Characterization of a High Photospeed Positive Thick Photoresist for Lead Free Solder Electroplating

Warren W. Flack, Ha-Ai Nguyen
Ultratech, Inc.
San Jose, CA 95134

Yasushi Washio, Mitsuaki Ohgake, Christopher Rosenthal
Tokyo Ohka Kogyo Co., Ltd
Kanagawa-ken, 253-0114 Japan

ABSTRACT

The introduction of lead free solder (SnAg) electroplating for advanced packaging applications has created new challenges for thick photoresist processes. Dry film laminate photoresist materials do not provide sufficient resolution or process control for the smaller bump diameters used with advanced design rules. The traditional positive tone DNQ-Novolak photoresists require large exposure doses and long processing times that are unacceptable for the total cost of ownership (COO) of the lithography cell in a manufacturing environment. Standard chemically amplified positive photoresists have interactions between the PAG and Cu or Cu_2O at the soft bake step which makes it impossible to obtain sufficient pattern fidelity for electroplating lead free solder on copper seed layer substrates.

This study will characterize a novel positive tone, chemically amplified photoresist (TOK PC-0059B PM) that can be double coated up to 100 μm thick for lead free solder electroplating. The PAG in the photoresist has been formulated to prevent any interaction with Cu or Cu_2O. This photoresist exhibits extremely high photospeed, excellent pattern resolution and ease of stripability after electroplating.

The lithographic performance of the thick positive photoresist will be optimized on 300mm wafers using a broad band, low numerical stepper. Enhanced process latitude and very high photospeeds will be demonstrated for thicknesses up to 100 μm. Cross sectional SEM analysis, process linearity, and electroplating performance are used to establish the lithographic capabilities.

Key Words: advanced packaging, flip-chip, thick photoresist, chemically amplified, low dose, lead free solder, cooper seed layers, electroplating, broadband stepper

1.0 INTRODUCTION

The semiconductor manufacturing industry is using advanced packaging techniques to reduce cost and improve performance by replacing single chip wire bonding with bump bonding applications as the final step in chip manufacturing. The advanced packaging market is growing at a compound annual rate of thirty percent [1]. The solder bump area is the largest component of this market. Today there is a rapid increase in the pin counts of most solder bump applications. The necessary corresponding reduction in bump pitch makes conventional "mushroom" type over plating impractical in high bump count devices [2,3,4,5]. Elimination of the umbrella requires even thicker photoresist layers since the entire solder volume is contained by the photoresist mold. Typical thicknesses for mushroom free processes are in the 60 to 100 μm range [3]. Extending the microlithographic processes into these rapidly growing areas is placing new demands on both the photosensitive materials and the lithography equipment.

Electroplating metals for micro-scale features is a well established technology. However, the fabrication of high aspect ratio linewidths for these applications is a new and challenging use of photolithography equipment and photoresists. The photolithography requirements for thick photoresists can be addressed by using optical lithography equipment similar to that developed for production of semiconductor devices. There are additional demands on the lithography process as bump processing extends to include 300 mm wafers. Coating thick photoresists on these larger size wafers is not trivial and posses many challenges. Thick photoresists typically require a high exposure dosage and a large depth of focus (DOF) for high aspect ratio lithography. For these reasons, it is advantageous to utilize a stepper with a broad band exposure system and low numerical aperture (NA) to maximize the illumination intensity at the wafer plane and to improve the DOF.

In parallel with the ultrahigh resolution thin film photolithography processes, the thick film processes have also become more demanding for today's lithographers involved in semiconductor manufacturing. Whereas the gate and contact patterns have shrunk in size to well below 100 nm, and forced implementation of novel masking and exposure techniques, the back end has also challenged photoresist manufacturers. They have needed to come up with creative chemical formulations to combat issues associated with newly implemented copper substrates and extremely thick films needed to create tall narrowly pitched structures, most notably for formation of solder bumps. This paper will examine TOK's PC-0059B photoresist, which was developed for SnAg solder electroplating directly on top of Copper substrates on 300mm wafers.

