Next-Generation Power Module for Automotive Applications – J1-Series

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In recent years, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have evolved remarkably, and in turn, there is a growing demand for higher performance, smaller, and lighter power modules as key components.

In response to these market needs, the smaller, lighter, higher-performance “J1-Series” has been developed. A direct water-cooling structure was adopted to achieve 30% lower thermal resistance, 40% smaller footprint, and 76% lighter weight.

1. Outline of J1-Series Power Module

The J1-Series comprises automotive power semiconductor modules integrating six each of seventh generation insulated-gate bipolar transistors (IGBTs) and seventh generation diodes in a pin-fin type direct water-cooling package (Fig. 1).

![Fig. 1 External appearance of J1-Series power module](image)

The product lineup covers various user needs by means of four models with the same outer dimensions and electrode layout, but with different ratings (Table 1).

<table>
<thead>
<tr>
<th>Model</th>
<th>Ratings (Ic/Vces)</th>
<th>Vce(sat) Typ. @Ic, 25°C</th>
<th>Package size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT600CJ1A060</td>
<td>600A/650V</td>
<td>1.4V</td>
<td>120x115.2x31 (6-in-1)</td>
</tr>
<tr>
<td>CT400CJ1A090</td>
<td>400A/900V</td>
<td>1.7V</td>
<td></td>
</tr>
<tr>
<td>CT300CJ1A120</td>
<td>300A/1200V</td>
<td>1.7V</td>
<td></td>
</tr>
<tr>
<td>CT300CJ1A060</td>
<td>300A/650V</td>
<td>1.4V</td>
<td></td>
</tr>
</tbody>
</table>

As shown in the circuit diagram (Fig. 2), the internal connection of the J1-Series uses a 6 in-1 configuration for size reduction and efficient installation at the user’s site. In addition, each IGBT chip is provided with a current sensor for short-circuit protection as well as an on-chip temperature sensing diode for overtemperature protection, which is able to directly monitor the chip temperature.

![Fig. 2 Circuit diagram of J1-Series](image)

2. New Package Structure

To implement the development concept, a new package structure has been developed for the J1-Series (Fig. 3).

![Fig. 3 Internal package structure of J1-Series](image)

The J1-Series no longer uses heat sink grease as required by the previous structure; instead, it is equipped with a cooling fin integrated with the module to allow direct cooling and improve the cooling performance. In addition, by optimizing the shape and layout of the fin, and eliminating the solder layer beneath the isolation layer, the thermal resistance between the chip and the cooling water, \( R_{\text{th}(j-w)} \), is reduced by more than 30% from the level of the conventional product that consists of three J-Series transfer-molded power modules (T-PMs) mounted on a Cu cooling fin with the heat sink grease between them (Figs. 4 and 5).

To increase the current carrying capacity and thus reduce the package size, a direct-lead-bonding (DLB)
structure has been adopted (Fig. 6), where the upper surface of the chip is directly bonded to the Cu lead. Compared to the conventional wire bonding (WB) structure, the contact area can be expanded, and thus the current carrying capacity can be significantly improved. In combination with the previously described improved cooling performance, the DLB structure has successfully reduced the package size and hence the footprint by 40%1 (Fig. 7).

In addition, the DLB structure ensures more uniform chip temperature while power is supplied compared to the WB structure, and thus generates less thermal stress in the chip and improves the power cycle tolerance.

The J1-Series uses aluminum as the cooling fin material to provide high corrosion resistance against cooling water and to reduce the weight by 76%2 from the conventional product (Fig. 4).

As described above, the J1-Series is smaller and lighter, and has higher cooling performance and enhanced current carrying capacity.

3. Evaluation Kit

To help the user evaluate the J1-Series, an evaluation kit has been newly designed and prepared as a support tool. The kit consists of a driver board, a DC-link capacitor and a water-cooling jacket. It is optimized to enhance the features of the J1-Series, that is, “higher performance” and “smaller and lighter”. The photo in Fig. 8 shows the J1-Series PM and driver board mounted on the water-cooling jacket.

The driver board is configured with an IGBT gate driver IC (M81603JFP), newly developed for the J1-Series PM.

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1 J1-Series 120×115 [mm²], Conventional product 220×105 [mm²]
2 J1-Series 335 [g], Conventional product 1250 [g]
4. Gate Driver IC (M81603JFP)

In addition to the protection functions equivalent to those of the conventional intelligent power module (IPM), namely, short-circuit protection (SC), overtemperature protection (OT) and undervoltage protection (UV), the gate driver IC, M81603JFP, is equipped with the following additional gate driver and protection functions all integrated in a single IC package.

1) By adding a function to switch the turn-off gate resistor according to the chip temperature, the IGBT switching loss is reduced by 20%.

2) By adding a correction circuit for the temperature characteristics of the overcurrent protection (OC) function, it is possible to lower the level of OC sensitivity to the temperature and thus it is no longer necessary to consider the chip temperature margin in the product design. Figure 9 shows the measurement results for the OC trip level when the correction is used.

3) By adding a circuit to switch the gate drive voltage from 12.7 V to VDD voltage\(^3\) during the turn-on period, the maximum short-circuit current is limited to below a certain level. In addition, the OC circuit is optimized to reduce the response time of the protection circuit at the time of short circuit. These additional features have reduced the power loss during the short-circuit period by 50%, and thus the product design no longer needs to consider the tradeoff between chip performance and short-circuit tolerance.

4) By providing an independent soft shutdown gate resistor to each of the SC and OC circuits, the surge voltage in the case of a short circuit is halved and the delay time in the case of an overcurrent is also halved.

5. Verification of Current Carrying Capacity

We verified the current carrying capacity of the J1-Series by evaluating its electrical characteristics and thermal resistance. Under the conditions of carrier frequency \(fc = 5 \text{ [kHz]}\), cooling water temperature \(Tw = 65 \text{ [°C]}\), and cooling water flow rate = 10 [l/min], a current carrying capacity of 600 A (= 424 A rms) or higher was demonstrated even when the electrical parameters and thermal resistance were set to the maximum values.

6. Conclusion

In response to EV and HEV market needs, the new “J1-Series” of automotive power semiconductor modules has been developed along with an evaluation kit. The J1-Series achieves high performance, compact size and light weight compared with the conventional products, contributing to development of the automotive inverter system.

The evaluation kit was developed as a user support tool. It consists of a water-cooling jacket and a driver board that includes driving and protection circuits optimized for the J1-Series.

We will continue to work on mass-producing products, enhancing the product lineup and offering products to users.

\(^3\) Power supply voltage of the IGBT driver circuit