Process Characterization of an Aqueous Developable Photosensitive Polyimide on a Broadband Stepper

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The number of lithographic applications that require the use of photosensitive polyimides is rapidly increasing. The major applications for photosensitive polyimides include flip chip bumping, advanced packaging, passivation stress buffer relief and interlevel dielectric films. The thickness requirements for these applications can vary from less than 1 micron to more than 20 microns. For processing simplicity and total cost of ownership, it is desirable to use an aqueous developable polyimide to maintain compatibility with standard photoresist processes.

Optical steppers offer significant advantages for processing thick photosensitive polyimides due to the tighter overlay and improved critical dimension (CD) control possible with these lithography tools versus contact printers or full wafer scanners. A stepper has an additional advantage with thick polyimide structures since the focus can be adjusted at various levels into the film, which will result in improved wall angles and enhanced aspect ratios.

For this study the performance of a commercially available, positive acting, aqueous developable polyimide is examined over a range of thicknesses using a novel broadband exposure system. This stepper exposes photosensitive films using the full mercury vapor spectrum output from 350nm to 450nm (g, h and i line) and allows rapid exposure of both broadband as well as narrow spectral sensitive films. The system has been optimized for thick photoresists and polyimides and uses a combination of low numerical aperture with maximum wafer level intensity to achieve well formed images in thick films yet offers the advantages of tighter CD control and tight overlay inherent in projection optics.

Basic photoresist characterization techniques established for thin films in IC manufacturing are applied to the photosensitive polyimide films. Cross sectional SEM analysis, process linearity and process windows are used to establish relative lithographic capabilities for different polyimide thicknesses and stepper exposure wavelengths. The trade-offs for each of the various process capability windows are reviewed to determine the optimum process conditions for different polyimide applications.

Key Words: polyimide, aqueous developable, photoresist characterization, broadband stepper

1.0 INTRODUCTION

Polyimides have become the standard material used in a variety of semiconductor manufacturing processes. They are commonly used as a passivation stress-buffer process (PSB) for devices in thin and ultra-thin packages [1]. Particular devices of concern include large-die devices packaged in plastic molding compounds, exemplified by dynamic random access memory (DRAM) components. These die are subject to significant amounts of stress, primarily resulting from differing coefficients of thermal expansion of the die and packaging compounds [2,3]. These stresses may lead to cracking of the package or the protective passivation layer, allowing the introduction of contaminants such as moisture and ionic particles. Imparted stress may also lead to metal or wire-bond deformation, possibly altering device parameters. In both cases device reliability and yield may be severely degraded. To reduce stress imparted to the die, a relatively thick layer of polyimide is applied over passivation.

Conventional, or non-photosensitive polyimides were historically used for PSB. During wafer fabrication, a layer of polyimide is applied on the wafer using a spin-dispense technique similar to that of photoresist. A layer of photoresist is then applied on top of the polyimide and exposed using a photolithography tool. The photoresist is then developed which exposes the areas of the polyimide to be removed, which is usually accomplished by a wet-etch process. This non-photosensitive polyimide application has a significant level of process complexity, as well as limited resolution and poor sidewall profile quality resulting from the isotropic polyimide etch process [3,4].

To address the process complexity and limited performance, polyimide suppliers introduced photosensitive polyimide products. These materials may be directly exposed using a photolithography tool which simplifies the process. The simplified photosensitive polyimide process decreases costs by eliminating manufacturing processes, decreasing cycle-time through the manufacturing facility, decreasing product handling near the end of the manufacturing cycle (increased yield), increasing available manufacturing capacity (as a result of process elimination), and reducing material costs (also as a result of process elimination). It also provides significant advantages of superior resolution and improved sidewall profiles and smaller process basis than conventional polyimides [4,5,6]. Because of the improved sidewall profile and smaller process basis the photosensitive polyimide layer can be used as the etch mask for the passivation layer. This allows the elimination of an entire photolithography level in the manufacturing cycle. This process simplification was not previously available with wet etch processes due to the lack of vertical sidewall profiles. These vertical sidewalls slope nicely after the final cure making the photosensitive polyimides compatible with subsequent metallization steps used in advanced packing and bumping interconnect processes.

Positive acting aqueous soluble, photosensitive polyimides are the newest materials in the overall polyimide market. These polyimides are an improvement both economically by reducing process cost of ownership and environmentally by reducing organic solvents and associated volatile organic compounds (VOCs). In addition, the new aqueous materials enable the process to use industry standard tetramethylammonium hydroxide (TMAH) photoresist developers. Overall, aqueous polyimides are easier to integrate into current high volume wafer fabs. Positive tone polyimides allow a smoother transition from non-photosensitive polyimides which usually utilizes a positive photoresist and associated reticle. Thus, the same set of reticles can be utilized. Being able to use the same reticles saves the wafer fab a significant amount of reticle design time and costs. Photosensitive polyimides also have good dielectric and planarization properties that allow them to be used as interlevel dielectrics. Currently photosensitive polyimides are being integrated into many front end, wafer fab, processes which are being required for advanced packaging such as flip chip, Chip Scale Package (CSP) and Wafer Scale Package (WSP) processes. For flipchip applications they serve as a protection and adhesion layer to the under bump metallurgy [7].

