Thermo-Mechanical Simulation of Wire Bonding Joints in Power Modules

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ABSTRACT

High voltage and high current power modules are key components for traction applications. In the future, railway locomotives, tramways and elevators will be equipped with Insulated Gate Bipolar Transistor (IGBT) modules. In this field of application high reliability is of decisive importance, especially for aluminum bond wires with diameters up to 500 µm, connecting the silicon device with the output pins. Reliability tests show that wire bonding and soldering may cause failures of the modules. In this work, we investigate the stress and strain distributions in the bonding zone after a temperature load step using finite-element analysis.

Keywords: Wire Bonding, Power Electronics, Thermo-mechanical Simulation, Failure Analysis, IGBT, Reliability

INTRODUCTION

In power electronic modules with blocking voltages up to 3.3 kV and current ratings up to 1200 A wire bonding is used for the electrical interconnection from the emitters of the chips to the output pins. High reliability is one of the most important requirements. The reliability of any electronic device depends in great part on its package. Wire bond lift-off and solder fatigue are the main limiters for the reliability of such packages [1]. Therefore, it is very important to increase the lifetime of the wire bond connections. The weakest point of the wire bonding joint is the heel and the tail of the bond foot. As this area is almost inaccessible to experiments we used finite-element simulations to analyze this region.

FAILURE MECHANISM

The package consists of a multilayer system where different materials are soldered together. In a power module the dies are soldered to one or more DCB substrates (Direct Copper Bonding) which facilitate the electrical isolation from the environment. These substrates, in turn, are usually soldered to the copper baseplate, which acts as heat sink during operation. Since the module consists of different materials with different thermal expansion coefficients, temperature cycling causes shear forces at the interfaces between adjacent materials. Usually power cycling tests are performed to investigate the reliability of the modules subjected to such thermomechanical stresses [2].

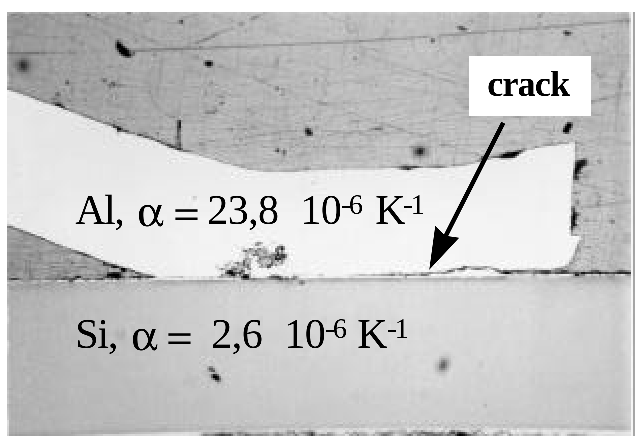


Figure 1: Cross section of an aluminum wedge bond with a crack in the bonding zone

Wire bond connections are susceptible to fatigue as a result of thermomechanical damage mechanisms occuring during power operation. In this paper, we investigate the wire bonding joint in power modules. Figure 1 shows a typical cross section of an aluminum wedge bond with a crack in the bonding zone which is observed after thermocycling. Cracks grow from the heel and the tail into the bonding zone [3]. When the two cracks are reaching the center of the bonding joint, the wire lifts off and the electrical contact is lost. Unfortunately, this is an self-accelerating process because the remaining wires have to conduct more current causing even higher heat dissipation in the wire and in the welded area which again accelerates lifting of further wires. However, the chips are not damaged by this process.

The wires are bonded on top of the dies with a bonding tool by ultrasonic vibration. To ensure that the material is 'bondable' it has to behave plastically, and therefore it is necessary to use high purity aluminum wires (99.99 %). During the bonding process the wire breaks the aluminum oxide film and is welded to the 3 µm thick aluminum pad which is deposited on the chips. In these power modules it is necessary to use a bunch of parallel wires with a large diameter to handle rated currents up to 100 A per chip. Due to the large bonding area the welding quality is not homogeneous across the bonding joint. In figure 2 the result of an ultrasonic measurement of the bonding joint quality is shown. The bonded wire and the chip were molded in epoxy resin. Afterwards the wire was abraded from the top side to a thickness of 20 µm. In this preparation state it is possible to image the quality of the bond connection.

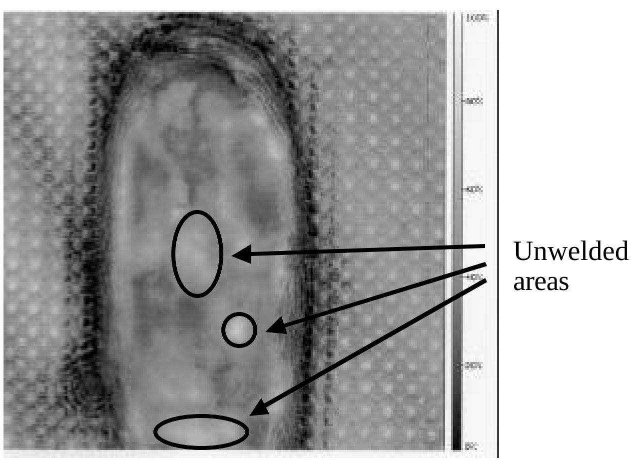


Figure 2: Ultrasonic measurement of a wire bonding joint (imaging frequency 200 MH_Z)

When the plane of focus is equal to the bonding plane the ultrasonic image is a direct indicator for the bond quality. The higher the amplitude of the reflected wave the worse the bond. The white areas in figure 2 indicates such badly welded or completely unwelded zones.

