

**Study Of Copper Applications And Effects Of Copper Oxidation
In Microelectronic Package**

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May 10, 2003

In Partial Fulfillment of MatE 234

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Abstract

Study Of Copper Applications And Effects Of Copper Oxidation

In Microelectronic Package

By Ying Zheng

Low cost, high thermal and electric conductivity, easy fabricating and joining, and wide range of attainable mechanical properties have made copper as one of main materials for lead frames, interconnection wires, foils for flexible circuits, heat sinks, and traces in PWB in electronic packaging. However, unlike aluminum oxide, the copper oxide layer is not self-protect so the copper is readily oxidized. Copper oxidation is considered as a serious reliability problem in microelectronic package. It produces cracks at Cu-Al interface on the copper interconnection wire, causes delamination between the copper lead frames die pad and molding compound, and induces poor adhesion between the copper lead frames and molding compound.

1. Introduction

Copper and copper alloys are widely used in microelectronic packaging [1]. The applications include in the following areas:

- Lead frames

Copper lead frame serves primarily to support the chip mechanically during the assembly of plastic package and to connect the chip electrically with the outside world. Copper alloy would be an ideal lead frame material from an electric and thermal conductivity standpoint.

- Interconnection wires

High thermal conductivity, low electric resistance, high pulling strength, low cost, and better connection of the wire to aluminum pad make the copper wires as one of main materials to replace the gold wires.

- Foils for flexible circuits

Copper foil is the most common used conductor for flexible circuits and flexible interconnections.

- Heat sinks

Heat sink is commonly used to transport heat dissipated by devices to a heat exchanger or to spread it over a large surface area to facilitate cooling by radiation or convection. At present, the most widely used heat sinks are laminated metal sandwiches consisting of two layers of copper bonded to a central constraining layer of invar or molybdenum.

- Traces in PWB

Copper is used as conducting materials in PWB

Among the choice of metals, Ag, Al, Au, Cu, and W, used in packaging, copper offers low electric resistivity, only Ag has a resistivity about 5% lower than that of copper [2]. Also, Copper has high thermal conductivity. Furthermore, Copper has wide range of attainable mechanical properties, easy of deposition, fabricating, and joining. Lastly, there are an abundance of supplies of copper [2].

However, unlike the aluminum oxide, the copper oxide layer is not self-protect, so the copper is readily oxidized even at low temperature. Therefore, study the copper oxidation is becoming very important in microelectronic packaging.

There are two different mechanisms of copper oxidation. In aqueous environments at ambient temperature, a thin layer of Cu_2O forms first on the copper surface by the oxidation and reduction partial reaction. Cu_2O is a p-type semiconductor with negatively charged vacancies [3]. The growth of the Cu_2O takes place on the top of surface through the mass transport of the Cu^+ ions and electrons in a direction normal to the surface via vacancies [3,4]. The second stage of oxidation, the formation of the CuO from Cu_2O is usually a slower process. It is governed by the in-diffusion of oxygen into the oxide.

Copper oxidation is considered as a serious reliability problem in microelectronic package. The primary effects of copper oxidation in copper interconnection wires and copper lead frames are:

- Copper oxidation at the interface of Cu-Al bonding area causes the cracks, decreases the interfacial shear strength, and weakens the Cu-Al bonding [5].
- Copper oxidation in the area of the copper lead frames die pad and molding compound causes the delamination of packages [6].

- Copper oxidation induces poor adhesion in the area of copper lead frame and molding compound so that the moisture is able to penetrate through the crevices creating corrosion problem in packages [7].

The purposes of this paper are to study copper applications and effects of copper oxidation in microelectronic packages.

2. Copper Applications In Microelectronic Package

2.1 Lead Frames [1]

Worldwide, copper alloys have become predominant lead frame materials in plastic packages. The copper alloy lead frame serves primarily to support the chip mechanically during the assembly of plastic packages and to connect the chip electrically with the outside world. Typically, lead frame strips are made first, and then the copper alloy lead frames are manufactured by stamping and etching on the lead frame strips. The process of etching lead frames involves coating with photoresist film, exposing through the lead frame pattern using an ultraviolet light, developing the finished pattern. The lead frame stamping is performed using tungsten carbide punches and die at the press until the final configuration of the part is achieved.

Copper alloy would be an ideal lead frame material from an electrical and thermal conductivity standpoint. The normal compositions of copper alloy lead frame are tabulated in Table 1.

Table 1 copper lead frame materials and properties [1]

Copper alloy	Designation	Nominal composition, net %
Cu-Fe	C19400	2.35Fe-0.03P-0.12Zn
	C19500	1.5Fe-0.8Co-0.05P-0.6Sn
	C19700	0.6Fe-0.2P-0.04Mg
	C19210	0.10Fe-0.034P
Cu-Cr	CCZ	0.55Cr-0.25Zr
	EFTEC	0.3Cr-0.25Sn-0.2Zn
Cu-Ni-Si	C7025	3.0Ni-0.65Si-0.15Mg
	KLF-125	3.2Ni-0.7Si-1.25Sn-0.3Zn
	C19010	1.0Ni-0.2Si-0.03P
Cu-Sn	C50715	2Sn-0.1Fe-0.03P
	C50710	2Sn-0.2Ni-0.05P
Other	C15100	0.1Zr
	C15500	0.11Mg-0.06P

The most widely used copper alloys have high electrical and thermal conductivity, high CTE, lower strength than that of nickel-iron, low cost, and low chemical stability.

