from planar structure, in which the IGBT cells are made plenary on the wafer surface, to the trench structure, in which the trenches are formed on the silicon surface and the gate structure is formed three-dimensionally. The fifth-generation U-series adopted the above FS structure and the trench gate structure and materialized the groundbreaking improvement of characteristics.

In the sixth-generation “V Series” commercialized this time, the lower ON-state voltage is materialized and the switching loss is reduced by making the FS structure developed for the fifth-generation U-series further thinner. In addition, the control of switching speed is improved by further optimizing the trench gate structure.

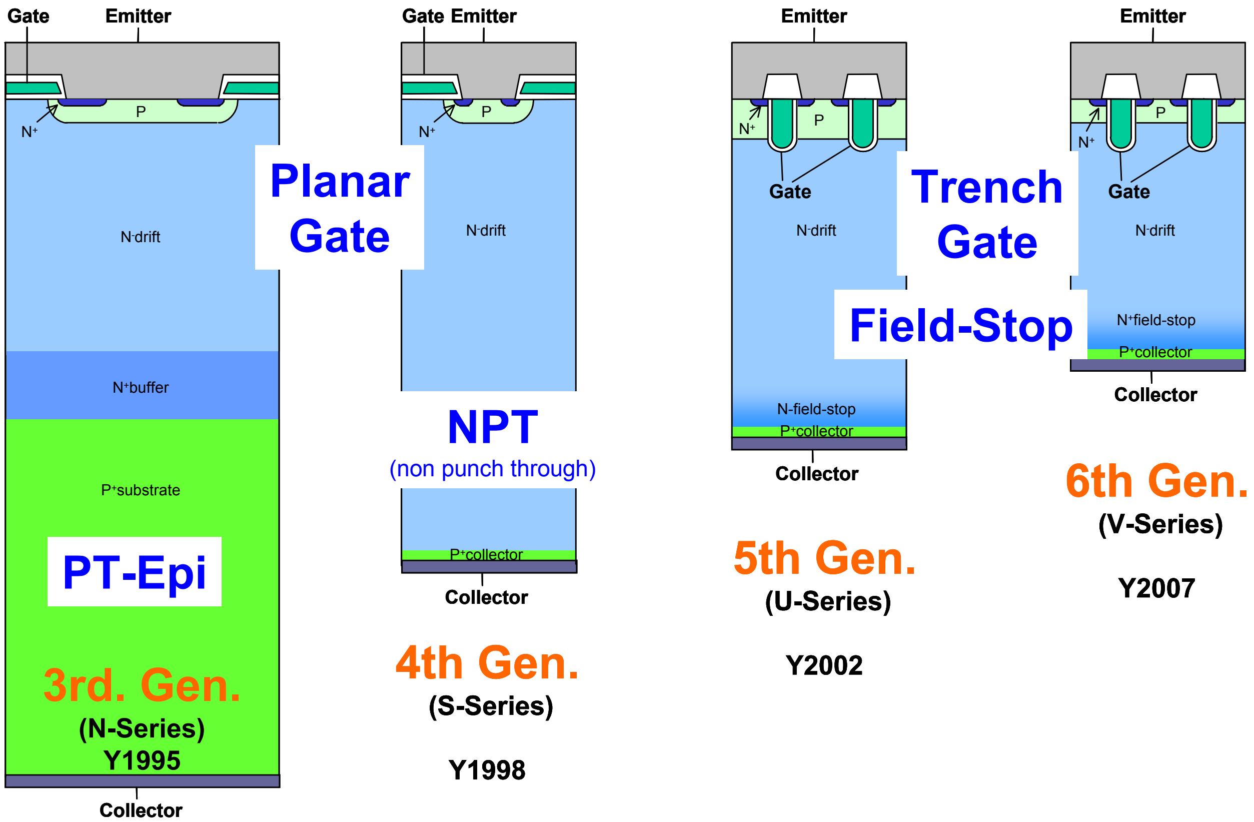


Fig. 2-1 Transition of Technologies Applied to IGBT Chips (1200V series)

Table 2-1 Technologies Applied to Respective Generation IGBTs (1200V series)

