Pushing the limits of miniaturization in microelectronic packaging via the application of ultra-thin micro dam structures

PATRICK SCHIRMER[1], Severin Ringelstetter[1], Kian Chong Tai[2], Muizzuddin Azfar[2]

1) DELO Industrial Adhesives
DELO-Allee 1
Windach, Bavaria 86949 Germany
Ph: +49 8193 99000
Email: patrick.schirmer@delo.de

2) NSW Automation
No. 1225, Lorong PSPN 1, Penang Science Park
14100 Simpang Ampat, Penang, Malaysia
Ph: +604-506006
Email: kctai@nswautomation.com

Abstract

The ever-increasing demand for miniaturization in semiconductor and microelectronic packaging is pushing the limits of what is feasible. On the design side, limitations such as space for keep-out zones (e.g. space for the fillet or the dispensing area of an underfill) and the potential flow of encapsulation compounds should not be overlooked in order to avoid contamination of surrounding components.

In addition, optical barriers in sensors can often only be achieved using mold structures or by placing barriers (e.g. caps). It is generally preferred that these barriers are narrower and flatter, but this is often limited due to manufacturing reasons.

With line widths of 100 µm and less combined with aspect ratios of above 5, DELO Industrial Adhesives, in cooperation with micro dispensing equipment manufacturer NSW Automation, has succeeded in developing a micro dam that creates new possibilities in the field of heterogeneous integration and optical packaging.

High dispensing speeds and curing via UV light or heat also make the application process more flexible. Almost limitless designs of free-form structures are thus now possible and completely new package designs can be realized.

Key words

Heterogeneous integration, Miniaturization, Size reduction, Micro dispensing, UV-light curing, Micro structures

I. INTRODUCTION

Space is becoming increasingly limited, be it in the package design itself or in the PCB layout. The number of components, gap sizes and miniaturization are progressing at a rapid pace, requiring new technological solutions to make this possible. [1]
Space is often "wasted" due to the process, such as in the design of necessary KoZ (keep out zones) around components that are provided with reinforcement solutions. Not only the spread of adhesives itself lead to limiting factors but also restrictions given by the existing and available standard equipment for dispensing. Multiple factors contribute to the limitations and inaccuracies of existing equipment, such as disruptive shock vibrations in equipment environments, the adverse effects of the coefficient of thermal expansion (CTE) on critical motion

components, constraints of vital sensing elements, and inefficiencies within the overall automation control system.

II. AREAS OF APPLICATION

DELO has entered a development partnership with NSW Automation to enable previously unrealizable narrow structures. Both companies benefit from the combined know-how of adhesive development and dispensing technology and UV-curing. The aim of this partnership was to develop a structure that is as fine as possible and easy to apply, which can also be processed quickly and can withstand the typical reliability tests that are common in the electronics industry. The resulting micro dam is intended to shift the existing boundaries to take miniaturization and packaging density in semiconductor and microelectronic packaging to a new level which is crucial to keep up with the challenges on heterogeneous integration.
With a structure width target of 100 µm, aspect ratios of 5 and more, the required space is reduced to a minimum. Curing in seconds via UV light and reliable product performance even after harsh stress tests under JEDEC MSL conditions are expected to make the developed micro dam a widely applicable solution.

A. *Keep out Zone (KoZ) reduction*

As mentioned in the introduction, space is also often "wasted" by the process, for example in the design of necessary KoZ (keep out zones) around components that are provided with reinforcement solutions (e.g. capillary underfills - CUF) on which space for adhesive dispensing is needed [2]. To minimize the footprint of these KOZ, flow barriers are applied to the substrates. This can be achieved either by fine trenches [3], realized by laser engraving or by the application of flow stop structures as shown in Figure 1. These must be as small as possible to maximize the space for surrounding components such as passive elements as in Figure 2 around the silicone die.