- Electrical conductivity

Copper is the best choice of all high conductive metals, namely Ag, Al, Au, Cu, and W. Copper offers higher electric conductivity, only Ag has conductivity about 5% higher than that of copper [2].

- Thermal conductivity

One of main advantages of copper alloys is their high thermal conductivity ranged from 380 W/m K (C15100) to 120 W/m K (C50710).

- High coefficient of thermal expansion

Most notable is that copper has a considerably higher CTE. Silicon/gold eutectic bonding cannot be used with the copper frames because its high elastic modulus couples thermally induced bending stress to the silicon. Silver-filled epoxies and polyimide chip-attach adhesive have been developed and are flexible enough to absorb the strain developed between chip and copper.

- Strength

The tensile strength of copper alloys is lower than that of nickel-iron. The addition of iron, zirconium, zinc, tin, and phosphorus serves to improve the heat-treating and work hardening properties of these alloys.

- Chemical stability

The oxidation of copper is one of the severe problems in copper lead frame technique. It causes lead frame delamination between the lead frames die pads and molding compound [6]. Also, Copper oxidation induces poor adhesion in the area of the lead frames and molding compound so that the moisture could penetrate through the crevices creating corrosion problem in the packages [7].

2.2 Interconnection Wires

In microelectronic packaging, wire bonding is the most widely used method to connect the chip to the outside world. Gold wires are the most successful interconnection materials used in wire bonding technique. However, the reliability problem of gold wire bond is associated with the alloying reactions that occur at the gold wire-aluminum bonding pad interface. Intermetallics, particular AuAl_2 (purple plague) and Au_5Al_2 (white plague), are brittle and, under condition or vibration or flexing, may break because of metal fatigue or stress cracking, resulting in bond failure. At elevated temperatures, Al rapidly diffuses into the AuAl_2 phase, leaving behind of voids at the aluminum- AuAl_2 interface [1]. The high cost and the reliability degradation of gold wire associated with bond interface voids formation demand alternative interconnection materials. The advantages of copper have rapidly established itself as one of the main materials for the wire bonding in microelectronic packaging.

The use of copper wire as an alternative interconnection material has following advantages.

- Cost

As the copper wire is inherently 3 to 10 times lower in cost compared to gold. An average yearly consumption on the order of several thousand kilometers copper wire could anticipate an annual cost savings of well over \$1,000,000 (US) [9].

- Mechanical properties

By nature, tempered and annealed copper wire, at both room and elevated temperatures, exhibits tensile strength and elongation characteristics that are comparable to, if not super to, those of gold wire. The ball shear and wire pull test conducted by S. L. Khoury et al. show that copper wire bond strength is greater than gold wire bond strength [8]. The copper ball bond shears at an average of 85-110 grams force, whereas the gold ball bond shears at an average of 60-80 grams force. Also, the copper wire pull strength averages 11-13 grams force, while gold wire pull strength averages 8-10 grams force. As a result, the copper wire displays excellent ball neck strength after the ball formation process and a high degree of loop stability during molding or encapsulation [9]. Furthermore, the strong pulling strength of copper allows for reducing wire diameter, which leads to reduce pads size and pads pitch [10].

- Electrical properties

To investigate the effect of copper versus gold on the electrical parameters, S. L. Khoury et al. conducted 100% AC/DC tests on copper and gold wires [9]. The results show that copper and gold exhibit identical performance within the accuracy of the

measurement systems. Additionally, the copper wire has a conductivity of $0.62 (\mu\Omega/\text{cm})^{-1}$, and the gold wire has conductivity $0.42 (\mu\Omega/\text{cm})^{-1}$. The copper wire has approximately 33% more conductivity than the gold wire [9].

- Thermal properties

The thermal performances of the copper and gold wires are evaluated with 4 different test vehicles assembled using thermal die by S. L. Khoury et al. [9]. For 50% heat, the copper wire will dissipate slightly more heat than gold wire [9].

- Compatibility with metallization and bond reliability

The copper wire has been successfully bonded to silver/nickel plated leads, aluminum and Al/Cu/Si metallization, and even bare copper [9]. A very important factor, not only in the formation of a bond, but also in the reliability of a bond, is the rate of intermetallic growth between wire and metallization. The comparison study regarding the interface between the Cu-Al and Au-Al conducted by L. Ainouz shows that the rate of intermetallic growth of Cu-Al interface is between 2 to 2.5 times slower than that of an Au-Al interface at comparable temperature. The Cu-Al interface provides lower electrical resistance, lower heat generation, and longer package life compared to the Au-Al interface.

The disadvantages of copper wire bonding are: first, the technology of copper wire bonding is not well convinced in the industry because additional bonding parameters such as the forming gas need to be defined and optimized. Second, the copper oxidation causes the corrosion cracks, decreases the interfacial shear strength, and weakens the Cu-Al bonding. Third, due to higher melting point of copper, the copper wires needs higher energy than the gold wires when they are bonded to pads.

2.3 Foils For Flexible Circuits [1]

Copper foils are the most commonly used conductor for flexible circuits and flexible interconnections in the flexible printed boards. The copper foils are available as either electrolytically deposited (ED) copper or rolled annealed (RA) copper. Electrolytically deposited copper has a columnar grain structure, forming by plating the copper from a solution so that the grain grows perpendicular to the plane of the foil. Rolled copper is formed by a mechanical process, taking ingots of pure copper, applying heat and rolling pressure to reduce the thickness, and forming a thin continuous web. This gives the foil a plate like grain structure that is parallel with the foil plane.

