Microelectronics Reliability xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Reliability design of direct liquid cooled power semiconductor module for hybrid and electric vehicles

Xiaoping Dai, Yangang Wang *, Yibo Wu, Haihui Luo, Guoyou Liu, Daohui Li, Steve Jones

[a] Power Semiconductor R&D Centre, Dynex Semiconductor Ltd., CRRC Times Electric Co. Ltd., Lincoln LN6 3LF, UK
[b] State Key Laboratory of Advanced Power Semiconductor Devices, CRRC Times Electric Co. Ltd., Times Road 169, Shifeng District, Zhuzhou, Hunan, PR China

ARTICLE INFO

Article history:
Received 29 June 2016
Accepted 8 July 2016
Available online xxxx

Keywords:
Direct liquid cooled
HEV/EV
IGBT
Packaging
Power module
Reliability

ABSTRACT

With the global interests and efforts in popularizing low carbon vehicles, automotive power module has been becoming one of the fastest growing sectors in power semiconductor industry. As working in a harsh environment, the performance and reliability requirements of automotive module are stringent than industrial products. In this work, an integrated direct liquid cooled power module with enhanced reliability for hybrid and electric vehicles (HEV/EV) is developed. The design and assembly of the module were optimized in terms of performance, weight, cost and reliability. The module is integrated Al direct liquid cooling structure, leading to about 40% reduction of weight and cost and almost 50% reduction of junction to heat sink thermal resistance. Therefore, the junction temperature stays below the upper limit at the worst operation case which enhances the thermal reliability and lifetime. By incorporating advanced die lead bonding, the parasitics can be reduced by 50%, which is beneficial to efficiency and reliability. Furthermore, the die and terminal attach technologies are investigated to improve reliability. The lifetime prediction under a typical driving cycle shows that the proposed module is capable of working in the whole vehicle service period.

1. Introduction

Hybrid and electric vehicles (HEV/EV) are generally regarded as fundamental products that help reduce dependence on fossil energy and alleviate global environmental pollution [1,2]. Therefore, the worldwide automotive industry is making big efforts to develop all levels of HEV/EV with substantial support from governments. It is expected that HEV/EV will be one of the strong growth products for automotive industry in the next few decades as a result of the improvement of performance, evolvement of technologies and reduction of ownership cost [1]. The growth of HEV/EV brings big opportunities to a series of assorted businesses, in which the power semiconductor industry is seeing considerable increment for supplying components and system to HEV/EV power train system. As the core component in the power system, automotive Insulated Gate Bipolar Transistor (IGBT) modules have been developed extensively in recent years [3–7].

It is forecasted that sales of HEV/EV will reach 6 M units in 2020 as shown in Fig. 1, which is about 5–6% of whole car market [8]. This results in a total sale of $5bn for automotive power modules [9]. Because of the requirements of high quantity and high quality, development of automotive module is becoming the top priority for power semiconductor industry. However, application of power modules in HEV/EV faces a series of challenges in power, performance, efficiency, reliability, volume, weight and cost. Among of them, reliability is the most critical issue that restricts automotive module and HEV/EV development, which is due to extremely high standard for vehicle safety and harsh environment [2,3, 10–15].

Reliability design of power module correlates closely with other aspects such as thermal, electrical and mechanical design. High reliability will in return benefit of power performance, temperature, efficiency and overload capability. Different designs and technologies have been proposed to enhance automotive module reliability. The Direct Liquid Cooled (DLC) is generally believed as a very promising solution for its advantages of thermal performance, reliability, integration, weight and size [16–19].

In this paper, a DLC power IGBT module with improved performance and reliability for HEV/EV is developed. By using CuAl plate and fins in DLC structure, the weight and cost are reduced by about 40% along with 50% reduction of junction to heat sink thermal resistance ($R_{th\ j\text{-}h}$). So the junction temperature (T_j) could be limited at a safe range at the worst case operation, leading to enhancement of thermal reliability and lifetime. Advanced die interconnection technology is proposed that results in about *50%* reduction in parasitic parameters and high efficiency and reliability. Moreover, the novel die and terminal attach technologies in the module assembly are proved to improve reliability. Finally, the module lifetime is predicted under a typical driving cycle

* Corresponding author at: Power Semiconductor R&D Centre, Dynex Semiconductor Ltd., CRRC Times Electric Co. Ltd., Lincoln LN6 3LF, UK.
E-mail address: yangang_wang@dynexsemi.com (Y. Wang).

http://dx.doi.org/10.1016/j.microrel.2016.07.063
0026-2714/

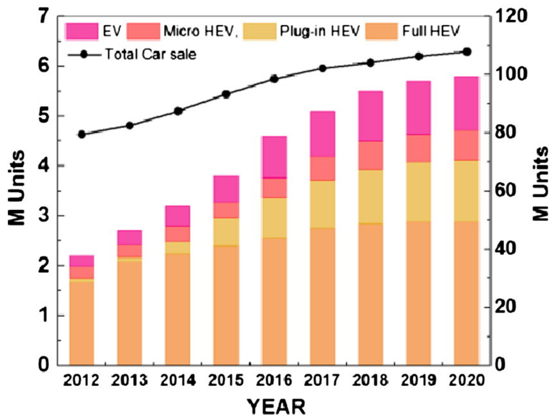

Fig. 1. The forecast of HEV/EV sales by 2020 [8].

and it is shown that the module can meet lifetime requirements of the automotive application.

