Investigation on the Effect of Copper Leadframe Oxidation on Package Delamination

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Abstract - The presence of a copper oxide layer on the leadframe of plastic IC packages was found to cause delamination at the diepad/mold compound interface. The failure mechanism seems to be the presence of voids at the oxide/metal interface, which increased as the degree of oxidation was increased. Elevated temperature processes used in assembly such as die attach curing and wire bonding were found to be the primary causes of oxidation. However, an important observation was made in that the duration of post mold curing was also found to have a great impact on the interfacial integrity of the oxidized interface within an encapsulated package. Depending on the degree of oxidation and the duration of post mold curing, the susceptibility of the package delamination during solder reflow was found to shift from die pad/compound interface to die attach region.

This paper also describes a novel method of characterising oxidation using SIMS (Secondary Ion Mass Spectroscopy) depth profiling. SEM (Scanning Electron Microscopy) and XPS (X-ray Photoelectron Spectroscopy) was used to characterise oxide morphology and oxide composition change on the samples. In parallel, the adhesion strength of the oxidized copper leadframe to a mold compound was characterised using an adhesion test. These data were correlated to the degree of package delamination on a QFP package using C-mode Scanning Acoustic Microscopy. This work shows that it is important to control the oxide thickness on the copper leadframe die pad for improved package integrity, especially when larger die pad sizes are considered.

Introduction

The susceptibility of an IC package to delamination, particularly in the area between the copper leadframe die pad and mold compound, has been a major concern to many IC manufacturers. With the trend towards higher device integration and density, higher pressure is being exerted on IC manufacturers for higher package performance and lower cost. There is a corresponding greater demand for copper alloys to be used as leadframe material in plastic IC packaging for better thermal and electrical performance. However, copper is susceptible to oxidation when subject to elevated temperature processes such as die attach curing and wire bonding.

Package delamination often precedes other package failure modes such as popcorn package cracking. This has been a major reliability concern for SMT devices. Despite its importance, published works on this subject remain limited. Yoshioka et al [2] reported poor adhesion of copper oxide to the mold compound that was causing a corrosion problem due to moisture ingress through formation of crevices. They proposed an improved leadframe surface finish. Kim [3] also reported poor adhesion between copper oxide and mold compound and studied adhesion properties at the copper oxide surface. More recently, Ohsuga et al [4] have reported the dependence of adhesion strength on copper alloys and degree of their oxidation. However, these papers do not provide information that can be related directly to oxidation induced by IC assembly processes such as wire bonding.

Copper by nature has a high affinity to oxygen and is readily oxidized when exposed to elevated temperatures. The degree of oxidation will in general be a function of temperature, environmental conditions, heating duration, surface impurities or contaminants and surface finish of the metal [1].

Die attach curing conditions in IC assembly are typically in the region of 150°C for 3 hours, depending on the type of material. The wire bonding temperatures can range from 180°C to 280°C for 20 to 200 seconds. These conditions render the metallic leadframe susceptible to oxidation. For IC assembly involving copper leadframes, oxidation due to die attach curing may be minimized by using an oven with an inert environment. However, the wire bonding process is usually performed in an open atmosphere due to difficulty in providing an inert environment. The copper leadframe oxidation induced during wire bonding may be severe, particularly at the die pad surface which is in direct contact with the wire bonding heater block. When the oxidized leadframes are encapsulated, the copper oxide layer separates the base metal from the mold compound. In the worst case, delamination may be observed at this region as early as after post mold cure process of packaging assembly. Figure 1 shows such a situation at the base metal/mold compound interface within an IC package. The purpose of this work is to understand oxidation in copper leadframes and more importantly to investigate its effect on package delamination. It focuses on oxidation as a result of wire bonding conditions.
Package delamination study

Fresh copper leadframes were processed with different wire bonding temperatures and exposure times during the assembly of the packages for the delamination study. The other assembly processes remained unchanged except PMC (post mold cure). The effect of PMC was investigated by the varying duration of the PMC process. Package delamination inspection was performed using C-mode Scanning Acoustic Microscopy (C-SAM). The degree of package delamination was characterized by measuring the area of delamination detected at the die-pad/mold compound interface.

