A Novel Photosensitive Material for Redistribution and Stress Buffer Reduction on 300 mm Wafers

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

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

ABSTRACT

The widespread adoption of advanced packaging techniques is driven by electrical device performance and chip form factor considerations. Flipchip packaging is currently growing at a 25% compound annual rate and it is expected that 90% of all 65 nm logic devices will be bumped. To ensure optimal productivity and cost of ownership, it is imperative to employ lithographic materials that are optimized for these applications and that meet all device specifications.

Bump processing typically has one or more levels that require a permanent layer either to relieve stress on the die (stress buffer layer) or to redistribute electrical connections (redistribution layer). Since these layers remain on the wafer, the mechanical and electrical properties of the material are as important as the lithographic properties. This study will characterize a novel negative, siloxane (Shin-Etsu SINR®) photoresist for the redistribution and stress buffer application on 300 mm wafers. Siloxanes are a good choice for redistribution and stress buffer layers because of their excellent physical properties, ease of processing and relatively low cure temperatures.

The lithographic performance of the SINR is optimized using a broad band, low numerical aperture, 1X stepper. This study evaluates softbake, post exposure bake (PEB), develop conditions and exposure optimization. Due to decreasing feature size at the redistribution level, it is critical to demonstrate CD uniformity and resolution across the entire 300 mm wafer surface. While the CD uniformity data is collected on 300 mm wafers, all process optimization results will be applicable for all standard wafer sizes. The physical properties of the SINR material are evaluated through curing temperature studies and sputtering tests.

Key Words: advanced packaging, flipchip, thick resist, low temperature cure, RDL, stress buffer, siloxane, 300 mm wafers

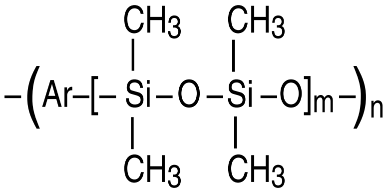
1.0 INTRODUCTION

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 wafer level packaging. The ability to continually shrink form factor 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.

Flip chip packaging frequently requires 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 first process step for redistribution is the deposition of a photosensitive dielectric layer. Thin film polymers are preferred on account of low dielectric constants, high temperature stability and moisture resistance characteristics [1]. Furthermore, there has been increasing demand for low temperature curing materials due to device damage that can occur during down stream processing. Temperatures above 200^{o} C can be detrimental to certain IC types. Therefore, it is imperative to have a material that cures at temperatures less than 200^{o} C.

Shin-Etsu has introduced a patented family of photosensitive siloxane materials known as SINR photoresist [2]. These materials have shown great promise for ease of use as well as good material and electrical properties [3]. The SINR photoresist is room temperature stable for at least one month, making the material easy to use in large scale manufacturing cost effectively. Furthermore, the SINR is hydrophobic, cured at low temperatures ($<200^{o}$ C), primeless adhesion, and develops with very simple materials such as IPA or PGMA.

Shin-Etsu SINR photoresist is a negative acting, 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.



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

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%. Changing the siloxane content changes the modulus of the material, which is important depending on the device requirements and packaging design. The addition of a photosensitizer in the form of chemical amplification allows siloxanes to be easily processed using conventional semiconductor processing equipment. Cationic curing conditions exist so that the final material exhibits relatively low shrinkage during cure.

Certain issues always have been prevalent in material used for 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. A mid-range dielectric constant of 2.9 to 3.0 is required for redistribution. The SINR 3150HSM photoresist properties are listed in Table 1.

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 [4]. Since subsequent processing after redistribution requires sputtering, the SINR photoresist also must exhibit an appropriate sidewall slope. With the addition of additives, it is possible to modify the SINR to achieve the needed slope for sputtering. This paper focuses on these modified SINR materials. Therefore, characterization and process latitudes are just as critical as the material properties of the film.

