Characterization of a Novel Photoresist Redistribution Material for Advanced Packaging Applications

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The widespread adoption of advanced packaging techniques is primarily driven by electrical device performance and chip form factor considerations. Flip chip packaging is currently growing at a 27% compound annual rate and it is expected that by 2005 over 60% of all 300 mm wafers will be bumped [1]. To ensure optimal productivity and cost of ownership it is imperative to provide lithographic materials that are optimized for these applications.

Flip chip packaging frequently uses one or more redistribution levels to increase the number of pads that can be bumped in the minimum form factor. The redistribution level requires a photosensitive dielectric material to be used as a permanent insulating layer. The mechanical, electrical and lithographic properties of the material for this level are all important. This study will characterize a novel photosensitive siloxane material (Shin-Etsu SINR™ Photoresist) for the use in the redistribution layer. Siloxanes are a good choice for redistribution because of their excellent physical properties, ease of processing and relatively low curing temperatures.

The lithographic performance of SINR photoresist has been optimized using a broad band 1X stepper to control critical dimensions (CD). This study evaluates process capability at multiple exposure wavelengths and post exposure bake (PEB) conditions. Cross sectional SEM analysis, process linearity, Bossung plots and process windows are used to establish the lithographic capabilities. Material modifications also were investigated to control the photoresist sidewall angles.

Key Words: advanced packaging, flip chip, redistribution, photosensitive dielectric, process optimization

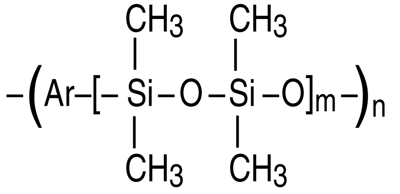
1.0 INTRODUCTION

The ever increasing complexity of integrated circuits (IC) has led to more advanced techniques in semiconductor processing. One particular area of great change is in packaging. Greater pin counts have been required in order to accommodate the increasing functionality of the ICs. In particular this is accomplished with bump processing or CSP (Chip Scale Packaging). The ability to continually shrink the feature size and improve the performance has occurred because of advancements in materials, equipment and processing technology. It is no longer sufficient to simply adapt processing methods for known materials to the requirements of ever decreasing device critical dimensions and higher pin counts. Furthermore it is important to choose a material that is easily processed such that in large scale manufacturing there would be low rework rate, high yield and low material waste in order to keep a low cost of ownership.

The transition to flip chip packaging also is being facilitated by redistribution techniques. Routing redistribution repositions the input/output (I/O) pads from the perimeter footprint to alternative locations on the chip. The use of redistribution allows utilization of greater area of the chip resulting in significant area savings, common I/O footprints, and enables the use of simpler, less expensive substrates. The increasing use of redistribution processes is placing tighter requirements for alignment, resolution and critical dimension (CD) control during the photolithography sequences. The first process step for redistribution is the deposition of a dielectric layer on the wafer to enhance the die passivation. Thin film polymers are preferred on account of low dielectric constants, high temperature stability and moisture resistance characteristics [1].

Bisbenzocyclobutene (BCB) has been widely used for redistribution layers because of its low dielectric constant and dissipation factor [2,3,4]. Dow Chemical Corporation produces a BCB photosensitive material called Cyclotene™ that contains a divinyl siloxane structure [5]. Shin-Etsu has recently optimized a family of photosensitive siloxane materials know as SINR photoresist. Potential applications include bump processing and passivation. These materials have shown great promise for ease of use as well as good material and electrical properties. No develop end point detection or descumb process is needed for the processing of the SINR photoresist. Furthermore the SINR photoresist is room temperature stabile, making the material easy to use in large scale manufacturing cost effectively.

Shin-Etsu SINR photoresist is a linear siloxane based polymer modified by a heat-resistant aromatic bond. A non-polar aromatic blocking element is used. SINR photoresist has a Photo Acid Generator (PAG), and after i-line, g-line or h-line mercury (Hg) irradiation, the aromatic part of the material and the crosslinking agent react to form an ether bond. The PAG content is very low, but the SINR photoresist has a very high sensitivity. Because of the high sensitivity it is easy to pattern films of 60 µm or greater. After final curing, the ether bond formation is finished and the generated acid from the PAG and PEB is removed from the system. The diagram below is a schematic of the chemical structure.



$$-\left(\mathrm{Ar}-[-\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{\mathrm{Si}}}-\mathrm{O}-\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{\mathrm{Si}}}-\mathrm{O}]_m-\right)_n \qquad (1)$$

SINR photoresist is easily modified to change the mechanical properties by simply changing the siloxane content. Typical ranges of percent siloxane vary from 10 to 70%. The addition of a photosensitizer in the form of chemical amplification allows siloxanes to be easily processed using conventional semiconductor processing equipment. Curing temperatures are relatively low, in the 220^{o}C range. Cationic curing conditions exist so that the final material exhibits relatively low shrinkage during cure. The properties of SINR 3170 photoresist (70% siloxane) are described in Table 1 for a 13 µm film. This thickness would be typical for a redistribution process.

