Cratering on Thermosonic Copper Wire Ball Bonding

Tan Chee Wei and Abdul Razak Daud

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Copper wire bonding offers several mechanical and electrical advantages as well as cost saving compared to its gold wire predecessor. Despite these benefits, silicon cratering, which completes the fracture and removal of bond pad underlayers, has been a major hurdle to overcome in copper wire bonding. Copper wire is harder than gold, and thus needs greater ultrasonic power and bond force to bond it onto metal pads such as aluminum. This paper reports a study on the influence of wire materials, bond pad hardness, and bonding-machine parameters (i.e., ultrasonic power and bond force) on silicon cratering phenomenon. Ultrasonic power and *z*-axis bond force were identified as the most critical bonding machine parameters in silicon cratering defects. A combination of greater bond force and lower ultrasonic power avoids silicon cratering and gives the desired effects. Results also show that a harder bond pad provides relatively good protection from silicon cratering.

Keywords bond force, copper wire bonding, silicon cratering, ultrasonic power

1. Introduction

Copper has been rapidly established as one of the main wire bonding materials in microelectronics packaging. This is due to its low cost and high electrical conductivity compared to gold or aluminum. Despite these advantages, complete fracture and removal of the bond pad underlayers during bonding (silicon cratering) is the major problem in copper wire bonding technology.[1-6]

Cratering is one of the bonding failures attributed to overbonding and appears as damage to the layers under the bond pad.[7] In severe cases, a hole is left in the substrate and a divot is attached to the wire. However, far more frequently cratering produces no visible damage but can degrade the device characteristics.[2,7,8] Cratering usually occurs in only a small percentage of the bonds, even though the bonds are created at the same time with the same bonding parameters.

Silicon cratering refers to complete fracture and removal of the bond pad underlayers during bonding. It is induced by overbonding or improper bonding parameters,[1,3,4,8-10] such as ultrasonic power, bond force, search speed, bonding time, and temperature, etc. The other possible causes are improper capillary profile[7,10] and bond pad hardness.[4,6] Large stresses could be imparted on the pad underlayers and the silicon (thus leading to open circuit failures) if cratering is not properly controlled. Sometimes, improper bonding parameters can transmit the load directly to the layer under the pad, called dielectric cracking, leading to hairline cracks with subsequent leakage failures.

Figure 1 shows the schematic diagram of a Cu wire bonding system. The aluminum metallization on the top contains 1% Si to prevent back-diffusion of silicon from shallow junctions into metal, which might damage the electrical properties of the device. Silicon nodules in aluminum bond pads can increase stress, which will crack the underlying silicon during thermosonic gold ball bonding.[5,8,11] Polysilicon contains more stacking faults, dislocations, and other defects than single crystals, and one can assume that the ultrasonic energy will interact with these and weaken the structure, similar to the manner in which it softens the metals.[10]

Clatterbaugh and Charles[9] found that the smaller the weld region, the more likely the underlying silicon will be cratered. They also mentioned that the taller the ball bond, the more likely the underlying silicon will crater.

The hardness of triangular, HT, of the test piece was obtained from the test load, at which the triangular indenter made the triangular indentation on the test piece surface and the surface area was determined by the height of the indentation, according to the following formula.[12]

$$\text{HT} = 160.07 \times \text{Test load}/(\text{height of indentation})^2$$

This article reports on the effects of wire materials, bond pad hardness, and bonding parameters on silicon cratering for cop-

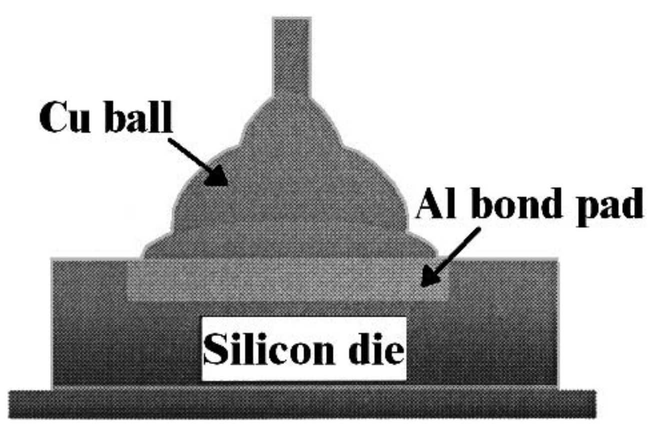

Fig. 1 Schematic diagram of Cu wire bonding system

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per wire. To investigate the effects of wire materials on silicon cratering, established gold wire was used as comparison.

