Sample Preparation for Deprocessing of 3D Multi-Die Stacked Package

H.B. Kor[1], Q. Liu[1] and C.L. Gan[1,2]
[1]Nanyang Technological University, Temasek Laboratories@NTU, 9th Storey, BorderX Block, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553.
[2]Nanyang Technological University, School of Materials Science and Engineering, 50 Nanyang Avenue, Singapore 639798.
Phone : +65-6592-3725, Email : hbkor@ntu.edu.sg

***Abstract*—3D packaging consists of a variety of architectures and types. Fault isolation and physical failure analysis (PFA) can involve non-destructive and destructive techniques. Previously, decapsulation techniques to gain access to individual dice in a 3D multi-die stacked package with very thin dice (100 µm) had been investigated. This paper introduces the sample preparation techniques required for the deprocessing of a thin die within the 3D multi-die stacked package.**

Keywords—sample preparation, deprocessing, physical failure analysis, 3D stacked-die packages, thin die

I. INTRODUCTION

The need for high performance and speed in devices has led to the introduction of 3D packaging. 3D packaging can be found in many forms, such as package-on-package (PoP), wafer level packaging (WLP), system-in-package (SiP), stacked-die packaging with wirebonds, through silicon vias (TSVs), interposers, etc. As a result, various non-destructive and destructive failure analysis techniques to access failures in 3D packaging has become increasingly challenging [1-8].

Previously, decapsulation of a 3D four-die stacked package was investigated. Fig. 1 shows a schematic of the cross-section of the four-die stacked package [9].

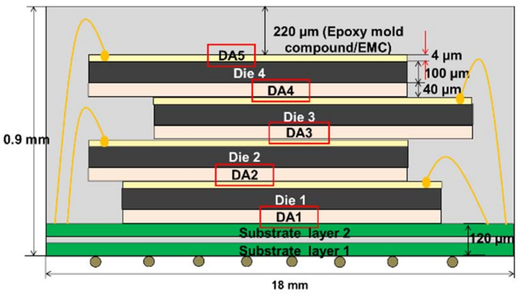
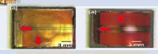
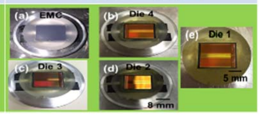


Fig. 1. Schematic of the cross-section of a four-die stacked package [9]

Decapsulation of the four-die stacked package using fuming nitric acid soak to obtain individual intact die usually yielded two dice (while the rest cracked) and the process was not repeatable. Decapsulation of the four-die stacked package itself (whether using laser decapsulation with manual or auto chemical decapsulation) always resulted in die crack. A combination of mechanical grinding (Grit 180 (75 µm) SiC grinding paper) to remove the epoxy molding compound (EMC) and each die; and chemical decapsulation techniques (fuming sulphuric acid (20% SO_3) mixed to 100% fuming nitric acid (1:1), at 100°C) to remove each die attach layer, was used to decapsulate the four-die stacked package, but package warping occurred when Die 2 was exposed. Thus, a cold mount epoxy mechanical support was used to encapsulate the four-die stacked package prior to decapsulation using the combination of mechanical grinding and chemical decapsulation techniques [9] described above. The mechanical support was necessary to relieve stresses at the package substrate to minimize package warping and prevent die crack. Decapsulation without die crack was achievable and repeatable from Die 4 to Die 1 [9]. The previous results are summarized in Table 1.

TABLE 1 SUMMARY OF PREVIOUS DECAPSULATION APPROACHES TO GAIN ACCESS TO INDIVIDUAL DIE IN A 3D FOUR-DIE STACKED PACKAGE [9]

Decapsulation approach	Results	Image
Acid soak	Usually yielded two dice (the rest cracked), process was not repeatable	
Laser decap with manual / auto chemical decap	Die crack	
Combination of mechanical grinding and chemical decap	No die crack, but package warping occurred when Die 2 was exposed	
Combination of mechanical grinding and chemical decap on four-die stacked package embedded in epoxy mechanical support	No die crack from Die 4 to Die 1, process was repeatable	

In PFA, it is a great challenge to precisely isolate a defect or failure found within a 3D package, due to the high density integrated multi-stacked structures, redistribution layers etc. Some form of sample preparation or other fault isolation techniques have to be used in complementary with PFA techniques to improve the resolution or accuracy of isolating failures [6].

