Meeting the Demand for Smaller and More Reliable Power Modules with the X Series RC-IGBTs

Modern power conversion involves an array of applications from electric vehicle onboard chargers (OBCs) and fast DC chargers to solar micro-inverters and larger industrial laser, welding, and automation use cases. One striking commonality between these applications is the continual push in chip design, fabrication, and packaging technologies to improve on power density, thermal management, and efficiency, all while maintaining a bottom line in cost. Traditional insulated-gate bipolar transistors (IGBTs) have been ubiquitously leveraged in power electronics applications, but users looking to move up the power spectrum will typically require either the paralleling of power modules or opting for a larger, bulkier module that has a higher voltage and current rating. Both of these options typically lead to a dimensionally larger solution with the same - if not more - heat dissipation and reliability concerns.

Reverse conducting IGBTs (RC-IGBTs) enable engineers to move up the power spectrum without increasing the form factor of their design. Their lower power dissipation and higher reliability allow for energy savings and higher mean time to failure (MTTF) than traditional IGBTs. This article explores the advantages of this next generation in IGBT technology and how this benefits industrial and automotive applications.

Setbacks of Traditional IGBTs

Issues with miniaturization and increasing the output current

IGBTs have long been one of the most popular power semiconductor switch devices in the market. These devices strike the balance between cost effectiveness and power density. Fuji has steadily improved on their IGBT technology in miniaturization, cost reduction, and performance (e.g., power density, thermal management, efficiency) since their commercialization in 1988. In this iterative process towards improvement, there are several outstanding design tradeoffs and bottlenecks that could potentially limit the IGBT technology—any further miniaturization of the traditional IGBT module increases power density, which can cause reliability issues. The increase to the output current of an IGBT module causes the operational temperature of the IGBT and the freewheeling diode (FWD) to rise, also potentially causing lower module reliability.

Snapback

IGBTs also often face the common issue of the “snapback” of the I-V characteristic. In this phenomenon, the IGBT is triggered at a high voltage and then falls back to conduction at a lower voltage. This process is started with a small current that flows from collector (anode) to emitter (cathode). As this current increases, so does the voltage drop between the buffer (field-stop) region and the anode. At this point, the anode will begin injecting carriers (holes) into the drift region as there is sufficient voltage drop in this junction. Snapback will occur when the carrier concentration in the drift region is comparable to the doping concentration. This is known as conductivity modulation where the drift region resistance drops significantly causing a snapback in voltage. IGBT snapback can cause several issues including the following [1]:

- Prevent full turn-on of the device
- Cause a high forward voltage drop, which may also increase the conducting energy loss
- Create a non-uniform current distribution, which can decrease the conducting capability and reliability of the device

Tradeoff between the saturation voltage and turn-off switching loss

Like any BJT, the IGBT will conduct current between the collector and the emitter and drop voltage between these two. This collect-emitter voltage (V_{CE}) is a representation of the voltage drop of the IGBT in the ON state. The power dissipated by the transistor is equal to the product of the collector current and collect-emitter voltage. This collect-emitter voltage (V_{CE}) will change in accordance with the collector current (I_C), gate voltage (V_{GE}), and temperature (T_j). The smaller the value of V_{CE}, the smaller the power dissipation loss. The collector-emitter saturation voltage ($V_{CE(sat)}$), has a trade-off relationship with turn-off switching losses. Generally, the higher the saturation voltage, the lower the turn-off losses. The lower the saturation voltage, the higher the turn-off losses. Ideally, an IGBT could keep the $V_{CE(sat)}$ low (and thus keep the turn-on/conduction losses low) while also limiting any turn-off losses.

RC-IGBT Chip Technology

In order to better meet growing market demands for power transistors, Fuji Electric developed reverse-conducting IGBT (RC-IGBT) technology to address these potentially limiting factors with IGBTs [2]. As shown in **Figure 1**, the RC-IGBT integrated an IGBT and FWD into a single chip to reduce the number of chips and total chip area. Along with this miniaturization, the RC-IGBT also exhibits improved performance. There is comparatively lower power dissipation along with a higher power density when combining the RC-IGBT technology with Fuji's 1,200 V 7th generation X-series module. The fusion of the chip and packaging technology enable the following:

