Performance of a 55 Micron Copper Pillar Bump Process Using a Positive Thick Chemically Amplified Photoresist

Dennis Crapse
Freescale Semiconductor
Chandler, AZ 85224

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

Elliott Capsuto, Craig McEwen
Shin-Etsu MicroSi, Inc.
Phoenix, AZ 85044

ABSTRACT

As pin counts and interconnection densities increase there is growing interest in copper pillar bumps for flip chip and wafer-level packaging. Copper pillars retain their shape in both the x, y and z directions during solder reflow, allowing finer interconnect pitches with predictable standoff heights. The fabrication of copper pillar bumps requires the use of a very thick photoresist layer for the copper electroplating. This photoresist material must be capable of coating, exposing, developing, electroplating and stripping with conventional equipment and standard ancillary process chemicals. In addition, photoresist sensitivity and process bake and development times are critical to minimize the cost of ownership of the lithography cell. For the electroplating process the photoresist profile, plating durability and stripability are important considerations.

This study will characterize a novel photosensitive photoresist (Shin-Etsu SIPR 7123M) for a single coat, 55 μm thick copper process for a manufacturing environment. This photoresist has been formulated for enhanced photospeed, ease of stripability and has additives to eliminate the cracking often seen with very thick films.

The lithographic performance of the thick positive photoresist will be optimized using a broad band, low numerical stepper. Enhanced process flexibility and productivity will be shown in regards to developer type and no wait times between process steps. Results will show excellent adhesion to copper with no surface treatment and no photoresist popping during exposure. Cross sectional SEM analysis, process latitude, and copper plating performance are used to establish the lithographic capabilities.

Key Words: advanced packaging, flip-chip, wafer-level packaging, thick photoresist, electroplating, copper pillar bump, process optimization, broadband stepper, chemically amplified

1.0 INTRODUCTION

As pin counts and interconnect densities increase, there is growing interest in copper pillar bumps as an alternative to conventional solder bumps for flip chip and wafer-level packaging. Conventional solder bumps use "mushroom" overplating, as shown in Figure 1 [1]. While solder bumps collapse during solder reflow, copper pillars retain their shape in both the x, y and z directions, allowing finer interconnect pitches with predictable standoff heights to be fabricated. During the assembly process, underfill applied between the die and substrate tends to flow more easily into the larger gaps with voids left in the smaller gaps. More uniform bump pitch and standoff distances facilitate more complete underfill and, ultimately, higher component reliability [2]. Larger standoff also improve reliability by reducing strains caused by coefficient of thermal expansion (CTE) differences between the die and substrate [3]. Copper pillars also offer several advantages by virtue of their reduced lead-content. With approximately an order of magnitude better thermal conductivity, copper provides three times the heat flow of conventional solder bumps. Copper has 25% better electrical conductivity, reduced power consumption and heat generation within the package [4]. The use of copper has also been shown to offer significant improvements in electromigration resistance [5]. Reduction in lead-content is also consistent with RoHS regulations.

A thick photoresist layer is needed for a copper pillar process, since the entire solder volume is contained by the photoresist mold. Typical thicknesses for mushroom-free processes are in the 40 to 100 μm range [6,7]. While electroplating metals into features of this size is a well-established technology, fabricating the high aspect ratio features needed for these applications is placing new demands on photoresists and lithography equipment.

The photolithography requirements for thick photoresists can be addressed by using optical lithography equipment similar to that developed for production of semiconductor devices. Thick photoresists typically require a high exposure dose 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.

Processing conditions for thick photoresists are considerably different than for thin photoresists. In the case of thin photoresists, the main concerns are resolution and exposure latitude [8,9]. With thick films, the concerns are centered around aspect ratios, downstream plating performance, exposure and focus latitudes, and productivity. As spin-coated photoresist films become more popular for these applications, it is important to study thicker coatings to determine how they might be optimized for performance and productivity [7,8,9].

Traditionally, photoresists useful in the 50 μm to 100 μm range are very difficult to formulate, especially in a positive tone. Advantages of positive tone photoresists include stripability, outgassing control, and compatibility with a dark field reticle [7,8,9]. It is very difficult to design a positive tone photoresist with the necessary transparency, resulting in ultra-high exposure doses. Furthermore, very thick positive novalak photoresists are often characterized by popping or void formation after exposure as a result of the nitrogen generated during exposure [9]. Chemically amplified photoresists, however, are characterized by good transparency, lack of voiding, and are capable of achieving a 90 μm thickness in a single coat.

The objective of this study is to evaluate a positive tone, chemically amplified photoresist for a 55μm thick production process on copper. Experimental results include CD linearity, DOF and exposure latitude, electroplating performance, and stripping performance.

