TOSHIBA

Technical Review

IGBTs and IEGTs to Achieve Energy Saving in Various Applications from Home Appliances to Power Transmission and Distribution Equipment

Insulated gate bipolar transistors (IGBTs) are widely used in various applications ranging from home appliances including motor drive units for air conditioners, microwave ovens, and induction heating (IH) cookers to equipment for electric power transmission and distribution systems. Moreover, due to the expansion of renewable energy systems, attention is being focused on injection-enhanced gate transistors (IEGTs), which can play a key role in energy saving for high-voltage DC (HVDC) power transmission systems due to their lower power loss.

In response to these diverse needs, Toshiba Electronic Devices & Storage Corporation has developed the following products by optimizing the structures of the respective devices: (1) voltage-resonant type IGBTs that can operate at switching frequencies of several tens of kHz for equipment such as home appliances, and (2) press-pack IEGTs with a high breakdown voltage and reduced conduction loss. The newly developed voltage-resonant type IGBTs achieve a 26% reduction in switching loss while also reducing noise compared with our previous products. Inverter systems using the newly developed press-pack IEGTs achieve a 31% reduction in loss compared with systems using our previous press-pack IEGTs.

1. Introduction

In recent years, the potential of power electronics technologies to efficiently use energy and thereby help realize a sustainable society has been a focus of rising expectations. Under these circumstances, demand is growing for power devices that are utilized in power converters for a wide range of applications, including industrial, consumer, automotive, and infrastructure equipment. An IGBT is a type of power device that combines the voltage drive characteristics of a metal-oxide-semiconductor (MOS) gate with the low saturation voltage ($V_{ce(sat)}$) characteristics of a bipolar transistor. The IGBT has higher operating frequency than the thyristor, another type of power device, and is capable of controlling higher electric power than the power MOS field-effect transistor (MOSFET). In addition to IGBTs, Toshiba Electronic Devices & Storage Corporation develops and provides IEGTs for various applications, which exhibit lower power loss than IGBTs because of the injection enhancement (IE) effect (**Figure 1**).

The electrical characteristics of IGBTs and IEGTs can be improved mainly by: (1) adjusting the chip thickness, (2) improving the MOS structure, and (3) optimizing the amount of hole injection (**Figure 2**).

In particular, the design principles for the MOS structure depend on the application of the device. The gate-emitter capacitance (C_{ge}) and the gate-collector capacitance (C_{gc}) are optimized to reduce switching loss whereas the IE effect and the channel resistance are optimized to reduce $V_{ce(sat)}$.

This report describes how we have reduced the power loss of the IGBTs for use in voltage-resonant circuits for home appliance applications and that of the IEGTs for HVDC power transmission applications.

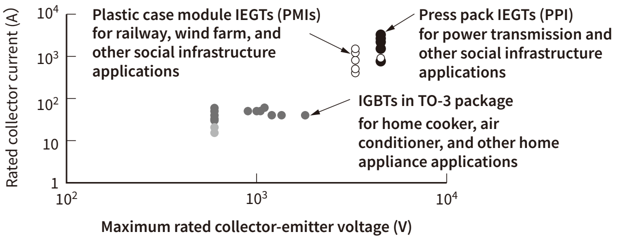


Figure 1. Rated ranges of Toshiba IGBTs and IEGTs

Wide ranges of IGBTs and IEGTs are available.

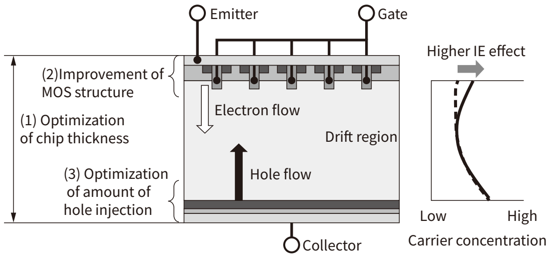


Figure 2. Design parameters to improve characteristics of IGBT and IEGT

Three design parameters mainly affect the electrical characteristics of IGBTs and IEGTs: (1) chip thickness, (2) MOS structure, and (3) amount of hole injection.