Certain issues always have been prevalent in material used for passivation or redistribution layers. For example, if the material oxidizes it loses its desirable mechanical and electrical properties. Furthermore, if there is not sufficient temperature stability there could be pattern deformation during solder reflow (the film must be able to sustain up to 300^{o}C for 30 seconds multiple times, as this is the high end of the solder reflow temperature). A mid-range dielectric constant of 2.9 to 3.0 is required for redistribution. The coefficient of thermal expansion (CTE) and the Young's modulus need to be well controlled, however it is difficult to separate the two factors when looking at mechanical performance. Resistance to bases also is important since there could be some extreme chemical environments. The SINR photoresist properties meet all of these requirements.

From a lithographic standpoint, the sidewall slope is important for metal step coverage since a vertical profile could lead to gaps in the metal coverage due to sputtering characteristics [6]. Since subsequent processing after redistribution requires sputtering, the SINR photoresist also must exhibit an appropriate sidewall slope. However, there are already proven process techniques that would eliminate the need for sloped profiles [7]. Long photoresist shelf life and ease of processing with good process latitude also are required. Without sufficient process latitude, yields would diminish or high reworks could occur. Therefore, characterization and process latitudes are just as critical as the material properties of the film. Since the redistribution process is used in large scale production, it is important that the photoresist be very robust to processing and environmental conditions. The photoresist has shown at least a four month shelf life at room temperature without any degradation of material or liquid properties. It offers a unique chemistry that provides good mechanical, electrical and processing characteristics.

Another critical issue for redistribution is the choice of lithography equipment. The fabrication of smaller contact structures for redistribution applications is a new and challenging use of photolithography equipment and photoresists. The photolithography requirements for redistribution can be addressed by using optical lithography equipment originally developed for production of semiconductor devices. Steppers, full wafer scanners and contact printers are used widely in the microelectronic industry and are highly evolved production tools. A stepper offers tighter overlay and improved CD control in comparison to contact printers or full wafer scanners. Most reduction steppers are designed for optimal performance when exposing submicron features in one micron thick photoresists. This is accomplished by using large numerical aperture (NA) and narrow exposure band optics as well as reticle enhancement technology such as phase shift masks and optical proximity correction. In contrast, redistribution levels typically require a large depth of focus (DOF) for thick film lithography of contact structures. For this reason, it is advantageous to utilize a stepper with a broad band exposure system to maximize the illumination intensity at the wafer plane and low numerical aperture (NA) to improve DOF.

2.0 EXPERIMENTAL METHODS

2.1 Lithography Equipment

Lithography for the thick photoresist evaluated in this study was performed on an Ultratech Stepper Saturn Spectrum 3 Wafer Stepper®. The optical specifications for the Saturn Spectrum 3 are shown in Table 2. 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 [8]. 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 Saturn Spectrum 3 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 [9].

A filter system was employed 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.

Multiple wafers were exposed in a focus/exposure pattern consisting of a nine by nine field array as illustrated in Figure 1. Nominal exposure doses were determined by measuring cross section of space patterns at the specific linewidth of interest with a Joel JSM 6340F and Hitachi S4100 SEM. Top down CD measurements also were performed on a Hitachi S7280H metrology SEM for the entire focus/exposure matrix. A zero percent threshold criteria was selected for the determination of the CD.

The Ultratech 1X reticle used for this study was designed primarily to support cross sectional SEM metrology. The reticle consists of two fields of 10 mm by 10 mm, one of each polarity to support both positive and negative acting photoresists. Each field contains contacts and line patterns from 0.5 to 50 µm. Both equal line and space patterns and isolated lines are included for all structure sizes. For each structure size the center line or space extends to create an isolated feature. There was no data biasing applied to the design data and CDs were held to within ±0.03 µm of a nominal chrome line. Reticle CD information also was obtained for all line sizes on both fields to establish the process linearity in reticle fabrication.

2.2 Photoresist Processing

SEMI standard 150 mm ultra-flat silicon wafers were used for this study. The ultra-thick photosensitive material used for this investigation was Shin-Etsu SINR® 3170M-13. No pre-treatment of the wafers was recommended by Shin-Etsu MicroSi. The Shin-Etsu SINR 3170M was coated to the 13 µm target thickness using the process and equipment described in Table 3. Photoresist thickness and uniformity were measured on a Nanometric 8300X measurement system. The thickness after final cure as measured by SEM cross section is 11.5 to 11.9 µm.

Shin-Etsu SINR 3170M photoresist is a siloxane based photosensitive liquid. The resist is sensitive to ghi-line wavelengths and is easily patterned using conventional semiconductor processing. The only exception is that development is with isopropyl alcohol (IPA) rather than a TMAH aqueous developer. Three post exposure bake (PEB) temperatures (90^oC, 100^oC, 110^oC) and three illumination conditions (i, gh, ghi-line) were studied. The exposure energy is approximately 200 mJ/cm^2 and the development time is 2 minutes puddle plus a 20-second rinse also with IPA. All wafers were cured by a 2-step bake in a convection oven as described in Table 4.

2.3 Data Analysis

After exposure all wafers were visually inspected and measured on a Hitachi S7280H metrology SEM to show the photoresist process latitude for 20 and 30 micron contacts and lines. CD measurements of dense spaces were taken at 5,000X and 3,000K magnification for 20 µm and 30 µm spaces respectively. Spacewidths of 20 µm and 30 µm were measured top-down on the SEM over the entire focus and exposure matrix as illustrated in Figure 1. This CD data was entered into a spreadsheet and analyzed with the assistance of Prodata® software by Finle Technologies, a division of KLA-Tencor. Both Bossung plots and process window plots were generated using ±1 micron CD control criteria. Cross sectional SEM photographs are presented to illustrate masking linearity for contact structures at different PEB temperatures and exposure wavelengths. Cross sections were taken on the Joel JSM 6340F and Hitachi S4100 SEM. The results from the data analysis are discussed in Section 3.0.

