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Comparison of Argon and Oxygen Plasma Treatments on LED Chip Bond Pad for Wire Bond Application

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Abstract— The efficiencies of Argon and Oxygen microwave plasma treatments were compared in terms of contaminant removal and wire bond interfacial adhesion in this paper. The efficiency in contaminant removal was analysed by applying Argon and Oxygen plasma treatments to Light Emitting Diode (LED) chip bond pad prior to wire bonding process. The bond pad samples were then wire-bonded and examined with ball shear test to investigate the improvement of wire bond interfacial adhesion. The results show that Oxygen plasma treatment can remove the bond pad surface contaminant and improve the wire bond interfacial adhesion more effectively compared to Argon plasma treatment.

Index Terms— Plasma treatment, Surface contaminant, Wire bond, Light Emitting Diode, Argon and Oxygen, Chip bond pad and Surface free energy

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1 Introduction

THERMOSONIC wire bonding is one of the critical packaging processes for Light Emitting Diode (LED) device where fine wires are mechanically bonded onto the LED chip bond pad for electrical connections [1]. During thermosonic wire bonding, gold wire is guided through a hole in the capillary of wire bonder, and an electrical flame-off is used to melt the tail of the gold wire into a spherical ball (free air ball) by high-voltage electrical discharging. The free air ball is then ultrasonic rubbed and compressed onto the heated LED chip bond pad to form a ball bond. An overview of the thermosonic wire bonding process is shown in Fig. 1.

In general, LED devices in automotive applications usually stressed under extreme conditions with a high temperature above 150°C during operation [2]. Mechanical stress that induced to the wire bond due to thermal expansion coefficient mismatch under high operating temperature causes the degradation of wire bond interfacial adhesion and the failure of electric contacts in LED devices via detachment [3]. In automotive applications, the "lifted ball bond" issue remains a potential critical point for LED device reliability [4]. Surface contamination at the bonding interface is one of the key factor that cause "lifted ball bond" issue to arise [5] [6]. Thus, LED chip bond pad surface cleaning prior to the wire bonding process is requested in order to improve the wire bond reliability.

Plasma treatment is the dominant cleaning method used in industry currently due to its advantages of fast processing and being damage-free to microelectronic devices [7]. Thus, the efficiencies of Argon and Oxygen microwave plasma treatments were compared in terms of contaminant removal and wire bond interfacial adhesion in this paper. Argon and Oxygen plasma treatments were applied to LED chip bond pad prior to wire bonding process respectively with the time interval of 45, 90, 135 and 180 seconds. These bond pad samples were then characterized with Field-Emission Scanning Electron Microscopy (FESEM), X-ray photoelectron spectroscopy (XPS), Atomic Force Microscopy (AFM) and contact angle measurement respectively. In order to investigate the efficiency of Argon and Oxygen plasma treatments on wire bond interfacial adhesion improvement, the bond pad samples were wire-bonded and examined with ball shear test.

2 Experimental Details

In order to investigate the efficiency of Argon and Oxygen plasma treatments, gold LED chip bond pad samples were treated inside a microwave generator plasma system (Tepla GIGA 80 Plus). During plasma treatment, argon and oxygen gas was introduced into the plasma chamber with a flow rate of 40ml/min. Once the process pressure was stabilized, a pulse DC power source with high voltage was supplied via electrodes at both sides of the plasma chamber. The pulse DC power supplied in Argon and Oxygen plasma treatments were set to 350W and 500W accordingly. In this experiment, the LED chip bond pad samples were plasma treated with the time interval of 45, 90, 135 and 180 seconds respectively.

