

Process to Produce High Aspect Ratio Electroplated Copper Pillars on 300 mm Wafers

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ABSTRACT

This work provides details of a complete and partially optimized process to manufacture high aspect ratio copper pillars with heights of up to 80 μm on 200 and 300 mm wafers. Across wafer uniformity data for all materials and process steps are given. Results will show excellent resist adhesion on copper and electroplating durability. Cross sectional SEM analysis of resist and electroplated pillars is used to establish process latitude. Lithography has been performed using a high performance negative photoresist specifically developed for solder bumping, copper pillars and MEMS applications targeting high film thickness, aspect ratios > 4 and short processing times with large process windows using a single coat process. The electrodeposition of copper was performed at deposition rates of up to 7.5 $\mu\text{m}/\text{min}$ using a process specifically designed for high rate, through resist copper pillar deposition.

Keywords: Negative photoresist, electroplating, copper pillar bumping, advanced packaging, MEMS

1. INTRODUCTION

Since its introduction by Advanpack Solutions PTE, Cu pillar bumping technology has been qualified by several companies as a cost competitive method to provide high density pitch bumps with predictable standoff heights.^{1,2} In addition, the technology provides numerous advantages for advanced microelectronic packaging, such as low electrical resistance, high thermal conductivity, excellent mechanical stability, ease of underfill and maintaining current standoff. With increasingly thinner wafers they may also help to improve chip stability.

This work provides details of a complete and partially optimized process to manufacture high aspect ratio copper pillars with heights of up to 100 μm on 200 and 300 mm wafers. Across wafer uniformity data for all materials and process steps are given. Results show excellent resist adhesion on copper and electroplating durability. Cross sectional SEM analysis of resist and electroplated pillars is used to establish process latitude. Lithography has been performed using a high performance negative photoresist specifically developed for solder bumping, copper pillars and MEMS applications targeting high film thickness, aspect ratios > 4 and short processing times with large process windows using a single coat process. In order to achieve the highest aspect ratios the resist was exposed using a broad band, low numerical aperture stepper. After descumming the wafers using an oxygen plasma process to ensure hydrophilic, wettable structures, plating experiments were performed on a Semitool CFD3 plating reactor using a standard copper plating solution and two new processes designed for higher deposition rates. Deposition rates of up to 7.5 $\mu\text{m}/\text{min}$ were demonstrated with a within wafer thickness non-uniformity of less than 5% (1-sigma) for all feature types and for each resist thickness. We also show the effect of resist thickness on bump shape at the different deposition rates. Finally the resist was stripped using a stripper originally designed for standard novolak positive resists.

2. EXPERIMENTAL

2.1 Lithography equipment

Lithography for the photoresist evaluated in this study was performed on a Xggee/Ultratech Unity AP300 Stepper. The stepper is based on the 1X Wynne-Dyson lens design employing Hg ghi-line illumination from 350 to 450 nm and having a 0.16 NA.³

Broadband exposure is possible due to the unique design characteristics of the Wynne Dyson lens system. This symmetric catadioptric lens system does not introduce the chromatic aberrations common to other lens systems when broadband illumination is used. The low NA and broadband illumination spectrum of the Unity AP300 Wafer Stepper provides a more uniform aerial image through the depth of the ultrathick photosensitive materials in contrast to steppers with larger NA's and a relatively narrow bandwidth.⁴ In addition, the AP300 is equipped with a filter changer, which allows ghi-line (350 to 450 nm), gh-line (390 to 450 nm) or i-line (355 to 375 nm) illumination to be selected. This approach can be used to optimize lithographic performance based on the spectral sensitivity of the photosensitive material. In addition, the stepper has dual illuminators with a wafer plane irradiance of ≥ 2400 mW/cm² to improve throughput in thick photoresist processing. The Unity AP300 Wafer Stepper is configured to run both 300 mm and 200 mm wafer sizes. The stepper is also configured with a Wafer Edge Exposure (WEE) unit, which uses Mercury arc lamp light source at the prealigner to expose resist at the edge of the wafer. In this study, since the resist is negative, combining Edge Bead Removal at coating and Wafer Edge Exposing at the stepper will create a seal ring to meet the plating set up requirement.

The Xgseq/Ultratech 1X reticle used to establish the process window was designed to support cross sectional SEM metrology. This reticle consists of two fields of 10 mm by 10 mm, one of each polarity. Each field contains line and square contact patterns from 10 μ m to 100 μ m. The reticle used for plating has a 20.5 mm by 12.9 mm field size, one of each polarity. Each field consists of round, square, and octagon contacts from 50 to 100 microns CD with 1:1, 1:2 and 2:1 pitches.