3.0 RESULTS AND DISCUSSIONS

3.1 Film Retention

Figure 2 shows the normalized film retention curve for the negative acting SINR 3170M photoresist. The after develop film thickness was measured at three PEB conditions over a wide range of exposure doses using ghi-line illumination. A value of 1 indicates that the after develop film thickness is the same as the pre-develop thickness of 13 µm. The 110^oC and 100^oC PEB show greater than 95% film retention at an exposure dose of less than 50 mJ/cm^2. However, the 90^oC PEB does not achieve full film retention even at the highest exposure dose of 150 mJ/cm^2. These results indicate that the 90^oC PEB temperature is not sufficient to complete chemical amplification of the photoresist which prevents it from being considered for an optimized process.

3.2 Linearity Comparison

Figure 3(a) shows the process linearity for the SINR 3170M photoresist for the same three PEB conditions. In all three cases the printed feature size is linear with respect to the reticle feature size. This plot was constructed using cross-sectioned SEM data for grouped contacts and is a best fit plot of the data to the equation:

$$\mathbf{y} = \mathbf{x} + \mathrm{b} \tag{2}$$

In this equation, **y** is the measured contact size, **x** is the reticle contact size and b is the mask bias. The mask bias is strongly dependent on the PEB temperature, and the mask bias results are summarized in Table 5. The mask bias is only 0.47 µm with the 90°C PEB. However, the film retention is maximized with the 110 and 100°C PEB as discussed in section 3.1. This suggests that a compromise PEB would be 100°C. This condition maximizes the film retention (approximately 1) while resulting in a moderate mask bias (-4.7µm).

Figure 3(b) shows the process linearity for the SINR 3170M photoresist for three exposure wavelength conditions. Again, the printed feature size is linear with respect to the reticle feature size. The mask bias variation is summarized in Table 5. Because of the broad sensitivity of the PAG used in SINR 3170M, there is less than 0.5 µm difference in mask bias between the various exposure wavelengths. This suggests that the final choice of exposure wavelength should be determined by SEM analysis of the photoresist profile. If the final choice of exposure wavelength is not a critical process consideration, then the wavelength should be chosen based on optimized stepper throughput.

Angled SEM photographs are shown in Figure 4 to illustrate masking linearity for 10, 12, 15 and 30 µm square contacts. The contacts are exposed at 190 mJ/cm^2 using ghi-line illumination and a 100°C PEB. Some corner rounding is observed on the 12 and 10 µm contacts. However, the 10 µm contacts are clearly open with no indication of the photoresist scumming. Current redistribution processes used in production require contacts greater than 30 µm in size. The 10 µm resolution suggests that SINR 3170M has the capability of easily supporting future generations of redistribution processes as feature sizes decrease.

3.3 PEB Conditions

SEM photographs were used to determine the impact of the PEB conditions on photoresist profiles of the SINR 3170M. Figure 5 shows cross sections of 30 µm lines and angle views of 30 µm contacts for 90, 100 and 110°C PEB. In all cases ghi-line illumination was used at an exposure dose of 190 mJ/cm^2. It is apparent that the line size and contact size is a strong function of the PEB. The 90°C PEB results in smaller lines and larger contacts which are consistent with the linearity results in section 3.2. This sensitivity to PEB is expected for negative chemically amplified resist. Near vertical sidewalls are observed in all PEB cases. This type of profile is typical of a chemically amplified photoresist. The 90°C PEB does exhibit a slight foot in the photoresist line, which is not observed at the 100 or 110°C PEB. This suggests that the 100 or 100°C PEB would be an advantage for applications requiring electroplating.

3.4 Wavelength Comparison

SEM photographs were used to determine the impact of exposure wavelength on resolution and photoresist profiles of the SINR 3170M. Figure 6 shows cross sections of 30 µm lines and angle views of 30 µm contacts for ghi, gh and i-line exposure. There is no obvious difference in the sidewall angle for the three exposure wavelengths. Figure 7 shows cross sections of 15 µm lines and angle views of 15 µm contacts for ghi, gh and i-line exposure. Again there is no observed wavelength dependency. Excellent resolution is observed with near vertical sidewalls for all cases. Based on these results the broadband ghi-line exposure is recommended since this provides maximum illumination intensity at the wafer plane (1700 mW/cm^2) and the corresponding highest throughput on the Saturn Spectrum 3 stepper.

3.5 Process Windows

Wafers were imaged on the Saturn Spectrum 3 stepper with exposure doses from 120 to 190 mJ/cm^2 with increments of 10 mJ/cm^2 and focus varied from -20 to +20 µm focus at increments of 5 µm. The SINR 3170M exhibits well behaved lithographic process characteristics. Figure 8 shows Bossung plots for 18.5 and 29.5 µm spacewidth features. Each curve shows how CD changes through focus at constant exposure dose. The two horizontal lines in each plot demarcate ±1.0 µm CD latitude for the given spacewidth. This CD latitude was chosen to correspond to an acceptable process control for this feature size in a redistribution application.

