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Microstructural evolution of ultrasonic-bonded aluminum wires

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ABSTRACT

The evolution of microstructural gradients, especially crystallographic texture gradients, after ultrasonic wire bonding process and after active power cycling (APC) of high purity, heavy aluminum (Al) wires is studied by electron backscatter diffraction (EBSD) and nanoindentation. The results improve the knowledge about microstructural changes and arrangements after wire bonding and during APC. After ultrasonic deformation by wire bonding, the evolution of a distinct rotated cube (RC) textured area within the wedge was proved by EBSD analysis. The RC texture is discussed as a result of shear deformation and oriented grain growth. Decreased hardness within the RC textured area provides evidence for local softening effects during wire bonding. During APC, besides crack propagation, grain coarsening as well as local low angle boundary migration occurs and the wedge texture changes to an overall random orientation. Effects of microstructure on the crack growth behavior were discussed and suggestions for the improvement of wire bond reliability were derived.

1. Introduction

Typical power modules consist of power semiconductors soldered to the top side metallization layer of a DBC substrate. Recent reliability improvements of the die-attach by using silver sintering or transient liquid phase bonding instead of conventional soldering have led to longer lifetimes of power modules and have shifted the reliability bottleneck back to the heavy wire bonds on top of the chips [1]. Due to the difference in coefficient of thermal expansion (CTE) between wire and chip material, the bonding interface is degrading rapidly during temperature cycling which commonly results in interface cracking.

Aluminum (Al) heavy wire bonding on Silicon (Si) substrate modules is still one of the key challenges in power electronics [1]. Al for bonding wires is essentially used in fine wire quality for Chip on Board (COB) technology and as heavy wires (diameter $\geqslant$100 μm) for power electronic devices [2]. The requirements for the application of both wire qualities (thin and heavy wires) are reliable wire bond contacts, i.e. high interface and heel strength. Both factors are strongly influenced by the wire bonding parameters. In the case of heavy wire bonding for power electronic applications high quality bonds are characterized by high shear forces and large shear residues. Due to the assumed large stable initial interconnection area between wire and metallization layer, large shear residues are associated with a high bond quality and enhanced lifetime in application [1].

Ultrasonic wire bonding processes of Al are characterized by microstructural changes, i.e. dynamic recrystallization and dynamic recovery processes [3–5]. During the bonding time, the acting parameters such as ultrasonic energy, directly controls the microstructure evolution of the Al wire. In the past, the change of heavy wire bond microstructure at the interface and also in the heel area could be demonstrated among others by EBSD measurements [6,7]. As a result, small grain sizes of 1 μm or less could be revealed in the interface region after wire bonding [1,8–10]. Comparing these results with the grain size of as-received 300 μm Al wires, which is about 50 μm, grain refinement during wire bonding could be proved [1,11]. Using 400 μm Al wires, Göhre et al. [1] demonstrated an enhanced lifetime performance and higher shear forces for wires which were bonded with a high ultrasonic energy level. After APC, wires bonded with higher ultrasonic energy also revealed finer grains within the wedge. In this case, the decreased grain size could be one possible reason for the enhanced lifetime. However after ultrasonic deformation by wire bonding, the microstructural evolution in the Al heavy wires slightly above the interface is still insufficiently investigated concerning its texture. This region is of particular interest because it is reported that crack growth and crack propagation during APC is occurring some microns above the interface [1,9].

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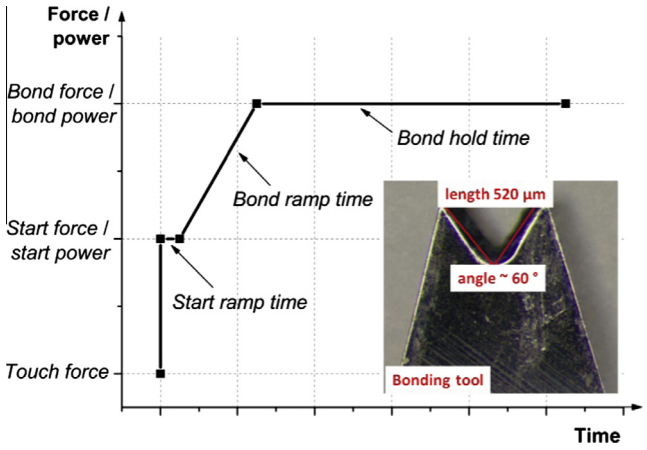

Fig. 1. Schematic demonstration of the acting parameters in heavy wire bonding and geometry of the used bonding-tool.