In terms of sample preparation, when accessing specific failure locations in a 3D multi-die stacked package (e.g. Die 2 in a four-die stacked package), the acid soak approach may not work, as the probability of die crack is high and the region of interest (ROI) or the failure may be removed in the process. Since it is challenging to isolate failure locations in 3D packages, a large ROI is preferred and the large ROI has to be preferably as intact as possible. Other techniques such as plasma FIB deprocessing [10], broad ion beam milling [11], fast laser deprocessing using green 532 nm laser [12] and microwave-induced plasma (MIP) [13] have some limitations. Xe Plasma FIB deprocessing is limited to a localized area about 100 µm x 100 µm. Using broad ion beam milling may be difficult to control if multiple materials are present in the sample. Fast laser deprocessing may not be able to provide uniformity over a large area. MIP may help to remove molding material of the package during decapsulation to obtain the top die. However, in order to access Die 3, Die 2 and Die 1, mechanical grinding of each die and chemical decapsulation of each die attach layer has to be carried out.

Hence, the motivation of this paper is to study the sample preparation techniques for the large area deprocessing on a 3D multi-die stacked package with a mechanical support.

II. Experimental Results and Discussion

A. Selection of mechanical support for sample preparation for deprocessing of a thin die within the 3D four-die stacked package

As deprocessing involves dry etching using reactive ion etching (RIE) to remove the passivation layer, wet chemical etching or polishing to remove the metallization layers and wet or dry etching to remove the oxide/inter-layer dielectric (ILD) layers, other types of mechanical support were investigated apart from the cold mount epoxy used previously [9]. Considerations include coefficient of thermal expansion (CTE) match between the package and mechanical support, chemical resistance to strong acids such as nitric acid, and versatility.

Three types of mechanical support were evaluated: the cold mount epoxy used previously [9] ("Molding Material A"), a chemical resistant (CR) mechanical support and "Molding Material B". The mechanical supports were used to encapsulate the four-die stacked package for decapsulation to access individual dice. Table 2 shows a comparison of the properties of the various mechanical supports.

TABLE 2 COMPARISON OF THE PROPERTIES OF VARIOUS MECHANICAL SUPPORTS

Properties	**Molding Material A**	**Chemical Resistant (CR) mechanical support**	**Molding Material B**
Composition	• Epoxy resin • Epoxy hardener	Trade secret	• Filler • Molding Material B Liquid • Molding Material B Powder
Curing conditions	Room temperature, 45 min	130°C, 12 h	Room temperature, 5 – 8 min
Coefficient of Thermal Expansion (CTE) ppm/°C	45 – 65 [14]	16 – 20	68 – 75 [14]
Crack after curing	No	Yes	No
Gap between sample and molding material support	No	Yes	No
Chemical resistance for decapsulation and deprocessing	Not as resistant to strong acids such as nitric acid and solvents such as acetone	Resistant to strong acids and solvents	Slightly resistant to strong acids and solvents
Versatility	Not versatile	Not versatile	Versatile

The CTE of the desired mechanical support has to be close to the CTE of silicon chip (2.3 – 3.5) and the four-die stacked package with generally epoxy / silica molding compound (7 – 25 (< Tg of 110 - 200°C); 40 – 70 (> Tg of 110 - 200°C) [15]. This will ensure that the mechanical support is compatible with the four-die stacked package such that decapsulation can be carried out without die crack, while chemical resistance is maintained during deprocessing.

From previous work, Molding Material A was able to provide the necessary support for decapsulation without die crack to access individual dice (Die 4 to Die 1) [9]. Using the CR mechanical support to encapsulate the four-die stacked package, it was found that die crack (encircled in red) occurred on the top die (Die 4), during sample preparation, as shown in Fig. 2.