- Downsized solution size
- Low power dissipation
- High reliability

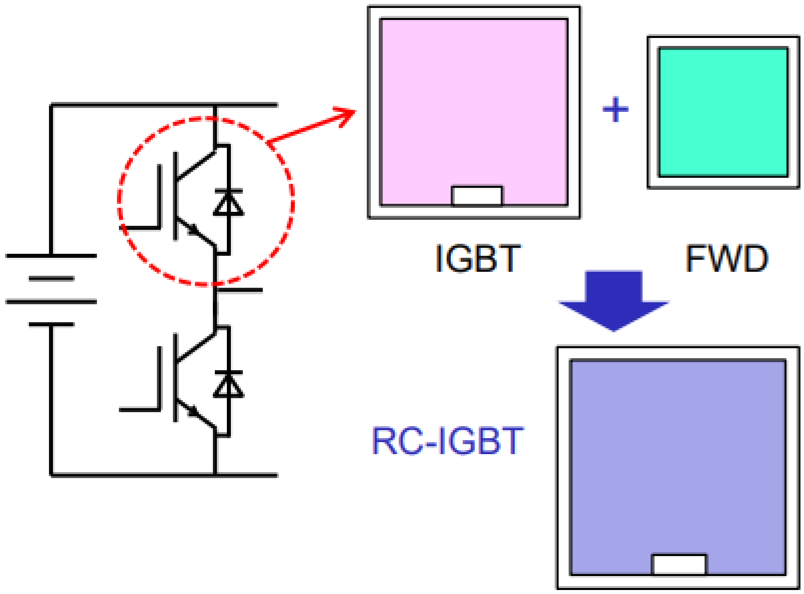


Figure 1 *Diagram and equivalent circuit of the 7th generation X-series RC-IGBT technology.*
Image Link

Downsizing the solution

There are several factors that allow the X-series RC-IGBTs to achieve a much higher power density than previous generations including the **improved chip technology** and **improved package technology**:

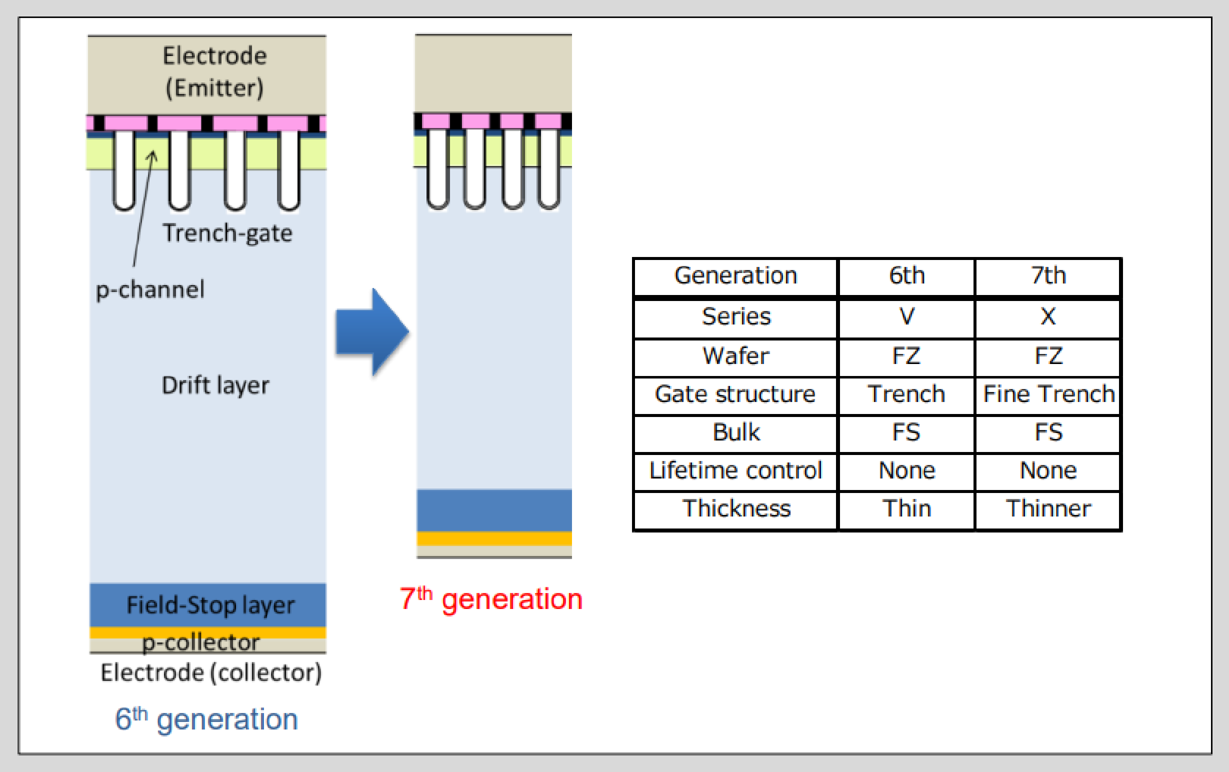
The combination of the optimized chip and package technology allows for an expanding current rating while also miniaturizing the IGBT module.