2.0 EXPERIMENTAL METHODS

2.1 Lithography Equipment

Lithography for the Shin-Etsu SIPR 7123M-20 photoresist evaluated in this study was performed on an Ultratech Unity AP300 Wafer Stepper. The optical specifications for the Unity 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 [10] for the Unity 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 Wafer Stepper provides a more uniform aerial image through the depth of the ultrathick photosensitive materials in contrast to steppers with larger NA values and a relatively narrow bandwidth [11]. 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 $\geq$ 2400 mW/cm^2 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 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.

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 10 μm to 100 μm. The reticle used for plating has a 37 mm by 15.5 mm field size and contains 30 μm to 100 μm round contacts with various pitches.

Multiple wafers were exposed in a focus/exposure pattern. Focus latitude of 50 μm contact was examined by cross section of square contact patterns with a Joel JSM 6340F SEM. Plating was done on wafers exposed at best focus and best exposure and CD were measured on the Hitachi S7280 SEM after plating.

2.2 Photoresist Processing

SEMI standard 200 mm prime Cu seed wafers were used for this study. The photoresist used is Shin-Etsu SIPR® 7123M-20. The SIPR 7123M-20 photoresist was coated to the 55 μm target thickness using the process and equipment described in Table 2. Photoresist thickness and uniformity was measured on a Steag ETA Optik thickness measurement tool.

Shin-Etsu SIPR 7123M-20 photoresist is a TMAH developable, chemically amplified positive photoresist. The thickness at 3000 RPM is 20 μm and it can easily coat up to 55 μm thick in a single application. TMAH 0.26N developer without surfactant was used in the experiment. The exposure wavelength selected was ghi-line of mercury. Post Exposure Bake (PEB) is not required. The development method is immersion at room temperature, followed by a DI water rinse.

For electroplating, the wafers were processed at nominal conditions (2000 mJ/cm^2 at –15 μm focus, ghi wavelength) with an edge width exposure of 1.5 mm. The photoresist can be easily stripped off by soaking in acetone.

2.3 Electroplating

A set of 200 mm Cu seed wafers were exposed using the nominal conditions of 2000 mJ/cm^2 at ghi-line wavelength, -15 μm focus with an edge width exposure of 1.5 mm. The wafers were sent to Freescale Semiconductor for Cu electroplating using their proprietary process. After electroplating the photoresist was stripped by soaking in acetone for 10 minutes at room temperature.

2.4 Data Analysis

After exposure the wafers were cleaved for cross section on a Joel JSM 6340F and Hitachi S4100 metrology SEM to show linearity and depth of focus of 50 μm spacewidths and square contacts. Bottom CD measurements were taken at 800 magnification for 50 μm square contacts to show depth of focus at nominal exposure and linearity at nominal exposure and focus as illustrated in Figure 2, 3, 4 and 5. Cross sectional SEM photographs and Bossung plots are presented to illustrate masking linearity and depth of focus at nominal exposure dose.

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

3.0 RESULTS AND DISCUSSIONS

3.1 Linearity

Figure 2 shows the process linearity for 55 μm thick SIPR 7123M photoresist on Cu substrates for a dense line and space pattern. The process conditions are 1800 mJ/cm^2 (ghi-line) with a -10 μm focus offset. This graph shows that the printed feature size is linear with respect to the reticle feature size. This plot was constructed using cross-sectioned SEM data for grouped spaces and is a best fit plot of the data to the equation:

$$\mathbf{y} = \mathbf{x} + b \tag{1}$$

In this equation, **y** is the measured spacewidth, **x** is the reticle spacewidth and b is the photomask bias. The photomask bias is -0.27 μm with an R^2 data fit of 0.999. Typically positive photoresists in this thickness range would have a larger photomask bias [4]. The small reticle bias is a significant process advantage since it can simply reticle design and fabrication. Figure 2 also shows cross sectional SEM photographs of the process linearity for space widths at 15, 20, 50 and 100 μm. The sidewall angle is excellent for all space widths. Very little rounding is observed at the top of the photoresist. There is a small foot at the base of the photoresist at the 15 and 20μm feature sizes shown in figures ❶ and ❷. However, the observed footing would have minimal impact for most Cu pillar electroplating applications.

Figure 3 shows the process linearity for 55 μm thick SIPR 7123M photoresist on Cu substrates for a dense array of square contacts patterns. The process conditions are 1800 mJ/cm^2 (ghi-line) with a -10 μm focus offset. The photomask bias is +1.1 μm with an R^2 data fit of 0.999. The reticle bias for the contacts is larger than that observed for the spacewidth. This is expected since the exposure dose for contacts is larger than dense lines and space patterns [9]. Figure 3 shows cross sectional SEM photographs of the process linearity for contacts at 15, 20, 50 and 100 μm. The sidewall angle is excellent for all contact sizes. The observed resolution of 15 μm far exceeds the contact size for copper pillars currently being considered for advanced packaging applications. This resolution margin provides excellent critical dimension control and process latitude.

