

Relationship of Cu Oxidation and Hardness towards Cratering in Wirebonding

Lee Chai Ying, Lee Cher Chia & Lim Chee Chian
Infineon Technologies Melaka Malaysia

P.O Box 52, Batu Berendam FTZ 75710 Melaka Malaysia

Phone: +06-2325266 (Extn:3036) Fax: +06-2325246

ChaiYing.Lee@infineon.com; CherChia.Lee@infineon.com; CheeChian.Lim@infineon.com

Abstract

Nowadays, copper wire ball bonding is gaining popularity due to its economic advantage and superior electrical performance. However, the idea of replacing gold wire with copper wire in the wire bond process does come with technical challenges. From mechanical point of view, copper is harder than gold. Hence, replacing gold wire with copper wire will introduce hardness related issues which concurrently contributes towards cratering defects. At the same time, copper also shows faster oxidation rate than gold and this native behavior is actually another limitation of utilizing copper wirebonding in semiconductor industries.

This paper was carried out in order to know the relationship of copper oxidation and hardness on the detectable oxidation layers on 22 μ m copper wire ballbond. Transmission Electron Microscopy (TEM) equipped with Energy Dispersive X-ray (EDX) Analysis was used to study the copper oxidation layers. A logarithmic relationship of oxidation and hardness was obtained from Vickers microhardness test results on Free Air Balls (FABs). This relationship was used in tracking cratering defect in wirebonding performance and found out that copper oxidation was not the major factor that caused cratering, but not optimum wirebonding parameters setting was. Therefore, in order to have a thorough look on this matter, wire related reliability tests were also carried out to evaluate Cu wire intermetallic performance.

Keywords: Copper Oxidation, Copper Wire, Vickers Hardness, Cratering Impact, Wirebonding

1. Introduction

Aside from the well-known high electrical and thermal conductivity, copper wirebonding is gaining great popularity recently due to its economic advantages, especially in fine pitch packaging assembly [1, 2]. However, a process difficulty with copper is its hardness that causes cratering and pad peel, as copper is readily oxidized and it is harder than gold by nature.

Several studies have been done to investigate the contributing factors towards copper wire hardness. According to H.M Ho et. al, the wirebonding parameters setting related to EFO (Electronics Flame Off) current and firing time would affect the copper wire hardness. On the other hand, Onuki et. al found out that the ball forming conditions was also another major influence in affecting the copper wire hardness, where copper FAB is softer when it is formed in an elevated shield gas temperature of 175°C compared to copper FAB that is formed in a room temperature shield gas [3].

Instead of wirebonding parameters setting and ball forming conditions, this paper was carried out to gain fundamental understanding on copper oxidation behavior and the correlation with the wire hardness. This study was then carried out to further understand of the correlation of cratering contributing by copper oxidation and hardness. This trial was carried out in the 22 μ m copper wirebonding process. Cratering is defined as a category of ballbond failure or defect which the ball lifts from the surface of the integrated circuit die-bond pad, taking with it a portion of bond pad metallization and the underlying oxide or silicon. Cratering also called as chip out under bond [4].

2. Developed Methodology

2.1 Sample Preparation

A set of Free Air Ball (FAB) consisted of 3 different copper wire oxidation rates was prepared based on different forming gas flow. The samples obtained were 1) the non oxidized FAB with optimum forming gas flow rate, 2) intermediate

oxidized FAB with half of the optimum forming gas flow set; and 3) oxidized FAB with no forming gas supply at all. Non oxidized and oxidized FAB were sent to scanning electron microscopy (SEM) inspection to ensure the oxidation severity based on the FAB shape and surface morphology prior to transmission electron microscopy (TEM). Similar oxidation severity of the FABs were reported by [5,6]. Non oxidized FAB has a spherical round shape and near to perfect smooth surface whereas oxidized FAB showed a pointed shape of ball and it has scaly surface as shown in Fig. 1. In the sample preparation, optimum wirebonding parameter setting was used in order to rule out any machinery influence in the entire wirebonding process.