Photosensitive polyimides have been processed in mass production using g-line (436nm) and i-line (365nm) exposure tools. Polyimide films absorb UV light very strongly below 350nm. This absorbency is due to the polymers high aromaticity that is also responsible for polyimides exceptional thermal properties which allows processing above 400 °C. This makes compatibility of current photosensitive polyimides questionable with DUV steppers. For this reason it appears that g-line and i-line steppers will be used for polyimide applications including 300mm wafer processing.

The photolithography requirements of a photosensitive polyimide stress buffer level typically pose less stringent resolution and overlay requirements than other lithographic levels. Bonding pads may be on the order of 100µm square with overlay requirements as large as several microns. However, resolution of small features, such as fuse windows in DRAMs, is frequently required in these film layers. These fuse windows may be less than 8µm square in film thicknesses approaching 20µm, making the height-to-linewidth aspect ratios comparable to those found in more advanced photoresist applications.

The problem of high aspect ratios in the use of thick polyimides can be addressed by using optical lithography equipment originally developed for production of semiconductor devices. Steppers, full wafer scanners and contact printers are widely used in the microelectronic industry and are highly evolved production tools. Projection optical systems can adjust the focal height relative to the surface of the thick polyimide that results in improved wall angles and better aspect ratios as compared to contact lithography tools [8]. 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 enhancement technology such as phase shift masks and optical proximity correction. Thick polyimides, however, typically require a high exposure dosage and large depth of focus (DOF) for high aspect ratio lithography of larger geometries. For these reasons, it is advantageous to utilize a stepper with a broad band exposure system and low NA to maximize the illumination intensity at the wafer plane and to improve DOF. This paper will examine HD-8000 polyimide exposed using a broadband stepper as described in section 3.0.

2.0 EXPERIMENTAL METHODS

2.1 Reticle Design and Manufacture

The Ultratech 1X reticle used for this study was designed primarily to support easy cross sectional SEM metrology for micromachining applications. The reticle consists of two fields of 42.8 by 21.4mm, one of each polarity to support both positive and negative acting polyimides. Each field contains horizontal and vertical grouped line and space patterns from 2 to 20µm in 2µm size increments, and from 25 to 40µm in 5µm size increments. Figure 2 shows a sample cell containing vertical lines. Both equal line and space patterns and isolated lines are included for all structure sizes. Each isolated line is separated from its nearest neighbors by a minimum of five times the linewidth. All of the line structures are 5mm in length to facilitate cross sectional SEM analysis. In order to increase the mechanical integrity of these long lines, they are placed in a zigzag pattern with a ten degree angle and a seven to one length to width ratio for each line segment. There was no data biasing applied to the design data and CDs were held to within ±0.03µm of a nominal 2.0µm chrome line. Reticle CD information was also obtained for all line sizes on both fields to establish the process linearity in reticle fabrication.

2.2 Lithography Equipment

Lithography for each 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 1. The Saturn Spectrum 3 stepper is based on the 1X Wynne-Dyson lens design employing Hg illumination with ghi-line from 350 to 450 nm and having a 0.16 NA [9]. 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 more uniform aerial image through depth in ultrathick photosensitive materials in contrast to steppers with larger NAs [10].

Illumination uniformity was verified prior to collecting the experimental data and was found to be 1.2 percent across the entire field. Multiple wafers were exposed in a focus/exposure pattern consisting of an eight by eight field array as illustrated in Figure 3. Nominal exposure times were determined by measuring isolated space patterns at the specific linewidth of interest with a Hitachi S-7280H metrology SEM. The bottom of the polyimide was selected for the determination of the CD.

A filter system was employed which allows ghi-line (350 to 450nm), gh-line (390 to 450nm) or i-line (355 to 375nm) illumination to be selected. This approach can be used to optimize lithographic performance based on the spectral sensitivity of the photosensitive material. Since the illumination intensity (mW/cm^2) at the wafer plane is different for each filter range, exposure times are used rather than exposure dose to compare performance.