Results and discussion

Isothermal oxidation of copper leadframes

Figure 4 shows the oxide thickness measured on the copper die-pad surface after various temperature and heating time combinations. The curves show an obvious trend of increasing oxide growth with temperature and time. Within the temperature range of our study, which is typical of wire bonding conditions, oxidation of the copper frame at higher temperatures (e.g., 280°C) shows a very rapid initial rate of oxidation. It then reduces as the duration of oxidation is increased, as shown in Figure 5. Oxide thickness growth up to 250 nm is possible within less than 200 seconds of exposure time. As the heating temperature is reduced to 240°C, the reaction rate is about 5 times less resulting in 35% reduction in oxide thickness. At 200°C or below, the oxidation rate is much lower and about constant throughout the entire 300 seconds of exposure time.
The reaction rate (nm/sec) at 200°C and 240°C within the first 50 seconds of oxidation indicates a change of reaction mechanism or a chemical composition transition in the oxidation process. To confirm this postulation, XPS (X-ray Photoelectron Spectroscopy) was used to analyse the surface oxide composition of various samples. Figure 6 shows the XPS core-level spectra for various copper samples oxidized at different temperatures. As can be clearly seen, the figure represents two predominant peaks with varying intensity. However, the result suggests that the lower BE (932.4) peak does not change with oxidation. This indicates that the peak, which corresponds to Cu2O, is predominantly present, on the basis of earlier reports. The peak appears at higher BE (934.7) grows in intensity as oxidation increased. The assignment of this peak is not straightforward. The FWHM of this peak suggests that it is a composite consisting of at least more than two peaks. The contributors for this peak intensity at higher BE can be from copper at higher oxidation states. Subsequently the atomic ratio between Cu+ and Cu++ has been determined by synthesizing the Cu2p3/2 peak based on earlier BE data on standard copper compounds and instrument sensitivity factors[5]. The values shown in figure 7 clearly indicate co-existence of cuprous and cupric oxide within the range of oxidation being studied and the transition of the predominant oxide from 200°C to 240°C wire bonding temperature.

\[ \text{Cu}^{2+} / \text{Cu}^{3+} \]

Figure 6: Core-level XPS Cu2p3/2 spectra of the oxidized copper samples

Figure 7: Calculated Cu2O/CuO ratio by atomic percentage

Adhesion strength of copper oxide to the mold compound

Figure 8 shows the adhesion test results performed after post mold cure of the test specimens. The Scanning Acoustic Microscope was used to perform delamination inspection before testing. All the data points with an adhesion strength of 100N or less were found to have delaminated interfaces and thus excluded from this chart. With the exception of the curve for the 200°C sample, the last point of each curve indicates conditions where the last well bonded lead was seen.

The results generally show that a copper leadframe exposed to higher temperature for longer periods have lower adhesion strength to the mold compound. The results generally agree with those of Yoshioka [2], Kim [3] and Ohsuga [4]. It is interesting to note that an optimum condition exists in which the adhesion strength is maximum for each heating temperature. This maximum strength is achieved only after a certain degree of oxidation occurs on the leadframes. In particular, the leadframes heated at 280°C show a rapid degradation of adhesion strength after the first 50 seconds of exposure. In contrast, the leadframes heated at lower temperature (e.g. 200°C) produce a higher adhesion strength than that of a fresh leadframe. For this temperature, the heating duration was about 400 seconds before the adhesion strength degraded below that for the fresh leadframe. This finding provides important information for optimization of adhesion strength between copper frame and mold compound. As high adhesion strength is desirable to achieve better resistance for interfacial delamination, it is advantageous to control the assembly process (e.g. wire bonding condition) such that optimum adhesion strength is obtained.
The loss of adhesion strength between copper oxide and the mold compound also correlates well with oxide thickness. Figure 9 clearly indicates such a relationship. Such a distinctive relationship is very useful for the prediction of critical oxide thickness in design and development of a new package. The prediction can be done by the package delamination modeling technique [6] developed here.

Figure 9: Correlation of lead pull strength with copper oxide thickness

Package delamination study

Having studied the oxide growth on copper leadframe and its adhesion strength to the mold compound, the effect of copper leadframe oxidation on package delamination was investigated using one type of encapsulated QFP package. The C-mode Scanning Acoustic Microscope (C-SAM) was used for this study. C-SAM utilizes a pulse echo technique in which a high frequency focused acoustic beam is incident on the interface of interest within an IC package. The reflected acoustic wave generated from the interface can be analyzed to determine the integrity of an interface within the IC package (i.e. delaminated or not). A typical image of a delaminated interface between die pad and mold compound produced by C-SAM is shown in Figure 10. The area of delamination on this interface was quantified to characterize the impact of copper oxide on package delamination in our study.

Figure 10: C-SAM image showing delaminated interface between die pad and mold compound

Figure 11 shows results from the C-SAM analysis of the die pad/mold compound delamination as a function of the wire bonding temperature. It is seen that higher wire bonding temperatures and longer heating times increase the delaminated area at this interface. This observation correlates well with both the oxide growth and adhesion strength results, that higher oxidation of copper leadframe induced during wire bonding can lead to package delamination because of poor adhesion strength between the oxidized copper leadframe and mold compound.

