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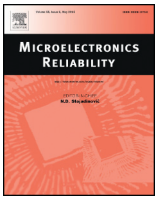

A thermal cycling reliability study of ultrasonically bonded copper wires

Elaheh Arjmand *, Pearl A. Agyakwa, Martin R. Corfield, Jianfeng Li, Bassem Mouawad, C. Mark Johnson

Department of Electrical & Electronic Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, UK

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ABSTRACT

In this work we report on a reliability investigation regarding heavy copper wires ultrasonically bonded onto active braze copper substrates. The results obtained from both a non-destructive approach using 3D X-ray tomography and shear tests showed no discernible degradation or wear out from initial conditions to 2900 passive thermal cycles from −55 to 125 °C. Instead, an apparent increase in shear strength is observed as the number of thermal cycles increases. Nanoindentation hardness investigations suggest the occurrence of cyclic hardening. Microstructural investigations of the interfacial morphologies before and after cycling and after shear testing are also presented and discussed.

1. Introduction

In advanced and novel applications of power electronic modules, modules must be designed and manufactured to be capable of achieving higher switching frequencies and thus higher junction temperatures [1]. Current packaging and assembly technologies require further optimization and improvement to find reliable packaging solutions [2]. Failure analysis reveals that wire bond interconnections and solder joints are perhaps the most important life-limiting areas in power electronic modules [3–6]. New packaging and assembly technologies can address these issues by modification of wire bonding and solder joint materials [2,7]. It has been suggested that Al wire bonds might be replaced by copper wire bonds [8,9] and solder joints replaced by low temperature silver sintering or diffusion soldering [10]. However, replacing existing technologies with new ones presents new challenges [11,12].

The recent interest in employing copper wire for interconnections instead of aluminium wire in semiconductor packaging is driven by a number of anticipated advantages [6]. Copper wire offers higher electrical and thermal conductivity compared to aluminium wire, and this may facilitate the achievement of higher current densities. It also has higher yield strength and mechanical stability which is expected to have a positive effect on thermo-mechanical reliability of wire bonds [4]. Table 1 shows a brief comparison of material properties between aluminium wire and copper wire.

Notwithstanding the abovementioned advantages, copper bonding suffers from some limitations. Copper wire is much harder compared to aluminium, so a higher bonding force and a higher value of ultrasonic power are required, and these can potentially damage the bond pad; this applies to either copper metallized die or copper substrates [11]. Furthermore, copper oxide easily forms at room temperature, and this can lead to poor bonding and a constant need to modify bonding parameters and set-up [11]. So far, indications are that copper wire bond reliability supersedes that of Al [4]; however, the mechanisms and modes by which copper bonds fail and the process parameters needed to achieve a reliable production process are still not well understood. In this paper, we characterise the reliability behaviour of copper wires bonded onto active braze copper substrates. Our aim is to attempt to elucidate the degradation behaviour of copper bonds.

2. Experimental procedures

99.99% pure annealed copper wires, 381 μm (0.015″) in diameter, were ultrasonically bonded on a F&K Delvotec ultrasonic wedge–wedge bonder at room temperature onto active metal brazed copper (AMB Cu) substrates with following bonding parameters: Time 300 ms; Ultrasonic power 165 digits; Bond force starts 600 cN; Bond force ends 1100 cN; Touchdown steps: 100 μm (see Fig. 1). The AMB Cu substrates consist of 300 μm top plate and 250 μm under plate layers of 99.95% pure copper on 1 mm thick aluminium nitride ceramic. A Versa-XRM500 microCT system supplied by Carl Zeiss X-ray Microscopy was used for a same-sample X-ray tomography study. Four bonds were randomly selected for X-ray tomography and imaged in the as-bonded condition and then after 900, 1300, 2100 and 2900 cycles, respectively. The pixel size was kept fixed at 1.73 μm for all datasets. The bonds were subjected to passive thermal cycling from −55 to +125 °C in an environmental chamber. A limited number of bonds were selected for shear testing and the remaining bonds were examined by tweezer pull-test after every 100 cycles in order to determine the occurrence of any lift-offs or failures. Optical microscopy, scanning electron

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* Corresponding author.
E-mail address: eexea8@nottingham.ac.uk (E. Arjmand).

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Table 1
Material properties of aluminium vs. copper [13].

Material properties	Aluminium	Copper
Thermal conductivity	~218 W/m·K	~399 W/m·K
CTE	23.6 ppm	17.7 ppm
Yield strength	29 MPa	140 MPa
Melting point	660.3 °C	1083 °C
Elastic modulus	69 GPa	110–128 GPa
Electrical resistivity	2.68 μOhm·cm	1.72 μOhm·cm

microscopy (SEM) and focused ion beam (FIB) ion channelling of polished cross-sections were used to evaluate the bond pad area and characterise the bond interface microstructures. These were prepared by mounting the samples in edge-retentive epoxy resin and curing at room temperature for 24 hours. This was followed by successive grinding with 1200, 2500 and 4000 grit silicon carbide papers, and 3 μm and 1 μm diamond slurries on a Buehler Metaserv automatic polisher. Etched microstructures were achieved by a final vibrational polish in a 0.06 μm colloidal silica suspension. Room temperature nanoindentation of polished cross-sections was performed using a CSM NHT2 machine platform equipped with a Berkovich indenter with a 50 nm tip radius. Indentation arrays were made which ran parallel to the bond interface and spanned both the wire and substrate. The indent spacing was set at 42 μm. The indentation tests were performed at a maximum load of 10 mN with a 10 s dwell at maximum load, and at a constant loading and unloading rate of 0.167 mN/s. Indentation hardness values were extracted from the load–displacement curves using the Oliver & Pharr method [14].

