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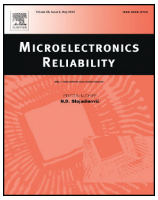

Comprehensive physical analysis of bond wire interfaces in power modules

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ABSTRACT

Power modules based on insulated gate bipolar transistors have become very widely used units in energy technology. Handling large currents and high voltages at high switching frequencies leads to degradation of materials in the devices, especially at interfaces and interconnections, eventually causing failures. In this paper we present a review on the set of our experimental and theoretical studies allowing comprehensive physical analysis of changes in materials under active power cycling with focus on bond wire interfaces and thin metallisation layers. The developed electro-thermal and thermo-mechanical models that can be applied to mimic the device under particular operation conditions and to evaluate stress factors related to heat dissipation are briefly presented. The results of modelling, which predict materials degradation, are compared with a few exemplary cases obtained using the micro-sectioning combined with optical microscopy and scanning electron microscopy assisted by focused ion beam milling. These experimental results show very good agreement with wear out effects predicted by simulations. Additionally, measurements of resistance using four-point probe method are demonstrated to be a very powerful tool to map the degradation of individual components and interfaces.

1. Introduction

Development of devices capable of converting electrical energy from one form to another has been an important technology since the beginning of electrical power systems. Nowadays, with implementation of sustainable and renewable energy sources as well as extensive electrical grids, the demands to electrical power transformation and conversion are significantly increased, i.e. requiring efficient and reliable power electronics [1–3]. Semiconductor devices are key elements of power electronics. Among them, power modules based on insulated gate bipolar transistors (IGBT) have become dominating units due to improvements in handling large currents and high voltages at high switching frequencies [4]. Under operational conditions especially in the case of high power loads the materials used in IGBT modules experience fatigue. Materials degradation eventually leads to device failure which is the subject of reliability physics [5]. Therefore, detailed physical analysis of the failure origins is extremely important to improve quality and reliability of power devices [4,6].

Addressing the failures of IGBT modules is a very broad topic. Since we are concentrating on the physical analysis, we should limit the failures to component level and further to materials properties. Thus, one needs to consider the typical structure of a power module section which is shown in Fig. 1 representing a relatively complex multilayer system. Modern power modules typically operate at pulsed load conditions with high currents and fast switching. Electrical pulses cause the resistive heating of chips with large temperature gradients and significant thermal fluctuations through the layers leading to mechanical stresses due to the material's expansion and contraction [7]. The most crucial areas are the interfaces where the stresses become the highest originated by the difference in the coefficient of thermal expansion (CTE) of the contacting (different) materials [8,9]. Therefore, bonding areas and thin interlayers are the weakest points of the module architecture with respect to the thermal-induced fatigue, degradation and failure.

Fatigue of bond wires leads to heel cracking or/and lift-off which is initiated by mechanical stress induced by materials thermal expansion. When the strain exceeds the elastic limit, the plastic deformation occurs which may eventually cause crack formation and propagation in the wire bond [10]. Materials fatigue and degradation also lead to microstructural evolution at the bond which is found to be strongly dependent on the power cycling conditions, structure and composition of materials at the bond interface as well as on the bond geometry [11,12]. Ultrasonic bonding conditions play an important role typically causing horizontal elongation of the wire grains as well as their refinement close to the bond interface [13]. The latter phenomenon is especially crucial for the wires with coarse structure. It is found that for such wire bonds the most probable area of fracture propagation is not at the bond interface but at the boundary between the pristine and refined area in the wire [14].

Other common mechanisms leading to failures are the metallisation reconstruction, solder fatigue and corrosion of interconnections. In this work along with the wire lift-off we also address problems with metallisation. Similar to wires, aluminium metallisation also has a

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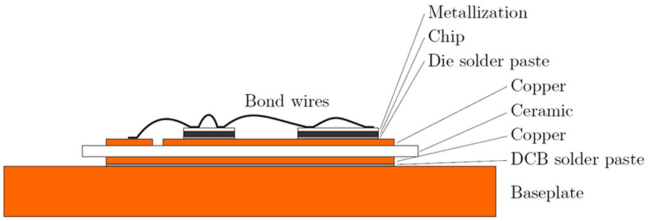

Fig. 1. Schematic side view of a power module section.

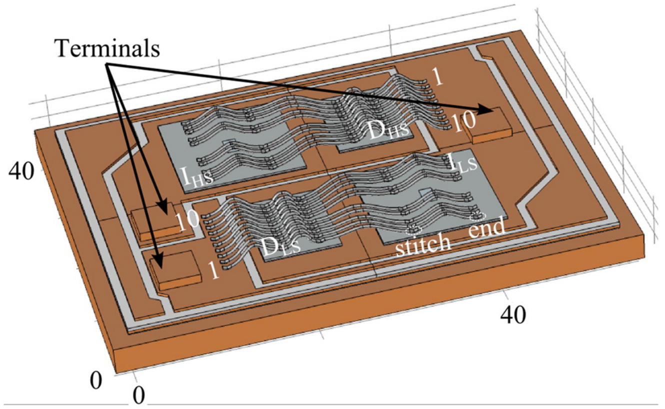

Fig. 2. Schematic 3D picture of individual section of power module. The dimensions are given in millimetres. Notations D_{HS} and D_{LS} stand for high- and low-side diode chips, respectively, I_{HS} and I_{LS} — IGBT chips. The wires are numbered sequentially from bottom to top at the low-side and from top to bottom at the high-side.