Generation	3rd	4th	5th	6th
Series	N	S	U/U4	V
Wafer	Epi	FZ	FZ	FZ
Gate structure	Planar	Planar	Trench	Advanced Trench
Bulk	PT	NPT	FS	FS
Lifetime control	Applied	None	None	None
Thickness	Thicker	Thick	Thin	Thinner

3 Characteristics of V-series IGBT chips

3.1 Improvement of V-series IGBT chip characteristics

3.1.1 Reduction of ON-state voltage

Figure 3-1 shows the comparison of output characteristics between the sixth-generation V-series IGBT chip and the fifth-generation U-series IGBT chip. As the figure clearly shows, the collector emitter voltage Vce of V series is significantly reduced compared with U series at the same current density.

By using this effect of characteristic improvement properly for making the chip size smaller, the IGBT is downsized and the rated current is improved within the same package.

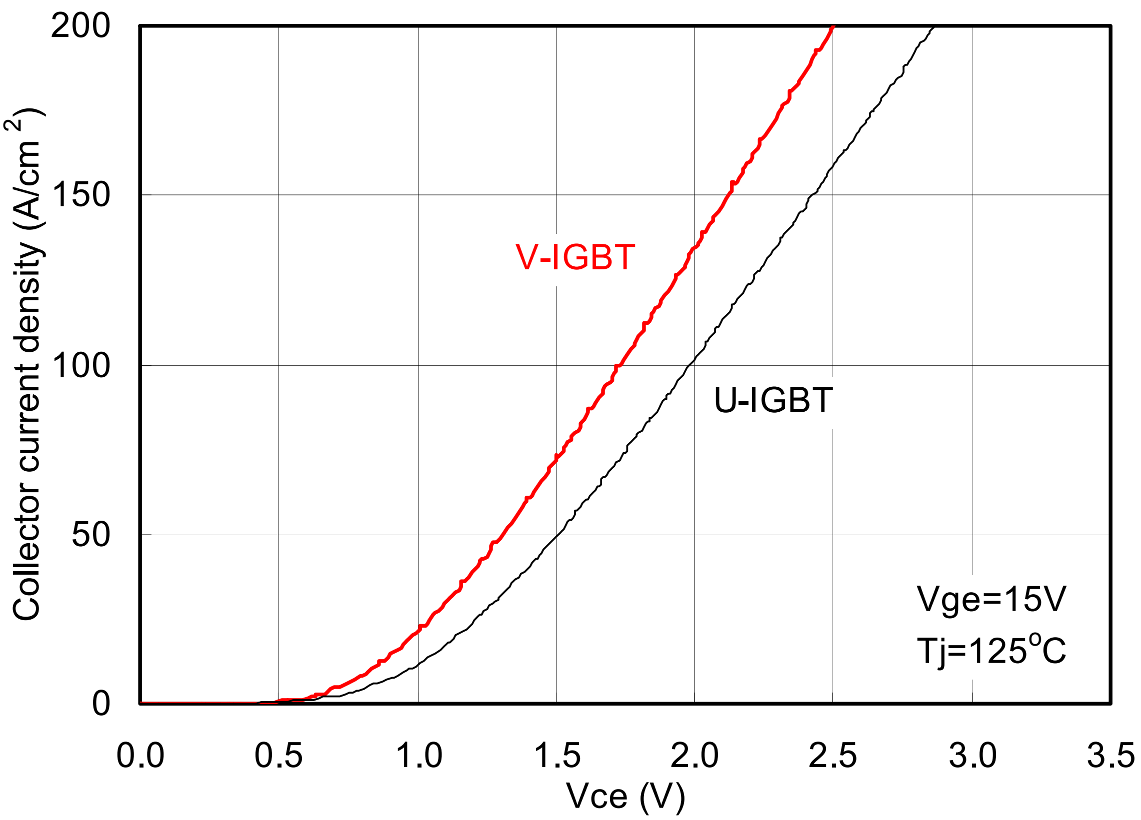


Fig. 3-1 Comparison of Output Characteristics (1200V series)

3.1.2 Reduction of turn-off loss

Figure 3-2 shows the trade-off characteristic comparison in turn-off loss and on-state voltage between the sixth-generation V-series IGBT chip and the fifth-generation U-series IGBT chip. This figure shows that the on-state voltage of V-IGBT is about 0.3V lower than that of U-IGBT when the on-state voltages are compared at the turn-off power loss of the same current density. As shown, the characteristics are significantly improved in V-IGBT.