Since the LED chip bond pad surface condition can directly affect wire bond interfacial adhesion quality, various surface characterization methods were conducted. The surface morphology of bond pad surface was observed by FESEM (FEI,

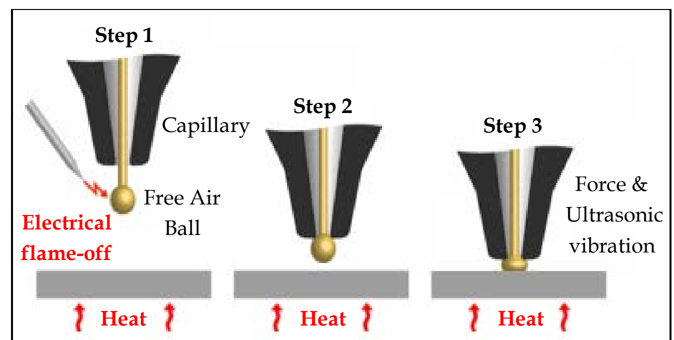

Fig. 1. Thermosonic wire bonding

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Nova NanoSEM 450) at X5000 magnification. The chemical composition of bond pad surface was examined by XPS (Escalab 250). The surface roughness of bond pad surface was analyzed by measuring the Root Mean Square (RMS) roughness with AFM (NanoScope Analysis 1.20) with a scan area of 5µm x 5µm. Besides that, contact angle measurement was also performed with a contact anglometer (Cam Micro, Tantec) by using sessile drop method. Bond pad surface free energy was then calculated from the contact angle obtained with Young-Dupre equation. In order to explain the surface free energy results, high resolution XPS measurement was employed to characterize the Carbon (C1s) chemical bonding state of bond pad surface.

Further to investigate the influence of Argon and Oxygen plasma treatments to wire bond interfacial adhesion quality, a 38µm of 99.99% gold wire was bonded onto the bond pad samples with an automated wire bonder (ASM Eagle-XL) as shown in Fig. 2. The dimensions of LED chip and the chip bond pad used were 1000µm x 1000µm and 158µm x 158µm respectively. During wire bonding, the wire bonding parameter such as bond force, bond time, bond temperature and ultrasonic power were optimized before the study and were set to 60gmf, 25ms, 150ºC and 100W accordingly. The ball shear test was then carried out with a ball shear tester (XYZTEX Condor 10) to examine the wire bond interfacial adhesion quality. Each testing category in this experiment consists of 30 samples.

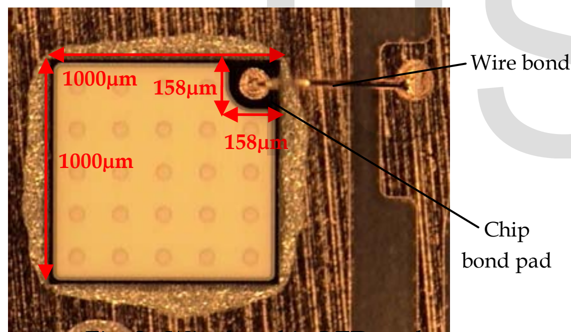

Fig. 2. Wire bond in LED package

3 Results and Discussion

3.1 Bond pad surface characterization results

Figure 3 displays the FESEM image of bond pad (a) before plasma treatment, (b) after 90 seconds of Argon plasma treatment and (c) after 90 seconds of Oxygen plasma treatment. Before plasma treatment, there are some white dots observed on the bond pad surface. The white dots become lesser after Argon plasma treatment, whereas the white dots completely disappear after Oxygen plasma treatment. The scratch mark on bond pad surface is the result from physical contact between probe tip and bond pad during electrical testing after LED chip fabrication [8].

Table I summarizes the atomic concentrations of elements detected on the Gold(Au) bond pad surfaces through XPS. Before plasma treatment, Carbon(C), Oxygen(O) and Nickel(Ni) impurities are detected with an atomic concentration of 10.72%, 8.97% and 4.44% respectively. The white spots as observed in Fig. 3 are the organic contaminant introduced by LED chip manufacturing material, i.e., passivation residue and photoresist residue, and LED package assembly processes before wire bonding, i.e., oxidation and epoxy outgassing during die attach epoxy curing, as high C impurity is detected [9] [10]. The appearance of O and Ni impurities due to the Ni migrates through the thin Au bond pad layer during high temperature processing, leading to oxidation upon exposure to environment after it reaches the bond pad surface [11]. After 90 seconds of Argon plasma treatment, the atomic concentration of C, O and Ni impurities reduces to 3.96%, 5.42% and 1.83%. Meanwhile, after 90 seconds of Oxygen plasma treatment, the atomic concentration of C, O and Ni impurities reduce to 1.25%, 7.38% and 1.01%. The C and Ni impurities on the bond pad surface after Argon plasma treatment is lesser compared to Oxygen plasma treatment. Although bond pad surface after Oxygen plasma treatment has higher O impurity content compared to Argon plasma treatment, these O impurities can improve surface free energy and wire bond interfacial adhesion by adding –OH and -OOH groups, which will be discussed in the next section. FESEM and EDX results conclude that Oxygen plasma treatment can remove the contaminant more effectively than Argon plasma treatment.

