Development of Under Bump Metallizations for Flip Chip Bonding to Organic Substrates

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Several under bump metallization (UBM) schemes using CuNi alloys as the solderable layer were investigated. Nickel slows down dissolution of the UBM into the solder and formation of intermetallics during reflow. To study the intermetallic reaction, CuNi foils of different concentrations were immersed in a eutectic PbSn solder bath for reaction times ranging from 30 seconds to 30 minutes. It was observed that when 10% and 20% Ni is added into copper, the intermetallic forms a continuous layer, instead of the discrete scallops seen in pure Cu/solder interfaces. However, the thickness of the intermetallic remained about the same. For 30% and 45% Ni alloys a definite decrease in the intermetallic thickness was observed compared to the lower Ni alloys. Actual under bump metallizations were also made on Si wafers to study the reactions when there is a limited supply of CuNi available. Cr or Ti was used as the adhesion layer, and the solderable layer was a copper-nickel alloy, instead of pure copper used in the conventional UBM scheme. The metal layers were deposited on a wafer by evaporation and patterned into contact pads. Eutectic PbSn solder balls were reflowed on top of the pads. SEM micrographs of the intermetallic that forms at the UBM/solder interface show the refining effect of Ni in the interfacial microstructure. Since nickel metallizations often have high stresses, stress in the UBMs was measured by the wafer curvature method. Stress vs Ni content plots show that while stresses increase somewhat with the Ni content, the adhesion layer under the CuNi layer has a much larger effect on the stress. UBMs with Cr/CrCu adhesion layer had stresses ranging from about 300 to 600 MPa, while the stresses in UBMs with Ti/TiNi layers were between 70 and 350 MPa.

Key words: Under bump metallization, flip chip soldering, copper nickel alloys, Ti adhesion layer, stress measurements, intermetallic reaction, microstructure

INTRODUCTION

In order to use flip chip bonding directly to organic boards, solders with relatively low reflow temperatures must be used to avoid damage to the board during reflow. The most commonly used solders on the circuit board level (such as eutectic PbSn) contain large amounts of tin, which makes them incompatible with the conventional Cr/CrCu/Cu/Au underbump metallization scheme introduced by IBM more than 25 years ago. The tin in the solder reacts with the copper layer of the UBM, depleting the UBM of copper.

The solder does not react with silicon or the chromium layer next to the silicon. However, given suffi-

cient time it can consume all Cu from the UBM by dissolution of the Cu into the solder and formation of Cu_6Sn_5 intermetallic.[1–3] For good adhesion between the solder and the UBM, there should be some unreacted copper left in the UBM after the reflow, since there is no adhesion between Cr and the Cu_6Sn_5 intermetallic. Therefore loss of all Cu from the CuCr layer results in a weak UBM/solder interface and the joint will fracture at small loads. The extent of the intermetallic reaction can be evaluated by microstructural characterization and performance of the joints in mechanical tests.

Since nickel shows slower reaction with the tin in the solder,[4–6] UBM schemes with Ni as the wettable layer have been identified by the semiconductor industry as preferable replacements to Cu-based UBMs. However, Ni-containing metallizations tend to have
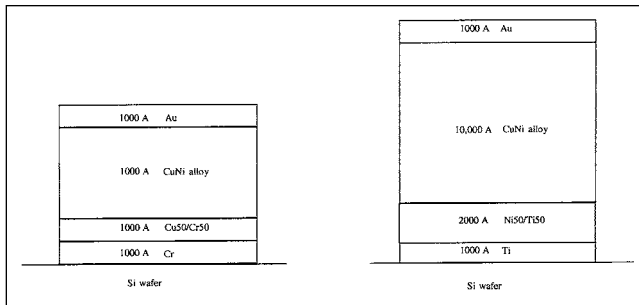
Fig. 1. Metallization schemes used in the stress measurements and reflow experiments. Six different CuNi alloy compositions were used for the CuNi layers.

high stresses that may lead to peeling off of the metallization or failure of the joint. In previous research[7–9] nickel has been successfully introduced into the several UBM schemes to suppress the growth of intermetallics. The interfacial strength was characterized by mechanical testing to find the best UBM schemes. In the present study, a more systematic approach was taken, and the Ni content of the solderable layer was varied while keeping the other layers constant, so that the effect of Ni on the stress, reaction rate, and intermetallic morphology and thickness could be determined.