2. Reducing power loss of IGBTs for use in voltage-resonant circuits for home appliance applications

2.1 Voltage-resonant circuits

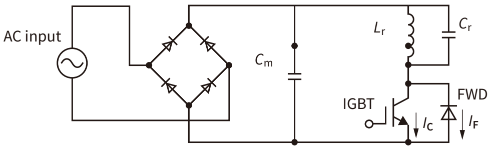
Voltage-resonant circuits are used in induction cookers, microwave ovens, and other home appliance applications. A typical voltage-resonant circuit is composed of a diode bridge, an LC tank consisting of a resonant coil (Lr) and a resonant capacitor (C_r) connected in parallel, a switching IGBT, and a freewheeling diode (FWD) as shown in **Figure 3**(a). Figure 3(b) shows the voltage and current waveforms applied to the switching IGBT and the FWD. While current is negative, it flows through the FWD connected in parallel with the IGBT. The switching loss of the IGBT is reduced by reducing V_{CE} during turn-on or I_C+I_F during turn-off as shown in Figure 3(b).

2.2 Issues and solutions concerning conventional IGBTs

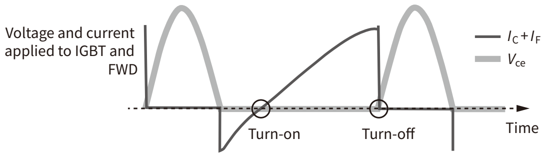
A voltage-resonant circuit tends to generate electromagnetic interference (EMI) radiation during the switching of an IGBT, which might cause peripheral devices and systems to malfunction. The latest revision of the Electrical Appliances and Materials Safety Act of Japan imposes stringent regulation on EMI, with regulation being particularly stringent on EMI events in the frequency range below 170 MHz. Increasing the value of the gate resistor for an IGBT causes its switching speed to decrease. This helps reduce EMI emissions, but at the expense of increased power loss.

In the case of the GT60PR21, an IGBT of the previous generation, it was possible to keep the EMI level below the regulatory limit by increasing the value of the gate resistor (R_g) from 10 Ω to 150 Ω. However, this incurred a 1.75-fold increase in total power loss (**Figure 4**(a)). With an R_g of 150 Ω, the switching loss (0.98) of the IGBT is roughly 2.4 times as large as its conduction loss (0.41). It is therefore crucial to reduce the switching loss for the applications requiring high-frequency operation. Since turn-on loss occurs when the collector current (I_C) and the collector-emitter voltage (V_{ce}) are almost zero, it is sufficiently lower than turn-off loss.

Figure 4(b) shows the turn-off waveform of the GT60PR21 when R_g = 150 Ω and junction temperature (T_j) = 125°C. As can be seen from this figure, its switching loss during the period from when the gate voltage (V_g) reaches 90% of 15 V to when I_C reaches 90% of its peak (E_{td}), including the Miller period during which V_g is almost constant, is larger than the loss during the subsequent period till the GT60PR21 turns off (E_{f_tail}). Therefore, we optimized the MOS structure in order to keep the EMI level below the regulatory limit even with a low R_g and to reduce E_{td}.



a) Typical resonant circuit

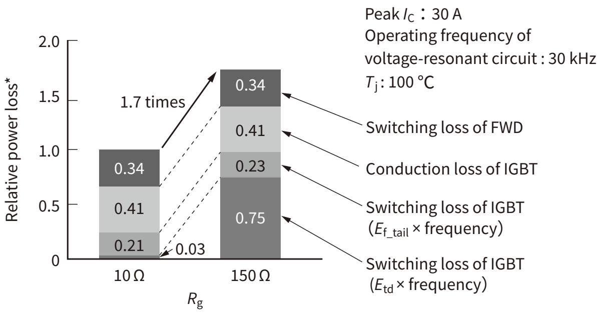


(b) Voltage and current waveforms of IGBT

C_m : smoothing capacitor I_F : current flowing through FWD
V_{ce} : collector-emitter voltage

