Ensuring Suitability of Cu Wire Bonded ICs for Automotive Applications

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Abstract

The transition to replace gold with copper bond wires in semiconductor components, primarily driven by the ever increasing price of gold wire, has been under way for several years. Cu wire bonds (Cu-WBs) are technically more challenging than gold to produce, requiring improved designs, processes and equipment. After introduction in consumer products, their use is now migrating to automotive electronics where product integrity for quality, reliability and durability (QRD) and safety over 10-15 years in a demanding harsh environment is paramount, in addition to managing cost in the highly competitive global automotive market.

Reliability issues with some Cu wire bonded components detected during the rigorous product validation durability–reliability tests of automotive electronics, however, are starting to appear. The indications are that only optimized package design with well-controlled assembly processes are suitable for high reliability (hi-rel) harsh environment applications such as automotive, military and aerospace. A concern is that non-optimized Cu-WBs and package materials issues are being detected in module-level durability validation tests in parts that were qualified as automotive grade per AEC Q-100 or AEC-Q101. This article will explore the issues and discuss potential solutions as the Automotive Electronics Council (AEC) – the organization that defines requirements for automotive grade electronic components – works to update qualification procedures for evolving Cu-wire bond technology.

Key Words: Cu Wire Bonds, Automotive, Reliability

I. Introduction - Cu-WB delamination issues

Mold compound delamination in a semiconductor component has been a potential failure issue that has needed to be managed since plastic encapsulated packages were invented. Delamination can occur rapidly during soldering if excessive amounts of moisture were absorbed by the mold compound resulting in popcorning fractures or interfacial fractures during soldering. Delamination can also occur slowly because of swelling from gradual absorption of moisture while in service or thermal expansion mismatch stresses. Delamination can cause fractured or lifted wire bonds that result in open circuits. It can result in cracks in the package that can allow contaminants to enter, leading to corrosion of copper wires or bond pads that also results in open circuits, or it can cause current leakage due to the presence of mobile ions.

IPC/JEDEC J-STD-020 revision D on Moisture/Reflow Sensitivity Classifications only applies to identifying moisture-sensitivities and related protective measures needed to avoid package popcorning or internal delamination damage during assembly soldering. However, there are no industry standards on delamination limit requirements after environmental stress testing of loose components, after board mounting, or after reliability testing with components mounted on circuit boards. J-STD-020 allows delamination if the component passes reliability testing, however, such testing may not correlate to a long life hi-rel application.

Because copper is less ductile than gold, copper is more sensitive than gold to package delamination induced wire fracture. Failures of some ICs during module-level durability tests have been related to soldering delamination issues that weaken the bond, resulting in the inability to endure module-level automotive durability requirements.

II. Thermal cycling-related Cu-WB issues

Recently, there have been cases of copper wire separation near the stitch bonds without package delamination. These issues occurred during automotive module-level thermal cycle validation testing and were not detected during component-level thermal cycle testing. The testing challenges are discussed below.

Module-level thermal cycling testing. These are accelerated life tests calibrated to focus on structural integrity of the assembled circuit board with its components and housing. This testing places emphasis on component-to-circuit board coefficient of thermal expansion (CTE) mismatch-driven attachment solder fatigue.

Component-level thermal cycle tests. These tests are focused on the CTE mismatch issues within a component such as between the die, lead frame, wire bond attachments and the package. These tests are performed using loose components and only assess the stresses generated within the component. CTE mismatch and elastic modulus of the mold compound against leads, and bond wires are important factors that create internal mechanical stress as temperature changes. Internal dimensions and geometries are important because serpentine internal package lead shapes can have different mechanical behavior than straight shapes.

Mold compound and lead frame materials, however, will also stretch, compress, and bend because of the additional externally applied thermal cycling forces on the leads resulting from the components being mounted to a circuit board and perhaps potted. If externally applied forces are added to the internal component generated forces, their addition can be sufficient to cause failure of non-optimized Cu wire or their bonds during module-level testing.

Some recent module-level thermal cycling issues have included wire heel breaks that have occurred at the point where the wire transitions out of the stitch bond, instead of a separation of the actual stitch bond (Figure 1). In these type of wire breaks, the root causes are typically: 1) Excessive capillary force resulting in a thin pinch point where the break occurs; 2) A worn capillary head that produces an insufficient transition back to the wire diameter (Figure 2); 3) A non-optimized capillary head will produce an undersized weld width and/or an under-sized heel bond (Figure 3).