TABLE I
Atomic Concentration of Elements Detected on Gold(Au) Bond Pad Surfaces Through EDX

Plasma treatment	Testing point	Atomic concentration of element (%)				
		Gold (Au)	Carbon (C)	Oxygen (O)	Nickel (Ni)	Titanium (Ti)
None	Bond pad	75.87	10.72	8.97	4.44	-
	White dots	50.37	32.01	12.61	-	5.01
Argon	Bond pad	88.79	3.96	5.42	1.83	-
Oxygen	Bond pad	90.36	1.25	7.38	1.01	-

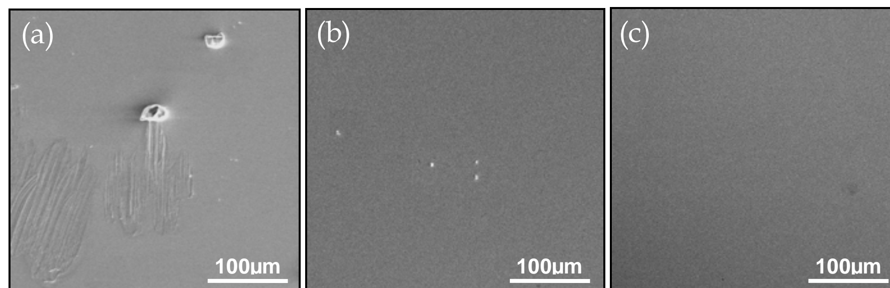

Fig. 3. FESEM image of bond pad surface (a) before plasma treatment (b) after Argon plasma treatment and (c) after Oxygen plasma treatment

During plasma treatment, high voltage is applied via electrodes at both sides of plasma chamber. Electrons from cathode accelerate towards anode and collide with the Argon and Oxygen gas atoms in the chamber. In Argon plasma treatment, Argon gas atoms are ionized into Ar+ ions after colliding electrons [12]. These heavy and inert Ar+ ions remove the surface contaminant through mechanical bombardment [13]. Meanwhile, in Oxygen plasma cleaning, Oxygen gas atoms are ionized into O monoatomic oxygen, O+ and O2+ ions after colliding with electrons. These high reactive O monoatomic oxygen, O+ and O2+ ions chemically react with organic contaminant to form volatile molecules, such as H2O, CO and CO2 [14]. The volatile molecules were then evacuated from plasma chamber before re-deposition occurs. Moreover, O+ and O2+ ions can also remove the surface contaminant through mechanical bombardment during the treatment. Thus, Oxygen plasma treatment which removes the surface contaminant through both chemical reaction and mechanical bombardment is more efficient than Argon plasma treatment which just removes the surface contaminant through mechanical bombardment.

3.2 Bond pad surface roughness analysis results

Fig. 4 displays the AFM morphology image of bond pad surface (a) before plasma treatment, (b) after 90 seconds of Argon plasma treatment and (c) after 90 seconds of Oxygen plasma treatment. Before plasma treatment, the peaks on the bond pad surface are blunt and wide. The tall flat irregularity peaks observed on the bond pad are the white spots in FESEM image as shown in Fig. 3(a). After Argon and Oxygen plasma treatments, the peaks on the bond pad surface become sharper and thinner. Fig. 5 illustrates the average RMS roughness of bond pad surface relative to Argon and Oxygen plasma treatment duration. Before plasma treatment, the average RMS roughness of bond pad surface is 1.188nm. The average RMS roughness of bond pad surface increases 22.22% into 1.452nm after 180 seconds of Argon plasma treatment, whereas increases 10.61% into 1.314nm after 180 seconds of Oxygen plasma treatment. This shows that Argon plasma treated surfaces were rougher than Oxygen plasma treated surface

