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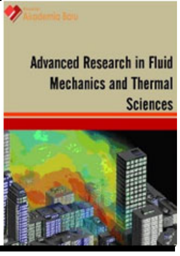

Effect of Annealing Temperature on the Surface Properties of Copper-Based Leadframe

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ABSTRACT

Microelectronics packaging has been widely explored by researchers since the application is critical in the electronics industry. One of the crucial products related to this issue is copper-based leadframe. Most electronic manufacturers prefer to use copper because of its characteristics which are good conductivity, resistivity and low cost. However, copper materials have a high tendency to oxidise when exposed to high temperatures. This research is focused on the effect of annealed temperature on copper leadframes. The surface and mechanical properties of copper leadframes with different annealing temperatures were investigated using atomic force microscopy (AFM) and nanoindentation. Surface morphology and roughness were characterised using AFM, while the mechanical properties of the surface structure were investigated using nanoindentation. The obtained results showed that the surface roughness changes were directly proportional with increases in temperature. The RMS increases with increases in temperature. The hardness and elastic modulus of the annealed temperature showed a positive increment compared to the control sample. However, when it achieved a certain temperature, the hardness and elastic modulus went down. This might be due to the voids formation at high temperatures or the softening effect of the material.

Keywords:
microelectronics, nanoindentation, Atomic Force Microscopy, copper material

1. Introduction

Copper (Cu) and its alloys are known as one of the most popular and widely used materials in various applications and industries including engineering, electrical, electronics, and semiconductor packaging as well as in the applied research field. In semiconductor packaging, copper is used extensively as the skeleton of IC packages called leadframe [1] and as interconnection material called wire bonding [2]. Copper has tremendous advantages over other materials such as gold (Au), aluminium (Al) and nickel (Ni) due to the low-cost factor, high mechanical stability, and excellent

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electrical and thermal conductivity [3]. All of these advantages attract a lot of development work on the application of copper as a workable technology.

Copper by nature has high affinity to oxygen and tends to oxidise easily when exposed to elevated temperatures. This oxidation phenomenon decreases the application of copper as it can cause serious reliability issues in the semiconductor packaging industry. For instance, the oxidation of copper leadframes on plastic IC package leads to the delamination of the epoxy molding compound (EMC) and the die-pad interface, and frequently causes the “pop-corn” failure due to the moisture absorption of the molding compound, thus finally resulting in the cracking of the whole plastic package. The oxidation of copper leadframe during the heat treatment process for die attach adhesive curing has led to wedge bonding failure due to its non-stickiness on lead (NSOL) [4]. The oxidation of interconnection wires also has an effect on its long-term reliability, where oxidised copper may lead to stress-corrosion cracking. It will also decrease the interfacial shear strength and weaken the Cu-Al bonding, causing a lot of wire bond lifting issues during the wire bond process.

In order to accomplish a technology breakthrough with copper, a solid understanding of the copper’s behavior at elevated temperatures is required. Owing to its importance, several studies on thermal oxidation of copper leadframes have been reported. Lahiri *et al.,* had characterised the oxidation of copper leadframes using the X- Ray Diffraction (XRD) technique [5] while Cho *et al.,* had utilised both XRD and X-ray Photoelectron Spectroscopy (XPS) techniques [6]. Although Cho *et al.,* included the Transmission Electron Microscopy (TEM) technique, the investigation was only carried out on the lateral view of the copper oxide. Investigation on the interfaces of the copper leadframe and copper oxide was not performed in both studies. This poses an open question on why delamination is likely to occur at this interface region.

In this research, the oxidation of bare copper alloy leadframe samples at elevated temperatures is studied since electronic packaging materials mostly have high tendency of exposure to elevated temperatures. Leadframe samples are subjected to heat treatment in air to promote oxidation. As the leadframe samples experience oxidation, the surface characteristic is expected to be altered compared to the as-received sample. Atomic Force Microscopy (AFM) and nanoindentation will be carried out in this study in order to investigate the surface properties of copper-based leadframes when exposed to different temperatures.

2. Materials and Method

2.1 Materials

In this study, a commercial copper alloy leadframe material was used. It has a weight composition of 97.05% copper (Cu), 2.6% iron (Fe), 0.15% phosphorus (P) and 0.2% zinc (Zn). It was cold worked in a leadframe fabrication process at the production line of Jade Precision Engineering Pte Ltd in Singapore.