The improvements associated with the release of PC-0059B come under three categories: non-interaction with copper, improved photospeed, and resistance to damage or defects during the plating process [6]. However, of the three areas list above, the ability of PC-0059B to perform well in direct contact with the underlying copper substrate is by far the most notable. Prior to the development of PC-0059B, TOK distributed PMER P-CA1000 that was an excellent photoresist for creating thick film (30 to 100 μm) patterns; however, due to its utilization of chemical amplification the photoresist tended to suffer from poisoning at the copper/photoresist interface. In the case of PMER P-CA1000, the copper served as a catalyst for the PAG (photo acid generator) reaction and with just the addition of heat during the soft bake, protons were generated in such concentration that resolution fidelity was almost completely lost upon development. A barrier film could be applied to the copper prior to photoresist coating to eliminate the issue, but of course this would come at the expense of throughput and cost increase to the process.

Thus, TOK set out to find a new PAG that would maintain the desirable properties of PMER P-CA1000, like high sensitivity to ghi-line (broadband) exposure, but would be immune to the catalytic properties of copper. The new PAG TOK found that met the criteria is an Onium-salt type PAG. Its special anion structure not only produces the desired acid generating response during exposure, but it is also stable even in direct contact with copper during soft bake. The objective of this study is to evaluate TOK PC-0059B, a chemically amplified photoresist, on 300 mm Cu wafers. The experimental results include coating uniformity, CD linearity studies, plating performance, stripping performance and CD control.

2.0 EXPERIMENTAL METHODS

2.1 Lithography Equipment

Lithography for the thick photoresist evaluated in this study was performed on an Ultratech AP300 Wafer Stepper on the Ultratech Unity Platform™. The optical specifications for the AP300 is shown in Table 1. 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 [7] for the AP300.

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 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 [7]. In addition, the Unity 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/cm^2 to improve throughput in thick photoresist processing. The Unity AP300 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 the edge of the wafer. The purpose of the WEE features is to create a photoresist free area around the edge of the wafer as a requirement at plating.

Multiple Cu substrate 300 mm wafers were exposed in a focus/exposure pattern.Focus latitude of 60 μm contacts was examined by cross section of square contact patterns with a Hitachi S7280H SEM. The Cu substrate wafers were also exposed at best focus and exposure for solder bumping.

The Ultratech 1X reticle used to establish the process window was designed primarily 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 50 μm to 100 μm.

2.2 Photoresist Processing

300 mm prime Cu wafers were used for this study. The photoresist used is TOK PC-0059B PM. The TOK PC-0059B PM photoresist was coated to the 100 μm target thickness using the process and equipment described in Table 2. Photoresist thickness and uniformity was measured on the Steag ETA Optik thickness measurement tool.

TOK PC-0059B PM photoresist is mostly i-line sensitive but can be patterned using broadband and is TMAH developable. The photoresist is capable of single coating up to 100 μm thickness using the TOK CS-A application type coating tool. However, for this study a double coat process was used to improve coating uniformity. The photoresist is processed using ghi-line wavelength and a Post Exposure Bake (PEB) is required. The development method is immersion at room temperature, followed by a DI water rinse. No delay time is necessary between lithography steps.

2.3 Electroplating

A set of 300 mm Cu seed wafers were exposed using the nominal conditions of 1200 mJ/cm^2 at ghi-line wavelength, -30 μm focus with an edge width exposure of 1.8 mm. The wafers were sent to Ebara Corporation for Sn-Ag solder electroplating to a target height of 70 μm. No descum process was used, however a liquid preclean process was performed immediately before electroplating. After electroplating the wafers were stripped in heated TOK 104 stripper for 30 minutes, followed by an IPA and DI water rinse. The plating processes are shown in Table 3.

2.4 Data Analysis

Coating uniformity was determined through thickness measurement across the 300 mm Cu wafer using a Steag ETA Optik non-contact thickness measurement tool. After exposure, sample wafers were cleaved for cross section Hitachi S-7280H metrology SEM to show the depth of focus, linearity and to determine the best focus and exposure conditions for patterning wafers for electroplating. Cross sectioned photoresist profiles were taken at 1K magnification to show depth of focus at nominal exposure for 60 μm square contacts and linearity at nominal exposure and focus as illustrated in Figure 2.

