

Mechanical Analysis on Ball Bond Lifting of Wire Bonding in an LED Package for Backlight Unit

Jong Woon Kim, Shan Gao, Si Joong Yang, Seog Moon Choi

Corporate Technology Operation HQ, Samsung Electro-Mechanics
314, Maetan3-Dong, Yeongtong-Gu, Suwon, Gyunggi-Do, Korea 443743
jw26.kim@samsung.com

Abstract

LED is replacing conventional CCFL as light source for BLU in displays of LCD TVs and laptop computers. It has the advantages of low power consumption, long durability, and mercury-free. In this paper, ball bond lifting failures in an LED package for BLU were investigated from the viewpoint of thermal stresses during curing and reflow processes after wire bonding. Interfacial tensile and shear stresses at ball bond interface were calculated by FEM simulation. From the simulation of LED packages with various wire loop shapes and pad layouts, failure mechanism of the ball bond lifting was described. In wire bonding for the LED packages, gold wires connecting pads on chips and lead frame have large loop height since the chips are mounted on a cavity designed for reflection of emitted light. Thermal expansion of thick layer of silicone encapsulant between the wire and lead frame induces large tension and bending of the wire, by which large interfacial tensile stress at the ball bond interface is developed during solder reflow. The mismatch of CTE between gold ball and sapphire chip induces interfacial shear stress at the interface during encapsulant curing. The interfacial tensile and shear stresses much depend on wire loop shape and pad layout, respectively, and optimal wire loop shape and pad layout were determined in order to minimize the stresses. When interfacial strength is weakened by defect, contamination, or process variation, the thermal stresses yield the ball bond lifting failure. The result agreed well with SEM and EDS of the ball bond interface and gathered data of failure rates.

Key words: LED packaging, wire bonding, ball bonding, ball bond lifting, thermal stress.

Introduction

Since excellent video quality and ultra-thin structure is required for the latest displays of LCD TVs and laptop computers, LED is replacing conventional cold cathode fluorescent lamp (CCFL) as light source for backlight unit (BLU) which is placed behind LCD. It has other advantages such as low power consumption, long durability, and mercury-free [1]. LED chips and copper lead frames are assembled into packages for electrical and mechanical interconnection as well as heat dissipation, and the packages are arranged in a plane or edges of the BLU.

Wire bonding connects pads on the LED chips and the lead frames through gold wires. Wire bonding failure during manufacturing increases rework and disposal cost. Even though packages with weak wire bonding passed electric test, failure occurred during display operation so that nonuniform luminance is easily detected by consumers. Because there are a large number of LED packages in the BLU, it is very

important to improve process yield and reliability of wire bonding.

The most widely used wire bonding method is ball bonding in which failure modes are categorized as lifting, breaking, shorting, and cratering. Among them, ball bond lifting, which refers detachment of the ball bond from the chip, is one of the most frequent failures in the LED packages. Its common causes are known as contamination on the bond pad, incorrect wire bond parameter settings, instability of the die during bonding, bond pad corrosion, excessive bond pad probing, Kirkendall voiding, intermetallic spiking due to the Devaney mechanism, excessive thermal stress resulting in excessive intermetallic formation, lifting between bond pad metallization and barrier metallization, and cratering [2].

Since the ball bond lifting occurs when stress exceeds strength at the ball bond interface, there are two approaches to prevent the failure: enhancing strength in material aspects and reducing stress in structural aspects. The interfacial strength can be

measured by wire pull test and ball shear test [3], while the interfacial stress can be estimated from structural simulation.

Previous research on ball bond lifting has been focused on the material aspects, such as intermetallic formation and Kirkendall voiding, related to the interfacial strength [4-11]. In structural aspects, breaking failures in the ball bond wires and wire loop formation were investigated [12-14]. However, there is little investigation on the failure mechanism of ball bond lifting from the viewpoint of interfacial thermal stress.