The materials were then heat treated. The copper alloy leadframe was cut into small pieces as shown in Figure 1. No pre-treatment or pre-cleaning was carried out prior to the experiment. An as-received copper alloy leadframe sample was used as the control sample in this study.

Oxidation of the copper alloy leadframe sample was introduced via a heat treatment process in an oven under an oxygen-induced environment. The oxidation temperature was varied at 30°C intervals at temperatures ranging from 60°C up to 240°C for 3 hours.

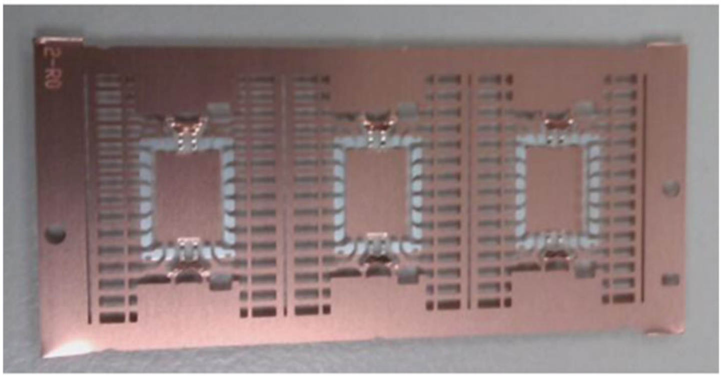

Fig. 1. As-received copper alloy leadframe sample

2.2 Method

The copper surface was characterized using two types of equipment, the AFM and Nanoindentation test. The AFM model utilised in this study is the D3100 series, manufactured by Digital Instruments. There are three primary imaging modes in AFM, namely the contact, non-contact and tapping modes. The surface roughness of copper leadframe samples was analysed using the tapping mode technique in AFM. In principle, AFM is configured with a sharp tip mounted on a soft cantilever to interact with the sample surface. A three-dimensional (3D) AFM image is then constructed by monitoring the motion of the tip as it scans over the sample surface.

In order to determine the hardness and elastic modulus of the surface, a nanoindentation test was conducted. Nanoindentation tests using the nanoindenter Shimadzu DUH 353 were performed. This equipment has a Berkovich shaped diamond tip with a load resolution of 0.1 mN. The distinguishing resolution is 0.2 nm. The hardness was calculated from the load-displacement curves using an analysis program. The specimen was put on the horizontal holder with a microscope directly located above the selected area. The conditions of the measurement are as follows: at room temperature (25°C) and at a relative humidity of around 55 %.

3. Results and Discussion

3.1 Surface Characterisation By AFM

The surface roughness of heat-treated copper alloy leadframe samples was quantified by the AFM surface roughness analysis. The RMS value obtained from the AFM analysis was plotted against temperature as shown in Figure 2 to understand the surface roughness changes as a result of the heat treatment process. In this graph, it is clearly seen that surface roughness increase exponentially with increases in temperature. The as-received sample showed an RMS value of 25nm. There is no significant change in the surface roughness of the samples that were heat treated at the temperatures of 60°C and 90°C. The surface roughness slightly increased at the temperatures of 120°C, 150°C and 180°C with RMS values of 26nm, 28nm and 31nm respectively. A significant increase in the surface roughness can be observed at the heat treatment temperatures of 210°C and 240°C. The RMS value had increased more than 10nm at this temperature range as compared to the as-received sample. The RMS values were 36nm and 46nm respectively.

The difference in surface roughness rate formation is due to the formation of surface oxide through oxide nucleation and oxide growth [7]. Chuang *et al.,* in their oxidation study of copper pads also observed that surface roughness increases at elevated temperatures, and it could possibly be associated with the formation of copper oxide [8].

Figure 3 is the qualitative AFM micrograph of the heat treated copper alloy leadframe samples. This AFM result is well correlated with the SEM micrograph where the surface of the samples becomes rougher as the heat treatment temperature increases. The as-received sample has a relatively fine and smooth surface. At temperatures above 150°C, a rougher sample surface can be observed.