Bump height and CD uniformity were determined for 60 μm bumps after electroplating. The plating height uniformity was measured using a KLA-Tencor P-11. The CD uniformity was determined by cross sectional SEM analysis using an Hitachi S-4300.

The results from the data analysis are discussed in Section 3.0.

3.0 RESULTS AND DISCUSSIONS

3.1 Coating Uniformity

Photoresist thickness was measured at 56 locations evenly distributed over the 300 mm wafer to determine coating uniformity. A contour plot of the coating uniformity is shown in Figure 1. The solid contour lines represent 2.0 μm intervals and the dashed contour lines are half way between each solid line. There is a clear high region in the center of the wafer at 102 μm while the edges of the wafer ar around 94 μm. This type of thickness variation would be expected from a double coating process. The average thickness is 97.5 μm with a one sigma of 3.5 μm. This equates to a coating uniformity of 10.7%.

3.2 Process Latitude

Figure 2 shows cross sectional SEM photographs of 60 μm square contacts in 100 μm thick TOK PC-0059B photoresist on Cu substrates. The exposure conditions are ghi-line exposure at 1200 mJ/cm^2. The sidewalls are virtually identical over the entire focus range from -20 μm (Figure 2a) to -50 μm (Figure 2d). Vertical sidewalls are observed at the top of the photoresist while a moderate foot is observed at the photoresist base. The actual photoresist CD was measured at 50% thickness and is shown for each focus offset of 70 μm round contacts. For this study a focus offset of -30 μm was selected for electroplating.

3.3 Linearity

Cross sectional SEMs were used to determine the CD linearity of the photoresist and the shape of the final electroplated solder bump structures. Figure 3 shows square contacts from 80 to 50 μm in 100 μm thick TOK PC-0059B photoresist on Cu seed substrates. The process conditions are ghi-line exposure, -30 μm focus and 1200 mJ/cm^2 exposure dose. The left side of the figures shows the photoresist profiles while the right side shows the corresponding electroplated structure from the same photoresist. The contacts were resolved down to 50 μm with similar sidewall profiles. The bumps show excellent sidewall profiles with no signs of underbump plating or any interaction with the Cu or Cu_2O. There is no indication of solder bridging between bumps even as small as 50 μm. Clearly the photoresist demonstrated adequate durability in the electroplating bath with no cracking or adhesion failure. The TOK photoresist used in conjunction with the equipment in this lithography cell exhibits solder bump fabrication capability that exceed current design requirements and offers the potential to meet future advanced packaging needs.

3.4 Electroplating Uniformity

3.4.1 Height Uniformity

The electroplating height uniformity of 70 μm round bumps was measured a 26 locations distributed over the 300mm wafer. A contour plot of the electroplated thickness uniformity of the 70 μm round bumps is shown in Figure 4. The solid contour lines represent 2.0 μm intervals and the dashed contour lines are half way between each solid line. The height is shortest at the center of the wafer at 66 μm and tallest at the wafer edges at 72 μm. The average CD is 68.3 μm with a sigma of 2.3 μm. This equates to an across the wafer height uniformity of 10.2 percent.

Figure 4 also shows angled SEM photographs of the height uniformity and shape of the solder bump at five locations across the 300mm wafer (top, left, center, right, bottom). Again the lowest point was in the center of the wafer. This possibly correlates with the thickest photoresist location in the center of the wafer.

3.4.2 CD Uniformity

The electroplating CD uniformity of 70 μm round bumps was measured a 13 locations across the 300mm wafer. A plot of the electroplated CD uniformity is shown in Figure 5. The measurements were made in the X direction at the Y center of the wafer. The CD uniformity does not exhibit any radial variation. The average CD is 76.0 μm with a sigma of 0.72 μm. This equates to an across the wafer CD uniformity of 2.8 percent. The CD uniformity and CD size measured is more than adequate to meet current and future packaging requirements.

Figure 5 also shows cross sectional SEM photographs of at three locations across the wafer (left, center, right). All of the locations show similar sidewalls and shape. The bumps show excellent sidewall profiles with no signs of underbump plating or any interaction with the Cu or Cu_2O.