This type of package delamination can be of particular concern as it occurs as early as after post mold cure. It is different from the well known "popcorn" package delamination and cracking problem in that no moisture conditioning and solder reflow is required for the delamination to occur. It is important to reduce or prevent such delamination from occurring within the package since they often precede other package failure modes.

In the same study, it was found that cleaning the severely oxidized die pad using diluted sulfuric acid followed by a thorough di-ionized water rinsing prior to molding is effective in preventing delamination between the die pad and mold compound. This shows that a good bond interface between the copper leadframe and mold compound is possible when the oxide layer is removed. While it may not produce the best result, it appears that leadframe cleaning prior to molding can be done for delamination resistance improvement purpose.

Lowering the wire bonding temperature and heating time was proved to be another effective way to prevent delamination between the copper die pad and mold compound, as shown in Figure 11. However, it is to be noted that wire bond integrity needs to be considered when reducing wire bond temperatures. The results show that no delamination occurs when the wire bonding temperature used is 200°C or below for the particular package that we have investigated. This is understandable since higher adhesion strength can be achieved as shown in the adhesion test performed earlier. The oxide thickness corresponding to this wire bonding condition was found to be about 20 - 30nm as shown in Figure 12 below.
Failure mechanism of delamination

To understand the failure mechanism of delamination, a study of the cross-section structure underneath the oxidized surface was performed. Various oxidized samples were micro-sectioned using the FIB (Focused Ion Beam) ion milling facility followed by SEM (Scanning Electron Microscopy) study. The study seems to indicate micro internal voids growth along the oxide/metal interface as the degree of oxidation is increased. This finding adds new insights to the deteriorating adhesion strength as the oxide thickness is increased, contrary to those reported previously [1][2][3]. The SEM micrograph of the sectioned oxidized structure is shown in Figure 13.

Effect of post mold cure (PMC) on package delamination

Contrary to the common belief that PMC improves package integrity, the current study shows that post mold curing can have adverse effects on interfacial integrity especially when oxidized copper/mold compound system is involved. Figure 14 shows the occurrence of interfacial delamination between die pad/mold compound as a result of different degree of oxidation and duration of PMC. It is seen that shorter curing durations and lower wire bonding temperatures result in a smaller delamination area. At 200°C, no delamination was detected. It appears that prolonged post mold curing degrades the interfacial adhesion strength.
c) After 3 hrs PMC: Larger oxide seen on mold compound

d) After 13 hrs PMC: Entire surface covered with oxide

Figure 15: Optical pictures showing decapped mold compound surface after separation from the die pad.

Figure 16: Effect of PMC on adhesion strength

Package reliability

For package reliability studies, samples with different wire bonding temperatures and PMC durations were subjected to moisture preconditioning (85%/85RH for 168 hrs) followed by three times IR reflow to simulate surface mount conditions. Internal delamination was studied using CSAM followed by microsectioning for confirmation. The results are shown in Figure 17 and 18 below. Depending on the severity of oxidation and the duration of PMC, the susceptibility of the package delamination during solder reflow was found to shift from die pad/compound interface to die attach region. Figure 19 showing pictures of such delaminations in the package. The observation suggests that when the adhesion strength between die pad/compound increases, the integrity of the other interfaces within the package become critical. This appears to support the anticipation of many previous works that package failure always tend to occur at the weakest interface. The result also provides further support on the postulation of oxide degradation during the PMC process.

Figure 17: Effect of wire bonding condition on package delamination after moisture precon & IR reflow

Figure 18: Effect of PMC duration on package delamination after moisture precon & IR reflow

Figure 19.a: Picture showing delamination at the die pad/compound interface
Conclusion

The following conclusions can be made from our study.

A) SIMS depth profiling was found to be useful for copper oxide thickness characterization.

B) Reducing the assembly process temperatures reduces the oxidation rate considerably and results in a thinner oxide layer. At 200°C or below, oxidation is minimum.

C) The adhesion strength between the copper leadframe and mold compound was found to be dependent on the degree of leadframe oxidation. In the worst case, delamination occurs between the die pad and mold compound.

D) An optimum thermal condition exists at which the adhesion strength is maximum. The copper oxide thickness that corresponds to this point was estimated to be about 20 - 30nm. Packages processed under this condition was found to be free from delamination between die pad and mold compound.

E) The failure mechanism of delamination seems to be related to the weakening effect caused by internal void growth along oxide/metal interface. Further work is required to confirm this.

F) Increasing the duration of post mold curing was found to degrade adhesion at the oxidized copper/compound interface; delamination occurs at the die pad interface when good adhesion exists at the die pad/mold compound interface.

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