Patterning high resolution features through the integration of an advanced lithography system with a novel nozzle-less spray coating technology

Jack Mach, Corey Shay
Applications Engineer
Rudolph Technologies
Wilmington, MA, USA
Jack.mach@rudolphtech.com

Stuart Erickson
President
Ultrasonic Systems, Inc.
Haverhill, MA, USA
SErickson@ultraspray.com

Gary Smith
Regional Manager
Sumitomo Chemical Advanced Technologies
Phoenix, AZ, USA
Gsmith@sumichem-at.com

***Abstract*—As demand for ever more powerful personal handheld devices and advanced computing systems continues to grow, front-end manufacturers have pushed Moore's Law to the limit and integrated more functionality into their chips while at the same time reducing their physical footprint. Modern chips are now packing more I/O channels into a smaller area than ever before. Being able to interface these devices is becoming more challenging and it is up to the advanced packaging industry to continue to develop technologies and methods to accommodate this requirement, while at the same time, reducing costs and increasing throughput.**

There are inherent topographical challenges associated with the growth of 2.5D and 3D packaging where chips are placed and interconnected horizontally and vertically. The industry's drive for cost reduction is building momentum toward large format panels and away from traditional wafers. Larger format panels are exacerbating existing issues, for example, warpage and film stresses. These variables affect the resist coating and exposure steps critical for optimal lithography. Moreover, the current liquid film application methods have encountered obstacles in meeting uniformity requirements for these large panel sizes. Non-uniform film thickness can cause processing variability and poor critical dimension control negatively impacting yield.

This paper demonstrates the feasibility of a revolutionary technique in the form of nozzle-less ultrasonic spray technology in conjunction with a next generation advanced packaging lithographic system for the creation of high-density, sub-2.0µm interconnects on a panel format. Performance parameters including resist thickness uniformity, sidewall angle and profile, will be compared and analyzed for this approach and other liquid film application methods. Results from the examination of the efficacy, cost reduction potential of this novel method for high-volume manufacturing will be presented.

Keywords-nozzle-less spray; RDL; PLP; WLP; panel; wafer; advanced packaging; stepper; photoresist

I. Introduction

Demand for more functionality and power in electronic devices continues unabated and will certainly continue into the future. Handheld personal devices, wearables, IoT devices, and even automotive components are all contributing to this momentum. This increased performance demand is accompanied by a seemingly conflicting goal of also reducing the form factor of these modern devices. With front-end-of-line (FEOL) approaching the absolute limits of what can be packed into a chip, it has fallen to the back-end-of-line (BEOL) to shoulder this burden.

Advanced packaging is one of the main BEOL suites of technologies where significant gains are still being made. Through the interfacing of chips coming from the FEOL, dedicated packages can be manufactured to meet the performance and dimensional requirements of today's electronics.

Traditionally, advanced packaging has been a predominantly wafer-centric affair, in fan-out wafer level packaging (FOWLP), silicon wafers are diced and reassembled on reconstituted wafers to allow for the redistribution of their I/O channels to other locations and/or chips. In recent years, though, driven in part by the constant need to increase yields and lower cost, panel-level packaging has become an attractive alternative with a growing number of manufacturers investigating and adopting this new medium. This switch has the immediate benefit of mitigating the "square peg, round hole" inefficiency that is inherent in wafer-level packaging. [1]

The changeover to panel-level packaging is not without new challenges. Issues that already affect WLP, such as warpage and film stresses become much more pronounced when scaled up to much larger panels. Furthermore, the topographies routinely encountered in modern packages can potentially create film voids when using traditional coating methods. These phenomena create immense difficulty in the crucial lithographic step of coating. Current liquid film application techniques have encountered shortcomings in being able to uniformly coat the larger format panels that are expected in the near future. This non-uniformity directly impacts the exposure step. Any variation in film thickness will result in variable dose, making targeting and maintaining a process window—an especially critical component for lithographic yield—very difficult.

Spin coating is a classic film coating method that involves dispensing a puddle on a substrate and then spinning the material to the desired thickness. The resulting film thickness is a function of viscosity of the material, spin speeds used and the duration of the spin. Spin coating is susceptible to particles on the substrate causing "comets", has trouble conforming to topography and is very wasteful since a large amount of the dispensed material is spun off. Additionally, spinning large panels is physically challenging.