By using this characteristic improvement effect properly for making the chip size smaller, the loss is reduced and the current rating is improved.

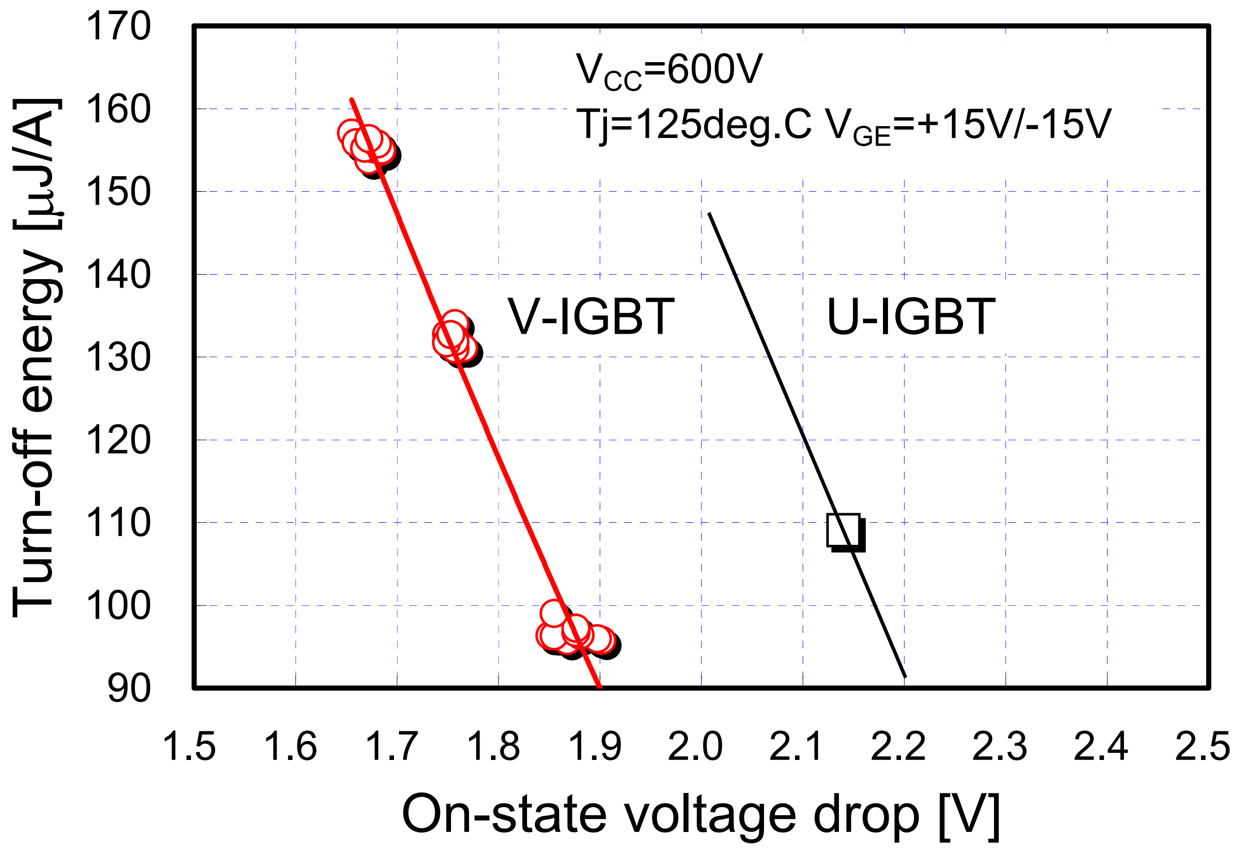


Fig. 3-2 Trade-off Comparison in V-IGBT and U-IGBT (1200V series)

