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Interface reliability and lifetime prediction of heavy aluminum wire bonds☆

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ABSTRACT

In this study a high frequency mechanical fatigue testing procedure for evaluation of interfacial reliability of heavy wire bonds in power semiconductors is presented. A displacement controlled mechanical shear testing set-up working at a variable frequency of a few Hertz up to 10 kHz is used to assess the interfacial fatigue resistance of heavy Al wire bond in IGBT devices. In addition, power cyclic tests were conducted on IGBT modules for in-situ measurement of the temperature distribution in the devices and determination of the thermally induced displacements in the wire bond loops. Finite Element Analysis was conducted to calculate the correlation between the thermally and mechanically induced interfacial stresses in the wire bonds. These stress values were converted into equivalent junction temperature swings (ΔT_j) in the devices based on which lifetime curves at different testing frequencies were obtained. Comparison of the fatigue life curves obtained at mechanical testing frequencies of up to 200 Hz with the power cycling data related to the wire bond lift-off failure revealed a very good conformity in the ranges of 50 to 160 K. A lifetime prediction model for Al wire bonds in IGBT modules is suggested by which the loading cycles to failure can be obtained as a function of ΔT_j and the mechanical testing frequency. The proposed accelerated shear fatigue testing procedure can be applied for rapid assessment of a variety of interconnects with different geometries and material combinations. Decoupling of the concurrent failure mechanisms and separation of the thermal, mechanical and environmental stress factors allows a more focused and efficient investigation of the interfaces in the devices.

1. Introduction

Power semiconductor modules such as insulated gate bipolar transistors (IGBTs) are widely used in power electronic systems for efficient generation, use, and distribution of electrical energy. Their fields of application include among others traction, electro-mobility, power transmission and distribution with a required fault-free operation of up to 30 years under harsh environmental and loading conditions [1,2,3]. Improved performance and lifetime of the power systems is directly related to the knowledge of the mechanisms and causes of failure in power semiconductor devices such as IGBT modules. The reliability of the modules that are composed of various materials with different physical and electrical properties is mainly affected by failure induced due to thermo-mechanical fatigue as a result of thermal mismatch in the material interfaces. Extensive investigations have shown that the main lifetime controlling failure mechanisms in such devices are related to wire bond degradation, reconstruction of the metallization films and fatigue of the solder layers [1,2]. The performance of the power modules are steadily improved by replacement of the traditional interconnection and packaging technologies in advanced devices [3]. To keep up with the encountered technical challenges, novel solutions for rapid and reliable evaluation methods are needed.

1.1. Power cycling testing and related issues

Power cycling tests (PC) are used to determine the resistance of semiconductor devices to thermal and mechanical stresses due to cycling the power dissipation of the internal semiconductor die and internal connectors [4]. In active PC tests the power chip is typically heated by constant DC current pulses and the temperature swings are generated by the power loss inside the active device. During the heating and cooling periods (t_{on}/t_{off}), the junction temperature (T_j) between the die and the interconnect increases and decreases, simulating the stresses induced during the actual circuit applications. This temperature swing ΔT_j, is a characteristic parameter for power cycling tests which is defined by the difference between maximal and minimal junction temperature during the heating and cooling period [1,4]. In addition to T_j, further parameters which are measured during the PC are the gate voltage V_G, the collector voltage V_{CE}, the loading current I_C and the case temperature T_c. The intention of the PC test is to simulate typical applications in power electronics in an accelerated manner to obtain the lifetime data in a reasonable time. The testing conditions are adapted to the particular application and the type of modules. The number of cycles to failure N_f is commonly presented in form of a power law

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in relationship with ΔT_j and an Arrhenius term in relationship with the absolute temperature T_j. The derived lifetime models for power modules are then extrapolated to field conditions with lifetimes in the range of 10 to 30 years.

Although power cycling is an industrially established procedure, investigations on the influence of testing conditions on the lifetime and dominant failure modes of the modules are not always consistent. Several studies have shown that variation of the parameters encountered in PC tests may alter the obtained reliability curves [1,5,6,7]. Another lifetime influencing factor is material aging and degradation, which may gradually alter the adjusted PC conditions during the testing [5,8]. For instance, solder fatigue can increase the thermal resistance of the component, or wire bond degradation can enhance the on-state losses in the device, both resulting in an increase of the temperature swing [8]. To avoid these unwanted effects, a number of PC control strategies have been suggested which are based on keeping the testing parameters such as timing (t_{on}/t_{off}), the base plate temperature swing ΔT_c, the power dissipation P_v and ΔT_j constant. However, these different control strategies may also deliver different lifetime results [7].

In the early 1990s a unified lifetime model was proposed for standard power modules which described the impact of testing parameters ΔT_j and medium temperature T_m on the lifetime of the modules [1]. This model was based on a large number of PC tests, which were conducted at different ΔT_j and T_m by using IGBT modules of different suppliers [1]. It was found that for the available Al wire bonding technology at that time, wire bond fatigue plays the dominant role in lifetime limitation for short power cycle times ($t_{on} < 5$ s). Schilling et al. studied aging of Al wire bonds of IGBT modules at a broad range of ΔT_j by using a solder material with high melting temperature to reduce the influence of chip solder aging on their results. The experiments and finite element analysis confirmed a low impact of absolute junction temperature on N_f [9]. The dependency of heating time t_{on} on the lifetime of the modules was included in an extended lifetime prediction model (CIPS08 model) [6]. It was shown that shorter heating times (t_{on}) leads to an increase of lifetime. Scheuermann and Schuler [7] found that PC tests under constant ΔT_j result in an increase of lifetime by a factor of three in comparison with constant timing controlled testing.