3.2 Baseline Photoresist Conditions

The process latitude of SIPR 7123M was evaluated using cross sectional SEM photographs of 50 μm line and space patterns in 55 μm thick photoresist on Cu seed substrates. Figures 4 show a Bossung plot of space width from -30 μm to +10 μm focus offsets with exposure doses from 1600 to 2000 mJ/cm^2 (ghi-line). The two horizontal lines in the plot shows a four percent CD latitude for the 50 μm spacewidth. At an exposure less than 1800 mJ/cm^2 the curves fall out of the CD limits for positive focus offsets. However, at exposure doses of 1800 mJ/cm^2 and larger the curves show essentially a flat response of CD versus focus offset. This gives a large focus latitude which can be very advantageous for controlling CD over local topography variations.

Figure 4 also shows cross sectional SEM photographs of 50 μm space widths in 55 μm thick photoresist on Cu substrates. The -30 μm focus offset in figure ❶ shows some rounding at the top of the photoresist. In contrast the +5 μm focus offset in figure ❸ shows a moderate foot and vertical sidewalls at the top of the photoresist. The best compromise between the footing and the top rounding is a focus offset of -10 μm as shown in figure ❷. Also at this optimum exposure and focus condition the photomask print bias is extremely small.

The process latitude of SIPR 7123M was evaluated using cross sectional SEM photographs of 50 μm square contacts in 55 μm thick photoresist on Cu seed substrates. Figure 5 shows a focus plot of contact width versus focus offset from -30 to +10μm at 1800 mJ/cm^2 (ghi-line). The two horizontal lines in the plot shows a four percent CD latitude for the nominal 50 μm contact size. The CD curve falls out of the limits at a focus offset of -5 μm. This gives a total focus latitude of 25 μm compare to the 40 μm observed for 50 μm spaces. The focus latitude would be expected to be larger at a higher exposure dose or biased photomask as discussed in section 3.1. However, higher exposure dose CD data was not collected during this study.

Figure 5 also shows cross sectional SEM photographs of 50 μm square contacts in 55 μm thick photoresist on Cu substrates. The -30 μm focus offset in figure ❶ shows moderate rounding at the top of the photoresist. In contrast the +5 μm focus offset in figure ❸ shows nearly vertical sidewalls at the top of the photoresist. The best compromise between maintaining CD and sidewall angle is a focus offset of -10 μm as shown in figure ❷.

3.3 Electroplating

Cross sectional SEMs were used to determine the CD linearity of the final electroplated Cu pillar structures. Figures 6(a) through (c) shows round Cu pillars from 30 to 100 μm in 55 μm thick photoresist on Cu seed substrates. The average pillar height is 30.0 μm as measured using a Dektak V300-Si. The pillars show excellent sidewall profiles with no signs of underbump plating. Clearly the photoresist demonstrated adequate durability in the electroplating bath with no adhesion failure.

Cross sectional SEMs were used to show grouped and isolated electroplated 50 μm Cu pillar structures. Figures 7(a) through (c) shows round Cu pillars from 12.5 μm spacing (4:1 ratio) to 100 μm spacing (1:2 ratio) in 55 μm thick photoresist on Cu seed substrates. There is no indication of Cu bridging between bumps.

The Shin-Etsu 7123M photoresist used in conjunction with the Ultratech AP300 stepper exhibits Cu pillar fabrication capability that exceed current design requirements and offers the potential to meet future advanced packaging needs.

4.0 CONCLUSIONS

The objective of this study is to evaluate a positive tone, 55μm thick chemically amplified photoresist for a Cu pillar production process. The SIPR 7123M was shown to meet these requirements. A unique feature of this material is a chemically amplified system that does not require PEB.

The SIPR 7123M photoresist performance easily meets requirements for both current and future generations of Cu pillar processing using the Ultratech AP300 stepper. This study demonstrated excellent photoresist resolution down to 15 μm with good process control. Cu electroplating was shown down to 30 μm pillars. In addition, adequate electroplating performance was achieved along with an excellent strip process. Also it should be noted that the resolution and CD control is more than sufficient to meet Cu pillar dimensions for future packaging requirements.

The Shin-Etsu 7123M photoresist used in conjunction with the Ultratech AP300 stepper exhibits Cu pillar fabrication capability that exceed current design requirements and offers the potential to meet future advanced packaging needs.