3.2 Suppression of turn-off oscillation

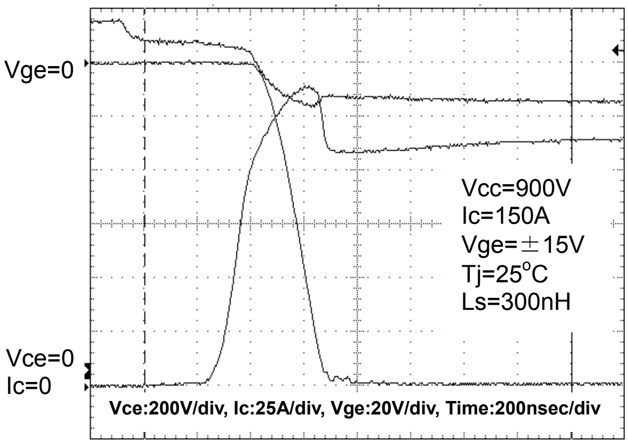
As well known, by making the silicon thickness thinner, ON-state voltage and switching characteristics can be improved. Therefore, the silicon thickness of each-generation IGBT was made thinner to improve the characteristics. In these days, however, the chip thickness of IGBT is as thin as 100μm and so it is also important to have enough breakdown voltage. Therefore, by adopting the field stop (FS) layer for the backside structure, the silicon thickness is made thinner to improve the characteristics and the enough breakdown voltage is obtained as well in the present IGBT.

It is well known that, in a FS IGBT, current and voltage oscillation is caused by reach-through phenomenon, in which the depletion layer extending at the time of turn-off reaches the FS layer.

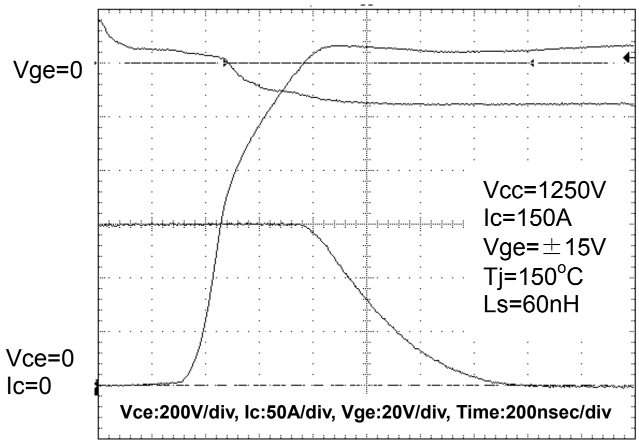
The limit voltage (oscillation starting voltage), at which turn-off oscillation occurs, and the element breakdown voltage conflict each other. When the resistance of drift layer is made higher to have enough element breakdown voltage, the oscillation starting voltage decreases. On the other hand, when the resistance of drift layer is made lower, enough breakdown voltage cannot be obtained easily, though the oscillation starting voltage can be made higher.

In the sixth-generation V-IGBT, the turn-off oscillation is suppressed while the optimal design for sufficient breakdown voltage is adopted.

Figure 3-3 shows the waveforms when the V series IGBT of 1200V is turned off in very severe conditions. Figure 3-3 (a) shows the waveforms when main circuit inductance is very large. Figure 3-3 (b) indicates the waveforms when voltage far severer than the normal conditions is applied and when the IGBT is turned off at Vcc=1250V exceeding the rated voltage. As these waveforms show, no oscillation is observed in current and voltage when IGBT is turned off in the very severe conditions. As shown, V-series IGBT modules cause no oscillation and customers can use them very easily.



(a) When main circuit inductance is large



(b) When applied voltage is high

Fig. 3-3 Turn-off Waveforms of V-IGBT (75A / 1200V)

3.3 Gate resistance controllability of switching characteristics

Recently the switching speed of IGBT modules is becoming higher because of the requirement for lower switching loss. However, higher switching speed causes EMI noise due to change in current and voltage. Especially it is well known that the turn-on characteristics have significant influence on generation of EMI noise. Therefore, in a situation where EMI noise becomes a problem, change of current and voltage must be made gradual (soft switching) when IGBT is turned on. Accordingly, it is important that the turn-on speed can be controlled by gate resistance.

In this situation, in the sixth-generation V-series IGBT modules, control of turn-on speed by gate resistance can be performed easily. Figure 3-4 shows the waveforms at the time of turn-on switching when gate resistance is changed at 1/10 of the rated current. The figure shows the FWD voltage of the opposite arm.