The main differences between ED and RA copper foils are their mechanical properties. Rolled-and-annealed copper foil has lower tensile strength and greater elongation properties, is softer, and has greater ductility. Electrode-deposited foils have high tensile strength, lower elongation, and tend to be stiffer and less ductile than RA copper.

The surface of both copper foils is usually treated by chemical to increase adhesion, to reduce resistance under cutting by etchants, and to reduce bond degradation by plating chemicals. A thin layer of zinc can be applied to the surface of the copper foil to increase bond strength and reduce corrosion.

2.4 Heat Sinks [1]

To ensure reliability operation of electronic components, junction temperature must be kept within specified limits, because failure rate increases dramatically with increasing temperature. Heat sink is commonly used to transport heat dissipated by devices to a heat

exchanger or to spread it over a large surface area to facilitate cooling by radiation or convection.

At present, the most widely used heat sinks are laminated metal sandwiches consisting of two layers of copper bonded to a central constraining layer of Invar or molybdenum, referred to as copper-clad Invar (CCI) and copper-clad molybdenum (CCM). The key requirements for heat sinks are that they have high thermal conductivity and low CTEs to match those of other components in the assembly. Table 2 presents the effective mechanical and thermal properties of CCI and CCM. The CTEs of CCI and CCM can be controlled by adjusting the relative thickness of the copper and constraining layers.

Table 2 Copper heat sinks and properties [1]

Materials	Density (g/cm ³)	Coefficient of thermal expansion (10 ⁻⁶ /k)	Thermal conductivity (W/m.k)	Elastic modulus (Gpa)
Copper-clad Invar	8.4	5.5	164	131
Copper-clad molybdenum	9.9	6.0	182	230

The limitations of CCI and CCM are they have high effective densities, and their thermal conductivity is in the range of aluminum alloys, which, although relatively good, may not be high enough for some applications.

2.5 PWB Traces [1]

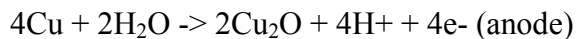
Copper is used as conducting materials in PWB. The copper traces are derived from copper cladding that is integral to the purchased substrate materials and/or from the electrolytic and electroless copper plating. The copper conductors in PWB can be made

by copper foil on an insulating substrate is selectively removed except where the circuitry is desired, or copper is selectively added to provide the interconnection circuitry.

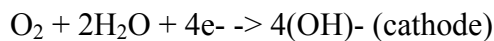
3. Copper Oxidation And Effects In Microelectronic Package

The advantages of Copper have rapidly established itself as one of the main materials for the lead frames and interconnection wires in microelectronic packaging. However, the applications of copper have been limited by oxidation of the copper. The copper oxidation causes the cracks and weakens the Cu-Al bonding, creates delamination between the copper lead frame die pad and molding compound, and allows moisture permeation through the crevices of the interface between the lead frames and molding compound.

There are two different mechanisms of copper oxidation. In aqueous environments at ambient temperature, a thin layer of Cu_2O forms first on the copper surface by the oxidation and reduction partial reactions [3]:



And



A Cu_2O is a p-type semiconductor with negatively charged vacancies. The growth of the Cu_2O takes place on the top of surface through the mass transport of the Cu^+ ions and electrons in a direction normal to the surface via vacancies. However, Cu_2O is hardly detected in experiments because Cu_2O is not stable in air, which will immediately change to CuO .

The second stage of oxidation, the formation of the CuO from Cu_2O is usually a slower process. It is governed by the in-diffusion of oxygen into the oxide.

3.1 Copper Oxidation On Interconnection Wires Causes The Cracks And Weakens The Cu-Al Bonding [4]

Copper wire bonding is normally formed by a copper ball onto an aluminum based bond pad in microelectronic package. However, copper oxidation at the interface of Cu-Al bonding area causes the cracks, decreases the interfacial shear strength, and weakens the Cu-Al bonding.

Surface analysis of ball-peeled pad of Cu-Al bonding using XPS demonstrates the copper oxidation in the Cu-Al interface after autoclave test (at 121°C and 100% relative humidity). The binding energy scans for Cu 2p on the specimen after 0, 192, 384, and 576 hours in autoclave test chamber is carried out. Figure 1 shows a great amount of Cu, trace Cu (OH)₂ and CuO at 0 hour corrosion. Figure 2 shows decreasing Cu and increasing CuO after 384 hours corrosion. In Figure 3, there is no more Cu detected, but CuO only after 576 hours corrosion. At 0 hours, the copper oxide peaks are very low as compared to 384 and 576 hours. After 576 hours corrosion, the chemical change of copper in a few atomic layers of surface from Cu to CuO. Furthermore, there are two major copper oxides peaks observed in the study, CuO and Cu(OH)₂. Cu₂O is not stable in air and change to CuO immediately. Therefore, Cu₂O is not expected to be detected at the specimen by XPS.

