Barrier Properties of Electroless Ni-B UBM for Solder Joining

Masaru Morita, Toshiya Akamatsu, Nobuhiro Imaizumi, and Seiki Sakuyama
Fujitsu Ltd.
10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197, Japan
Ph: +81-46-250-8268; Fax: +81-46-250-8235
Email: morita.masaru@jp.fujitsu.com

Abstract

As demands accelerate for high density, high speed transmission and low power integrated circuits, 3D-ICs with through-silicon via (TSV) is pursued. In the structure of 3D-ICs, the first die is attached to the second die with micro bump, and the second die is attached to the circuit substrate with a C4 solder bump. The electrode structure of the second die is Cu/Ni UBM. The stress of the Ni-B layer is less than that of the Ni-P layer, and the Ni-B layer can suppress stress and die warpage. The purposes of our study are to clarify the difference in the barrier properties of the Ni-B UBM and Ni-P under bump metal (UBM) and the relevance of the barrier properties of Ni UBM and intermetallic compound (IMC) growth. It was found that an electroless Ni-B plating layer is superior to a Ni-P plating layer for UBM in liquid phase diffusion and in solid phase diffusion, and that a segregated B layer is formed under the IMC layer of a Ni-B land due to reflow soldering. It was estimated that this B layer plays the role of being a barrier layer for solder diffusion.

Key words

Electro-less plating, Ni UBM, Ni-B plating, C4 bumping, Barrier properties

I. Introduction

As demands accelerate for high density, high speed transmission and low power integrated circuits, 3D-ICs with through-silicon via (TSV) is pursued. In 3D-ICs, the interconnect distance between dies can be reduced, allowing for faster performance and better power integrity. The first die is attached to the second die with micro bump, and the back of the second die is attached to the circuit substrate with a C4 solder bump, as shown Fig. 1 [1]. The land structure of the back of the second die is a Cu land, which is joined to a TSV, and Ni UBM, which is joined to the C4 solder bump. When forming the Ni under bump metal (UBM), electroless Ni plating can eliminate the need for photolithography and the spattering process, which typical Ni electroplating requires. For electro-less Ni plating, Ni-P is generally used,

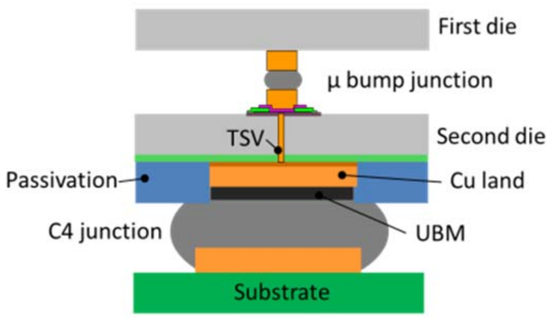

Fig. 1 The structure of a 3D-ICs

but an Ni-P layer places a large amount of stress on the die, causing it to warp greatly and this may cause bump failure or damage to the die. In 3D-IC, the thickness of the second die is about tens of μm, so the stress of Ni UBM causes warp greatly. The stress of the Ni-P layer could be reduced by increasing the concentration of P [2], but doing so cause soldering failure.

In this study, electroless Ni-B plating is focused on because lowering the concentration of B in Ni-B could reduce the stress of the Ni-B layer [3], and this creates good wettability for soldering [4]. Figure 2 shows the correlation between the thickness of an electro less Ni plating layer on a 6 inch Si wafer and the stress of a Ni plating layer. The concentration of P in Ni-P layer is 7 wt%, and concentration of B in Ni-B is

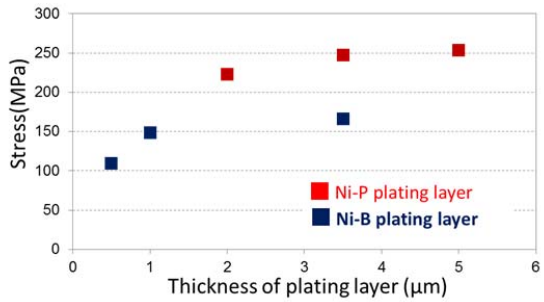

Fig. 2 The stress of Ni-B and Ni-P plating layers on 6-inch Si wafer

0.25 w%. The stress of the Ni-B layer is less than that of the Ni-P layer, so the Ni-B layer can suppress stress and die warpage. However, the barrier property of the electroless Ni-B layer is not yet clarified.