This figure clearly shows that the reverse recovery dV/dt caused by turning on an IGBT module varies significantly by changing the gate resistance. Thus, in V-IGBT, change of current and voltage can be controlled easily by the gate resistance. As described later, by selecting proper resistance, the optimal design for trade-off of EMI noise and switching loss can be made.

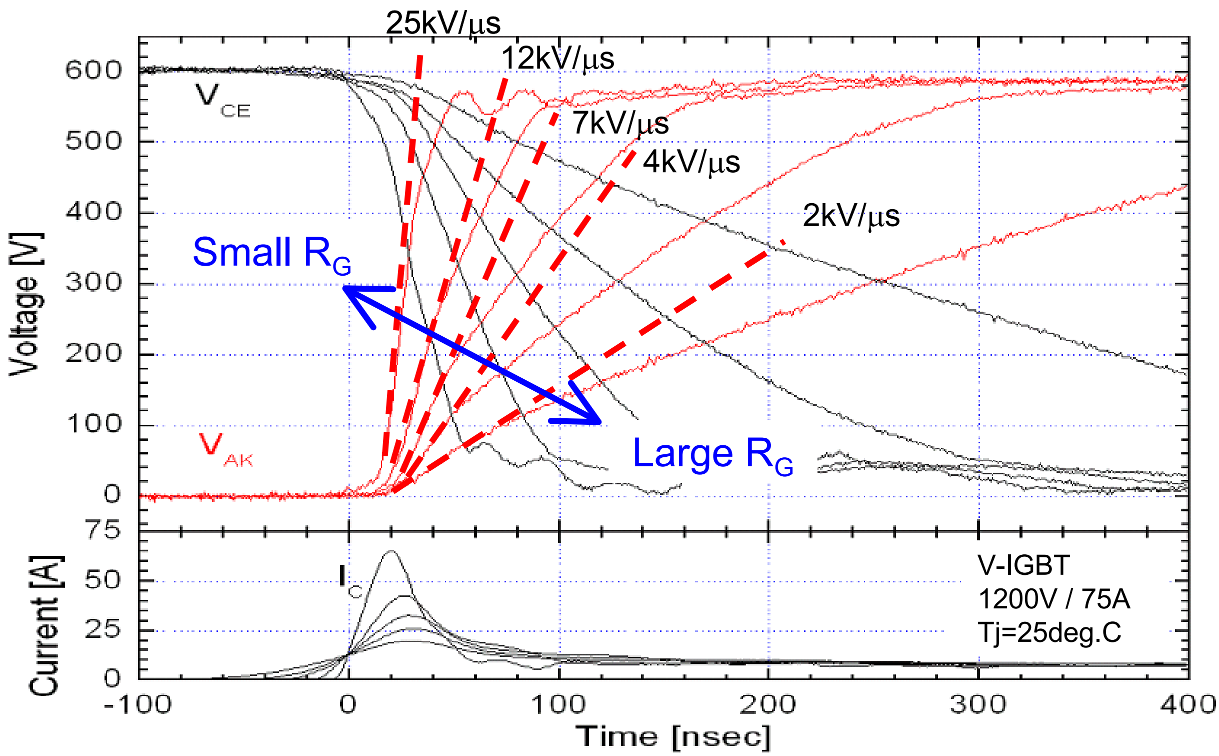


Fig. 3-4 Dependency of Turnoff Switching Waveform on Gate Resistance

3.4 Reverse recovery dV/dt and turn-on loss

As described before, when the gate resistance is made higher to suppress the EMI noise, the turn-on loss becomes larger due to gradual change of current and voltage. The EMI noise and the turn-on loss are traded off. Therefore, in addition to improving the controllability of turn-on speed by gate resistance, it is important to improve the tradeoff with turn-on loss.

Figure 3-5 shows the relation between the turn-on loss and the reverse recovery dV/dt that is a factor for EMI noise. This figure shows that the turn-on loss of V-series IGBT is smaller than that of conventional U-series IGBT when they are compared at the same turn-on loss. On the other hand, the reverse recovery dV/dt of V-series IGBT is smaller when they are compared at the same turn-on loss.