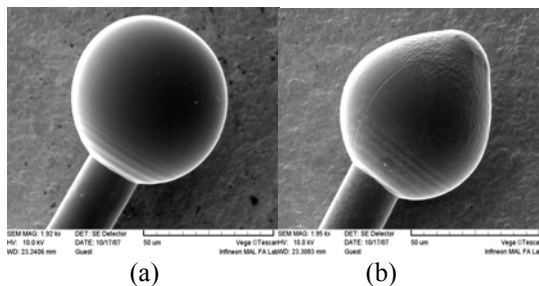


Fig. 1 SEM Images for (a) non oxidized FAB that shown spherical round shape and smooth surface and (b) oxidized FAB which gives pointed shape ball and scaly surface.

2.2 Copper FABs Oxidation Analysis

Three samples of copper FAB with different oxidation rates were examined by using transmission electron microscopy (TEM) equipped with energy dispersive X-ray (EDX) analysis. TEM samples were prepared with focus ion beam (FIB) DualBeam in situ lift out method where the samples were FIB polished and thinned. EDX analysis had also been done to identify the elements of the samples. The areas of interest of the FAB samples inspection were sample surface morphology, TEM pre-lamella morphology, copper oxidation behaviors and preliminary observation on the bulk copper wire.

2.3 Hardness Test

All the copper wire hardness was evaluated by using Vickers Hardness Test in the mode of HV 0.005. The hardness test was conducted under the applied load of 1g and the application time was 10sec. The sample size taken for each sample group was 60 readings from 8 pieces cross section molded pellets.

2.4 Cratering Analysis

Two methods of chemical analysis were conducted to analyze the silicon damages under chip bondpads after wirebonding for bonded samples built

with significant oxidation severity. The oxidation rates were referred to non oxidized (with forming gas) and oxidized (without forming gas). The chemical analysis methods were aluminium bondpads removal by using sodium hydroxide solution and copper wire removal by using hydrochloric acid.

3. Results and Discussion

3.1 Copper FAB Preliminary Observation

Copper oxidation behavior was done by using SEM/FIB analysis tool. Prior to TEM inspection, there was a sample preparation required, where a piece of sample was cut out, polished and thinned by FIB bombardment.

Fig. 2 shows the overview of the 3 samples with different oxidation rates before FIB bombardment. Visible and clear grain structure on non oxidized FAB can be seen. On the other hand, the scaly surface of intermediate and oxidized FABs also reveal with smaller grain structure as compared to non oxidized FAB.

After targeted at the selected piece on the FABs, FIB bombardment was carried out and revealed the cross sectioned fragments (or pre-lamella for TEM inspection) that gave valuable observation and information as shown in Fig. 3. Non oxidized FAB shows very clean surface that is as smooth as the top surface can be observed in Fig. 3(a). In Fig. 3(b) is the intermediate oxidized FAB where several air traps were going upwards to the surface was observed. These air traps are believed due to the insufficient protective environment provided during the FAB formation. The air traps were combined into bigger air trap in not spherical shape and surfaced themselves to the outer part of the oxidized FAB as can be seen in Fig. 3(c). This phenomenon may because of the environment equilibrium during the unprotective FAB formation process. Besides oxidation layer, stripes formation was also observed underneath the oxidation layer as shown in Fig. 3(c).

In higher magnification of 80,000x, there was a detectable copper oxidation layer found underneath the platinum protective layer in intermediate oxidized FAB and oxidized FAB. No oxidation layer detected in non oxidized FAB. The zoom-in images of the detectable oxidation layer of the FABs are shown in Fig. 4. Measurement on the FABs copper oxidation layers had been done under TEM inspection. The oxidation thickness reported for intermediate oxidized FAB is in the range of 60 to 70 nm while oxidized FAB is between 190 to 240nm. The measured images on the oxidation layers were reported in Fig. 5.