Suss ACS200 and ACS300 tracks were used to coat, bake and develop the resist. After exposure the wafers were cleaved and cross-sectional images were taken on Amray SEM.

2.2 Photoresist processing

AZ[®] EXP 125nX-10A covers film thickness in the range of 40 to 120 μ m by single coating. Film thicknesses up to 200 μ m were achieved by double coating. The AZ[®] EXP 125nXT-10A resist is developable in both TMAH developer (AZ[®] 300 MIF) and inorganic developer (AZ[®] 303N). SEMI standard 200 mm and 300 mm ultra-flat silicon wafers and silicon wafers sputtered with 3500 Angstroms of copper were used in this study. Film thickness and coating uniformity were analyzed with Foothill KT-22 measurement system. As an example, the process conditions of AZ[®] EXP 125nXT-10A and equipment were described in Table 1. The target film thickness is 70 μ m by single coating.

2.3 Electroplating process

The patterned wafers were sent to Semitool for Cu electroplating. The wafers were plated up to 80% of the resist film thickness by using the plating conditions listed in Table 2. Only minimal descum is needed due to the high photoresist contrast. After electroplating, the photoresist was easily removed in AZ[®] 400T stripper at 75°C for 15 min.

3. RESULTS AND DISCUSSION

3.1 AZ[®] EXP 125nX-10A -- Novel acrylic negative photoresist

Acrylic negative photoresists are widely used in electroplating applications. The photoresists are based on radical polymerization systems formulated by multifunctional acrylic monomer, photoinitiators, and acrylic polymers that are soluble in aqueous-base developer. Upon exposure, photoinitiators decompose to generate organic radicals and the multifunctional acrylic monomers are polymerized in the exposed areas. The radical polymerization of acrylates with more than two acrylate moieties bound the same molecule yields three-dimensional (3D) cross-linked network, resulting in poor solubility in developer and strong chemical resistance. The large contrast between the exposed and unexposed areas results in high resolution. The multifunctional acrylic monomers usually have low molecular weight and contribute to the relatively lower viscosity of the negative resists with higher solid contents. Therefore, the acrylic negative photoresist is easily processed for ultra-thick film applications. Since both acrylic monomers and acrylic polymer binders that have high transparency are available for the resist formulation, the thickness dependency of the negative photoresists is relatively small. The formation of 3D cross-linking provides the good combination of high resolution and strong plating resistance, but the photoresists suffer from stripping difficulty.

AZ[®] EXP 125nXT-10A is a negative working acrylic photoresist. Acrylic polymer binders and acrylic monomers are precisely selected to provide sufficient solubility of the unexposed resist in 2.38% TMAH aqueous solution. The

exposed areas of the resists are not soluble in the developer solution under normal processing conditions and provide good adhesion to a variety of substrates, such as Si, Cu, Au, Ti and glass. The 3D cross-linking network of exposed areas provides high contract to achieve high aspect ratio of more than 6. On the other hand, the cross-linking densities are relatively low, resulting in some solubility of the exposed resist in the strong alkaline strippers. Thus, the stripping of AZ[®] EXP 125nXT-10A photoresist is readily achieved. For examples, AZ[®] EXP 125nXT-10A photoresist enables complete stripping without residue in AZ[®] 400T, a common stripper for DNQ-based positive photoresists. The photoinitiators show main absorption band in the range of 320 to 440 nm. The precise optimization of photoinitiators provides AZ[®] EXP 125nXT-10A photoresist the UV broadband absorption and the perfect surface/though cure balance, resulting in the ideal sensitivity to the emission of light sources and the clean features with straight wall profiles.

AZ[®] EXP 125nXT-10A was developed for wafer-bumping and MEMS applications. The resist material can cover wide range film thicknesses in the range of 40 μm to 200 μm and shows good lithographic performance. The spin curves of the three photoresist are shown in Figure 1. The resist has good coating uniformity and minor edge bead even at film thickness as high as 120 μm . The resist was coated on 300 mm Si wafers to achieve 121.5 μm film thickness by single coating. The height of edge bead was 139 μm and standard deviation was 5.6% when the edge exclusion was 4 mm. In the following sections, we will discuss the coating feasibility, process conditions, plating compatibility and uniformity.