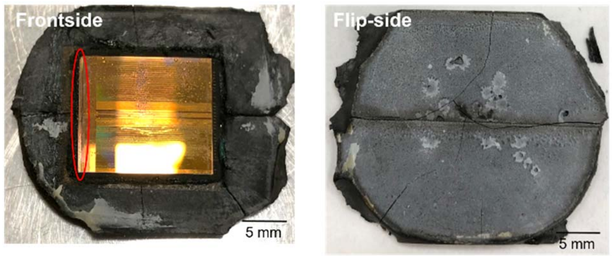


Fig. 2. Four-die stacked package encapsulated in chemical resistant (CR) mechanical support after sample preparation. Crack on Die 4 is encircled in red.

2D X-ray imaging was employed to investigate the root cause of die crack across the cross-section of the four-die stacked package encapsulated in CR mechanical support, as shown in Fig. 3.

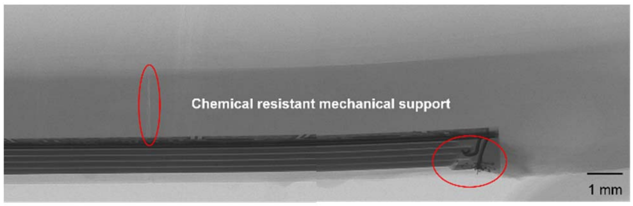


Fig. 3. 2D X-ray image of the cross-section of the four-die stacked package encapsulated in CR mechanical support after sample preparation. Crack in the mechanical support after curing and die crack are encircled in red.

It could be observed that there was die crack at the top die (Die 4) and there was also another crack in the CR mechanical support itself. The reason for the die crack could not be ascertained with 2D X-ray imaging.

Since non-destructive X-ray imaging could not help in understanding the root cause of die crack, destructive mechanical grinding of the cross-section of the four-die stacked package encapsulated in CR mechanical support was carried out. Fig. 4 shows the dark field optical image of the sample after mechanical grinding of the cross-section.

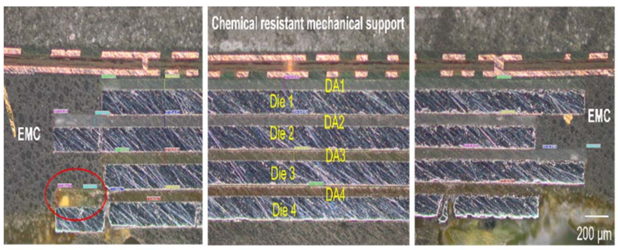


Fig. 4. Dark field optical image of four-die stacked package encapsulated in CR mechanical support and mechanically grinded to reveal the root cause of die crack. Root cause of die crack is due to die attach swelling (encircled in red). Other cracks could have been induced by too much force applied during grinding

There were gaps at the interface between the four-die stacked package and the CR mechanical support after curing, in comparison to no gaps between the package with Molding Material A and Molding Material B. The CR mechanical support could have shrinkage during curing and its viscosity might not be good enough to fill the gaps between the package and itself. Additionally, the CR mechanical support is inherently brittle and lacks toughness. Shrinkage during curing also contributes to stress at the interface between the CR mechanical support and the package, thus resulting in cracks found on the CR mechanical support.

During decapsulation, the gap issue becomes dominant, as the fuming nitric acid seeped through the gaps at the interface and etched the EMC of the four-die stacked package faster than the CR mechanical support. The fuming nitric acid reacted with the die attach, causing the die attach to swell from 44 µm to about 70 µm. Moreover, the die attach was adhered between two large and thin dice in a staircase architecture. The swelling generated mechanical stresses, hence die crack resulted. Knowing the root cause of the die crack, it was understood why the acid soak and decapsulation experiments without mechanical support had a high failure rate to obtain intact individual dice for further PFA.

Following the comparison, Molding Material B cures very fast at room temperature and does not crack after curing. While Molding Material A was chemical resistant to a certain extent during sample preparation, it was less chemical resistant than Molding Material B. The CR mechanical support is the most chemical resistant amongst all, but its high temperature curing over a long duration is a concern during sample preparation. In addition, Molding Material A and CR mechanical support are not as versatile as Molding Material B, which can be easily softened and removed quickly with acetone. This implies that Molding Material B can be used as and when it is desired. When deprocessing to Die 4 and Die 3, Molding Material B can be removed once the processes are completed. However, when deprocessing to Die 2 and Die 1, it may be useful to encapsulate with Molding Material B to provide the mechanical support since package warping occurred when Die 2 was exposed from earlier experiments [9]. Hence, Molding Material B was selected as the mechanical support for deprocessing of the thin die within the four-die stacked package.