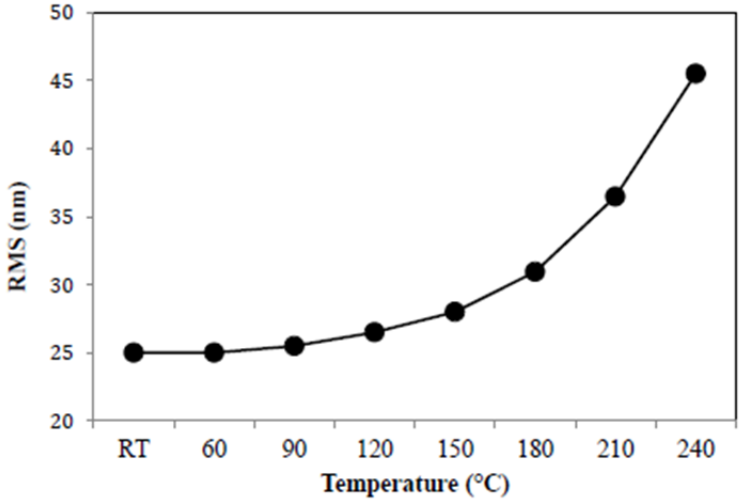

Fig. 1. Surface roughness as a function of temperature

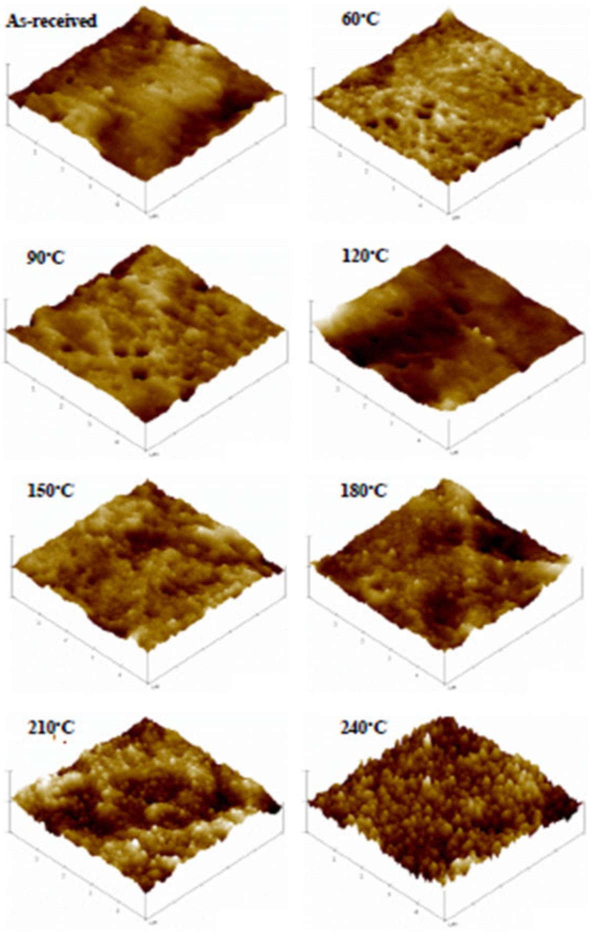

Fig. 2. AFM structure of Cu-based leadframe at different annealed temperatures

3.3 Mechanical Properties of The Surface Structure

In this study, a mechanical analysis of the surface structure was investigated using nanoindentation. Nanoindentation was performed on all Cu leadframes annealed at different temperatures, with the same peak load of 10 mN. Figure 4 shows a typical load/unload curve for a Cu-based material. It can been seen from Figure 4 that the load/unload curve for all samples at different annealing temperatures has almost a similar curve trend and this might be attributed to the similar crystalline structure of Cu-based materials [9].