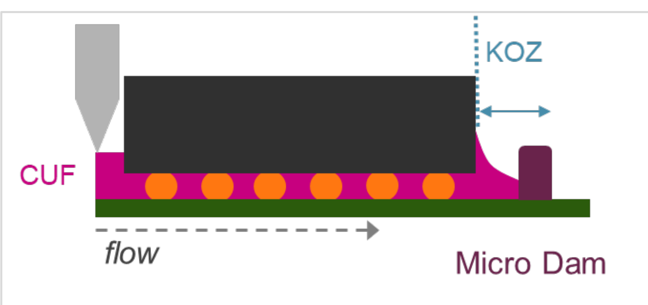

Figure 1 Schematic illustration of micro dam application as flow stop

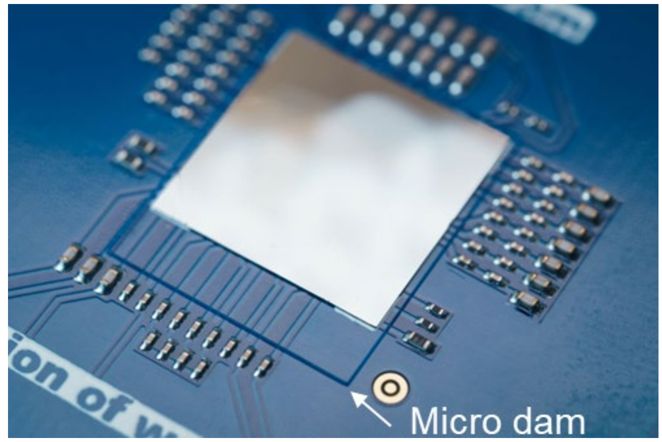

Figure 2 Dispensing of a micro dam as flow stop on a dummy CPU test vehicle

B. *Optical sensing and LED packaging*

In addition to the reduction of keep-out zones, such fine structures are also extremely relevant in optical sensor packaging, e.g. in the design of proximity sensors. The closer the emitter and receiver can be placed next to each other without affecting the signals, the smaller the final package size will ultimately be. This increases UPH and reduces costs as more packages can be made per substrate. Low transmission is particularly important here to rule out miscommunication within the sensor.
In LED packaging, the density of the individual dies in arrays has been increasing significantly for years. To ensure clean optical separation of the respective dies, a structure with particularly low transmission is also required here. The challenge is the dispensing of a grating structure. The overlap of the lines should be almost invisible. Therefore, at line crossings, the dispensing speed and quantity must be adjusted to avoid material accumulations.

III. ADHESIVE DEVELOPMENT

The importance of material technology in micro-dispensing cannot be overstated. Given the microscopic scale at which dispensing operations occur, the properties of the material being dispensed play a crucial role in the success of the process. Adhesives must possess specific rheological properties to ensure precise flow and deposition at the micro-scale [4]. Moreover, they need to exhibit uniformity, consistency, and stability to guarantee reproducibility and reliability in manufacturing. Innovations in material technology involve the development of advanced formulations tailored for micro-dispensing applications, incorporating characteristics such as tailored rheological behavior, high surface tension, and compatibility with the dispensing equipment. These materials also need to exhibit minimal shrinkage or expansion upon curing to maintain dimensional accuracy at the micro-scale. Achieving the desired material properties is fundamental to unlocking the full potential of micro-dispensing technology and enabling its widespread adoption in mass production scenarios.

A. Rheology

Previous dam solutions were based on the long-established encapsulation solutions from dam & fill encapsulants. Here, the line width was not of such great importance until now. Tests to reduce the line width with existing standard products have resulted in minimum dimensions of approx. 250 µm. Aspect ratios of approx. 3 could be achieved but were difficult to maintain due to the decreasing viscosity with increasing temperature in the heat curing step and often collapsed to a ratio of approx. 2 after curing. In addition, the fillers present ine existing formulations predetermined the minimum dispensing needle diameters. In order to be able to dispense the narrowest possible structures, an adhesive with the necessary properties is required in addition to the right dispensing equipment. The basic viscosity, the thixotropy index, the shear recovery and the choice of fillers have a significant influence here.
The base viscosity essentially determines the behavior of the adhesive at idle, i.e. after dispensing onto the substrate. On the one hand, this must be as high as possible to be able to achieve a stable bondline geometry, but on the other hand, it must be possible to reduce it as much as possible by shearing in order to enable stable dispensing behavior with the finest needle diameters (≤ 100 µm). The shear-thinning behavior can be adjusted and influenced by fillers and thixotropic agents and is determined using rheological testing, for example, using an Anton Paar rheometer to measure viscosity at different shear rates as shown in Figure 3. This also provides the shear recovery value, which describes how quickly the shear-thinned adhesive recovers to its initial level (the time dependence of the recovery after shearing is termed thixotropy). In addition, to the viscosity itself and the choice of filler also have a significant influence on the dispensing result. As a rule of thumb, the maximum filler diameter should not be more than 20% of the needle diameter to ensure uninterrupted dispensing.
Fillers are usually added to adhesive formulations in order to influence certain properties like the CTE or the Young´s modulus. In the case of micro dam, the focus is on the dispensing performance and flexibility, so fillers have not been added to tune the CTE but to ensure the micro dam is able to withstand deformations caused by temperature cycles or expansion of other materials being directly in contact with, such as the CUF (capillary underfill) in reinforcement applications.