B. *Decapsulation to access individual die using selected mechanical support*

First, two pieces of double-sided copper tape was pasted across a glass slide for flatness during mounting and also to allow easy removal of the 3D four-die stacked package embedded in Molding Material B. Next, a Teflon (can be other material types) fixture was then placed onto the double-sided copper tape, followed by placing the 3D four-die stacked package with its frontside (this is to be grinded) facing down on the double-sided copper tape. The Teflon fixture was made with an opening of 22 mm x 22 mm (much bigger than the 3D four-die stacked package of 18 mm x 16 mm to allow room for decapsulation). Molding Material B was prepared at the same time and poured into the setup described, as shown in Fig. 5(a). Fig. 5(b) shows the sample after curing and removal from the Teflon fixture.

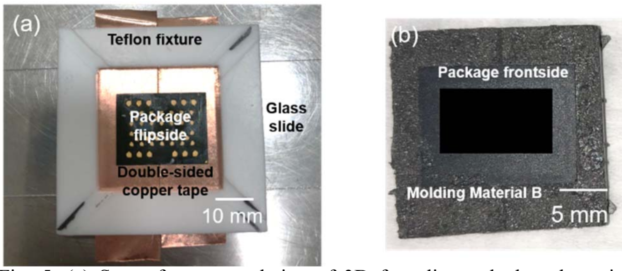


Fig. 5. (a) Setup for encapsulation of 3D four-die stacked package in Molding Material B and (b) cured sample (note that the line at the centre of Molding Material B was due to the two vertical pieces of double-sided copper tape placed side by side for mounting of the package onto a piece of glass slide for flatness, it is not a crack in the molding material

Using Molding Material B as the mechanical support, decapsulation was conducted to gain access to each individual dice. Manual mechanical grinding was carried out using SiC paper pasted onto a stub to remove the EMC and stop at DA5, as in previous work [9]. The result is shown in Fig. 6.

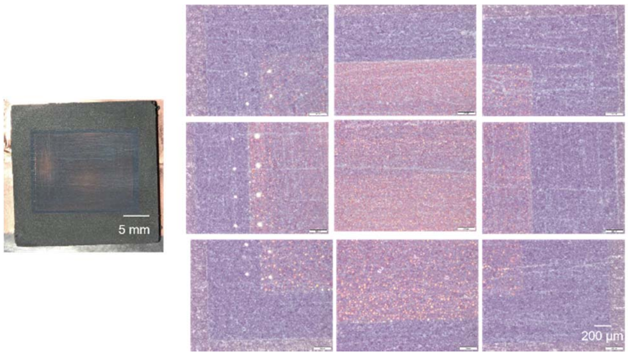


Fig. 6. After manual mechanical grinding using SiC paper to grind the EMC to stop at DA5.

Fuming sulphuric acid (20% SO_3) mixed to 100% fuming nitric acid (1:1) at 100°C on the hotplate was dripped onto DA5. It was left to react for a few minutes, brushed with cotton bud and cleaned with separate cotton bud soaked with acetone. This was done repeatedly until Die 4 was exposed, as shown in Fig. 7.

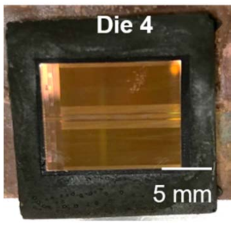


Fig. 7. After chemical decapsulation with fuming sulphuric acid (20% SO_3) mixed to 100% fuming nitric acid (1:1), at 100°C on the hotplate to remove DA5 to expose Die 4

The combination of mechanical grinding and chemical decapsulation was carried out to access each die within the same four-die stacked package. Fig. 8 shows the results of the full decapsulation of the four-die stacked package encapsulated in Molding Material B mechanical support.