Figure 9 shows process window plots for 18.5 and 29.5 µm spacewidth features. The envelope region outlined in black demonstrates a ±1.0 µm CD control limit for this spacewidth. Shaded in gray is the largest area rectangular process window that fits within the envelope region. Other rectangles can be drawn in the envelope region depending on exposure and focus latitude requirements for a given process. At the center of the 18.5 µm line process window the exposure energy is 158 mJ/cm^2 and the focus is -3.0 µm for the 29.5 µm line the exposure energy is 154 mJ/cm^2 and the focus is -4.0 µm. The similar exposure dose for both sizes is indicative of the excellent linearity discussed in section 3.2. The process windows correspond to a greater than 25 µm depth of focus and the exposure latitude of greater than 35% for both feature sizes.

3.6 Sidewall Angle

Chemical amplification in combination with the siloxane leads to vertical profiles independent of processing and equipment conditions including PEB conditions, defocus and wavelength selection. However, it is possible to modify the SINR photoresist chemistry with an additive to change the sidewall slope. Figure 10 shows 40 and 60 µm features with 75 degree slopes at a cured thickness of 14.5 µm. Exposure had to be significantly increased while keeping the PEB at 100^{o}C. In this particular case a 30% siloxane was chosen to test the capability of achieving a sloped profile. This sidewall angle may provide an advantage for metal step coverage depending on the metal deposition technique.

4.0 CONCLUSIONS

This study has shown the feasibility of processing SINR 3170M photoresist on an Ultratech Saturn Spectrum 3 stepper for a redistribution level. SINR 3170M is a negative acting, acid catalyzed, siloxane based material that can be easily processed using conventional semiconductor processing equipment. This photoresist has unique physical properties, electrical properties and ease of use that make it an ideal redistribution material for advanced packaging applications. Ease of use also was demonstrated since no develop end point detection or descumb process was required. Furthermore, the process was easily repeatable with the same batch of SINR photoresist being stored at room temperature.

A linearity analysis was performed to investigate PEB and exposure illumination effects. The mask bias is strongly dependant on the PEB temperature and is minimized by using a 90^{o}C PEB. However, the 90^{o}C PEB does not achieve full film retention so a higher PEB of 100^{o}C is recommended. Because of the broad sensitivity of the photoactive compound used in SINR 3170M, there is less than 0.5 µm difference in mask bias between the various exposure wavelengths.

Cross sectional SEM analysis and process window analysis were used to establish the lithographic capabilities of the SINR 3170M. The 10 µm resolution suggests that SINR 3170M has the capability of supporting future generations of redistribution processes as feature sizes decrease. Near vertical sidewalls are observed in all PEB cases. This type of profile is typical of a chemically amplified photoresist. However, with a slight change to the SINR photoresist chemistry and process it is possible to achieve a 75 degree slope. A summary of recommended lithographic process for the SINR 3170M is given in Table 6.

5.0 ACKNOWLEDGEMENTS

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Parameter	Value
Breakdown voltage	280 V/μm
Volume Resistivities	2 x 10^{16}
Dielecetric Constant	2.9 at 1 Mhz
Dissipation Factor	2 x 10^{-3} at 50Hz
Tensile Strength	20 MPa
Elongation	40%
Glass Transition temperature (T_g)	Not Observed
Coefficient of Thermal Expansion	150 ppm/ ^{o}C
Young's Modulus (25^{o}C)	90 MPa
Water Absorption	<0.2%

Table 1: Film properties of Shin-Etsu SINR 3170.

Parameter	Spectrum 3
Reduction factor	1X
Wavelength (nm)	350 - 450
Numerical aperture (NA)	0.16
Partial coherence (σ)	1.0
Wafer plane irradiance (mW/cm^2)	1750

Table 2: Optical specifications of the Saturn Spectrum 3 stepper used in this study.

Process Step	Parameters	Equipment
SINR 3170M-13 Coat	Static dispense; Spread: 300 rpm for 5 seconds Spin: 3000 rpm for 60 seconds	Solitec Spinner
Softbake	120 seconds at 100^{o}C, contact	ACS200 Hotplate
Post Exposure Bake	120 seconds at 100^{o}C, contact	ACS200 Hotplate
Develop	30 seconds x 4 puddles at 21^{o}C Isopropyl Alcohol (IPA)	Solitec Spinner
Rinse	10 seconds rinse (IPA) at 3000 rpm 20 seconds dry at 3000 rpm	Solitec Spinner

Table 3: Process conditions for Shin-Etsu SINR 3170M-13 for 13 μm thickness after lithography.

Process Step	Bake Time
Ramp from 105°C to 130°C	15 minutes
130°C bake	30 minutes
Ramp from 130°C to 220°C	30 minutes
220°C bake	60 minutes

Table 4: Hardbake conditions for Shin-Etsu SINR 3170M-13 using a Blue-M convection oven.

Exposure	Post Exposure Bake	Mask Bias
GHI line	90°C	0.47
GHI line	100°C	-4.72
GHI line	110°C	-8.44
GH line	100°C	-5.04
I line	100°C	-4.60

Table 5: Shin-Etsu SINR 3170M mask bias determined from the linearity regression analysis in equation (1). The mask linearity is shown in Figure 3. The mask bias is in units of microns.