2. Experimental Procedure

2.1 Effects of Wire Materials

Gold and copper wires were bonded onto the same device by setting ultrasonic power and bond force slightly higher than the upper control limit. Bonded wires were examined to select sticking bonded balls with diameter between 150 to 225 μm. Eighty pieces of both Au and Cu bonded wire were subjected to the bond etch test (i.e., immersed in hydrochloric acid, at about 65 °C for 20 min) and the amount of cratering was then recorded.

2.2 Effects of Bond Pad Hardness

The main purpose of this experiment was to investigate the capability of bond pad hardness to act as a barrier against excessive bonding parameters and to prevent cratering. Five different top metal recipes of Al-based bond pad of 4 μm thickness were subjected to hardness test using the model DUH-202 dynamic hardness tester (Shimadzu Corp., Japan). These were then bonded with copper wire using the same bonding machine, and a bond etch test was performed (the unmolded units were heated at about 65 °C in hydrochloric acid for 20 min to remove Al metallization and to expose the silicon layer).

2.3 Effects of Wire Bonding Parameters

The effects of bonding machine parameters; namely bond force and ultrasonic power, on silicon cratering were investigated using an experimental setup as in Table 1. Copper wire was bonded onto Al-1%Si metallization using a model SDW-35 wire bonding machine (Shinkawa, Japan). Eighty bondings from each run were subjected to the bond etch test immediately after the wire bonding process. The amount of exposed silicon or cratering was reported in a percentage, i.e., by comparing the number of silicon cratering obtained to sample size, 80.

3. Results and Discussion

3.1 Effects of Wire Material

The results in Fig. 2 indicate that Cu wire induced more cratering than Au wire, i.e., 1.25% and 7.5%, respectively. In this study, metal extrusion, as shown in Fig. 3(a), is not considered as silicon cratering. Figure 4 shows a cross-section of a copper wire bonded to an Al pad that shows silicon cratering. Copper wire is 1.5 times harder than gold wire;[6] therefore, greater bond force and ultrasonic power are needed for copper to form stacks and well-bonded ball bonding. These bonding conditions increase the possibility of silicon cratering during the wire bonding process.

Gold wire, the softer material that could deform easier and weld to the wire bonded material, contributes less stress or

Table 1 The Experimental Setup of Wire Bonding Parameters

Run	Force (N)	Power (mW)	Time (ms)
1	1.57	60	30
2	1.57	80	30
3	1.57	100	30
4	1.57	120	30
5	1.57	140	30
6	0.98	80	30
7	1.18	80	30
8	1.37	80	30
9	1.76	80	30
10	1.96	80	30