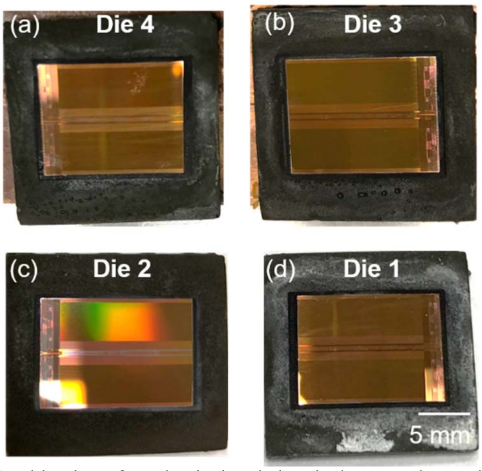


Fig. 8. Combination of mechanical and chemical approach to gain access to individual die of four-die stacked package encapsulated in Molding Material B mechanical support (a) Die 4, (b) Die 3, (c) Die 2 and (d) Die 1

There was no die crack and the process was repeatable from Die 4 to Die 1 on the same package.

C. *Sample preparation process flow to decapsulate and deprocess the 3D four-die stacked package*

a) Removal of FR4 and Decapsulation of the four-die stacked package

The steps in Section B were repeated, this time with the FR4 removed by mechanical grinding, prior to decapsulation. It was recommended to remove the FR4 on the flipside of the package prior to mounting the package in Molding Material B and carrying out decapsulation, as FR4 may contribute to further CTE stress [16] and result in package warpage when the package gets thinner and thinner. Fig. 9 shows the result after the combination of mechanical grinding and chemical decapsulation.

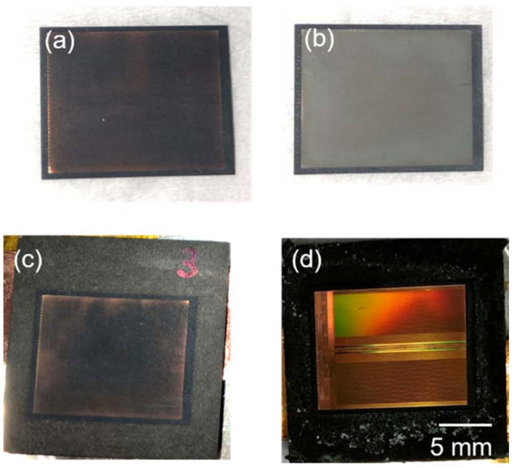


Fig. 9. (a) Frontside, (b) flip-side of 3D four-die stacked package with FR4 removed by mechanical grinding, (c) encapsulation in Molding Material B mechanical support and mechanical grinding with SiC paper to remove the EMC to stop at DA5 and (d) after chemical decapsulation with fuming sulphuric acid (20% SO_3) mixed to 100% fuming nitric acid (1:1), at 100°C on the hotplate to remove DA5 to expose Die 4

It is recommended that the height of the molding material of the package is slightly lowered with respect to the die to facilitate the subsequent deprocessing, especially during the manual polishing step. This is to ensure that the polishing process can be carried out as large an area as possible, uniformly during deprocessing. The lowering of the height can be done during the decapsulation step by using fuming nitric acid to brush the four edges of the package.

After Die 4 was exposed, Molding Material B was removed. Die 4 in the four-die stacked package was ready for deprocessing.

b) Deprocessing of M4 layer of the four-die stacked package

Fig. 10 shows the FIB cross-section of a thin die within the four-die stacked package. There are a total of four metal layers.

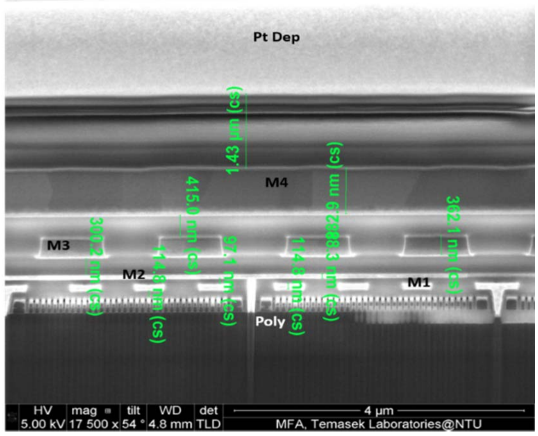


Fig. 10. FIB cross-section of an individual die of the four-die stacked package

Table 3 shows the thicknesses of various layers within an individual thin die.