EXPERIMENTAL

Two types of experiments have been used to study the intermetallic reactions in the solder/CuNi systems. In the immersion tests, a fluxed metal foil is immersed into a eutectic PbSn solder bath. The temperature of the bath was held at 213°C and immersion times ranged from 30 sec to 30 min. The compositions of the metal foils ranged from pure Cu to Cu55Ni45

alloy. In this type of experiment, there is a practically unlimited amount of substrate material available, and the intermetallic thickness is limited only by the reaction kinetics. For examining the intermetallic morphology, the samples were mounted in epoxy, cross-sectioned, ground and polished. The solder was partially etched to reveal the structure of the intermetallic. The UBM/solder interface was then analyzed with SEM/EDS.

In the UBM experiments several different under bump metallizations were deposited on a silicon substrate, and solder bumps were reflowed on the UBM pads. In this kind of experiment the growth of the intermetallic layer is limited by the thickness of the UBM. Figure 1 illustrates the two types of metallizations that were used. The first scheme (on the left) consists of Cr and CrCu adhesion layers next to the silicon, a CuNi wettable layer and a protective gold finish. Six different metallizations of this type were made, each with a different CuNi concentration in the solderable layer, ranging from pure Cu to pure Ni. In the other scheme, the adhesion layer consists of Ti and TiNi layers. Again, metallizations with 6 different CuNi concentrations were fabricated. Metallization layers were deposited on top of an oxidized silicon wafer by evaporation. From wafer curvature measurements before and after the evaporation, the stress in the metal layer could be determined.

After stress measurements, circular, 25 mil diameter pads were defined onto the metallized wafer with photolithography, and the excess metal was etched away so that only the circular pads remained. Rosin (R) flux was applied to each pad to assist in wetting, and 16 mil diameter eutectic PbSn solder balls were placed on the contact pads and reflowed. The reflow
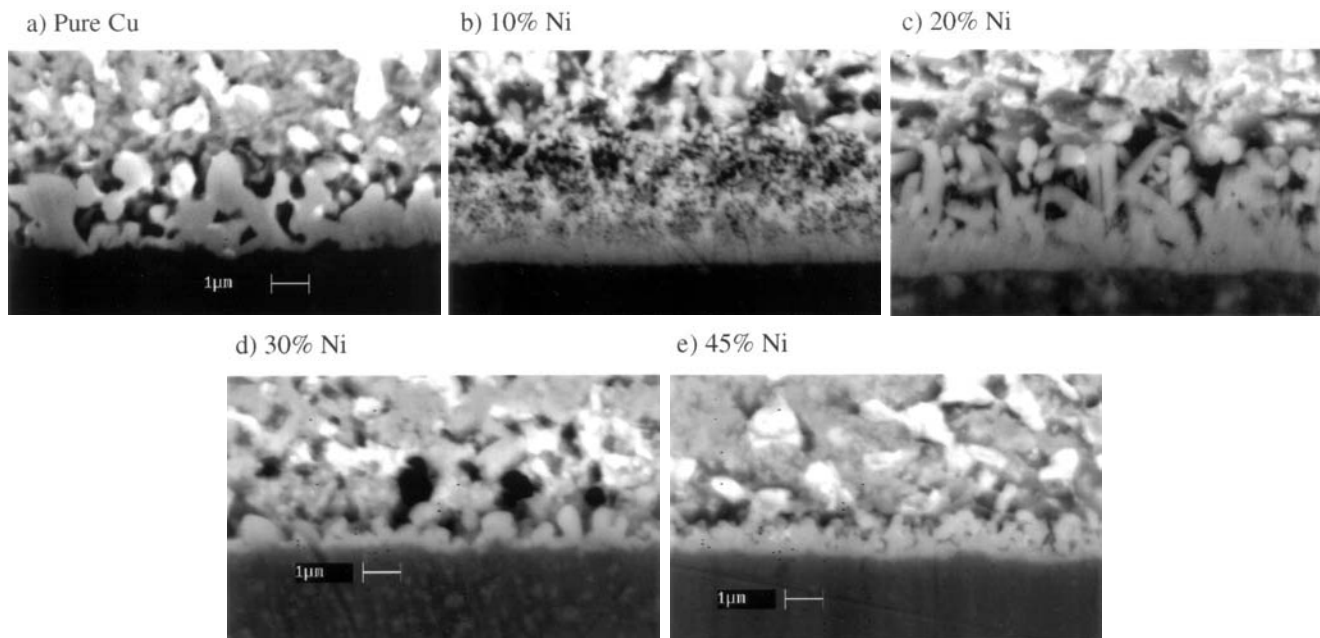