2.3 Processing Conditions

SEMI standard 150mm ultra-flat silicon wafers were used for this study. HD-Microsystems HD-8000 was selected as the polyimide since it is self priming, positive acting and aqueous developable. Two polyimide thicknesses were selected assuming a PSB application. The most common cured thicknesses for PSB are approximately 5µm for logic devices and 8 to 10µm for memory devices. Since the HD-8000 shrinkage is approximately 50% between pre-bake and final cured thickness, the materials were evaluated at 9.6 and 19.0µm pre-bake thickness. The 9.60µm target thickness used the process and equipment described in Table 2. The 19µm target thickness used the process and equipment described in Table 3. Polyimide thickness and uniformity were measured on a Dektak 3030 surface profilometer measurement system.

All wafers used for this work were new. This was to prevent any adhesion problems from previous adhesion promoters or cleaning processes. All post exposure and softbakes of the wafers on Soletic hotplates required removal of the covers. It was observed that solvent can condense on the underside of a cover and drip back onto the wafers. Without a high level of exhaust the solvent will not evaporate out of the film adequately.

2.4 Data Analysis

Wafers coated with both polyimide thicknesses were exposed on the three-wavelength ghi-line lithography system. All wafers were visually inspected and measured on a Hitachi S-7280H metrology SEM to determine the photoresist linearity over a range of linesizes. CD measurements of isolated spaces were taken at 10kX magnification. Multiple spacewidths were measured top-down on the S-7280H over the entire focus and exposure matrix as illustrated in Figure 3. This CD data was entered into a spreadsheet and analyzed with the assistance of Prodata® software by Finle Technologies. Both Bossung plots and process window plots were generated using 10 percent CD control criteria. Cross sectional SEM micrographs are presented to illustrate masking linearity for isolated spaces. The CD linearity data is also plotted for each photoresist. The results from the data analysis are discussed in Section 3.0.

3.0 RESULTS AND DISCUSSIONS

3.1 Linearity Analysis

Figure 4 shows the mask linearity for each of the two polyimide thicknesses evaluated. This graph shows that the printed feature size is linear with respect to the reticle feature size. This plot was constructed using top down SEM data for isolated spaces and is a best fit plot of the data to the equation:

$$\mathbf{y} = \mathbf{x} + b \qquad (1)$$

where **y** is the measured spacewidth, **x** is the reticle spacewidth and b is the mask bias. The mask bias and goodness of fit for each of the photoresists is shown in Table 5. Note that the mask bias is four times as large for the 19µm thick polyimide than for the 9.6µm film.

Both thicknesses of polyimide exhibit a region of linear correlation between photomask features and printed features. This allows designers a range of device geometries on a single photolithography level using a single biasing offset between the mask feature and the printed feature. Mask linearity will be discussed in more detail for each polyimide thickness in subsequent sections.

3.2 HD-8000 19 Microns

Wafers were imaged using ghi-line illumination with exposure times from 390ms to 525ms (425 to 600 mJ/cm^2) at increments of 17ms and -7 to +7µm focus range at increments of 2µm. HD-8000 demonstrated a 6µm resolution for isolated spacewidths as shown in the cross sectional SEM micrographs shown in Figure 5a. The sidewall angle is approximately 66 degrees and is independent of spacewidth down to 6µm features. The sidewall angle is not critical for the PSB process, but a slope of approximately 60 degrees is optimal for bump redistribution processes for metal step coverage. Even better resolution than 6µm spacewidths has been demonstrated with via patterns. Figure 7a shows 2µm vias on a 6µm pitch in a cured polyimide film.

HD-8000 exhibits well behaved process characteristics. Figure 5b shows process window plots for 10µm spacewidth features for the ghi-line, gh-line and i-line exposures. The envelope demonstrates a ten percent control limit for the 10µm spacewidth. The shaded area reflects the largest rectangular process window that fits within the envelope. There is a significant difference between the process windows for the different exposure wavelengths. The exposure time for the ghi-line is about 440 msec (490 mJ/cm^2) at the center of the process window. The exposure times for the gh-line is 640 msec (550 mJ/cm^2) and the i-line is 1.64 sec (740 mJ/cm^2) at the center of their process windows. These are 26% and 370% higher than the ghi-line exposure times respectively. The process windows show that for maximum throughput the 19µm HD-8000 should be exposed with ghi-line illumination. The DOF is also different for the three exposure ranges. The ghi-line has a DOF of 7µm with a -3µm focus offset. The i-line illumination has a DOF of 14µm with no focus offset. The DOF at i-line is probably larger since the entire process window has not been mapped out in this study. The process windows show that for maximum process latitude the 19µm HD-8000 should be exposed with i-line illumination.

Clearly the choice of exposure wavelength for the HD-8000 depends on the application requirements. For larger CD features where process latitude is not an issue, the polyimide should be exposed with ghi-line illumination for maximum throughput. For critical CD features there may be a significant advantage to using i-line illumination and accepting the loss in stepper throughput.