4.0 CONCLUSIONS

The objective of this study was to develop a process for a 100 μm photoresist for lead free solder electroplating on 300 mm wafers. This study showed that the TOK's PC-0059B photoresist performance easily meets requirements for both current and future generations of bump processing on 300 mm wafers using the Ultratech AP300 lithography stepper. This study demonstrated excellent resolution and sidewall control down to 50 μm, a good process window, and CD control of 2.2 μm (3σ) after plating for a 70 μm features. In addition the photoresist demonstrated no-interaction with copper, a high photospeed, and resistance to damage or defects during the solder electroplating process.

5.0 ACKNOWLEDGEMENTS

The authors would like to thank Ebara Corporation for their support in Sn-AG electroplating. We would also like to thank Ishihara Chemical Company and Mitsubishi Materials company for providing electroplating solutions.

Finally we would like to recognize Steag Hammatech for their support in setting up the track processes in this study.

6.0 REFERENCES

1. M. Ranjan and S. Kay, “Lithography for Advanced Packaging”, *Advanced Packaging*, August 2002.

2. B. Avrit, E. Maxwell, L. Huynh, E. Capsuto, “Characterization of an Ultra-Thick Positive Photoresist for Electroplating Applications”, *Advances in Resist Technology and Processing XX Proceedings*, SPIE **5376**, 2004.

3. W. Flack, A. Nguyen, E. Capsuto, “Characterization of an Ultra-Thick Positive Photoresist for Electroplating Applications”, *Advances in Resist Technology and Processing XX Proceedings*, SPIE **5039**, 2003.

4. W. Flack, A. Nguyen, E. Capsuto, “Process Improvements for Ultra-Thick Photoresist Using a Broadband Stepper”, *Optical Microlithography XIV Proceedings*, SPIE **4326**, 2001.

5. B. Todd, W. Flack, S. White, “Thick Photoresist Imaging Using a Three Wavelength Exposure Stepper”, *Micromachining and Microfabrication Process Proceedings,* SPIE **3874**, 1999.

6. K.Misumi, K.Saito, H.Obiya, “Development status of thick film photoresist for semiconductor packaging”, *Advances in Resist Technology and Processing XXII Proceedings,* SPIE **5753**, 2005.

7. G. Flores, W. Flack, L. Dwyer, “Lithographic Performance of a New Generation i-line Optical System”, *Optical/Laser Lithography VI Proceedings,* SPIE **1927**, 1993.

Parameter	Ultratech AP300
Reduction factor	1X
Wavelength (nm)	ghi-line (350 - 450)
Resolution (μm)	2.0
Depth of Focus (μm)	10.0
Wafer plane irradiance (mW/cm^2)	≥ 2400

Table 1: Optical specifications of the AP300 stepper used in this study.

Process Step	Parameters	Equipment
TOK First Coat	Dispense: dynamic at 50 rpm for 12 sec Spread: 400 rpm for 6 seconds Spin: 1270 rpm for 10 seconds with backside rinse on Dry: 400 rpm for 10 seconds	Steag Hamatech Modutrack
Softbake	Hotplate, 0.1 mm proximity, 30 minutes at 110°C Cooling: 22°C for 30 seconds	Steag Hamatech Modutrack
TOK Second Coat	same as first coat	Steag Hamatech Modutrack
Second Softbake	same as first softbake	Steag Hamatech Modutrack
Exposure	ghi-line, focus-exposure matrix	AP300 Stepper
PEB	Hotplate, 0.1 mm proximity, 5 minutes at 74°C	Steag Hamatech Modutrack
Develop	TOK NMD-W 2.38% TMAH, 12 minutes at 21°C Constant and aggressive agitation DI water rinse, spin rinse and dry	Wet sink

Table 2: Process conditions for TOK PC-0059B PM for 100 μm thickness on 300 mm Cu wafers.

Process Step	Parameters	Equipment
Precleaning	Wafer rinse, 10 minutes Dilute Sulfuric Acid, 1 minute Water rinse, 1 minute	Wet sink
Electroplating	Mitsubishi UTB TS-140, Pb-free eutectic Sn-Ag alloy Current density: 4 A/dm^2	Ebara UFP-300M
Photoresist Stripping	TOK 104 Stripper, 30 minutes at 70°C IPA rinse, 10 minutes dip at 23°C DI water rinse, 10 minutes dip at 23°C	Wet sink

Table 3: Process conditions for lead free solder electroplating.

