Investigation of Automotive Power Semiconductor Module Operates at Elevated Cooling Temperature

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Abstract:

The degradation of performance and reliability of power semiconductor module with increment of temperature is an important issue to deal with in Hybrid and Electric Vehicles (HEV/EV) application. The high ambient and cooling temperatures are challenges to HEV/EV modules as the automotive industry is interested in cooling power electric system by sharing with engine's high temperature coolant. The elimination of low temperature cooling circuit has significant benefits to cost and volume/weight. However, the performance and reliability will be worsened to a large degree which may affect the feasibility of module application. In this work, an investigation is done to evaluate the electrical, thermal performance and reliability of a standard direct liquid cooled automotive IGBT module operates at 105°C coolant.

1. Introduction

Power system has substantial influence on development and popularization of Hybrid and Electric Vehicles (HEV/EV) as it is the critical part limiting performance, reliability and cost of whole vehicle. The overall characteristics of power system are dependent on its core active component, usually power semiconductor Insulated Gate Bipolar Transistor (IGBT) module. With the automotive market becoming one of the fastest growing sectors in power semiconductor industry, huge efforts is being made in developing high standard automotive IGBT modules [1–3].

In HEV/EV, the internal combustion engine requires a coolant loop with the maximum temperature of 105°C and an additional loop is required at lower temperature (typically 65°C) for power system due to temperature limitations of power electronics [4–6]. The automotive industry is keen to cool power system by sharing coolant with engine for reasons of eliminating the additional cooling system, reducing cost and volume/weight. The elevated cooling temperature narrows the margin to permitted maximum junction temperature (T_{jmax}) and restricts output power and current, and accelerates degradation of power module. However, IGBT module and power systems are capable of operating with a coolant temperature (T_F) of more than 90°C are reported [6–9].

IGBT module performance and reliability are affected negatively by high junction temperature (T_j). The critical electrical parameters are degraded with increase of T_j, and the module reliability will deteriorate at high T_{jmax} and high excursion of T_j (ΔT_j). The increase of saturation voltage ($V_{CE\ on}$), switching energies and leakage current can increase power loss significantly which in return elevates T_j. At the module level, high T_j and ΔT_j will accelerate exponentially the degradation of joining and interconnection materials, leading to significant reduction of module lifetime [10–13]. Therefore, the benefit of high T_F for automotive module must be evaluated in terms of performance and reliability.

In this work, the detailed investigation of automotive power IGBT module operates at elevated T_F is done. A 650V automotive module integrated with direct cooling structure, packaged with advanced switches, optimized materials, and novel interconnecting technologies is selected as benchmark to evaluate the electrical, thermal performance and reliability with 105°C engine cooling systems.

2. The benchmark automotive power module

The power train system in HEV/EV has functions of driving electric motor and charging battery in regenerative braking [3]. The power semiconductor module is of the most importance that limits power, performance, reliability, volume, weight and cost of the power system [14, 15]. The power required to drive HEV/EV is from a few kW to more than 100kW depending on vehicle hybrid level and size. It is summarized in Table 1 with DC voltage (V_{DC}) levels and power devices ratings.

Table 1 Full voltage HEV/EV power system and semiconductors

	Start-stop	Micro HEV	Mild HEV	Full HEV	Plug-in HEV	EV
DC voltage (V)	12	48	48–150	150–350	>350	>350
Power (kW)	≤5	≤5	5–15	15–50	20–50	80–120
Power devices	MOSFET 30–60V	MOSFET 60–100V	IGBT 400V	IGBT 650V	IGBT 650–1200V	IGBT 650–1200V

The objectives of high power density, high temperature, high efficiency and high reliability are required by HEV/EV. IGBT module with a blocking voltage of 650V, output power of 80kW and the T_{jmax} of 150°C is currently the benchmark product for passenger cars [16]. For enhancing module reliability, electrical, thermal and mechanical designs must be improved for automotive application as the working environment and missions are stringent, and as the increment of T_F.

In this work, a direct liquid cooling IGBT module with Cu pin fin is selected as benchmark for investigating the performance and reliability at high cooling temperatures.