Fig. 2. Morphology of the intermetallic as a function of Ni concentration of the metal foil immersed into eutectic PbSn solder bath. The pure copper foil shows discrete scallops typical to Cu/solder interfaces, while the substrates with Ni show a more refined microstructure. All micrographs have the same magnification.
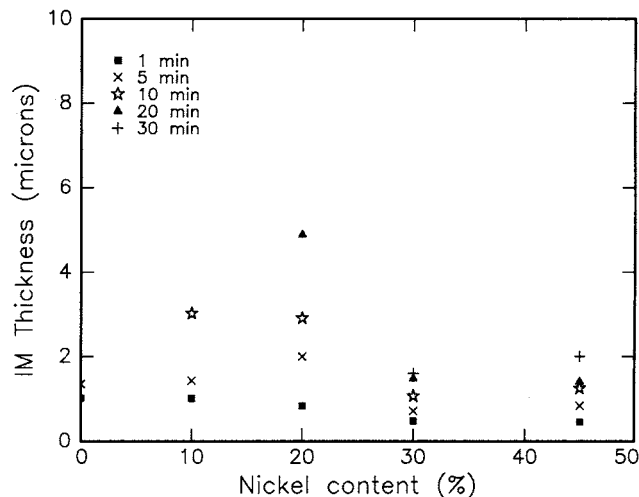
Fig. 3. Intermetallic thickness vs. nickel content in the immersed metal foil.
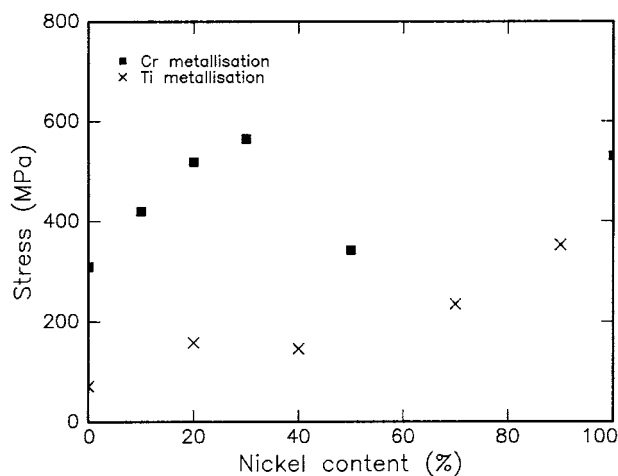

Fig. 4. Stresses in metallized wafers deposited on Cr and Ti adhesion layers as a function of the Ni concentration in the solderable layer.

profile consisted of heating the solder to 160°C for 1 min, followed by 1 min ramp to 230°C, then 1 min reflow at 230°C, followed by forced air cooling at about 20°C/min. The samples were then mounted in epoxy, cross-sectioned, ground, polished, etched and characterized with SEM/EDS.

RESULTS AND DISCUSSION

Immersion Tests

To study the intermetallic reaction between PbSn solder and CuNi alloy, tests were made in which CuNi alloy foils were immersed in a molten PbSn solder bath. The temperature of the bath was 213°C, or 30 degrees above the melting temperature of eutectic PbSn. Foils of 5 different compositions were used: pure Cu, Cu90Ni10, Cu80Ni20, Cu70Ni30, Cu55Ni45 (in weight percent). Figure 2a to f show the intermetallic layer in the metal foils after a 5 minute immersion. The figures are backscatter images, where CuNi substrate has dark contrast and intermetallic (IM) is the gray layer next to the substrate. In the pure copper foil (Fig. 2a), the IM forms large scallops, which is typical for Cu/Sn interfaces. When copper is alloyed with 10% and 20%, definite changes in the IM morphology can be seen. In Fig. 2b and 2c, a continuous IM layer is observed and the thickness of the layer is more even. However, the total thickness of the IM does not change noticeably. In the Fig. 2d and 2f, displaying the interface on the 30% and 45% Ni foils, small scallops can be seen, but the intermetallic is continuous and thinner than in the samples containing more copper.

Similar results were obtained for other immersion times. Figure 3 shows graphically the results of IM thickness vs. substrate Ni content as a function of the immersion time. In general, the IM thickness does not change with addition of 10 to 20% Ni into Cu alloy. However, at 30% Ni content, IM thickness decreases for all immersion times.

Another effect that was observed during the experiment was the fast dissolution of the low-Ni foils into the solder bath. The original thickness of the alloy foils was 20 microns. After a 10 minute immersion, the pure copper foil had completely dissolved into the solder bath. The 10%Ni foil had totally dissolved after 15 minutes, and the 20%Ni foil after 20 min. The 30%Ni and 45%Ni foils were still left after a 30 min immersion.