3.3 HD-8000 9.6 Microns

Wafers were imaged on the ghi-line stepper with exposure times from 170ms to 300ms (125 to 300 mJ/cm^2) at increments of 16ms and -7 to +7µm focus range at increments of 2µm. HD-8000 demonstrated a 4µm resolution for isolated spacewidths as shown in the cross sectional SEM micrographs shown in Figure 6a. The sidewall angle is approximately 68 degrees and is independent of spacewidth down to 4µm features. Again, the sidewall angle is optimal for bump redistribution processes.

HD-8000 exhibits well behaved process characteristics. Figure 6b shows process window plots for 4µm spacewidth features for the ghi-line, gh-line and i-line exposures. The envelope demonstrates a ten percent control limit for the 10µm spacewidth. The shaded area reflects the largest rectangular process window that fits within the envelope. There is a significant difference between the process windows for the different exposure wavelengths. The exposure time for the ghi-line is about 285 msec (275 mJ/cm^2) at the center of the process window. The exposure times for the gh-line is 400 msec (315 mJ/cm^2) and the i-line is 800 msec (340 mJ/cm^2) at the center of their process windows. These are 40% and 280% higher than the ghi-line exposure times respectively. The optimal exposure for i-line is probably higher than 800 msec since the entire process window has not been mapped out in this study. Similar to the 19µm polyimide, the 9.6µm HD-8000 should be exposed with ghi-line illumination for maximum throughput.

The DOF is also different for the three exposure ranges. The ghi-line has a DOF of 6µm with a -3.5µm focus offset. The i-line illumination has a DOF of 12µm with no focus offset. Similar to the 19µm polyimide, the 9.6µm HD-8000 should be exposed with i-line illumination for maximum process latitude. The same trade-offs between throughput and process window apply for the 9.6µm thick polyimide.

3.4 HD-8000 Cured Films

Several of the 9.6µm thick HD-8000 wafers were sent to DuPont for polyimide cure. The wafers were baked at 350^oC for 60 minutes in a diffusion furnace. This completes the imidization process and removes the photoinitiator and residual solvents. The after cure thickness was 5.1µm or 53% of the coated thickness. Figure 7a shows 2 micron vias on a six micron pitch. The sidewall angle is approximately 60 degrees. Figure 7b shows 7µm lines and spaces. The sidewall angle is approximately 63 degrees. There was no observable change in pattern performance or resolution as a result of the cure step.

4.0 CONCLUSIONS

Standard photoresist characterization techniques have been applied to two thicknesses of HD Microsystems HD-8000 positive acting, aqueous developable polyimide. Cross sectional SEM analysis and process window analysis were used to establish relative lithographic capabilities exposed on a three-wavelength ghi-line stepper. The trade-off between the various exposure wavelengths were reviewed and compared with the process requirements for PSB and flipchip bump bonding.

The 19µm HD-8000 produced a resolution of 10µm features with wall profiles of 66 degrees using ghi-line exposure. The ghi-line has the further advantage of requiring the lowest exposure time; an advantage for stepper throughput and overall cost of ownership. The exposure times for the i-line are about 370 percent higher than the ghi-line. However, the DOF of the process window is 100 percent larger at i-line than ghi-line. Clearly the choice of exposure wavelength for the HD-8000 depends on the application requirements. For larger CD features where process latitude is not an issue the polyimide should be exposed with ghi-line illumination for maximum throughput. For critical CD features there may be a significant advantage to using i-line illumination and accepting the loss in stepper throughput. The 9.6µm HD-8000 produced a resolution of 4µm features with wall profiles of 68 degrees using ghi-line exposure. The sensitivity of the 9.6µm polyimide to exposure wavelength is similar to the 19µm polyimide.

This paper has explored the performance of a positive acting, aqueous developable polyimide for PSB and flipchip bump bond applications on the Ultratech ghi-line stepper. The Saturn Spectrum 3 offers significant process latitude and short exposure times for the polyimide studied. A summary of recommended lithographic applications for the two thicknesses of HD-8000 is given in Table 6.

5.0 ACKNOWLEDGEMENTS

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Parameter	Saturn 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 1: Optical specifications of the lithography systems used in this study.

Process Step	Parameters	Equipment
Polyimide Coat	Static dispense; 1000 rpm for 5 seconds Spin: 3750 rpm for 30 seconds	Solitec 5110C Coater
Softbake	130 seconds at 110^{o}C, hard-contact	Solitec VBS-200
Develop	PD523AD developer at 21^{o}C 90 seconds immersion with agitation	Batch
Rinse	Rinse with DI water for 30 seconds then gently air dry	Batch

Table 2: Process conditions for HD 8000 polyimide for 9.6μm thickness.