2. CuAl DLC HEV/EV power module

In a conventional IGBT module design, plain metal or Metal Matrix Composite (MMC) base plate is integrated for the purpose of thermal management and mechanical support. An external heat sink cooled by air or liquid is contacted to the base plate, and the contact is usually enhanced by thermal interface layer. However, this traditional module and its mounting are usually not suitable for HEV/EV due to low cooling efficiency, high volume and heavy system [2].

DLC power module has been becoming more and more popular to automotive industry since its development. The base plate of DLC module is integrated with pin-fin or wick structures that enable coolant flowing directly through the plate. It has superior thermal performance and can deliver higher power than plain base or base plate free modules. The pin fins are usually made of Cu that is not effective in cost and weight [20].

In this work, we propose a CuAl plate bonded with pin fin system for HEV/EV module to provide enhanced performance and reliability, and to overcome the cost and weight disadvantages of conventional DLC module. Fig. 2 shows the packaging structure and concept of the CuAl DLC power module for a HEV/EV DC/AC system, as well as a module prototype using this concept.

The prototype is a six pack 3-phase DLC module with a blocking voltage of 650 V. Negative Temperature Coefficient (NTC) resistors are integrated into each phase to monitor T_j in operation. The maximum T_j (T_{jmax}) in switching is 150 °C. Enhanced alumina substrate is selected which has a double thermal capability of traditional alumina. A thin Cu layer is on top of the DLC base plate for substrate soldering, and a layer of Al and Al fins are bonded below the Cu layer by the micro deformation technology (MDT). This base plate system is light-weight, cost efficient and without nickel plated layer as Al has good resistance against corrosion. The mechanical reliability, cost and weight advantages of the CuAl pin fin system are addressed by [21–23]. The continuous and peak power outputs of the module are 100 and 120 kW at 300 V DC voltage and 230 A RMS. Table 1 is the list of material and optimized dimension of the DLC automotive module.

3. Reliability design for DLC HEV/EV module

In HEV/EV applications, power modules are stressed heavily and frequently by thermal, electrical and mechanical stresses, so the device itself and packaging parts are required to be robust enough during their operational life. On the other hand, the system is restricted by space, weight and cost of whole vehicle [6–8]. For these reasons, extensive effort has been taken to improve performance and reliability of automotive modules, and optimized design and packaging solutions have been proposed [2–7,16–20].

Design of automotive module should address the performance and reliability issues related to electrical, thermal and mechanical etc. The power devices, module structure, materials and packaging technologies are responsible for performance, reliability, cost, volume and weight.

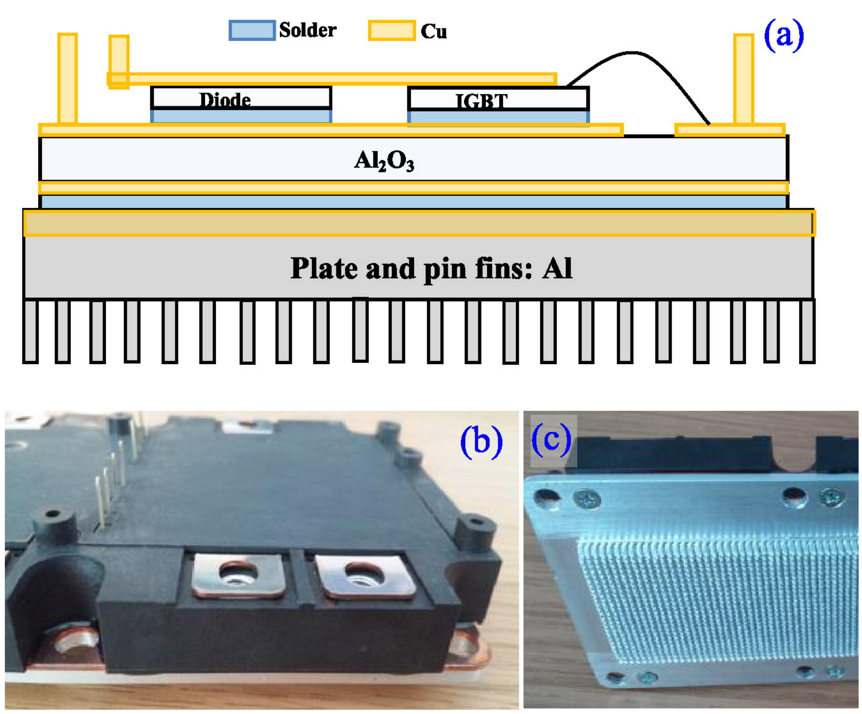

Fig. 2. Direct liquid cooled (DLC) automotive IGBT module concept (a), prototype (b) and (c).