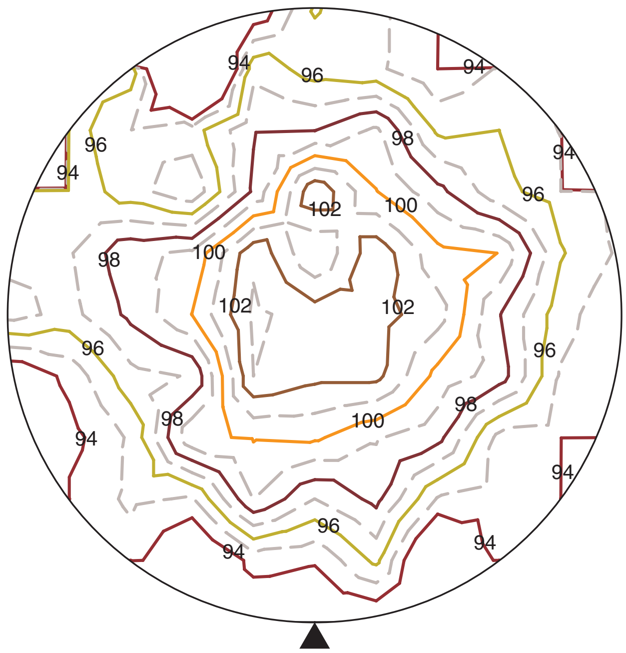
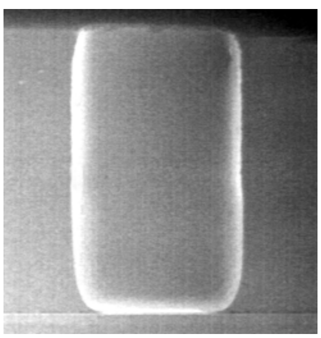
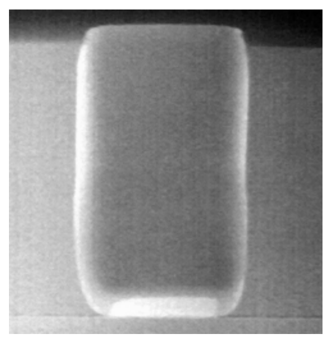


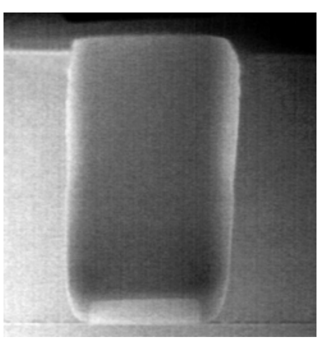
Figure 1: Photoresist thickness uniformity of 100 µm thick TOK PC-0059B on a 300 mm wafer. The solid contour lines are at 2.0 µm intervals and the dashed contour lines are half way between. The average thickness is 97.5 µm and the standard deviation is 3.48 µm.



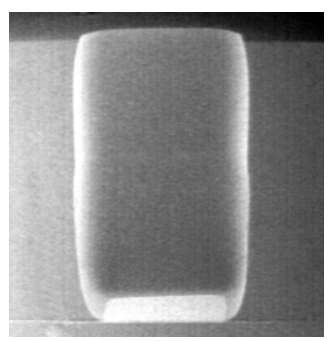
(a) F = -20 µm, CD = 60.4 µm



(b) F = -30 µm, CD = 61.0 µm



(c) F = -40 µm, CD =62.3 µm



(d) F = -50 µm, CD =62.0 µm

Figure 2: SEM photographs illustrating the depth of focus of nominal 60 µm square contacts in 100 µm PC-0059B. The exposure conditions are ghi-line at 1200 mJ/cm^2. The photoresist CD is measured at 50% thickness.

