High Performance 7th Generation Chip Installed Power Module for EV/HEV Inverters

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Abstract
This paper presents a high performance power module series (J1-Series), which is equipped with next generation ultra-thin chip technology. The 7th generation IGBT is having an optimized $V_{\text{CE(sat)}}$ - $E_{\text{off}}$ trade-off characteristic. For inverter operation, the 7th generation diode as the Free Wheel Diode (FWD) is finely tailored to have an optimized triangular trade-off characteristic between $V_F$, $E_{rr}$, and reverse recovery softness. Additionally, two specific technologies, that is wire-bond-less Direct Lead Bonding (DLB) structure and direct cooling structure with an integrated water-cooled Al fin, are applied to address major requirements of high power-density, low loss, and high reliability for Electric and Hybrid Electric (EV/HEV) power-train inverter applications. The combination of DLB structure and these latest generation chips successfully achieved high efficiency inside a compact module with high power handling capability.

1. Introduction
Since the very successful release of the world’s first mass-produced HEV in 1997, the number of HEVs and EVs has been gradually increasing in major cities around the world. Along with the increase of the market size, the system of the operation is also diversified, and high power density modules have become a requirement especially in recent years. The "J1-Series" has been developed to meet these requirements of “high reliability”, “compact size” and “high efficiency” (Fig.1). Firstly, “high reliability” is achieved by the DLB structure. Compared with conventional Al wire, the power cycling lifetime of the DLB structure was increased by ten times [1]. Secondly, “compact size” was achieved by a newly designed compact package with improved thermal performance in spite of small foot print and module’s weight [2]. Thirdly, “high efficiency” was achieved by the next generation ultra-thin chip technologies, 7th generation IGBT and Relaxed Field of Cathode (RFC)-diode [3-6]. The optimized combination of these technologies has brought successful improvement of the “J1-Series” performance dedicated for EV/HEV application.

Fig. 1. External appearance in front and rear side view of the J1-Series Power Module
2. CHIP TECHNOLOGY

2.1. 7th generation IGBT

Fig. 2 shows the cross-sectional structure of conventional Punch Through (PT) IGBT and 7th generation Light Punch Through (LPT) IGBT. The fabrication process of ultra-thin wafer enabled to use the LPT structure for the 650V class IGBT leading to higher efficiency by reducing both the saturation voltage $V_{CE(sat)}$ by 13% and the turn-off switching loss $E_{off}$ by 14% as shown in fig.3. The switching test was performed using the 600A/650V power module as a representative example of the J1-Series under the following conditions: $V_{cc} = 420V$, $I_c = 600A$, and $T_j = 125^\circ C$. Fig.4 shows the turn-off waveforms of 7th generation IGBT and conventional IGBT, demonstrating that $E_{off}$ is markedly improved thanks to the tail current suppression especially at the high temperature. Furthermore, the saturation current of 7th generation IGBT is also optimized to be less than half of the conventional IGBT. The short circuit test was performed using the 600A/650V power module as a representative example of the J1-Series under the following conditions: $V_{cc} = 420V$, and $T_j = 125^\circ C$. Fig.5 shows the experimental short circuit waveforms of 7th generation and conventional IGBT. The short circuit current peak of 7th generation IGBT is saturated and suppressed by half of the conventional IGBT. Additionally, the on chip-sensors such as current-sensor and temperature-sensor are available that they allow the control of circuit protection at proper timing. Accordingly, 7th generation IGBT can be turned-off safety whenever short circuit mode operation occurs.

(a)Conventional IGBT

(b)7th generation IGBT

Fig. 2. Cross-sectional view of the conventional IGBT and 7th generation IGBT
Fig. 3. Experimental results for trade-off characteristics between $V_{CE(sat)}$ vs. $E_{off}$ of the conventional IGBT and 7th generation IGBT

Fig. 4. Experimental turn-off waveforms of the conventional IGBT and 7th generation IGBT

Fig. 5. Experimental short circuit waveforms of the conventional IGBT and 7th generation IGBT
2.2 7th generation diode

The 7th generation diode is also thinner than a conventional diode, and a RFC-diode structure is employed to achieve the reverse recovery softness with superior electrical characteristics. Fig.6 shows the cross-sectional structure of conventional and 7th generation diode. Generally, high speed turn-on is required in order to improve the turn-on switching loss $E_{on}$, but it is limited by the reverse recovery softness of FWD especially in the case of the thin diode.