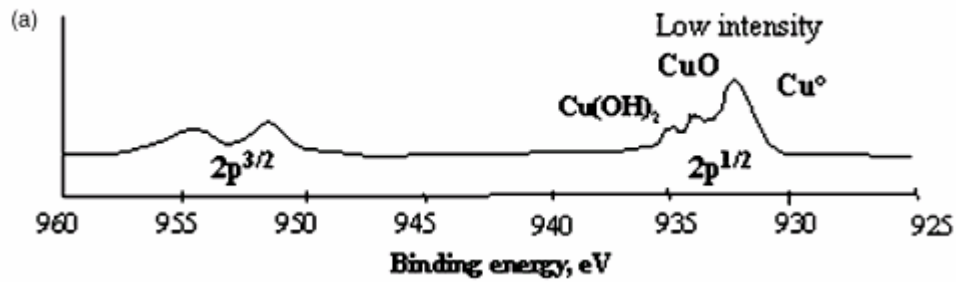


Figure 1 ESCA scan spectra after 0 hour corrosion. [4]

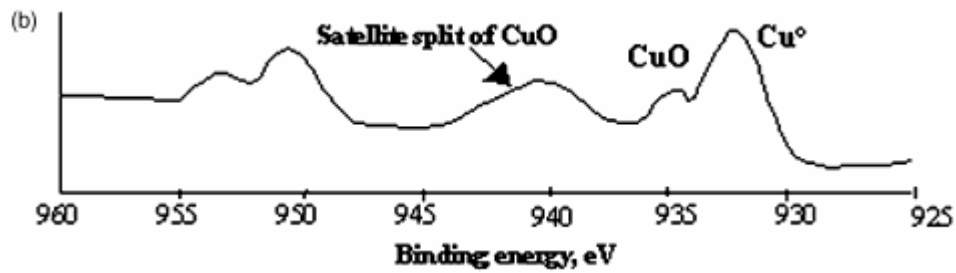


Figure 2 ESCA scan spectra after 384 hours corrosion. [4]

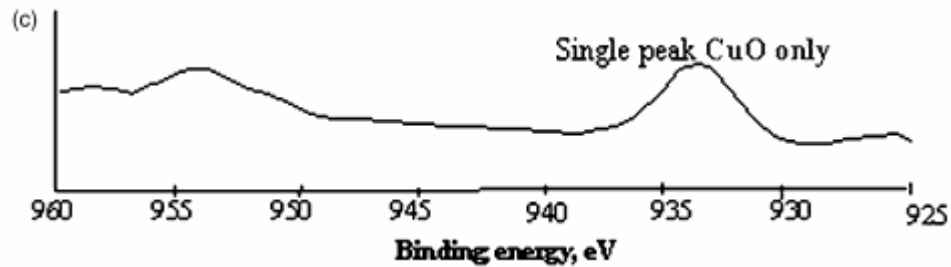


Figure 3 ESCA scan spectra after 576 hours corrosion. [4]

Figure 4 shows the corrosion rate of copper specimen as the function of autoclave test time. Initially, Cu has higher percentage than CuO, which is 59% and 41%. However, the CuO concentration increases gradually after 384 hours under autoclave test. At 576 hours, the Cu turns into CuO completely, while no Cu is detected.

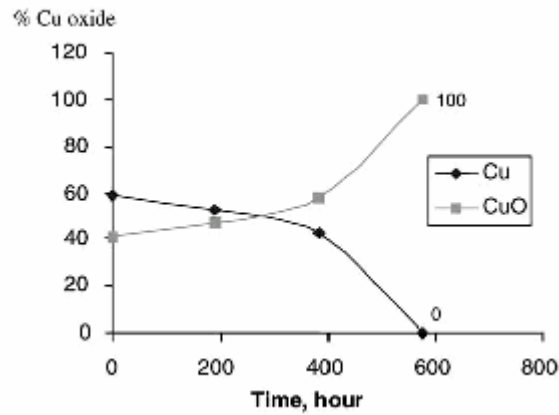


Figure 4 Copper oxide concentration and rate of corrosion as a function of exposure time. [4]

SEM is used to seek the Cu-Al bonding surrounding area or at bonding interface periphery of specimens. Figure 5 shows the copper ball after 0, 188, 384, and 576 hours autoclave test (at 121°C and 100% relative humidity). The Cu-Al interfaces at 0 hours are visually clean. However, autoclave test provides a corrosion environment so that the copper oxidation starts from wire, upper bonded area, and then the bonding interface. A crack at Cu-Al interface is observed after 384 hours in autoclave test, this crack propagates and detaches Cu-Al bonding after 576 hours.

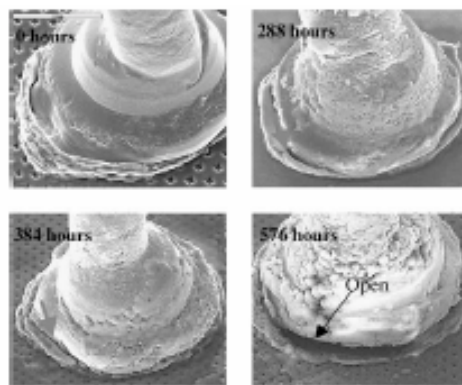


Figure 5. SEM pictures show corrosion and a crack after test hour increase (X1000) [4]

Interfacial shear force of copper wire bonding after autoclave test (at 121°C and 100% relative humidity) is showed in Figure 6. Initially, the interfacial shear force increases from 130 gf to 157 gf after 192 hours. However, the interfacial shear force starts to decrease after 288 hours and reaches to 97 gf after 576 hours. The result shows that the Cu-Al bonding becomes weak due to the copper oxidation, and the attack is more severe after 384 hours in autoclave test.