Slot die coating is a ubiquitous technology in the flat panel display (FPD) industry. A film of material is extruded from a head, typically the width of the substrate, and drawn across the length of the panel. Thickness is a function of head speed, viscosity and the integrity of the meniscus. Unfortunately, the only similarity between FPD and PLP substrates are the shape. The PLP substrates are much more warped. In some cases, the warpage can exceed 12mm. This presents serious uniformity challenges for slot die coating as any variation in the distance between the substrate and the die will cause the meniscus to vary and result in local non-uniformity. This would apply to any topography as well.

One emerging technology that is showing immense promise is ultrasonic nozzle-less spray coating. The big difference with this system versus other systems is in the manner in which the spray pattern is formed.

In order to prove the viability of this new method, certain performance characteristics must be proven to be the same, if not better, when compared with the current offerings. The topics discussed in this paper center around the coating process and related details such as resist thickness uniformity, economics and any potential impact on the lithographic process. Lithographic characteristics including sidewall angle (SWA), profile, and critical dimension (CD) will be investigated.

II. Equipment and Material

A. Spray Coater

Spray coating resist is not a new concept. Unfortunately, there is a weakness with most traditional spray technologies. Spray nozzles of all types tend to produce a conical or elliptical shaped coating pattern on the substrate. This results in a more "parabolic" coating distribution across the width of a single sprayed segment.

The spray coating system used for this series of experiments and tests was the Ultrasonic Systems, Inc. Prism 800. What makes this spray system different from the others is the manner in which the spray is generated by the spray head as well as the way it is coupled with a precision coating system platform where all critical process parameters are under machine control.

This technology is capable of spraying a wide variety of materials from pure solutions to suspensions and slurries while producing a uniform coating layer on the substrate. [2,3,4]

The spray head is an integrated assembly consisting of an ultrasonic transducer with a spray forming tip, a liquid applicator and air directors as shown in Fig. 1. The ultrasonic transducer vibrates at an ultrasonic frequency (> 20 kHz). The particular ultrasonic frequency is selected based upon the material to be sprayed and the coating application requirements. In general, a lower frequency ultrasonic transducer is capable of spraying a higher viscosity liquid and producing higher flow rates. The amplitude of vibration of the spray-forming tip is also set with the ultrasonic generator.

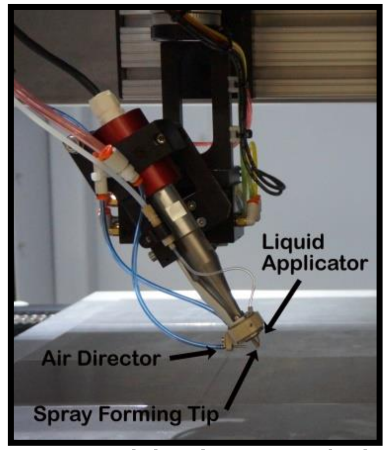

Figure 1. Nozzle-less ultrasonic spray head.

The photoresist is delivered to the spray-forming tip on the ultrasonic transducer by liquid applicator. The liquid photoresist is stored in a reservoir and fed to the liquid applicator at a precisely controlled flow rate by a positive displacement pump as shown in Fig. 2. The ultrasonic vibrations of the spray-forming tip break up the liquid into small drops and propel them from the tip in the form of a spray. The spray produced with ultrasonic energy alone has a very low velocity "sheet-like" pattern.

Air directors are used to produce air streams to shape and accelerate the ultrasonically-produced spray. The air director impinges a jet of air on the tip of the spray head opposite the liquid feed side. The resulting airflow entrains and expands the ultrasonically-produced spray to produce a flat (rectilinear) pattern up to five times the width of the pattern produced by the ultrasonic energy alone. When using the air directors, the spray pattern width is a function of the spray-forming tip width and tip-to-substrate distance. In this case, the spray pattern width is 20mm.

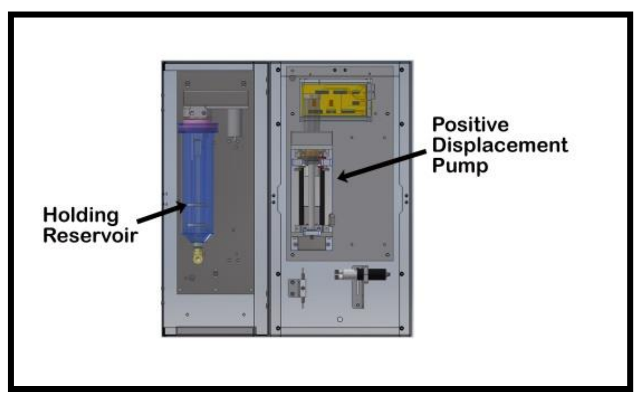

Figure 2. Liquid delivery system.