As shown, the relation between the reverse dV/dt and the turn-on loss is improved in V-IGBT compared with the conventional U-IGBT.

V-series IGBT modules combines the low turn-on loss and the low noise and so customers can use them easily.

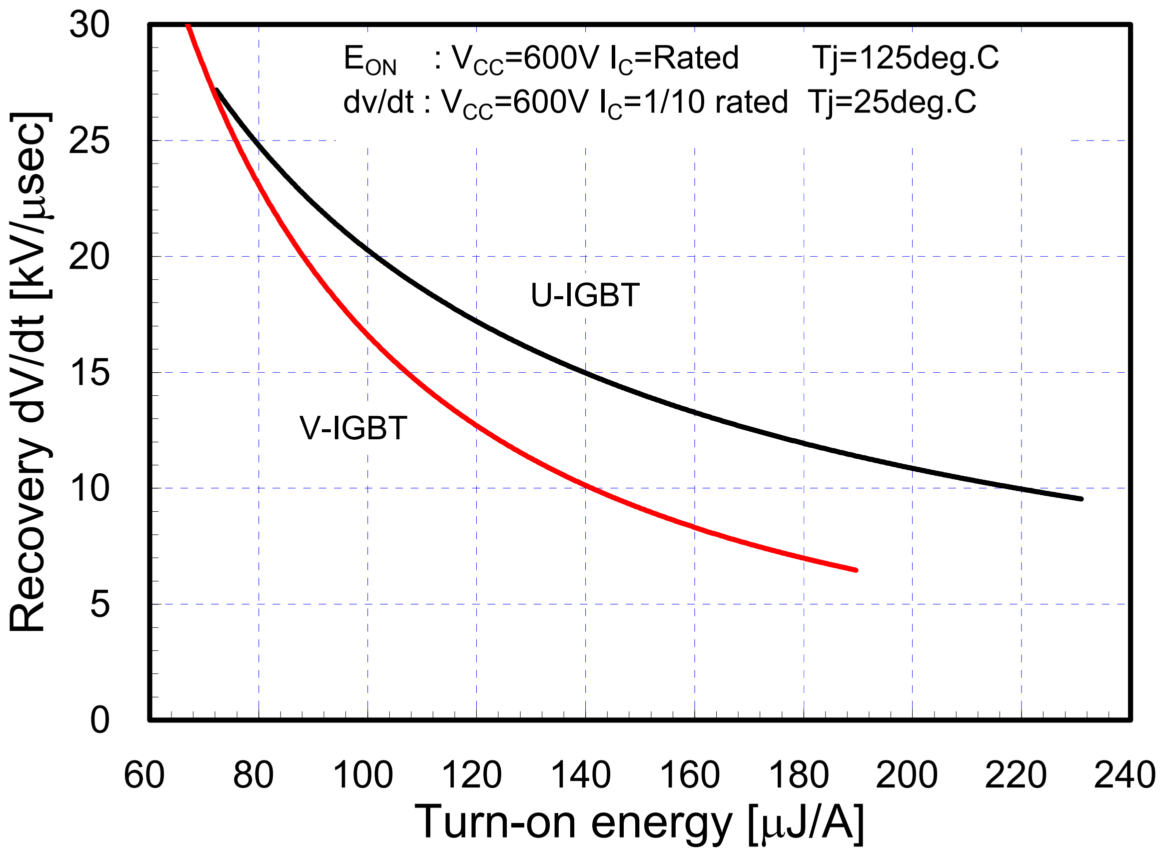


Fig. 3-5 Relation between Reverse Recovery dV/dt and Turn-on Loss (1200V series)

4 Use of highly thermal conductive ceramic insulated substrate

The size of IGBT module must be made smaller to downsize the various power conversion systems. However, downsizing inevitably increases the power density and so the temperature of chip within the module increases. Therefore, the heat generated in the chip must be radiated effectively.

The V-series IGBT module is downsized by improving the chip characteristics and optimizing the interior layout. In addition, for some current ratings, in which power density is high, highly thermal conductive ceramic insulated substrates (silicon nitride substrate and aluminum nitride substrate) are used to significantly extend the current rating.