In this paper, the ball bond lifting failures in an LED package for BLU were investigated with analyzing thermal stresses during encapsulant curing and solder reflow after the wire bonding process. Interfacial tensile and shear stresses at the ball bond interface were calculated by finite element method (FEM) simulation. From the simulation of LED packages with various wire loop shapes and pad layouts, failure mechanism of the ball bond lifting was described and validated by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) of the ball bond interface and gathered data of failure rates.

Thermal Stress Simulation

In the LED package for BLU, two sapphire-based LED chips are assembled with a substrate comprised of copper lead frame and polymer insulation as shown in Fig. 1. After die-bonding the chips on a cavity designed for reflection of emitted light, pads on the chips and the substrate are interconnected by wire ball bonding with gold wires. Although gold pads are formed on the chips in order to suppress intermetallic formation at the ball bond interface, interfacial strength variation is not narrow enough to completely prevent ball bond lifting. Then the substrate and wires are encapsulated by silicone resin mixed with fluorescent particles.

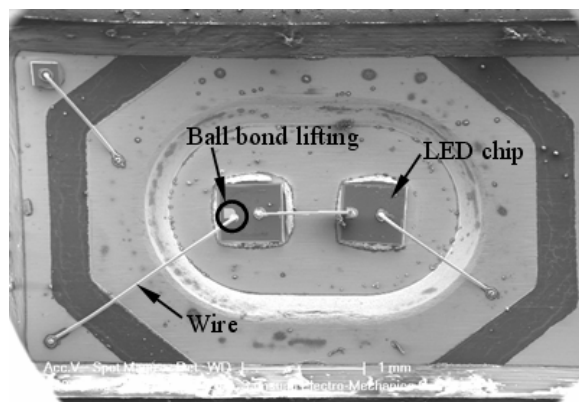


Fig. 1 Decapped LED package for BLU

There are thermal processes after the wire bonding: oven curing to solidify silicone encapsulant and solder reflow to assemble lead frames on a board. When the LED package made up of different materials undergoes temperature cycles, coefficient of thermal expansion (CTE) mismatch induces thermal stresses. The ball bond lifting may occur due to the stress when interfacial strength is weakened by defect, contamination, or process variation.

In order to reduce failure rates due to the ball bond lifting, it is needed to reduce interfacial strength variation, determined by process and material, as well as thermal stress, related to structure design. The former requires a numerous test to gather strength data and high cost of process improvement, while the latter can be easily achieved by design optimization.

Therefore, thermal stress simulation was performed to find out design method to reduce stress at the ball bonding interface. Fig. 2 shows FEM model of a decapped LED package with the corresponding coordinate system where fine mesh was given near the ball bond interface. Fig. 3 shows wire loop shape modeled as a spline with 1-mil diameter. The wire loop height and vertical and horizontal distances between pads were 0.32, 0.17, and 2.05 mm, respectively. Table 1 shows linear thermoelastic properties used in the simulation. Plastic behavior of gold was not considered because the purpose of the simulation is qualitative comparison between stresses in different designs rather than accurate prediction of stress level or deformation. Calculated interfacial stresses might be overestimated so that they cannot be directly compared with interfacial strengths.

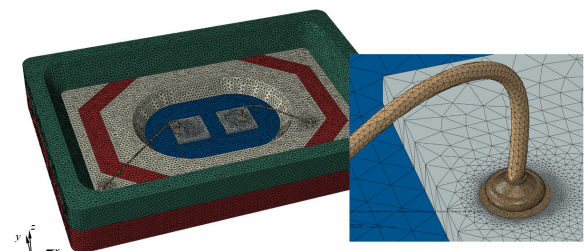


Fig. 2 FEM model of decapped LED package

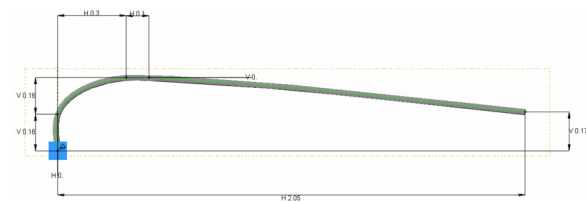


Fig. 3 Spline model of wire loop shape

Table 1 Thermoelastic properties used in simulation

Material	E (GPa)	CTE (ppm/°C)	ν
Gold	77.2	14.5	0.42
Sapphire	379	5.6	0.27
Copper	127	17.0	0.31
Silicone	0.080	200	0.4
Plastic	9.1	71	0.4