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SINR 3170M	13 microns
Stepper Model	Saturn Spectrum 3
Wavelength	ghi-line
Post Exposure Bake (°C)	100
Nominal Exposure (mJ/cm^2)	155
Exposure Latitude (mJ/cm^2)	60
Focus Latitude (µm)	25
Reticle Bias (µm)	-4.7

Table 6: Recommended process application for Shin-Etsu SINR 3170M.

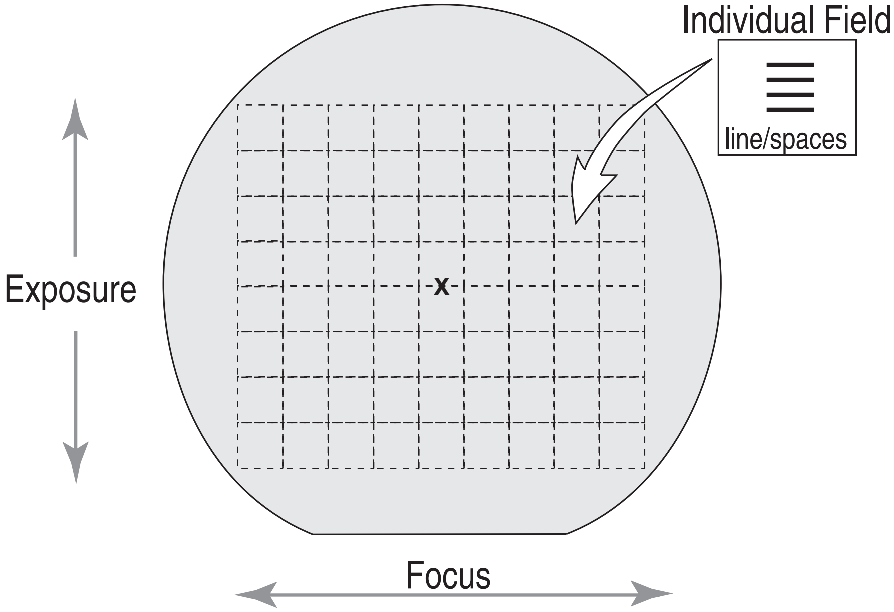


Figure 1: Wafer layout for the focus and exposure matrix. A nine by nine field array was exposed with focus varying in the horizontal axis and exposure dose varying in the vertical axis.

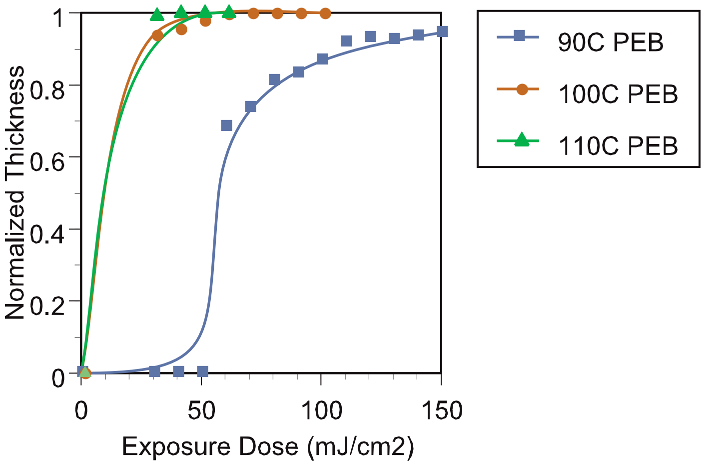
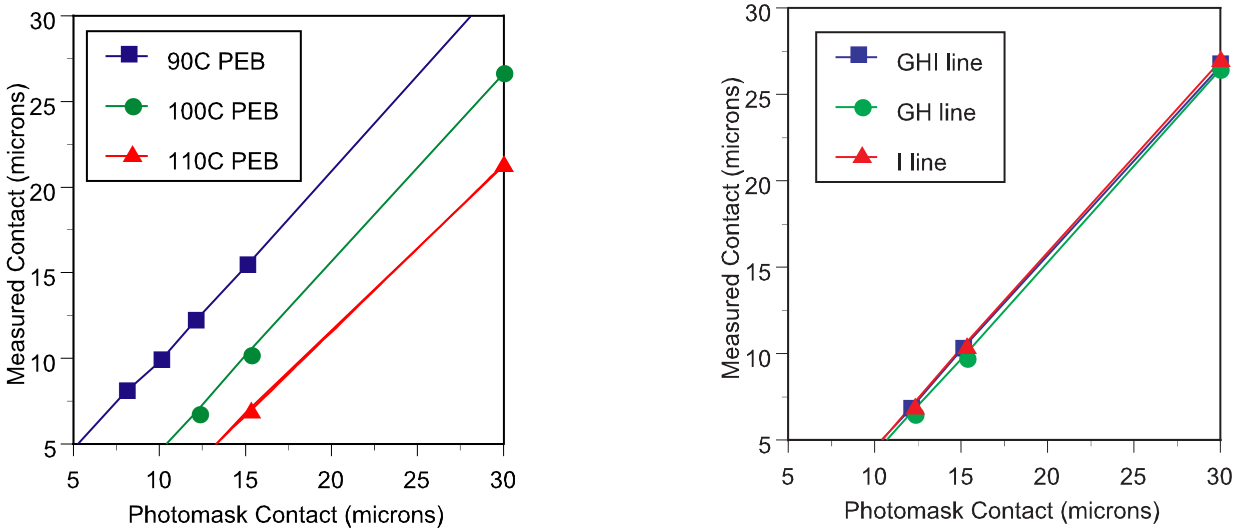


Figure 2: Film retention curve for SINR 3170M exposed at ghi-line illumination. A value of 1 indicates that the film thickness is the same as the pre-develop thickness of 13 µm.