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6.0 REFERENCES

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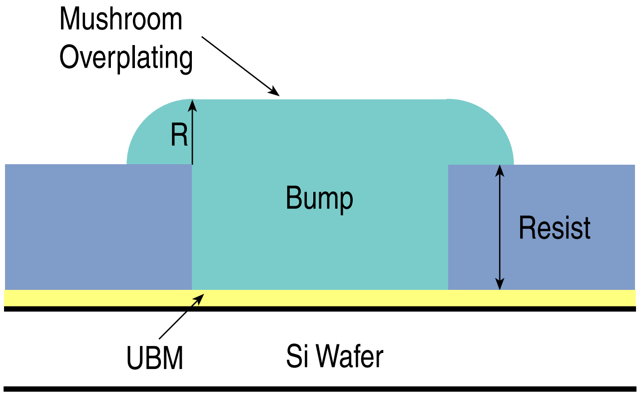


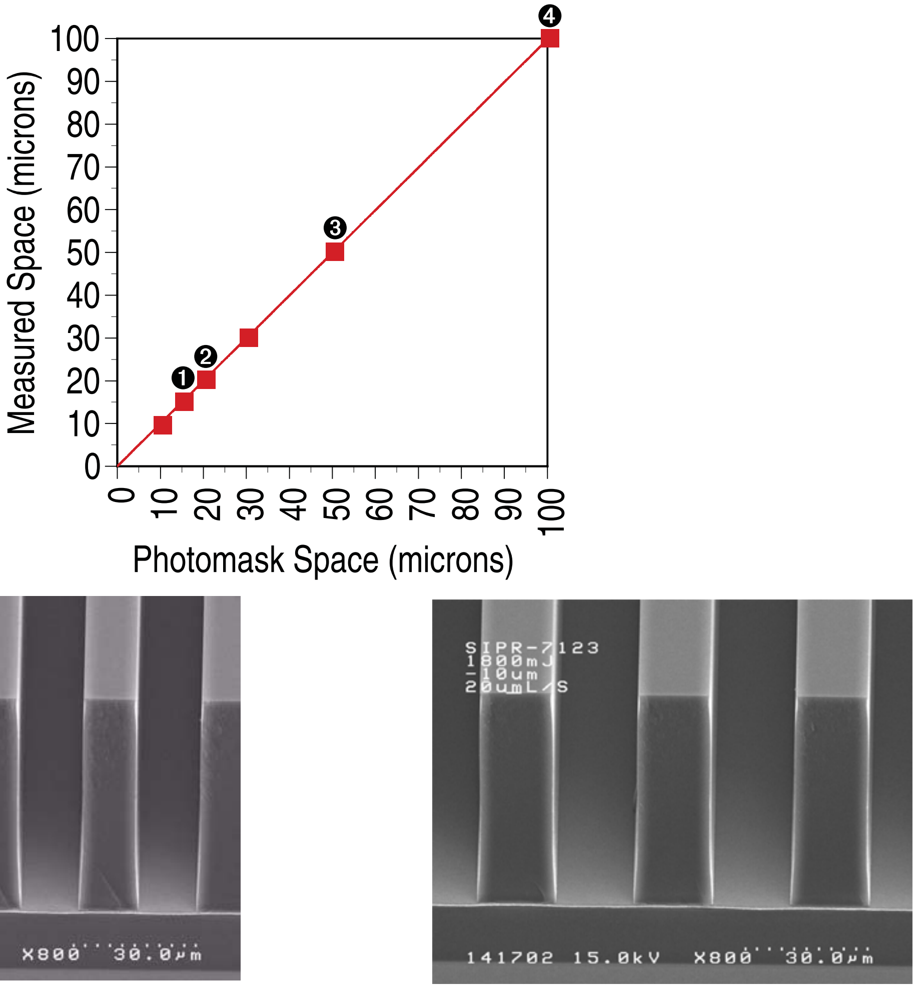
Figure 1: Cross section of a typical mushroom shaped solder bump.

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.

