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A mini review on elucidating wire lifting defects due to Au_5Al_2 formation in LED thermosonic bonding

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ABSTRACT

The light-emitting diodes (LEDs) are commonly employed as a light source because of their energy efficiency and great light intensity. The reliability of LED components is critical, especially when they are used as safety equipment in medical devices, automobiles, and aerospace, among other applications. LED malfunctions resulting from wire connections must be meticulously prevented. Wire bonding is a technique employed in the production of LEDs. Ball lifting and wedge lifting are failures encountered in the wire bonding process. Ball lifting is the process of separating a ball bond from a semiconductor device's bond pad. There are numerous explanations for why this might be the situation. Ball lifting and wedge lifting are caused by an improper wire bonding configuration and contamination of the bond pad surface. Unstable workpiece holders, incorrect wire bond parameter configurations, and outdated wire bonding equipment are all factors in an inadequate setup. Inadequate initial welding and insufficient intermetallic formation are the results of this, and the bond pad and the ball are both affected. The connection will break because of this problem, and the LED will stop working.

Keywords: *Light-emitting diode (LED), Gold wire bonding, Thermosonic bonding, Gold-aluminium intermetallic, Kirkendall voiding, Performance measurement*

1. INTRODUCTION

A semiconductor light-emitting diode, more commonly referred to as an LED, is an important component of the technology that is used today. An LED is a device that emits light energy whenever a current flows through it [1]. When an appropriate voltage is applied to a p-n junction diode, a phenomenon called electroluminescence develops in which electrons join with electron holes in the component, discharging energy in the shape of photons [2]. The first attempt to properly explain p-n junction electro-luminescence [3] was developed in the 1920s by Oleg Lossev. The "Father of the Light-Emitting Diode," Nick Holonyak Jr., who General Electric employed at the time, was the inventor of the first LED, which was visible to the human eye, in the year 1962 [4]. In the early 1990s, researchers developed bright green, orange-red, orange, and yellow LEDs using substrate materials. Later afterward, in 1994, Shuji Nakamura created ultra-bright blue LEDs, which served as a model for modern commercial LEDs [5]. With the rapid advancement of semiconductor technology, employing LEDs as a lighting source is more feasible, therefore replacing conventional light sources with characteristics such as higher luminous potency, more robustness, longer life, higher colour rendering index (CRI), and higher reliability [6, 7].

The predominant method for establishing microelectronic linkages among an integrated circuit, a lead frame, and LEDs is wire bonding [8, 9]. Wire bonding is a connection method employed in LED packaging that integrates temperature, force, ultrasonic energy, and duration to join two metallic components: a wire and a bond pad. The predominant method for integrated circuit and LED packaging in the industry is wire bonding [10]. Additionally, wire bonding constitutes over 90% of the integrated circuit packaging market, attributed to its adaptability and cost-effectiveness. The organization possesses a substantial base of equipment, materials, and manpower [11]. The wire bonding process utilized in electrical wiring integrates thin wire with heat, pressure, and/or ultrasonic energy. Wire bonding is an established welding technique that involves the direct contact of two metallic components, specifically the wire and the pad surface. Wire bonding remains an essential procedure in the semiconductor packaging process. This is partly due to the benefits of compliant wires when subjected to temperature and bending stress conditions, which leads to high reliability in packaged interconnections [12]. Figure 1 shows an example of a completed wire bonding process.

However, the semiconductor manufacturing sector is starting to implement copper (Cu) wire bonding. Copper wire bonding presents multiple advantages when compared to gold wire bonding. These advantages include lower and more stable costs relative to gold, increased rigidity that

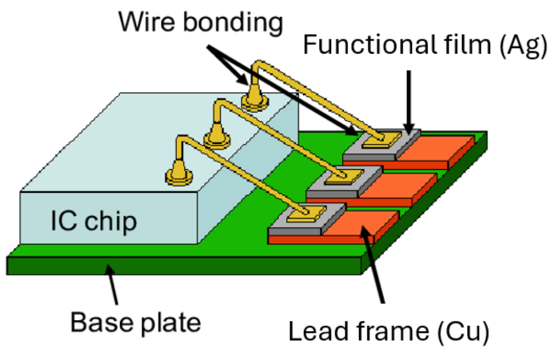

Figure 1. Schematic of chip-and-wire technique by wire bonding using lead frame with functional film [1]

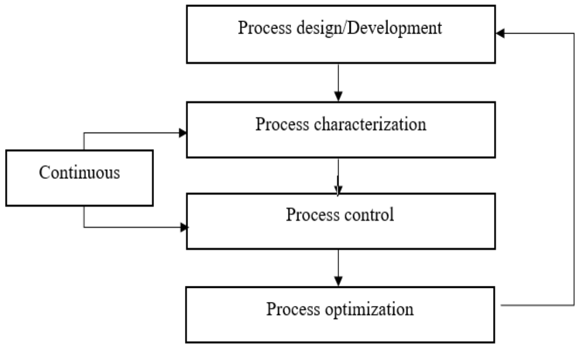

Figure 2. Process flowchart for the development of a typical wire bond

minimizes wire sweep, superior electrical conductivity, and reduced rates of intermetallic development for Al–Cu in contrast to Al–Au, with copper being 25% more conductive than gold [4, 13]. But the drawbacks with copper wire bonding are that the hardness of copper (which can induce cratering and aluminium (Al) pad squeezing), ball-neck fatigue failures in plastic encapsulation during temperature cycling, oxidation of wire surfaces, diminished tail bondability, and corrosion were all issues with copper wire bonding.

The primary goal of this review study is to describe the various types of flaws that commonly occur throughout the LED fabrication process that uses a gold-aluminium wire bond system, particularly due to Au_5Al_2 formation. Depending on which sub-process was involved during the thermosonic bonding, the parameters that caused the defects were addressed separately. This study also includes results from other studies on faults that develop during thermosonic wire bonding.