Improved chip technology

The 7th generation of RC-IGBT chip technology enables a thinner drift layer, the miniaturization of the trench gate structure and an optimized field stop layer (**Figure 2**). This drastically reduces the collector-emitter saturation voltage ($V_{CE(sat)}$). The products are formed into a thin wafer to improve the trade-off relationship with turn-off loss and $V_{CE(sat)}$. Typically, the utilization of thin wafer technology will have the additional consideration of voltage oscillations at turn-off and a reduction in the breakdown voltage. However, even this is improved upon through the optimization of the field stop layer—the voltage withstanding structure on the backside of semiconductor chips. Overall, these improvements ultimately reduce inverter power losses and increase the efficiency of the end design.

Improved package technology

The 1,200 V 7th generation X-series module features an improved stability and high durability under high temperature conditions. New materials are used along with an optimized bonding wire diameter for a more robust structure and a new silicone gel solution allows a maximum continuous operating temperature (T_{vjop}) of 175°C (previous generation is 150°C). This allows the RC-IGBT to have a higher output power without increasing the package size. For instance, the rated current of the 1200 V PIM (Power Integrated Module) package for X-series is increased to 75A from 50A of the previous generation, this yields a 50% expansion of rated current.



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 2 *IGBT cross-section comparison between the older (6th) generation of IGBT and the new (7th) generation of X-series RG-IGBTs.*
Image Link

Low power dissipation

Improving the tradeoff between turnoff losses and saturation voltage

The on-state voltage drop (V_{CE}) of the X-series RG-IGBTs is reduced by 0.25 V. As a result, power dissipation during device conduction decreases and the power conversion efficiency of the end design increases. However, this does not come with the common tradeoff of more turn-off losses (**Figure 3**). In fact, the X-series turn-off energy has dropped by 10% by significantly reducing the tail current. This reduction in the tail current is achieved by employing the thinner drift layer (see “Improved chip technology” section). This chip optimization directly realizes a power loss reduction despite the fact that the chip has been shrunken.

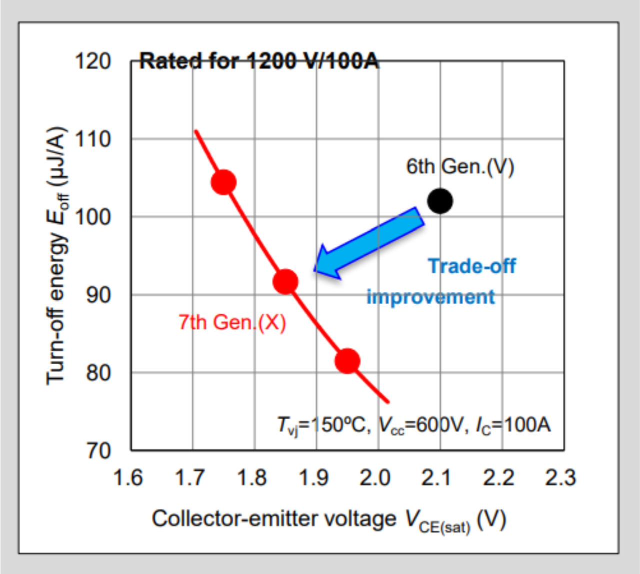


Figure 3 *Turn-off energy (E_{off}) over collect-emitter voltage ($V_{CE(sat)}$). The 7th generation of RC-IGBTs shows an improvement in both E_{off} and $V_{CE(sat)}$.*
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High reliability

Rooting out the reliability issues of traditional IGBT modules

The high reliability of the X-series RC-IGBTs is realized with its enhanced stability and durability against high temperatures with a guaranteed T_{vjop} of 175°C. Typically, an IGBT module consists of a ceramic substrate for insulation that is soldered to a base plate that is generally constructed of copper (**Figure 4**). The high heat dissipating ceramic substrate has the biggest impact on the thermal resistance between the chip and the heat sink. Alumina (Al_2O_3) and aluminum nitride (AlN) ceramics are often used due to their high thermal conductivity and cost-effectiveness. However, the AlN substrate is generally thick and therefore fairly rigid. This will cause reliability issues with the solder layer under the substrate--thermal stress can cause cracks and deformations at this interface. This was improved upon by thinning the AlN ceramic layer while maintaining a good thermal resistance and material strength through optimal ceramic sintering condition, which allows for a high heat dissipation substrate that is less prone to failures due to thermal stress (increasing reliability while decreasing module size).