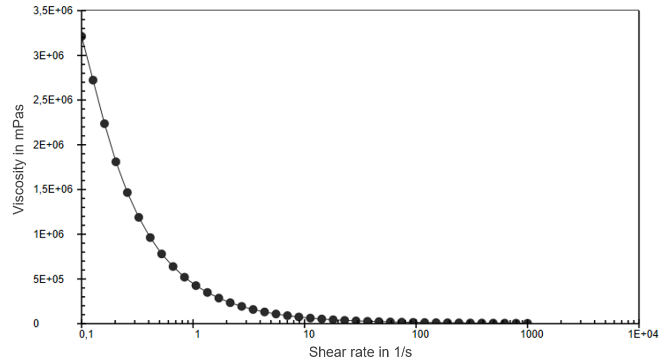

Figure 3 Viscosity measurement via shear rates using rheometer method

B. Curing

Typically, the viscosity of solvent-free adhesives decreases during thermal curing, which leads to a reduction in the aspect ratio, an increase in the footprint and a reduction in the dam height.
To counteract this, the curing option via UV light was considered from the very beginning during development, as curing takes place in just a few seconds without significant increase in temperature. The limiting factor in this case, however, is the color and optical density of the adhesive. For a sufficient reaction of the photo initiator, adequate intensity in the respective wavelength must reach the entire structure. Very dark or highly filled adhesive systems can have shielding properties and thus seriously impair curing. This is investigated by real time IR measurement in which samples with defined adhesive layer thickness are being checked for the time needed to reach the full curing which is defined by a minimum of 90 %. As an example, shown in Figure 4, the minimum curing time in 100 µm thickness was about 4 seconds for the respective micro dam adhesive. For the study of sufficient curing time for specific layer thickness the wavelength of 400 nm and intensity of 200 mW/cm² stayed the same. As expected, and shown in Figure 5, the required irradiation time increases significantly for thicker layers. For the dark black version, it was impossible to fully cure it via UV light in layers of 500 µm and above.
As the applicability of the micro dam should be as broad as possible, a combination curing was also implemented. The chemical base, an acrylate, enables not only light curing but also modification for dual curing, which gives the user the freedom to choose between UV light or heat curing.
In the case of the micro dam developed here, it only takes 5 minutes at 150 °C in a convection oven to achieve complete curing. The reduction in viscosity described above is marginal in this case, as the high base viscosity means that only minimal flow occurs.
The free choice between UV light or heat curing allows the product to be used in applications that are inaccessible to UV light, so-called shadow zones.