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 wafer aligners 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 wafer aligners 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 AP300 Wafer Stepper on the Ultratech Unity Platform™. The optical specifications for the AP300 is 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 [5,6] 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 AP300 provides a more uniform aerial image through the depth of the thick photosensitive materials in contrast to steppers with larger NA and a relatively narrow bandwidth [7]. 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. The 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) and Wafer Edge Protection (WEP) subsystems to create a photoresist free area around the edge of the wafer for either positive tone (WEE) or negative tone (WEP) photoresist.

In addition, for processing ultra thick photoresist that requires high exposure dose, the AP 300 stepper can be configured with a dual illuminator to provide a wafer plane irradiance about twice that of the system with a standard single illuminator to increase throughput without compromising the photoresist performance.

Multiple Si and SiN substrate 200 mm wafers were exposed using i-line with exposure matrices at zero focus. SEM cross sectional photographs of square contacts were taken with a Joel JSM 6340F and Hitachi S4100 SEM to investigate photoresist sidewall angles versus softbake temperature and post exposure bake temperature.

Square contacts were selected rather than circular contacts since they are easier to cleave. Linearity and exposure latitude at optimum softbake and post exposure bake conditions also are presented. The Si an SiN substrate wafers also were exposed at best exposure for checking resist performance after curing. In addition, 300 mm Si wafers were processed and CD were measured to check for intra-wafer CD uniformity.

The Ultratech 1X reticle used in this experiment 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.

2.2 Photoresist Processing

SEMI standard 200 mm prime Si and SiN wafers and 300 mm prime Si wafers were used for this study. The photoresist used is Shin-Etsu SINR® 3150HSM-8.0 for 200 mm wafers and Shin-Etsu SINR® 3150HSM-6.0 for 300 mm wafers. The SINR 3150HSM photoresist was coated to the 8 μm target thickness using the process and equipment described in Tables 3 and 4 for 200 mm and 300 mm wafers respectively.

Shin-Etsu SINR 3150HSM photoresist is i-line sensitive and is PGMEA solvent developable. One of the objectives was to use the same spin bowl for both coating and developing of the SINR (standard Novalak photoresists and SINR are drain compatible). On 200 mm wafers we were able to modify the Edge Bead Removal (EBR) process at the coater unit, which used Fujifilm RER600 PGMEA solvent by programing the dynamic dispense from center to edge and back to form a good puddle. The EBR supply pressure is increased to obtain high dispense rate to ensure complete wafer coverage of the solvent. When processing 300 mm wafers, due to the limitation of the dispense rate, the EBR solvent is dispensed manually from a squirt bottle.

Two softbake temperatures (120^{o}C, 130^{o}C) and three post exposure bake (PEB) temperatures (140^{o}C, 145^{o}C, 150^{o}C) were studied. The exposure wavelength is i-line. The focus is kept at zero (resist surface) for all tests since the effect of focus is insignificant for an 8 μm thick chemically amplified photoresist on our broadband stepper.

2.3 Data Analysis

After exposure the wafers were cleaved for cross section of square contacts on a Joel JSM 6340F and Hitachi S4100 metrology SEM. The feature size selected for analysis is 40 μm since this meets all current and predicted size requirements for the next few years. Cross sectional SEM photographs are presented to illustrate changes in photoresist sidewall angle versus softbake and PEB temperature. The sidewall angles are calculated using high magnification cross sectional photographs of the 40 μm contacts. The single wall angle target was set at 45^{o} to provide optimal metal step coverage.Exposure latitude and linearity at optimum softbake and post exposure bake conditions on Si wafer also are presented.

Data also include contact profiles on Si, SiN and Cu substrate after curing and sputtering. The cure and sputtering processes are described in Table 5. Intra-wafer CD uniformity also is showed through CD measurement of 40 μm contacts on 300 mm Si wafer.