2. THEORETICAL BACKGROUND

2.1. Process Optimization

When it comes to the development and improvement of production, the initial stages of process design and development, process characterization, process control, and process optimization frequently prove to be extremely important. The procedure diagram that is presented in Figure 2 illustrates how these processes interact with one another to create a continuous loop between characterization and control, along with periodic optimization and development.

Setting attainable goals at the early stages of the process requires knowledge of the process's capabilities. Relevant data can be acquired through laboratory investigations, published literature, and the experiences of industry and equipment vendors. In the second step (process characterization), data regarding wire bonding issues, including off-centre bonds, insufficient adhesion to the die, and wire fractures, are gathered and classified. The efficacy of a process relies on the third stage, referred to as "process control." To attain consistent performance, it is essential to minimize operating factors such as bond program parameters, machine setup and operational procedures, bonding tool installation, wire pull operations, and product modifications. The residual variables must be meticulously controlled. Ensuring consistency throughout the process, particularly in the training of operators, is essential. Process optimization can be carried out if the earlier phases of process development have been completed. Statistical process control (SPC) can be used to monitor processes and reduce process drift for items like wire pull once they are running in a production environment.

2.2. Thermosonic Bonding

Thermosonic bonding of gold (Au) or copper (Cu) wire to aluminium (Al) bond pad has been a significant manufacturing procedure in the semiconductor industry. Since the 1980s, this system has been the subject of substantial research and development [14, 15]. The thermosonic (TS) wire-bonding technique integrates ultrasonic and thermocompression welding, utilized for establishing connections between integrated circuit (IC) chips and lead frames [16]. Thin gold wire is frequently employed to connect the components cohesively. The wire bonds represent the connections that have been established. Due to its established performance and reliability, thermosonic gold wire bonding has become one of the most prevalent interconnecting technologies. The manufacturing technology shapes the environment, which is why the thermosonic gold wire bonding technique is utilized in the semiconductor sector to ensure high quality and consistency in material attributes [17]. The thermosonic bonding process necessitates the application of ultrasonic energy, elevated temperatures, specific bonding durations, and adequate bonding forces. Figure 3 provides a visual representation of this concept.

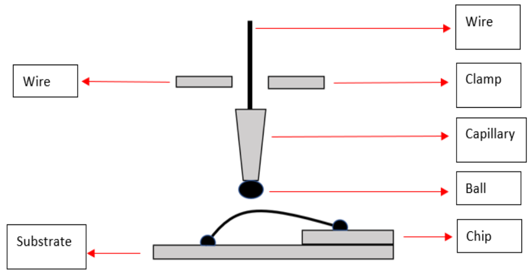

Figure 3. Overview of gold wire bonding

Currently, over 95 percent of all wire bonds are produced using thermosonic bonding methods [17]. Thermosonic bonding constitutes one of the fundamental bonding processes, alongside thermocompression and ultrasonic bonding, which are the other two methods in this category.

2.3. The Properties of Gold Wire and Aluminium Substrates in Wire Bonds System

The material composition of the wire used in the wire bonding process is a crucial area of investigation in the electronic packaging field. The characteristics of the wire play a vital role in evaluating the dependability of the wire bond [18]. The use of gold (Au) wire for connecting to aluminium (Al) substrates stands as the primary technique adopted in the industry. At elevated bonding temperatures, the gold wire exhibits strong adhesion to aluminium. Exposure to elevated temperatures exceeding 150°C will promote the development of intermetallic compounds (IMCs). The presence of IMC leads to a reduction in electrical conductivity and negatively impacts the overall quality of the electrical assembly. The development of an IMC can lead to fracture propagation, which may ultimately cause connection failure [19].

Gold (Au) is chosen for this study due to its beneficial qualities in wire bonding. The substrate material is one more process modulator that can be examined. A variety of substrates have been investigated in the same way as wire material has. Aluminium is the predominant material used for bonding to gold wire. Aluminium is relatively cost-effective when compared to other substrate materials, owing to its abundance as one of the most common metals found on Earth [20]. Aluminium has a low density, which helps electronic equipment be more portable by reducing system weight. The interconnect's corrosion- and oxidation-resistant qualities help to extend its life. Although, aluminium forms intermetallic growth gold is prone to underpad damage [21], as previously stated.

2.4. Ball Bonding Method

The ball bonding method represents a specific procedure within the broader category of wire bonding techniques. This technique emerged in the 1950s and has since evolved swiftly, aligning effectively with industrial needs. The ball bonding technique employs an Electric Flame Off (EFO) unit that utilizes high voltage to generate a Free Air Ball (FAB). During the operation, a strong current breached the EFO gap, leading to a high voltage spark that melted the tail of the metal wire in a glow discharge, resulting in the creation of a spherical ball, thus giving rise to the name of the technique [22]. The ball bonding process utilizes a capillary, a single-use tool akin to a needle, to establish a weld at both ends of the wire through the integration of heat, bonding force, and ultrasonic radiation.

Figure 4 (a) to (e) illustrates the standard steps of the ball bonding process. A high voltage electrical flame-off (EFO) occurs between the wire and an electrode due to the surface tension of the molten metal, resulting in the melting and