polycrystalline structure. During power cycling, heating causes compressive stress in the plane parallel to the substrate while during cooling the tensile stress prevails. Repetition of the process may, depending on load and initial geometry, lead to grain deformation towards so-called "pancake" shape [15]. Generally, with increasing number of power cycles, polycrystalline aluminium film undergoes significant plastic deformation, also known as reconstruction. The compressive stress leads to sliding of dislocations and grain-boundaries originating protruding the grains above the surface (hillocks). The tensile stress causes the formation of voids which become oxidised under conventional atmospheric conditions, thus, preventing healing during the next compression phase [16–19]. Finally, thermo-mechanical fatigue may eventually evolve into fractures penetrating the entire metallisation layer with cracks and cavities propagating from the surface to Si chip, thus, breaking the layer continuity and drastically increasing sheet resistance [20, 21].

One of the ways to consider the stresses in the modules is to develop appropriate electro-thermal and thermo-mechanical models allowing to mimic the device under particular operation conditions, i.e. subjected to active power cycling. Such approach is recently suggested [22] and it will be briefly overviewed in this paper showing the important consequences of heat dissipation affecting the materials properties and causing the degradation. The results of modelling, which predict materials degradation, are compared with a few exemplary cases on the structural analysis on power cycled devices using a micro-sectioning (MS) method combined with optical microscopy and scanning electron microscopy (SEM) assisted by focused ion beam (FIB) technique for obtaining cross-sections [19,23]. The research cases are focused on bond wire fatigue leading to lift-off and on the reconstruction of metallisation which also affects the wire interfaces [21]. At the end, a four-point electrical probing method is discussed demonstrating a capability to obtain data on change of electrical parameters of given components of a power module and relate these changes to the wear and degradation [24,25]. Good correlations with microscopy results are obtained proving that the four-point probing can be applied as a simple and independent method of degradation mapping of power modules. Hence, we give an overview of a set of experimental and theoretical studies carried out on the same type of power modules and focus on comparison and correlation of the data, thus, providing a platform for comprehensive physical analysis.

2. Tested devices

All analysis and modelling methods were applied to the same type of IGBT modules. Every module consists of six identical sections. In each section (see Fig. 2) there are two IGBT and two diode chips. Every IGBT/diode pair is connected by 10 Al bond wires. The modules were subjected to active power cycling under switched sinusoidal current load of 922 A at peak and 6 Hz output frequency with 1000 V DC-link voltage. Devices were switched at 2.5 kHz. Under the accelerated tests, module baseplates were directly water cooled keeping the baseplate temperature $T = 80$ °C. One can find more details about the test conditions in [26]. Five modules with different number of power cycles (at different stages on the lifetime curve) were studied. One module was run until catastrophic failure assuming the corresponding number of power cycles to be end of the lifetime (100% lifetime) and the other four correspond to approximately 25%, 50%, 70%, and 90% of the lifetime. The modules have been given the following notations: A — new, B — 25%, C — 50%, D — 70%, E — 90% and F — 100%.

3. Modelling of degradation

Coffin–Manson (CM) and CM–Arrhenius (CMA) are the most common methods in assessment of lifetime [6,27]. The mean chip temperature T and its change ΔT are used as the load parameter and they are put in accordance with accelerated test data using fit parameters α and β to predict number of power cycles N_f until the device will fail.

$$N_f = \beta(\Delta T)^{\alpha}, \tag{1}$$

$$N_f = \beta(\Delta T)^{\alpha} exp\left\{\frac{E_A}{k_B T}\right\}, \tag{2}$$

where E_A is the activation energy and k_B is the Boltzmann constant. Eqs. (1) and (2) correspond to CM and CMA models, respectively.

Relative simplicity of the models facilitated their popularity in past decades. However, the increasing demands to improve design, quality and reliability of power devices require more comprehensive models which should be able to take into account: (i) geometry of components and material composition as well as variations in production quality; (ii) other input parameters besides ΔT in order to separate different failure mechanisms; (iii) inhomogeneity in the fatigue, wear and degradation processes to distinguish elements or parts causing failures in the first place.

3.1. Concept of the model and geometry of tested devices

All degradation processes in cyclic systems are based on the same fundamental steps: load, damage and recovery. By utilising this concept simulation of component degradation can be separated into two parts, namely stress analysis and material degradation.

3.1.1. Thermo-mechanical stress

The primary stressors causing bond wire fatigue and metallisation reconstruction are temperature variation and thermal-induced mechanical effects. Both of these are ideal for finite element (FEM) based simulations, which is possible in several commercial software packages like ANSYS Icepak together with ANSYS Mechanical or COMSOL

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