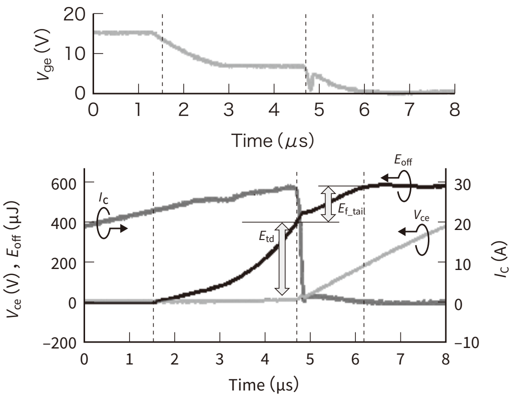
Figure 3. Example of voltage-resonant circuit using IGBT and its operating waveform

IGBTs are utilized in resonant circuits for induction rice cookers,induction cooktops, and microwave ovens.



(a) Effects of R_g on power loss

*Normalized such that power loss is equal to one when R_g=10 Ω



(b) Turn-off waveforms when R_g=150 Ω

V_{ge} : gate-emitter voltage E_{off} : loss per turn-off event

Figure 4. Loss simulation and turn-off waveform of voltage-resonant circuits using previous IGBT products

In the case of the previous IGBT, increasing R_g to reduce EMI radiation causes the switching loss to increase considerably during the Miller period.

2.3 Reducing EMI radiation

Figure 5 shows the simulated electron and hole concentrations in two different MOS structures in the on state (with the same chip size, backside structure, and chip thickness). Type A has higher carrier concentration near the surface, resulting in a higher IE effect than for Type B. Therefore, Type A has lower conduction loss. Next, we incorporated Type A and Type B IGBT prototypes into a commercially available tabletop induction cooker together with a gate resistor (R_g) of 62 Ω. **Figure 6** shows the measured EMI levels from the induction cooker. It indicates that the EMI level of Type B is lower than that of Type A by more than 5 dBµV/m at 30 MHz. In the IGBT, a hole current flows from the collector electrode through a path near the gate electrode. It is known that this hole current induces charge in the gate electrode and thus affects V_g(1). From the foregoing, we consider that Type A is more subject to variations in V_g than Type B because of higher near-surface hole concentration and that this eventually affects I_C, increasing the EMI level. Therefore, a MOS structure with a suppressed IE effect is more suitable for reducing EMI noise.

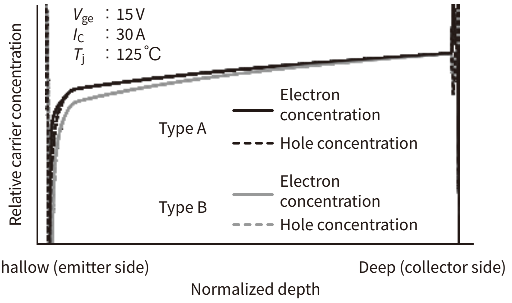


Figure 5. Simulated on-state carrier distribution

This figure shows the results of simulating the electron and hole concentrations in two different MOS structures in the on state. Since Type A is designed to have higher carrier concentration near the surface, Type A exhibits lower conduction loss than Type B.

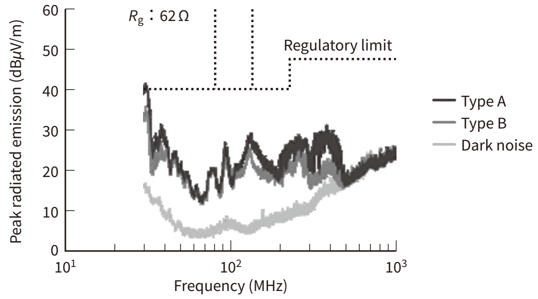


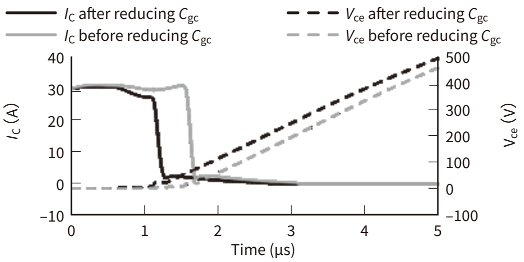
Figure 6. Comparison of radiated noise using two different surface structures

Type A with higher carrier concentration near the surface generates higher EMI noise than Type B.