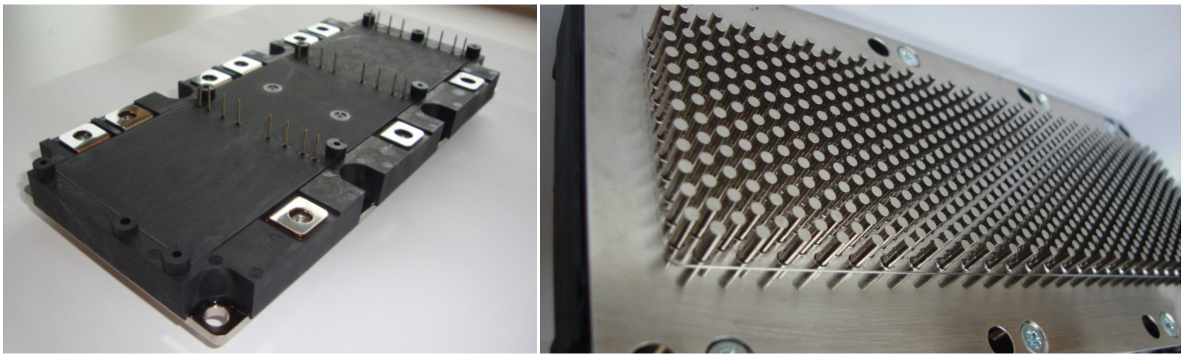


Fig. 1 Direct liquid cooling automotive module with Cu pin fin base plate

As shown in Fig. 1, the module has 3-phase topology with blocking voltage of 650 V and nominal current of 550A. It is qualified for passenger HEV/EV systems of which peak V_{DC} is about 400 V. 80kW continuous and 120kW peak power can be output with the superior cooling structure. Power dissipation is optimized by the advanced IGBT and Free Wheeling Diode (FWD) technologies.

The thermal performance is enhanced significantly by direct liquid cooling structure as no Thermal Interface Layer (TIL) between case and heat sink. The base plate itself, with substrate attached on by soldering, acts as heat sink and directly contacts coolant through fins [3]. In Fig. 2, the junction to heat sink thermal resistance ($R_{th\ j\text{-}h}$) of conventional module and the benchmark automotive module are simulated and compared. It is found that the TIL of grease contributes about 50% of the total $R_{th\ j\text{-}h}$ in conventional module, meaning that the direct cooling module can reduce almost half of the system $R_{th\ j\text{-}h}$ [9, 13]. Therefore, ΔT_j will be decreased accordingly, which is essential to keep T_j under T_{jmax} at elevated T_F and to improve the long term reliability.

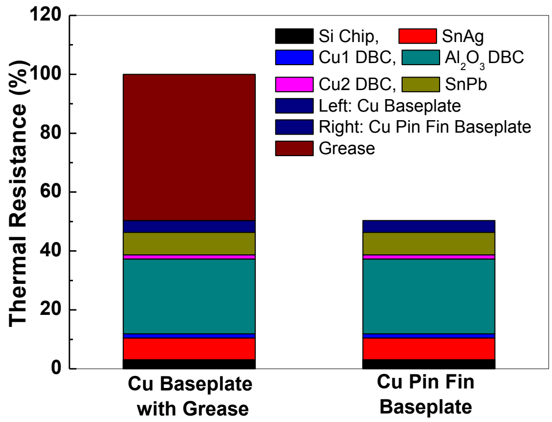


Fig. 2 Comparison of $R_{th\ j\text{-}h}$ between conventional and direct liquid cooled IGBT modules

3. Performance of automotive module at elevated temperature

The effects of high temperature on IGBT are known to increase $V_{CE\ on}$, switching time and energy, and increase leakage current. To apply IGBT module at elevated T_F of 105°C, the extensive investigation should be done on its power capability, performance and reliability.

3.1 Saturation and forward voltage

With increasing of temperature, the lattice vibration and impact ionization are enhanced substantially, the carrier is scattered intensively by lattice and the ionized impurity, which result in the negative temperature coefficient of carrier mobility and increase of on resistance and $V_{CE\ on}$ at high temperature. This effects are significant in unipolar device such as MOSFET, and in IGBT it is compensated by injection of carrier from back side p+ layer and by the front side design to enhance carrier density. The forward voltage (V_F) of a diode has negative temperature coefficient because of the increase of thermal voltage (V_T) with temperature.