3.2 Lithographic performance

We have previously reported the process optimization of AZ[®] EXP 125nXT-10A resist to achieve straight side wall profiles.⁵ The resist showed good reproducibility in the resist process and lithographic performance. Figure 2 shows cross section images of solid lines and posts for AZ[®] EXP 125nXT-10A at film thickness of 60 μm by single coating. The resist shows very good adhesion on both Si and Cu wafers. The aspect ratio of 6:1 was achieved on Cu wafers. The resist has high thermal stability and can be baked on hot plates at the temperature as high as 140°C. Another advantage of the resist is high development speed. For film thickness of 60 μm , the development time is only 80 seconds, i.e. two puddles at 40 seconds for each.

In this study, AZ[®] EXP 125nXT-10A was coated on 200 (300mm wafers and exposed on Xggeg/Ultratech AP 300 stepper. The process latitude of AZ[®] EXP 125nXT-10A was studied by varying the exposure dose from 2000 to 3500 mJ/cm^2 . Figure 3 shows the cross section SEM images of 50 μm contact holes in 70 μm film thickness at a fixed focus offset of -15 μm . At 2000 mJ/cm^2 , a slightly wider profile on the bottom in 50 μm C/H was observed, indicating the resist was under exposed. The dose for optimal sidewall profile was above 2250 mJ/cm^2 . Even at the highest dose of 3500 mJ/cm^2 , the resist showed clean patterns without obvious footing. The profiles had minimal change in the dose range from 2250 to 3500 mJ/cm^2 . Thus, the resist has broad exposure latitude. We chose 3000 mJ/cm^2 to expose wafers with FT=70 μm for plating tests because we did not have enough time to optimize the process conditions. 2250 mJ/cm^2 should be sufficient for this film thickness. The SEM images of cubic, octagonal and circular contact holes were also shown in the figure. Little footing of less than 100 nm and straight profile were observed at the film thickness of 70 μm on Cu substrate.

The process latitude of AZ[®] EXP 125nXT-10A was studied on Xggeg/Ultratech AP300 stepper by changing focus from -22.5 μm to -7.5 μm from the resist surface. Figure 4 shows the cross section images of 50 μm C/Hs in 70 μm thick resist with an exposure dose of 2500 mJ/cm^2 . The -7.5 μm focus offset shows a small footing while the -22.5 μm focus offset shows wider profile on the bottom. The best compromise between the footing and straight sidewall is a focus offset of -15 μm yielding vertical sidewall profiles with little footing. The open widths of 50 μm C/H at the top of the resist and sidewall angle were measured at different focus offsets. Both parameters showed minimal change with focus offset, indicating the broad focus latitude of the photoresist. The side wall angle and width of 50 μm C/Hs were also plotted against the focus offset change in Figure 4. Over the wide focus range, the sidewall angle was observed in the range of 89 to 89.3 degree.

Figure 5 shows the resolution of AZ[®] EXP 125nXT-10A on Cu substrate at film thickness of 70 μm with an exposure dose of 2000 mJ/cm^2 and focus offset of -15 μm . 15 μm C/Hs with vertical sidewalls were resolved.

3.3 Electroplating and stripping

The electrochemical deposition of copper was performed using 200mm and 300mm Semitool CFD3 reactors and three different commercially available Cu plating solutions. A majority of the wafers were processed with Semitool's BKM Cu process, which uses sulfuric acid based chemistry (Bath 1) and a few wafers were plated using two new high-deposition-rate chemistries currently in the development phase. For Cu pillar type applications with photoresist

thickness of 50 μm and greater, the BKM process is capable of deposition rates between 1-3 $\mu\text{m}/\text{min}$ depending on resist thickness. For this work, where resist thicknesses of 40, 70, and 100 μm were evaluated, we demonstrated a deposition rate of 2 $\mu\text{m}/\text{min}$ using the baseline BKM chemistry. At 2 $\mu\text{m}/\text{min}$, the within wafer thickness non-uniformity was 2.0% (1-sigma), calculated using the 13-point measurement map shown in figure 6. Thickness data from this wafer is also shown in figure 6.

Figure 7 contains SEM images from a 200 mm wafer, which was coated with 100 μm of photoresist before forming 80 μm tall Cu pillars at a Cu deposition rate of 2 $\mu\text{m}/\text{min}$ using the BKM process. The various bump shapes included in the test pattern are useful for examining the shape of the bump surface after plating. The circular and octagonal bumps had flat, uniform surfaces, while the square bumps tend to be somewhat domed, with the corners plating lower than the center of the bump. Feature geometry has a direct impact on bump surface shape.