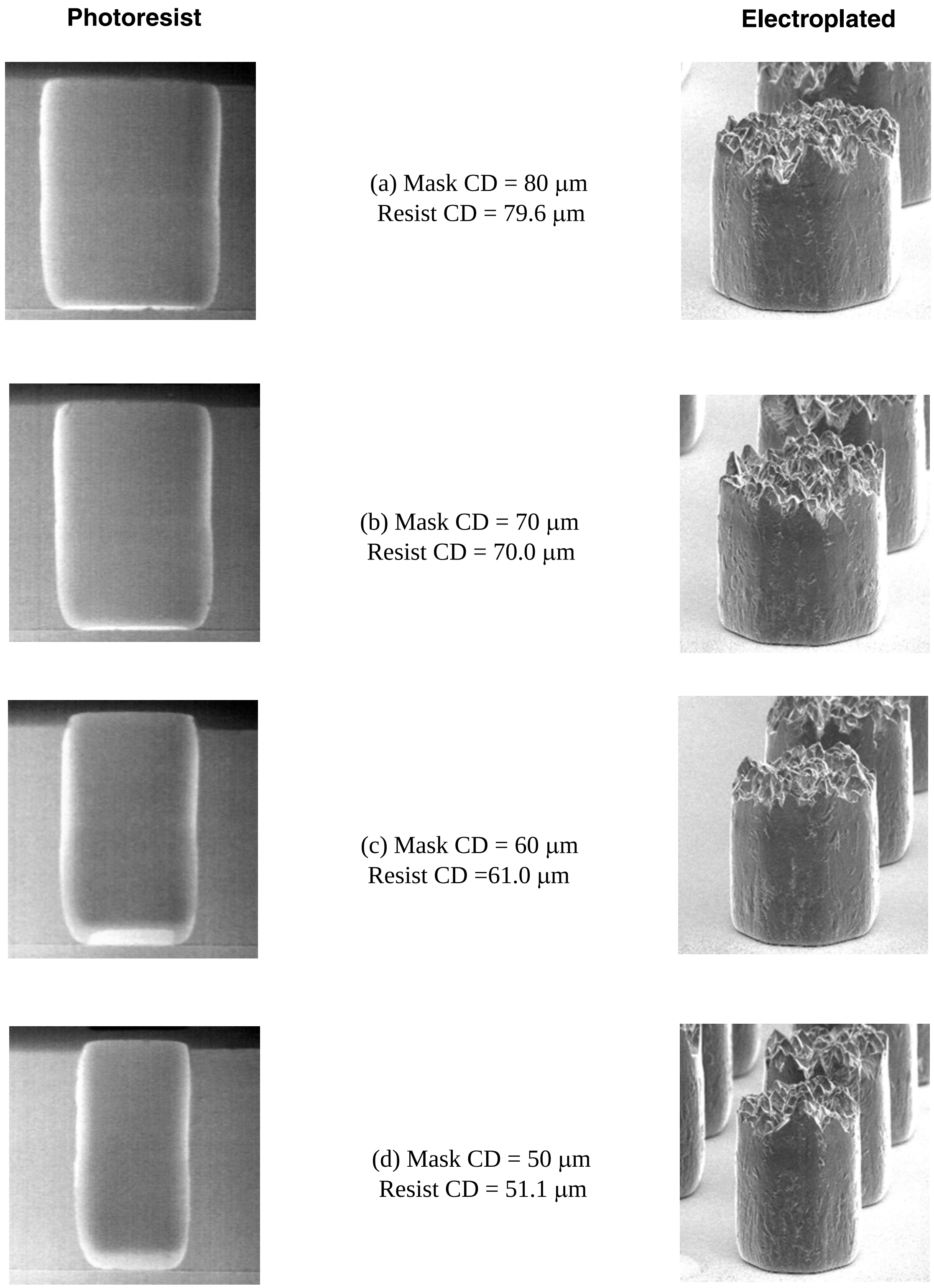


Figure 3: SEM photographs illustrating the CD linearity of 100 μm thick TOKPC-0059B. The exposure conditions are ghi-line, -30 μm focus, 1200 mJ/cm^2. The photoresist CD is measured at 50% thickness.