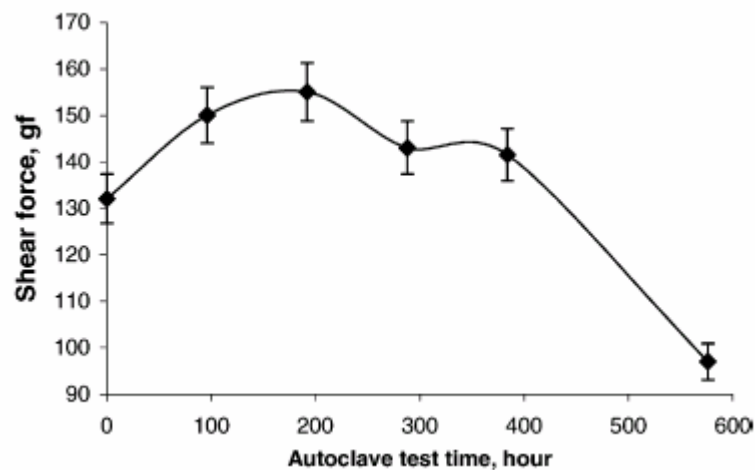


Figure 6. The shear force of copper wire bonding that undergone autoclave test [4]

Therefore, copper oxidation appears in the interface of copper ball and aluminum based bond pad in microelectronic package. The Cu-Al bonding is weakened by copper oxidation that creates the cracks and reduces the interfacial shear force.

3.2 Copper Oxidation On Lead Frames Die Pad Causes Package Delamination [6,11]

The copper oxidation causes the delamination in the area of the lead frames die pad and molding compound in plastic package at elevated temperature used in assembly such as die attach curing and wire bonding, as shown in Figure 7.

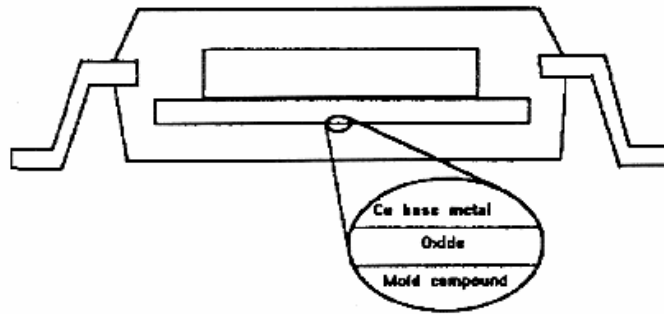


Figure 7 Copper oxide layer between base metal and molding compound [6]

Die attach curing is typically performed in the region of the temperature 150°C for about 3 hours, depending on materials. The wire bonding temperature is ranged from 180°C to 280°C, and the wire bonding duration time is about 20 to 200 seconds. These conditions cause the copper lead frames to oxidize. The copper oxidation due to die attach curing may be minimized by using an oven with an inert environment. However, the wire bonding process is usually finished in an open atmosphere, so that the copper lead frame oxidation induced by wire bonding is severe, particularly at the die pad surface that is in direct contact with the wire bonding heater block. As a result, the copper oxidation separates the lead frame from the molding compound.

Figure 8 shows the oxidation thickness of the copper lead frames measured under the temperature 120-280°C, at humidity 70%, and in the time range 0-300 seconds. The curves indicate an obvious trend of increasing the oxidation of the copper lead frames with temperature and time. At the high temperature 280°C, the oxidation of the copper lead frames has very rapid initial rate, and as time increases, the thickness of the oxidation increases.

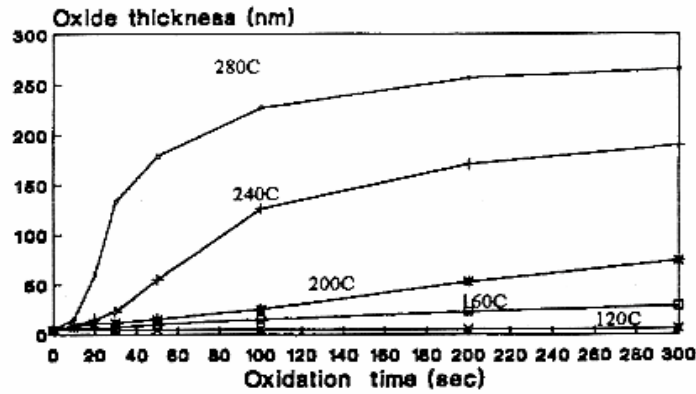


Figure 8 Oxidation thicknesses measured in isothermal oxidation of copper frames [6]

Figure 9 is the XPS spectra for the copper lead frame samples oxidized at different temperature. The results suggest that copper oxidation CuO start to occur at temperature 200°C.

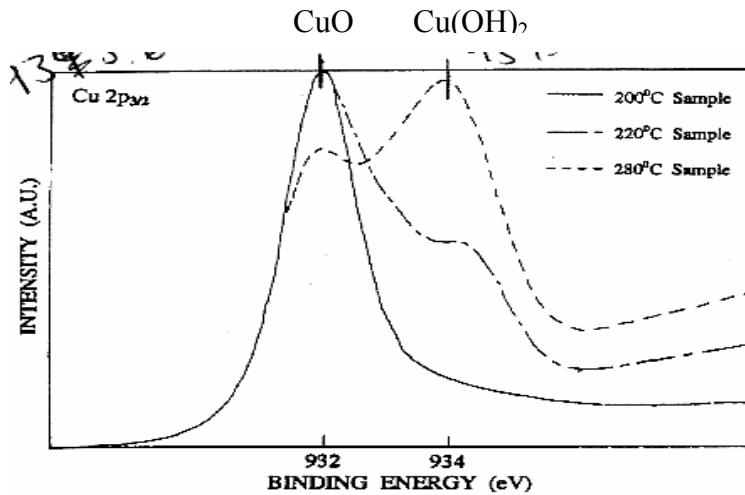


Figure 9 XPS core level peaks of Cu_{2p3/2} of the oxidized copper samples [6]

The adhesion strength of the lead frames die pad and mold compound is studied by lead pull strength test. The results, as shown in figure 10, indicate that the copper lead frames exposed to higher temperature for longer period time have lower adhesion strength to the molding compound. In particular, the maximum strength is achieved for each temperature before it is decrease. This maximum strength is reached after a certain

degree of oxidation occurs on the copper lead frames. However, at temperature 280°C, a degradation of adhesion strength is rapid after first 50 seconds of exposure. In contrast, the copper lead frame heated at lower temperature 200°C produces higher adhesion strength than that of a fresh lead frame. For this temperature, the heating duration is about 400 seconds before the adhesion strength degrades below that for the fresh lead frame.