This nozzle-less ultrasonic spray head produces a substantially rectangular-shaped coating distribution on the substrate. The rectangular shape is ideal for producing a uniform coating on a flat surface. The actual coating distribution is uniform across about 90% of the width of the sprayed pattern and the edges are "feathered" from the applied coating thickness to zero thickness. Fig. 3 shows the spray pattern distribution comparison between the nozzle-less spray head and a traditional spray head as well as the resultant distribution after a series of overlapping passes.

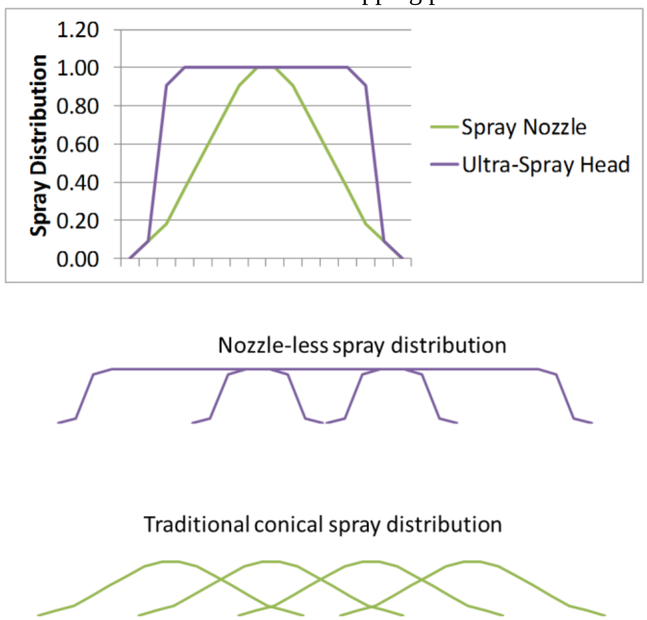

Figure 3. Spray distribution comparison between nozzle-less spray head compared to traditional spray nozzle.

In this instance, the parabolic coverage of a traditional spray head would yield poor uniformity and improving uniformity would likely result in needing to run extra passes, sacrificing throughput.

B. *Lithography System*

When processing a thick photoresist, well controlled sidewall angles are a critical requirement, especially when electroplating tall copper pillars and redistribution layer (RDL) structures. Most front-end tools have high numerical aperture (NA) lenses with low depth of focus (DOF) that prevent adequate penetration of thick films with sufficient image contrast to achieve the side wall angle and resolution requirements. Mask aligners struggle with high aspect ratio imaging, not because of their NA, but because they are unable to provide the necessary focus offset required to penetrate the film at high resolution, limiting their ultimate aspect ratio and side wall angle control. Although photoresist sidewall angles are primarily a function of the photoresist material and its processing (pre-bake, post-bake, developing, etc.), the exposure system plays an important role. Accurate focus control across the wafer or substrate is required to achieve consistent and accurate CD control with straight and perpendicular side walls.

The lithography stepper utilized in this study was the Rudolph Technologies JetStep® S3500 System. This system is a panel system but for the purposes of this study, an adapter was manufactured to allow for the accommodation of wafers as well as panels. This particular system uses a 2x reduction, 0.1 NA, single-telecentric lens system that provides a very large DOF to maintain image integrity and CD control, a priority for high aspect ratio imaging in the film thicknesses typically experienced in advanced packaging. The stepper lens is achromatized and the installed “filter wheel” provides the user a choice of illumination wavelengths to expose the photoresist layers. Specifically, the user has the ability to image at either “broadband” ghi- (350-450nm), gh- (390 to 450nm) or i-line (365nm) wavelengths. For this study, all exposures were done at i-line.

The system utilizes an “on the fly” focus control system to ensure that every exposure is at the optimum focal plane height. This capability is essential when advanced packaging substrates become warped by film stress and thermal cycling, stressing already tight process windows.

C. *Resist*

A variant of Sumitomo Chemical’s Xi family of resists were selected for this study. The Xi resists were a suitable candidate for this testing because they cover a very wide range of film thicknesses and are sensitive for i-line and broadband exposures making these products ideal for wafer- and panel-level process requirements such as 2/2 RDL and 2.1/2.5D packaging. Compatible for all coating methods and customized to suit most substrate and plating requirements, they are very flexible for many applications being developed for packaging solutions.