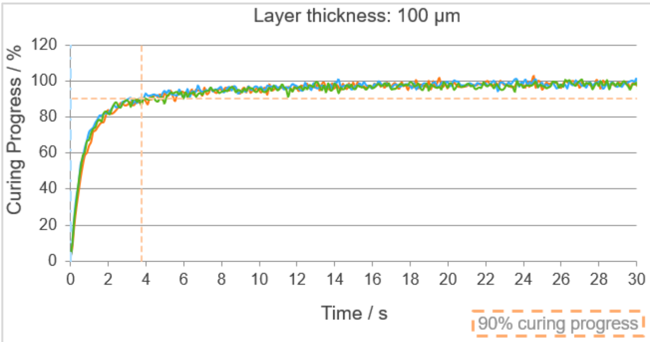

Figure 4 Real time IR measurement on 100 µm adhesive layer

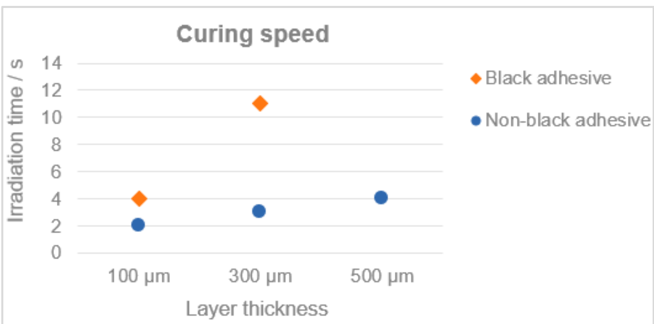

Figure 5 Curing speed as a function of the adhesive layer thickness

IV. Dispensing technology

A. Dispensing Head Technology

The dispensing head is the interface between the adhesive reservoir and the substrate, responsible for precisely controlling the dispensing process. In micro-dispensing applications, where volumes can be as small as microliters or even nanoliters, the design and performance of the dispensing head is paramount. Advanced dispensing head technologies are characterized by features such as ultra-fine nozzles or tips, micro-valves for precise flow control, and non-contact dispensing mechanisms to prevent substrate damage or contamination. Additionally, the dispensing head must be compatible with a wide range of materials and capable of handling high-speed dispensing while maintaining accuracy and repeatability. Continuous innovation in dispensing head technology focuses on enhancing resolution, speed, versatility, and reliability to meet the demanding requirements of micro-dispensing production at scale.

B. Motion Platform Technology

The motion platform serves as the foundation for positioning and moving the dispensing head relative to the substrate with high precision and accuracy. In micro-dispensing applications, where the targeted features are often on the order of micrometers or smaller, motion control becomes critical for achieving sub-micron resolution and tight tolerances. Advanced motion platforms utilize technologies such as linear motors, piezoelectric actuators, or air-bearing stages to deliver smooth, precise, and dynamic motion control. These platforms are equipped with sophisticated feedback systems, such as encoders or laser interferometers, to ensure positional accuracy and repeatability. Moreover, they incorporate vibration damping mechanisms and thermal stability features to mitigate the influence of environmental factors on dispensing accuracy. Continuous advancements in motion platform technology aim to push the boundaries of precision, speed, and reliability to enable the efficient and scalable production of micro-dispensed components and devices.

V. The Elaboration of Micro-dispensing Head Technology

A. The Squeezing Pump Dispensing System

The squeezing pump dispensing system shown in Figure 6 heralds a groundbreaking advancement in dispensing technology, seamlessly combining time pressure controls with a proprietary pressurized fluid squeezing chamber. This innovative system, in conjunction with the designated Fluid-Sequences-Controller (FSC unit), achieves unparalleled precision in dispensing minuscule UV adhesive dots and lines. Notably versatile, it effortlessly accommodates a broad spectrum of materials, including high-thixotropic and high-viscosity substances, whether they contain fillers like solder paste or non-fillers like UV or dual curing adhesives.

A standout feature of the squeezing pump resides in its elimination of moving mechanism parts within the dispensing material chamber. This design element significantly mitigates the risk of altering material composition or behavior due to mechanical shock or over-pressurization, ensuring consistent performance. Particularly advantageous when handling filler materials such as silver-filled UV adhesives, it prevents the crushing of silver fillers or issues with material separation within the mixture, thereby reducing the incidence of filler deformation—a common culprit behind nozzle clogging during dispensing.

Moreover, the squeezing pump's pressurized fluid squeezing chamber is ingeniously engineered to obviate the need for excessively high chamber pressure to expel material from the nozzle while maintaining consistent dispensing volumes. In contrast to alternative dispensing systems like auger dispensers or jetting systems, this technology delivers precise dispensing in microscopic volume without requiring excessive air pressure force.

Complementing the squeezing pump technology is the indispensable role played by a meticulously designed motion platform. Crucially, achieving precise dot or line dispensing hinges on maintaining an optimal dispense gap—typically around 30% to 40% of the physical dispensed width or dot size [5]. Conventional motion platforms often falter in handling such minute gaps effectively, underscoring the necessity for an innovative, reliable, and high-performance motion platform. This platform must exhibit exceptional rigidity, stability, and motion accuracy to ensure precise dispensing control.