EDX analysis was carried out to confirm the elements of the copper oxidation layer by using one

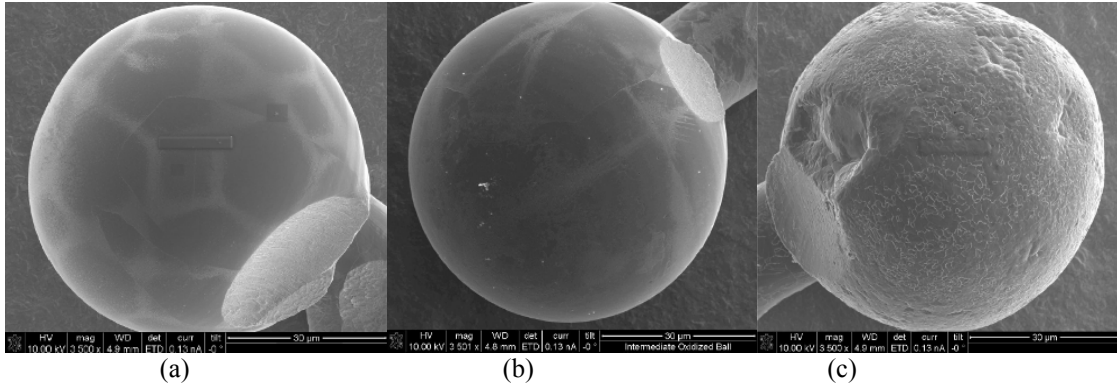


Fig. 2 SEM/FIB images prior to TEM inspection on 3 FAB samples at different oxidation rates: (a) non oxidized FAB, (b) intermediate oxidized FAB and (c) oxidized FAB.

of the TEM system configurations which is known as scanning transmission electron microscopy (STEM) conducted in dark field. As shown in Fig. 6, two elements of copper and oxygen found on EDX analysis point 1 and only copper was detected in the copper bulk area at point 2. The carbon and oxygen elements found in point 2 could cause by sample preparation contamination, where the quantitative amount of elements detected was insignificant.

3.2 Nanoindentation

Since copper oxidation layer detected was in nanoscale, therefore nanoindentation test was required in order to know the hardness of the oxidation layer as well as the bulk copper area. The area selected for the indentation was $2\mu\text{m} \times 2\mu\text{m}$. The nanoindentation measuring was done by using the normal force of $2\mu\text{N}$ with a dynamic force of $1.5\mu\text{N}$ oscillating at 200 Hz.

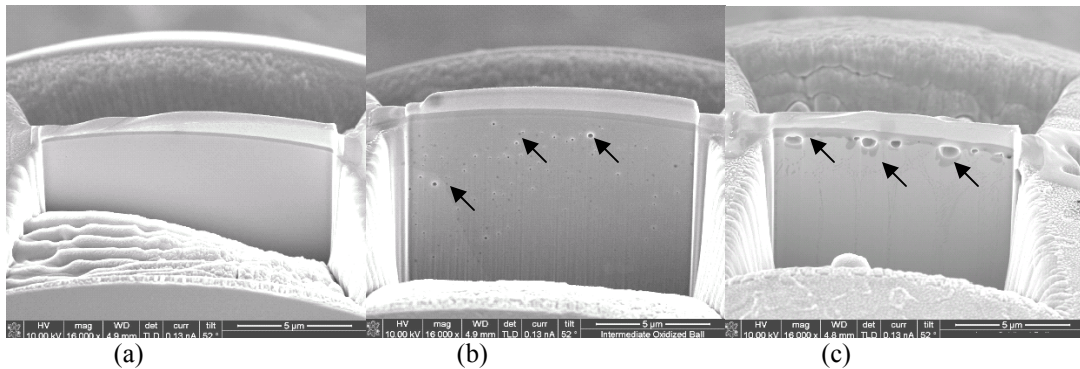


Fig. 3 Pre-lamella images after FIB cross sectioning: (a) non oxidized FAB, (b) intermediate oxidized FAB and (c) oxidized FAB.

