Microelectronic Engineering 120 (2014) 114–120

Contents lists available at ScienceDirect

Microelectronic Engineering

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

Electro-thermal finite element analysis and verification of power module with aluminum wire

Li-Ling Liao [a,b], Tuan-Yu Hung [b], Chun-Kai Liu [a], Wei Li [a], Ming-Ji Dai [a], Kuo-Ning Chiang [b,c,*]

[a] Electronic and Optoelectronics Research Laboratories, Industrial Technology Research Institute, HsinChu 300, Taiwan, ROC
[b] Dept. of Power Mechanical Engineering, National Tsing Hua University, HsinChu 300, Taiwan, ROC
[c] Advanced Packaging Research Center, National Tsing Hua University, HsinChu 300, Taiwan, ROC

ARTICLE INFO

Article history:
Available online 25 January 2014

Keywords:
Insulated gate bipolar transistor (IGBT)
Power module
Finite element (FE) analysis
Electro-thermal FE analysis
Current crowding effect
Infrared detecting camera

ABSTRACT

As a three-terminal power semiconductor device, an insulated gate bipolar transistor (IGBT) chip is characterized by its fast switching and low switching loss, explaining its extensive use in high-power electrical products. However, Joule heating may be induced during high current conditions, subsequently raising the temperature of the power module. Correspondingly, an uneven temperature distribution may decrease reliability and diminish the life of a power module in long-term operations. Therefore, this study investigates the temperature effect of current crowding and corresponding Joule heating on the IGBT chip. The electro-thermal finite element (FE) behavior of the power module is also investigated, based on a numerical analysis. The current densities of solder, IGBT chip, and aluminum pad are also examined to observe the current crowding effect. Analysis results indicate that the maximum current density occurs at the interface between aluminum pad and the aluminum wire. Additionally, the maximum current density may induce electromigration or failure behavior in long-term operations. These characteristics and temperature distribution can be analyzed during an electrical loading, based on electro-thermal FE analysis. Additionally, the test sample is designed to validate the temperature distribution in the simulation and experimental results. Moreover, the steady temperature of the test sample under electrical loading is determined using an infrared-detecting camera and T3ster. Comparing the simulation and experimental results demonstrates the reliability of the temperature validation method. Furthermore, the temperature from the electro-thermal FE analysis is treated as temperature loading in the thermo-mechanical FE analysis. Efforts are underway in our laboratory to investigate the temperature induced thermal stress. Results of this study demonstrate that numerical analysis can replace and reduce the number of experiments, as well as forecast the electrical, thermal, and mechanical behaviors of the power module efficiently.

1. Introduction

As a three-terminal power semiconductor device, an insulated gate bipolar transistor (IGBT) chip is characterized by its fast switching and low switching loss. The IGBT chip has been extensively adopted in high-power electric products, including hybrid vehicles and AC/DC inverters. However, Joule heating induced during high current conditions, subsequently raising the temperature in the power module. Temperature excursion may decrease the reliability and life of the power module in long-term operations. The behavior of metal wires in the power module has received considerable attention, especially the aging and failure mode in cyclic power loading. Different test conditions have revealed heel cracking, chip fractures, wire lift off, and metallurgical damage [1]. Notably, a decrease in the bonding area corresponds to a decreased shear strength of wire bonds under thermal cycling, resulting in fatigue crack propagation from the bond heel to the bond center [2–4]. Crack growth is visible in the interface between aluminum wires and aluminum–silicon during the thermal fatigue cycle test [5]. According to a previous study, optimizing the configuration design improves the temperature distribution in the IGBT chip, subsequently reducing the maximum junction temperature difference [6]. Related studies performed electro-thermal analysis of the transient thermal performance in the IGBT module by using finite element (FE) analysis, as well as recorded the temperature history with infrared meter during the power cycling test [7,8]. By using numerical analysis, simulation can quickly predict

---

* Corresponding author at: Dept. of Power Mechanical Engineering, National Tsing Hua University, HsinChu 300, Taiwan, ROC. Tel.: +886 3 5742925; fax: +886 3 5745377.

E-mail address: knchiang@pme.nthu.edu.tw (K.-N. Chiang).

http://dx.doi.org/10.1016/j.mee.2013.12.033
0167-9317/© 2014 Elsevier B.V. All rights reserved.

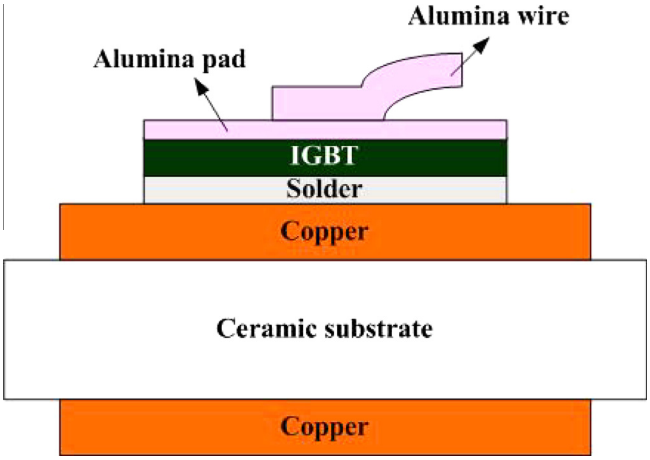

Fig. 1. Schematic diagram of power module.

the electrical, thermal, and mechanical behaviors of the power module. Although numerical simulation can simplify the design procedure of the power module, the measured temperature of an experiment cannot verify the forecasted temperature from electro-thermal FE analysis.