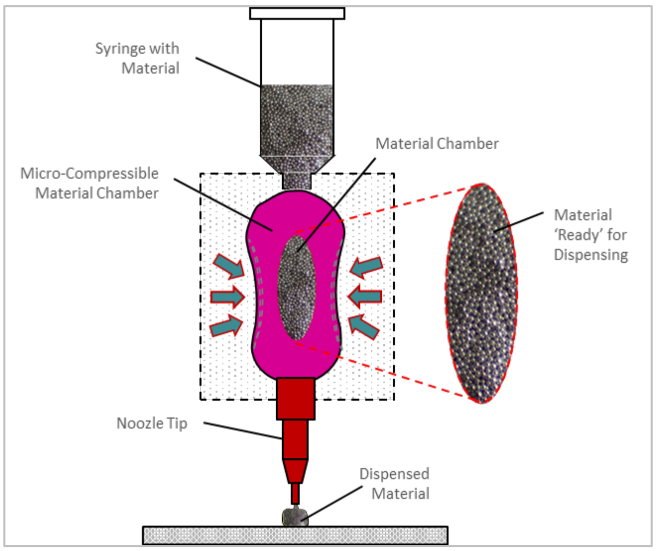

Figure 6 Provides a visual representation of the squeezing pump's operation.

B. The Advantages of a Bi-Directional Material Stabilizer in Squeezing Pump

Introducing a bi-directional material stabilizer (bi-directional temperature stabilizer) into this advanced dispensing system offers a substantial value proposition by significantly enhancing the stability of the micro-dispensing process through precise control of adhesive viscosity and flow behavior. This technology ensures optimal performance regardless of whether the equipment environment temperature is higher or lower.

A bi-directional material stabilizer maintains the adhesive at a consistent temperature, counteracting fluctuations in the surrounding environment. This consistency is crucial because temperature changes can significantly impact the viscosity of the dispensed adhesive, leading to variations in flow rates and compromising dispensing accuracy. By actively stabilizing the temperature—both heating and cooling as needed—the adhesive´s viscosity remains stable, ensuring precise control over the dispensing process.

C. The Volumetric Dispensing System

In conjunction with the innovative squeezing pump dispensing system, the volumetric dispensing pump system (figure 6), also recognized as the positive displacement piston pump, represents a pinnacle of micro-dispensing technology. Distinguished by its meticulous definition of dispensed volume through the interplay of piston diameter and stroke, this system is propelled by a specialized motorized control mechanism, enabling unprecedented fine volume dispensing capabilities reaching resolutions as precise as 0.3 nanoliters. This remarkable precision is calculated based on a 2mm piston diameter and a 0.1 micrometer piston stroke movement, underscores its status as an industry leader in micro-dispensing technology.

D. The volumetric pump system offers an array of advantages

1) *Superior Fine Dispensing Resolution*
Elevating dispensing precision to unprecedented levels, the system achieves fine volume resolutions as precise as 0.3 nanoliters. This capability enables the deposition of minute volumes with exceptional accuracy, meeting the stringent demands of microscopic dispensing requirements endemic to cutting-edge manufacturing environments.

2) *Versatility Across Viscosity Spectrum*
Demonstrating remarkable adaptability, the system accommodates an extensive range of material viscosities—from the low end of 1 mPas, akin to water, to approximately 50,000 mPas —without compromising dispensing volume accuracy. This versatility ensures consistent and reliable performance across diverse material types and applications, augmenting its utility in a myriad of industrial contexts spanning microelectronics to biotechnology.

3) Resilience to Viscosity Fluctuations
Unlike certain dispensing systems vulnerable to fluctuations in material viscosity over time, the volumetric dispensing pump system remains unaffected. This resilience stems from its unique working principle: the system utilizes air pressure to fill the dispensing pump's chamber, and once switched to dispensing mode, the air pressure is completely cut off, relying solely on piston movement to dispense the adhesive. This ensures that dispensed volumes remain unaffected by material rheological or behavioral changes over time,

maintaining consistent and precise dispensing outcomes.

Seamlessly aligning with the exacting requirements of contemporary manufacturing landscapes, particularly in advanced packaging and heterogeneous integration domains, this system emerges as an indispensable tool for facilitating precise adhesive deposition in the microelectronics fabrication processes. Whether tasked with dispensing adhesives, encapsulants, or other pivotal materials, the volumetric pump system stands as a cornerstone of micro-dispensing technology, poised to elevate production capabilities to new heights of precision and efficiency.