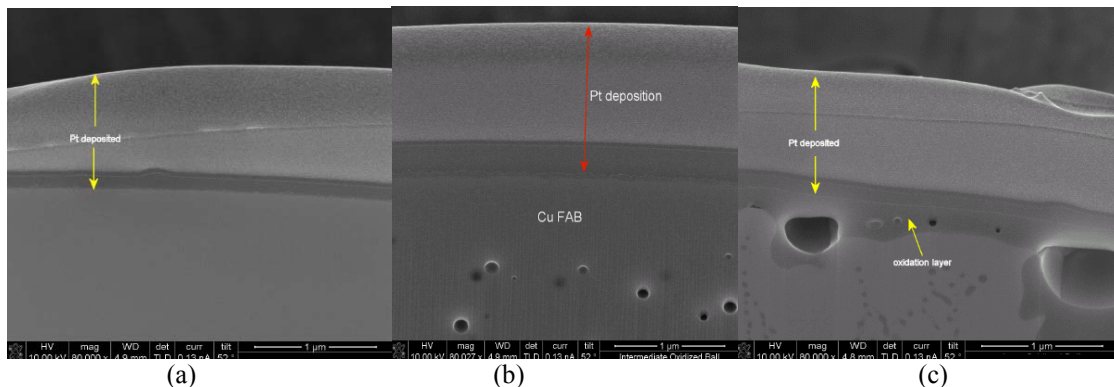


Fig.4 80,000x magnification images under SEM/FIB observation on the visible oxidation layer on FABs: (a) non oxidized FAB, (b) intermediate oxidized FAB and (c) oxidized FAB.

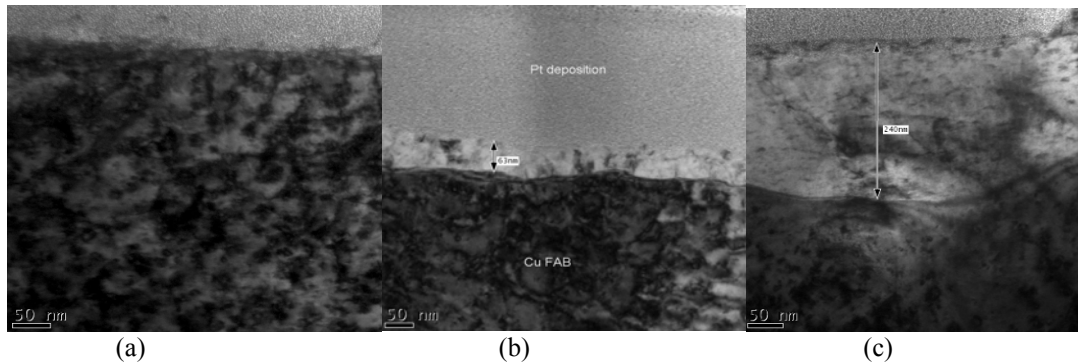


Fig. 5 Copper oxidation layer measurement for FABs under TEM inspection: (a) non oxidized FAB with no detectable oxidation layer, (b) intermediate oxidized FAB with 60-70nm oxidation thickness and (c) oxidized FAB with 190-240nm oxidation thickness.

A diamond 90° cube-corner probe was used to create the modulus map of the selected sample area which including the oxidation layer and the copper bulk area. Prior to the modulus mapping, a topographical image from scanning probe microscopy (SPM) was required to ensure proper placement of the diamond indenter before any indentation being made, as shown in Fig. 7. From the modulus mapping interpretation, a conclusion of the stiffness (that can refer to the hardness) comparison was made. The copper oxidation layer found relatively less stiff or less hard compared to the bulk oxidized copper area, which is the modulus ratio range of 125 to 180. This observation was significant surprising and more validation on the results was carried out by using Vickers microhardness test, which will be discussed further in the next section.