Using one of the new high rate processes (Bath 2), we have demonstrated the capability to electroplate Cu at as high as 7.5 $\mu\text{m}/\text{min}$ through 40 μm thick photoresist on 200 mm wafers. The average Cu bump thickness was 19.2 μm and a within wafer thickness non-uniformity was achieved as low as 1.4% (1-sigma). SEM images of Cu bumps from this process are shown in Figure 8. Figure 9 shows the flat bump profiles plated at the rate of 1 $\mu\text{m}/\text{min}$ up to average thickness of 32 μm . The features sizes of circular bumps changed from 100 to 50 μm with 1:1 and 1:2 pitches.

We also demonstrated the capability to electroplate Cu through 70 μm thick photoresist on 300 mm wafers at the rate of 4 $\mu\text{m}/\text{min}$ by using the second new high rate process (Bath 3), as shown in Figure 10 (wafers have resist residue because they were stripped manually using acetone). This new process, still in the developmental stage, produced flat bump profiles at high deposition rates but also produced a rougher deposit than standard Cu processes. For bump and pillar applications where solder is deposited on top of the Cu, the rougher Cu surface may improve the Cu/solder interface properties. Typical surface roughness values for this process are 500-700 Angstroms average roughness.

Figure 11 shows Cu bumps plated at 2 $\mu\text{m}/\text{min}$ through 70 μm of resist on 300 mm wafers using the BKM (Bath 1) process. The average Cu thickness was 39.9 μm and the within wafer thickness variation was less than 3.4 μm . The SEM images show smooth and uniform surface morphology, flat bump profiles, and slightly less than 90°, well defined sidewalls and feature corners. We also measured the within wafer thickness non-uniformity from 70 μm resist on 300 mm wafer by using a 9-point map. 50 μm circular features at 1:1 pitch were measured at each measurement location on SEM. As shown in Figure 12, the average Cu bump thickness was 55.1 μm and the within wafer thickness non-uniformity was 1.7%.

AZ[®] EXP 125nXT-10A photoresist enables complete stripping without residue in AZ[®] 400T, a common stripper for DNQ-based positive photoresists. The stripping times were 15-20 min at the temperature of 70°C for the three resist film thicknesses of 40, 70 and 100 μm .

4. CONCLUSIONS

Novel acrylic negative AZ[®] EXP 125nXT-10A resists were coated on 200 mm and 300 mm wafers to achieve 40, 70 and 100 μm film thickness by single coat. Process conditions were optimized on Xgseq/Ultratech AP300 to achieve straight and nearly vertical side wall profiles. At the film thickness of 70 μm , 15 μm contact holes were resolved, reaching the high aspect ratio of 4.6:1. The resist was compatible for standard Cu plating process and two new developmental processes. By using Semitool's BKM Cu process at a rate of 2 $\mu\text{m}/\text{min}$, we produced Cu bumps with smooth and uniform surface morphology, flat bump profiles and well-defined sidewalls and feature corners. On 300 mm wafers, the Cu bump average thickness was 55.1 μm from 70 μm resist and the within wafer thickness non-uniformity was 1.7%. For the new high rate plating processes, it was demonstrated to electroplate Cu through 70 μm thick resist at rates of 4 $\mu\text{m}/\text{min}$ and up to 7.5 $\mu\text{m}/\text{min}$, achieving a within wafer thickness non-uniformity as low as 1.4% (1-sigma). The resist was stripped completely in AZ[®] 400T stripper at 75°C for 15 min.

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Table 1. Process conditions for AZ[®] EXP125nXT-10A @ FT=70μm

Process step	Parameters	Equipment
Coating	Dynamic dispense: 400 rpm for 4 seconds Spread: 1600 rpm for 4 seconds spin: 1000 rpm for 10 seconds	Suss ACS300
Softbaking	Hotplate, 0.1 mm proximity 12 min at 140 °C	Suss ACS300
Exposure	Dose: 3000 mJ/cm ² Focus: -15μm	Xgqe AP300
Development	3 puddles at 40 Second for each Room temperature DI wafer rinse	Suss ACS200

Table 2. Electroplating conditions for AZ[®] EXP125nXT-10A @ FT=70μm

Process step	Parameters	Equipment
Oxygen Descum	10 min / 300 W	Plasma Start AXIC Equipment
Cu Electroplating	Semitool's BKM Cu Process Temperature: 30°C Flow rate: 4.5GPM Wafer rotation: 40 rpm Deposition rate: 1-3μm/min	Semitool CFD3 Reactor
Stripping	AZ [®] 400T at 70 °C for 15 min Spray: Bi-directional Wafer rotation: 50 rpm Flow: 8 L/min	Semitool Batch Solvent Spray Tool