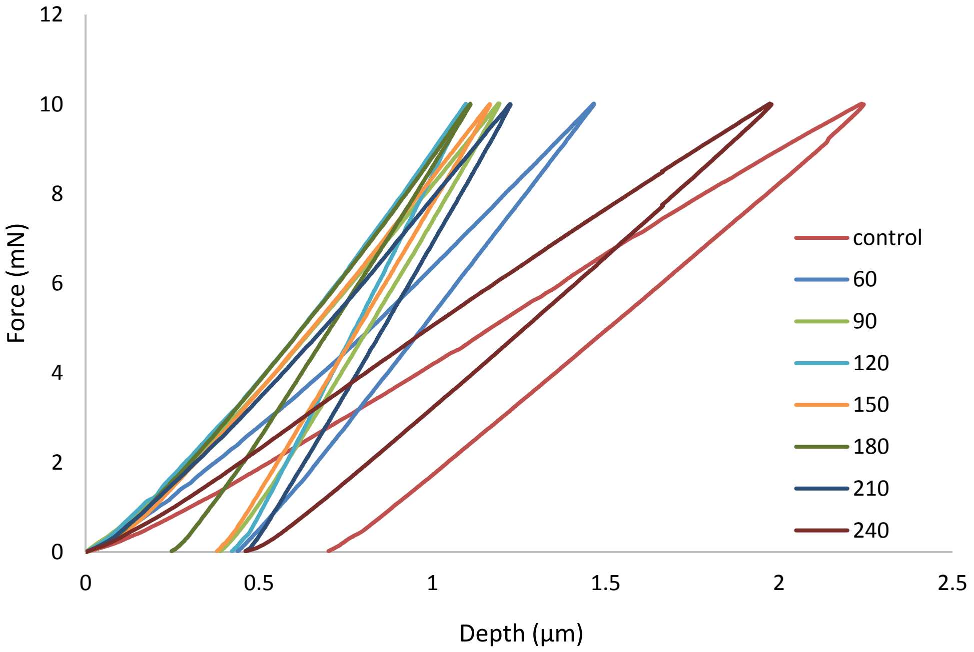

Fig. 3. Load/unload curve at maximum load peak 10mN of Cu based leadframe at different annealed temperatures

Besides that, the nanoindentation curves shifted to the right with increases in annealing temperature from 60^{0}C to 180^{0}C and it moved back to the left when the temperature further increased to 240^{0}C. The sample temperature of 240^{0}C is near to the control sample, which is due to the higher penetration at higher temperatures caused by the lower hardness structure of the copper oxide surface layer. The sharp curve in Figure 5 is due to the high loads applied. When the sharp indentation impressions were examined, thin sheets of material extruded around the periphery of the indenter were observed. This extensive plastic flow was interpreted as evidence for the transformation from a diamond cubic Cu to the metallic phase under the pressure of indentation [10].

Different load-indentation depth curves for the Cu films annealed at different temperatures imply different indentation plastic characteristics for these Cu-based materials. These curves can be separated into the following three stages: pure elastic deformation stage at the beginning of the load; elastic- plastic deformation stage after the displacement jump; and elastic response during unload. The lower the annealing, the less the elastic displacement. The displacement jump was caused by dislocation pileup, and increments on the plastic deformation region had increased with the increase of the grain size. With decreases in grain size, the density of the grain boundaries increased. It cannot only act as the source of dislocation, but also cause decreases the dislocation of activation energy [9,11,12].