The purposes of this study are to clarify the difference of in the barrier properties of Ni-B UBM and Ni-P UBM and the relevance of the properties of Ni UBM and intermetallic compound (IMC) layer growth.

II. Experimental Method

A. Cu/Ni 2 layer land structure

Figure 3 shows the land structure used in this study. A Cu land was formed by Cu electroplating on a Si wafer with SiO_2. The Cu land was 140 µm square, and its thickness was 4 µm. A passivation layer was formed on the land. Its thickness was 5 µm. An aperture was formed in the passivation layer in the center of the Cu land, and its opening size was 80 µm. Ni UBM was formed as a barrier layer on the aperture by electroless Ni plating. The Ni plating contained Ni-P and Ni-B layers. The concentration of P in the Ni-P layer was 7 wt%, and that of B in the Ni-B layer was 0.25 wt%. To evaluate the barrier properties of Ni UBM in a short time, the thickness of the Ni UBM (Ni-P, Ni-B) was 0.2 µm, which was 1/10 the thickness generally used for UBM. An Au layer was formed on the Ni-P UBM to prevent the Ni UBM surface from oxidizing. However, an Au layer was not formed on the Ni-B UBM because it was assumed that the wetting of the Ni-B UBM was superior to that of the Ni-P UBM [5]. After forming the UBM by Cu and Ni plating, the Si wafer was diced into 23.0 mm square chips.

B. Method for evaluating barrier properties of Ni-UBM

Tables 1(a) and (b) show the list of the evaluated samples as liquid phase diffusion and solid phase diffusion. To evaluate the solder joints of the Ni-P and Ni-B UBM, a 60 µm thick solder bump was formed on the Ni UBM by printing solder paste and reflow soldering at 250 °C. After the soldering, and initial junction interface of solder and UBM was observed by cross section analysis. Moreover, the UBM was heated by repeated 250 °C reflow soldering 3, 6, 9, and 12 times to observe liquid phase diffusion and heated in a 150 °C high temperature storage test (HTST) to observe solid phase diffusion. The repeated reflows simulates chip-on-chip bonding or chip-on-board bonding, and the HTST simulates the heat generated from semiconductors working in the environment of use. After the Ni UBM was heated, Cu-layer and IMC layer growth were observed by SIM(Scanning Ion Microscope) and EPMA(Electron Probe MicroAnalyser).

In this evaluation, the Cu consumption of the Cu land caused by the reflow soldering or HTST was used as an indicator of the barrier properties of Ni-P and Ni-B UBM. Figure 4 shows the measurement point of Cu consumption by repeated reflow soldering or HTST. In Fig. 4, the length of a_1 and a_2 indicate the thickness of the initial Cu land before soldering, and the length of b_1, b_2, and b_3 indicate the thickness of the land consumed by repeated reflow soldering or HTST. The amount of Cu consumption (= X) by reflow soldering or HTST was calculated in the following equation.

$$X = \frac{a_1 + a_2}{2} - \frac{b_1 + b_2 + b_3}{3} \quad (1)$$

Table 1(a) List of samples (liquid phase diffusion)

Sample no.	Ni UBM	Thickness of Ni UBM (µm)	Thickness of Au (µm)	Reflow times after soldering at 250°C
1	Ni-B	0.2	—	0 (initial)
2				3
3				6
4				9
5				12
6	Ni-P	0.2	0.05	0 (initial)
7				3
8				6
9				9
10				12

Table 1(b) List of samples (solid phase diffusion)

Sample no	Ni UBM	Thickness of Ni UBM (µm)	Thickness of Au (µm)	150°C HTST times (hour)
11	Ni-B	0.2	—	250
12				500
13				1000
14				1500
15	Ni-P	0.2	0.05	250
16				500
17				1000
18				1500