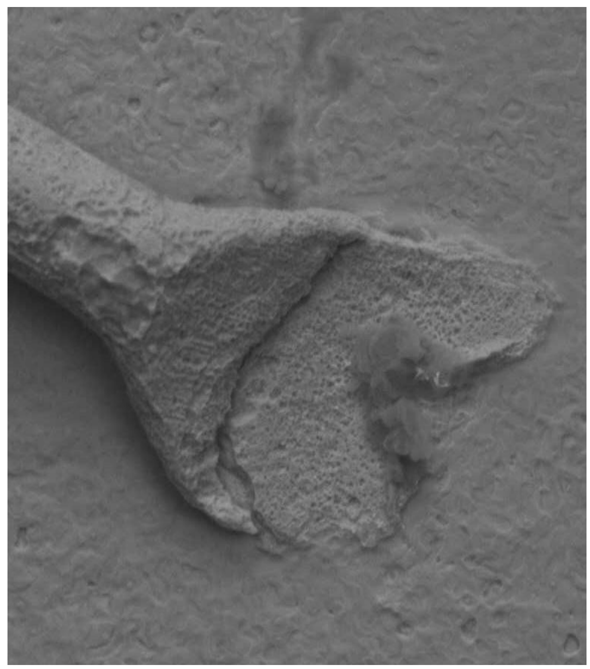

Figure 1: Example of a copper bond wire broken at the heel point where the wire exits from the stitch bond. The break occurred during module level thermal cycle test, from-40°C to +120°C, and package delamination was not a factor.

The strongest stitch bonds are produced by using a capillary head with a large tip diameter, which produces a larger bond. A face angle, of 8 degrees, combined with a large outer radius produces a gradual transition slope with a large heel weld needed to avoid the type of pinch point that resulted in the wire break shown in Figure 1.

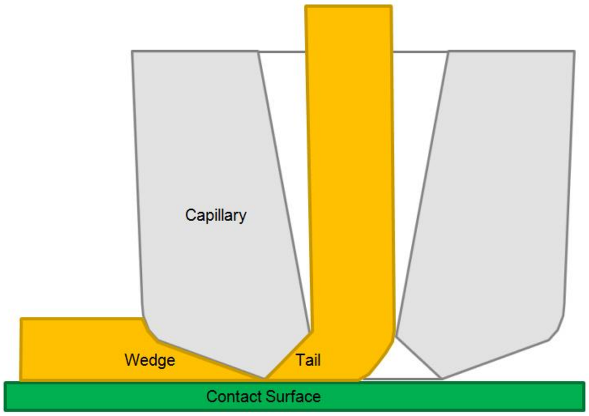

Figure 2: An optimized, non-worn wire bonding capillary head that is sized and shaped to provide an adequate heel weld and a gradual transition back to the wire diameter applied with proper calibration and wear monitoring/maintenance is required to prevent excessive flattening and pinch points.

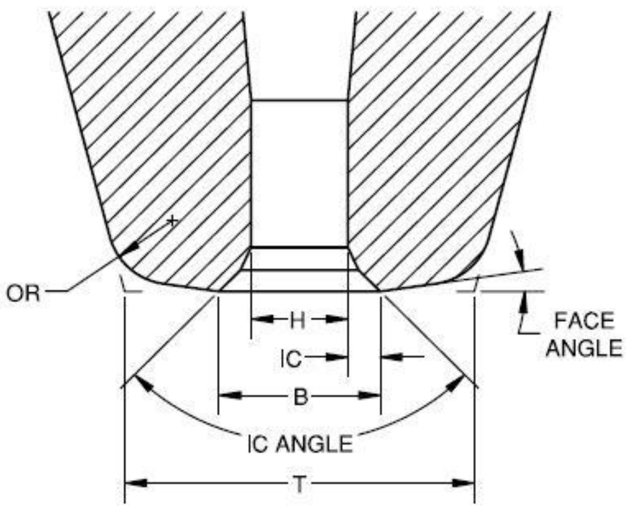

Figure 3: Bonder capillary head geometry determines the size and shape of the wire bonds, which affect bond durability and robustness.