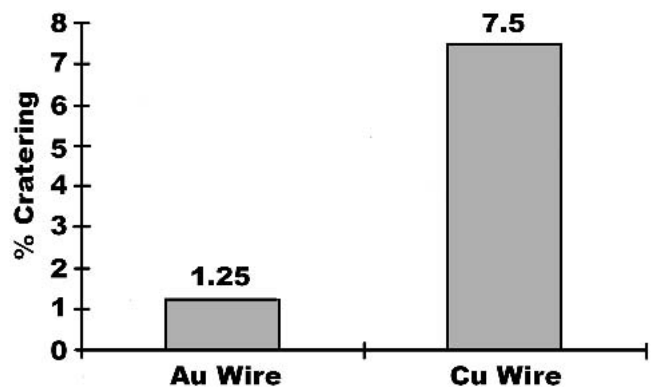
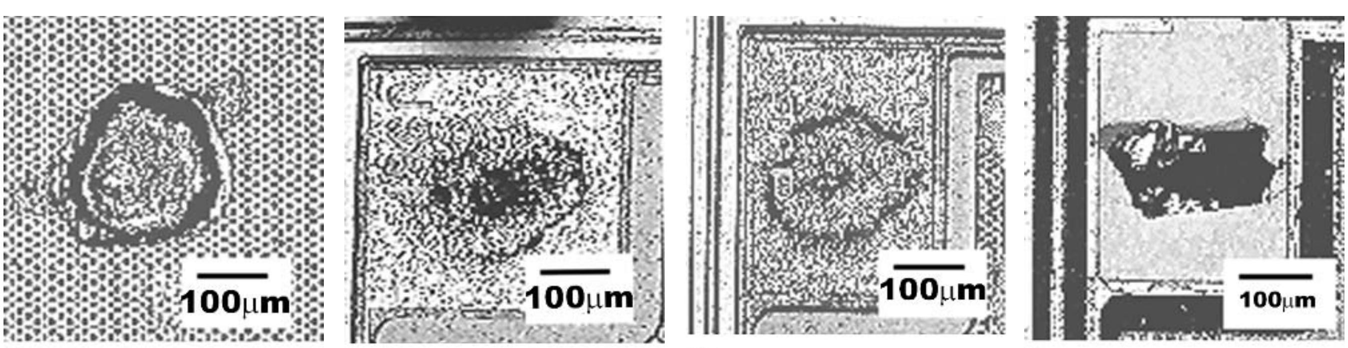


Fig. 2 The contributions of Au and Cu wire to cratering



(a) (b) (c) (d)

Fig. 3 **(a)** Metal extrusion, **(b)** marginal cratering at the center of bond, **(c)** marginal cratering at bond periphery, and **(d)** silicon cratering pressure on the substrate. Copper ball does not deform as easily as gold wire during capillary descending; therefore, copper transmits the excessive energy to the substrate and thus damages it. Therefore, a thicker or harder front metal, such as Ti or W, is used to protect the substrate from cratering, especially in copper wire bonding.[4] The possible types of silicon cratering that were induced in this experiment are shown in Fig. 3(b-d) and 4.

3.2 Effects of Bond Pad Hardness

Table 2 shows hardness test result for five different Al-based metallization recipes, type A, B, C, D, and E. Type A and B bond pads consist of pure Al (100%), which is expected to be the softer bond pad. For Al-1%Si constructed bond pad, type C, D, and E have higher hardness compared to the pure Al bond pad.

Figure 5 shows the effect of bond pad hardness on silicon cratering. Bond pad type A, which has the softest top metal, has the highest percentage of cratering, 18.5%, followed by type B, with 2.5%. No cratering was observed on bond pad type C, D, or E. Nguyen et al.[4] found that the bond pad hardness value should exceed a critical threshold value to avoid silicon cratering. Therefore, the critical bond pad hardness for eliminating silicon cratering in a 50 μm copper wire bonding was found to be about 59 HT. A study performed by Omar[6] also showed that in order to have a good and reliable copper bond without any potential cratering, the relative bond pad hardness value must exceed 59 HT.

According to Harman,[10] one might assume that a softer bonding pad metal would inhibit cratering by absorbing ultrasonic energy and deforming easily, whereas a hard pad would more readily transmit the bonding forces to the substrate. However, the combination of normal Al metallization over a hard interfacial layer (Ti, W, Cu, etc.) appears to be the least subject to cratering.[7] Hard copper-doped top metal could be more crater-prone, because copper oxide or corrosion products on the surface require more energy to bond rather than hardness of the film.[7]

In this study, however, we found that the harder bond pad helps to reduce the silicon cratering. Because Al-based metallization pads were used for both wire materials, there is no hard copper dopant in the metallization. Furthermore, the pad hardness variation is small, therefore the harder bond pad is believed to act as a barrier to bond force or impact energy.