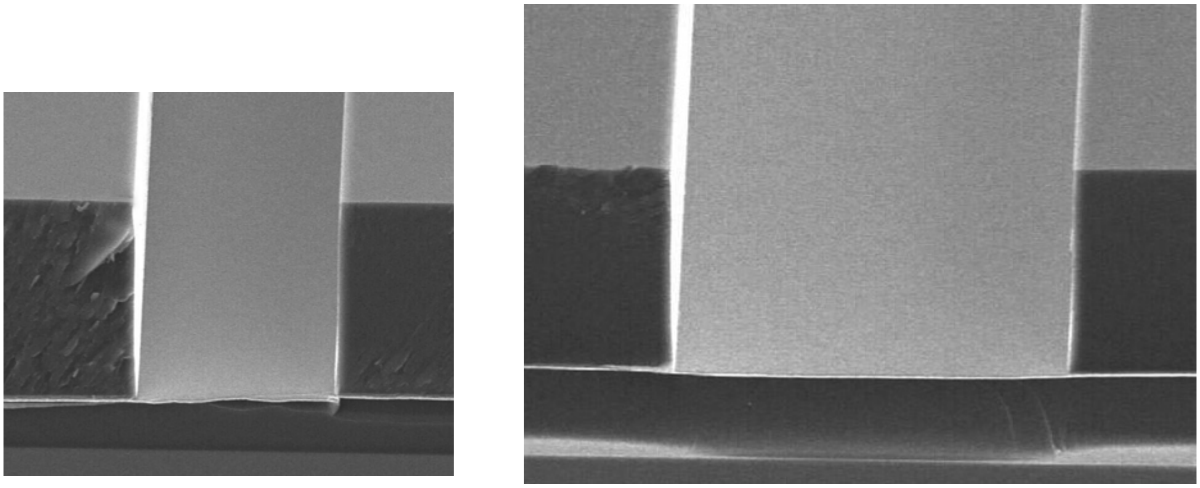
Process Step	Parameters	Equipment
Shin-Etsu SIPR 7123M-20 Coat	pre-wet: Fujifilm RER 600 for 10 seconds Dry at 1400 rpm for 1 second Static dispense for 16 seconds Spread: 500 rpm for 5 seconds Spin: 480 rpm for 80 seconds Backside Rinse: 480 rpm for 20 seconds Dry: 480 rpm for 10 seconds	ACS 200
Softbake	Hotplate, 0.2 mm proximity 2 minutes at 90°C 8 minutes at 130°C	ACS 200
Exposure	ghi-line, focus-exposure matrix 1.5 mm WEE PEB: not required	AP 300
Develop	7 minutes immersion in 2.38% TMAH, 21°C Constant and aggressive agitation DI water rinse Spin rinse and dry	

Table 2: Process conditions for Shin-Etsu SIPR 7123M-20 for 55 µm thickness on 200mm Cu wafers.