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

3.0 RESULTS AND DISCUSSIONS

3.1 Bake Conditions

3.1.1 Prebake Conditions

Cross sectional SEM photographs were taken to establish the effect of softbake on the photoresist sidewall angle. Figure 1 shows SEM photographs of 40 μm contacts in 8 μm thick SINR 3150HSM photoresist at 120^oC and 130^oC softbakes. The PEB is held constant at 145^oC and the exposure dose is 510 mJ/cm^2. High magnification SEM photographs at 90^o tilt (not shown) were used to measure the sidewall angle.

The 120^oC softbake temperature gives a sidewall angle of 32^o. This sidewall angle is below the target value of 45^o and exhibits a very large tapered foot. It is extremely difficult to control CD after descum for this type of profile. The 130^oC softbake temperature gives a sidewall angle of 43^o which is much closer to the target value. Higher prebake temperatures were not evaluated since they degrade the photospeed and process control of the photoresist.

The CD at the 120^oC softbake is 45μm, which is significantly above the photomask CD of 40 μm. For the 130^oC softbake, the CD is 39μm, which is well within an acceptable print bias. Additional screening experiments confirmed the 130^oC softbake was the best condition and it was used for the balance of this study.

3.1.2 Post Exposure Bake Conditions

The effect of PEB on photoresist sidewall angle and CD for a 40 μm square contact then was evaluated. Figure 2 shows SEM photographs of 40 μm contacts in 8 μm thick SINR 3150HSM photoresist at 140, 145 and 150^oC PEB. The softbake is held constant at 130^oC, and the exposure dose is 510 mJ/cm^2. High magnification SEM photographs at 90^o tilt (not shown) were used to measure the sidewall angle.

The 140^oC PEB gives a sidewall angle of 36^o. This sidewall angle is below the target value of 45^o and exhibits a very large tapered foot. It is extremely difficult to control CD after descum for this type of profile. The 150^oC PEB gives a sidewall angle of 55^o, which is well above the target value. The 145^oC PEB gives a 43^o, which is close to the target value.

The 29 μm CD at the 150^oC PEB is unacceptably small. However, the CD at both 140^oC and 145^oC PEB are 39μm, which is close to the photomask CD of 40 μm. Additional screening experiments confirmed the 145^oC PEB was the best condition, and it was used for the balance of this study.

3.2 Exposure Latitude

Cross sectional SEM photographs were taken to establish the effect of exposure dose on the photoresist sidewall angle. Figure 3 shows SEM photographs of 40 μm contacts in 8 μm thick SINR 3150HSM photoresist at 130^oC softbake and 145^oC PEB. The stepper focus offset is held constant at zero since this SINR 3150HSM is a chemically amplified photoresist. High magnification SEM photographs at 90^o tilt (not shown) were used to measure the sidewall angle.

The lowest exposure dose of 390 mJ/cm^2 (Figure 3a) shows the shallowest slope of 34^o while the highest exposure dose of 750 mJ/cm^2 (Figure 3d) shows the steepest slope of 72^o. These results are not surprising since SINR 3150HSM is a negative acting photoresist. The exposure range from 510 to 630 mJ/cm^2 (Figures 3b and 3c) shows a consistent slope of 43 to 44^o. This is near the target value of 45^o. This suggests that there is wide exposure latitude for the SINR 3150HSM to maintain consistent sidewall angle control.

3.3 CD Linearity

Figure 4 shows cross sectional SEM photographs of the process linearity for square contacts exposed in 8 μm of SINR 3150HSM photoresist on Si substrates. The CD values in this figure refer to the photomask size. All of the contacts were exposed at 510 mJ/cm^2 with a zero focus offset. The sidewall angle is consistent for all contact sizes down to 30 μm. The observed contact resolution easily exceeds the target value of 40 μm for this study and shows that the process can support future CD requirements.