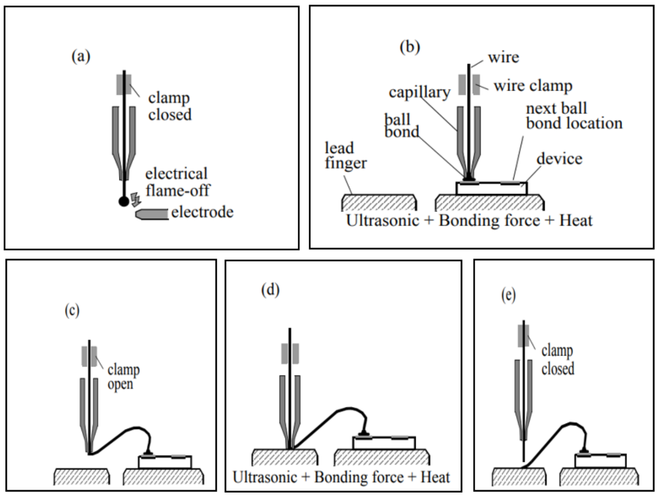

Figure 4. The sequence of ball bonding process shown schematically

solidification of the wire, which forms a ball as illustrated in Figure 4 (a). The capillary is subsequently lowered to the chip, which has been heated to a temperature range of 100 to 150 degrees Celsius. The attached transducer emits ultrasonic oscillations towards the capillary. Figure 4(b) illustrates the formation of the bond between the ball and the chip surface through a solid-state bonding technique [14]. The capillary is subsequently positioned in the substrate region where wiring of the chip is required, as illustrated in Figure 4(c). The capillary descends once more to the substrate's surface. Heat energy, force, and ultrasonic energy are employed to solder the wire, this time without any ball formation, as illustrated in Figure 4 (d). This stage is termed the crescent bond, and it is also known as the wedge bond, stitch bond, or second bond. In the final stage, the capillary ascends to the predetermined height and severs the wire while the clamp remains closed, leading to a new electrical flame-off (EFO), as illustrated in Figure 4 (e).

2.5. Wedge Bonding Method

The wedge bonding method is classified as a wire bonding procedure, alongside the ball bonding method. This method employs ultrasonic energy and pressure to create a bond between the wire and the bond pad. When gold or copper wire is used, wedge bonding employs temperatures up to 150 degrees Celsius, and this process is known as thermosonic (T/S) bonding, which is comparable to ball bonding [23]. In contrast to the ball bonding method, wedge bonding is unidirectional, meaning that the looping must follow the initial bond's symmetry centerline. Each wire bond typically requires the rotation of the substrate holder. Wedge bonding facilitates reduced bonding pitches owing to the dimensions of the initial wedge bond. Additionally, wedge bonding does not require any heat input, such as the electrical flame off (EFO), and is less sensitive to any type of contaminants. Unlike ball bonding, this method does not produce a ball for the first bond, giving finer pitch applications down to 40 microns or less [24].

Figure 5 illustrates an ultrasonic wedge bonding technique, typically involving the bonding of gold or aluminium wire to

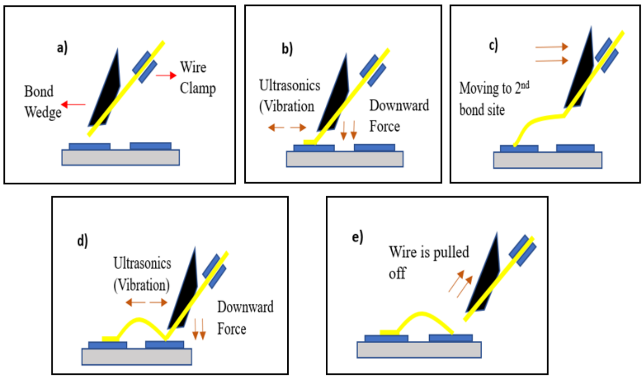

Figure 5. Standard wedge bonding flow

aluminium bond pads. The wire is drawn through the tool toward the wedge, as shown in Figure 5 (a). The wire is subsequently pressed against the bond pad with a specified force. A transducer that vibrates the wedge parallel to the substrate and in a direction parallel to the wire axis at a frequency of 120 to 140 kHz [9] generates the ultrasonic energy, which is applied simultaneously as illustrated in Figure 5 (b). The tool subsequently proceeds to the second bond site, illustrated in Figure 5 (c), and performs a similar bond to the first bond, depicted in Figure 5 (d). Finally, as illustrated in Figure 5 (e), the wire clamp is closed, and the wire is extracted directly behind the wedge by retracting the tool. Ultrasonic wedge bonding of gold wire is an effective room-temperature technique that accommodates both thin and thick wire for fine-pitch and high-power applications. Automated wedge bonding methods are characterized by their slow operation and limitations in producing various loop forms and directions [25, 26].

2.6. Gold-aluminium Intermetallic

Chemical compounds that have a unique stoichiometry are known as intermetallic. They are composed of atoms from two or more metals that are arranged in a certain order in the crystal lattice. In addition to being metallic, the chemical bonds that hold the atoms in the lattice together can also be partially ionic or covalent [27, 28]. A gold-aluminium intermetallic is when gold and aluminium metals come into contact, and an intermetallic combination is created. Because both metals are highly conductive and resistant to corrosion, Au–Al contact wire bonds are commonly used in electronics [29]. Nonetheless, the advantageous properties of gold and aluminium have been considerably diminished by the formation of intermetallic compounds at the interface of the metals. The Au–Al system's significant contact-potential difference causes these intermetallics to have low toughness and perhaps low corrosion resistance [30]. Gold and aluminium contain a high affinity for forming intermetallic phases and can form up to five different intermetallic compounds. The five metallic compounds that can form between gold and aluminium are Au_5Al_2, AuAl, Au_2Al, Au_5Al_2, and Au_4Al [31, 32]. The most documented of these intermetallic compounds is the $AuAl_2$, popularly known as "purple plague". After the wire bonding process, $AuAl_2$ is frequently observed as a feathery intermetallic phase near the gold-aluminium contact. The phase obtained its nickname due to its distinctive colour and presence during many early wire bond failure [9, 33]. The other intermetallic phases are less well-documented and are not as distinctive. The intermetallic phase of AuAl is a white compound, while the remaining phases, Au_2Al, Au_5Al_2, and Au4Al are all tan compounds [34].

2.7. Kirkendall Voids in Wire Bonds

There are three types of voids in aluminium-gold wire bonds: initial, annular, and minute [35]. Probe markings and adhesive pad contamination are the causes of initial voids. Intermetallic development would be slowed and wire material diffusion blocked by initial voids. During thermosonic wire bonding, the ultrasonic squeezing effect results in annular voids. Grain boundary effects on the gold ball's surface after it meets the electronic flame-off or various Au4 Al phase formation events cause minute voids to occur during the Au4 Al phase.