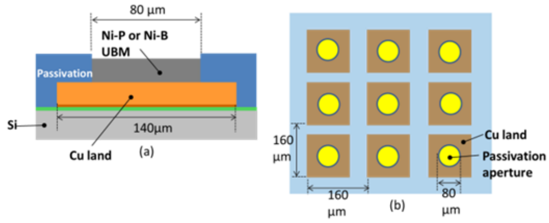

Fig. 3 Structure of Cu/Ni land

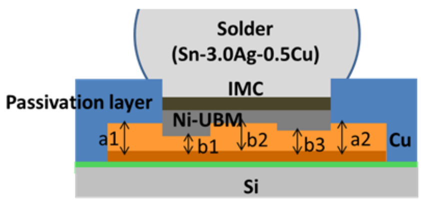

Fig. 4 Measure point of Cu consumption

III. Results and Discussion

A. Barrier properties of Ni UBM in liquid phase diffusion

Figure 5 and 6 shows cross-sectional SIM images of the Cu/Ni-B and Cu/Ni-P lands after being heated by repeated reflow soldering. From Fig. 5, the thickness of the Cu layer in the Cu/Ni-B land was at the initial 3.7 μm. And it was 3.67 after 6 times reflow soldering, and 3.66 μm after 6 times. So, there was little change in the thickness of the Cu layer and the IMC layer grew uniformly until 6 times reflow. The thickness of IMC layer after 6 times was 3.57 μm, an increase of 1.56 μm from the initial thickness. However, after 12 times, the thickness of the Cu layer was 1.48 μm, a reduction of 2.20 μm from the initial thickness. Then, the two IMC layers were separated by solder. These results mean that 0.2 μm thick Ni-B UBM has good barrier properties until reflow soldering 6 times after bonding such as in chip-on-chip bonding or C4 bump bonding but does not have enough barrier properties after 12 times.

From Fig. 6, the thickness of the Cu layer in the Cu/Ni-P land was reduced gradually the repeated reflow times increased. The thickness after 6 times was 2.18 μm, a reduction of 0.72 μm from the initial thickness. The IMC layer grew gradually through repeated reflow soldering. In particular, at 6, 9, and 12 times, an IMC layer more than 7 μm thick grew locally. These results mean that a 0.2 μm thick Ni-P UBM does not have enough barrier properties after 6 times of reflow soldering after bonding.

From these results, the correlation between Cu consumption and reflow times after soldering was calculated by using equation (1), as shown in Fig. 7. Cu consumption of the Cu/Ni-B land could be reduced more than 35 % from that of the Cu/Ni-P land until 6 times of reflow. In particular, the Cu consumption of Cu/Ni-B increased only 0.1 μm during 3 and 6 times of reflow soldering. Thus, it was found that the barrier property of Ni-B UBM was superior to that of the Ni-P UBM until 6 times. However, the Cu consumption of the Cu/Ni-B and Cu/Ni-P lands was almost same at 12 times.

Figures 8, 9, 10, and 11 show area analysis results of the surface composition of samples No. 3 and No. 5 (Cu/Ni-B land) by EPMA mapping. The IMC layer was Cu-Ni-Sn compound in sample No. 3. The B element was not detected by this area analysis because B is a light element and very difficult to detect by EPMA mapping.

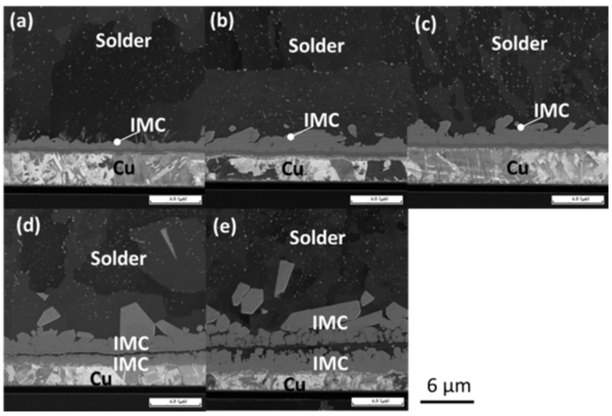

Fig. 5 SIM picture of Cu/Ni-B land heated by repeated reflow. Samples (a) 1, (b) 2, (c) 3, (d) 4, (e) 5.

Then, qualitative analysis was performed at points a, b, c, and d, shown in Fig. 9(a). Figure 9(b) shows the spectrum of X-ray energy. A peak in X-ray energy of 0.183 keV was detected at point a, which was under IMC layer and in the IMC layer a little, and this peak was of the B element, which was not detected in other areas like the Cu and solder. This result means that the B in the Ni-B layer did not diffuse into the solder like Ni but segregated in the Ni layer due to the reflow soldering.