TABLE 3 THICKNESSES OF VARIOUS LAYERS WITHIN AN INDIVIDUAL DIE IN THE 3D FOUR-DIE STACKED PACKAGE

Layer	Thickness
Passivation	1.43 µm
M4	882.9 nm
ILD between M4 & M3	415.0 nm
M3	362.1 nm
ILD between M3 & M2	300.2 nm
M2	88.3 nm
ILD between M2 & M1	97.1 nm

In this sample preparation, RIE, chemical etching and polishing were conducted to expose the M4 and M3 layers. Fig. 11 shows an overview of the passivation layer (Die 4) before RIE, while Fig. 12 shows a localized optical image of the passivation layer before RIE.

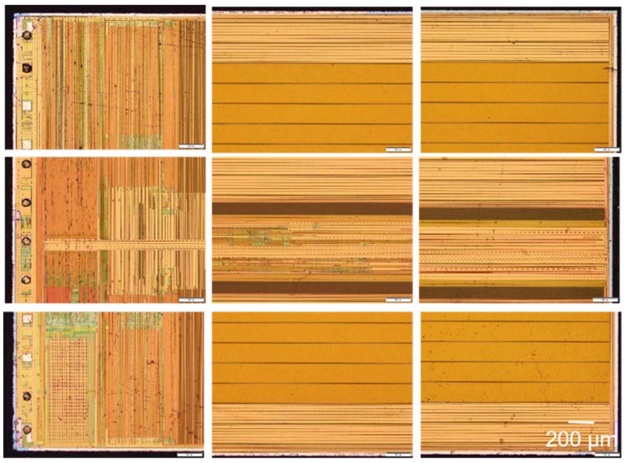


Fig. 11. An overview of the passivation layer (Die 4) before RIE

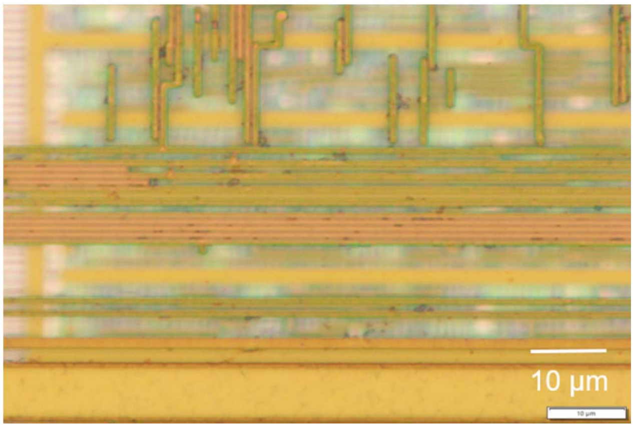


Fig. 12. Localized optical image of the passivation layer (Die 4) before RIE

The M4 Aluminium layer was exposed using RIE with oxide etching recipe, as shown in Fig. 13 and Fig. 14.

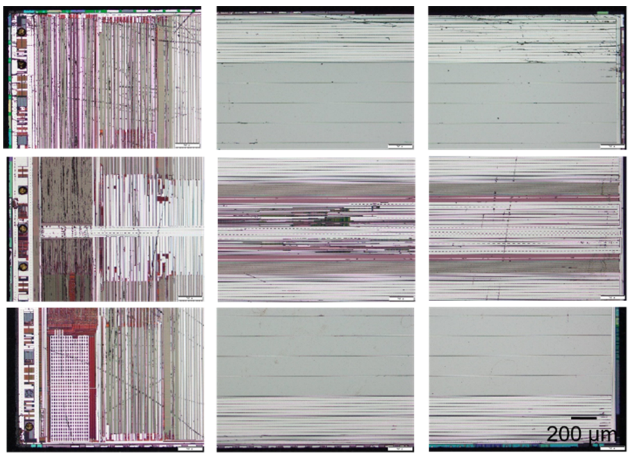


Fig. 13. An overview of the M4 Aluminium layer (Die 4) exposed after RIE with oxide etching recipe