Recently Forest et al. proposed a new approach for reducing the power cycling testing time for evaluation of IGBT modules based on Pulse Width Modulation (PWM) operation [10]. They found the maximal frequency of the thermal swing in power cycling tests to be about 10 Hz which was derived depending on geometrical and thermal characteristics of the devices. An advantage of this procedure is the ability to study the aging behavior of the wire bond and emitter metallization, since during the very short heating time, the other parts of the module are not stressed because of their higher time constants. A comparison of conventional DC on/off tests with a cycling frequency of 0.2 Hz and the fast PWM method with a frequency of 2 Hz showed the same failure mode (wire bond lift-off) while a frequency effect on the lifetime was not observed. In contrary, other investigations showed an increase of lifetime with increasing the frequency of power loading [6,11].

New technologies are in progress to eliminate the weak sites of the power modules and improve the reliability of the devices. Investigation of the fatigue response of each influencing factor is beneficial and necessary for improvement of the device quality. However in most cases separation of the different failure modes occurring in standard power modules under power cycle testing conditions may be difficult. Wire bond contacts are still known to be particularly vulnerable to degradation and failure during operation. In certain application types they are considered as important life time limiting factor. It has been reported that in automotive and renewable energy applications, the emitter contact is the most stressed joint and a variety of technologies have been proposed for improvement of the reliability of this bond contact [12]. One example is replacement of the Al wire bond with Al–Mg_2Si alloys which was found to increase the lifetime by a factor of 5 to 10 times [13]. Recently new packaging technologies have been developed to replace the solder layers with more temperature resistant materials such Ag sintered layers [11]. Application of these technologies has further increased the lifetime of modules in active power cycling tests. It can be concluded that knowledge of the resistance of wire bonds to cyclic loading and prediction of their lifetime is still crucial to the reliability design and assessment of the whole module [14].

The brief overview of the studies on the reliability of power modules, with focus on wire bond reliability, shows that accelerated power cycling testing parameters might highly affect the predicted lifetime. Separation and determination of the concurrent degradation mechanisms in the modules is a challenging task. Determination of acceleration factors based on extensive and time consuming experiments may provide the possibility to consider the different influencing factors on the predicted lifetime of the modules. However due to physical characteristics of the devices, there are limitations to accelerated power cycling tests. Further acceleration may result in degradation of the devices but it can also lead to unrealistic failure modes and lifetime data.

1.2. Accelerated mechanical fatigue

Due to the technological advancement and economic reasons, highly accelerated, still practice relevant reliability assessment procedures for power modules are increasingly required. One approach for further acceleration of the reliability testing procedures is based on the application of isothermal mechanical fatigue testing as an alternative to accelerated thermal or power cycling procedures. While thermal acceleration is achieved by increasing the temperature excursions and/or shorter heating times, the duration of testing can be efficiently reduced by increasing the mechanical testing frequency [15,16]. In addition to the time factor, the high advantage of mechanical fatigue testing is the possibility of decoupling of thermal, mechanical and environmental stress factors.

Principally the idea of replacement of thermo-mechanically induced strains by means of mechanical stresses/strains for evaluation of electronic components has been attractive for researchers as well as manufacturers since a while. However serious efforts in development and establishment of mechanical testing procedures which can be used as an alternative to time consuming thermal cycling tests have turned to be a recent trend. A prerequisite for successful application of accelerated testing methods is identification and reproduction of the dominant failure modes and definition of the relevant failure criteria specific for each device considering the respective operational conditions. Selection of the appropriate accelerated testing procedure for each type of device or component is a key factor to obtain the desired useful and realistic experimental results. The frequency range of mechanical fatigue testing is principally not limited and may vary from below Hz to kHz and above. Application of high frequency fatigue testing set-ups allows inducing the strain ranges equivalent to those imposed by thermal cycles to the components. However, while thermally induced acceleration may be misleading by evoking irrelevant failure mechanisms, reduction of the testing time by mechanical means might not necessarily result in the same degree of degradation as in real operational conditions. Thus in most cases determination of proper acceleration factors is required. Frequently depending on the purpose of the testing, compromises shall be made.

In the present study interfacial fatigue resistance of heavy Al wire bond in IGBT devices has been investigated by using a high frequency mechanical fatigue testing set-up working in the range of 20 Hz up to 10 kHz. Power cyclic tests on IGBT devices were conducted to obtain the temperature distribution and mechanical displacements in the various components of a module. Finite element simulations were used for the correlation of thermally and mechanically induced interfacial stresses in the wire bonds. A lifetime model as a function of junction temperature difference and mechanical testing frequency for Al wire bonds in IGBT modules is proposed.