In sample No. 5, it was confirmed that there were two IMC layers that sandwiched the solder layer; the top one was a Cu-Ni-Sn compound, and the bottom one was Cu-Sn compound including few Ni, as shown in Fig. 10. In the analysis map, a thin B layer was detected barely under Cu-Ni-Sn compound. Next, qualitative analysis was performed at points a, b, c, and d, shown in Fig. 11(a). Figure 11(b) shows the spectrum of X-ray energy. A peak in X-ray energy of 0.183 keV was detected at point a, which was under Cu-Ni-Sn compound, and this peak was of the B element, which was not detected in other area like the Cu, IMC layer, and solder.

A segregated B layer was detected under Cu-Ni-Sn compound at both 6 and 12 times of reflow. The peak of the B spectrum at 12 times was higher than that at 6 times. It was estimated that the segregation of B in Ni-B had progressed much at 12 times.

Figures 12 and 13 show an area analysis of the surface composition of samples No. 8 and No. 10 (Cu/Ni-P land) by EPMA. The IMC layer was a Cu-Sn compound in both samples. Ni was barely detected in the IMC layer of sample No. 8 (after 6 times). Ni was not detected in the IMC layer of sample No. 10 (after 12 times), and P was detected not in the IMC layer but in the void. Figure 14 shows an area analysis of the surface composition of the entire bump of sample No. 9. P was detected in the void (red line 1) and at the surface of the solder (red line 2). From these results, it was estimated that P diffuses in the solder like Ni when Ni diffuses into solder completely, and P is observed in the void or at surface of the solder.

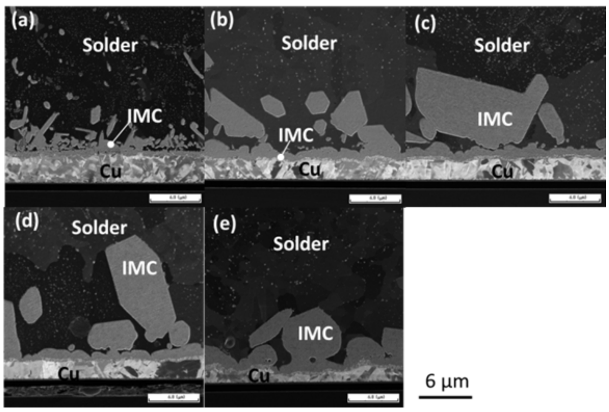

Fig. 6 SIM picture of Cu/Ni-P land heated by repeated reflow. Samples (a) 6, (b) 7, (c) 8, (d) 9, (e) 10.

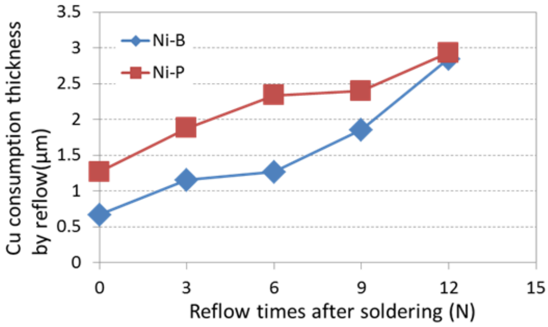

Fig. 7 Cu consumption by number of repeated reflow times

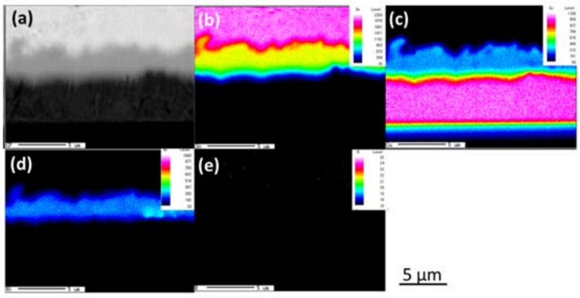

Fig. 8 Surface composition analysis map of sample No. 3 obtained by EPMA. (a) Compo, (b) Sn, (c) Cu, (d) Ni, (e) B.