Stress Measurements

Stresses were measured by the wafer curvature method for all the 12 metallizations deposited on silicon wafers. Metallization schemes are presented in Fig. 1. Different CuNi alloy concentrations were used in the solderable layer, and the relationship between the amount of Ni and the resulting stress was studied. The stress vs. Ni concentration has been plotted in the graph in Fig. 4. In both stress vs. Ni concentration curves, it can be observed that the stress begins to increase with Ni content as Ni is introduced into Cu. However, at around 50% Ni, there seems to be a
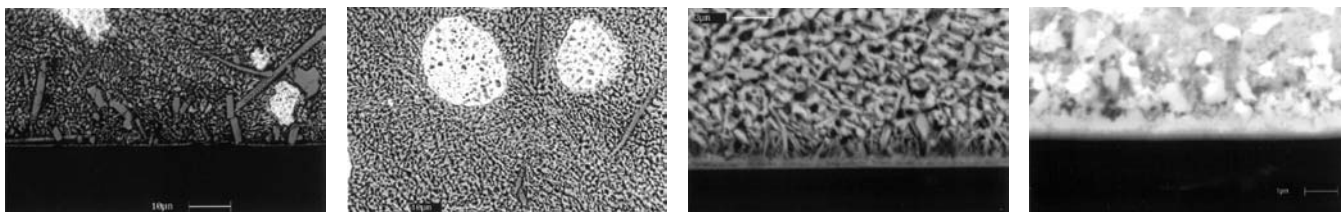

Fig. 5. The microstructure of the interfacial region between UBM and solder. For a) pure Cu solderable layer, large intermetallic needles form; some needles can also be observed b) inside the solder bulk. When c) 20% Ni or d) 50% Ni is added into the solderable layer of the UBM, continuous intermetallic layer can be observed.

plateau or even a decrease in the stress. The stresses increase again at the high Ni concentrations.

Although the Ni concentration has an effect in the stress level, the adhesion layer seems to be much more important. It can be seen that the stresses for the Ti UBMs are significantly lower than the stresses for the Cr UBMs, although the CuNi layer in the Ti UBMs is 1 micron thick, compared to only 0.5 micron CuNi layer in the Cr UBMs. Ni and Ni-based alloys deposited on Cr are known to exhibit high tensile residual stresses as a result of the film deposition, whether using dry or wet process. Such residual stresses are generally believed to be associated with the columnar grain structure and/or other lattice defects forming during film deposition. Subsequent relaxation of grain boundary structure and other lattice defects leads to densification of the films such that the films are put in tension and the wafer in compression.

In previous research,[7–9] we found that we were able to deposit only about 0.5 micron of Ni on top of Cr without causing peeling off of the Ni layer immediately after deposition. As a solution to this problem, the Ti/TiNi adhesion layer was developed. TiNi films are known to have an amorphous structure. Apparently the Ni and NiCu layers grown on TiNi do not have the high-stress columnar grain structure of Ni-layers deposited on Cr. On top of the Ti/TiNi layers, it is possible to deposit thicker wettable layers containing more Ni, which provides more resistance to repeated reflows.

Microstructure at UBM/solder Interface

Figure 5a to 5d show the interface in the UBM samples, where a eutectic PbSn solder ball has been reflowed on the metallization. The reflow time was 1 minute in 230°C. In the pure Cu UBM, the intermetallic (IM) forms thin needles that become detached from the interface and float up into the solder, as seen in Fig. 5a and 5b. The Si wafer is shown as black, solder and IM have gray contrast and Pb-rich areas are white. EDS analysis from the UBM/solder interface shows only a Cr peak, with no Cu left in the interfacial region. Apparently also the Cu which was present in the CuCr layer of the UBM has been depleted by the Sn-Cu reaction. However, in the UBM with Cu80Ni20 as the solderable layer (Fig. 5c), a continuous, even IM layer can be seen. For the Cu50Ni50 UBM, in addition the continuos IM layer shown in Fig 5d, some large IM bumps were observed. However, the total thickness of the intermetallic is smaller than at lower Ni concentrations. At higher magnification, it can be seen that the CrCu layer is still intact and at some regions there is unreacted.

Similar results were obtained for the UBMs deposited on Ti/TiNi UBMs. In these metallizations, the solderable layer was thicker, and even in the pure Cu UBM there was still a continuous IM layer left after the reflow. With the addition of 20% Ni, the IM layer was slightly thinner with less IM needles sticking out of the layer. For 40%Ni, the layer was significantly thinner and there were again some large IM bumps.

CONCLUSIONS

Ni additions into Cu were shown to slow down both the dissolution of the metal into solder and the formation of intermetallic compounds. In underbump metallizations, addition of 20% Ni into the wettable layer of the conventional Cr based UBM was shown to decrease the dissolution of the UBM into solder and to prevent spalling off of the intermetallic. In the stress measurements, it was shown that while stresses in the metallizations generally increase with Ni content, the adhesion layer has a larger effect on the total stress than the Ni content. The metallizations with Cr/CrCu adhesion layer had significantly higher stresses than the metallizations deposited on Ti/TiNi.

ACKNOWLEDGMENTS

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