3.3 Vickers Microhardness Test

Guideline was given by the nanoindentation modulus map indirectly, where the microscale indentation should be done in the bulk oxidized copper area due to its higher relative stiffness value.

As shown in Fig. 8, a logarithmic relationship was plotted between the copper oxidation and its responsive hardness value. From this relationship, hardness value increased once oxidized and stayed stable regardless of oxidation rate. Non oxidized FAB has lower hardness value compared to oxidized group of FABs (intermediate oxidized and oxidized gave almost the same hardness value).

To further verify the copper oxidation is less stiff than the bulk oxidized copper, microhardness test was repeated at the stripes formation area and the hardness values assured that the nanoindentation statement is true. The validation of the data was given in Fig. 9. The diamond shapes indented at the oxidation stripes were found bigger (therefore, softer) than the bulk copper indenter's diamond shapes.

3.4 Cross Section as New Failure Analysis Method

In the hardness test sample preparation, all the samples need to be mechanical cross sectioned and an interesting observation was discovered, as shown in Fig. 10. Stripes formation found and this observation was similar to the TEM inspection as shown in Fig. 3(c).

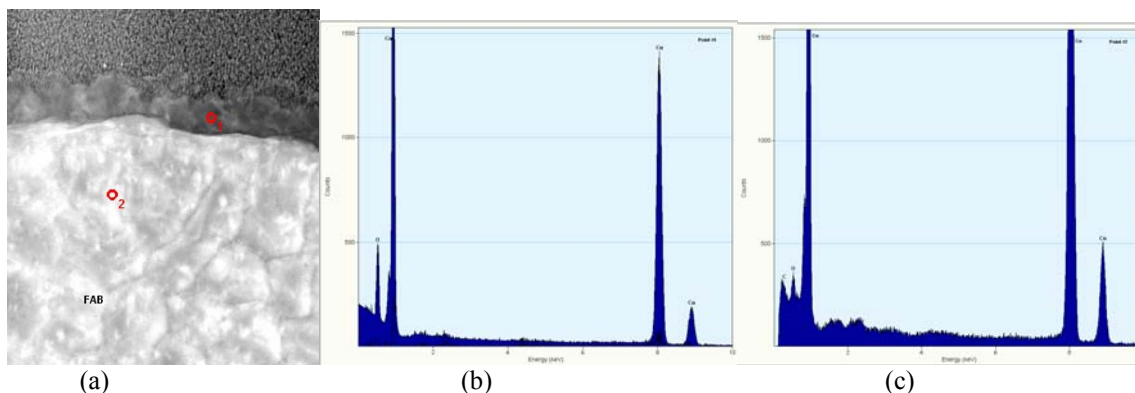


Fig.6 Identification of elements at the oxidation layer: (a) STEM images which shown the EDX analysis points taken on Point 1 and Point 2, (b) EDX spectrum on Point 1 and (c) EDX spectrum on Point 2.

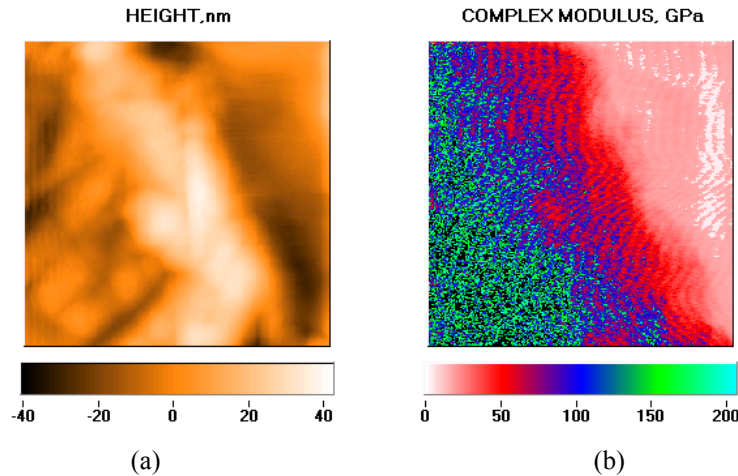


Fig. 7 A 2 μm x 2 μm area of the edge of the oxidized FAB with the bulk copper area is at the left bottom part of the image: (a) a topographical *in-situ* image and (b) the corresponding Modulus Map.

