# Early fatigue failures in Copper wire bonds inside packages with low CTE Green Mold Compounds

Bart Vandevelde, Geert Willems
Imec, Kapeldreef 75, 3001 Leuven, Belgium
Bart.Vandevelde@imec.be,
Tel.: +32 16 28 15 13

## Abstract

This paper reports a second reliability concern related to the introduction of the low-CTE green mold compounds in advanced IC packaging. The increased mismatch between the CTE's of copper wire and mold compound causes high mechanical stresses in the copper wire bonds during temperature cycling tests. The repeated plastic deformation in each temperature cycle results in fatigue cracking of the copper wire bond.

This paper gives an explanation for this new failure using thermo-mechanical finite element modelling. It shows that only under the combination of copper wire and low CTE overmold, the stresses become high enough in the wire in order to get plastic deformation, which finally leads to low cycle fatigue cracking.

## Introduction

The introduction of low CTE (coefficient of thermal expansion) mold compounds is a consequence of the need for lower moisture sensitivity for lead-free assembly, the need for reduced thermal mismatch between mold compound and die for advanced IC technologies, market demand for "green" electronics and cost minimalisation. These so-called green mold compounds have a high silica filling (>85%) resulting in high stiffness (25 GPa – 30 GPa) and low CTE (7 – 9 ppm/°C).

In an earlier publication [1], it was reported that introducing **green mold compounds** (GMC) with low coefficient of thermal expansion substantially reduces the life time of the second level solder joints. This is mainly due to the higher CTE mismatch between component and PCB by introducing low CTE overmold materials. The change to green mold reduces the solder joint fatigue life from 10% to even 80%, depending on the package type and printed circuit board properties. It can even initiate new failure modes such as copper lead fatigue fracture in TSOP's. For high reliability applications and electronics operating under severe conditions, this mold compound change creates a major reliability concern and requires thorough evaluation.

In the same period, there is a trend to switch over from gold to **copper wires** to reduce cost and increase electrical performance (lower electric resistivity) [2]. Copper also has a benefit over gold regarding thermal conductivity, giving it the advantage at pulling heat away from the die, leading to better performance at elevated temperatures and greater reliability. This performance advantage is particularly evident when copper wire is bonded on die pads plated with thick copper and nickel palladium finish in analog and power products where support for high currents is essential. In this case, the metal joint formed is a solid-solution weld that is extremely stable at high temperatures. In addition, the metal's hardness means that bonds stay more stable mechanically in stressed operating environments.

However, the higher stiffness of copper leaded to higher bond forces on the bond pads requiring a stronger design of the bond pad protecting the underlying circuitry [4]. As a result, new-generation wire bonders are designed to bond copper wires more precisely on circuit pads, with more finely tuned force, heat and ultrasound energy applied to create the bond. Modifications to the bonding wire capillaries were also introduced in order to make the wire adhere better to package pads and form a tighter bond.

In this work, another reliability concern is shown, namely the reduced life time of the copper wire bonds when they are used in packages encapsulated with low CTE mold compounds. *Fig.* ***1*** indicates that the coupled transition leads to a substantial CTE mismatch between the wire material and the mold compound.

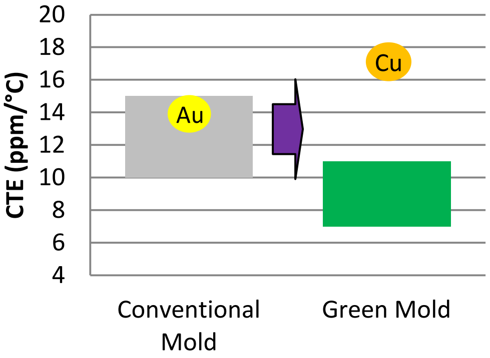

*Fig. 1: Schematic representation of the evolution of CTE of mold and wire bond material creating a substantial thermal expansion mismatch.*

## Experimental finding

In qualification tests for packages, failures in the copper wire bond (Fig. 2) have been found. The cracking is under an angle of 45°, which indicates that the copper wire got vertical stretching and compression leading to the highest shear stress under an angle of 45° (Mohr's law). The repeated plastic deformation in each temperature cycle lead to crack initiation followed by propagation and finally ended into fracture. This failure happens within the duration of a qualification test which is limited to few thousands of temperature cycling. This so-called low-cycle fatigue is only feasible when **plastic** deformation occurs in every cycle. This could be a show stopper for the use of copper wire bonds in high reliability applications.