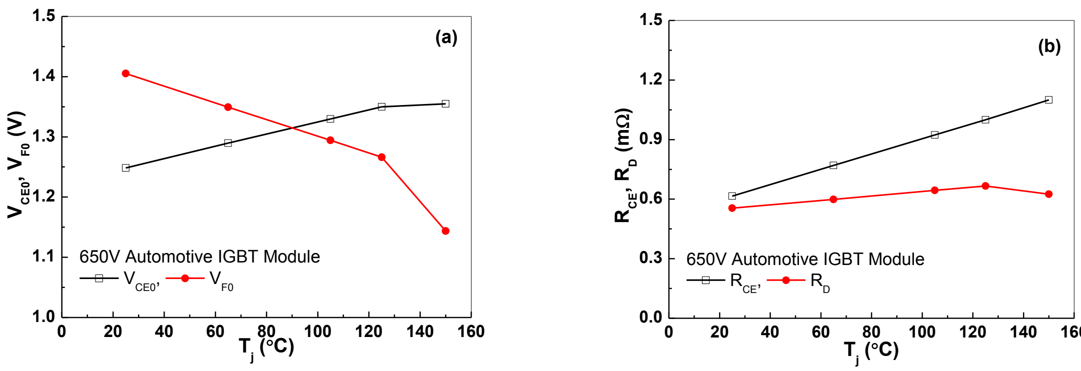


Fig. 3 Effects of temperature on V_{CE0}, V_{F0} (a), and R_{CE} ,R_D (b)

Fig. 3 is the variation of V_{CE0} and V_{F0} (saturation and forward voltage at zero current), and on state resistance (R_{CE} for IGBT and R_D for FWD) of the selected automotive module with temperature. $V_{CE\ on}$ and V_F are calculated by Eq. (1). The average conduction power loss

(P_{CT} for IGBT and P_{CD} for FWD), which are in proportion to on state voltage and resistance can be expressed by Eq. (2) [17].

$$V_{CE\,on} = V_{CE0} + R_{CE} \times I_{CE}, \qquad V_F = V_{F0} + R_D \times I_F \qquad (1)$$

$$P_{CT} = V_{CE0} \times I_{CE\,av} + R_{CE} \times I_{CE\,rms}^2, \qquad P_{CD} = V_{F0} \times I_{F\,av} + R_D \times I_{D\,rms}^2 \qquad (2)$$

Where I_{CE} and I_F are current of IGBT and FWD, $I_{CE\,av}$ and $I_{CE\,rms}$ are the average and RMS current of IGBT, $I_{F\,av}$ and $I_{F\,rms}$ are the average and RMS current of FWD.

In addition, the threshold voltage of IGBT ($V_{GE\,th}$) decreases with increase of temperature. The main reason is surface potential (equals to 2 times of Fermi potential) reduces with the Fermi level approaching middle of the band gap.

3.2 Switching energy and power dissipation

High temperature has influence on module's dynamic behaviour, in which switching off and reverse recovery are susceptible to temperature. The typical turn-off waveform has an initial close stage of MOS structure channel with a short and fast current fall, then shows the traditional current tail stage. The long tail current is supposed due to lack of hole injection from p+ anode then across the buffer layer into the n– body layer. So the high amount of electron in the area cannot be disappeared quickly through recombination with hole, resulting in long turn-off delay and high switching off energy [5].

For the anti-parallel diode, the carriers stored in depletion layer must be discharged in reverse transition stage which generates reverse recovery current and power dissipation. The effects are enhanced by high temperature.

The 3rd generation and above IGBT has achieved good trade off between $V_{CE\,on}$ and turn-off time/energy by trench gate and field stop layer [5, 18], and the fast switching technologies for diode are effective to reduce reverse recovery energy.

Fig. 4 is the effects of temperature on switching energies of IGBT and on reverse recovery energy of diode measured on the benchmark automotive module. The switching on performance is not temperature sensitive, but the switching off and reverse recovery energy increase by 12 and 85%, respectively from 65 to 150°C. This will reduce significantly the efficiency of power system, and result in high ΔT_j and the T_{jmax} in application. Therefore, the parameters of energy dissipation are very critical to power device evaluation and selection.