As compared to non oxidized sample, no stripes would be detected as shown in Fig. 10 (c). Therefore, cross section could be a new, less expensive and convenient failure analysis method to detect copper wire oxidation.

3.5 Cratering Analysis on Bonded Samples

After gaining the fundamental understandings on copper oxidation, two lots of samples were built respectively with non oxidized and oxidized condition. Right after wirebonding process, about 1200 pieces of samples from each lot have been sent for chemical analysis to check for cratering. The result was tabulated in Table 1. The result showed that no cratering detected for both lots of the sample even after double confirmation of repeated chemical analysis in consequence manner. This finding

implies that copper oxidation is not the dominant factor in causing cratering. This could be because of the less stiff outer layer of copper oxidation that gives cushioning impact during ballbonding process. However, the samples were assessed until reliability to further understand the Cu/Al intermetallic performance.

According to [4], cratering is a failure that usually caused by improper bonder set up. Therefore, another quick experiment was carried out in order to have clearer view on this matter. The result was given in Table 2 and found that not optimum parameters setting is the main key factor that contributing to cratering.

3.6 Reliability Study on Oxidized Samples

Temperature cycling test is a wire related

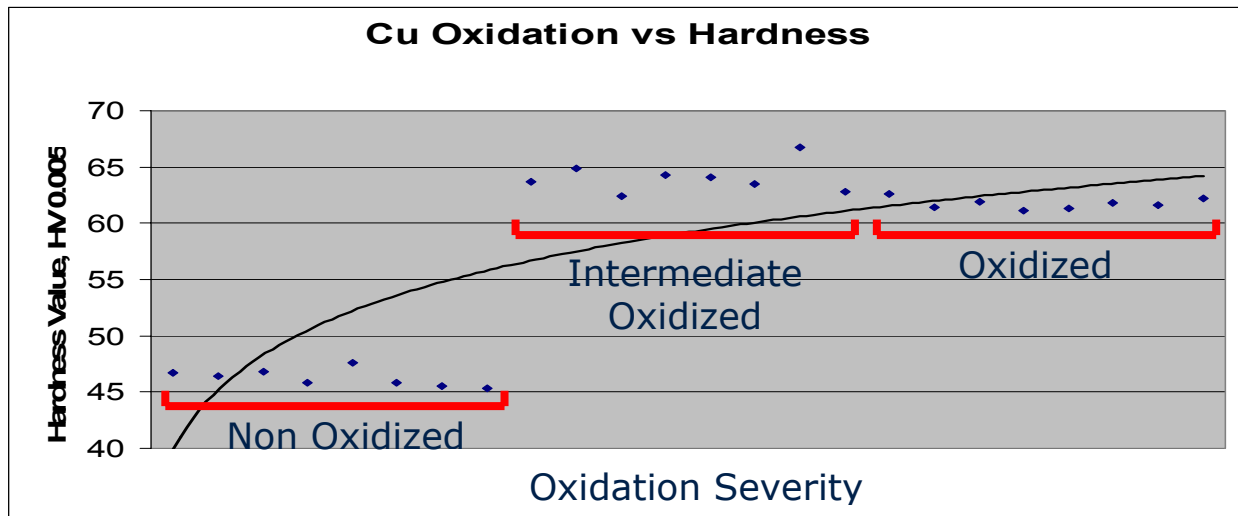


Fig. 8 Logarithmic relationship of copper oxidation and hardness.