This problem has never been experienced before with Au wire bonds or with Cu wire bonds in combination with the conventional high CTE overmold.

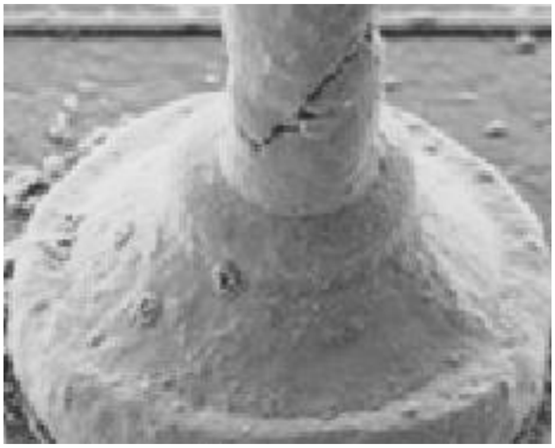

*Fig. 2: SEM picture of a broken copper wire seen after a temperature cycling test.*

## High CTE versus low CTE overmold compound: impact on wire bond stress

In order to understand the impact of the combination of two transitions, namely from Au to Cu wire material, and from high CTE (conventional) to low CTE (green) mold compound, a thermo-mechanical stress simulation study using FEM, is performed for a particular QFN package with 25 µm (1 mil) diameter wire bond. Most interest goes to the ball bond on top of the die bond pad.

Table 1 shows the properties for copper and gold wire bond materials as found in the Heraeus bonding wire brochure [5]. With respect to Au wire, the stiffness of Cu wire is about 55% higher, the CTE 16% higher and the yield stress 20% lower. As a reference, also the resistivity is shown which shows that the resistivity of Cu is about 23% lower than for Au which gives copper higher capability to drive electric current

*Table 1: Material properties for 25µm gold and copper wire based on Heraeus bonding wire brochure [5]*

| Property | Gold wire | Copper wire |
|---|---|---|
| Young's modulus | 79000 MPa | 123000 MPa |
| CTE | 14.2 ppm/°C | 16.5 ppm/°C |
| Yield stress | ~ 200 MPa | ~ 160 MPa |
| Electrical Resistivity | $2.2\ 10^{-8}\ \Omega$ m | $1.7\ 10^{-8}\ \Omega$ m |

Table 2 shows the properties of two mold compounds selected for this study. The data are based on input from the material supplier's data sheets. The conventional mold compound has a rather high CTE which is quite well matched with the BT laminate and printed circuit board. The green mold compound has a much lower CTE which is better matched with the silicon die, which is beneficial for CPI (chip-package interaction) failures in the BEOL. A side effect of the lower CTE is that the E-modulus increases (due to higher content of silica particles). In reference [1], it was shown that the product of E-modulus and CTE is about a constant value.

*Table 2: Material properties for a specific conventional and specific green mold compound*

| | **E-mod.** | **CTE (T<Tg)** | **CTE (T>Tg)** | **Tg** |
|---|---|---|---|---|
| **Conventional (high CTE) Mold Compound** | 17 GPa | 13 ppm/°C | 49 ppm/°C | 150°C |
| **Green Mold (low-CTE) Compound** | 28 GPa | 7 ppm/°C | 30 ppm/°C | 130°C |

The Finite Element Model (FEM) is shown in Fig. 3. A 3D slice model is chosen which is sufficient to model the stress impact of the mold onto the wire bond. The package is a QFN package, but it can represent any copper leadframe based package. The model includes the temperature dependent E-modulus and CTE for the mold compound and also the yield stress for the wire material. The applied load is a cooling down after molding, followed by a temperature cycling between -40 and 150°C. Besides deformations and stresses, also the plastic deformation in the wire material is a result of interest in this study.