In summary, the integration of either squeezing pump or volumetric pump dispensing system with a cutting-edge motion platform represents a paradigm shift in micro-dispensing technology, enabling unprecedented levels of precision and reliability in heterogeneous integration and advanced packaging applications.

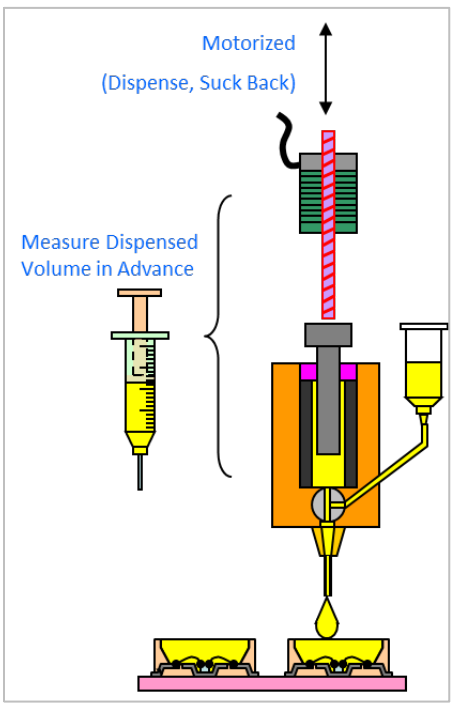

Figure 7 Provides a visual representation of the volumetric pump's operation.

VI. Experiment Methodology

This study focused on comparing the process capabilities of micro dam structures with 80µm dispensed widths and aspect ratios of 1x, 3x, and 8x. The objective was to create 100 sets of micro dam structures continuously, comparing the results with and without the application of UV curing. Additionally, the experiment aimed to assess the overall feasibility and quality of the dispensed micro dam structures at this production scale. At least four measurement points were taken from each micro dam structure, encompassing both width and height dimensions. Measurements were conducted both before and after curing.

Since, in addition to the investigation of the dispensing and curing behavior, the aging behavior also plays an important role, tests are carried out according to typical aging steps. Here, the elongation at tear and tensile strength using a shoulder bar test on a Zwick universal testing machine as well as the Young's modulus via DMTA are tested. Ageing is carried out in long-term storage at 85 °C / 85 % r.h. and at a high temperature of 150 °C, which corresponds to typical requirements from the automotive sector.

The final step is an adhesion test in the form of a die-shear test, which is carried out initially and in accordance with JEDEC MSL 1 and 500 hours 85 °C / 85 % r.h. The purpose of this test is to rule out a potential loss of adhesion in the interface between micro dam and substrate due to the high ageing load. Chosen as substrate material have been FR4 and copper which represent common surfaces the adhesive as to stick to. To be able to test the adhesion by pure light curing, glass cubes were used, which can be irradiated with UV light.

VII. The Test Vehicle

The selected test specimens for this experiment comprise an 8" bare Silicon wafer and FR4 board. The decision to utilize an 8" bare wafer stems from its notable characteristic of possessing a highly flat surface, thereby intended to mitigate any potential variability attributed to surface flatness. Conversely, the inclusion of an FR4 board with a warpage condition serves the purpose of evaluating the viability and efficacy of dispensing this micro dam feature onto a non-planar surface. This strategic choice facilitates a comprehensive assessment of the dispensing process under varying substrate conditions, thereby contributing to a robust understanding of its applicability and performance across different substrates.

Figure 8 8" bare wafer

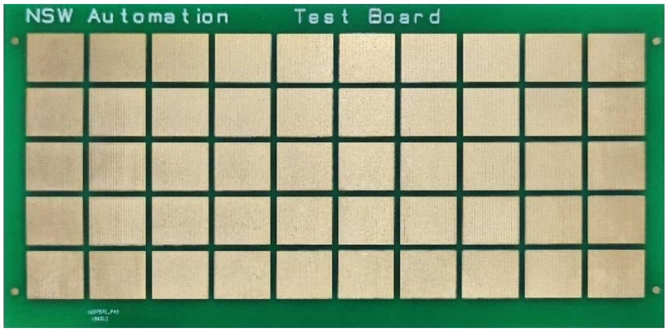

Figure 9 NSW FR4 test board

VIII. The Test Equipment

- NSW Micro-squeezing pump on both W12-2020 and N4 micro-dispensing motion platform.
- NSW S50-C series ceramic nozzle with Ø 100 µm inner diameter (Figure 21)
- DELO LUX 20/400 A1 UV lamp
- Keyence VHX6000 high power digital microscope with magnification up to 2000x.