D. *Panel Track*

The track system used for this study contains a series of inline modules fed by a conveyor system. Each of the inline modules handles a different portion of the develop process, i.e. 2.38% TMAH puddle immersion, DI water rinse, and air dry. Total process time is set by the conveyor speed. Therefore, lengthening or shortening any of the individual process steps would result in a corresponding change in the process times in the other inline modules. Because the develop module is a singular module, multiple puddles are not feasible.

E. *Wafer Track System*

Wafer processing duties, with the exception of the spray coated wafer, were handled by a combination spin coat and develop system. This system has four modules that work independently of each other with inter-module transfers being handled by a transfer arm. There are stations for spin coating, hot plate, chill plate and develop.

III. TEST PROCEDURE

A. *Resist Preparation For Spray*

The spray system being tested can handle viscosities from 1 to 40 centipoise. In order to optimize the resist for spraying, it was necessary to dilute the resist with PGMEA. Precisely controlling the ratio of resist to PGMEA is important to achieve the correct dilution. To determine the correct dilution rate between resist and solvent, it was necessary to first determine the solids content of the undiluted resist. A precision syringe-based dispensing system was used for all volumetric measurements. 5mL of resist was dispensed into an aluminum cup that was pre-tared on a scale. The starting mass was recorded and then the cup, with resist, was placed on a hot plate and baked until no more mass change was observed. This final mass was then divided by the starting mass to determine the solids content of the material. PGMEA was then added to the resist to bring the solids content to the desired number for spray application.

The resist meant for spin coating was left untouched as it would normally be used as formulated from the resist manufacturer.

B. Spin Coat Process

Spin coating was done with the wafer track described previously. The recipe progression followed a typical spin coat progression of resist dispense on the wafer, spinning the material to the correct thickness and then a post application bake (PAB) on a hot plate which was then followed by a chill step.

C. Spray Coat Process

The spray coat process begins with the mixing/dilution of the resist. When this technology is scaled up, resist manufacturers will likely have special formulations optimized for this type of processing, mitigating the need for this step. The substrate was then loaded to the stage and then sprayed. After spraying, the substrate was allowed to relax so that the remaining solvent could dry out before then being placed into an oven and baked.

The PAB step for this spray coating process is a bit unconventional in that it was done using a convection oven. The panel was hung from a rack using hooks. Due to this arrangement, there is much less heat transfer than a normal bake in which the substrate is typically in contact with a hot plate/heating surface. This results in a much longer PAB time at slightly higher temperatures.

D. Lithography

One of the focuses of this test was to show that there were no detrimental effects from the spray coating of the resist as opposed to traditional spin coating. Of particular interest were any differences of the sidewall angles and profiles as well as the CDs achievable between nozzle-less spray coating and spin coating. Testing these points would involve spray coating a 510mm x 515mm copper-clad laminate (CCL) panel with the selected resist as well as spin coating a copper-seeded wafer with the same material to roughly the same thicknesses. These two substrates were then exposed with the reticle feature shown in Fig. 4 in focus exposure matrix (FEM) layouts. The reticle feature contains line/space and post/via structures ranging from 1.0µm up to 50µm. In this study, particular attention was paid to the sub-5.0µm modules.

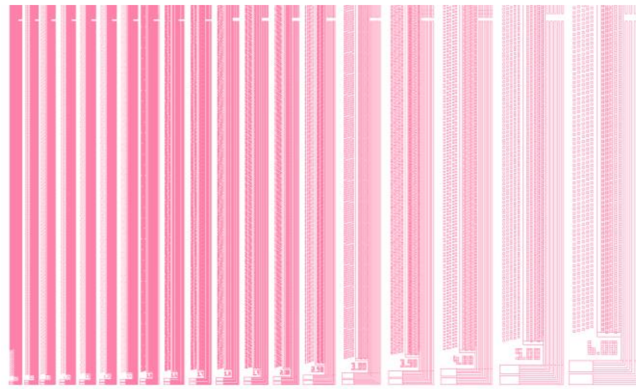

Figure 4. Resolution module used in FEM.

An FEM layout contains a large range of programmed focus and exposure conditions at a fixed stepping distance to enable quick and efficient characterization of the lithographic process window and the focus and exposure settings needed to achieve the best result. Figs. 5 and 6 show the FEM matrix applied to each test substrate.