3.4 Cure and Sputtering Results

Cross sectional SEM photographs were taken to establish the effect of sputtering on the SINR film integrity. Figure 5a and 5b shows SEM photographs of 40 μm cured and sputtered contacts on Si and SiN, respectively. Figure 5c shows SEM photographs of 30 μm cured contacts on Cu. All three substrates were processed with 8 μm thick SINR 3150HSM photoresist at 130^{o}C softbake and 145^{o}C PEB. The SINR 3150HSM on all three substrates shows excellent reliability for the cure and sputter processes. The final photoresist thickness after cure is reduced approximately 15% from the thickness after softbake.

A slight modification in the SINR 3150HSM chemistry was required for Cu processing. This was shown to be sufficient to address an adhesion loss on Cu observed with the initial version of the photoresist.

3.5 300 mm CD Uniformity

After development, the CD uniformity was measured at 30 locations evenly distributed over the 300 mm wafer. A contour plot of the photoresist CD uniformity of 40 μm square contacts is shown in Figure 6. The solid contour lines represent 0.4 μm intervals, and the dashed contour lines are half way between each solid line. The average CD is 39.27 μm with a three sigma of 0.21 μm. This equates to a CD uniformity of 0.54 percent across the wafer. The CD is smallest at center of the wafer with a size around 38.8 μm.

4.0 CONCLUSIONS

The lithographic performance of the SINR 3150HSM was characterized for redistribution applications. The softbake temperature showed a decrease in sidewall angle and an increase of CD at lower temperatures. In addition, higher PEB temperature resulted in an increase in sidewall angle and decrease in CD. By optimizing these bake conditions the SINR met the sloped sidewall requirements for metal step coverage. Exposure latitude, linearity and curing/sputtering performance of the SINR were more than sufficient to meet the needs of future packaging and lithographic requirements.

The SINR demonstrates the mechanical and electrical properties needed for both a stress buffer application and redistribution application. The slight modification needed for copper processing was a sufficient fix to the adhesion loss on copper observed with an earlier version. The relatively low curing temperature is also of benefit for certain bump applications. Being able to use the same photoresist bowl for coating and developing and the room temperature stability of the SINR enhance the ease of use of the material. In addition the Ultratech AP300 stepper showed excellent performance for CD control and process latitude.

5.0 ACKNOWLEDGEMENTS

The authors would like to thank both Mr. H. Kato and Mr. K. Toba from Shin-Etsu Chemical for their photoresist and metrology support. We would also like to thank Kelly Abreau from Steag Hamatech for his support for processing the 300 mm wafers.

6.0 REFERENCES

1. Ranjan, M., et. al., “Characterization of Dielectric Material for Redistribution Using 1X Stepper Technology” Semicon Japan 2001.
2. United States of America patent number 6,590,010 B2.
3. Flack, W., Nguyen, H., Capsuto, E., “Characterization of a Novel Photoresist Redistribution Material for Advanced Packaging Applications”, *Advances in Resist Technology and Processing XIX Proceedings*, SPIE **4690**, 2002, pg. 1203-1216.
4. MacNaughton, R.et. al., Improvement of Metal Step Coverage of VLSI Device Structures in Manufacturing Environment, SPIE **1805**, pp. 90-104.
5. Flores, G., Flack, W., Dwyer, L., “Lithographic Performance of a New Generation i-line Optical System,” *Optical/Laser Lithography VI Proceedings*, SPIE **1927**, 1993.
6. W. Flack, W. Fan, S. White, “The Optimization and Characterization of Ultra-thick Photoresist Films,” *Advances in Resist Technology and Processing XV Proceedings*, SPIE **3333**, 1998, pg. 1288-1303.
7. Flack, W., White, S., Todd, B., “Process Characterization of One Hundred Micron Thick Photoresist Films”, *Advances in Resist Technology and Processing XVI Proceedings*, SPIE **3678**, 1999, pg. 474-490.