During oven curing, the package is heated up to curing temperature and cooled down to room temperature. A decapped model without encapsulant was used in heating simulation because of negligible elastic modulus of uncured encapsulant. Fig. 4(a) shows von Mises stress at the ball bond interface induced during heating from 25 °C to 180 °C, where maximum stress was 197 MPa at the side near chip edge. Main stress component was shear stress in the xz-plane while other components were small. An encapped model was used in cooling simulation. Fig. 5(a) shows von Mises stress at the interface induced during cooling from 180 °C to 25 °C, where maximum stress was 251 MPa at the center of interface. Main stress component was compressive stress in the z-direction which does not cause crack initiation or propagation.

After oven curing, the temperature rises up to 260 °C for solder reflow and returns to room temperature. Stress-free temperature of the encapped model was set as 180 °C, curing temperature of encapsulant, in the simulation. Fig. 6 shows deformed shape at 260 °C. Fig. 7(a) shows von Mises stress at 260 °C, where maximum stress at the interface was 102 MPa at the center and main stress

component was tensile stress in the z-direction which can cause crack initiation or propagation. Main stress component during cooling was compressive stress in the z-direction like the case of oven curing.

From the above simulation results, it was found that the design method to reduce ball bond lifting failures is minimizing interfacial shear stress and interfacial tensile stress under heating cycles during oven curing and solder reflow, respectively.

Pad Layout Design

Since the interfacial shear stress during oven curing is concentrated at the side near chip edge as shown in Fig. 4(a), effect of pad location on the stress was investigated to eliminate the stress concentration. Fig. 8 shows two types of pad layouts, Pad-A and Pad-B, in which distances between pads and edges of 6 mm × 6 mm chip are 0.1 and 0.2 mm, respectively. Von Mises stresses at the interface during oven curing and solder reflow were calculated by FEM simulation as shown in Figs. 4(b), 5(b), and 7(b). The maximum values of von Mises stresses and main stress components are listed in Table 2. The pad layout effected on shear stress during oven curing, and the stress concentration in Pad-A was eliminated in Pad-B.

The strain in the x-direction during oven curing is shown in Fig. 9. The shear stress was developed at the ball bond interface constraining strains of high-CTE gold ball and low-CTE sapphire chip in the x-direction. The chip, meanwhile, is also attached with high-CTE copper lead frame and thus expands more than expansion due to its CTE. Accordingly, the interfacial shear stress in Pad-B was decreased. However, this effect was limited in Pad-A near the

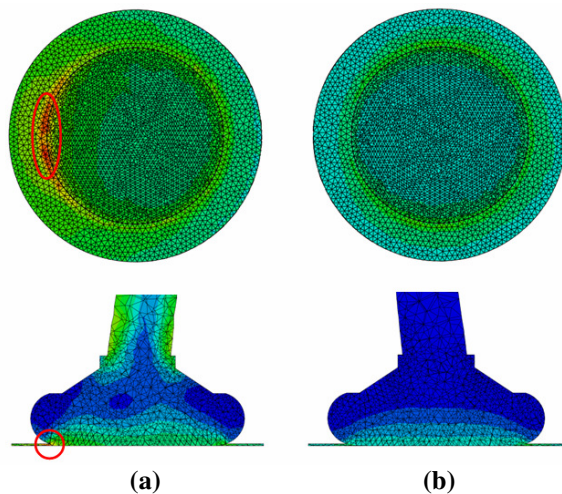


Fig. 4 Von Mises stress at the ball bond interface during heating of oven curing: (a) Pad-A, (b) Pad-B