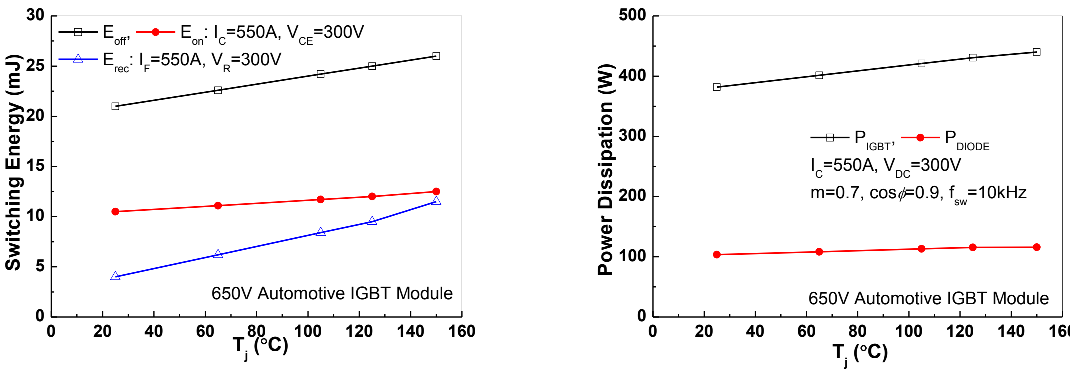


Fig. 4 Effects of temperature on switching energy and reverse recovery energy (Left)
Fig. 5 Increase of power dissipation with T_j (Right)

Fig. 5 shows the simulation results of power dissipation with variation of T_j. In the simulation, the module works at the rated V_{DC} and output current (I_{out}), and at a switching frequency of 10kHz. By increasing T_F from 65 to 105°C, the loss of IGBT and Diode can increase by 4.9

and 4.6%, respectively. The additional loss increment will in turn elevate T_j by about 2 and 1°C that estimated by power loss and $R_{th\ j\text{-}h}$ of IGBT and FWD.

3.3 Junction temperature and power output

T_j is simulated at different T_F and the rated output current level of 550A for this benchmark automotive module. It is crucial to ensure that T_j is well below T_{jmax} at any time, and a T_j safe margin of ~20°C is recommended in application. In Fig. 6, T_j reaches 147°C if the module output a 140kW and is cooled by 105°C coolant, which is not reasonable for the safety and reliability reasons. Therefore, the module can be either derated or be cooled by coolant of low T_F. However, it is possible to rise the T_F to 90–100°C which will give a 10–20°C margin to T_{jmax} if the module is required to work at the rated output levels.

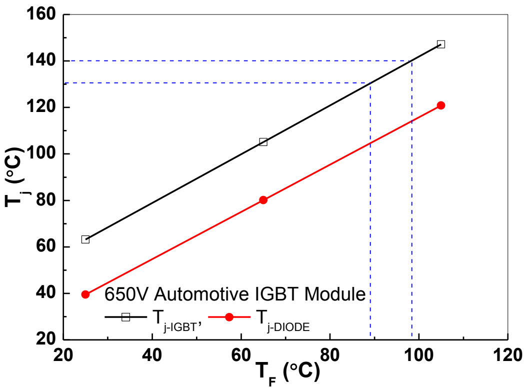
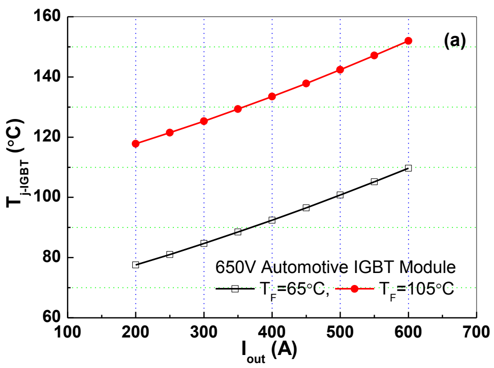


Fig. 6 T_j versus T_F at the rated output current

The maximum current and power output are predicted at different T_F. They are limited by the chip's 150°C of T_{jmax}, T_F and $R_{th\ j\text{-}h}$. The maximum power loss is obtained by temperature margin and $R_{th\ j\text{-}h}$, which can be taken for calculating the I_{out}. Fig. 7(a) shows that the I_{out} of the selected automotive module can be from 350 to 500A at which T_j is 130–140°C. I_{out} is limited by T_j at this operation conditions with high modulation index. The T_j of diode may become the limit factor with mission and modulation changes.