Parameter	Value
Breakdown voltage	300 V/µm
Volume Resistivities	5 x 10^{14} Ωm
Dielecetric Constant	2.6 at 1 GHz
Dissipation Factor	2.3 x 10^{-5} at 1GHz
Tensile Strength	28 MPa
Elongation	40%
Glass Transition temperature (T_g)	Not Observed
Coefficient of Thermal Expansion	130 ppm/ ^{o}C
Young’s Modulus (25^{o}C)	240 MPa
Water Absorption	<0.1%

Table 1: Film properties of Shin-Etsu SINR 3150HSM.

Parameter	Ultratech AP300
Reduction factor	1X
Wavelength (nm)	350 - 450
Numerical aperture (NA)	0.16
Partial coherence (σ)	1.0
Wafer plane irradiance (mW/cm^2)	2250

Table 2: Optical specifications of the AP300 stepper used in this study.

Process Step	Parameters	Equipment
SINR 3150HSM-8.0 Coat	Dispense: static Spread: 1000 rpm for 2 seconds Spin: 3000 rpm for 40 seconds	Suss ACS200
Softbake	Hotplate, 0.2 mm proximity 120 seconds at 130^{o}C	ACS200 Hotplate
Exposure	i-line, Exposure matrix at 0 µm focus	AP300 Stepper
PEB	120 seconds at 145^{o}C, 0.2 mm proximity	ACS200 Hotplate
Develop	3 puddles (15 seconds dispense, 30 seconds puddle each) using Fujifilm RER600 PGMEA solvent. Dry for 30 seconds at 1000 RPM Dry for 20 seconds at 2000 RPM	Suss ACS200

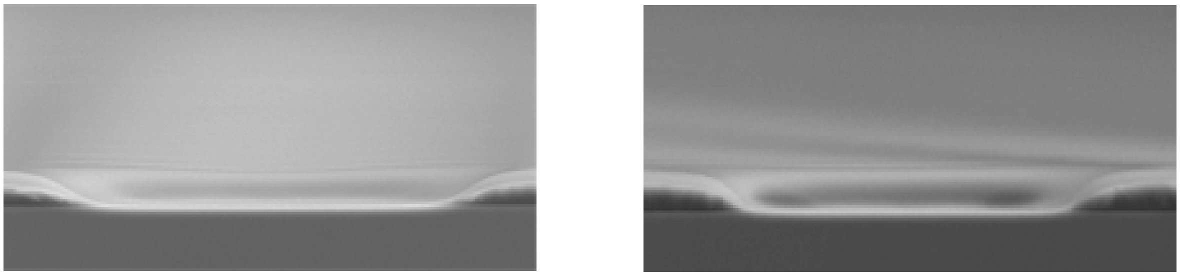
Table 3: Process conditions for SINR 3150HSM-8.0, 8 µm thick on 200 mm Si wafer.

Process Step	Parameters	Equipment
SINR 3150HSM-6.0 Coat	Dispense: dynamic at 25 rpm for 15 sec Spread: 150 rpm for 2 seconds Spread: 700 rpm for 10 seconds Spin: 1475 rpm for 10 seconds	Steag Hamatech Modutrack
Softbake	Hotplate, 0.1 mm proximity 120 seconds at 125^{o}C	Steag Hamatech Modutrack
Exposure	i-line	AP300 Stepper
PEB	Hotplate, 0.1 mm proximity 120 seconds at 140^{o}C	Steag Hamatech Modutrack
Develop	3 puddles (10 seconds dispense, 60 seconds puddle each) using Fujifilm RER600 PGMEA solvent. Rinse with RER600 for 10 seconds at 200 RPM Dry for 20 seconds at 2500 RPM	Steag Hamatech Modutrack

Table 4: Process conditions for SINR 3150HSM-6.0, 8 μm thick on 300 mm Si wafer.