(a) Post Exposure Bake
ghi-line Exposure

(b) Exposure Wavelength
PEB = 100°C

Figure 3: Mask linearity plot of 13 µm thick SINR 3170M for contact holes. The exposure dose is 190 mJ/cm^2 for all cases. The exposure is ghi-line only for (a) and the PEB is held constant at 100°C for (b).

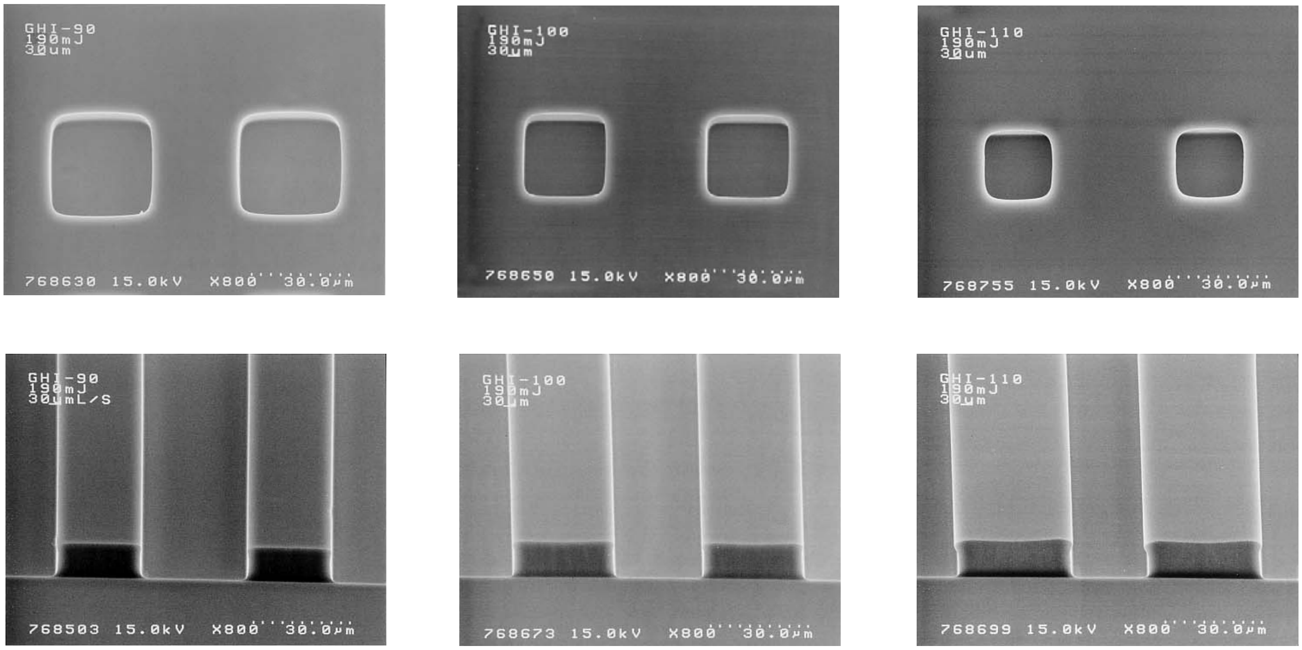
(a) 10 micron

(b) 12 micron

(c) 15 micron

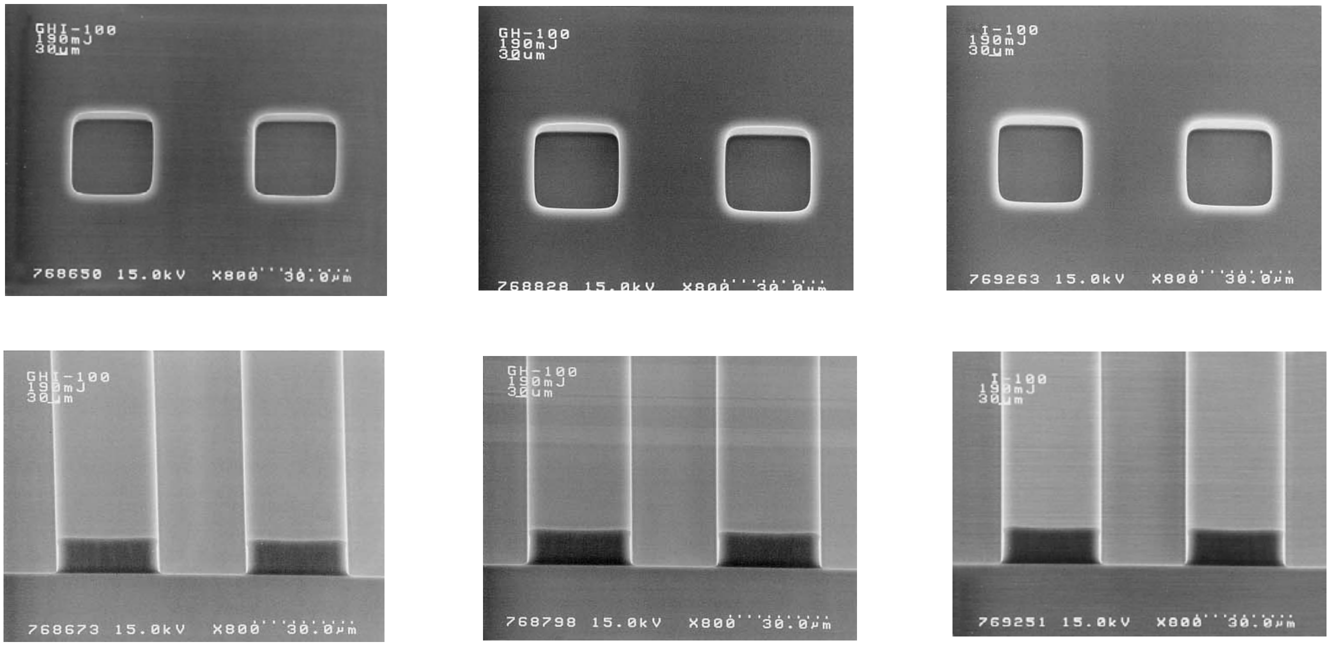
(d) 30 micron