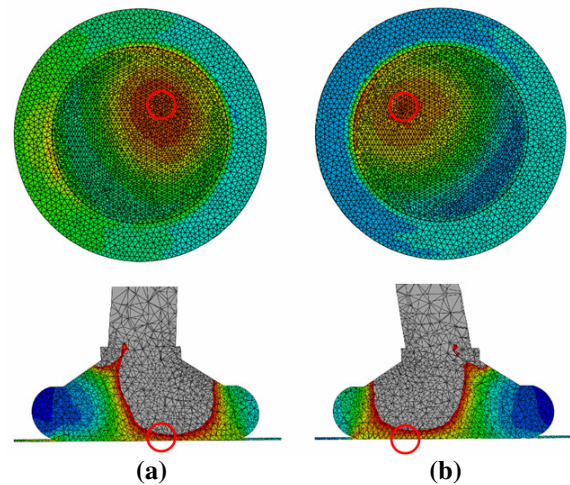
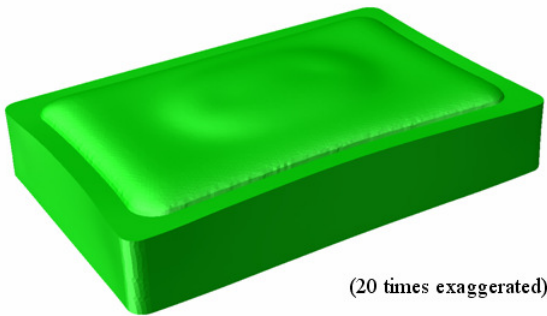
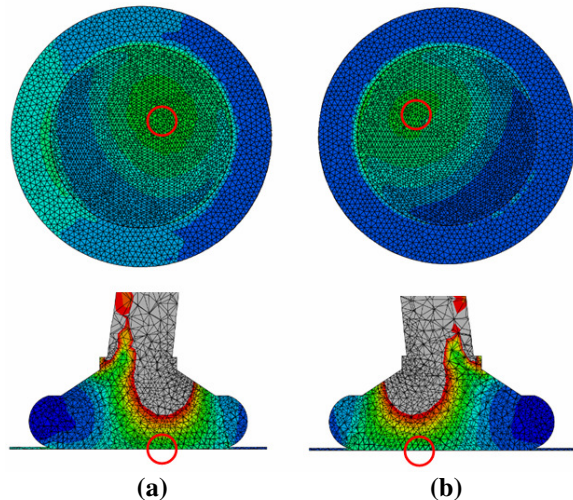


Fig. 5 Von Mises stress at the ball bond interface during cooling of oven curing: (a) Pad-A, (b) Pad-B

Table 2 Thermal stresses at the ball bond interface during oven curing and solder reflow