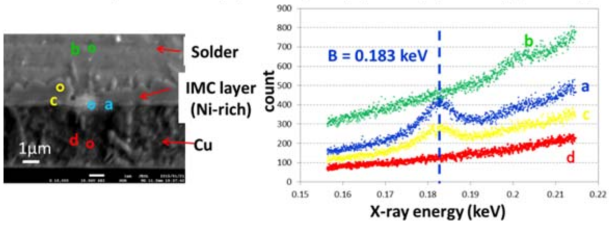

Fig. 9 X-ray energy by qualitative analysis (No. 3)

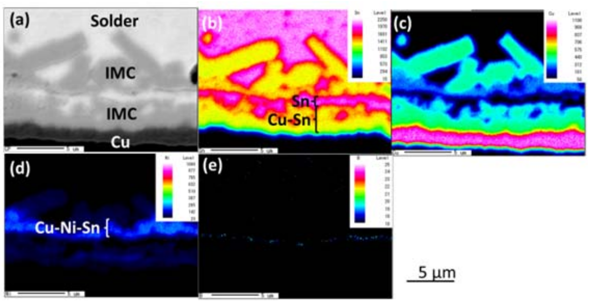

Fig. 10 Surface composition analysis map of sample No. 5 obtained by EPMA. (a) Compo, (b) Sn, (c) Cu, (d) Ni, (e) B.

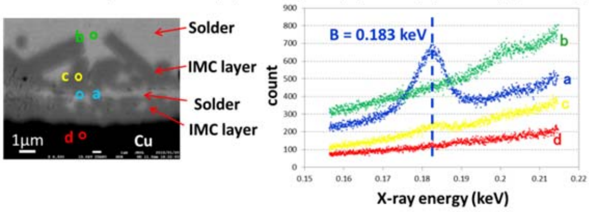

Fig. 11 X-ray energy by qualitative analysis (No. 5)

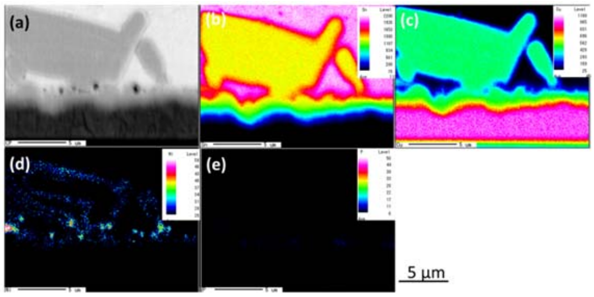

Fig. 12 Surface composition analysis map of sample No. 8 obtained by EPMA. (a) Compo, (b) Sn, (c) Cu, (d) Ni, (e) P.

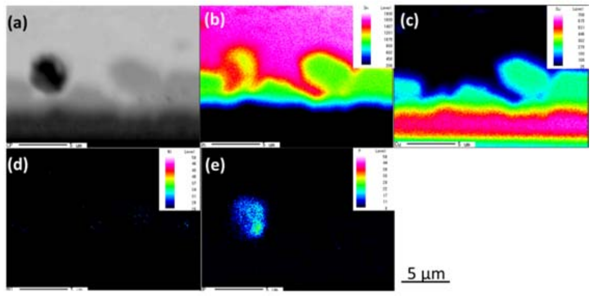

Fig. 13 Surface composition analysis map of sample No. 10 obtained by EPMA. (a) Compo, (b) Sn, (c) Cu, (d) Ni, (e) P.

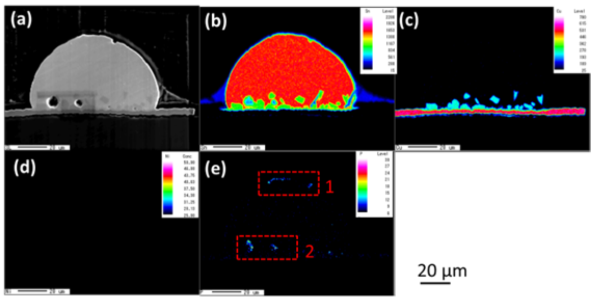

Fig. 14 Surface composition analysis map of sample No. 9 obtained by EPMA. (a) SEM, (b) Sn, (c) Cu, (d) Ni, (e) P.

B. Barrier properties of Ni UBM in solid phase diffusion

Shown in Figs. 15 and 16 are cross-sectional observation results obtained by SIM of the Cu/Ni-B sample (No. 11 - 14) and Cu/Ni-P sample (No. 15 - 18), which were obtained in a 150 °C HTST.