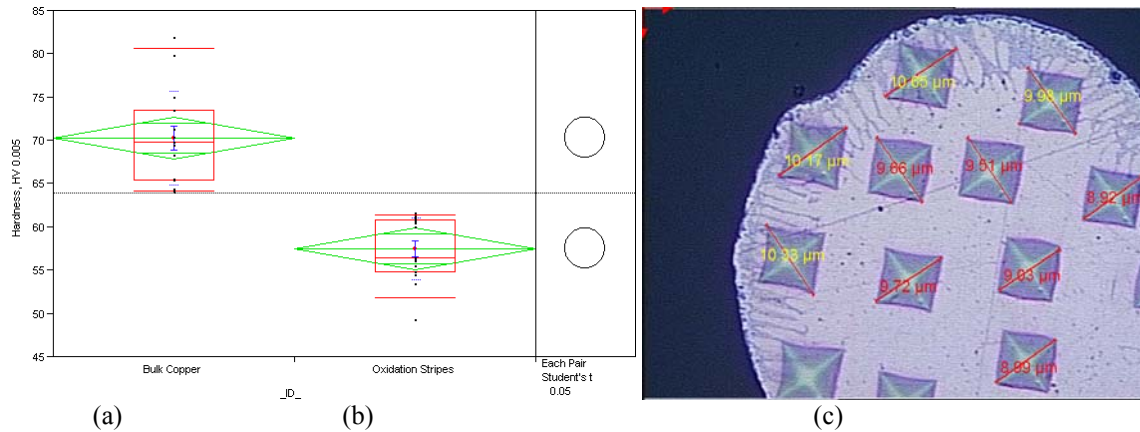


Fig. 9 Vickers hardness values to further verify the nanoindentation result: (a) bulk copper, (b) oxidation stripes and (c) Microindention diamond image.

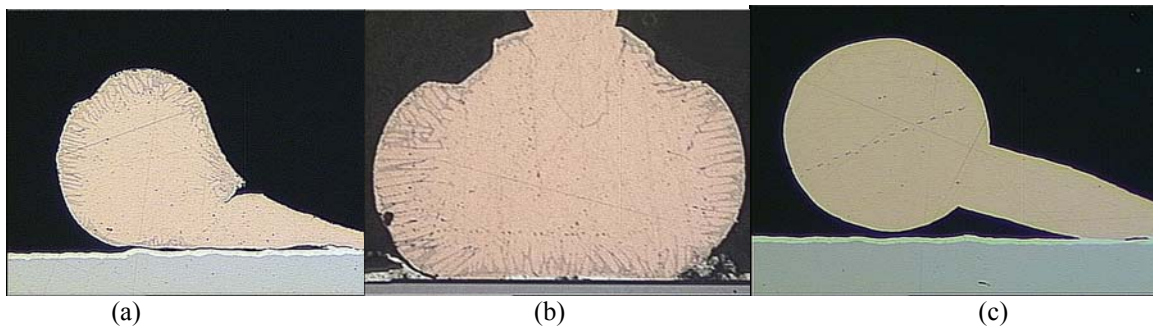


Fig. 10 Cross section optical images of FABs and bonded ball that showing stripes formation in oxidized samples: (a) oxidized FAB, (b) bonded oxidized ballbond and (c) non oxidized FAB.

Table 1 No cratering found in oxidized bonded samples.

Analysis Methods	Cratering Check (Yes/No)	
	Non Oxidized	Oxidized
Cu wire removal	No	No
Al removal	No	No
Cu wire Removal & Al Removal	No	No

Table 2 Not optimum parameters setting is the dominant factor to cratering.

Parameters Setting	Cratering Check (Yes/No)	
	Non Oxidized	Oxidized
Optimum	No	No
Not Optimum	Yes	Yes

reliability test and requires preconditioning prior to perform the test. The test condition performed was according to JEDEC JESD22-A104 Condition H. In this test, oxidized samples still able to sustain in preconditioning and started to fail after 300

temperature cycles. The failure electrical parameters were HFE and VBESAT.