A failure mechanism known as Kirkendall voids in wire bonding is defined by the differential motion of the interface between two metals, which is caused by differing rates of metal particle diffusion. Kirkendall voids in wire bonds are caused by the gold-aluminium phase's excessive intermetallic development. A higher temperature speeds up its growth [36–38]. The existence of impurities like Al_2O_3 and crystal structural vacancies might start the growth of Kirkendall voids. Jalar *et al.* [39] specify the thickness of the intermetallic layer:

$$X = Ce^{-E/kT}t^{1/2} \quad (1)$$

where C is a constant, E is the activation energy, *k* is the Boltzmann constant, *T* is the absolute temperature and *t* is the time. According to Lee *et al.* [40], the diffusion of O_2 can increase the formation of Al_2O_3 that initiate the formation of voids through:

$$4Au_4Al + 6O \longrightarrow 2Al_2O_3 + 16Au \quad (2)$$

Presence of halides such as bromide (Br) also can accelerate the formation of Al_2O_3 through:

$$Au_4Al + 3Br \longrightarrow 4Au + AlBr_3 \quad (3)$$

$$2AlBr_3 + 3O \longrightarrow Al_2O_3 + 6br^- \quad (4)$$

3. WIRE LIFTING DEFECTS IN WIRE BONDING

The main defects to be focused regarding wire bonding in this study are ball bond lifting and wedge bond lifting. The quality of the wire bond connector influences the reliability of the IC chip during its operational tasks in the application [41]. Poor and inconsistent wire bond connection quality significantly affects the device's reliability, dependability, and cost. Consequently, the quality verification of the wire bond is essential in the integrated circuit manufacturing process [42]. The subsequent subsection evaluates common defects in the wire bonding process, specifically ball lifting and wedge lifting. These issues are acknowledged as they

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often lead to significant degradation of electrical connections and LED malfunction.

3.1. Ball Bond Lifting Defects

Ball bond lifting (Figure 6), also referred to as ball lifting or ball lifting failure, is the detachment of a ball bond from the bond of a semiconductor device. A malfunction in ball lifting indicates a severely inadequate interaction between the ball and the bond pad [43]. The malfunction of the ball lift indicates that the connection has either not been established or has deteriorated. Contaminants on the bond pad can induce ball lifting by serving as obstructions between the ball and the bond pad. Unetched glass, residual photoresist, and silicon sawdust are prevalent contaminants that hinder effective bonding. Resin bleed-out from the die attach material may impede adequate bonding and result in ball lift. Halides, such as Cl, on the bond pad can induce corrosion, which is an additional cause of ball lifting.

The bonding process is adversely affected by a disordered or uneven surface on the bond pad. Excessive probe digging results in the formation of aluminium heaps and exposes the substrate or barrier metal area, which hinders optimal intermetallic development. Poor ball bonding may also result from the presence of silicon nodules on the surface of bond pads [44].

3.2. Wedge Bond Lifting Defects

Wedge bond lifting refers to the detachment of a crescent bond from the lead frame bonding finger or a wedge bond from the bond pad or bonding post. Like ball lifting, this phenomenon can be influenced by various factors, including wire-bonder configuration and contamination of the bond pad surface [42]. Examples of inadequate setup include improper parameter settings, unstable workpiece holders, and worn-out tools. Poor bonding may occur between the wedge and the bond pad, post, or finger [45].

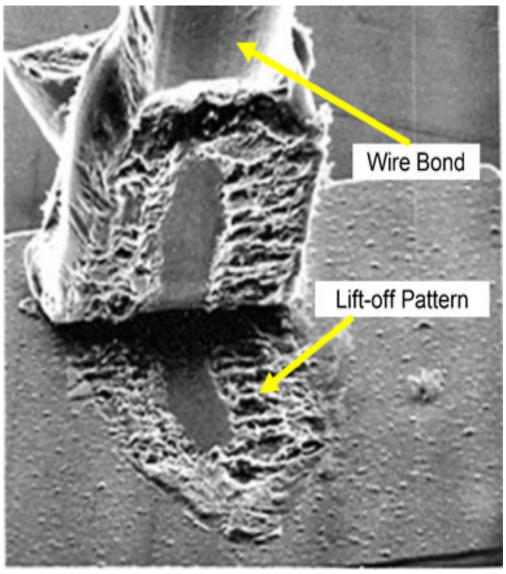

Figure 6. Scanning electron microscopy (SEM) image of wire bond lift-off pattern [33]

Wedge lifting can occur due to contaminants present on the bond pad, post, or bonding finger. Contaminants impede the bonding area and the wedge. Sawdust, unetched glass, and unremoved photoresist are prevalent contaminants that impede effective bonding. Halides, such as Cl, on the bond pad can facilitate corrosion, contributing to wedge lifting. Silicon nodules present on bond pad surfaces lacking underlying barrier metallization may lead to suboptimal ball bonding outcomes [46].

Sub-bond pad cratering represents a distinct type of failure, characterized by a lifted wedge formation, wherein the silicon beneath the bond pad detaches from the bond. Wedge lifting may also result from the detachment of bond pads from the barrier metal. Wedge lifting from the bonding post and fingers due to metallization peel-off is also possible. Studies have also linked excessive probing damage to the bond pad with wedge lifting [45].