The Cu layer of the Cu/Ni-B land formed almost uniformly up until 500 hours but did not do so after 1000 hours due to Cu consumption. Cu consumption and IMC layer growth increased gradually with the high temperature test times, but the thickness of the Cu layer at 1500 hours was more than 0.6 μm, and the Cu land was not consumed completely in the HTST. Two IMC layers that sandwiched the solder like in Fig. 5(e) were not observed. This result means that 0.2-μm Ni-B UBM has good barrier properties for solid phase diffusion.

The thickness of the Cu layer of the Cu/Ni-P land at 250 hours was 0.84 µm, and Cu consumption had already progressed at 250 hours. The Cu layer of the Cu/Ni-P was consumed completely at 1000 and 1500 hours. The IMC layer at 1000 hours was Cu_3Sn and Cu_6Sn_5, and that at 1500 hours was Cu_6Sn_5. These results mean that the barrier property of Ni-P UBM was inferior to that of Ni-B UBM in solid phase diffusion.

With these results, the correlation between Cu consumption and HTST time after soldering was calculated by using formula (1), as shown in Fig. 17. The Cu consumption of the Cu/Ni-B land could be reduced more than 30% from that of the Cu/Ni-P land up until 1000 hours. Thus, it was found that the barrier property of Ni-B UBM was superior to that of Ni-P UBM in solid phase diffusion, as the same as in liquid phase diffusion.

Figures 18 and 19 show an area analysis of the surface composition of samples No. 13 and 14 (Cu/Ni-B land) by EPMA. At 1000 and 1500 hours of the HTST, three IMC layers formed: a Cu_3Sn compound, Ni-Sn compound, and Cu_6Sn_5 compound from the Cu land. The B element was not detected clearly in the analysis. Then, qualitative analysis was performed at points a, b, c, and d of sample No. 13, as shown in Fig. 20(a). Figure 20(b) shows the spectrum of X-ray energy. A peak in X-ray energy of 0.183 keV was detected at point a, and this peak was of B, which was not detected at point b (in Cu_3Sn) and point c (in Cu_6Sn_5). Point a was directly under the Ni-Sn compound. This means that Ni diffused, and the B in Ni-B was segregated into the Ni UBM during the HTST. This trend was same as that in liquid phase diffusion in Section III-A. It was estimated that the segregation of B in Ni-B UBM contributed to the good barrier properties of the Ni-B UBM.

Figure 21 shows area analysis results of the surface composition of sample No. 16 (Cu/Ni-P land) obtained by EPMA. The IMC layer was a Cu-Sn compound including few Ni, and its thickness was 9.9 µm. Ni spread to the entire layer, and P was detected barely at the boundary of the IMC layer and solder. This means that Ni and P diffused easily

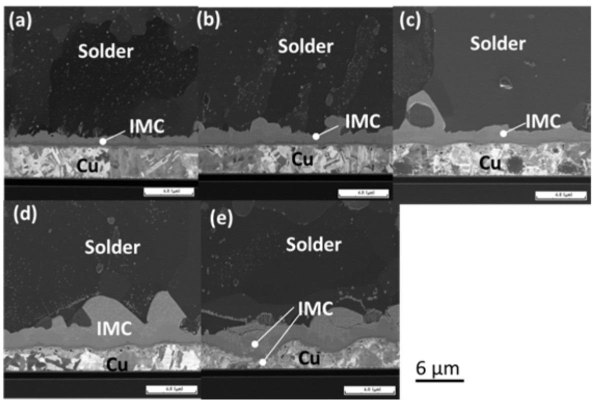

Fig. 15 SIM picture of Cu/Ni-B land heated during HTST. Samples (a) 1, (b) 11, (c) 12, (d) 13, (e) 14.

into the solder when UBM was Ni-P and that P does not contribute to the barrier layer like the B in Ni-B. This result supports the idea that the barrier properties of Ni-B UBM are superior to those of Ni-P UBM, as shown in Figs. 7 and 17.