While module-level thermal cycling tests have also occasionally resulted in gold bond wire failures, the reduced ductility or copper wire and the challenges of copper bonding makes understanding the capabilities of copper wire and copper bonding under long-life harsh environmental conditions a priority in hi-rel industries. While most Cu-WB components can pass both automotive component- and module-level validation, the few that do not have resulted in efforts to identify the critical to quality (CTQ) reliability physics characteristics that ensure robustness and durability. Additional efforts are ongoing to develop ways of consistently validating good component and screen out weak components at the component level.

III. Automotive OEM Expectations

Ensuring the performance suitability, QRD, and safety of an automotive electrical/electronics (E/E) module is a primary objective of automotive module-level validation procedures. Before validation test failures result in extra cost and time to identify the root cause and correct problems, automotive OEMs desire that products be designed right on the first attempt so that validation is achieved on the first attempt. This allows budgets and schedules to be maintained, which results in fast and efficient product development processes. OEMs do not want to find what they see as component-level issues, discovered during module-level validation tests, they want component-levels issues resolved down the supply chain. They also desire to get more potential board- and module-related design and assembly problems designed out, prior to validation testing. This tactic is known as the "design for reliability" (DfR) approach to product development. It is an improvement over the traditional "reliability growth/design-build-test-fix, trial and error" approach to product development. The DfR approach is becoming even more essential under the current safety critical atmosphere in the auto industry related to the recent increase of global vehicle safety recalls for E/E issues that have been accompanied by significant media coverage, record fines and congressional investigations and proposals for new legislation and regulations. Furthermore, the development of robotic self-driving vehicles is well under way. Cars with limited camera aided self-parking and emergency braking features are already here. Fully autonomous vehicles are expected between 2020 and 2025 [1].

The safety-critical issues of self-driving vehicles demand a quantum leap in the QRD performance of vehicular E/E systems and components. In

Europe, the release of the new ISO-26262 Standard for Vehicle System – Functional Safety is driving increased emphasis on E/E QRD and safety for comprehensive product integrity throughout the entire E/E supply chain.

IV. WB design and CTQ Characteristics

The primary Cu-WB QRD issues are related to ball bond separation, pad or die damage, corrosion, and stitch bond separation, which are related to Cu being a harder material than gold that is more prone to oxidation. Primary critical to QRD characteristics for Cu-WB are:

Formation of the Cu ball bond. To prevent damage to the ball bond pad and IC die and to ensure a good bond – a very symmetrical, spherical ball, of precise dimensions, that is oxide free – has to be consistently formed at the tip of the bond wire during the electronic flame off (EFO) process. Copper oxide on the ball surfaces will make bonding difficult. Misshaped spheres can damage the pad or result in weak, partial bonds that may fail either after molding, or in the field under usage stresses. Because copper readily oxidizes, it has a short shelf life; Cu bond wire must therefore be used within one week of package opening. At the elevated temperatures of the EFO sphere creation process, oxidation occurs rapidly. To prevent this situation, Cu spheres were initially formed in a nitrogen (N_2) inert atmosphere. It was later found that a mixture of 95% nitrogen and 5% hydrogen (called forming gas) is more effective at preventing Cu oxidation (Figure 4).

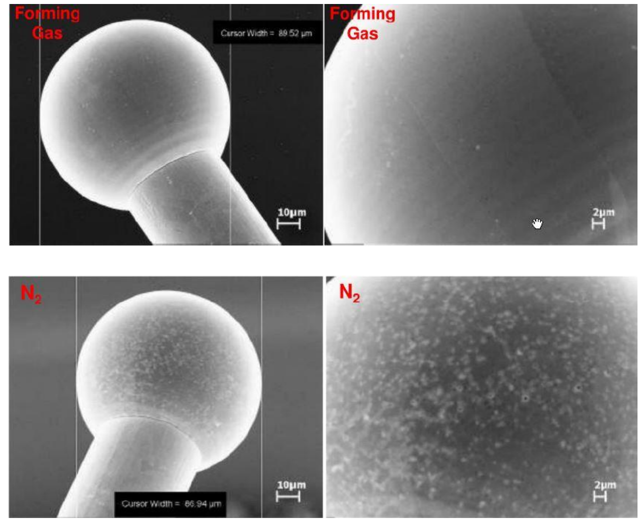

Figure 4: The use of forming gas during Cu wire bonding (upper images) reduces Cu oxide formation more than an inert N_2 atmosphere (lower images) [2].