Sometimes the bond pad serves as a cushion to protect the underlying layer, e.g., SiO_2, silicon, polysilicon, or GaAs, from damage due to stresses of bonding. Lycette[13] reported that an increase of the total metallization thickness significantly reduces the cratering.

3.3 Effects of Wire Bonding Parameters

Figure 6 shows that high ultrasonic energy results in a significant increase in the amount of silicon cratering, especially ultrasonic energy higher than 100 mW, when bond force is fixed at 1.57 N. Excessive ultrasonic energy is more often cited as a cause of craters than any other bonding parameter.[1,3,4] This is even more apparent when one considers that silicon cratering is seldom encountered with thermocompression wire bonding, and that this bonding method is the safest to use on crater-prone wafers, e.g., GaAs.[7] In thermosonic copper wire bonding, ultrasonic power provides vibration energy that will scrub the copper ball on the metallization and finally weld it onto the metallization to form a weld. Mori et al.,[1] Kosh,[2] and Koyama et al.[8] found that an Si chip was damaged when excess ultrasonic power was applied. It was also reported that cratering occurred when Si nodules of Al-Si metallization had a damaged insulator during wire bonding.[8] Koyama et al.[8] also found that the ultrasonic applied condition gave a greater impact on silicon cratering formation compared to the wire bonding force. This is because Si nodules damages are enlarged by ultrasonic vibration.[8]

Table 2 Hardness of the Al-Based Bond Pads Measured in Hardness of Triangular (HT)

Bond Pad	Hardness (HT)
Type A	36
Type B	52
Type C	59
Type D	75
Type E	155

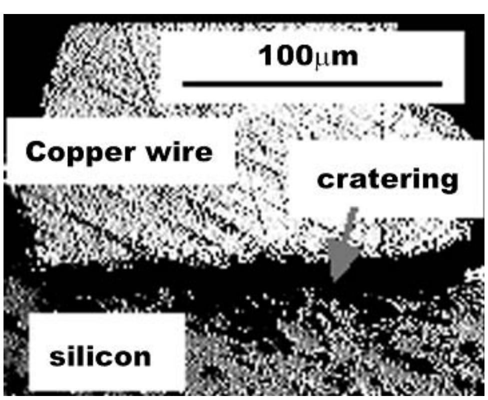


Fig. 4 A cross-section of a copper wire bonded to Al pad shows cratering occurs under the bond. The wire is slightly lifted and cratering could be seen after chemical etching.