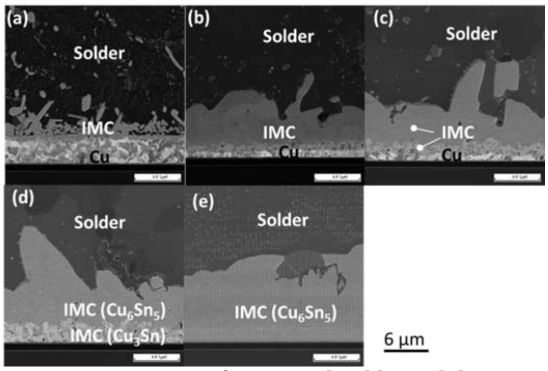

Fig. 16 SIM picture of Cu/Ni-P land heated during HTST. Samples (a) 6, (b) 15, (c) 16, (d) 17, (e) 18.

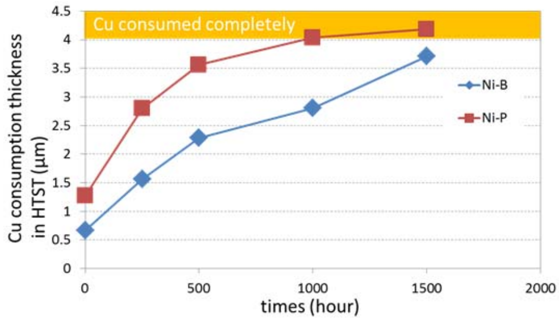

Fig. 17 Cu consumption by 150 °C HTST times.

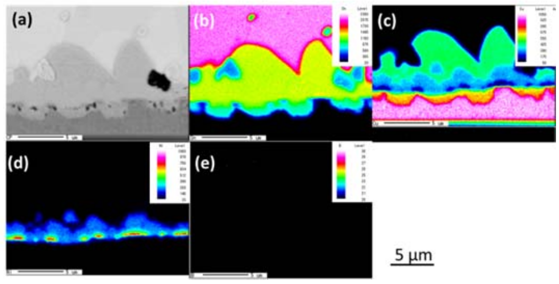

Fig. 18 Surface composition analysis map of sample No. 13 obtained by EPMA. (a) Compo, (b) Sn, (c) Cu, (d) Ni, (e) B.

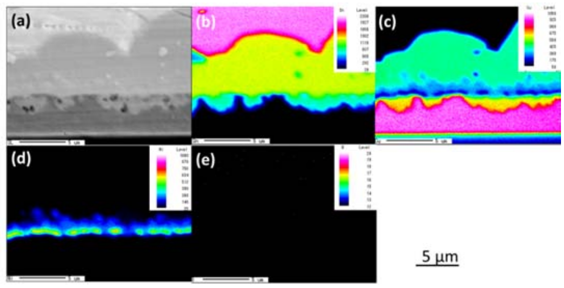

Fig. 19 Surface composition analysis map of sample No. 14 obtained by EPMA. (a) SEM, (b) Sn, (c) Cu, (d) Ni, (e) B.

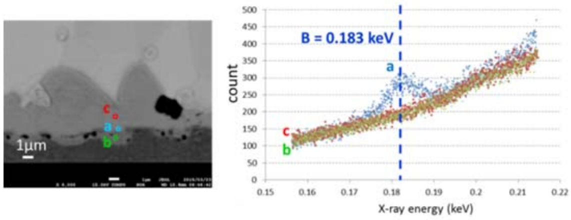

Fig. 20 X-ray energy by qualitative analysis (No. 14)

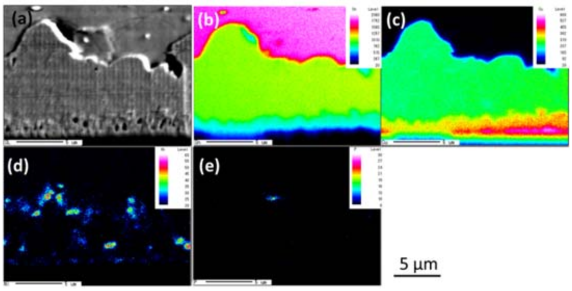

Fig. 21 Surface composition analysis map of sample No. 16 obtained by EPMA. (a) SEM, (b) Sn, (c) Cu, (d) Ni, (e) P.