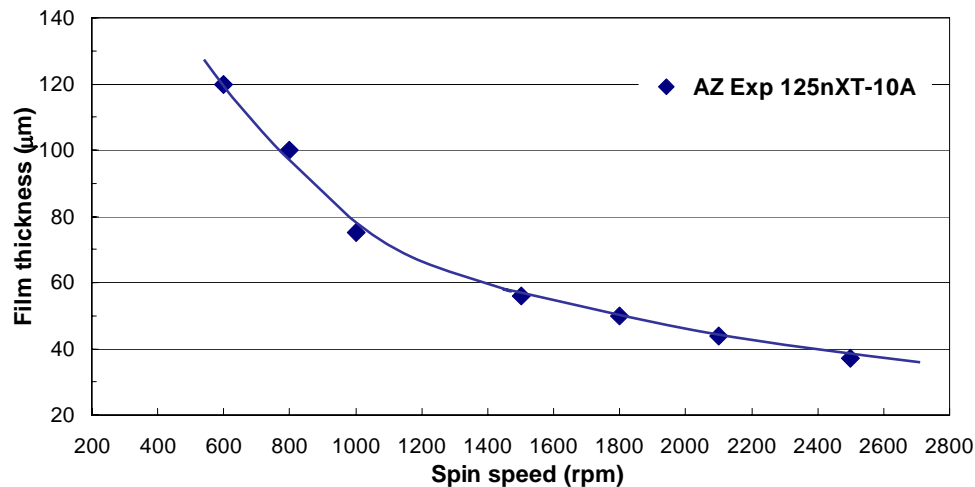


Figure 1. The spin curves of AZ[®] EXP 125nXT-10A resist. Substrate: 200 mm Si wafer; Coating Track: Suss ACS300

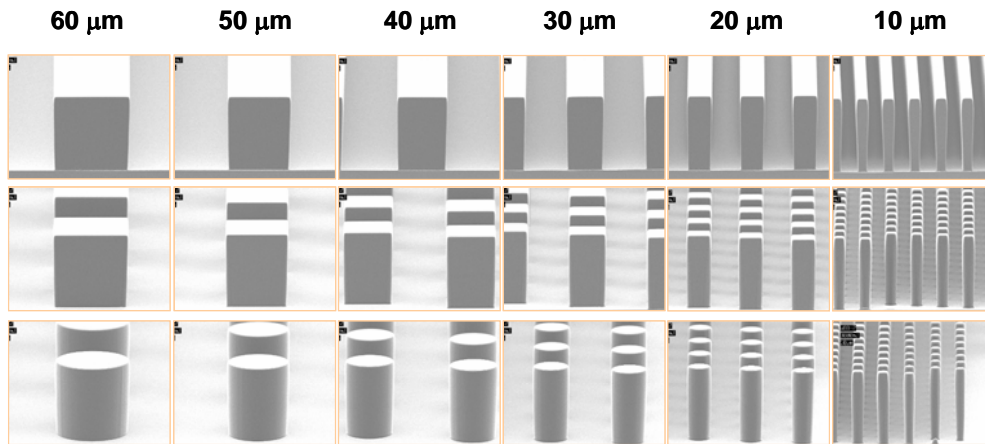


Figure 2. The solid line and post images of AZ® EXP 125nXT-10A @ FT = 60 μm . Substrate: 200 mm Cu wafer; Coating Track: Suss ACS300; bake, 140°C for 8 min; Exposure dose, 1800 mJ/cm^2 ; Developer track: Suss ACS300, 2x40 puddle.

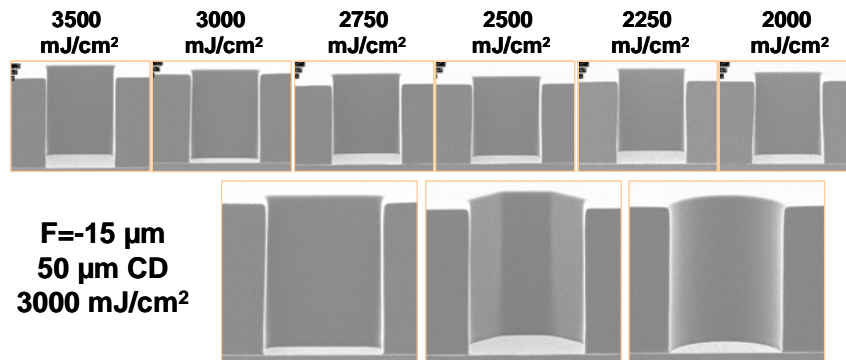


Figure 3. The exposure latitude of AZ® EXP 125nXT-10A @ FT = 70 μm . CD: 50 μm ; Substrate: 200 mm Cu wafer; Coating Track: Suss ACS300; bake, 140 °C for 12min; Exposure: Ultratech AP300; Developer track: Suss ACS200, 3x40 puddle.