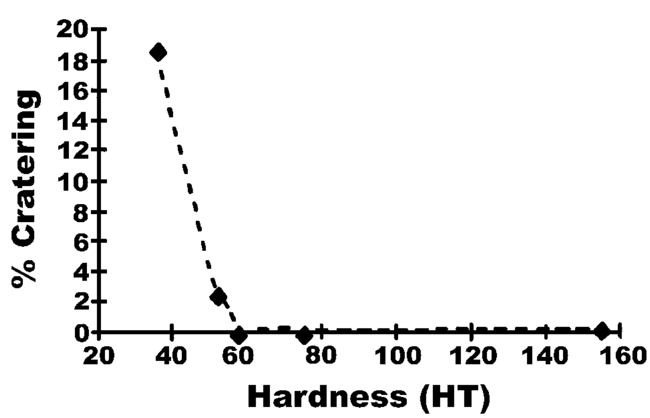


Fig. 5 The relationship of bond pad hardness to the occurrence cratering

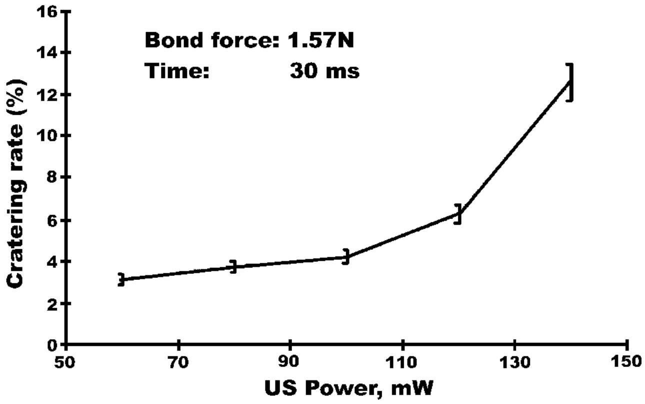


Fig. 6 The effect of ultrasonic power on cratering

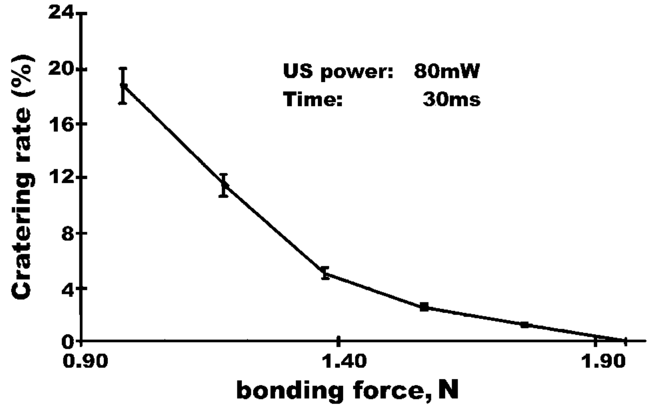


Fig. 7 The effect of bond force on cratering function

Figure 7 shows that low bond force results in a higher amount of cratering, whereas high bond force (1.96 N) does not induce any cratering, when the ultrasonic power is fixed at 80 mW. Theoretically, higher impact energy may reduce the cratering in copper wire thermosonic wire bonding. In this case, the capillary and ball descended rapidly to the bond pad and left the ball hot at touchdown, where the softened ball will absorb some of the impact force. The application of ultrasonic energy before the touchdown will mature the bond without significant additional deformations, and will reduce the force to the underlying layer. It would be better if top metals were hard, to prevent the impact force transmitted to the underlayer. However, when bond force exceeds the bonding parameter window or ability of metallization to absorb impact energy, the excessive force will be transmitted into the underlying layer and cause metal extrusion, as shown in Fig. 3(a).

The main purpose of bonding force is to deform the ball-shaped wire tip and pin, or hold it during the wire bonding process while ultrasonic vibration is applied to weld the ball onto the bond pad. A combination of results in Fig. 6 and 7 show that low force and high power induced silicon cratering remarkably. This is probably because the lower force failed to pin the ball during wire bonding, thus allowing capillary chatter across the top of the ball, which leads to bulk movement of the ball rather than of atoms during the vibration of wire materials when ultrasonic power is applied. This movement might over-scrub the top metal and transmit the excessive energy to the underlying silicon. In fact, only atoms at the ball bonding interface will be scrubbed on the top metals if the ball is held properly by bonding force or capillary.

According to Toyozawa et al.,[3] extremely high bond force increases the cratering percentage. They found that at high bond force, the edges of some crushed copper balls protruded from the pad, and the aluminum film remaining under the pad acted as buffer. This is the metal extrusion type of cratering, which is not considered in this study because it has a different failure mechanism. In addition, the lower ultrasonic power showed less silicon cratering and it combines well with high force to eliminate cratering.[3] Therefore, higher bond force should be applied whenever ultrasonic power is increased to eliminate the cratering. Later, the group found that multistage bonding technology helps to prevent this mechanical failure more effectively[3,4]

4. Conclusions

Results indicate that wire hardness, bond pad hardness, ultrasonic power, and bond force could affect the formation of silicon cratering. Copper wire requires additional ultrasonic power and bond force to produce a proper bonding, but leads to silicon cratering. Thicker and harder top metal would act as a good protective barrier to silicon cratering. Ultrasonic power and bond force were identified as the most critical bonding-machine parameters to silicon cratering, because a greater ultrasonic power requires a greater bond force to pin the ball. To eliminate cratering in copper wire bonding, high force, low power, short dwell time, and high stage temperature should be applied according to the wire size, wire materials, metallization recipe, and hardness of the bond pad.

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