❶ 15 µm space

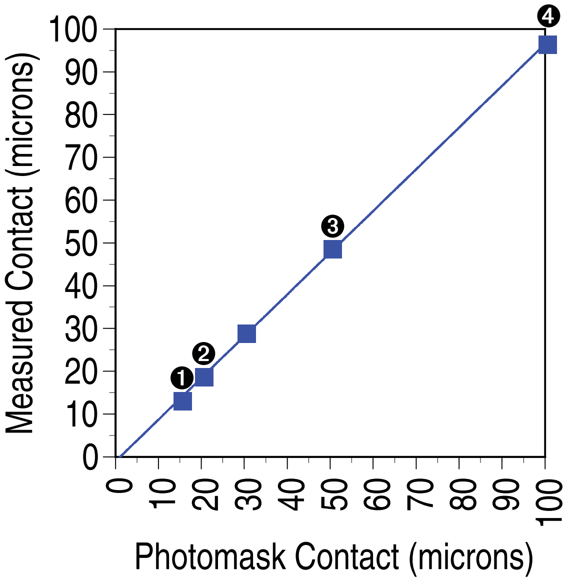
❷ 20 µm space

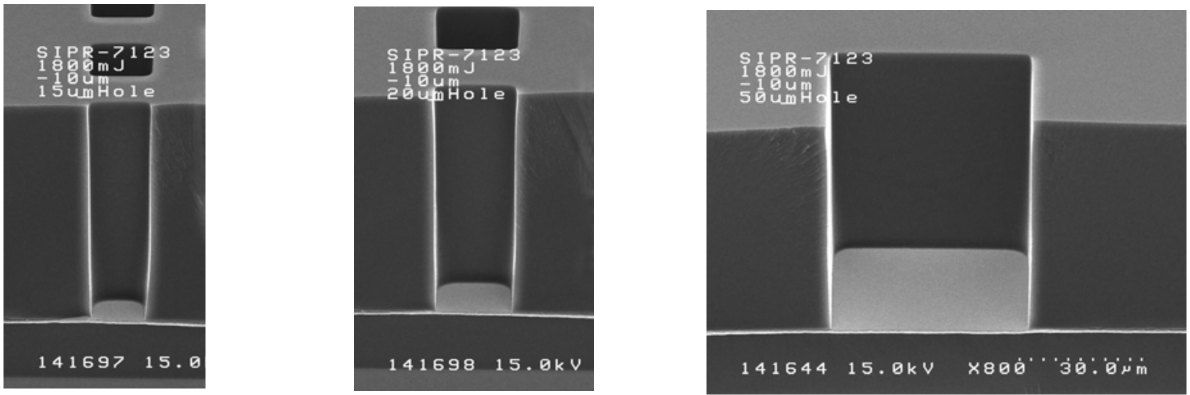


❸ 50 µm space

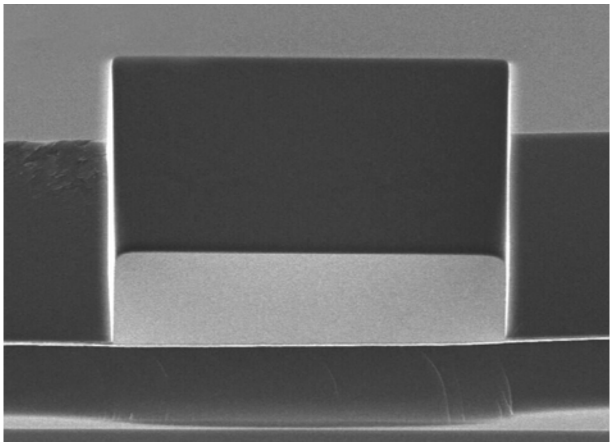
❹ 100 µm space

Figure 2: Mask linearity plot of 55 µm thick SIPR 7123M-20 for equal lines and spaces on Cu substrates. The process conditions are 1800 mJ/cm^2 (ghi-line) with a -10 µm focus offset. The photomask bias is -0.27 µm with an R^2 data fit of 0.999. The SEM photographs show spaces for the four photomask sizes indicated on the plot.



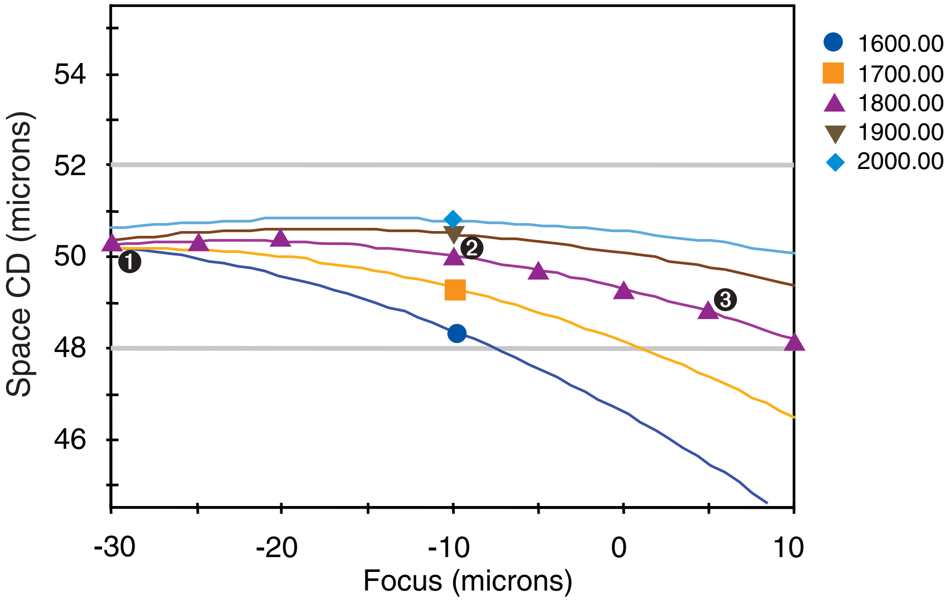


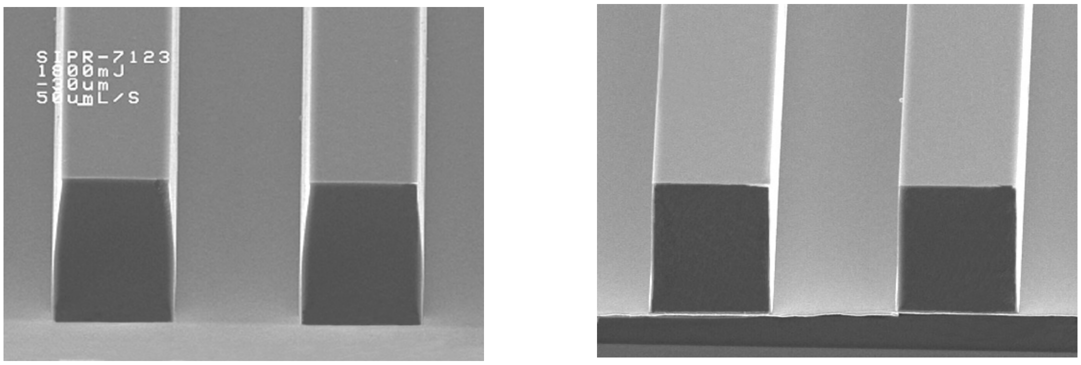
❶ 15 µm contact ❷ 20 µm contact ❸ 50 µm contact