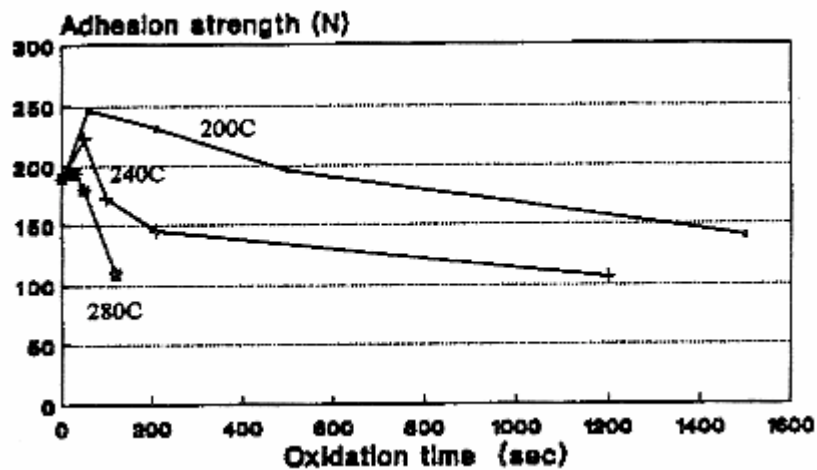


Figure 10. Lead pull strength on oxidized copper lead frames [6]

The effect of the copper lead frame oxidation on package delamination is also investigated by Scanning Acoustic Microscope (SAM). A typical image of the delamination by SAM is shown in Figure 11. The area of the delamination on this interface is qualified as function of temperature to characterize the impact of copper oxidation on package delamination, as shown in Figure 12. The result shows the higher the temperature, the severer the copper oxidation, and the larger percentage of delamination.

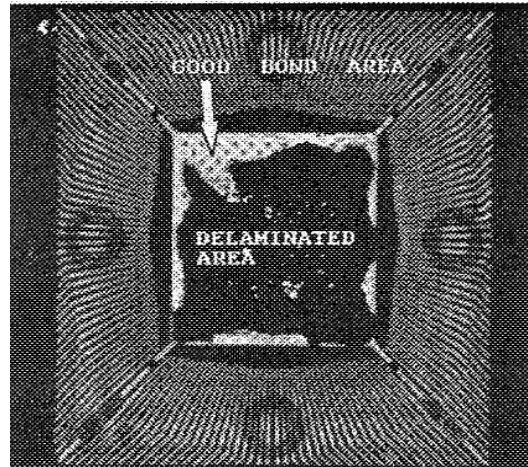


Figure 11 SAM image of delaminated interface between die pad and mold compound [6]

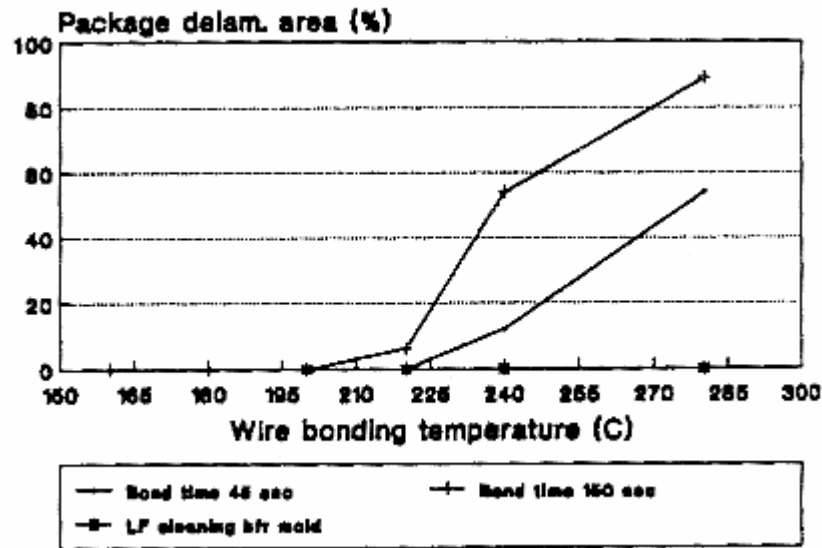


Figure 12. Package delamination vs. wire bonding temperature [6]

Therefore, copper oxidation happens in the interface between the copper lead frames and molding compound. Due to the copper oxidation, adhesion strength between the lead frame die pads and molding compound decreases, and the package delamination appears. Furthermore, the copper oxidation, adhesion strength, and package delamination become worse as the temperature and process time increase.

3.3 Copper Oxidation On Lead Frames Allows Moisture Permeation Through The Crevices Of The Interface Between Lead Frames And Mold Compound [7]

The copper oxidation causes poor adhesion in the area of the lead frames and molding compound so that moisture ingress through formation of crevices creating corrosion problem in microelectronic packaging, as shown in Figure 13, and this corrosion is accelerated by ionic impurities.