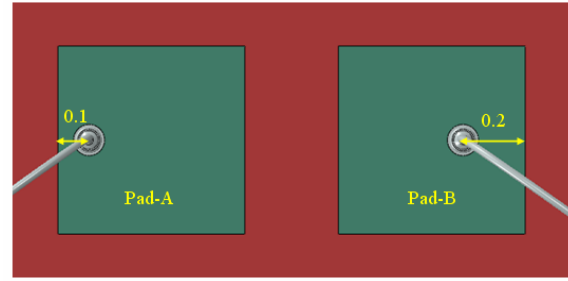
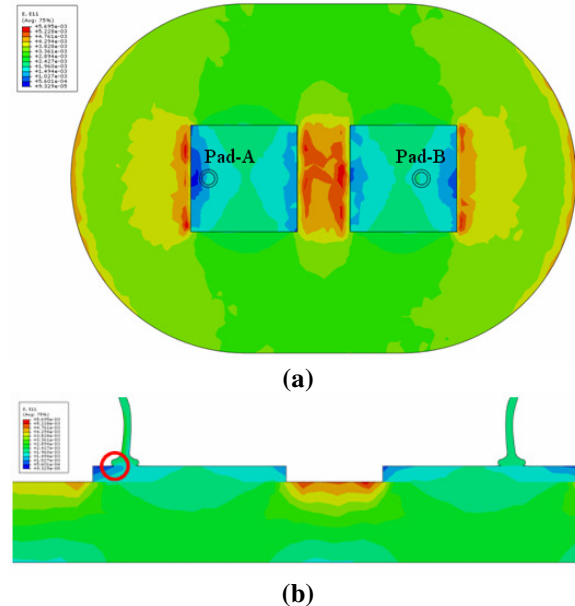
Process	Max. stress (MPa)	
Stress component	Pad-A	Pad-B
<i>Oven curing (heating)</i>		
Von Mises	197	114
Shear in xz-plane	93	39
<i>Oven curing (cooling)</i>		
Von Mises	251	233
Compressive in z-direction	273	260
<i>Oven curing (heating)</i>		
Von Mises	102	96
Tensile in z-direction	139	140

**Fig. 6 Deformed shape of the package during heating of solder reflow****Fig. 7 Von Mises stress at the ball bond interface during heating of solder reflow: (a) Pad-A, (b) Pad-B**

chip edge because of stress relief in the x-direction. Therefore, locating pad on chip far enough from chip edge is recommended.

Wire Loop Shape Design

In order to reduce the interfacial tensile stress

**Fig. 8 Two types of pad layouts****Fig. 9 Strain distribution in the x-direction during oven curing: (a) die surface, (b) cross-section**

during solder reflow, various shapes of wire loops in Fig. 10 were modeled for thermal stress simulation. Wires #1-#3 have small, middle, and large curvatures, respectively, while Wire #4 has large reverse looping. Wires #1-#4 have same loop height. Fig. 11 shows wire loop shapes before and after heating. Wires #5-#7 in Fig. 11(b) represent vertical wires with normal, half, and zero heights, respectively.

Fig. 12 shows a typical distribution of the interfacial tensile stress during solder reflow, where local maximum stresses occurred at the center and corner. Fig. 13 shows results of thermal stress simulation with respect to the wire loop shapes: the local maximum interfacial tensile stresses during solder reflow and the maximum interfacial shear stresses during oven curing. The tensile stress much depended on the loop shapes while the shear stress was independent of the loop shapes. In the cases of Wires #1-#3, as the curvature increased, both tensile stresses at the center and corner decreased. In the

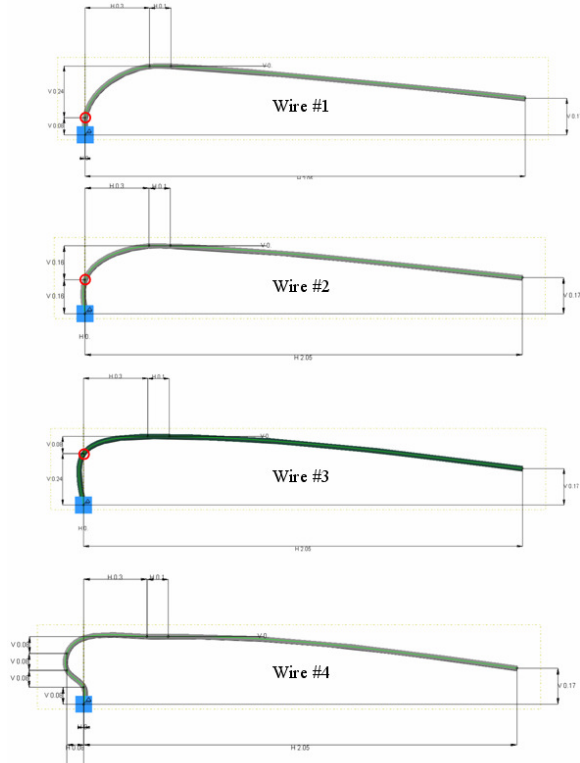


Fig. 10 Wire loop shapes of Wires #1-#4

cases of Wires #5-#7, as the wire height decreased, both tensile stresses decreased.