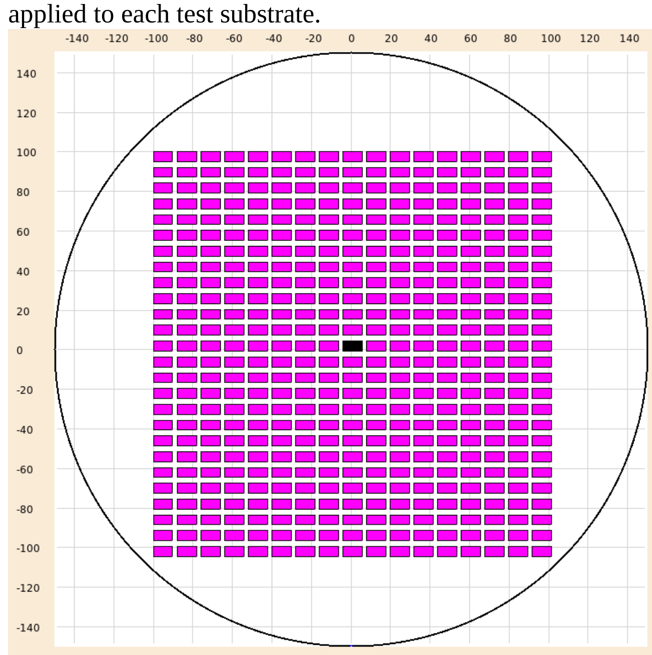

Figure 5. Wafer FEM layout.

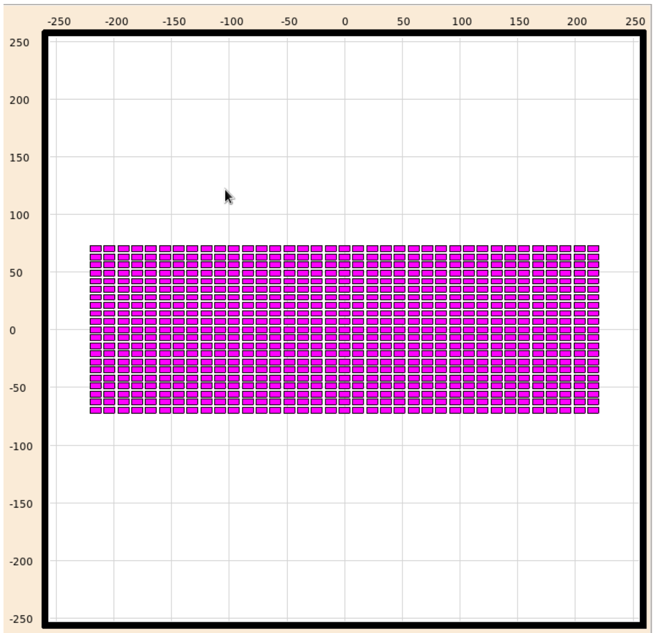

Figure 6. Panel FEM layout

E. *Development process*

After exposure, the substrates were developed with no post-exposure bake (PEB) applied. The previously determined optimal develop cycle for this resist is three separate 60 second puddles using 2.38% tetramethylammonium hydroxide (TMAH). These conditions were arrived at through extensive testing on the wafer track system.

The wafer was processed on the wafer track system using the process conditions noted earlier.

Because of size limitations of the spin coater and develop system, which could only handle up to a 300mm wafer, the panel could not be processed in the same manner. Panel processing was done on the track system. As mentioned earlier, this system, with its conveyor track, cannot produce multiple puddle develop cycles. In this case, it was important to emulate, as closely as possible, the best known develop method. To do this, the track conveyor speed was programmed to allow the panel 180 seconds inside of the develop module. The multi-puddle approach is typically used to replenish the developer on a wafer mid-develop and with the much larger volume of the puddle immersion available in the panel track, this lack of multiple puddles would have much less significance on the ultimate results.

IV. RESULTS AND DISCUSSION

Data collection was performed on the substrates after processing. Film thickness measurements were done along with SEM analysis.

A. *Film Thickness Uniformity*

Film thickness uniformity is one of the most critical elements to control in high volume manufacturing lithography. In general, a thicker film of a given material will require a higher dose, thin film effects and swing curves aside. It is obvious then that variations in film thickness across a substrate will result in variable exposure doses needed for different areas of the substrate. This will cause variable critical dimensions (CD) across the substrate, negatively impacting yield. It is therefore imperative that a coating system be able to deliver excellent film thickness uniformity. In order to compare film thickness uniformity between the new nozzle-less spray technology against spin coating, a test was performed in which two 300mm copper-seeded wafers were coated with photoresist to 7µm using the two methods. Since the spin coater could not handle panels, but the spray coater could handle wafers, copper-seeded wafers were selected in order to limit the number of variables in the experiment.