3.3. Factors that Contribute to Ball and Wedge Lifting Defects

3.3.1. Presence of Contaminants

The main factor for wire bonds to lose their bondability and dependability is surface contamination. Hydrocarbons and halogens are two examples of pollutants that weaken bonds. Halogens, such as those involved in plasma etching, plating impurities, sulfur, various organic contaminants, ambient air due to poor storage conditions, and other pollutants, have been identified as detrimental to bonding integrity, leading to corrosion and compromised adhesion [47–49]. Human sources of contamination include small particles such as skin, hair, sweat, spittle, and mucus. Activities such as talking, coughing, sneezing, yawning, head shaking, and scratching can transfer contaminants to the surface of the device. A motionless individual produces around 105 particles larger than 0.3 μm in diameter every minute. As movement increases, this amount rises exponentially. A person in a full suit will disperse 50,000 particles in the same amount of time while they are in a Class 100 clean room. Other contaminants could come from emissions from cleaned clothing (i.e., solvents used in dry cleaning) or being carried in the air as hydrocarbons and ions like Cl^- and Br^-. This illustrates the vulnerability of the wire bonding process, indicating that additional measures are required to safeguard it against potential contaminants.

Research conducted by Sethu [50] discusses the common problem of non-stick on pad (NSOP) failures in semiconductor assembly, which result in high rejection rates for devices when wire bonds do not adhere correctly to bond pads. In addition to discussing identification and preventive strategies, the article looks at failure mechanisms related to low bond pad quality, finding reasons from both wafer manufacture and assembly processes. Bond pad quality can be deteriorated during wafer manufacture by elements such as surface imperfections, inadequate passivation, and environmental contamination, which can lead to NSOP failures. In the event that contaminants are present on the surface during wire bonding, the ultrasonic energy is transferred to the contaminants on the top layer rather than the aluminium bond pad, which causes the wire material to adhere to the contaminants. Figure 7 shows NSOP occurrence because the wire bonders' ultrasonic energy is transferred to silicon and $Al_2(SiO_3)_3$ particles on the surface and not to the aluminium bond pad. If the contaminated surface area is small this won't be an issue because the diffused intermetallic region is large in relation to the bond pad size. NSOP happens in a big contaminated region.

Schneuwly *et al.* [51] investigated to determine the chemical composition, type, and thickness of the contamination layer and its impact on the bond substrates. Pull force measurements are a recognized testing method within the semiconductor packaging sector, utilized to evaluate the strength of wire bonds. This technique has been employed to investigate the effects of contamination on the quality of bond contacts. The results clearly indicate a strong correlation between pull strength values and levels of substrate contamination. Table 1 presents the results obtained by the researchers from their experimentation. Substrates A, B, C, and D demonstrate a higher resistance to pull force compared to substrates E, F, G, and H. This difference in performance is attributed to the absence of contamination in substrates A, B, C, and D, whereas substrates E, F, G, and H exhibit contamination from carbon and oxygen.

3.3.2. Looping Problems

During wire bonding, proper wire looping is critical [52]. Inadequate wire looping may cause severe strains at the bond neck or heel when the device is subjected to thermos-mechanical loads, potentially resulting in neck and heel breakage [53]. Excessive wire looping may lead to sagging and sweeping wires, which can result in wire shorting [54–56]. The 'Kirkendall Effect' leads to void formation when there is a disparity in the diffusivities of the two metals used in the wire bond [39, 57, 58]. In gold ball bonding, the diffusion rates of gold atoms from the gold ball into the bond pad and aluminium atoms from the bond pad into the gold ball are not uniform. Milton *et al.* [60] investigated enhancements to the looping process in wire bonding by optimizing the wire clearance between adjacent loops and various wire loop tiers. These researchers employ 3D looping design software to demonstrate the optimal loop tier configuration. Figure 8 below presents an illustration created by the researchers to demonstrate adjustable clearance zones surrounding a specific wire loop.

3.3.3. Bond Placement/Geometry Problems

The bond must be firmly embedded in the bond pad. If a bond is partially situated outside the bond pad's open window, it may result in inadequate bonding or, more severely, short-circuiting with an active metal or another bond. Suboptimal bond geometry, including inadequate or excessive bond sizes and/or an improper aspect ratio, may lead to compromised bonding [60, 61]. Figure 9 illustrates an example of wire bond geometry in the semiconductor industry. The bond must be firmly affixed to the bond pad. If a bond is partially situated outside the bond pad's open

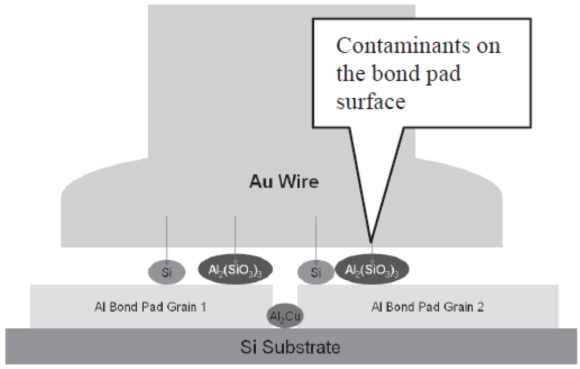

Figure 7. Contaminants on the bond pad surface [50]

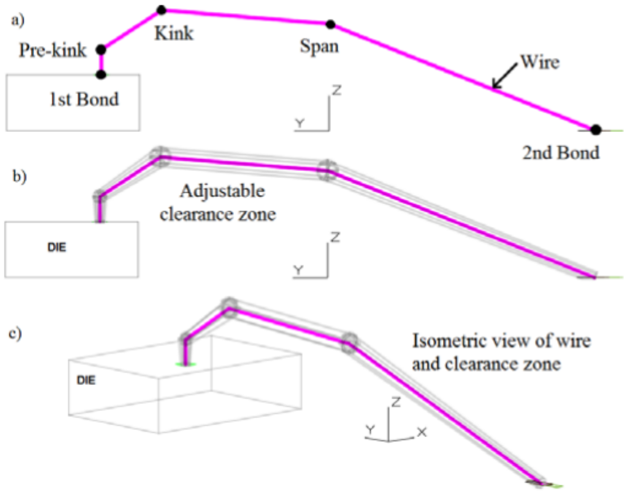

Figure 8. a) A typical wire bond loop with pre-kink, kink, and span bends seen from the side. b) Wire loop with a variable radius clearance zone that may be adjusted. c) An isometric representation of the clearance zone and wire [60]

Table 1. Pull force measurements for the corresponding substrates [60]

Pull force measured on the Au/Ni coated MCM substrate A–H								
Substrate								
Pull Force (cN) at	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
1 W US Power		6.5	4	4.9	3.7	2.9	2.3	3.2
2 W US Power	6.9	6.7	5.6	6.0	3.9	3.7	3.0	3.0
3 W US Power	6.8	7.3	6.2	6.5	4.2	3.2	3.5	3.1

window, it may result in inadequate bonding or, in a worse scenario, shorting with an active metal or another bond. Suboptimal bond geometry, including inadequate or excessive bond sizes and/or an improper aspect ratio, may lead to compromised bonding [62].