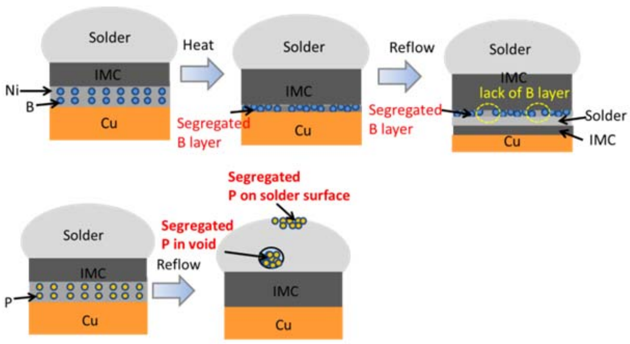

Fig.22 The difference of the barrier properties of Ni-B and Ni-P UBM

C. Difference of barrier properties of Ni-B and Ni-P UBM

Figure 22 shows the difference in the barrier properties of the Ni-B and Ni-P UBM. Whether heated by reflow soldering or in the HTST, B segregates in the Ni when the UBM is Ni-B. After Ni diffuses into the solder completely, the segregated B layer stays directly under the Ni-Sn compound. It was estimated that the segregated B plays the role of being a barrier layer to solder because B does not react with Sn in soldering [6]. This segregated B layer may have drawbacks, causing the solder to pass through the B layer and two IMC layers to sandwich the solder at 12 times of reflow soldering. Meanwhile, P diffuses into the solder, is seen in the void or at the surface of solder bumps, and does not play the role of a barrier layer to solder.

IV. Conclusion

1. Cu consumption of Cu/0.2 μm thick Ni-B could be reduced more than 35 % from Cu/0.2 μm thick Ni-P up until 6 times of 250 °C reflow soldering and more than 30 % up until 1000 hours of a 150°C HTST. These results mean that Ni-B UBM is superior to Ni-P UBM in liquid phase diffusion and in solid phase diffusion.
2. A segregated B layer was formed directly under the Cu-Ni-Sn compound in liquid phase diffusion. Meanwhile, a segregated P layer was observed in the void or on surface of the solder like Ni in the reflow process. However, two IMC layers sandwiched the solder at 12 times of reflow soldering because the solder passed through the B layer and reacted with the Cu land.
3. At 1500 hours of a 150 °C HTST, the thickness of the Cu layer was more than 0.6 μm, the Cu land was not consumed completely, and B segregated in Ni UBM. Meanwhile, the Cu layer was completely consumed by the solder at 1000 hours of the HTST.
4. B did not react with the Sn in solder, and it was estimated that a segregated B layer located directly under the Ni-Sn or Cu-Ni-Sn compound plays the role of being a barrier for liquid phase diffusion and solid phase diffusion. This supports the idea that the barrier properties of Ni-B UBM are superior to those of Ni-P UBM.

Acknowledgments

This paper is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

References

[1] Surya Bhattacharya and Dim-Lee Kwong, "3D IC Future in Singapore" Available: http://prod.semiconsingapore.org
[2] J.Y. Song et.al. "Residual stress measurements in electroless plated Ni–P films" Thin Solid Films, vol. 415, pp. 167–172, 2002
[3] Katsuhiko TASHIRO Ken OHTAKA, Seiji YAMAMOTO, Satoshi KAWASHIMA and Hideo HONMA "Bath Stability of Electroless NiB Plating Using DMAB as a Reducing Agent and Evaluation of Solder Wettability of Deposited Films" Journal of the Japan Institute of Electronics Packaging, vol. 5 no. 6 pp. 591–598, 2002
[4] Jeong-Won Yoon, Ja-Myeong Koo, Jong-Woong Kim, Sang-Su Ha, Bo-In Noh, Chang-Yong Lee, Jong-Hyun Park, Chang-Chae Shur, Seung-Boo Jung, "Effect of boron content in electroless Ni–B layer on plating layer properties and soldering characteristics with Sn–Ag solder" Journal of Alloys and Compounds, vol. 466 pp. 73–79, 2002
[5] Tadayoshi TAMURA, "Present and Development of Electroless Nickel Plating" Journal of The Surface Finishing Society of Japan, vol. 42, no. 11, 1991, pp. 1087–1092
[6] T.B. Massalski, "BINARY ALLOY PHASE DIAGRAM" ASM International, vol. 1, 1990