In Fig. 7(b), the output power and T_j are shown with I_{out} varying at T_F equals to 105°C. The maximum I_{out} and power can reach to 400–520A RMS and 92–120kW at T_F=105°C and V_{DC}=300V. This is qualified to typical EV that needs 100kW at the moment. By reducing $R_{th\ j\text{-}h}$ with optimized material and structure, the power output increases accordingly.



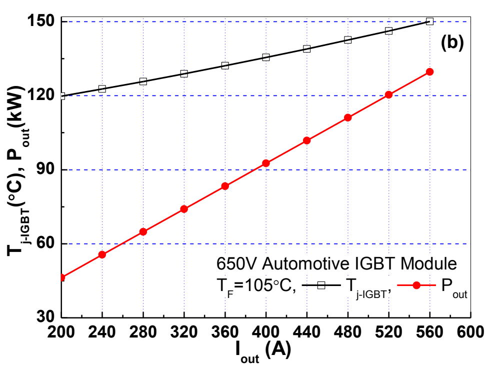


Fig. 7 T_j varies with I_{out} at different T_F (a),
T_j and output power at different I_{out} and 105°C coolant (b)

3.4 Thermal stability and lifetime

Except for electrical performance, power module's long time reliability is very sensitive to ambient and junction temperatures. It is generally believed that IGBT module failure results from thermal mechanical stress generated by difference of thermal expansions of materials during temperature variation. The stress destroys joining and interconnection parts such as solder layer, wire bonds, terminals and pins joints etc., which induce module failure because the increase of $V_{CE\ on}$, R_{th} and leakage current [3, 19, 20].

The automotive module works at high ambient and cooling temperature, and frequent active power cycling, so it always experiences high passive and active temperature excursions. The weak points in module are prone to delaminate and fail due to high absolute temperature and high ΔT_j. Lifetime of power module is limited by the weakest point of these parts, and it reduces exponentially with increase of minimum/maximum junction temperature (T_{jmin}/T_{jmax}) and ΔT_j. T_{jmin}/T_{jmax} is affected by T_F in the liquid cooling system. An outstanding thermal design gives smaller ΔT_j because of low $R_{th\ j\text{-}h}$ can enhance reliability substantially [10, 12, 21, 22]. The predicted module lifetime can decrease by more than 50% if the T_F increases from 65 to 105°C.

The lifetime of benchmark direct liquid cooled module is predicted by following reported procedures [3]. We adopt the New European Drive Cycle (NEDC) as HEV/EV mission, which represents the typical usage of passenger car in Europe, consisting of four repeated urban driving cycles and one Extra-Urban driving cycle. The automotive module in power train system is required a lifetime of 15 years or more than 250k km. The passive and active temperature cycles are simulated and counted, and are used in lifetime models to calculate the cycles to failure. It is found that lifetime is limited by chip solder joints for this application, but even at 105°C cooling temperature, the benchmark power module is capable of working for more than 15 years.

4. Conclusion

Cooling of power electronics system is regarded as one of the most important issues in HEV/EV development. The power semiconductor industry prefers to cool power module with lower temperature coolant which is beneficial to electrical, thermal performance, and to the long term reliability. However, HEV/EV manufacturer is trying to push the sharing of high temperature coolant between power module and engine with the advantages of system simplification, low cost and low volume/weight.

In this paper, a benchmark direct liquid cooled 650V automotive IGBT module is investigated at elevated cooling temperature. With increase of saturation voltage and switching loss, power dissipation can increase 5% if the coolant temperature increases from 65 to 105°C. However, because of the low junction to coolant thermal resistance, the junction temperature is still in the safe region when the module operates at its rated current and cooled at 105°C. Owing to the thermal and technology designs, the module can meet the power, junction temperature and lifetime requirement of HEV/EV system with sharing 105°C engine coolant..

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