Regarding this, the main objective of this study is to investigate the microstructural changes and the evolution of texture gradients after wire bonding. Microstructural gradients within the wedge are assumed to strongly influence the results of shear tests. Moreover, it also influences the crack growth rates during APC. To evaluate the relevance of the local wedge microstructure for the wire bond reliability under defined loading conditions, the microstructural evolution and crack growth during APC are examined by EBSD measurements.

2. Experimental procedure

2.1. Wire bonding and active power cycling

In this study, a 300 µm high purity Al wire (breaking load 320 cN, elongation 22%) is investigated. The wire is bonded with an Orthodyne wire bonder on a MOSFET chip (5 µm $AlSi_1Cu_{0.5}$ metallization layer deposited on Si). In order to robustly produce bonds with high quality, the bonding parameters were optimized using shear tests for evaluation. Thereby, high quality bonds are characterized by reproducible high shear forces and residues over 75% of the initial interface area.

A picture of the bonding tool and the schematic trend of force and power for the wire bonding process are given in Fig. 1.

The touchdown of the bonding tool/wire on the chip metallization takes place with a defined touchdown force. Afterwards, the mechanical start force and ultrasonic start power are activated simultaneously during start ramp time. Within the bond ramp time, the bond force and bond power are approached and hold constant during bond hold time. The bond power can be correlated proportionally to the amplitude of bonding tool oscillation [12,13]. The oscillation generates a relative motion between wire and substrate which result in a break-up of interfacial aluminum oxide layers. The horizontal relative motion leads to horizontal forces and thereby plastic deformations in the wire and substrate surface. The start force and bond force are assumed to introduce strain hardening. The ultrasonic start power and bond power lead to softening effects simultaneously [4,5,14,15].

After wire bonding, shear tests were performed. The resulting shear residues were measured. During the shear tests the shear height was set to 10% of the wire diameter. For the optimized parameters (Table 1), the sheared wedges exhibit residues >75% of the initial interface area. An image of the sheared wedge and corresponding shear residue is shown in Fig. 2.

Table 1 lists the optimized wire bonding parameters used in this study and corresponding results of shear tests.

The wire bond was further tested by APC. During APC a square wave pulsed current of maximum 10 A was applied to generate defined temperature cycles. Each cycle had a period of 2.5–4 s and amplitude of approximately 90 K starting from 303 K up to 393 K. To monitor the accuracy and stability of the temperature amplitude, IR thermography was applied. Wire embedding did not take place. For a detailed description of the temperature measurement, the authors refer to [16]. An image of the APC setup and of the tested device is shown in Fig. 3.

2.2. EBSD and nanoindentation measurements

The microstructure of the as-received Al wire and wire bonds before and after APC were investigated by EBSD using a FEI Quanta FEG 400 scanning electron microscope (SEM) with an EDAX DigiView 4 CCD camera. A constant acceleration voltage of 20 kV and a step size ranging from 50 nm to 1 µm were used. All measurements were carried out at metallographic prepared longitudinal sections. All samples were carefully grinded up to the wire radius and subsequently polished with diamond and silicon oxide suspension. Finally, the sample surfaces were etched by ion beam.

Table 1
Optimized bonding parameters and corresponding results of shear tests.

Touch force (cN)	Start force (cN)	Bond force (cN)	Start power (a.u.)	Bond power (a.u.)	Start ramp time (ms)	Bond ramp time (ms)	Bond hold time (ms)	Shear force (cN)	Shear residues (%)
150	300	600	50	100	5	20	80	1400	>75

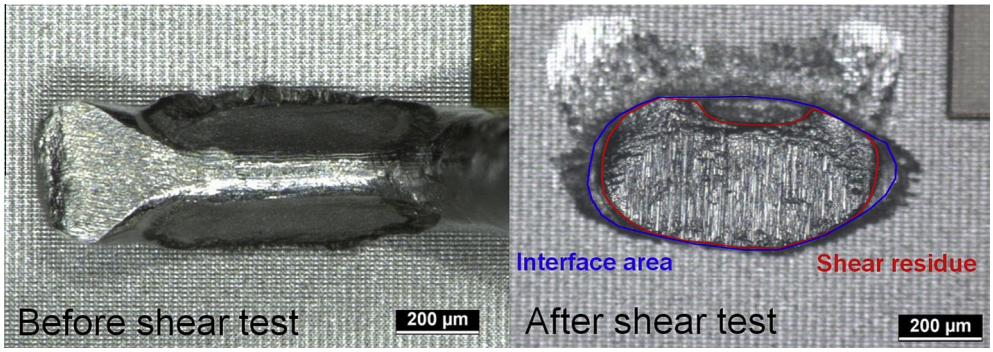

Fig. 2. Image of the wire bond before and after the shear test (shear residue of >75%).