FINITE ELEMENT SIMULATION

Geometry and grid layout

We analyzed the behavior of a wire bonding joint on the basis of a simplified finite element model. The 2-dimensional model consists of the aluminum wire and the chip (figure 3). Assuming mirror symmetry with respect to the middle of the wire bow only one half of the stitch bond has to be simulated. The bond diameter is 300 µm and the chip thickness is 220 µm. The bow height is 4.8 mm, and the two bonds at its ends are 9.6 mm apart from each other. Expansion of the chip is restricted to the x-direction. Therefore, the effect of chip bending is not considered. The model is linear in geometry but non-linear in material behavior [4]. The metal has a linear-elastic, ideal plastic stress-strain curve with a Young's modulus of 70 GPa and a yield strength of 10 MPa. The device, of course, has linear elastic behavior with a Young's modulus of 165 GPa. The element used for the wire and the chip was an 8-noded plane element with two translational degrees of freedom per node (standard element in the FEM code ANSYS used for our calculations). The FEM grid was built with an automatic mesh generator. It was refined at the crack tip in order to improve the geometric resolution. For more accurate results at the interface of the two-layer system, the area of interest, a second model was used. This model is a circular part of the heel of the wire bond in the coarse model as shown in figure 3. In a first step the coarse model is calculated with the correct boundary conditions. Afterwards the obtained solution was used to define the boundary conditions for the calculation of the fine model. This procedure called submodeling technique is a well-known calculation concept. For calculations of full temperature cycles it is necessary to use contact elements from the lower free surface of the wire following the bond connection to the chip surface to prevent that the different materials intersect.

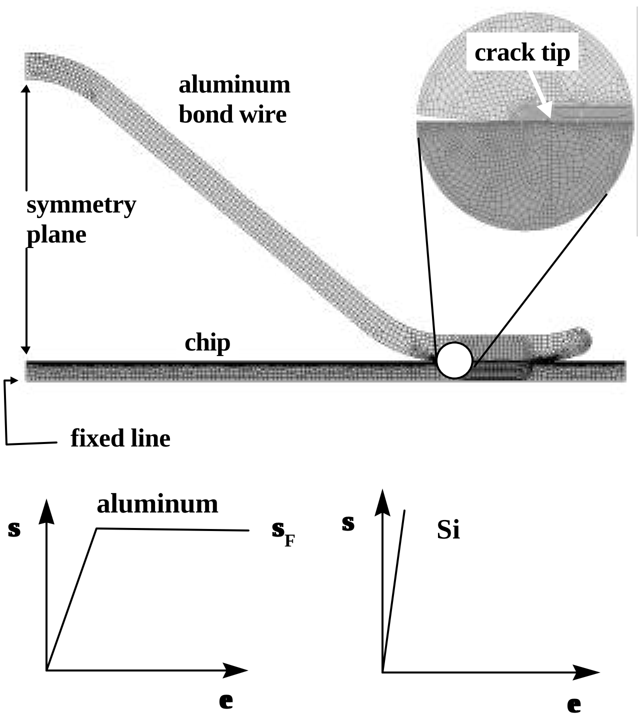
Calculation results

In the initial state, the whole model is free of mechanical tension. Then the temperature of the whole structure is instantaneously increased by a step of 75 K. This simulation condition represents a typical operating state of the transistor. For the calculation the absolute temperature is not important as the material parameters are independent of temperature.

As the wire behaves elastically there is a stress singularity at the ends of the bond wires in the vicinity of the crack tip extending in horizontal direction along the interface. Its analytical description is given by [5]:

$$(\sigma_y + i\,\tau_{xy})_{\varphi=0} = \frac{K\, r^{i\varepsilon}}{\sqrt{r}}, \qquad (1)$$

where σ and τ are stress components, r is the distance from the crack tip, ε is called bimaterial constant and K is the complex stress intensity factor (SIF) which characterize, the singularity. The higher the load the higher the SIF. When the SIF reaches a maximum value, the bimaterial cracks. But this stress-intensity factor concept is not applicable to a non-linear simulation with large expansion, where no stress singularity exists. It is evident that when the thermal strain exceeds the elastic limit in the wire, the stress is relaxed by plastic deformation. From the simulation result the plastic strain after a heating step of 75 K can be evaluated.