After the wafers were coated, the film thickness profile of each one was measured. The film thickness measurement was done using a system that employs spectral reflectance.

By measuring in 2mm increments across one axis of the wafer, the profile of the coating could be ascertained and the nonuniformity of the film understood. The axis of the measurements is shown in Fig. 7.

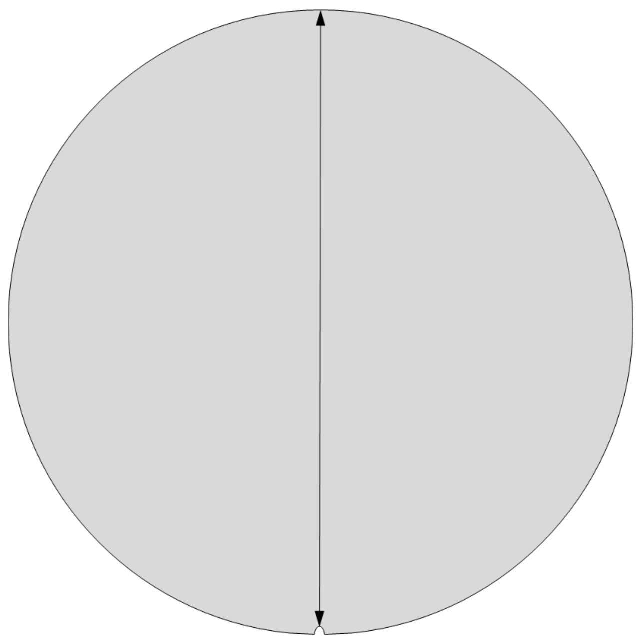

Figure 7. Axis of film thickness profile measurements.

The profile of the data suggests, as expected, that the film thickness is a function of the radius from center. Also seen in the measurement is the roll off of the edge bead along the edges of the wafer. This is the step measuring approximately 4.5µm of thickness on either side of the wafer. Omitting the step from the edge bead, the average film thickness on the spun wafer is 7.47µm. With a range of 310nm, this yielded a film thickness non-uniformity of 4.15%.

The profile across the sprayed wafer can be seen in Fig. 8. Immediately obvious is the extremely uniform profile. The near zero readings toward the edges of the wafer are an artifact of the measurement beam interfering with the edges of the wafer, resulting in a poor match with the film stack model. Omitting the data on the edges of the wafer yields an average film thickness of 6.675µm with a range of 133nm. This yields a film thickness non-uniformity of 1.99%.

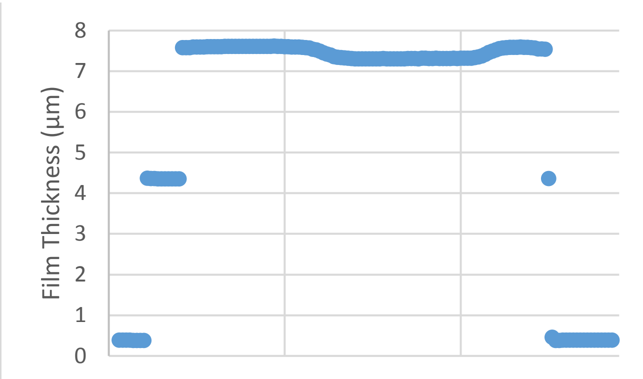

Figure 8. Film thickness profile of spin coated wafer.

The data shows that there is an improvement of over 50% in film thickness uniformity when moving from the traditional spin coat method to the new nozzle-less spray technology (Fig. 9).

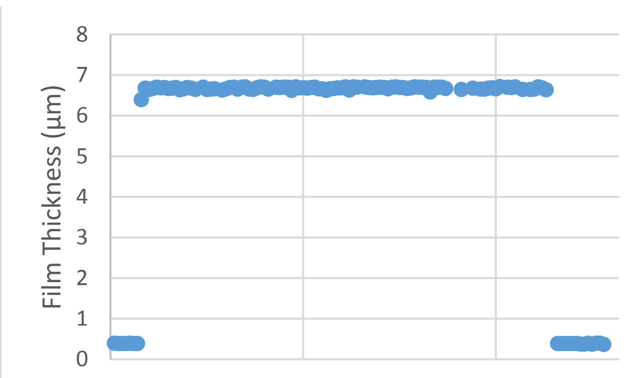

Figure 9. Film thickness profile of spray coated panel.