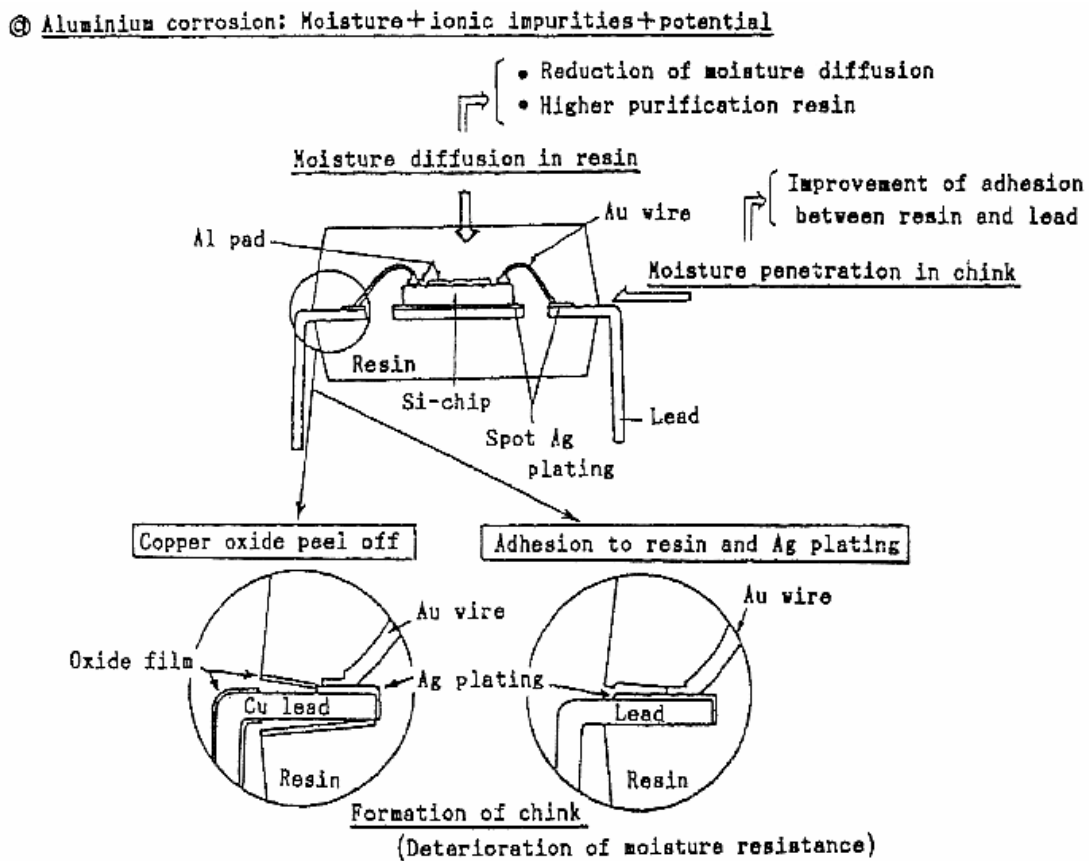


Figure 13. Problem of plastic encapsulated package [7]

Copper, copper alloys, and 42-alloy are subjected to oxidation at 400°C. The growth rates of oxidation films are shown in figure 14. It is obvious that the growth rate of copper oxide film is very rapid compared with 42-alloy. In particular, the lower the content of alloying elements is, the quicker the copper oxide growth is.

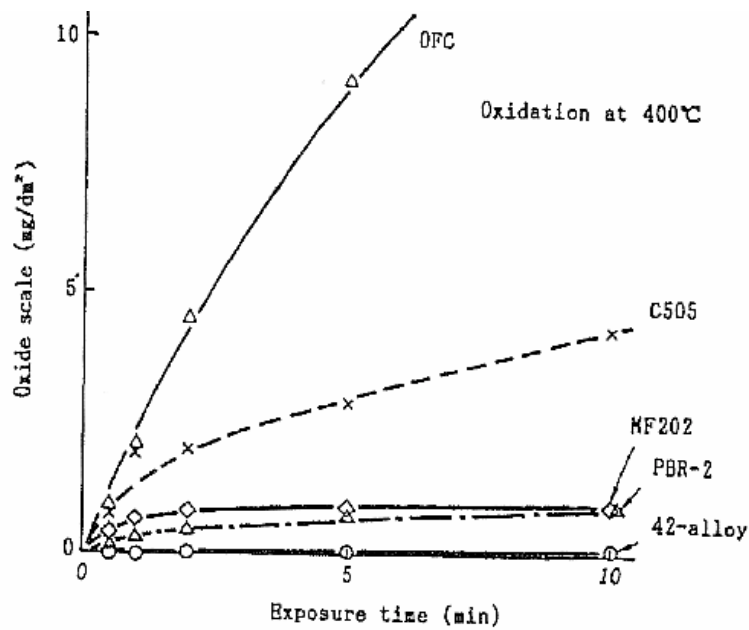


Figure 14. Lead frame materials oxidation rate [7]

The adhesion properties of copper, copper alloys, and 42-alloy lead frame after oxidation at 400°C are studied by tape peel test, as shown in Figure 15. The results are tabulated in Table 3. The copper and copper alloys show the poor adhesion, while, the 42-alloy does not peel off at all.