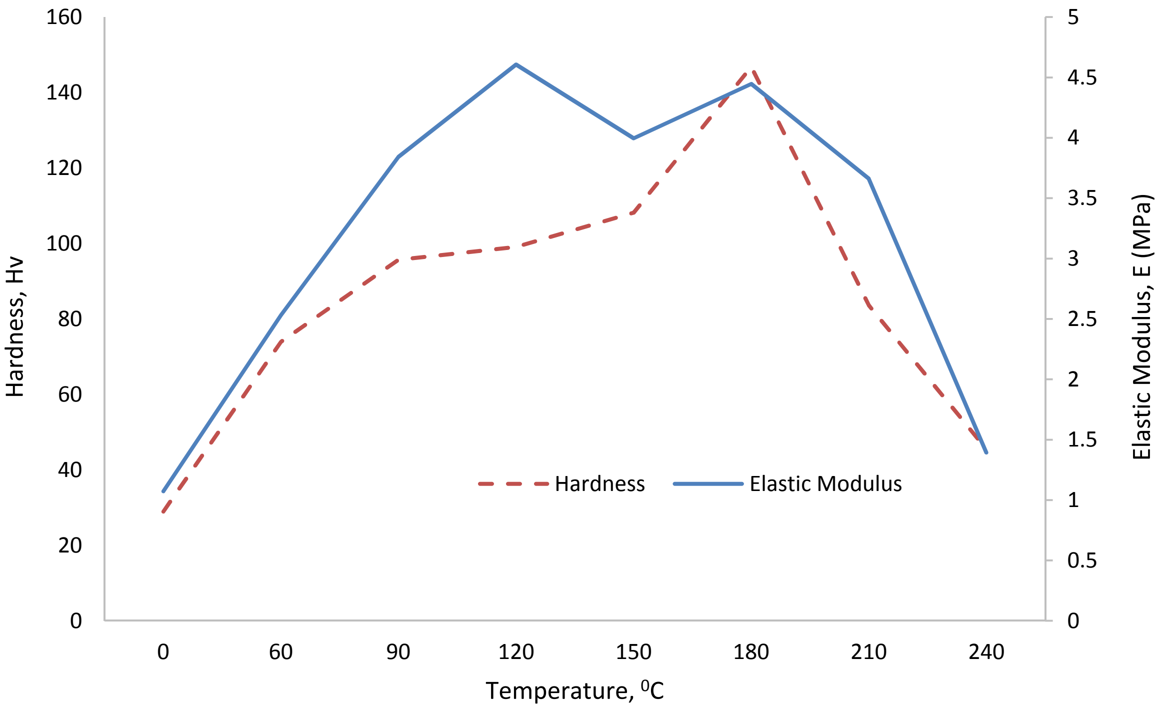

Fig. 4. Hardness and elastic modulus versus annealing temperature of Cu-based leadframe

Table 1 shows the surface properties of the Cu-based leadframe at different annealing temperatures. The depth penetration of Cu surface decreases when the hardness is increased. It can be clearly seen that the highest depth is from the control sample where the hardness is also the lowest. It is an indication of the re-strengthening effect due to the temperature applied to the Cu-based leadframe. The critical point of the transition occurs at temperature 180^0C as shown in Table 1. In this situation, the highest hardness and elastic modulus are obtained at 146 and 4.46 MPa respectively. The surface hardness increased 273% compared to the control sample, while the elastic modulus increased 314%. Both of the properties were strengthened when the temperature increased from 60^0C to 180^0C, but then weakened when temperature was further increased. These phenomena might be due to the voids formation under the surface between the copper and copper oxide layer at 180^0C. Omar *et al.,* have conducted a study on the effect of temperature to the copper oxide layer. In their study, they found that voids formation had occurred at 180^0C and became worse when the temperature was further increased [13]. Therefore, more voids formation under the oxide layer will decrease the hardness properties and the elastic modulus as well. This might be caused by the vacancy diffusion of the thermal stress effect during the annealing process.

Another possible reason for the decreasing hardness and elastic modulus transition might be the softening effect that comes with increases in temperature as discussed by several authors [14–16].

As mentioned above, the elastic modulus increased compared to the control samples and decreased beyond the critical point at 180^0C. Elastic modulus is one of the intrinsic properties of a material [17]. Elastic modulus is an important indicator to reflect the bond strength between the atoms. Many factors can affect the elastic modulus such as texture, grain coalescence, and microcrack [18]. From the literature, the elastic modulus of Cu thin films will decrease 20% when 1/3 of grain boundaries is destroyed based on the microcrack mechanism [9].

Table 1
Surface properties of nanoindentation results of the Cu-based leadframe at different annealing temperatures.

Temperature (^{0}C)	F_{max}	h_{max}	h_p	Eit (10^3)	HV*
As-received (control)	10.01	2.2378	0.7003	1.073	28.951
60	10.02	1.4654	0.4383	2.531	73.951
90	10.02	1.1905	0.3878	3.842	95.702
120	10.01	1.096	0.422	4.607	99.088
150	10.01	1.1653	0.3783	3.996	108.149
180	10.01	1.1092	0.2477	4.446	146.834
210	10.01	1.2236	0.4617	3.662e	83.622
240	10.02	1.9731	0.4609	1.393	45.472

4. Conclusion

The effect of annealing treatment on copper-based leadframe was investigated using AFM and nanoindentation techniques. Surface topography and microstructural evolution after annealing was studied in detail. A relationship between the surface topography and mechanical properties of the copper-based leadframe was also proposed. For microelectronic applications, large residual stress will cause cavity, crack, and peeling of Cu films which will cause circuit deformation and even short circuit or open circuit. Annealing is usually taken during IC. Although the resistivity of the copper leadframe decreased a little, the reliability of the system was greatly increased.

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