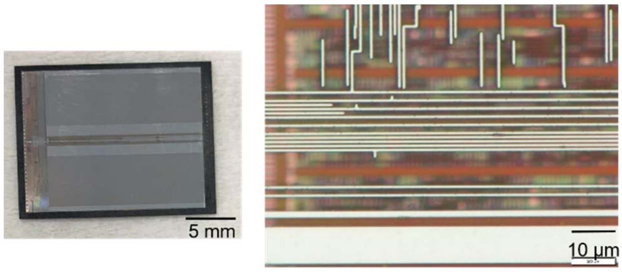


Fig. 14. Localized optical image of the M4 Aluminium layer (Die 4) after RIE with oxide etching recipe

The M4 Aluminium layer was removed using wet chemical etching with acids or polishing, while the ILD was removed by dry etching with the RIE (oxide etching recipe) to expose M3. The result is shown in Fig. 15 and Fig. 16.

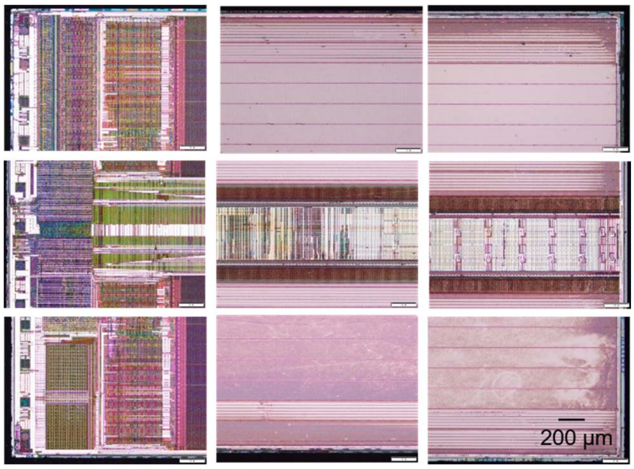


Fig. 15. Overview of M3 Aluminium layer exposed after RIE with oxide etching recipe

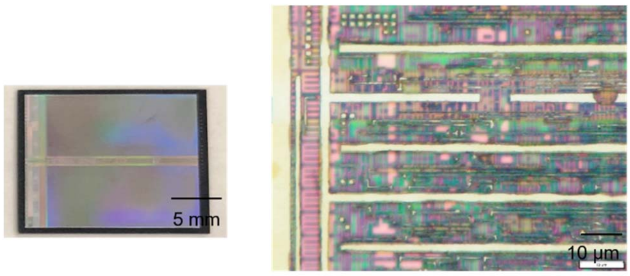


Fig. 16. Localized optical image of M3 Aluminium layer exposed after RIE with oxide etching recipe

The subsequent deprocessing can be carried out using Aluminium technology deprocessing techniques [17,18].

It was challenging to remove the passivation layer uniformly with RIE on the package, as the Aluminium of the thin metallization layers tend to be exposed earlier than the thick metallization layers. This could be due to RIE micro-loading effect [19]. Hence, if there were under-etched regions, they were manually polished away before further deprocessing. Corner rounding is also inevitable, as the die is large (16 mm (L) x 14 mm (W)).

III. CONCLUSION

Different mechanical supports have been studied in this paper. The key factors for the selection of a suitable mechanical support for deprocessing of a thin die within a 3D multi-die stacked package include CTE match between the package and the mechanical support, chemical resistance to strong acids and solvents during decapsulation and deprocessing, as well as versatility. Molding Material B had been selected as the most suitable mechanical support for large area sample preparation to deprocess a thin die within a 3D four-die stacked package.

Sample preparation for deprocessing of a thin die within a 3D four-die stacked package encapsulated in Molding Material B mechanical support is crucial, especially where acid soak may not work due to high probability of die crack. Depending on the PFA applications, the sample preparation techniques developed in this study to access specific areas in a multi-die stack will be beneficial.

ACKNOWLEDGMENT

The authors would like to thank Lim Song Kiat Jacob for providing the CR mechanical support for the experiments.