This study investigates the temperature effect of the current crowding and corresponding Joule heating on the IGBT chip during electrical loading. A 3D FE model of a power module is also developed, and electro-thermal FE analysis is conducted using the commercial software ANSYS in the simulation. Additionally, electro-thermal behavior of the power chip is predicted during current loading, including current density, current crowding, and temperature induced through Joule heating. Current density is also estimated under direct current load. Moreover, the behavior of current crowding, which occurs at the aluminum pad, IGBT chip, and solder, is investigated. The junction temperature and thermal effect are subsequently induced through Joule heating. The temperature distributions of the power chip and aluminum wire are also observed in the electro-thermal FE analysis. A test sample is simplified and manufactured based on an actual power module in the experiment. Fig. 1 schematically depicts the power module. IGBT chip, which is mounted on a direct bonded copper (DBC) substrate by soldering. An aluminum wire is bonded to connect the surfaces of the aluminum pad and DBC substrate. Furthermore, the junction temperature during electrical loading is determined using an infrared-detecting camera and T3ster. Finally, the measurement results are compared with the electro-thermal analysis results to validate the temperature of the power chip.

2. Power module and test sample

Fig. 2(a) shows a power module of 450 A, 1200 V, which is used in the study design. The power module was developed by the Industrial Technology Research Institute. Fig. 2(b) shows a single IGBT chip (150 A, 1200 V, ABB, Switzerland) mounted on the DBC substrate, which was fabricated as a test sample; construction of the power module was simplified as well. Six aluminum wires were bonded and connected to the aluminum pad of the IGBT chip and DBC substrate. A particular amount of heat can be generated from the power chip during electrical loading. Thermal conductivity of the power module extends from the IGBT chip transmit to solder, DBC substrate and heat sink or cooling system, and a slight portion of is transmitted to the aluminum wires. Following rearrangement of the metal wires, the bonding position followed the method of Ishiko et al. [6]. Layout of the collectors, emitter, and gate poles was designed on a test sample to provide the collector–emitter and gate–emitter voltage of the IGBT chip.

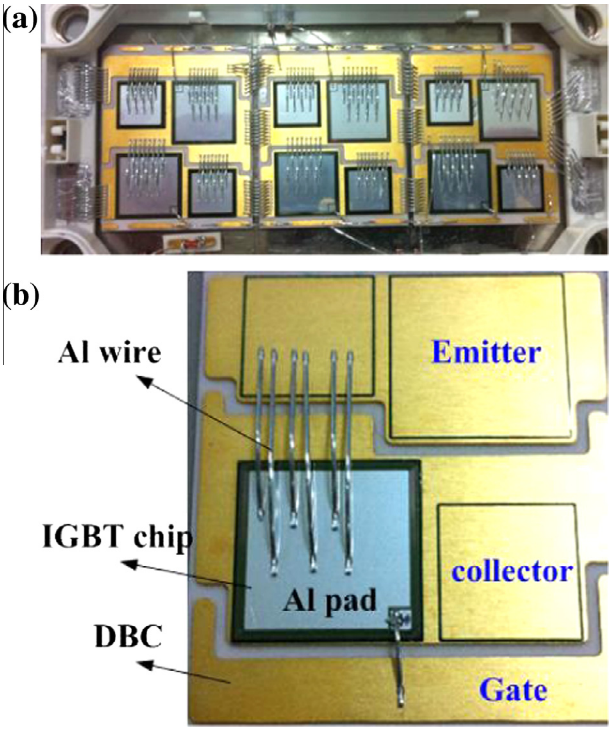

Fig. 2. (a) 450 A and 600 V power module and (b) test sample.

3. Finite element mode and material properties

Fig. 3 illustrates the established FE model based on a test sample. The aluminum pad was deposited on the IGBT chip surface. The IGBT chip was mounted on the DBC substrate by soldering. The substrate between the upper and bottom copper of DBC is Al_2O_3. Six aluminum wires were bonded and connected to the surfaces of the aluminum pad and upper copper of DBC. A constant temperature boundary condition was applied to the bottom copper, which was measured below the center of the IGBT chip by a thermal meter. The heat transfer coefficient of the upper surface at the aluminum pad, IGBT chip, and upper copper of the DBC was set according to the following experimental equation of Ellison [9]:

$$h_c = 0.833f\left(\frac{T_j - T_a}{L_{ch}}\right)^n$$

where L_{ch} denotes the characteristic length; f and n represent undetermined coefficients; T_j refers to the junction temperature; and T_a denotes the ambient temperature.

The electrical loading applied in region 1 is 80 A, and the output voltage set in region 2 is 0 V. The driver direction of current loading is from the loading region through the copper, solder, IGBT chip, aluminum pad, and aluminum wire. Finally into the output voltage region.

Table 1 lists the material properties examined in the electro-thermal FE analysis. The data sheet of the ABB IGBT chip reveals that electrical resistivity of the IGBT chip is temperature-dependent [10]. In this study, power loss of the IGBT chip is calculated and also applied in the simulation model under different electrical loadings. Other material properties are set as constants. Specific heat, density, electrical resistivity, and thermal conduction can affect the current density and temperature distribution of a power module.