Figure 15. Tape peel test [7]

Table 3 Adhesion properties of oxidation film [7]

Alloy	Chemical composition	Adhesion of oxide film	
		400°C x 1min	400°C x 2min
OFC	Cu: >99.9%	Δ	Δ
C505	1.25 Sn, other: Cu	X	X
MF202(C50710)	2.0 Sn, 0.2 Ni, other:Cu	X	X
PBR-2	6.0 Sn, 0.2 P, other Cu	O	X
42-Alloy	42 Ni, other Fe	O	O

(Δ-partially peel out X-totally peeled out O-not peel out)

Moisture penetration on the copper, copper alloys, and 42-alloy lead frame after pressure cook test (121°C, 2 atm, 100% RH) are detected by Fluorescent Penetrated Inspection (PFI). The result is expressed in the ratio of fluorescent fluid penetration to the length of each lead, as shown in Figure 16. Copper and copper alloy having lower adhesion to molding compound due to copper oxidation show the higher degree of moisture penetration as compared with 42-alloy.

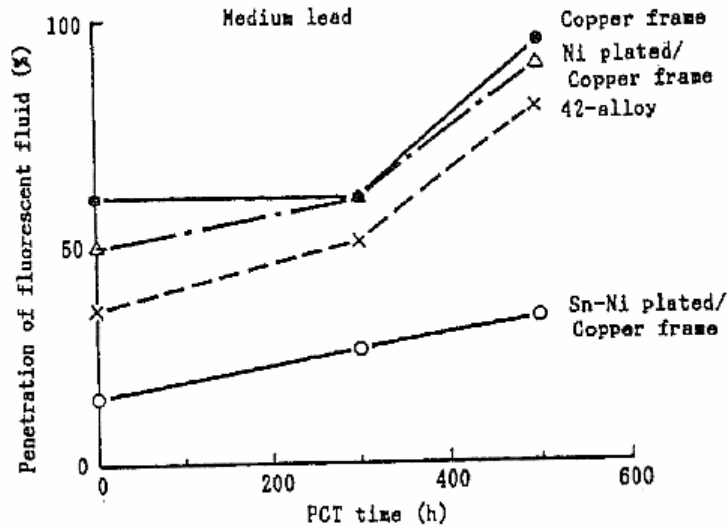


Figure 16. Penetration degree of moisture after PCT aging [7]

Therefore, the copper oxidation on the surface of copper lead frame causes poor adhesion between the copper lead frames and molding compound, resulting in moisture penetration in the packages and causing corrosion problems in packages.

4. Summary

Low cost, high thermal and electric conductivity, easy fabricating and joining, and wide range of attainable mechanical properties have made copper widely used in electronic packaging, such as lead frames, interconnection wires, foils for flexible circuits, heat sinks, and WPB traces. However, unlike the aluminum oxide, the copper oxide layer is not self-protect. Therefore, copper is readily oxidized, especially at elevated temperature. Copper oxidation is considered as a serious reliability problem in microelectronic package. The copper oxidation at the interface of Cu-Al bonding area causes the cracks, decreases the interfacial shear strength, and weakens the Cu-Al bonding. Also, Copper oxidation in the area of the lead frames die pad and mold compound causes the delamination of packages. Furthermore, the moisture penetrates through the crevices because copper oxidation induces poor adhesion in the area of the copper lead frames and molding compound, creating corrosion problem in the packages.

Reference

1. "Electronic Materials Handbook," Vol. 1, (ASM international, 1989), pp 1-1140.
2. W.A. Lanford, P.J. Ding, W. Wang, S. Hymes, S.P. Murarka, "*Alloying of copper for use in microelectronic metallization*," Materials Chemistry and Physics, Vol 41, pp 192-198 (1995).
3. "ASM handbook, Corrosion," 9th ed. Vol. 13, (ASM international, 1987), pp 610-640.
4. Z.E Horvath, G. Peto, Z.Paszti, E. Zsoldos, E. Szilagyi, and G. Battistig, "*Enhancement of oxidation resistance in Cu and Cu(Al) thin layer*," Nuclear Instruments and Methods in Physics Research B 148, (1999).
5. C.W. Tan, A.R. Daud, and M.A. Yarmo, "*Corrosion Study at Cu-Al Interface in Microelectronics Packaging*," Applied Surface Science 191, (2002).
6. G.L. Ang, L.C. Goh, K.W. Heng, and S.K. Lahiri, "*Oxidation Of Copper Lead Frame*," International Symposium on the Physical & Failure Analysis of Integrated Circuits, 1995.
7. O. Yoshioka, O. Okabe, R. Yamagishi, S. Nagayama, G. Murakami, "*Improvement of moisture in plastic encapsulants MOS-IC by surface finishing copper lead fame*," Proceedings-Electron Components Conference, pp 464-471, (1989)
8. S.L. Khoury, D.J. Burkhard, D.P. Galloway, and T.A. Scharr, "*A Comparison Of Copper And Gold Wire Bonding On Integrated Circuit Devices*," 40th Electronic Components & Technology Conference, (May 1990)
9. L. Ainouz, "The use of copper wire as an alternative interconnection material in advanced semiconductor packaging,"
10. K. Toyozawa, K. Fujita, s. Minamida, and T. Maeda, "*Development of Copper Wire bonding Application Technology*," Electronic Components & Technology Conference, (May 1990)
11. S.K. Lahiri, N.K.W. Singh, K.W. Heng, L. Ang, and L.C. Goh, "*Kinetics of oxidation of copper alloy lead frames*," Microelectronics Journal 29, (1998)