Young's modulus: 70 Gpa

Yield stress: 10 MPa

Young's modulus: 165 GPa

Figure 3: Geometry design, finite-element mesh and material behavior of the model

The top of the wire bow rises up by 25 µm because the wire expands more than the chip. This pulls up the wire bond and causes crack opening under the heel (mode 1). On the other hand, because of the higher thermal expansion coefficient the wire descends at the edges of the connecting bonds. The latter effect closes the crack, the former opens it. At the left side of the connecting bond these two effects overlap, where the effect of wire descending is predominant. However, because of the different thermal expansion coefficients the shear forces lead to crack mode 2.

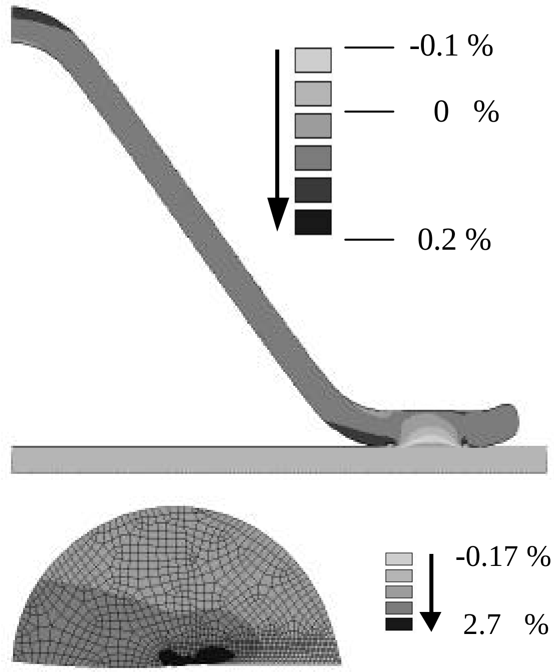


Figure 4: Calculated plastic strain of the coarse model and of the submodel after a temperature step of 75 K

Figure 4 shows the calculated plastic strain in the coarse model. There is compression in the center region of the wire bond (-0.1 % Δl/l) and tension at the ends, where the highest pressure strain is observed. The whole wire is plastically deformed. The plastic strain of the wire termination at the heel of the connection is shown in more detail in the enlarged submodel. In the vicinity of the crack tip the plastic strain reaches 2.7 % Δl/l. Figure 5 shows the plastic strain behavior at the beginning of the bonding zone along the interface direction and along the direction perpendicular to it. Close to the crack tip the wire is under tension in x-direction and under compression in y-direction. Locations of plastic strain play an important role for the cracking mechanism. Initially microcracks start from surface intrusions [6]. These cracks nucleate at positions where the cyclic plastic deformation is higher than the average, in other words, in places of plastic strain concentrations.

From the calculated results a lifetime criterion for the bonding joints is derived. The basic equation used in the analysis is the Coffin-Manson equation [7] which defines a power relation between the number of cycles to failure N_f and the plastic strain induced per cycle ε_{pl}. For high plastic deformations the elastic part can be neglected, and the law is written as follows:

$$N_f = \left(\frac{C_w}{e_{pl}} \right)^2 , \qquad (2)$$

where C_w is the so-called fatigue coefficient. This coefficient is between 0.5 and 1 [8].

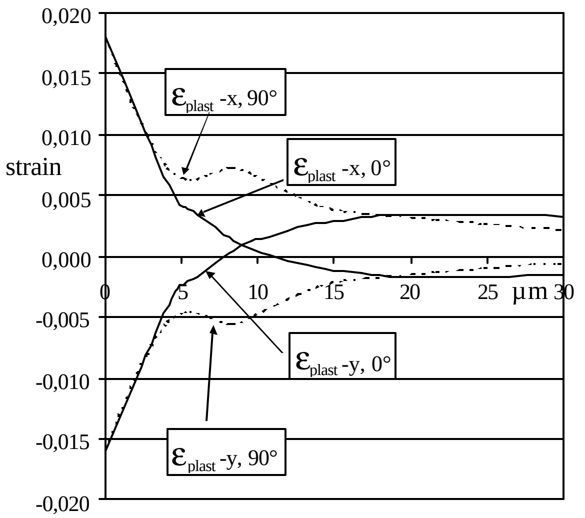


Figure 5: Plastic strain behavior at the beginning of the bonding zone in the interface direction (0 °) and in perpendicular direction to it (90 °)

Applying the Coffin-Manson law to the simulation results the cycles to failure of the bonding joint are calculated between 340 and 1370. At this low number of cycles the bond termination begins to degrade. In this passive simulation we assumed a uniform temperature distribution, i. e. temperature gradients were not included. When the crack length increases the bonded joint gets smaller and smaller and the load at the terminations decreases. In an active power test under real operating conditions the crack will not stop because of the increasing current density and the increasing temperature. Further simulations with more accurate material parameters are in progress.

CONCLUSION

In power electronic modules, wire bonding is used for the electrical interconnection between the chips and the output pins where high reliability is of uppermost priority. In this work, we investigated the thermo-mechanical behavior of an aluminum wedge bond under power cycling conditions using non-linear finite element analysis. With the Coffin-Manson law it is possible to estimate the lifetime in power cycling conditions until crack initiation occurs at the beginning of the bonding area.

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