Process Step	Parameters	Equipment
Polyimide Coat	Static dispense;1000 rpm for 5 seconds Spin: 1800 rpm for 30 seconds	Solitec 5110C Coater
Softbake	260 seconds at 110^{o}C, hard contact	Soletic VBS-200
Develop	PD523AD developer at 21^{o}C 180 seconds immersion with agitation	Batch
Rinse	DI water rinse for 30 seconds then gently air dry	Batch

Table 3: Process conditions for HD 8000 polyimide for 19μm thickness.

Thickness	Mask bias (μm)	Data fit R^2
9.6 microns	0.045	0.999
19 microns	0.183	0.999

Table 5: HD 8000 polyimide mask bias determined from the linearity regression analysis in equation (1). The mask linearity is shown in Figure 4. The mask bias is in units of microns.

Photoresists	9.6 microns	19 microns
Stepper Model (wavelength)	Saturn Spectrum 3(ghi)	Saturn Spectrum 3(ghi)
Resolution (μm)	4.0	6.0
Nominal Exposure (msec)	275	440
Exposure Latitude (msec)	20	20
Focus Latitude (μm)	6	8
Reticle Bias (μm)	0.045	0.183

Table 6: Recommended lithographic applications on Ultratech steppers.

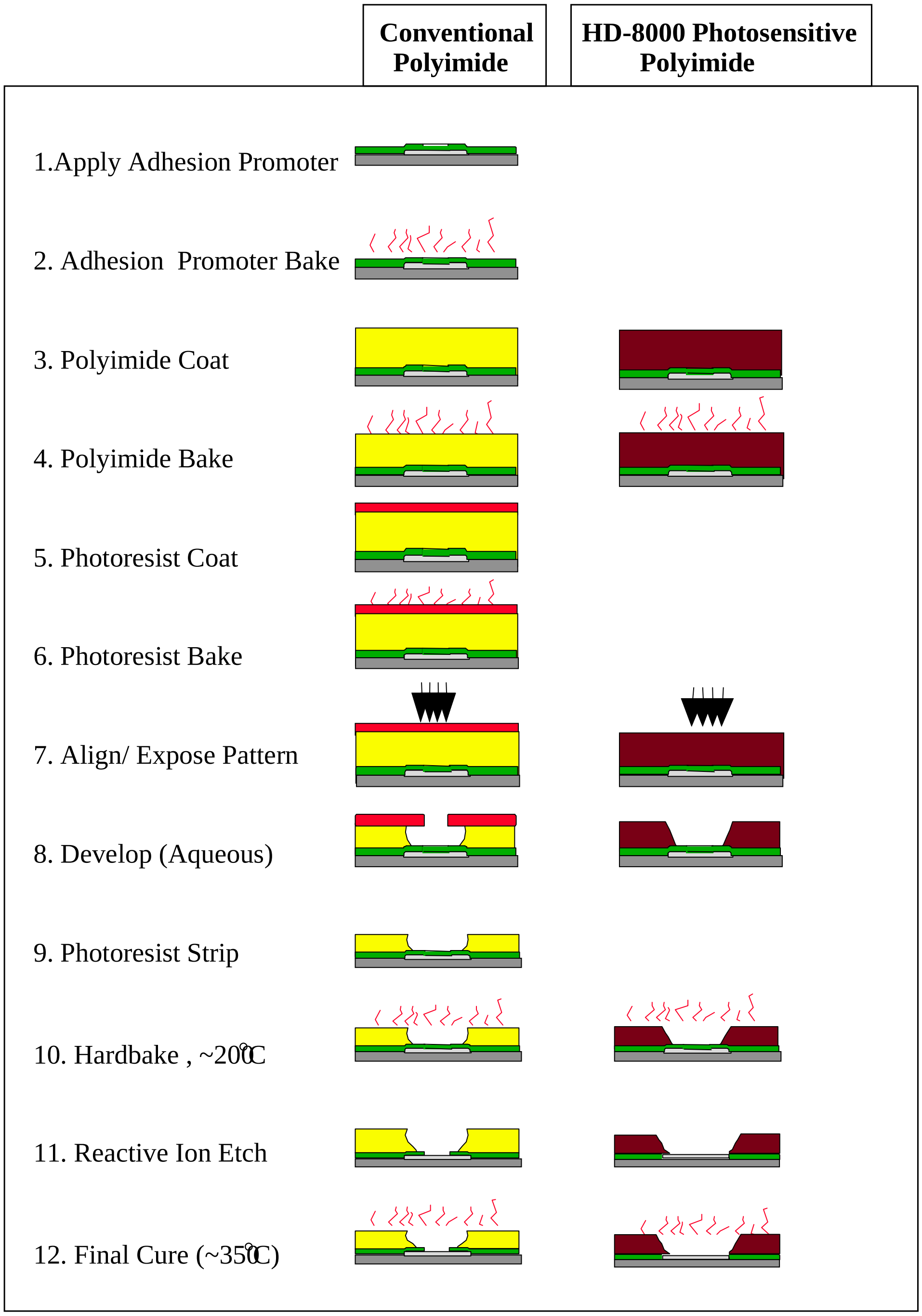


Figure 1: Comparison of conventional polyimide process and positive acting photosensitive polyimide process. The photosensitive polyimide process eliminates multiple steps and decreases cycle time.