Among the wire loop shapes, Wire #1 showed high tensile stresses and reverse looping of Wire #4 obstructs light emission from chip. For Wires #2 and #3, remained candidates with low tensile stresses, the effect of loop height was studied. Fig. 14 shows Wires #2L and #2H with lower and higher loop heights than Wire #2, respectively, while curved shapes of Wires #2L and #2H were remained similar to Wire #2. Wires #3L and #3H were named in the same way. The interfacial tensile stresses of Wires #2L, #2, #2H, #3L, #3, and #3H were calculated as shown in Fig. 15. As loop height increased, stresses at the center and corner increased and decreased, respectively. Wire #3L with the lowest stress was selected as the optimized wire loop shape.

In wire bonding for the LED package for BLU, gold wires connecting pads on chips and lead frame have large loop height since the chips are mounted on a cavity designed for reflection of emitted light. Fig. 16 shows a schematic diagram of the wire loop shape near the chip. When the thick layer of high-CTE silicone encapsulant expanded in the z-direction during heating, pulling upward the vertical part A of wire yielded wire tension while lifting upward the horizontal part C yielded wire tension as well as wire bending. The wire tension induced stresses both at

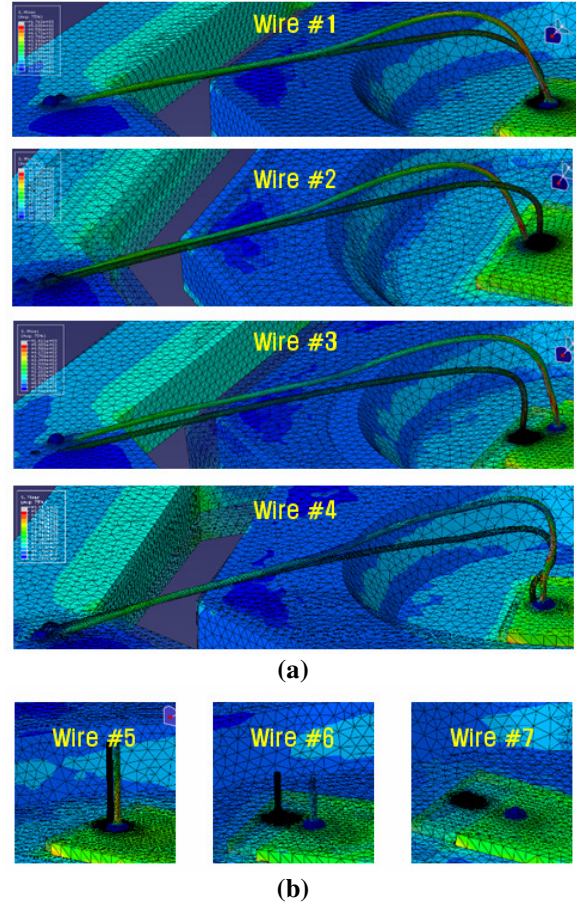


Fig. 11 Wire loop shapes before and after heating of solder reflow with 5 times exaggerated deformation: (a) Wires #1-#4, (b) Wires #5-#7

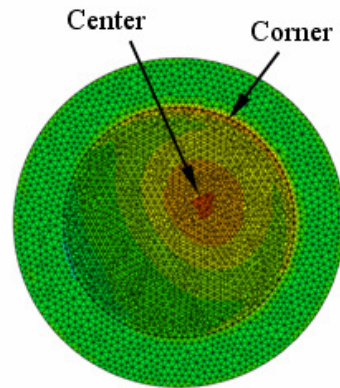


Fig. 12 Typical distribution of the interfacial tensile stress

the center and corner of ball bond interface while the wire bending induced stress at the corner of the interface.