Figure 4: Angled SEM photographs for 13 µm thick SINR 3170M square contacts exposed at 190 mJ/cm^2 using ghi-line illumination and a 100°C PEB. The magnification is marked on each picture.



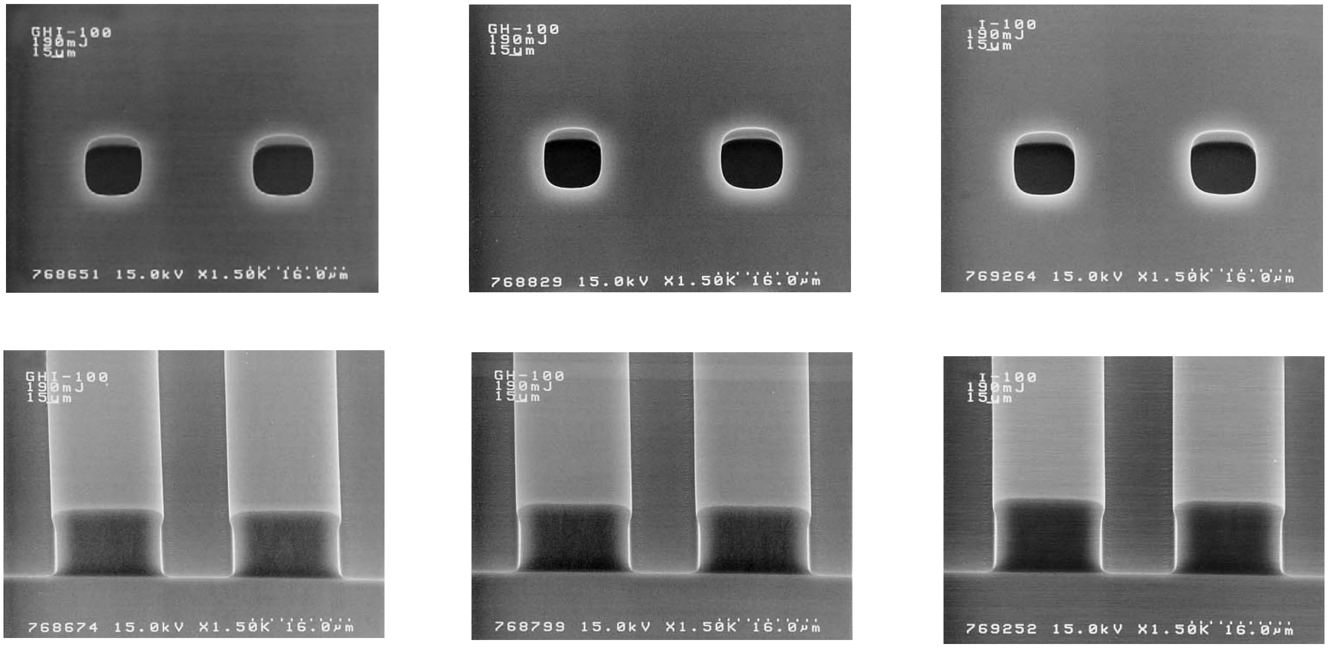
(a) 90^{o}C PEB (b) 100^{o}C PEB (c) 110^{o}C PEB

Figure 5: SEM photographs for 13 µm thick SINR 3170M for 30 micron lines and square contacts exposed at 190 mJ/cm^2 using ghi-line illumination. The magnification is 800X in all pictures.