IX. Results

The optimization of adhesive rheology, dispensing setup and parameters resulted in impressive micro dam dimensions as illustrated in figure 10, 11 & 16 (picture taken after UV curing). Bondline width and height could meet targets and even more. Measurement examples in Figure 12 – 15 show stable dimensions all along.

Figure 10 Investigation micro dam result on 8" bare wafer via microscope.

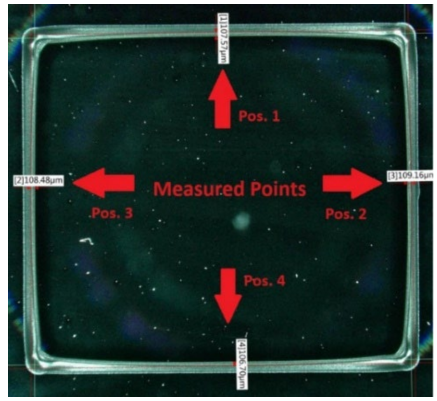

Figure 11 Measured points of each width and height

Figure 12 Width comparison of 1x aspect ratio micro dam

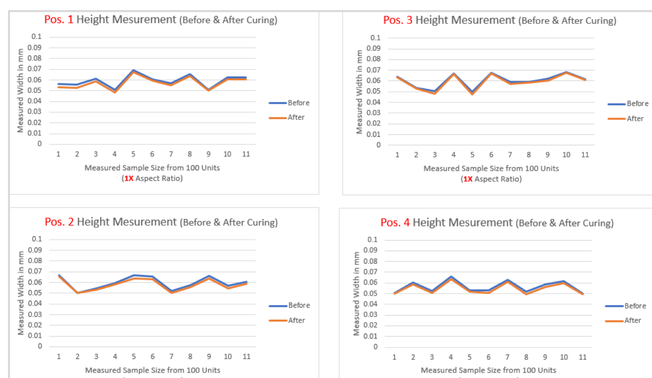

Figure 13 Height comparison of 1x aspect ratio micro dam

Figure 14 Width comparison of 8X aspect ratio micro dam

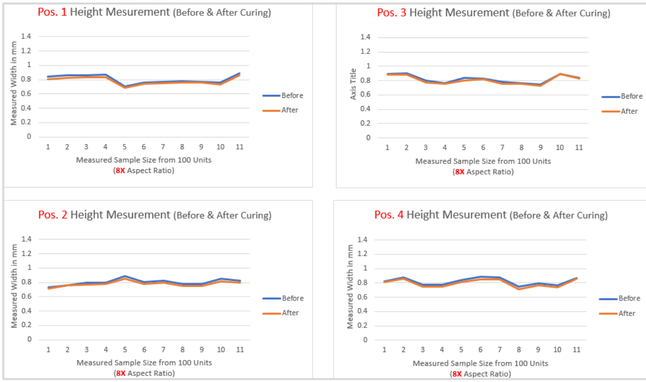

Figure 15 Height comparison of 8x aspect ratio micro dam

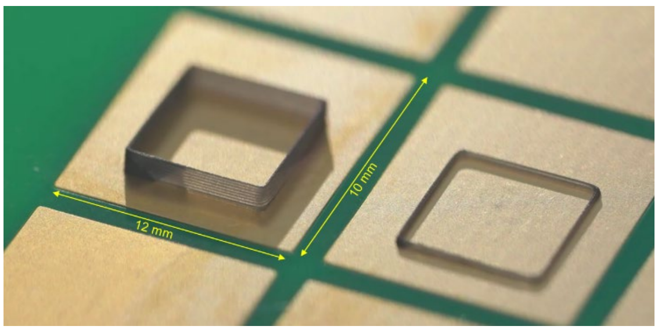

Figure 16 Investigation micro dam result on FR4 via microscope

Aspect ratios in the range of 5 while maintaining a maximum width of less than 100 µm provide design freedom footprint of the micro dam.