B. *Imaging Performance*

Proving out the film thickness uniformity capabilities of nozzle-less spray technology was merely the first step. The next step was to prove out that there is no detrimental effect from spraying the resist on the actual imaging performance. After the lithographic step, the FEMs exposed were analyzed in a scanning electron microscope (SEM). Of particular interest were sidewall angles and profiles as well as the ultimate CDs achieved. Here, the desired characteristics include vertical sidewall angles as well as the highest resolution possible. These traits lend themselves favorably to the continued evolution of RDL dimensions likely required in the future of advanced packaging. Fig. 10 is a SEM image of 2µm line/space in 7µm of resist on a spin coated copper-seeded wafer.

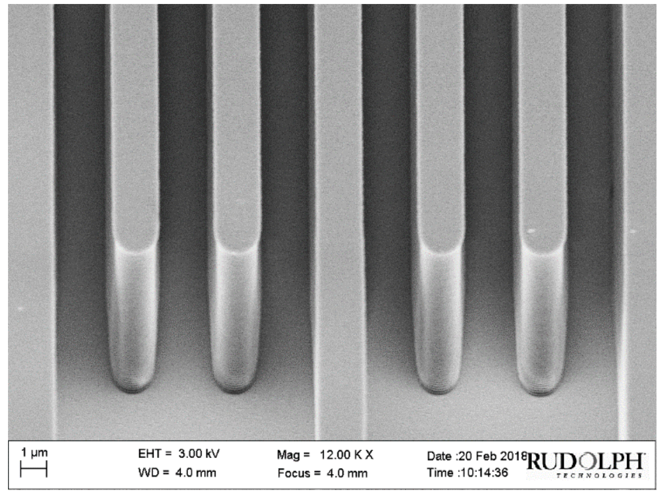

Figure 10. Profile of 2µm L/S in 7µm of resist on Cu seeded wafer.

This image clearly shows all of the desired characteristics that were previously discussed. The sidewalls are nearly vertical, yielding trenches that can be plated to an aspect ratios of over 3:1.

To confirm that spray coating had no detrimental effects, a copper-seeded wafer was spray coated with the USI system and then exposed and processed. This yielded impressive results as well. Fig. 11 shows this clearly.

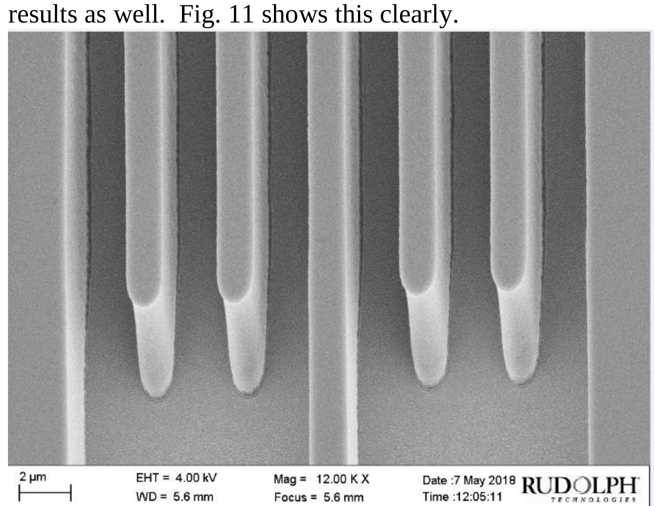

Figure 11. Profile of 1.8µm L/S in 7µm of resist on spray coated copper seeded wafer.

With the spray coated wafer, the resist and equipment combination was able to achieve 1.8µm line/space in 7µm of resist. Again, the sidewalls are nearly vertical.

The next step was to apply spray coating technology to a substrate much more relevant to, and representative of, the future of packaging. A CCL panel was spray coated, exposed and developed (Fig. 12).