Figure 4-1 shows the comparison of impedance characteristics between the aluminum oxide substrate and the silicon nitride substrate. The figure shows that the transient thermal impedance is reduced and the steady-state thermal resistance is reduced by about 25% by using the silicon nitride substrate. On the other hand, the temperature increase ΔT(j-c) between the chip and the case at the steady state is the product of the consumed power and the steady-state thermal resistance and so the power consumption can be made about 25% larger. This increased portion of power consumption can be used to improve the power density and so can be used to increase the current rating within the same package.

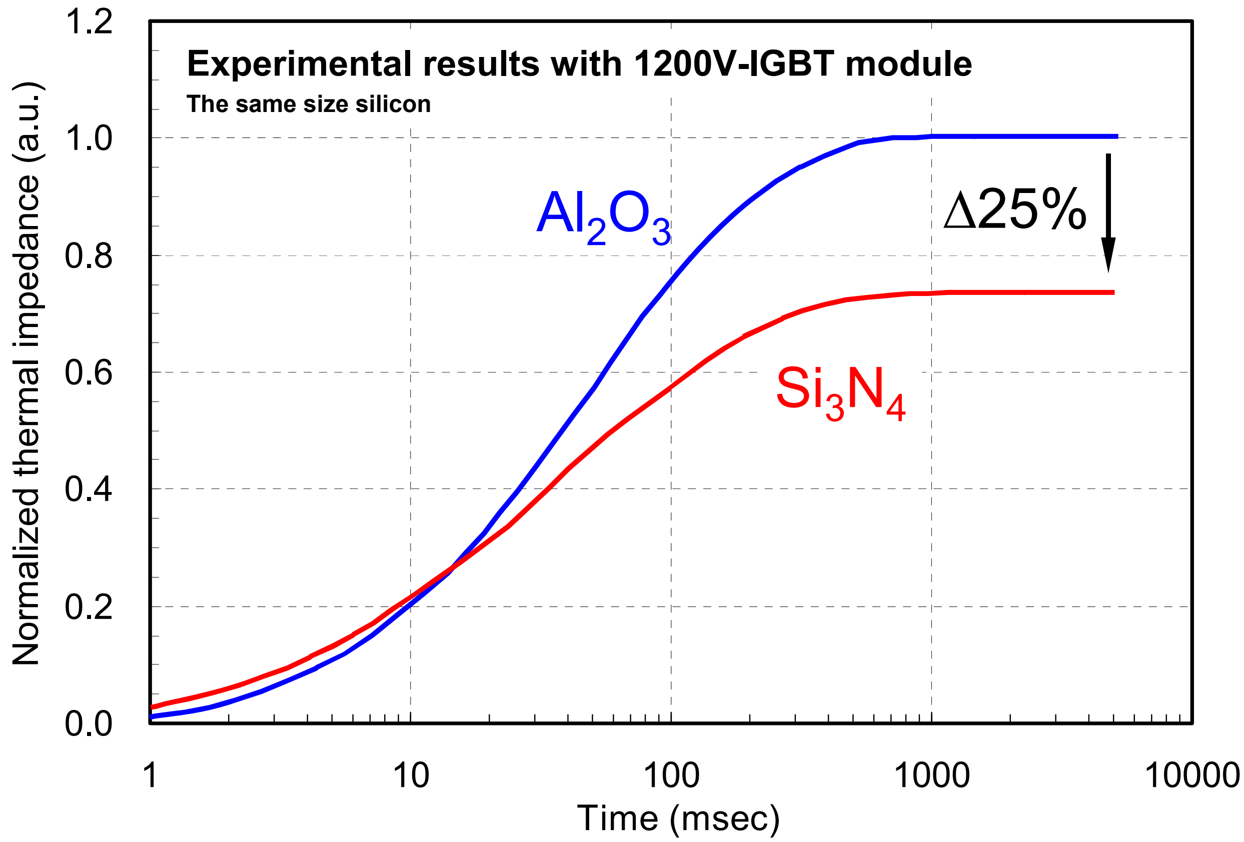


Fig. 4-1 Comparison of Transient Thermal Impedance Characteristics (Aluminum Oxide Substrate and Silicon Nitride Substrate)

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