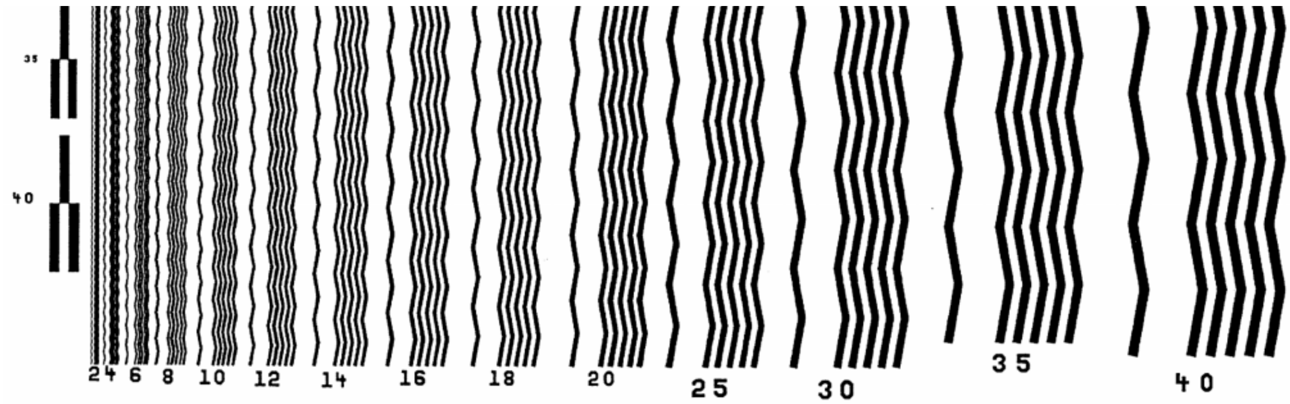


Figure 2: Partial view of the photomask layout showing vertical grouped and isolated lines from 2 to 40μm in size. The long SEM lines are placed in a zigzag pattern to increase mechanical integrity of the photoresist.

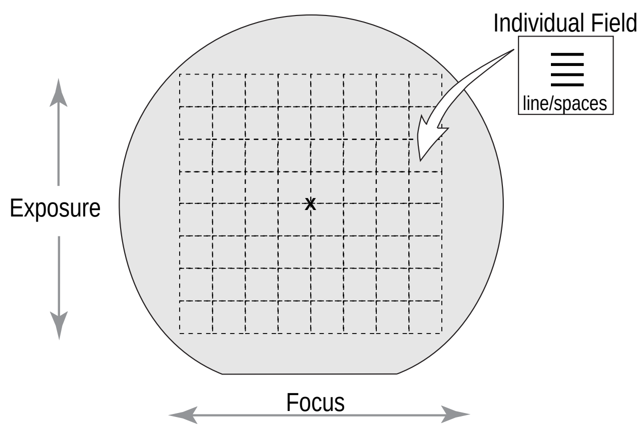


Figure 3: Wafer layout for the focus and exposure test matrix. An eight by eight field array was exposed with focus varying in the horizontal axis and exposure dose varying on the vertical axis.

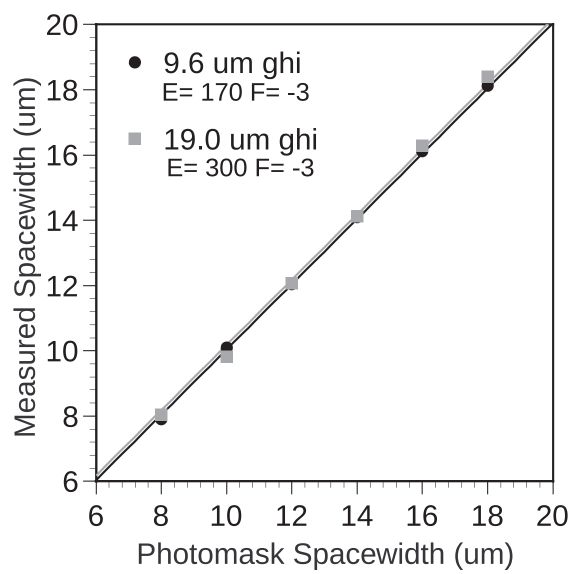
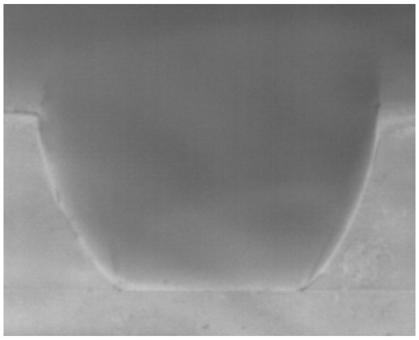
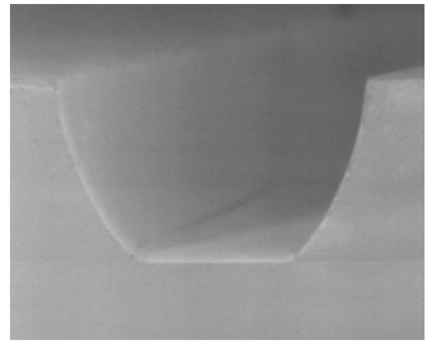