REFERENCES

[1] Handbook of 3D Integration: Volume 3 - 3D Process Technology, Chapters 1 - 3: Wiley-VCH, 2014.

[2] F. Altmann, S. Brand, M. Petzold, "Failure Analysis Techniques for 3D Packages", 25th International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA), 2018.

[3] I.D. Wolf, K. Croes and E. Beyne, "Expected Failures in 3-D Technology and Related Failure Analysis Challenges", IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 8, No. 5, 2018, pp. 711-718.

[4] S.M. Zulkifli, B. Zee, W. Qiu, A. Gu, "High-Res 3D X-ray Microscopy for Non-destructive Failure Analysis of Chip-to-Chip Micro-bump Interconnects in Stacked Die Packages", 24th International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA), 2017.

[5] Y. Chen, P. Lai and Q. Shi, "Advanced Fault Isolation Techniques for 3D Packaging", 23rd International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA), 2016, pp. 212-215.

[6] F. Altmann and M. Petzold, "Innovative Failure Analysis Techniques for 3-D Packaging Developments", IEEE Design & Test, 2016, pp. 46-55.

[7] H-Y. Son, T. Oh, J-W. Hong, B-D Lee, J-H Shin, S-H. Kim and N-S Kim, "Mechanical and Thermal Characterization of TSV Multi-Chip Stacked Packages for Reliable 3D IC Applications", IEEE 66th Electronic Components and Technology Conference (ECTC), 2016, pp. 356-360.

[8] F. Chao, X. Li, "3D Package Failure Analysis Challenge and Solution", 17th Electronics Packaging Technology Conference (EPTC), 2015.

[9] H.B. Kor, Q. Liu, Y.W. Siah and C.L. Gan, "Decapsulation of 3D Multi-Die Stacked Package", 22nd International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA), 2015.

[10] P. Carleson, D. Donnet, O. Sidorov and C. Rue, "Delayering on Advanced Process Technologies using FIB", Conference Proceedings from the 40th International Symposium for Testing and Failure Analysis (ISTFA), 2014, pp. 439-444.

[11] P. Nowakowski, M. Ray, P. Fischione and J. Sagar, "Top-down delayering by low energy, broad-beam, argon ion milling — a solution for microelectronic device process control and failure analyses", 28th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC), 2017, pp. 95-101.

[12] H.H. Yap *et al.*, "Application of Fast Laser Deprocessing Techniques in Physical Failure Analysis on SRAM Memory of Advance Technology", Conference Proceedings from the 40th International Symposium for Testing and Failure Analysis (ISTFA), 2014, pp. 277-282.

[13] J. Tang, M.R. Curiel, S.L. Furcone, E.G.J. Reinders, C.Th.A. Revenberg and C.I.M. Beenakker, "Failure Analysis of Complex 3D Stacked-die IC Packages using Microwave Induced Plasma Afterglow Decapsulation", IEEE 65th Electronic Components and Technology Conference (ECTC), 2015, pp. 845-852.

[14] Engineering ToolBox, (2003). Coefficients of Linear Thermal Expansion. [online] Available: https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html [Accessed 28 Apr 2020].

[15] H. Ardebili, J. Zhang, and M. G. Pecht, "Encapsulation Technologies for Electronic Applications", Second ed. Elsevier Inc., 2018, p. 504.

[16] G. Liechty and C. Richardson, "Uniform Mechanical Deprocessing of Stacked Memory Modules," in 44th International Symposium for Testing and Failure Analysis (ISTFA), 2018, pp. 514-519.

[17] K.S. Wills and S. Perungulam, "Delayering Techniques: Dry Processes, Wet Chemical Processing and Parallel Lapping" in Microelectronics Failure Analysis Desk Reference Fifth ed., 2004, pp. 444-463.

[18] F. Beck, "Integrated Circuit Failure Analysis: A Guide to Preparation Techniques". John Wiley & Sons Ltd., 1998, p. 173.

[19] S. Franssila, "Deep Reactive Ion Etching," in Introduction to Microfabrication, Second ed.: John Wiley & Sons, Ltd, 2010, pp. 255-269.