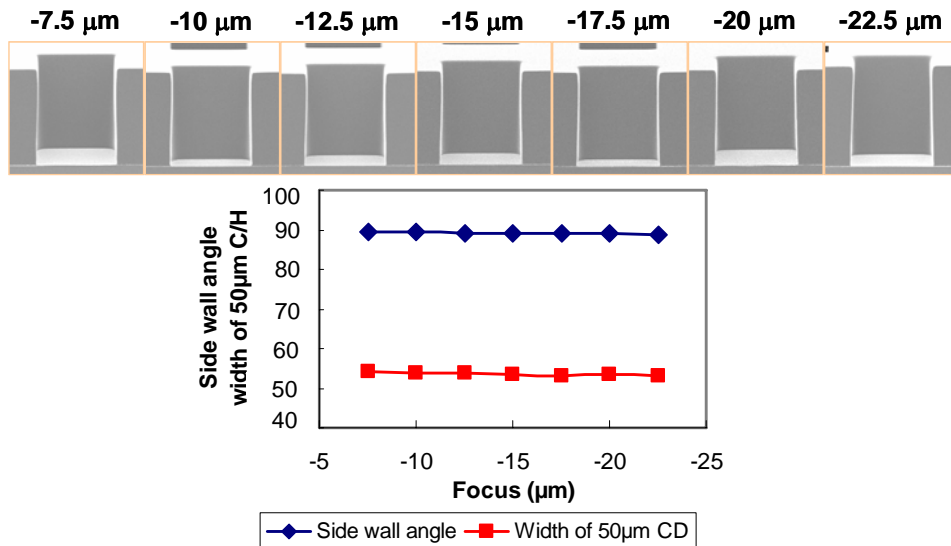


Figure 4. The focus latitude of AZ® EXP 125nXT-10A @ FT = 70 μm . CD: 50 μm ; Substrate: 200 mm Cu wafer; Coating Track: Suss ACS300; bake, 140 °C for 12 min; Exposure: Ultratech AP300; dose, 2500 mJ/cm^2 ; Developer track: Suss ACS200, 3x40 puddle.

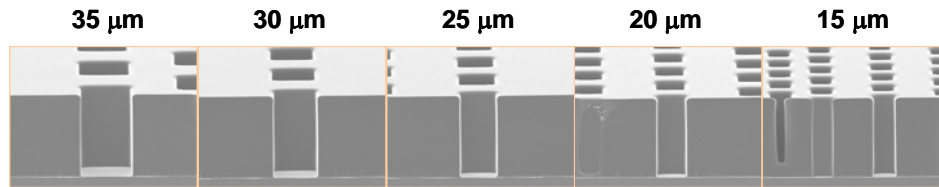


Figure 5. The resolution of AZ® EXP 125nXT-10A @ FT = 70 μm . Substrate: 200 mm Cu wafer; Coating Track: Suss ACS200; bake, 120 $^{\circ}\text{C}$ for 10 min; Exposure: Ultratech AP300; dose, 2000 mJ/cm^2 ; Developer track: Suss ACS300, 3x40 puddle.

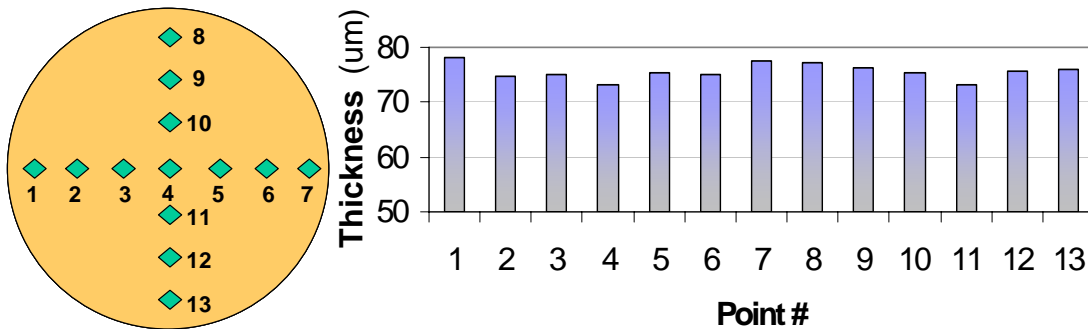


Figure 6. 13-point profilometer map used for Cu bump thickness measurements. Data from 200mm wafer with 100 μm of resist; plated at 2 $\mu\text{m}/\text{min}$ using Semitool's BKM process (Bath 1).