3.3.4. Bonding Site/Substrate Issues

Aside from surface contamination, other wire bonding sites or substrate difficulties might cause bonding failures. This encompasses excessive probing on bond pads, detachment of the bond pad metal, voids in the silver plating of the lead fingers, and silicon damage beneath the bond pad, all of which may result in a cratering effect (silicon damage under the bond pad) [63]. Cratering, a distinct form of failure, may manifest as a ball lift, with the silicon beneath the bond pad detaching along with the bond. Cratering is typically induced by excessive probing and over-bonding [64–66]. Ball lifting can also be caused by bond pad peel-off, which occurs when the bond pad metal peels away from the barrier metal or substrate [42, 67, 68].

3.3.5. Kirkendall Voiding due to Au_5Al_2 Formation

Kirkendall voids, which develop simultaneously with the intermetallic formation or intermetallic phase degradation brought on by impurities or corrosion, have been blamed for failures in gold-aluminium wire bond systems [69]. Kirkendall voids occurs due to unequal diffusive rates of gold into aluminium and aluminium into gold. In the gold-aluminium couple, aluminium diffuses into gold at a higher rate than gold diffuses into aluminium due to grain boundary diffusion of aluminium into gold. Therefore, Kirkendall voids will typically form between the Au_5Al_2 phase [70] and can be seen in Figure 11.

As stated by Philosfsky [34], Au_5Al_2 is the phase that grows the fastest out of the five phases mentioned, which are Au_5Al_2, AuAl, Au_2Al, Au_5Al_2 and Au_4Al, and it is frequently blamed for bond failures. The fact that Au_5Al2 nucleates quickly and grows much more quickly than the surrounding phases is the main cause of the bond failures in connection to this phase. Therefore, the diffusion of aluminium atoms into the intermetallic phase creates Kirkendall voids. By using bonding techniques that do not require high temperatures, like ultrasonic welding, or by creating circuitry with aluminium-to-aluminium or gold-to-gold junctions, it is possible to eliminate all issues brought on by gold-aluminium intermetallic.

4. PREVENTION METHODS

Wire lifting defects in wire bonding can lead to reliability issues in semiconductor packaging. Preventing wire lifting requires a combination of optimized process parameters, high-quality materials, proper environmental controls, and rigorous quality monitoring. By implementing these preventive measures, wire lifting defects can be significantly reduced, ensuring better reliability in wire bonding applications.

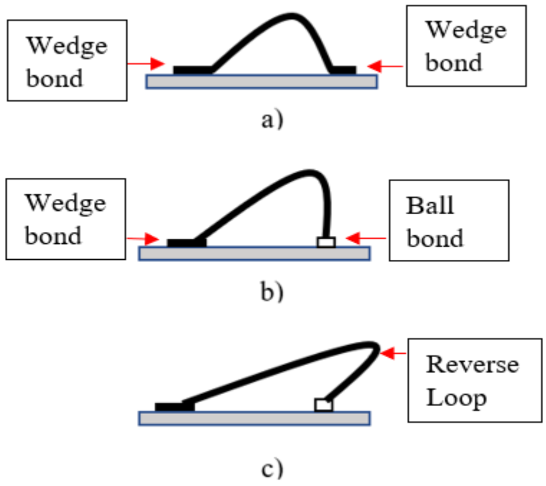

Figure 9. Typical geometry of wire bonds. (a) Wedge-wedge wire bond. (b) Wedge-ball wire bond. (c) Wedge-ball wire bond with reverse loop [60]

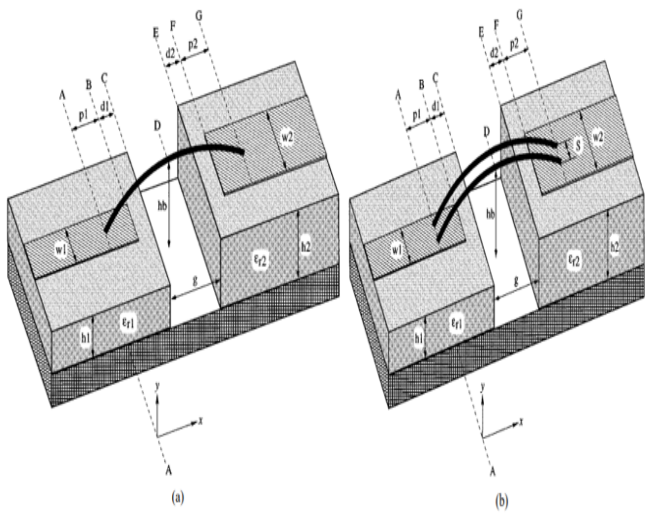

Figure 10. Dimensions of the bonding cable.
(a) One wire connection. (b) Two wire connection [52]