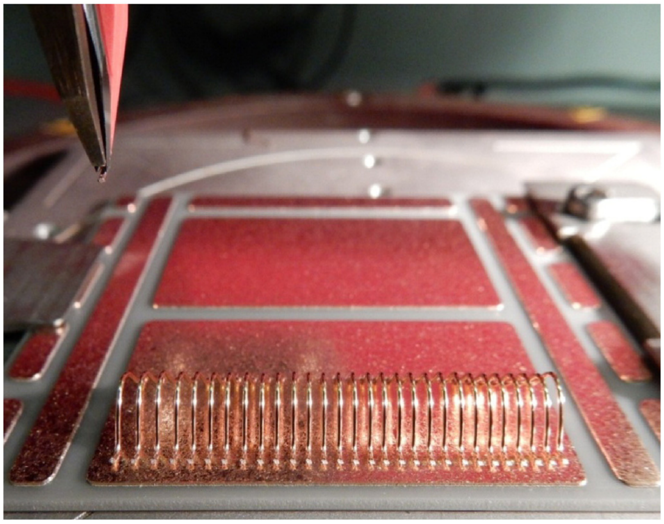

Fig. 1. Copper wires bonded onto AMB cu substrate.

3. Results and discussions

3.1. 3D X-Ray tomography analyses

Four bonds were randomly selected for tomography as can be seen in Fig. 2.

The bonds were imaged at zero cycles (i.e. the as-bonded condition) in order to provide information about initial bond conditions. The bonds were then subjected to thermal cycling between −55 to 125 °C and the same bonds were repeatedly imaged at 1300 cycles, 2100 cycles and 2900 cycles. Virtual cross-sections in the X–Y (lateral) plane of two different bonds are shown in Fig. 3.

These same cross-sections of the interface were analysed at each imaging stage. The arrows in Fig. 3 show some initial pre-cracked regions, mainly in rising heel and tail regions of the bonds. Apart from pre-cracks the bond interfaces seem free of damage in the initial condition, and the bond interfaces do not show any further sign of damage as the number of cycles increases. Interestingly, the analysis of images in the Y–Z plane (as given in Fig. 4) show initial pre-cracks underneath the wire interface, which are not parallel but propagate through the substrate at a 45 degree angle; this is most evident in Bond 2. In addition, no further degradation can be seen as the number of cycles increases (see Fig. 4). Thus far, no lift-offs have been observed.

3.2. Shear test results and microstructural characterisation

Shear testing was also undertaken to determine any changes at the bond interfaces. During the shear test, a shear tool applies a horizontal force to the wire bond to push it off. 24 bonds in total were randomly selected for shear test at zero cycles and then after thermal cycling. Mean values of maximum shear force are presented below in Fig. 5. It is remarkable to note that the average shear force apparently increases with increasing number of cycles: an increase of 25% was observed after 2900 cycles.

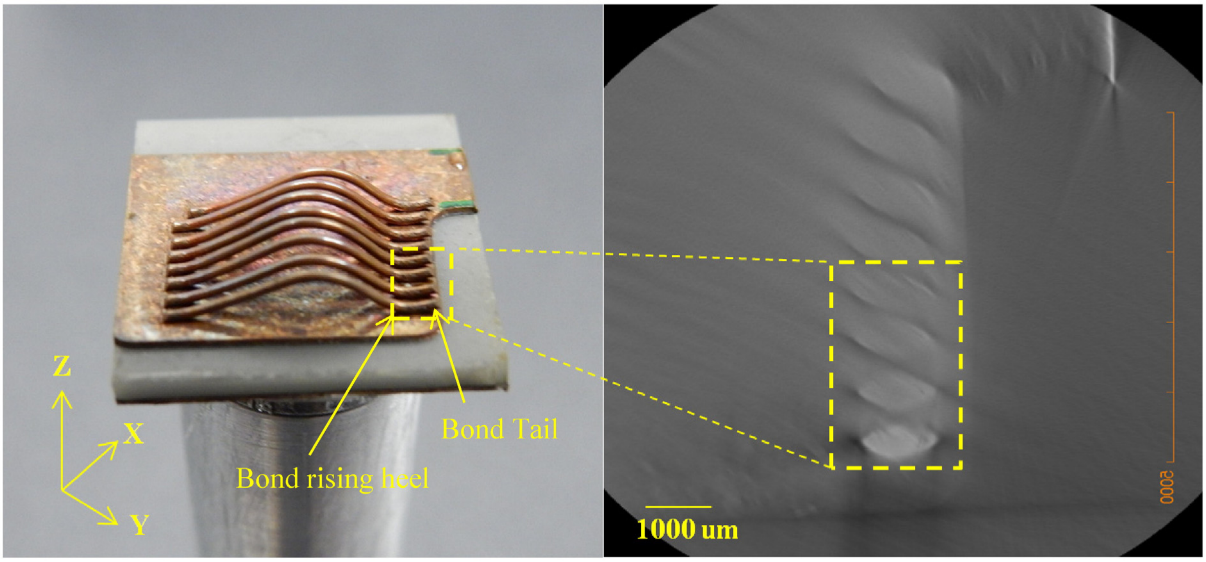

Fig. 2. Selected copper bonds for tomography.

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