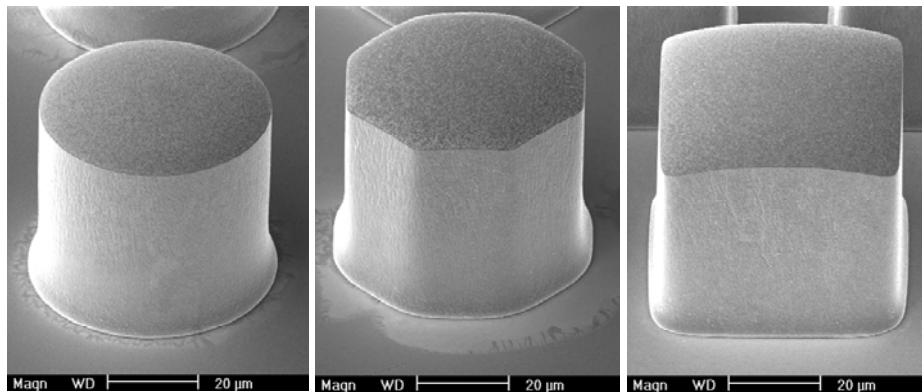


Figure 7. Flat bump surfaces on the circular, octagonal, and square bumps. 200 mm wafer with 100 μm resist, plated at 2 $\mu\text{m}/\text{min}$ using Semitool's BKM process (Bath 1).

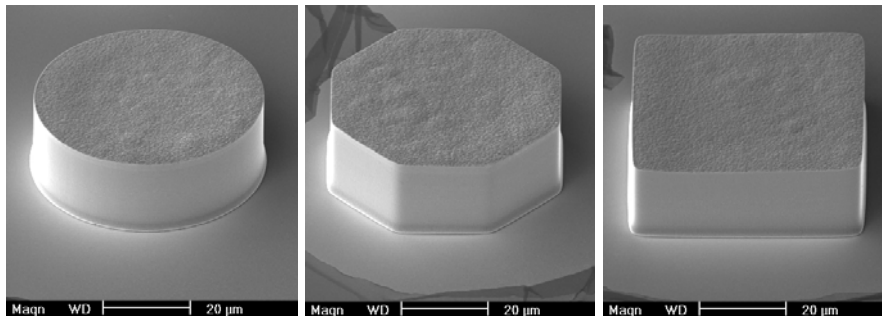


Figure 8. Flat bump profiles at deposition rate as high as 7.5 $\mu\text{m}/\text{min}$ using a new high-rate process (Bath 2). 200mm wafer with 40 μm of resist; average thickness of 19.2 μm and a within wafer thickness non-uniformity of 1.4% (1-sigma).

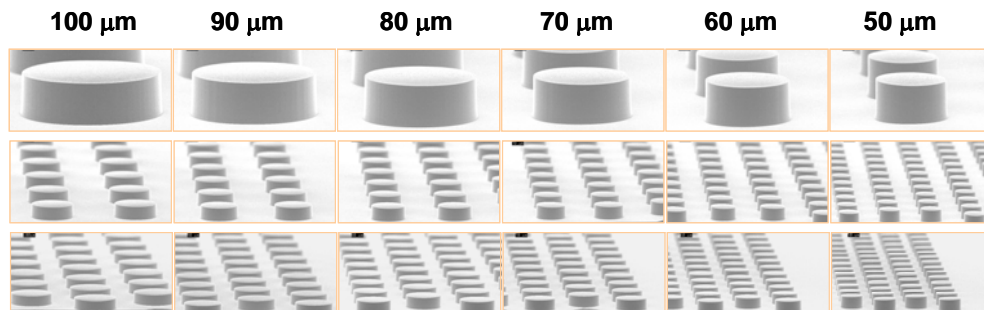


Figure 9. Flat bump profiles plated at 1.0 $\mu\text{m}/\text{min}$ using Semitool's BKM process (Bath 1). 200 mm wafer with 40 μm of resist; average thickness of 32 μm .