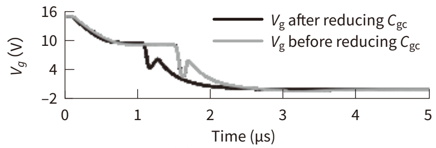
2.4 Reducing power loss during Miller period

When a voltage-resonant circuit turns off, C_r helps reduce an increase in V_{ce}. Therefore, unlike IGBTs for hard-switching applications, the depletion region does not extend into the drift region sufficiently, making it difficult for C_{gc} to decrease early during the switching period. This means that reducing C_{gc} is effective in shortening the Miller period.

Figure 7 shows the results of simulating how reducing C_{gc} helps reduce the E_{td} of an IGBT (without changing the chip size, backside structure, or chip thickness). We confirmed that the optimization of the trench shape to reduce C_{gc} resulted in a roughly 27% reduction in E_{td}.



(a) Comparison of I_C and V_{ce}



(b) Comparison of Vg

Characteristic	Relative Miller period	Relative E_{td}
Before reducing C_{gc}	1	1
After reducing C_{gc}	0.65	0.73

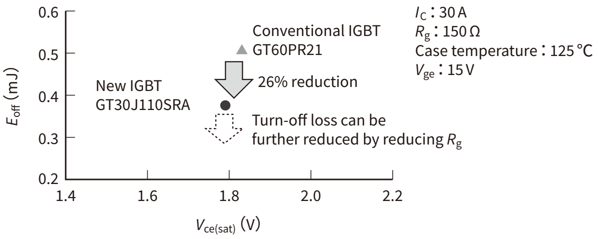
(c) Comparison of Miller period and E_{td}

Figure 7. Comparison of simulated turn-off waveform with and without gate-collector capacitance reduction

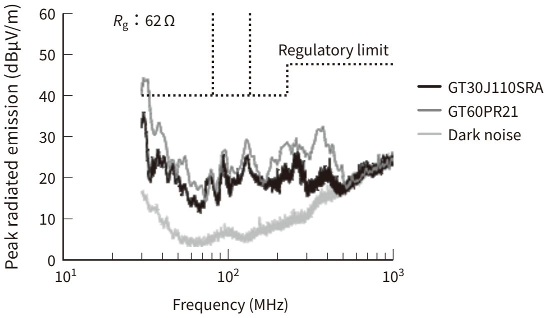
Reducing C_{gc} helps reduce the switching loss during the Miller period.

2.5 Comparison of optimized and conventional IGBTs

We succeeded in reducing both EMI noise and switching loss by reducing the IE effect and C_{gc}. Since a reduction in the IE effect causes an increase in conduction loss, we optimized the chip thickness to reduce the switching loss compared to the conventional IGBT with the same $V_{ce(sat)}$. Furthermore, we integrated an FWD into the IGBT chip. This type of IGBT is called a reverse-conducting IGBT (RC-IGBT), which provides a reduction in chip size since it shares the drift region between an IGBT and an FWD. **Figure 8**(a) compares the power loss per turn-off event (E_{off}) of the conventional GT60PR21 IGBT and the new GT30J110SRA IGBT when R_g=150 Ω. The E_{off} of the GT30J110SRA is 26% lower than that of the conventional IGBT at almost the same $V_{ce(sat)}$. We confirmed that the EMI radiation from the GT30J110SRA is lower than the regulatory limit even with a gate resistor (R_g) of 62 Ω (Figure 8(b)). Using a 62 Ω gate resistor helps to further reduce E_{off}.