From simulation results of Wires #1-#3, higher curvature of curved part B induced lower interfacial stresses both at the center and corner, because more

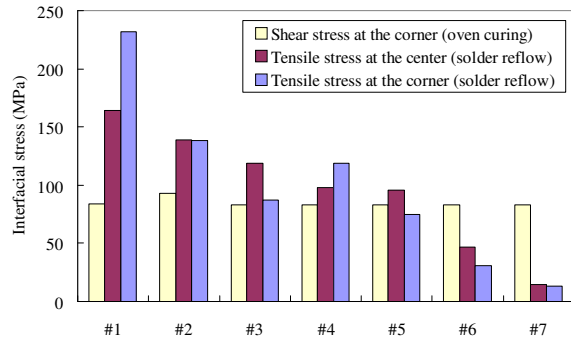


Fig. 13 Interfacial shear stress during oven curing and interfacial tensile stresses at the center and corner during solder reflow

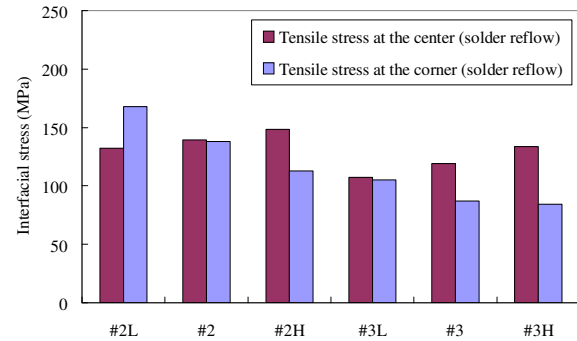


Fig. 15 Interfacial tensile stress at the center and corner during solder reflow

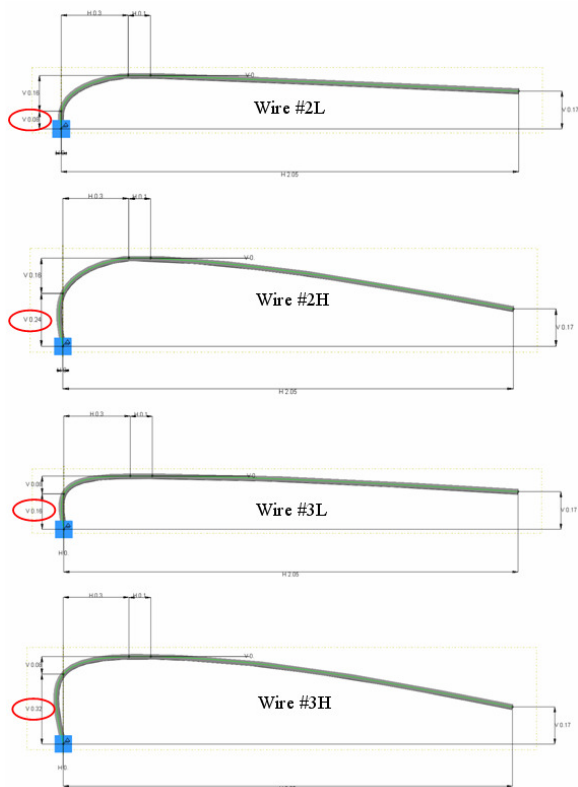


Fig. 14 Wire loop shapes of Wires #2L, #2H, #3L, and #3H

portion of lifting displacement of part C was absorbed as deformation of part B. In the cases of Wires #5-#7, longer part A induced higher interfacial stresses both at the center and corner due to higher wire tension. The simulation results of Wires #2L, #2, #2H, #3L, #3, and #3H showed that longer part A induced higher interfacial stress at the center due to higher wire tension and lower interfacial stress at the corner due to reduced effect of wire bending. In short, for design of the wire loop shape, high curvature of part B is preferred while the length of part A can be

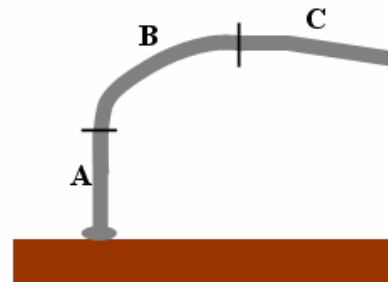


Fig. 16 Schematic diagram of wire loop shape near the chip

optimized to equalize interfacial stresses at the center and corner.