During plasma treatment, Ar+, O+ and O2+ ions with high kinetic energy are mechanically bombarded onto the bond pad surface to knock-off the contaminant. This ion bombardment also simultaneously gives rise to the surface etching, leading to the change of bond pad surface structure and the increase of bond pad surface roughness [15]. Argon which has higher atomic mass of, i.e., 39.948u than oxygen, i.e., 15.999u, causing the surface etching effect of bond pad is more severe [16]. Thus, the bond pad surface after Argon plasma treatment is rougher compared to Oxygen plasma treatment.

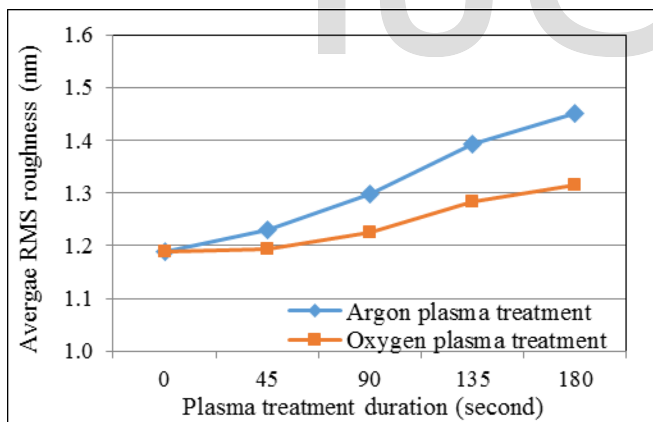

Fig. 5. Average RMS roughness of bond pad surface relative to plasma treatment duration

3.3 Bond pad surface surface free energy analysis results

Dispersive adhesion is a mechanism for adhesion which attributed to the molecular interactions between two contacting bodies, where each has a region of positive and negative polarity [17]. These dispersion adhesion intermolecular interactions include polar interactions (dipole-dipole, dipole-induced dipole and hydrogen bond interactions) and non-polar or dispersive interactions (instantaneous dipole interaction). Thus, surface free energy also consists of two components which are polar component, γ^p and non-polar or dispersive component, γ^p respectively [18]. According to Young-Dupre equation, the overall bond pad surface free energy, γ_{pad} can be calculated by determining the surface free energy components through contact angle measurement of two different liquids, i.e., DI water and Diiodomethane on bond pad surface as given in (1) and (2)

$$\gamma_{pad} = \gamma_{pad}^{p} + \gamma_{pad}^{d} \quad (1)$$

$$\gamma_L(1+\cos\theta) = 2[\sqrt{\gamma_L^p \gamma_{pad}^p} + \sqrt{\gamma_L^d \gamma_{pad}^d}] \quad (2)$$

where θ is the contact angle of the liquid, γ_L is the overall surface free energy of liquid, γ_{pad}^{p} and γ_{pad}^{d} are the polar and

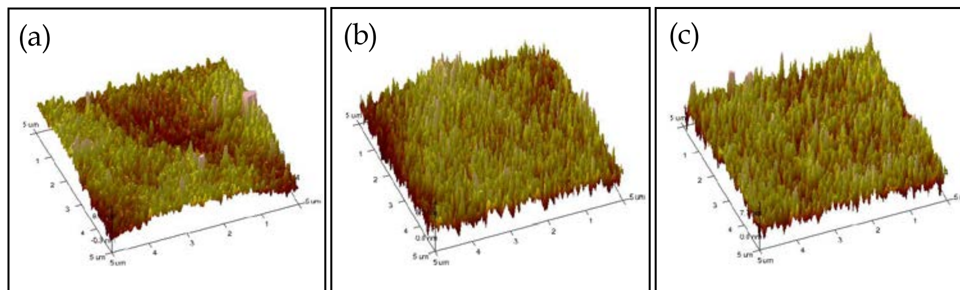

Fig. 4. AFM image of bond pad surface (a) before plasma treatment (b) after Argon plasma treatment and (c) after Oxygen plasma treatment

dispersive surface free energies of bond pad, γ_L^p and γ_L^d are the polar and dispersive surface free energies of liquid.