(a) Comparison of E_{off} and $V_{ce(sat)}$



(b) Comparison of radiated EMI noise

Figure 8. Comparison of turn-off loss and radiated noise of previous and newly developed IGBTs

The E_{off} of the new IGBT is 26% lower than that of the conventional IGBT at the same $V_{ce(sat)}$.

3. Reducing power loss of IEGTs for HVDC applications

3.1 HVDC

In the field of power transmission and distribution, high-voltage direct-current (HVDC) power transmission is being increasingly deployed around the world because it is so well suited to efficiently transmitting bulk power over long distances. For land power transmission over a distance of more than 800 km and submarine power transmission over a distance of more than 50 km, HVDC compares favorably with the conventional high-voltage alternating-current power transmission in terms of cost. There are two types of HVDC converters: line-commutated converters that use thyristors as switching devices and self-commutated converters that use IEGTs or other devices with a current-interrupting capability. Although line-commutated HDVC was previously predominant, self-commutated HDVC has recently been spreading because of its ability to control reactive power independently from active power, a black start capability, and ease of creating multi-terminal HVDC grids. Under these circumstances, we have focused on commercializing press-pack IEGTs (PPIs) with a hermetically sealed, double-sided cooling structure that provide a high cooling capability and weather resistance. Our latest PPI, which features a high current capability and low power loss, was selected for use in the world's largest ±800 kV, 5 GW self-commutated HDVC system.

3.2 Optimization of the MOS structure

Figure 9 shows the structure of the PPI that does not have any bonding wire. Instead, multiple chips are crimped in parallel onto a copper electrode to create an electrical connection. The PPI allows the power density to be increased because it dissipates heat from both sides of the package. In addition, the PPI has a low likelihood of suffering an open-circuit failure. Furthermore, the absence of solder and bonding wires means the PPI is hardly susceptible to thermal fatigue and therefore provides high reliability.

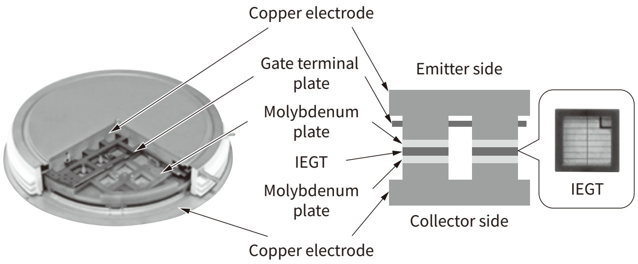


Figure 9. Structure of press-pack IEGT

Multiple chips are electrically connected in parallel through crimping to increase the power density and reliability.

The IEGT has a high rated voltage and a drift region resistance orders of magnitude higher than the channel resistance. It is therefore crucial to prioritize a bipolar operation in creating a circuit design so as to reduce conduction loss. **Figure 10** shows the simulated carrier distribution in the on state. In the conventional IEGT, the near-surface area has lower carrier concentration and thus exhibits higher resistance than the deeper area. In order to increase the carrier concentration near the surface and thereby further improve the IE effect, we utilized a trench structure for the new IEGT. As a result, the new IEGT, ST3000GXH31A, provides considerably lower $V_{ce(sat)}$ than the conventional IEGT(**Figure 11**).

Conversely, increasing the carrier concentration causes the current-interrupting capability of the IEGT to decrease. We have also resolved this issue by optimizing the carrier distribution. **Figure 12** shows the turn-off waveform at double the rated collector current, which indicates that the ST3000GXH31A provides a sufficient current-interrupting capability.

Since IEGTs are utilized at relatively low carrier frequency in HVDC systems, reducing $V_{ce(sat)}$ is effective in reducing the power loss during inverter operation. The ST3000GXH31A provides a 31% reduction in the total power loss of a two-level inverter, compared with the previous IEGT as shown in **Figure 13**.