After failure analysis verification, lifted ballbonds detected (as shown in Fig. 11) which shown the poor intermetallic growth of Cu/Al. This observation implies that oxidized ballbond is bondable; however even without cratering, it is unable to withstand wire related stress test.

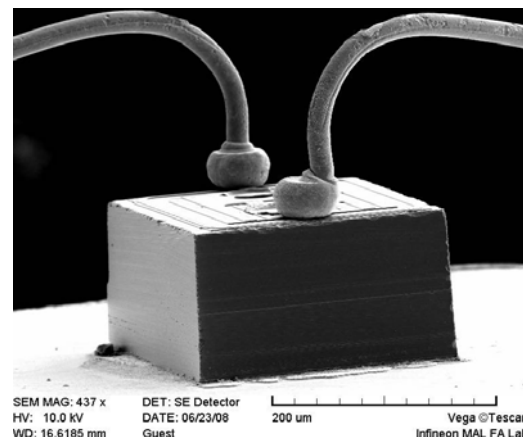


Fig. 11 Lifted ballbond after TC 300x of oxidized samples.

4.0 Conclusions

In this paper, nanoscale oxidation layer was detected on oxidized copper FABs and its hardness was less than the bulk oxidized copper. A strong correlation of copper oxidation and its respective hardness was found in the logarithmic scale. In this relationship, stable hardness values were observed regardless of oxidation severity. Besides, cross section could be a new, inexpensive and convenient failure analysis method based on the oxidation stripes formation detected surrounding the outer layer of copper FABs or ballbonds.

From the sample build experience, copper oxidation was learnt not the major factor that caused cratering, but not optimum wirebonding parameters setting was the dominant contributor to minimize cratering defect. Even though oxidized copper wire was bondable without cratering, it is not recommended to use as it can't withstand wire-related stress test and revealed with lifted ballbonds after 300x temperature cycle test.

Future Work

The mechanism of the copper wire oxidation can be studied in order to further improve the process quality in controlling the wire oxidation. Besides, the crystal structures of the copper oxidation will be the other interest to understand the copper oxidation in wire form in the future work.

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Biography

Lee Chai Ying. She was graduated from University Kebangsaan Malaysia with M.Sc in Pure Chemistry after obtaining her first degree from University Technology Malaysia in Industrial Chemistry in 2005. She joins Infineon Technologies Sdn. Bhd as her first career as a Manufacturing Engineer. Her core job function is majoring in material research and development.

Lee Cher Chia. He was graduated from State University of NY at Buffalo, with B.Sc in Electrical Engineering minor in Computer Science. He has been working in semiconductor field for 5 years focus in FOL assembly process with exposure to various packages. He is a co-author of 1 technical publication with new idea of process and manufacturing. Currently he is attached at Infineon Technologies (Malaysia) as Manufacturing Engineer.

Lim Chee Chian. He was graduated from University Kebangsaan Malaysia with B.Eng (Hons) in Mechanical & Materials Engineering plus Diploma in Petroleum engineering from University Technology Malaysia. He has been working in the semiconductor field for 13 years and held 13 US patents plus 2 technical publications with breakthrough innovative processes, packaging design solutions and manufacturing concept. He also held numerous awards like Siemens recognition awards, Motorola patent awards, Special Motorola Departmental Recognition awards, Motorola technical excellence award, Infineon patent awards and Infineon technical recognition awards. Besides he has vast & extensive experience and knowledge in packaging design and development, platform concept establishment, line set up & transfer, project management, line sustaining engineering from wafer backgrind till test and packing with FOL core competency.

He is currently attached to Infineon Technologies (Malaysia) Sdn Bhd as Manufacturing Engineering Manager and Sr. Staff Engineer. Prior to

joining Infineon Technologies he was attached to Chippac Semiconductor Malaysia Sdn Bhd as Engineering manager and Carsem semiconductor as Sr. Engineering Section manager. In the earlier phase

of his career he was working in Motorola Seremban Sdn Bhd and Siemens Semiconductor (adv tech) Sdn Bhd as technical engineer.