Fig. 6 displays the average bond pad surface free energy relative to plasma treatment duration. The bond pad before plasma treatment has a surface free energy of 23.6mJ/m2. The surface free energy increases drastically in the initial stage and slowly increases as plasma treatment duration increase. The bond pad surface free energy increases 201.4% into 71.2mJ/m2 after 180 seconds of Argon plasma treatment, whereas increases 232.24% into 78.5mJ/m2 after 180 seconds of Oxygen plasma treatment. This shows that Oxygen plasma treatment can improve bond pad surface free energy more effectively than Argon plasma treatment.

Generally, surface free energy is significantly affected by the polar component on the bond pad surface [19]. Oxygen plasma treatment which able to remove the carbon impurities and reduce the weak polarity of C-C/H bonds on the bond pad surface more effectively, causing the surface free energy improved better compared to Argon plasma treatment [20]. Moreover, bond pad surface free energy has better improvement after Oxygen plasma treatment due to more high polarity and strong hydrogen bonds are introduced, such as C=O, C-OH, C-OOH bonds [13]. Fig. 7 displays Carbon (C1s) XPS band of bond pad surface (a) before plasma treatment, (b) after 90 seconds of Argon plasma treatment and (c) after 90 seconds of Oxygen plasma treatment. Before plasma treatment, C-C/H (284.6eV) and C-O/OH (285.6eV) bonds were detected on bond pad surface. After Argon plasma treatment, C=C

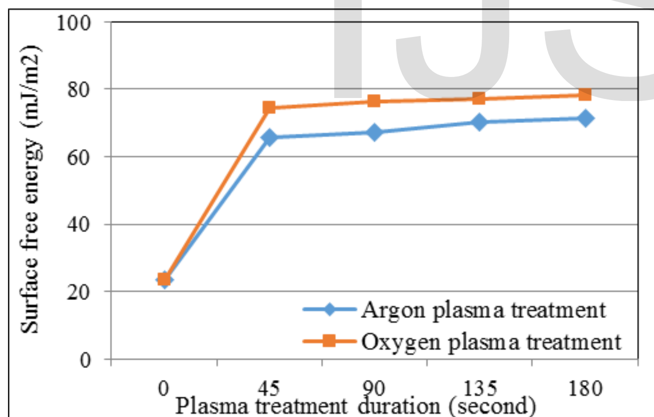

Fig. 6. Average bond pad surface free energy relative to plasma treatment duration

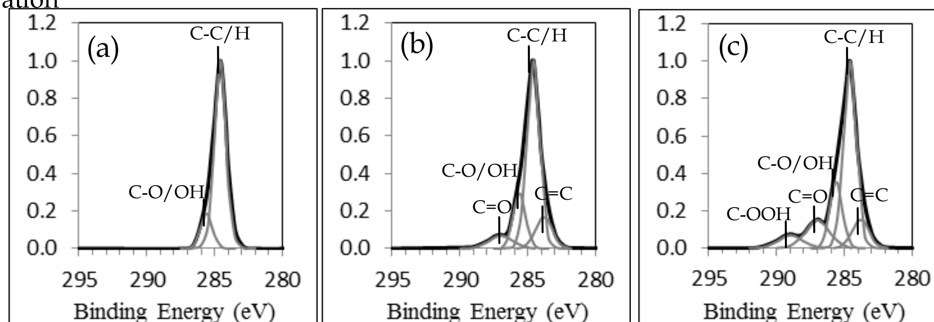

Fig. 7. Carbon (C1s) XPS band of bond pad surface (a) before plasma treatment (b) after Argon plasma treatment and (c) after Oxygen plasma treatment