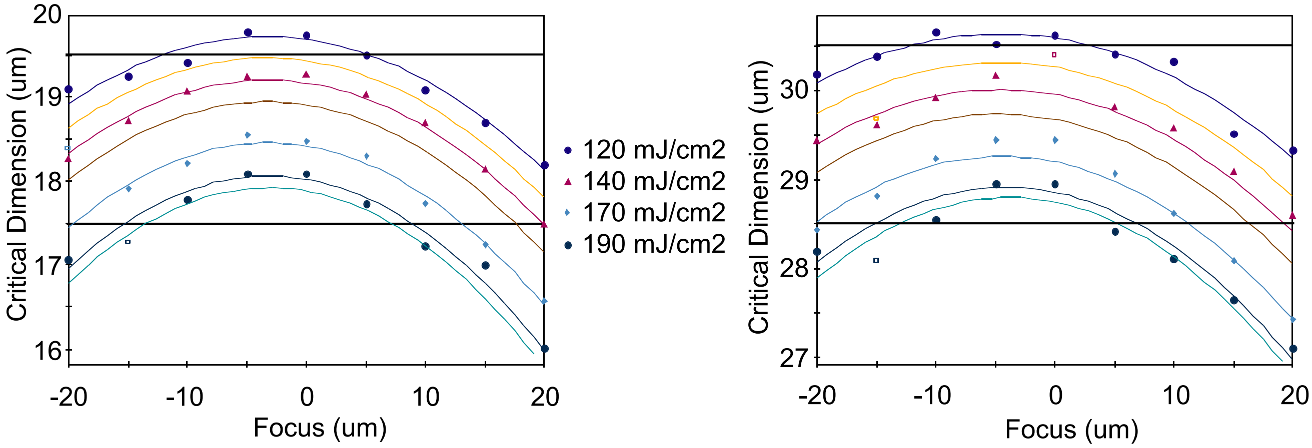
(a) ghi-line (b) gh-line (c) i-line

Figure 6: SEM photographs for 13 µm thick SINR 3170M for 30 micron lines and square contacts exposed at 190 mJ/cm^2 with a 100^{o}C PEB. The magnification is 800X in all pictures.



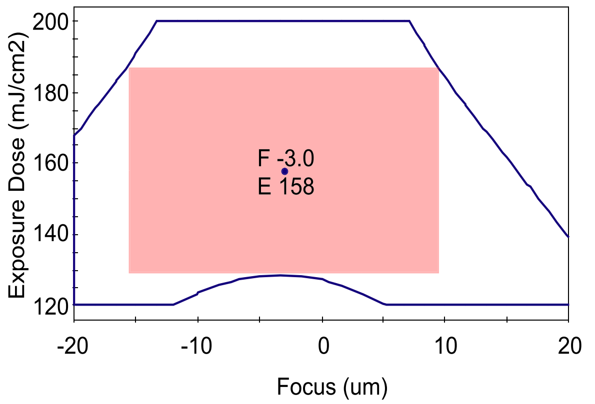
(a) ghi-line (b) gh-line (c) i-line

Figure 7: SEM photographs for 13 µm thick SINR 3170M for 15 micron lines and square contacts exposed at 190 mJ/cm^2 with a 100^{o}C PEB. The magnification is 800X in all pictures.



(a) Nominal CD 18.5 microns (b) Nominal CD 29.5 microns

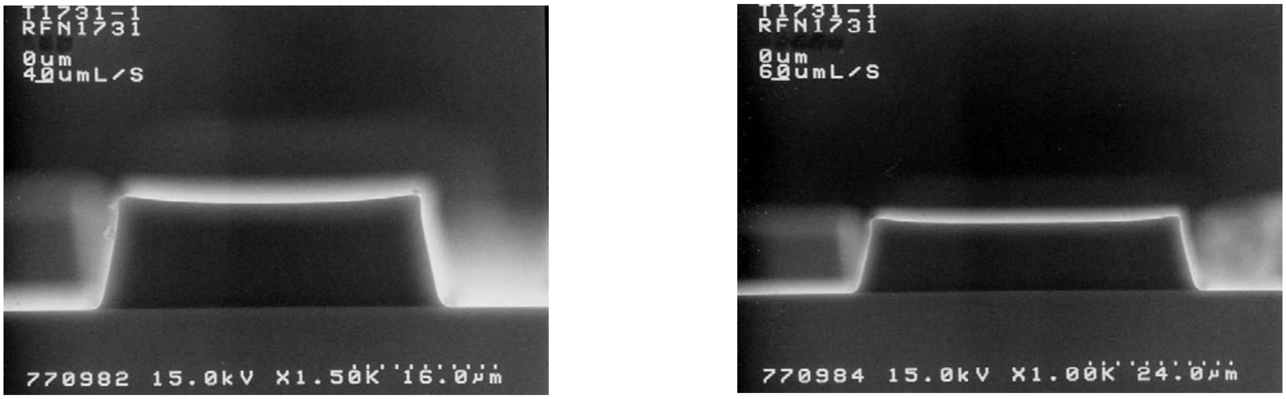
Figure 8: Bossung Plots of dense lines and spaces in 13 µm thick SINR 3170M exposed with ghi-line illumination and a 100^{o}C PEB. The horizontal lines show ± 1 µm control limits.



(a) Nominal CD 18.5 microns

(b) Nominal CD 29.5 microns

Figure 9: Process window of dense lines and spaces in 13 µm thick SINR 3170M exposed with ghi-line illumination and a 100^oC PEB. The process envelope shows ±1 µm control limits.



(a) 40 µm line/space

(b) 60 µm line/space

Figure 10: SEM photographs for 14.5 µm thick SINR 3230M for line and spaces with a 100^oC PEB. The hard bake conditions are given in Table 4. The magnification is marked on each picture.