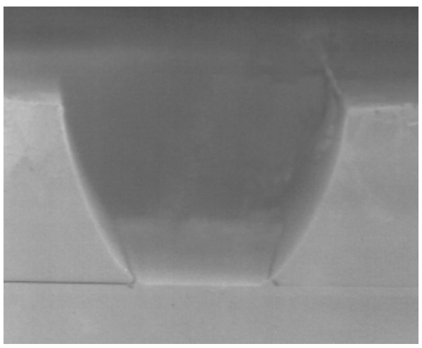
Figure 4: Mask linearity plot for 19.0μm and 9.6μm thick HD-8000 polyimide using a ghi-line stepper. The reticle bias was determined for each photoresist by regression analysis and is summarized in Table 5.



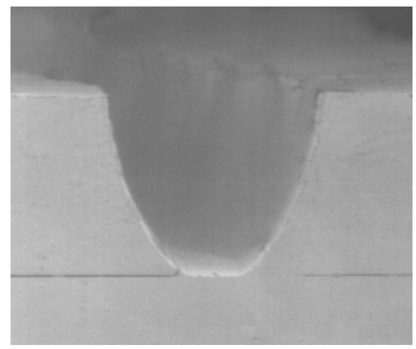
14µm Spacewidth



12µm Spacewidth

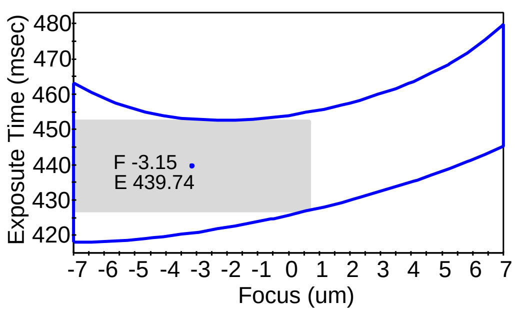


10µm Spacewidth

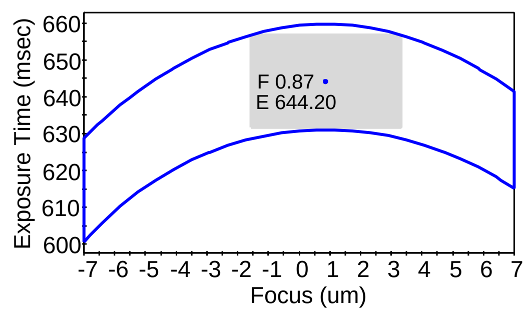


6µm Spacewidth

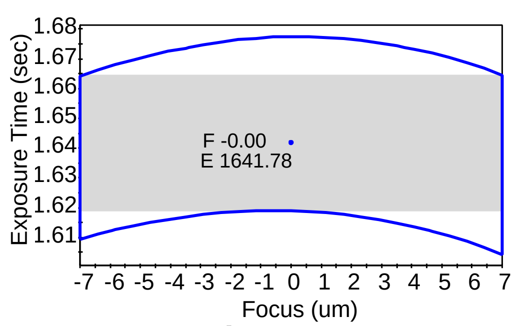
Figure 5a: Spacewidth linearity for 19µm thick HD-8000 polyimide exposed with ghi-line illumination. The exposure time is 440 msec (490 mJ/cm^2) and the focus offset is -3µm.