Preventing pad and die damage and Cu ball bond failure. Because copper wire is harder than gold, more force is required during thermosonic bonding. Excessive force can displace bond pad aluminum and sometimes damage die material or features under the pads.

Aluminum splash is a when bonding forces causes pad aluminum to flow out from under the ball bond or the ball can punch through the pad and damage the die. The bonding process must be controlled so that ≥0.2µm of the original aluminum pad thickness remains for the pad to maintain the strength needed to prevent pad fractures or tearing. This can be mitigated with pads that are thicker than the typical 1µm Al thickness used with gold wire bonds. It is also essential that the CuAl inter-metallic compounds that form the bond are created over at least 70% of the ball contact area.

Die cracks and cratering damage to the die or circuitry under the pads from excessive bonding or probing forces can disrupt circuit functions or undermine pad attachment strength, ultimately resulting in bond separation. Using very pure Cu, which is softer, is one way to reduce these risks. Robustness against die damage can also be improved by up front design considerations for components that will be using Cu bond wires. Circuit features and vias should not be routed in die layers under Cu bond pads. If this is not possible, very careful calibration and control of the Cu bonding process is required to reduce die damage risks. The use of silicon- doped aluminum bond pad metallization should be avoided because it results in silicon nodules that act like grit under the bond pad. Barrier layers are a preferred method to prevent contact spiking and produce a more robust pad structure. Finally the use of low k dielectric materials should be avoided because they are more fragile and more prone to cracking than high k dielectrics.

Chlorine corrosion of the Cu-WBs can occur from high chlorine (Cl^-) content and high pH in the package encapsulant molding material. Humidity, temperature and electrical bias drive this failure mechanism. When a forward bias is applied, Cl^- ions are attracted to the positively-charged pad causing corrosion that can eventually result in bond separation. This mechanism is accelerated by the high humidity and temperature conditions automotive electronics are required to endure. Using a molding compound with a low pH (between 4-6) and a low chlorine content <20ppm, (preferably <10ppm) is essential for alleviating failure risks. It is also important to minimize voids or irregularities in CuAl IMC bonds that would allow moisture ingress that could hasten corrosion degradation and separation stresses within the bond.

Preventing 2nd stitch bond failure. The stitch bond is created by impressing the wire against the bond surface of the terminal lead frame. Oxidation of the wire is again a concern because the wire was not freshly formed in an EFO process as the ball head was. The main concern is that the harder Cu wire may not deform enough to expose fresh metal for the bond. Enhanced ultra-sonic action known as stitch bond enhancement (SBE) features have been proven to produce stronger stitch bonds [4]. A thin palladium coating over the copper wire also produces a stronger stitch bond. However, this further increased wire hardness might increase risk for pad/die damage during ball bonding, so this trade off needs to be carefully managed.

During the introduction of Cu-WBs, retrofitted conversion kits were developed to adapt existing gold bonding equipment for producing Cu bonds. As experience grew, enhancements to IC die design and material issues were identified and new bonding equipment systems were developed to account for the differences and needs of copper wire bonding. When these design features and properly calibrated equipment are used, the optimized Cu-WBs discussed in the previous sections can be produced.

Qualification of automotive semiconductors with Cu-WBs. The challenge now is to further optimize qualification procedures for automotive grade semiconductors to enable distinction between marginal Cu-WBs and the optimized Cu-WBs needed to survive in automotive applications. The AEC is developing a new automotive industry specification to be used when qualifying components that have copper wire. A document has been drafted that will add additional requirements over and above what is specified in the AEC-Q100 and AEC-Q101 documents when copper wire is used. The document is under discussion, but will likely include mold compound delamination requirements before and after environmental stress testing, and physical analysis requirements after environmental stress testing. Under consideration is a requirement for a circuit board-mounted thermal cycle test.

One OEM has suggested that semiconductor suppliers perform thermal cycle testing to 3X the AEC requirement in order to catch the failures that 1X testing at the component level has not detected. However, extending AEC testing to more cycles on loose components may not correlate with module-level thermal cycle performance because the stresses experienced by the component are significantly different when mounted to a substrate. Performing a board-level stress test followed by physical analysis to validate package robustness, may be a more effective approach to catch package weaknesses early in the package development phase.

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