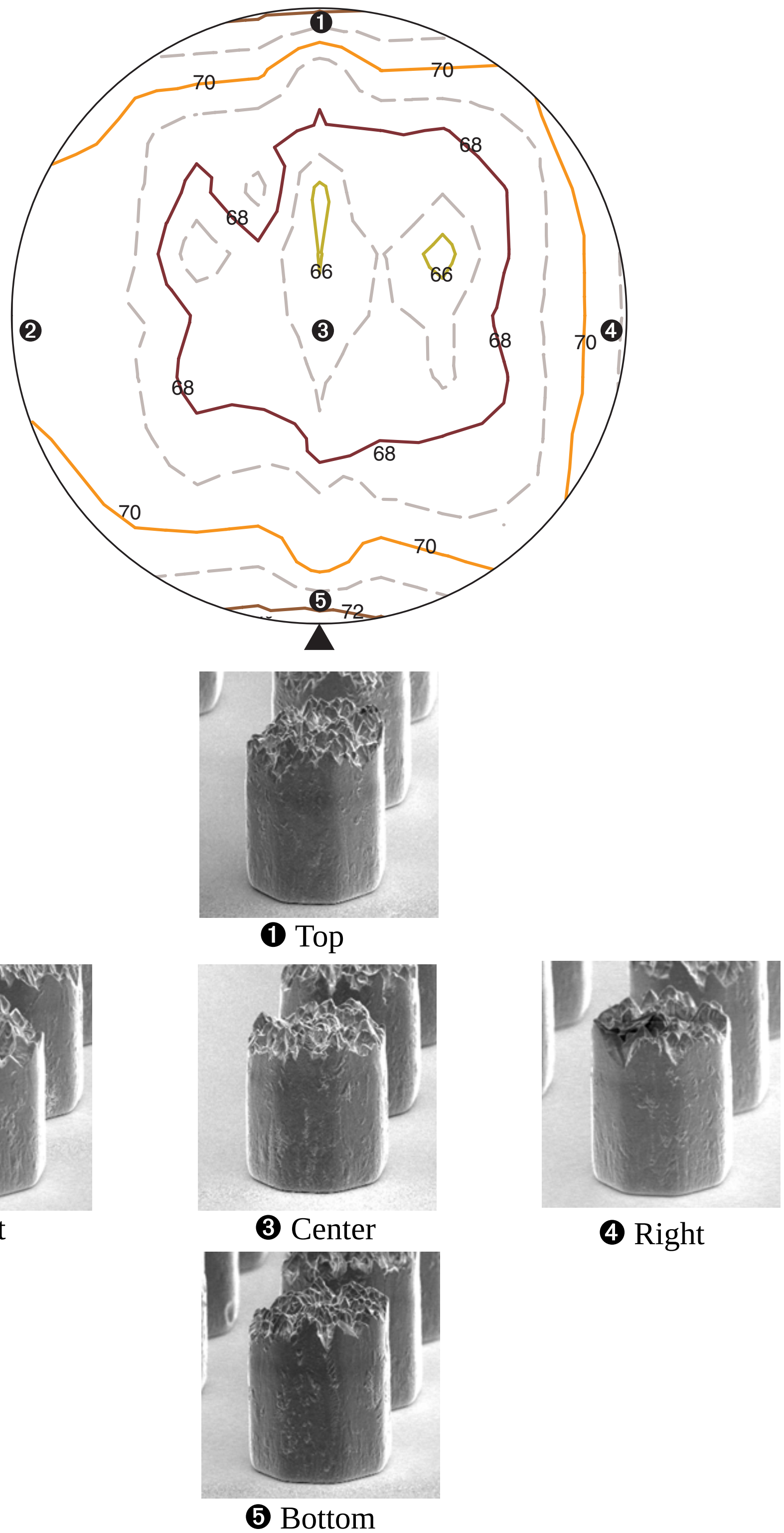


Figure 4: Electroplating thickness uniformity of 70 μm round bumps on a 300 mm wafer. The contour lines are at 2.0 μm intervals and the dashed contour lines are half way between. The average thickness is 68.3 μm and the standard deviation is 2.3 μm. The SEM photographs show electroplating profiles at five sites on the wafer.