(283.8eV) and C=O (287eV) bonds have been introduced on the bond pad surface. Meanwhile, after Oxygen plasma treatment, C=C, C=O and C-OOH (289eV) bonds have been introduced on the bond pad surface. During plasma treatment, Argon and Oxygen gas atoms are excited into higher energy state after collision with electrons and fall back to ground state with the emission of photons. These emitted photons break C–C/H and C–O bonds and lead to the formation of C=C bonds on bond pad [14]. At the same time, significant carbon radicals are also formed onto the bond pad surface during the plasma treatment [14]. C=O and C-OH bonds are formed after Argon plasma treatment as the carbon radicals react with oxygen contaminant inside the plasma chamber during the treatment. Meanwhile, C=O, C-OH, C-OOH bonds are formed after Oxygen plasma treatment as the carbon radicals react with oxygen plasma during the treatment. C-OOH bond is not introduced on the bond pad surface treated by argon plasma due to the less of oxygen component inside the plasma chamber during the treatment [13].

3.4 Ball shear force results

Ball shear test is the dominant test method used in industry to assess the wire bond interfacial adhesion quality, whereas ball shear strength is the strength that a ball bond can withstand from being sheared off. Figure 8 illustrates the average ball shear strength relative to Argon and Oxygen plasma treatment duration. Before plasma treatment, the average ball shear strength of bond pad surface is 0.167N/mm2. The average ball shear strength increases 12.98% into 0.189N/mm2 after 180 seconds of Argon plasma treatment, whereas increases 14.77% into 0.193N/mm2 after 180 seconds of Oxygen plasma treatment. This shows that Oxygen plasma treatment can improve wire bond interfacial adhesion more effectively than Argon plasma treatment.

Generally, interfacial adhesion of wire bond is significantly influenced by the contact area between wire bond interfaces. This is because larger contact area contribute to a higher degree of the mechanical interlocking between wire bond interfaces. Liu et al. proposed that an increase of surface free energy is comparable to an increase of the contact area between two contacting bodies [13]. Thus, Oxygen plasma treatment which able to improve bond pad surface cleanliness and surface free energy more effectively causes the wire bond interfacial adhesion has better improvement compared to Argon plasma treatment. Although bond pad surface after Argon plasma treatment is rougher and has larger contact area com-

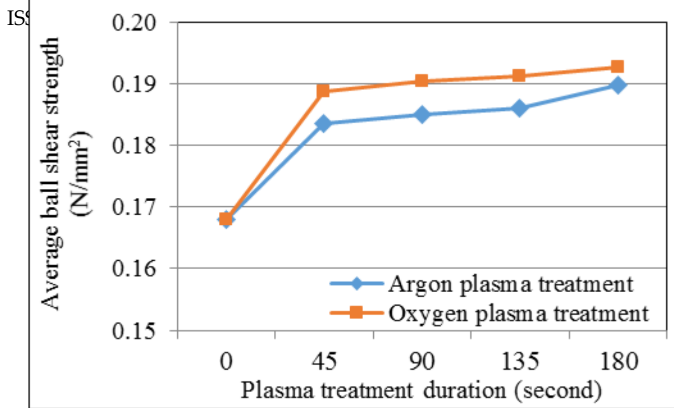

Fig. 8. Average ball shear force relative to plasma treatment duration

pared to Oxygen plasma treatment, its impact to wire bond interfaces adhesion quality changes is negligible compared to bond pad surface cleanliness and surface free energy as the RMS roughness difference is just in nanometer (nm) scale.

4 Conclusion

The efficiency of Argon and Oxygen plasma treatments was compared in terms of contaminant removal and wire bond interfacial adhesion quality in this paper. The bond pad surface characterization results show that Oxygen plasma treatment which removes the surface contaminant through both chemical reaction and mechanical bombardment is more efficient than Argon plasma treatment which just removes the surface contaminant through mechanically bombardment. Thus, bond pad surface after Oxygen plasma treatment with lower carbon impurity content has better surface free energy than Argon plasma treatment as evaluated through contact angle measurement. The ball shear test results show that Oxygen plasma treatment can improve the wire bond interfacial adhesion more effectively compared with Argon plasma treatment as higher ball shear force is obtained.

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