Process Step	Parameters	Equipment
Cure	1 hour at 180^{o}C	Blue M Oven
Descum	200W, 60 seconds 26 Pa, 0_2 / CF_4 flow = 70 / 30 sccm	ANELVA DEM-451
Sputter	Ti and Cu	ANELVA L-313S

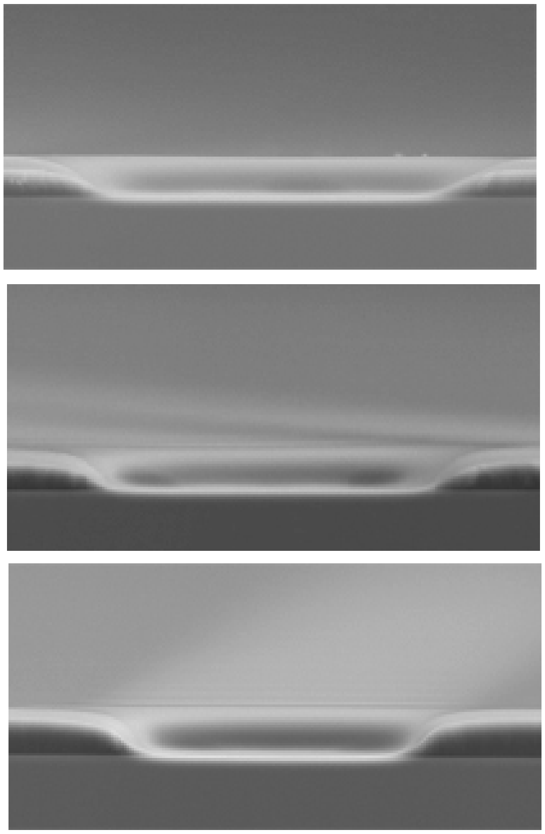
Table 5: Cure and Sputter conditions for Si and SiN wafers.



(a) Via Opening, Softbake = 120^{o}C
Sidewall Angle = 32^{o}
CD = 45 μm

(b) Via Opening, Softbake = 130^{o}C
Sidewall Angle = 43^{o}
CD = 39 μm

Figure 1: Dependence of SINR 3150HSM sidewall profile on softbake temperature. The nominal photomask CD is 40 μm in 8 μm thick photoresist on Si, the PEB is 145^{o}C and the exposure dose is 510 mJ/cm^2.