❹ 100 µm contact

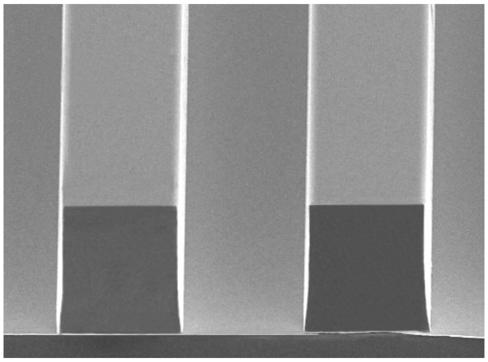
Figure 3: Mask linearity plot of 55 µm thick SIPR 7123M-20 for a dense array of square contacts on Cu substrates. The process conditions are 1800 mJ/cm^2 (ghi-line) with a -10 µm focus offset. The photomask bias is +1.1 µm with an R^2 data fit of 0.999. The SEM photographs show the four photomask sizes indicated on the plot.





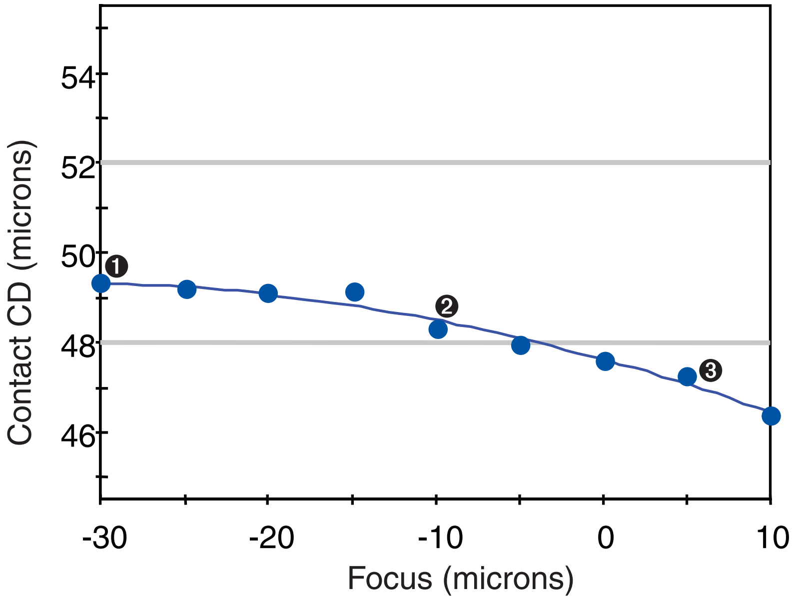
❶ -30 µm focus

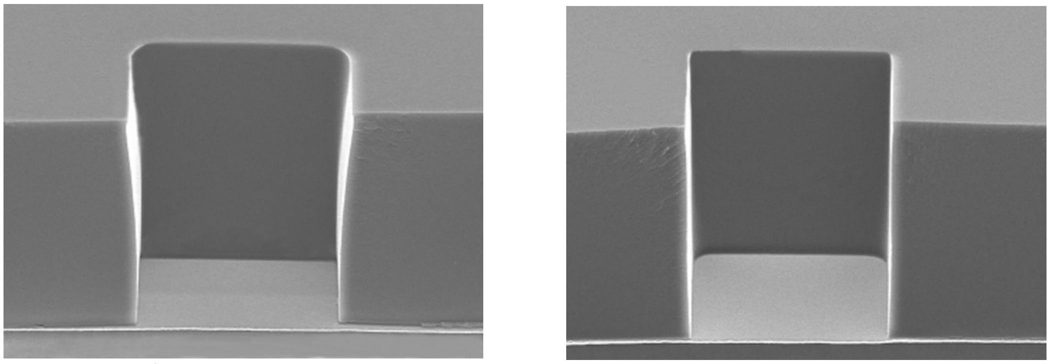
❷ -10 µm focus



❸ +5 µm focus

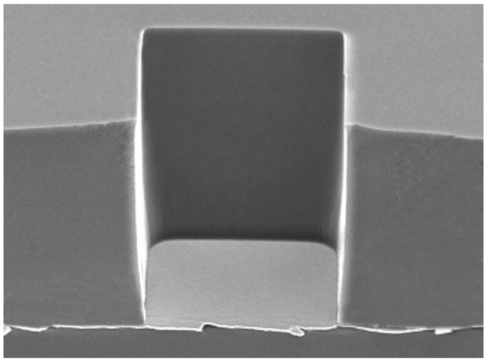
Figure 4: Focus and exposure matrix of 55 µm thick SIPR 7123M-20 for 50 µm equal line and spaces. The control limits in grey are ± 2µm. The SEM photographs show line and spaces at an exposure dose of 1800 mJ/ cm^2 (ghi-line).