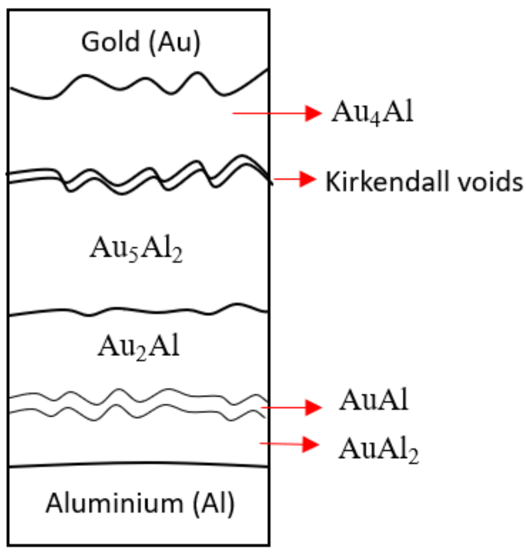

Figure 11. Formation of Kirkendall voids in gold-aluminium wire bond system

4.1. Optimize Wire Bonding Parameters

A recent study conducted by Rosli *et al.* [71], proper tuning of bonding parameters is crucial to ensure strong and reliable wire bonds. For example, if the bond force is too little, then it would result in weak bonds, if it's excessive, it can damage the bond pad or wire. After that, proper ultrasonic energy application is needed to create strong intermetallic bonds without damaging the wire. Lastly, sufficient bonding duration ensures strong adhesion while preventing over-bonding, which can weaken the structure. Figure 12 shows the ramp plot for the optimized system using the desirability function gathered by Rosli *et al.* The wire bond strength recorded the highest when the factors were set at time at first bonding site at 300 ms, loop height at 1200 1200µm, wire bond Y-axis length at 992 µm, and ultrasonic force at second bonding site at 300 mN. These optimized wire bonding parameters ensure reliable connections and prevent wire lifting occurrences.

4.2. Use High-quality Bonding Wire

The wire's mechanical qualities and purity should be in line with industry standards. The intrinsic qualities of the material, processing, and design are some of the elements that affect wire quality [72]. For example:

A. Metal purity: At least 99.9999 percent pure gold, also known as "four nines" or "4/9," is required. There are fewer impurities like oxides that might lead to fatigue or issues with wire drawing when the melting stock is of higher grade [73].
B. Shape: The wire could slip or not work properly if it was slightly out of round, making it impossible to pass through the capillary of the bonding machine. As a result, stress risers should be avoided in silicon-based alloys since they could obstruct capillaries or jeopardise the integrity of the bond [2].
C. Annealing: When creating bonding wire, heat treatment, also known as annealing, is a crucial step. In the case of an aluminium-silicon alloy, treating the raw material guarantees that the silicon is evenly distributed; the wire can then be drawn to its ultimate size and annealed once more to stabilise the alloy. The wire gains some external protection during this last heat-treating step in the form of a mild oxidation patina, which aids in halting rapid oxidation [74, 75].

4.3. Maintain Clean Bonding Surfaces

Contaminants can significantly weaken the bond, leading to wire lifting defects. Ensuring cleanliness is essential for achieving strong and reliable wire bonds. Research conducted in 2003 [76], pointed out that maintaining bond pad cleanliness and minimising oxidation throughout the wire bonding process is essential for bonding to copper dies. To prevent oxidation of the copper bond pad, an organic coating layer has been applied. The organic coating layer is eliminated, and a metal-to-metal weld is created during the wire bonding procedure. This organic layer is a monolayer that forms on its own. Even in the absence of previous plasma cleaning, copper and gold wires have been successfully wire-bonded to the copper die. Figure 13 shows a comparison of both non-clean and clean copper bond pads to show how contaminants on the surface would affect the reliability of the wire bond by cluttering it.

4.4. Optimize Bond Pad Metallization

The bond pad material and structure play a crucial role in wire bonding reliability. Proper metallization ensures strong adhesion, prevents wire lifting, and enhances long-term durability. A study conducted by Song *et al.* [77], to learn how the thickness of bond pad metallisation affects the copper wire bonding process, characterisation study has been conducted. The outcome implies that, without further parameter adjustment, there is an ideal range of pad metallisation thickness to get satisfactory Cu wire bond responses. By decreasing aluminium push-out, adding

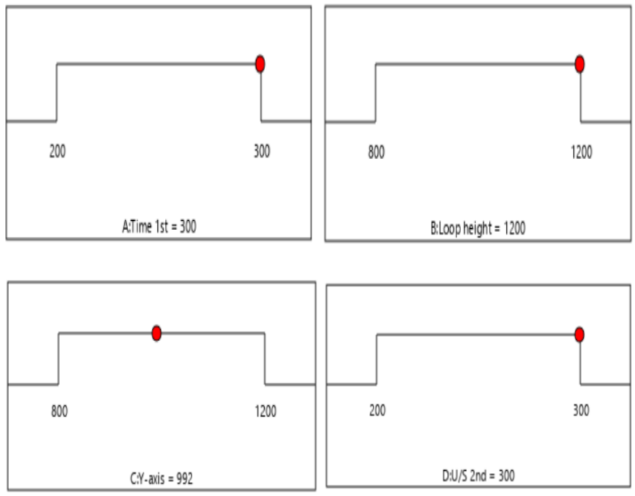

Figure 12. Ramp plot analysis for system optimization [71]