As the dispensing and curing of the adhesives only prove their suitability in the initial state after curing, tests were then carried out on their aging behavior. Core properties such as tensile strength, elongation at tear and the Young's modulus was tested initially as well as after aging, which is typical for the semiconductor and microelectronic industry. The following diagrams in Figures 18, 19 and 20 show the change after the respective ageing steps compared to the original condition. It can be seen that material aging has very little influence on the mechanical properties, which is essential in order to achieve the desired consistently high performance in the final package.

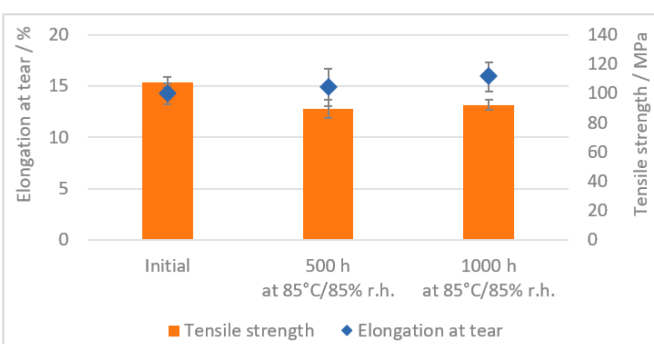

Figure 17 Investigation of tensile strength and elongation at tear

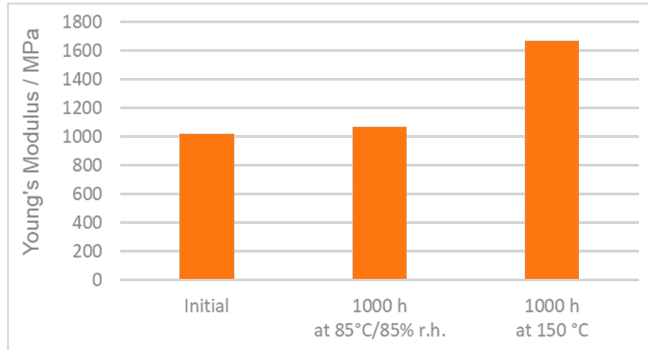

Figure 18 Investigation of Young´s modulus

As described earlier the behavior of adhesion after aging is of greater importance. The performed die shear strength measurements showed stable results on high level without significant decrease after reliability testing as shown in Figure 19.

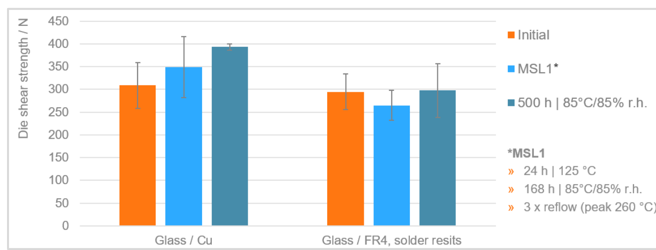

Figure 19 Investigation of die shear strength

Acknowledgment

We would like to thank NSW and DELO for the exceptionally good cooperation. Special thanks to Chng Kheng Poh from DELO, who acted as a link for the flow of information and exchange.

References

[1] Kai Hollstein, Kirsten Weie Zaage, „Advances in Packaging for Emerging Technologies “, Pan Pacific Microelectronics Symposium, 2020

[2] Brad Perkins, Jared Wilburn, “Throughput vs. Wet-Out Area Study for Package on Package (PoP) Underfill Dispensing”, APEX EXPO IPC, 2013

[3] Christophe Faucher-Courchesne, David Danovitch, Lise Brault, Marie-Claude Paquet, Eric Tucotte, “Controlling Underfill Lateral Flow to Improve Component Density in Heterogeneously Integrated Packaging Systems”, IEEE 68th Electronic Components and Technology Conference, 2018

[4] Jiajia Zou, Mengquiu Huang, Dan Zhao, Fang Chen, Daochang Wang, „Modeling the contact dispensing process of conductive adhesives with different viscosities and optimization of droplet deposition”, Polymeric and Composite Materials, 2023

[5] Ping Zhu, Zheng Xu, Xiaodong Wang, Yuansong Zheng, Xiaoyu Xu, Liding Wang, “Influence of initial distance between needle tip and substrate on contact dispensing of high-viscosity adhesive”, International Journal of Adhesion and Adhesives, Volume 85, October 2018, Pages 23-28,