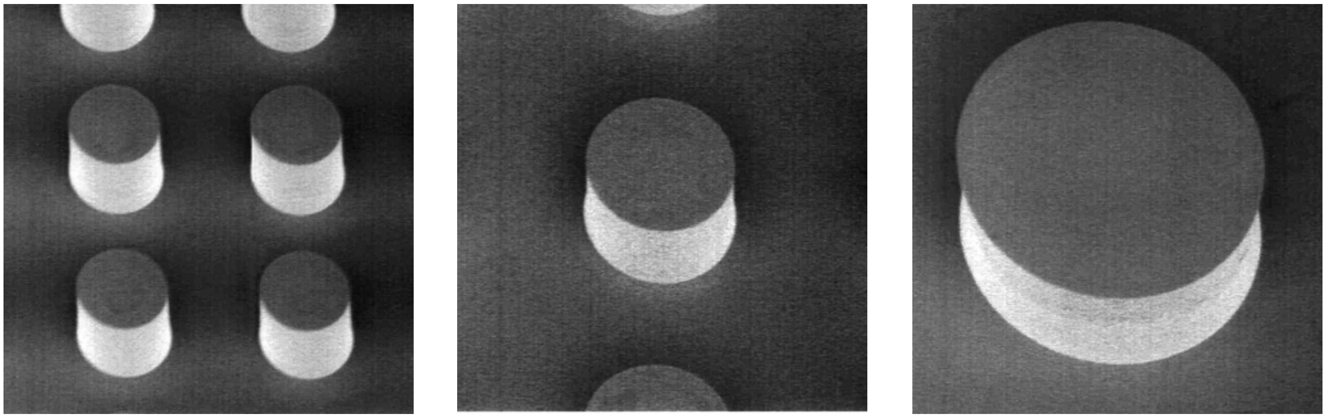
❶ -30 µm focus

❷ -10 µm focus



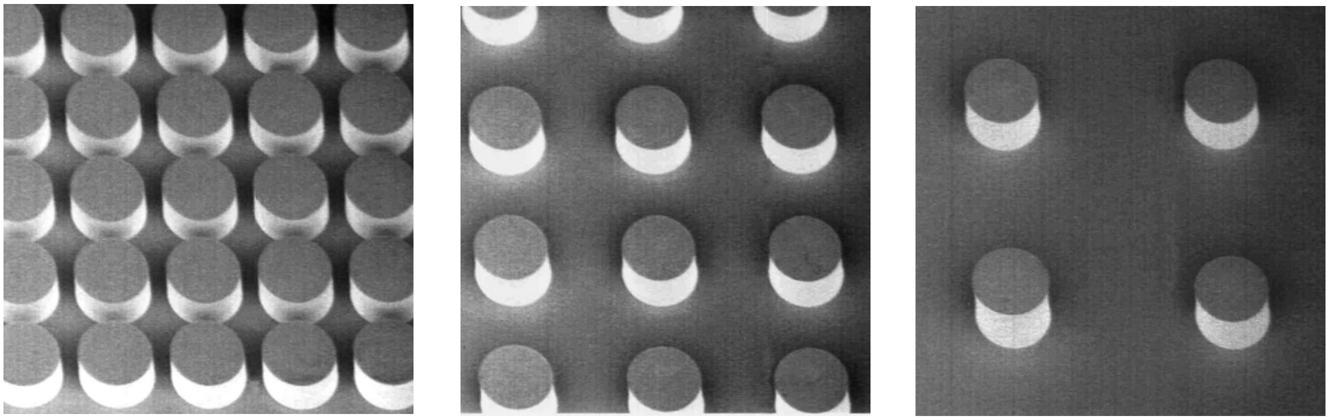
❸ +5 µm focus

Figure 5: Focus latitude plot of 55 µm thick SIPR 7123M-20 for square contacts at an exposure dose of 1800 mJ/cm^2 (ghi-line). The control limits in grey are ± 2µm.



(a) 30 μm pillar (b) 50 μm pillar (c) 100 μm pillar

Figure 6: SEM Photographs illustrating the pillar CD linearity of 55 μm thick Shin-Etsu SIPR 7123M after Cu electroplating. The average pillar height is 30.0 μm.



(a) 12.5 μm spacing (b) 50 μm spacing (c) 100 μm spacing

Figure 7: SEM Photographs illustrating grouped and isolated 50 μm pillars in 55 μm thick Shin-Etsu SIPR 7123M after Cu electroplating.