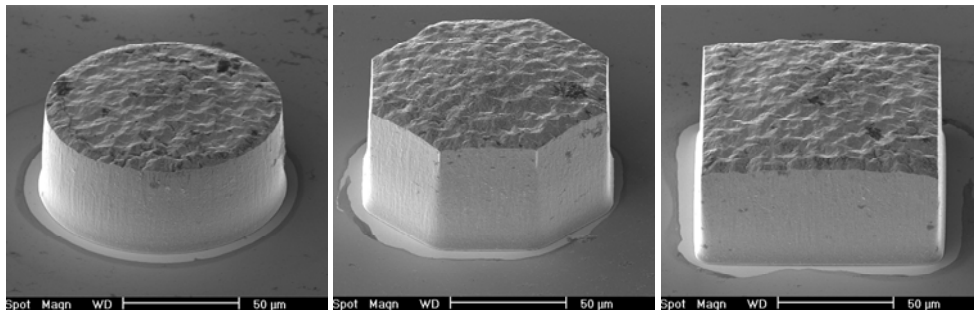


Figure 10. This new process (bath 3), still in the developmental stage produces flat bump profiles at high deposition rates, but also produces a rougher deposit than standard Cu processes. 300 mm wafer with 70 μm of resist, plated at 4 $\mu\text{m}/\text{min}$, average thickness of 49.4 μm .

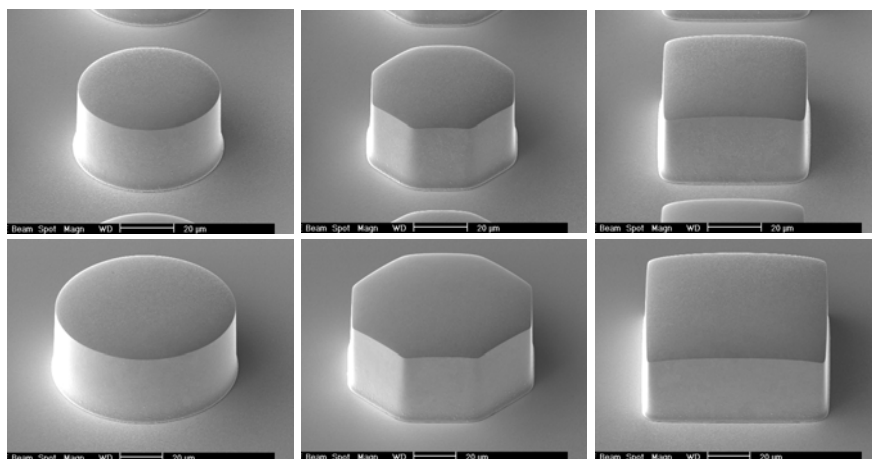


Figure 11. Smooth and uniform surface morphology, flat bump profiles, and slightly less than 90°, well-defined sidewalls and feature corners. 300mm wafer with 70 μm of resist, plated at 2 $\mu\text{m}/\text{min}$ using Semitool's BKM process (Bath 1). with an average thickness of 39.9 μm and a within wafer thickness range of 3.4 μm .

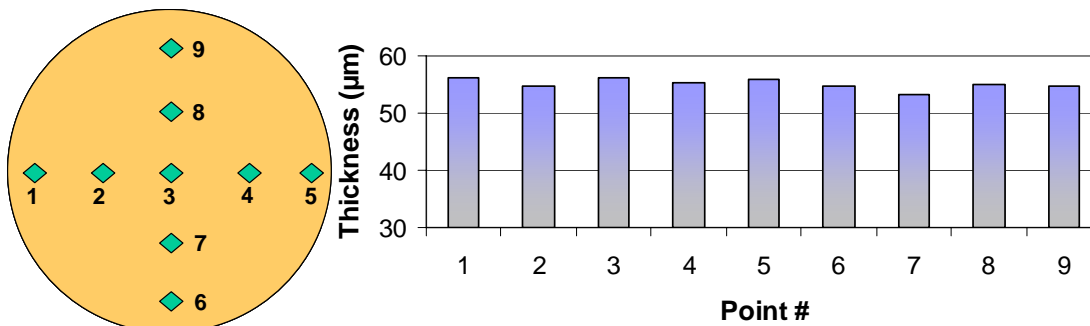


Figure 12. 9-point profilometer map used for Cu bump thickness measurements. Data from 300mm wafer with 70 μm of resist; plated at 2 $\mu\text{m}/\text{min}$ using Semitool's BKM process (Bath 1).