Another potential failure mechanism for IGBT modules is the solder joint under the chip and the connected wire on the chip’s surface. At this joint, the mechanical strain between the two interfaces can be severe at high temperatures. The different coefficients of thermal expansion (CTE) between the surfaces directly leads to an oscillating mechanical stress at the joints. This can lead to failure. The 7th generation X-series modules resolve this by optimizing the bond wire diameter and length to ensure a sufficient power cycle withstand capability at the continuous operation temperatures of 175°C.

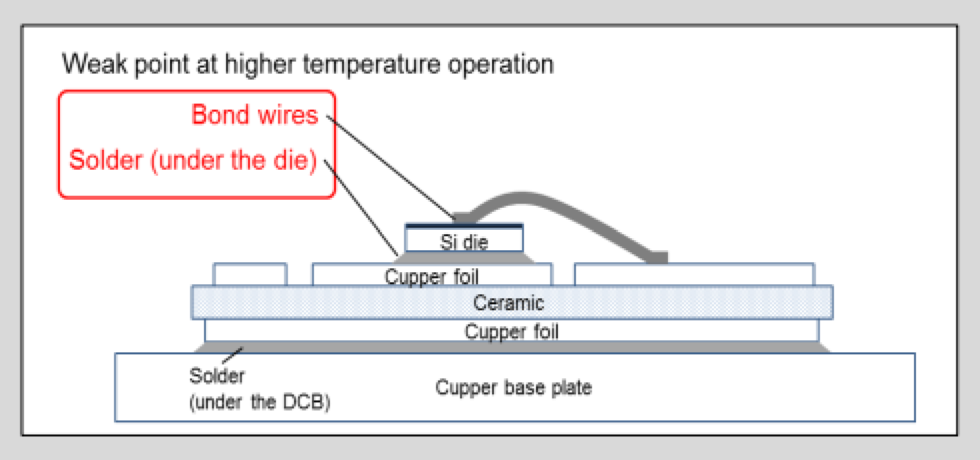

Figure 4 *Module structure for IGBTs. The AlN ceramic layer resolved the major issue of a decreased solution reliability with miniaturization and temperature rise while the Silicon gel was improved upon to prevent hardening/cracking at high temperatures. The bond wire diameter and length were both optimized to mitigate the mechanical stress at the joint between the bond wire and the die.*

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Improvement in snapback

The snapback phenomenon was resolved by optimizing the structure of the chip. Electrons are injected into the cathode layer of the FWD region, this suppresses hole injection from the collector layer of the IGBT and hinders conductivity modulation; the prominent reason for the snapback phenomenon (**Figure 5**). This greatly improves device reliability by mitigating all the negative effects of snapback.

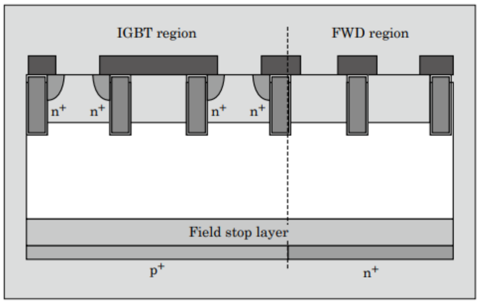

Figure 5 Cross-sectional diagram of RC-IGBT structure

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Conclusion

The combination of the improvement in chip technology and package technology ultimately leads to an increase in power density and reliability of the IGBT module. Enhancements to the chip level include a thinner drift layer, miniaturization of the trench gate structure, and an optimized field stop layer. At the package level, the thinning of the AlN substrate, improvement of the Silicone gel, and the optimization of the bonding wire diameter and length all allow for device reliability at high continuous operating temperatures. The combination of all of these enhancements allow for an expanding current rating and the miniaturization of the IGBT module. This ultimately allows the end design (e.g., inverter) to be more efficient, power dense, and reliable while maintaining its cost-effectiveness.

References

1. Weizhong Chen, Zehong Li, Yong liu, Min Ren, Bo Zhang, Zhaoji Li, A snapback suppressed reverse-conducting IGBT with built-in diode by utilizing edge termination, Superlattices and Microstructures, Volume 70, 2014, Pages 109-116, ISSN 0749-6036, https://doi.org/10.1016/j.spmi.2014.02.018.
2. A. Yamano et al., "The Series of 7th-Generation "X Series" RC-IGBT Modules for Industrial Applications," PCIM Europe 2018; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 2018, pp. 1-8.