Validation

The mechanical analysis on thermal stresses at the ball bond interface was correlated with ball bond lifting failures occurred during mass production. Fig. 17 shows SEM image of ball bond surface of an LED package sample, where the sample passed electrical test right after oven curing but open failure was detected after solder reflow. There were two zones with different surfaces and silicone on one of the zones was detected by EDS. It implies that a crack was initiated before full-curing of encapsulant and propagated during solder reflow. Since the fracture mechanism is related to both oven curing and solder reflow, pad layout and wire loop shape are important to prevention of the failure.

Failure rate of each failure mode was gathered during mass production. Table 3 shows the ratios of ball bond lifting failures of Pad-A and Pad-B to whole failures. Failure rate of Pad-A right after oven curing was much higher than that of Pad-B as expected from the simulation. More failures occurred in Pad-A than Pad-B during solder reflow because there were already more cracks in Pad-A before solder reflow.

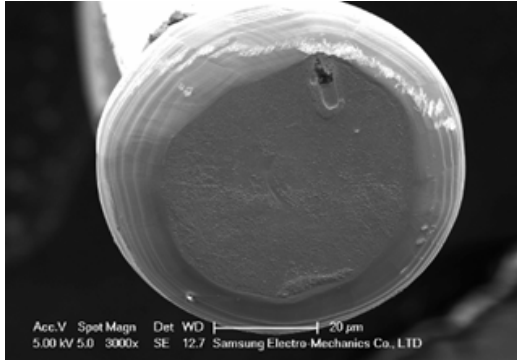


Fig. 17 SEM image of ball bond surface in a failed sample

The wire loop shape for mass production was changed from Wire #2 to the optimized wire loop shape, Wire #3L, as shown in Fig. 18. Monitored failure rate was reduced by 58% by virtue of the optimized design and additional process improvements.

Conclusion

From thermo-mechanical simulation of the LED package for BLU, thermal stresses at the ball bond interface were analyzed, and it was found that interfacial shear stress during oven curing and interfacial tensile stress during solder reflow induced the ball bond lifting failures. For pad layout design, locating pad on chip far enough from chip edge eliminated concentration of the interfacial shear stress. In the analysis of wire loop shapes, the interfacial tensile stress was explained in terms of wire bending and wire tension, and an optimized wire loop shape with appropriate length of vertical part and high curvature of curved part was selected. The simulation result agreed well with SEM and EDS of failed ball bond interface and gathered data of failure rates during mass production.

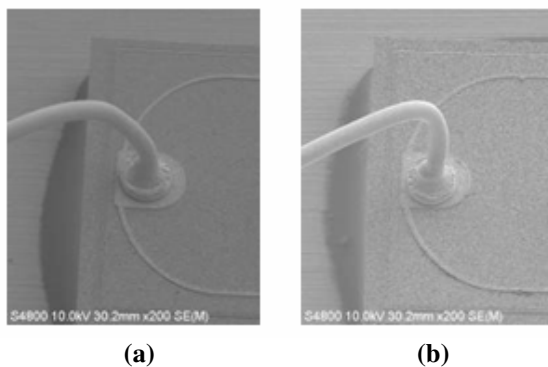


Fig. 18 Wire loop shape for mass production: (a) Wire #2, (b) Wire #3L

Table 3 Ratios of the ball bond lifting failures to whole failures

	Ratio of ball bond lifting to whole failures	
	Pad-A	Pad-B
After oven curing	68%	20%
After solder reflow	45%	21%

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