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An analysis of the reliability and design optimization of aluminium ribbon bonds in power electronics modules using computer simulation method

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ABSTRACT

Ribbon bonding technique has recently been used as an alternative to wire bonding in order to improve the reliability, performance and reduce cost of power modules. In this work, the reliability of aluminium and copper ribbon bonds for an Insulated Gate Bipolar Transistors (IGBT) power module under power cycling is compared with that of wire bonds under power and thermal cycling loading conditions. The results show that a single ribbon with a cross section of 2000 μm × 200 μm can be used to replace three wire bonds of 400 μm in diameter to achieve similar module temperature distribution under the same power loading and ribbon bonds have longer lifetime than wire bonds under cyclic power and thermal cycling conditions. In order to find the optimal ribbon bond design for both power cycling and thermal cycling conditions, multi-objective optimization method has been used and the Pareto optimal solutions have been obtained for trade off analysis.

1. Introduction

The applications of power electronics systems using semiconductors such as insulated gate bipolar transistors (IGBT) and metal oxide semiconductors field effect transistors (MOSFET) are wide ranging and continuously increasing. They are used in drive systems such as elevators, subways, locomotives, electric vehicles to industrial pumps, household appliances and in power generation, conversion and transmission. There is a constant demand for high power density power electronics with higher switching frequency. Other desired requirements include reduced weight and volume, lower cost, high reliability and ability to operate at increasing severe operating conditions. To meet such demands, designers and manufacturers in the power electronics industry are devising new packaging methods and materials. Some of these include new electrical interconnect designs that have low on-state resistance [1], use of sintered silver joints, integrated packaging and the use of high temperature operating materials such as wide band gap semiconductors. For electrical interconnection, one of the techniques that has been proposed is the use of aluminium (Al) ribbon bonds interconnections in power modules to replace the conventional Al wire bonds.

Ribbon bonds are not entirely new technology as they have been used extensively for high frequency applications for example in optical and optoelectronic devices [2]. They have also been used for power electronic applications such as in compact DC- DC MOSFET converters like D^2PAK and quad-flat-no lead (QFN) packages [3]. However, recently, their use in the IGBT power electronic module such as in Toyota Prius 2010 model [4] has been gaining attention. The advantages of ribbon over conventional round wire have been discussed in [5] and references therein. One of the reasons ribbon is gaining attention is because a single ribbon usually has a lower electrical resistivity than a single wire of the same length. Therefore a higher current handling capability. This allows a single ribbon to replace a number of wires in order to meet the same current rating requirement or to achieve the same conducting resistance.

2. Wire bond failure modes

The wire bond is prone to two major failure modes. Fig. 1 show the locations of the heel crack, bond crack and bond wire lift-off failure. The two failure modes occur at its two weakest point—the bond tail (foot) and the bond heel, with the bond wire lift-off being the most frequent.

The wire bond failure is mostly due to thermo-mechanical fatigue from temperature swings caused by environmental conditions, power dissipation from the power chips during switching and conduction, and ohmic heating in the wire itself. When temperature changes in the power module, shear stress at the interface of the bond wire and the bond pad develops because of coefficient of thermal expansion CTE mismatch between the Al bond wire and the silicon chip. This stress results in the initiation and propagation of cracks near the interface and eventually leads to wire bond lift-off failure [8]. Also due to the

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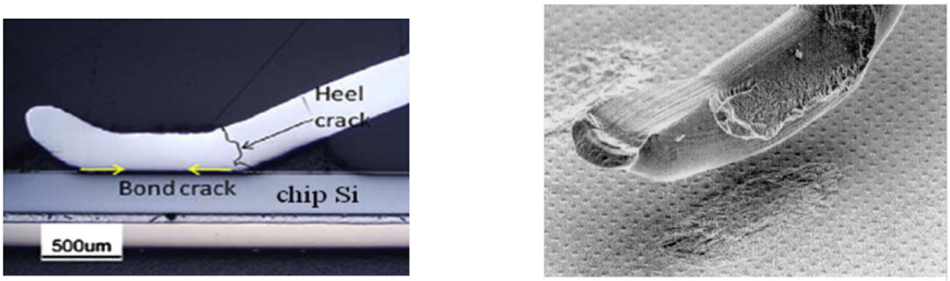

(a) (b)

Fig. 1. (a) Locations of bond wire heel and bond crack [6]. (b). Wire bond lift-off failure which is the result of bond crack [7].

repeated flexure of the wire during the thermal swing, cracks may develop at the bond heel which leads to heel cracking failure [9]. The effect of wire bond failure results in changes in either contact resistance value or internal distribution of current leading to increased temperature above the safe operating area (SOA) of the power device. Some ribbon bond thermo-mechanical behaviour studies in the literature for different applications and their limitations has been presented in Ref. [5].