ghi-line exposure

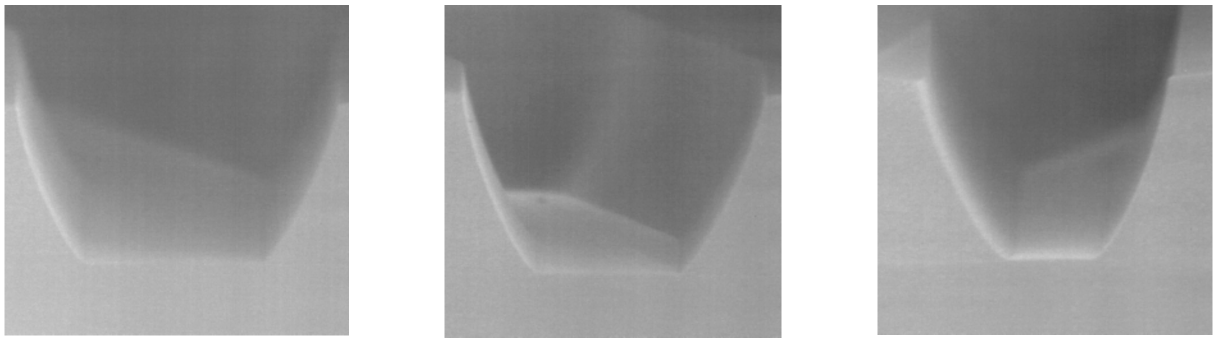


gh-line exposure



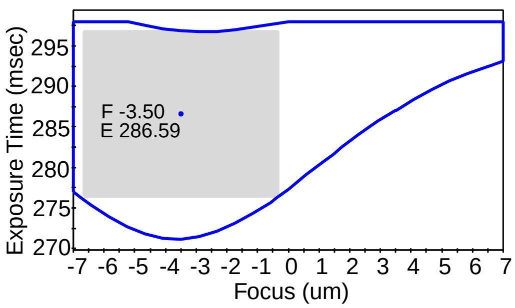
i-line exposure

Figure 5b: Process window for 10µm spacewidth in 19µm thick HD-8000 polyimide exposed in ghi-line, gh-line and i-line. The process envelope shows ±10 percent CD control limits.

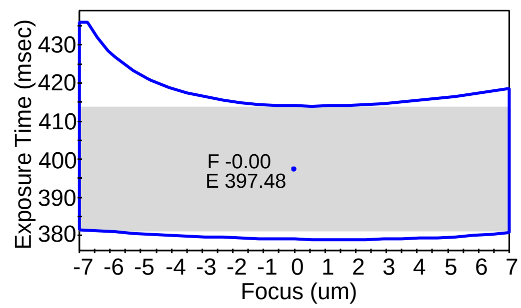


8µm Spacewidth   6µm Spacewidth   4µm Spacewidth

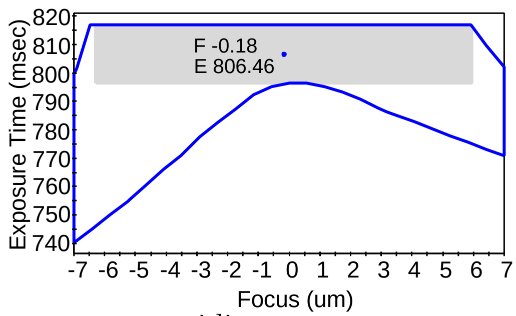
Figure 6a: Spacewidth linearity for 9.6µm thick HD-8000 polyimide exposed with ghi-line illumination. The exposure time is 250 msec (235 mJ/cm^2) and the focus offset is -3µm.



ghi-line exposure

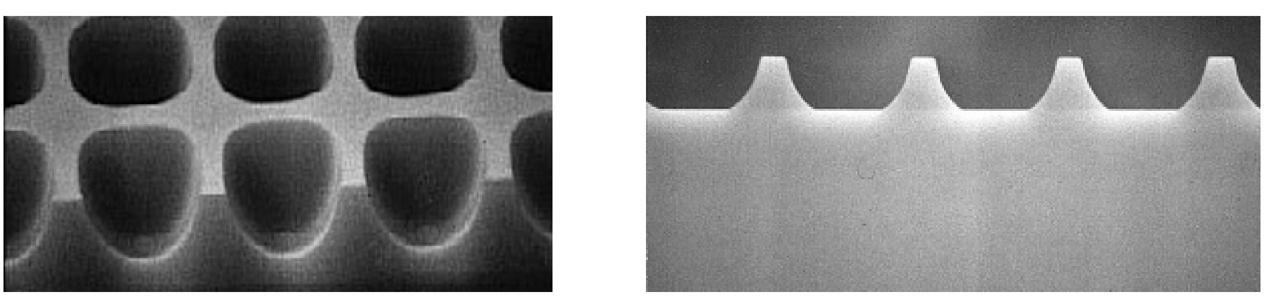


gh-line exposure



i-line exposure

Figure 6b: Process window for 4µm spacewidth in 9.6µm thick HD-8000 polyimide exposed in ghi-line, gh-line and i-line. The process envelope shows ±10 percent CD control limits.



(a) 2.0µm vias on a 6 µm pitch   (b) 7.0µm lines and spaces

Figure 7: Cross sections of 5.1µm cured HD-8000 polyimide exposed with gh-line illumination.