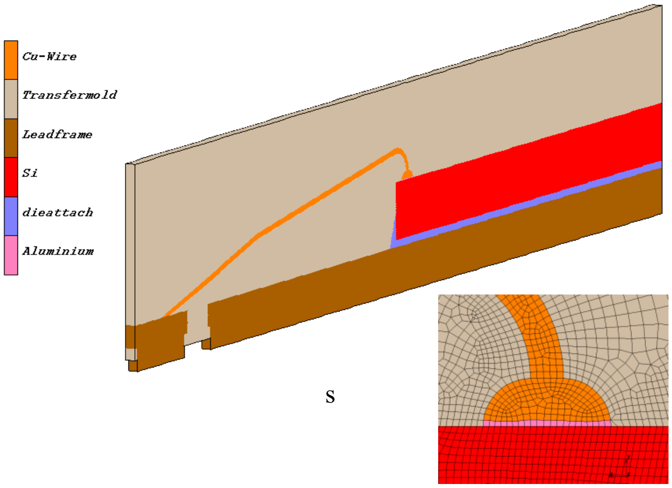

*Fig. 3: 3D slice FEM of a QFN package with one 25µm∅wire modelled in detail.*

The results of the simulation study are shown in Table 3. Only in the case of low-CTE overmold and copper wire, a plastic deformation is found. This means that the stresses induced by the thermal mismatch between the overmold and the wire reach the yield stress of copper (160 MPa). In general, repeated plastic deformation should be avoided in the wire bond as it always leads to rather low number of cycles to failure.

*Table 3: Plastic deformation per temperature cycle calculated by FEM for two wire materials and two molding componds.*

| | **Conv (high CTE) overmold** *13 ppm/°C* | **Green (low CTE) overmold** *7 ppm/°C* |
|---|---|---|
| **Au wire** *(14.2 ppm/°C)* | No plastic deformation | No plastic deformation |
| **Cu wire** *(16.5 ppm/°C)* | No plastic deformation | **$\Delta\varepsilon_{pl} = 0.37\%$** |

Fig. 4 shows that the location of highest plastic deformation is achieved just above the neck of the ball bond. This agrees well with the location of the failure shown in Fig. 1. Life time models for copper wire are not available. Using a life time model of copper plated through holes (PTH) in PCB, the mean life time to failure would be **~1500 cycles**. Although the copper material in PTH's is different from copper wire bond, the estimated life time does make sense as it falls into typical qualification tests for high reliability applications.

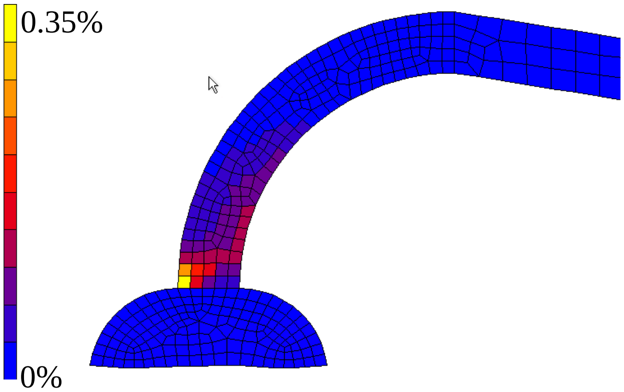

*Fig. 4: Plastic strain induced by one temperature cycle (Cu wire surrounded by green mold compound with 7 ppm/°C)*

## Parameter study

The two molding materials selected in the study above are two extremes in the available gamma of molding compounds. As a low CTE overmold materials have some benefit regarding CPI, it is of interest to know from which CTE on we don't get any plastic deformation anymore. In reference [1], it was shown that the elastic modulus varies inversely proportional to the CTE of overmold. Therefore, six different overmolds are selected (Table 4).