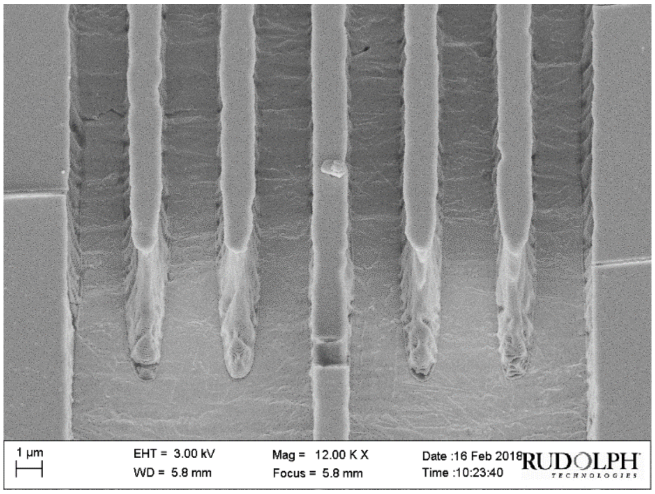

Figure 12. Profile of 1.8µm L/S in 7µm of resist on spray coated CCL panel.

With the spray coated CCL panel, the resist and equipment combination was able to achieve 1.8µm line/space in 7µm of resist coated on a very rough copper surface. Again, the sidewalls are nearly vertical. The roughness of the profiles are likely attributable to the rough copper surface scattering light in various directions as the effect was not seen in the spray coated wafer.

C. *Resist Efficiency*

In the cost-conscious world of advanced packaging, as with any type of high volume manufacturing, any time less material can be used directly translates to savings per unit. Testing was done to determine the absolute smallest amount of material that could be used to completely spin coat a wafer and spray coat a panel.

By determining the total area of each substrate and then dividing it by the amount of resist required, a ratio of area covered per milliliter could be calculated, offering a simple way to analyze and compare efficiency between both coating methods. A higher area covered per milliliter is desirable by this metric.

In the case of the spin coated wafer, the absolute minimum amount of resist to cover a 300mm wafer was 5mL. In this case, the resist covers 14,137.17mm^2/mL. For the spray coated panel, a total of 14.77mL of 50:50 PGMEA-diluted resist was used to coat a 510mm x 515mm panel, yielding coverage of 17,782.67mm^2/mL. If the fact that this resist was diluted is taken into account, an efficiency gain of 2x when using nozzle-less spray is realized.

V. CONCLUSIONS

Advanced packaging continues to evolve and along with it, there are warped panels and substrates, topography and ever more demanding geometries with which to contend. Many of the traditional coating technologies are approaching limitations when facing these challenges. Through the combination of the latest in packaging stepper technology, a novel new nozzle-less spray technology and an optimized resist, gains have been shown in film thickness uniformity that will help tightening process windows. The same combination has also yielded sub-2.0µm L/S suitable for next-generation RDL requirements while simultaneously showing marked gains in resist usage efficiency, allowing for greater profit margins.

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REFERENCES

[1] Rich Rogoff, Rudolph Technologies, "A Square Peg in a Round Hole – The Economics of Panel-based Lithography for Advanced Packaging Applications", Solid State Technology, February 2014.

[2] Tao Wang, Nicholas W. Scarratt, Hunan Yi, Alan D. F. Dunbar, Andrew J. Pearson, Darren C. Watters, Tom S. Glen, Andrew C. Brook, James Kingsley, Alastair R. Buckley, Maximilian W. A. Skoda, Athene M. Donald, Richard A. L. Jones, Ahmed Iraqi, David G. Lidzey. "Fabricating High Performance, Donor–Acceptor Copolymer Solar Cells by Spray-Coating in Air", Advanced Energy Materials, 2013

[3] Jonathan Griffin, Anthony J. Ryan, David G. Lidzey, "Solution modification of PEDOT:PSS inks for ultrasonic spray coating", Elselvier

[4] Stuart Erickson, Ultrasonic Systems, Inc., "NEW APPLICATION METHOD FOR PACKAGE LEVEL EMI SHIELD COATING"; IEEE Proceedings from the CSTIC Packaging & Assembly Symposium; Semicon, Shanghai 2018

[5] Klaus Ruhmer, Rudolph Technologies, "Lithography Challenges FOR 2.5D Interposer Manufacturing", ECTC

[6] Mark Lapedus, "Fan-Out Wars Begin", Semiconductor Engineering, https://semiengineering.com/fan-out-wars-begin/

[7] Roger McCleary, Philippe Cochet, Tom Swarbrick, ChinTiong Sim, Gurvinder Singh, Rudolph Technologies, Yong Chang Bum, Andy KyawOo, Aung, STATS ChipPAC, "Panel Level Advanced Packaging", ECTC