By using ultra-thin wafer fabrication technology, with backside lithography process, the RFC diode with both the lower forward voltage $V_F$ and the soft reverse recovery is achieved. In the recovery operation, whenever the high speed recovery $dV/dt$ occurs, the reverse recovery current is soften by the injection of the hole current from the cathode P+ region.

RFC-diode can achieve the reverse recovery softness and allow high speed recovery operation, therefore 7th generation IGBT can turn on at higher $dV/dt$ and improve the turn-on switching loss $E_{on}$. Finally, the 7th generation diode has improved the trade-off, $V_F$ is improved by 14% at the same $E_{rr}$ as shown in Fig.7. The switching test was performed using the 600A/650V power module as a representative example of the J1-Series under the following conditions: $V_{cc} = 420V$, $I_c = 600A$, and $T_j = 125°C$.

Fig. 6. Cross-sectional view of the conventional diode and 7th generation diode

Fig. 7. Experimental results for trade-off characteristics between $V_F$ vs. $E_{rr}$ of the conventional diode and 7th generation diode
3. PACKAGE TECHNOLOGY

The DLB structure compared with conventional wire-bonding structure is illustrated in Fig.8. The DLB structure can realize high power cycling lifetime and also suppress the parasitic inductance of internal wiring of module by almost 50% compared with conventional wire bonding structure [1]. If the parasitic inductance is higher, e.g. the one of a wire bonded module, the peak of the reverse recovery surge also will rise higher and its dv/dt will be sharpened potentially causing the oscillation of $V_{AK}$. The utilized DLB structure halves the parasitic inductance and breaks through the limitation of switching speed for wire bonded structures. Moreover the DLB reduces the wire resistance and improves DC loss by almost 50%. Thanks to this improvement of high current flow capability the single chip operation is realized even in a very high current application.

![Fig. 8. Schematic view of wire-bonding structure and DLB structure](image)

4. Experimental Results

The power handling capability of “J1-series” has also been improved by the 7th generation chip technology with DLB structure. Fig.9 shows the maximum junction temperatures of 7th generation and conventional chips installed in the J1-series 600A/650V power modules during inverter operation under the following conditions: Main battery voltage = 420V; three phase PWM switching frequency (fc) = 5kHz; coolant temperature (Tw) = 65°C; coolant flow-rate = 10 l/min.; In the module equipped with 7th generation chips, the maximum junction temperature was decreased by 15°C compared with conventional generation chips at an operation current of 450 Arms. The 7th generation chips provided to the “J1-series” module an extra thermal margin to the indicated 150°C limitation.

![Fig. 9. Experimental results for maximum junction temperature during the inverter operation of 7th generation and conventional chips installed “J1-series”module.](image)
5. Conclusion

High Performance 7th Generation IGBT and diode chips for the “J1-series” have been developed to meet the requirements of the evolving EV/HEV market. The 7th generation of IGBT achieves lower $V_{CE(sat)}$, $E_{off}$, and the RFC-diode improves the triangular trade-off between $V_f$, $E_r$, and reverse recovery softness which allows high speed turn-on of the IGBT, resulting in improved $E_{on}$ loss. The DLB structure realizes lower parasitic inductance and resistance, enabling higher $di/dt$ switching of the next generation chips. Finally the experimental results reveals that a combination of 7th generation chips and the proposed DLB structure expanded the achievable operation current reducing the junction temperature 15°C compared with conventional chips installed in the same module. As conclusion, the new “J1-Series” can realize a wide range inverter operation and accommodate a variety of requests for EV and HEV applications.

6. Literature