*Table 4: Six overmold material selected for the parameter study.*

| | CTE | E-modulus | |
|---|---|---|---|
| **OM1** | 7 ppm/°C | 30000 MPa | Green MC |
| **OM2** | 8 ppm/°C | 26500 MPa | |
| **OM3** | 10 ppm/°C | 24000 MPa | |
| **OM4** | 12 ppm/°C | 21000 MPa | |
| **OM5** | 14 ppm/°C | 18500 MPa | |
| **OM6** | 16 ppm/°C | 15000 MPa | Conventional MC |

Fig. 5 shows the results of the parameter study.

- For **Au wire**, only plastic deformation is found when the CTE of the overmold is 16 ppm/°C. The reason is that the CTE above Tg becomes very high and is causing some strong deformation onto the wire. For low CTE overmolds, there is no plastic deformation seen;
- For **Cu wire**, plastic deformation is seen below 12 ppm/°C for overmold, and is highest for lowest mold CTE. This indicates that the CTE difference between copper and mold is the dominating parameter for the induced plastic deformation. Important to mention is that the size of the induced plastic strain in the copper wire depends on the shape of the wire bond and also the package type.

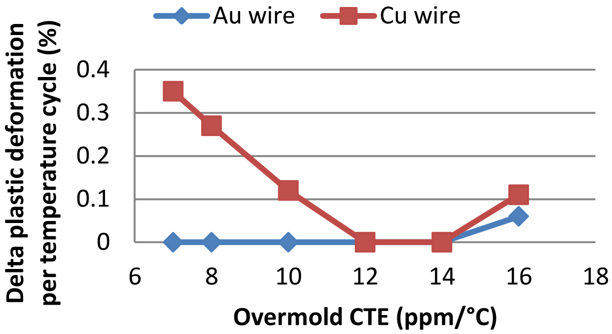

*Fig. 5: Plastic strain induced in wire bond for 6 different overmold materials.*

## Conclusions

It was found in reliability experiments that the combination of the switch from Au to Cu wire and the introduction of low-CTE GMC's leads to a reduced life time of the wire bond. This could be a show stopper for the use of copper wire bonds in high reliability applications. The main reason is the mismatch in thermal expansion between the copper wire and the overmold. In the conventional (non green) packages, the CTE of Au wire (14 ppm/°C) matches well with the conventional overmold (13 – 17 ppm/°C). With the double switch, the mismatch increases to near 10 ppm/°C (Cu: 16.5 ppm/°C, GMC: 7-9 ppm/°C). In temperature cycling, the copper wire will be stressed by the GMC. In cycling mode, this will lead to mechanical fatigue cracks.

This trend was well explained by thermo-mechanical simulations. A parameter study revealed that plastic deformations occur below 12 ppm/°C of the overmold material.

## Acknowledgments

This work has been supported by the IWT (Flemish government) within the frame of the I SEE project.

## References

1. B. Vandevelde, M. Lofrano and G. Willems, Green mold compounds: impact on second level interconnect reliability. In: Electronics Packaging Technology Conference - EPTC. ieee, 2011. (7-9 December 2011; Singapore, Singapore.)
2. U. Chaudhry, D. Corral, G. Ryan, TI's journey to high-volume copper wire bonding production, TI white paper.
3. L.A.Lim, J. Castaneda, S. Shirakawa, Fine Pitch Copper Wire Bonding Process and Materials Study, ASM publication.
4. D.Degryse, B.Vandevelde, E.Beyne, Mechanical FEM simulation of bonding process on Cu lowK wafers, IEEE

Trans. Components and Packaging Technologies, missing publisher, Vol. 27 (4), pp.643-650, 2004.

5. http://heraeus-contactmaterials.com/media/webmedia_local/media/downloads/documentsbw/brochure/HERAEUS_BondingWire_Brochure.pdf
6. Saraswatiet al, "High temperature storage (HTS) performance of copper ball bonding wires," Proc. of 7 th Electronic Packaging Technology Conference, 2005, pp. 602-607
7. Singh, Inderjit, Sr.et al, "Enhancing Fine Pitch, High I/O Devices with Copper Ball Bonding," Proc. of 55 th Electronic Components and Technology Conference, 2005, pp. 843-847.