Meyyappan [10] studied the influence of wire geometry on its reliability using the beam curve theory and minimization of the potential energy. The study used thermal cycling only and focused on microelectronics wire bonds where power/current density is usually low. Celnikier et al. [6] investigated the loop height variations (displacement) of ribbon bonds using analytical solutions of thermal cycling. The geometric effect of bonding constraints under power cycling has not been established and correlated with that of thermal cycling to enable effective design optimization of the wire/ribbon bond. In general, information of what would help the optimal design of ribbon bond in power modules is scarce and this work is to address this issue.

Despite of the above mentioned works, the reliability of the ribbon bonds based on heat generation from joule heating and cyclic power loss in the power device especially for IGBT power modules applications has not been fully investigated yet. Design optimization of ribbon bond considering power cycling has not been carried out. In an earlier work by the authors of this paper, the thermo-mechanical behaviors of ribbon bonds under simplified power cycling loading conditions were analysed and compared with those of conventional wire bonds, and it was concluded that ribbon bonds are more reliable than wire bonds under the given conditions [5]. In the present work, more realistic loading conditions are used in the thermal mechanical simulation. Copper ribbon bonds have also been considered as potential replacement for Al wire/ribbon bonds and the reliability of Cu ribbon bonds has been compared with Al ribbon bonds. Furthermore, parametric reliability analysis has been carried out which can be used for design optimization. To find the trade-off relationship between the objective of keeping the maximum temperature in the device low and that of keeping the mechanical fatigue damage low in ribbon bonds, a multi-objective optimization technique has been used in this work.

3. Methodology

Two IGBT power modules models shown in Fig. 2 are studied using Finite Element Method (FEM). The IGBT power module dimensions are given in Table 1. The layout and characteristics of these power module models are similar to that of the Powerex IGBT half-bridge module CM150DU-24NFH [11]. The power transistors and diodes in the IGBT modules are similar in characteristics and dimensions to that of commercial ABB IGBT Die 5SMY 12M1280 [12] and Diode-Die 5SLY 12J1200 [13] respectively.

Based on cross-sectional considerations, a single ribbon of specific dimensions can replace several number of wires of a certain diameter for equivalent current carrying capability [1,14]. In this work, the case of replacing three 400 μm aluminium wires with a single ribbon of 2000 μm × 200 μm in cross-section has been studied. The models are shown in Fig. 2.

Fig. 3 shows the schematic of an IGBT power module. It can be seen that an IGBT power module is made of several layers of different materials. The power semiconductor devices such as IGBT and diodes are mounted on an insulated substrate. The substrate is usually direct bonded copper (DBC). Solder materials are used as attachment material. The DBC is made of a ceramic substrate such as aluminium nitride (AlN) sandwiched between two copper layers. The DBC is mounted on a base plate using solder material as interconnect. Wire bonds are used for electrical connection of the power devices to other conductors.

3.1. Finite element analysis (FEA) simulation

Thermal-mechanical analysis of the power module models has been carried out using ANSYS V. 17.1, a commercial multi-physics FEA software package. Power cycling loading is realized by switching heat generation in the module on and off. A power cycling test circuit can be either AC or DC circuit depending on the current used for the testing. Different power cycling circuit and testing conditions in the literature were outlined in [15].

In this simulation, the IGBTs are assumed switched on permanently during the power cycling. The current load is taken to be from a constant DC source switched on and off by external circuit. Experimentally, in this type of power cycling set-up condition, the IGBT gate is permanently set to a constant value. The gate voltage V_{GE} must be set to a value higher but close enough to the gate-emitter threshold voltage $V_{GE(th)}$ [7,16] to ensure that same current and temperature swing is obtained in the IGBTs. So the diodes were not loaded and therefore no diode power loss and no switching losses. This simulation assumption is similar to the experimental power cycling tests using DC circuits such as in [7]. However, with the exceptions of current load values, heating/cooling times. Initial setting of lower and higher temperature limits and adjusting cooling systems were not used in this study. The turn on and turn off of the source current is assumed continuous until a cyclic equilibrium temperature distribution in the power module is achieved. This is based on the assumption that the damage progress (i.e. the crack growth rate per cycle) in the wire bond will remain relatively constant at this cyclic condition. And also to justify the use of cyclic equivalent plastic strain in the fatigue life prediction. Therefore, this testing condition is to test only the reliability of the wire/ribbon bonding configuration in the power module due to temperature swing. A continuous cooling is also assumed.

Since the study is focused on the wire/ribbon bonding failure, the cycle period should be within seconds as described in many IGBT power module power cycling tests such as in [17,18]. This is because, cycle period < 1 min is more sensitive to wire bond fatigue. Therefore a constant turn-on (heating) and turn-off (cooling) times of 4s and 11s respectively were used giving a 15s cycle period. Changing this turn