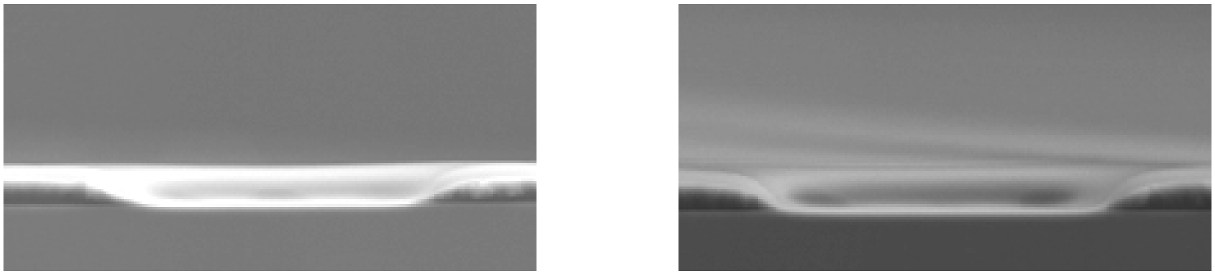


(a) PEB = 140^{o}C
Sidewall Angle = 36^{o}
CD = 39 µm

(b) PEB = 145^{o}C
Sidewall Angle = 43^{o}
CD = 39 µm

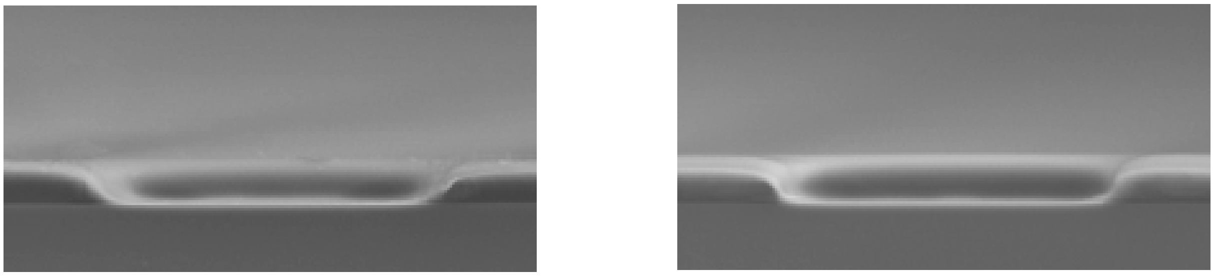
(c) PEB = 150^{o}C
Sidewall Angle = 55^{o}
CD = 29 µm

Figure 2: Dependence of SINR 3150HSM sidewall profile on PEB. The nominal photomask CD is 40 µm in 8 µm thick photoresist on Si, the softbake is 130^{o}C and the exposure dose is 510 mJ/cm^{2}.



(a) Exposure = 390 mJ/cm^{2}, Sidewall Angle = 34^{o}

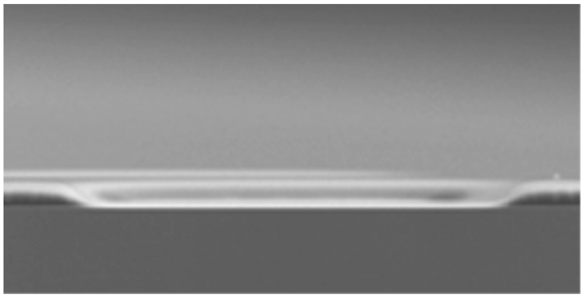
(b) Exposure = 510 mJ/cm^{2}, Sidewall Angle = 43^{o}



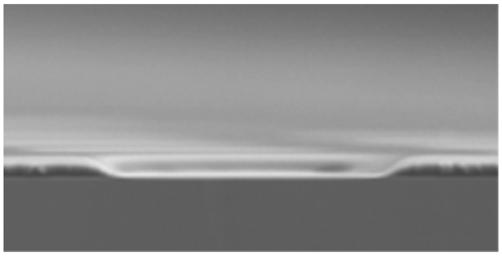
(c) Exposure = 630 mJ/cm^{2}, Sidewall Angle = 44^{o}

(d) Exposure = 750 mJ/cm^{2}, Sidewall Angle = 72^{o}

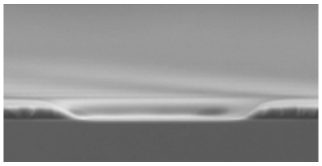
Figure 3: Dependence of SINR 3150HSM sidewall profile on exposure dose. The nominal photomask CD is 40 µm in 8 µm thick photoresist on Si, the prebake is 130^{o}C and the PEB is 145^{o}C.