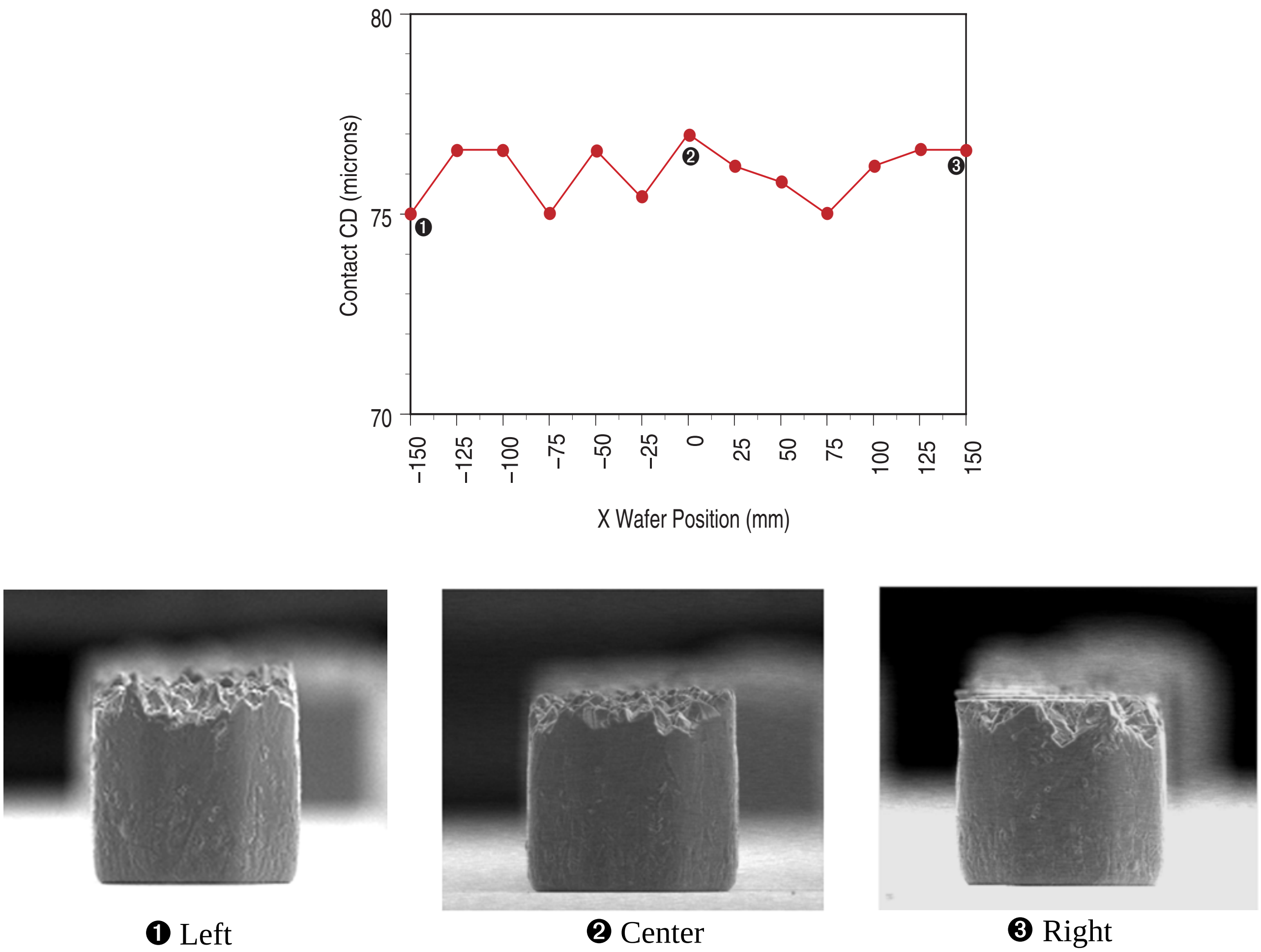


Figure 5: Electroplating CD uniformity of 70 µm round bumps across a 300 mm wafer. The average CD is 76.0 µm and the standard deviation is 0.72 µm. The SEM photographs show electroplating profiles at three sites across the wafer.