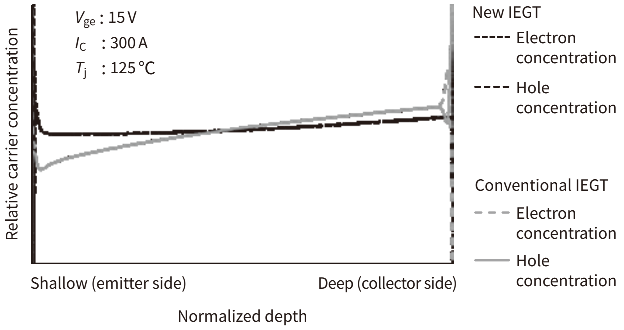


Figure 10. Simulated vertical carrier distribution in on-state

The new IEGT has higher carrier concentration near the surface than the conventional IEGT.

Characteristic	New IEGT ST3000GXH31A	Conventional IEGT ST3000GXH24A
$V_{ce(sat)}$ (V)	2.5	3.5
E_{on} (J)	11.6	22
E_{off} (J)	19.7	17

E_{on} : Loss per turn-on event

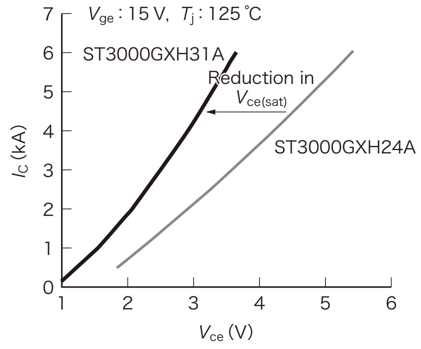


Figure 11. Electrical characteristics of newly developed ST3000GXH31A

The new IEGT has considerably lower $V_{ce(sat)}$ than the conventional IEGT.

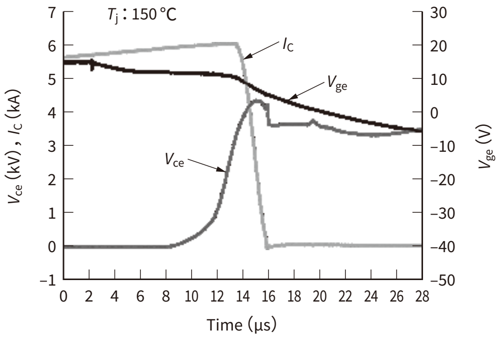
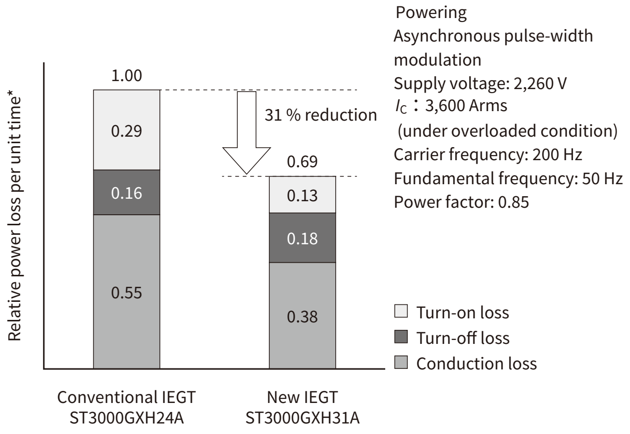


Figure 12. Turn-off waveform of ST3000GXH31A (double rated collector current)

The turn-off waveform at double the rated collector current indicates that the ST3000GXH31A provides a sufficient current-interrupting capability.



* Normalized such that total loss of conventional IEGT is equal to one.

Figure 13. Comparison of loss of previous product and ST3000GXH31A

Compared to the conventional IEGT, the ST3000GXH31A, a newly developed IEGT, provides a 31% reduction in the total loss of a two-level nverter.

4. Conclusion

We have mainly improved the MOS structure of the IGBTs for use in voltage-resonant circuits for home appliance applications and that of the IEGTs for HVDC applications according to their specific requirements. This report has discussed the technologies that we used to reduce their power loss.

We will continue to contribute to energy saving by offering semiconductor products optimized for their applications.

References

(1) Omura I. et al. 1996. “Oscillation effects in IGBT's related to negative capacitance phenomena.” IEEE Trans. Electron Devices. 1999(**46**) 1: 237–244.