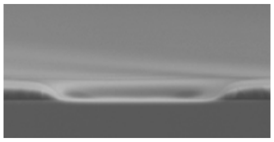
(a) CD = 100 µm



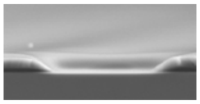
(b) CD = 70 µm



(c) CD = 50 µm

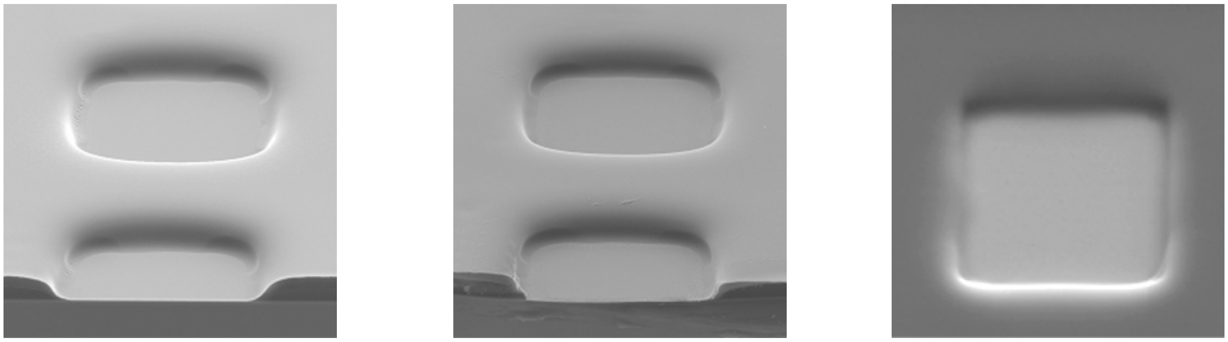


(d) CD = 40 µm



(e) CD = 30 µm

Figure 4: SEM photographs showing contact linearity in 8 µm thick SINR 3150HSM on Si. The exposure is 510 mJ/cm^2 with a focus offset of 0 µm. The prebake is 130^{o}C and the PEB is 145^{o}C. The CD values in this figure refer to the nominal photomask size.



(a) Silicon
40 μm contact
Exposure = 510 mJ/cm^2
Cure at 180^{o}C for 1 hr.

(b) Silicon Nitride
40 μm contact
Exposure = 610 mJ/cm^2
Cure at 180^{o}C for 1 hr.

(c) Copper
30 μm contact
Exposure = 700 mJ/cm^2
Cure at 160^{o}C for 2 hr.

Figure 5: SEM photographs of 8 μm thick SINR 3150HSM on Si, SiN and Cu substrates. The Si and SiN substrates are cured and sputtered while the Cu substrate is cured only. The prebake is 130^{o}C and the PEB is 145^{o}C for all cases. The CD values in this figure refer to the nominal photomask size.

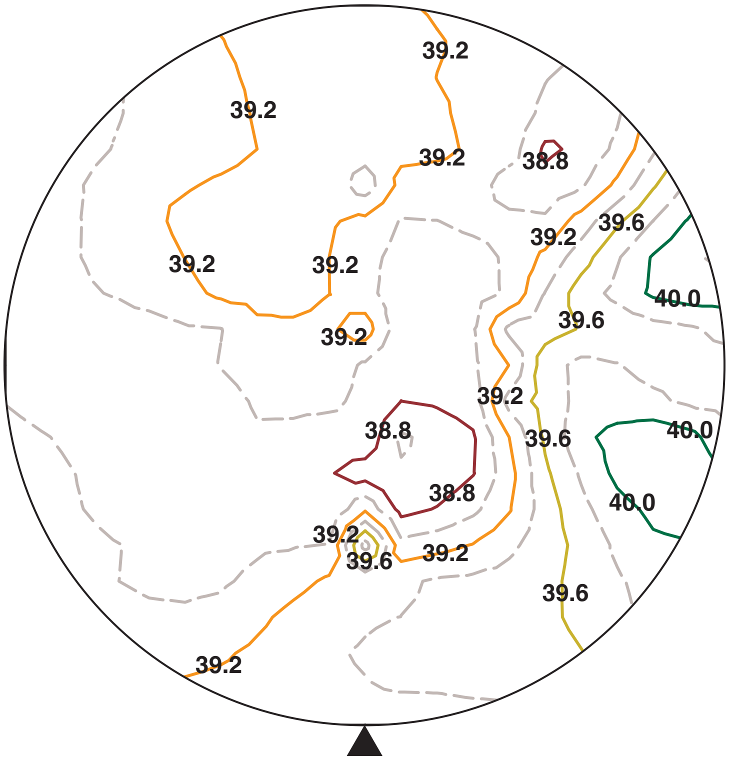


Figure 6: CD uniformity of 40 μm spaces in 8 μm thick SINR 3150HSM on a 300 mm wafer. The solid contour lines are at 0.4 μm intervals and the dashed contour lines are half way between. The average is CD is 39.27 μm and the standard deviation is 0.071 μm.