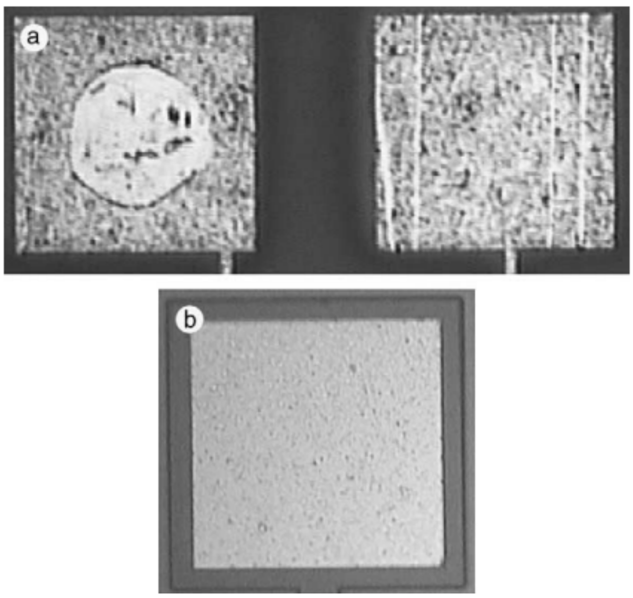

Figure 13. (a) Non-cleaned copper bond pad (b) clean copper bond pad [76]

tungsten to standard Al/Cu metallisation can increase the pad's hardness and, consequently, the bondability of copper wire. Figure 14 shows that, for thinner pad metal, there is a substantial association between the failure rate of bonded pad metal peeling, pad metal peeling during wire pull testing, and crater. The underlying structure sustains less damage when the pad metal is thicker. Pad metal peeling and cratering stopped after the thickness of the metal reached a particular threshold.

5. CONCLUSION

This paper presented a brief overview regarding wire lifting defects that have been identified to be occurred in Au_5Al_2 LED thermosonic bonding. The initial development of wire bonding, its characteristics, wire lifting defects that develop during productions, the factors that causes the defects, and preventive measures for those defects are among the issues covered in this study. The following remarks are made based on this mini review:

1. Gold-aluminium (Au-Al) wire bonding has been widely used in semiconductor packaging but presents several challenges:
   - Intermetallic Compound (IMC) Formation: Au-Al bonding creates intermetallic compounds (IMCs), which can lead to Kirkendall voids and brittle fracture over time.
   - Cost & Material Scarcity: The rising price of gold makes Au-Al bonding less economical.
   - Reliability Concerns: Bond degradation due to high-temperature aging, humidity exposure, and contamination.
2. Due to these challenges, research has shifted toward alternative wire bonding technologies:
   - Cu-Al Wire Bonding: Copper (Cu) offers lower cost and better electrical conductivity but requires careful process optimization to avoid pad damage and oxidation issues.
   - Ag-Al Wire Bonding: Silver (Ag) bonding provides good electrical performance with reduced IMC-related reliability concerns.
   - Advanced Coated Wires (Palladium-Coated Copper, Silver-Alloy Wires, etc.): Coated wires improve bondability, reduce oxidation, and enhance reliability.
3. For future research opportunities regarding this research are:
   - New Coating Technologies for Bonding Wires: Developing novel surface coatings to improve oxidation resistance and adhesion properties.
   - Optimized IMC Formation in Alternative Wire Bonds: Studying intermetallic growth in Cu-Al and Ag-Al bonding to enhance long-term reliability.
   - Machine Learning for Process Optimization: AI-driven algorithms to optimize bonding parameters and defect detection.

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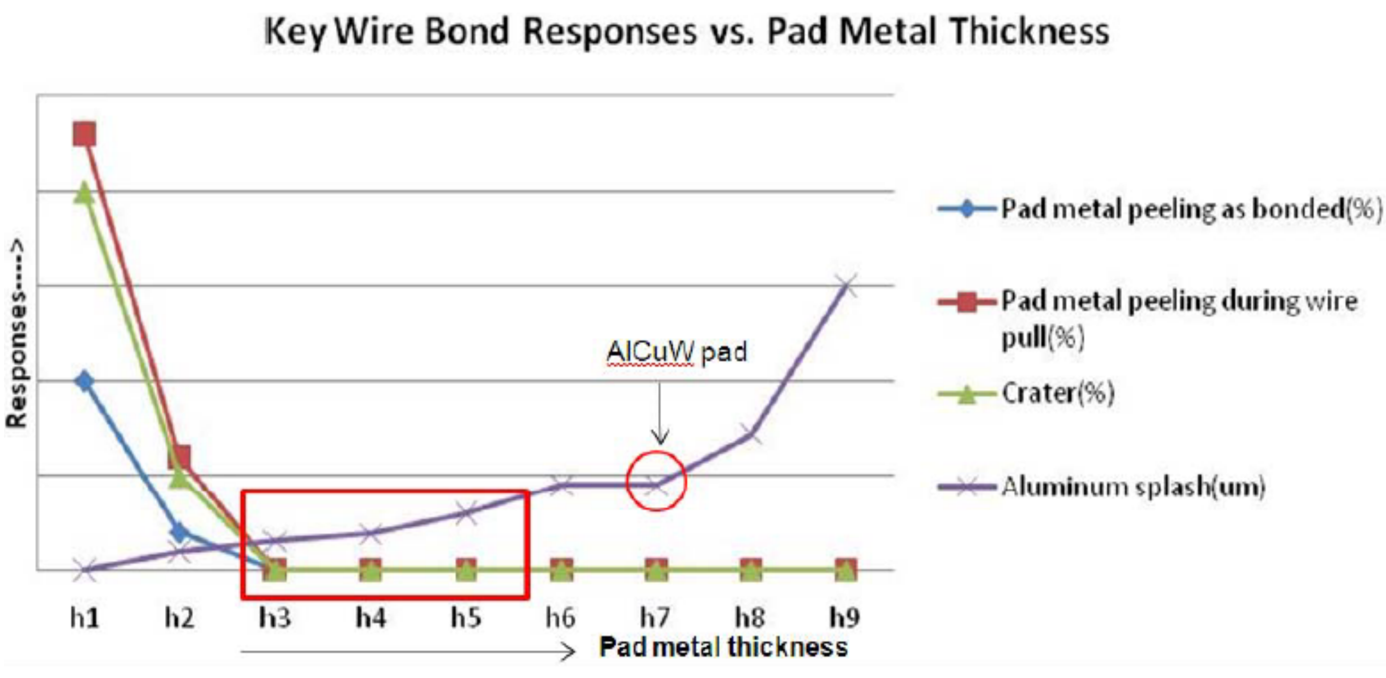

Figure 14. Overall responses data versus pad metal thickness [77]

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