Characterization Study of an Aqueous Developable Photosensitive Polyimide on 300 mm Wafers

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The advent of 300 mm wafer processing for semiconductor manufacturing has had a great impact on the development of photolithographic materials, equipment and associated processes. At the same time advanced packaging techniques for these semiconductor devices are making strides for smaller, faster and lower cost parts with improved reliability. Photosensitive polyimides are used for passivation stress buffer relief and soft error protection on almost all memory devices such as DRAM as well as final passivation layers for subsequent interconnect bumping operations on most of today's advanced microprocessors. For processing simplicity and total cost of ownership, it is desirable to use an aqueous developable polyimide to maintain compatibility with standard photoresist processes.

This study will investigate the feasibility of processing photosensitive polyimides on 300 mm wafers. The performance of a commercially available, positive acting, aqueous developable polyimide is examined at a thickness appropriate for logic devices. A broadband stepper is utilized since polyimides are highly aromatic polymers that strongly absorb UV light below 350 nm. This stepper exposes photosensitive films using mercury vapor spectrum output from 390 nm to 450 nm (g and h-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.

Process capability for 300 mm wafers is determined by analyzing polyimide film thickness uniformity and critical dimension (CD) control across the wafer. Basic photoresist characterization techniques such as cross sectional SEM analysis, process linearity and process windows are also used to establish lithographic capabilities. The trade-offs for various process capability windows are reviewed to determine the optimum process conditions for different polyimide applications.

Key Words: polyimide, photoresist characterization, broadband stepper, 300 mm wafer

1.0 INTRODUCTION

As with the previous evolutions of wafer size, 300 mm is being driven by the requirement for more chips per wafer and economies of scale. Of the 300 mm pilot and production wafer fabrication facilities currently underway and planned, nearly 50 percent have been slated for the manufacture of Dynamic Random Access Memory (DRAM) with the balance being microprocessor (MPU) and Digital Signal Processor (DSP) devices [1]. These device types all use polyimides in various processes as the final photolithography layer in the wafer fab.

The dominant application of polyimides is as a Passivation Stress Buffer (PSB) for devices in thin and ultra-thin packages [2]. Particular devices of concern include large-die devices packaged in plastic molding compounds, exemplified by 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 [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 [2]. 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. Due to polyimide's high aromaticity, the PSB layer has also been used effectively to reduce soft-error rates of high-density memory devices by absorption of alpha particles from the trace radioactivity in the Epoxy Molding Compounds (EMC) and cosmic rays [4].

Polyimides are also an integral contributor to the reliability of the various solder bump interconnect structures such as IBM's Controlled Collapse Chip Connection (C4). The polyimide provides excellent adhesion to the chip passivation, underbump metallization (UBM) and to epoxy underfill materials [5]. The solder bumps replace the wirebonds as the chip to package or chip to board interconnect. If a device designed for wirebonding is to be bumped, the final metal bond pads usually need to be redistributed throughout the face of the die to allow for the proper placement and pitch of the subsequent bumps. Known as Bond Pad Redistribution (BPR) or Redistribution Layer (RDL), this metallization process can be performed by first applying a layer of photosensitive polyimide and opening up to the standard bond pad metal and curing before the redistribution metal is processed [6]. The polyimide's mechanical properties protect the glass passivation from the additional stresses and its dielectric properties are well suited for the device performance as well.

Polyimide can be placed over the BPR metal with vias to the new locations of the redistributed metal bond pads. Again, additional metals are deposited around the polyimide openings. This part of the typical bump process is known as the Under Bump Metallization (UBM) layer. Therefore combining the Bond Pad redistribution and the Underbump Metallization Layer creates a structure as shown in Figure 1.

In the past, non-photosensitive polyimides (NPDs) have routinely been used as the polymers of choice for high volume multi-level processes. 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, this same developer isotropically etches the underlying uncured NPD. This NPD 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. In the case where the polyimide layer must have subsequent metallization, such as UBM in C4, a sloped via profile is necessary for complete metallization coverage [7].

To address the process complexity and limited performance of NPD polyimides, suppliers introduced photodefineable polyimide products (PDPIs). These materials are directly exposed using a photolithography tool, which simplifies processing. The PDPI 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). A typical PSB process comparison between NPD and PDPI polyimides is shown in Figure 2. PDPIs also provides significant advantages of superior resolution and improved sidewall profiles, and smaller process bias than conventional polyimides. For these reasons the PDPI layer can be used as the etch mask for the underlying passivation layer. This allows the elimination of an entire photolithography level in the manufacturing cycle. Using the PDPI layer as the etch mask is referred to as the "one mask" process since the polyimide mask is the same mask used for the bond pad passivation etch. The sidewalls of the PDPIs slope nicely after the final cure making the PDPI compatible with subsequent metallization steps used in advanced packaging and bumping interconnect processes.

Positive acting aqueous soluble, photosensitive polyimides provide further 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 smooth transition in fabs where NPD polyimides were previously used. This is because the NPDs usually use the same developer and reticle.

PDPIs 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. If the polyimides aromaticity were to be lowered to accommodate for DUV transmission it would lessen the mechanical and heat resistance properties of the polyimides. This makes compatibility of current PDPIs questionable with DUV steppers. For this reason it appears that g-line and i-line steppers will be used for polyimide applications for 300 mm wafer processing.

The photolithography requirements for thick photosensitive polyimides can be addressed by using production optical lithography equipment. 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 reticle 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.

2.0 EXPERIMENTAL METHODS

2.1 Reticle Design and Manufacture

The Ultratech 1X reticle used for this study was designed to support easy cross sectional SEM metrology for micromachining applications. The reticle consists of two fields of 10.0 by 10.0 mm, 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 12 µm in 2 µm size increments and 15 µm, 20 µm, 30 µm, 40 µm, 50 µm and 60 µm structures. 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 5 mm in length to facilitate cross sectional SEM analysis. There was no data biasing applied to the design data and CDs were held to within ±0.03 µm of a nominal 2.0 µm 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 this study was performed on an Ultratech Stepper 300 mm Wafer Stepper. The system is designed to process both 200 and 300 mm wafers to provide enhanced flexibility for back-end wafer fabs. The optical specifications for the stepper are shown in Table 1. The stepper is based on the 1X Wynne-Dyson lens design employing Hg illumination with gh-line from 390 to 450 nm and having a 0.32 NA. Broadband exposure is possible due to the unique design characteristics of the Wynne Dyson lens system [9]. 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 stepper 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 eleven by eleven field array. 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.

2.3 Processing Conditions

SEMI standard 300 mm ultra-flat silicon wafers were used for this study. HD-Microsystems HD-8001 was selected as the polyimide since it is self priming, positive acting and aqueous developable. The most common cured thicknesses for PSB are approximately 5 μm for logic devices and 8 to 10 μm for memory devices. Since the HD-8001 shrinkage is approximately 50% between pre-bake and final cured thickness, the material was evaluated at 9.6 μm pre-bake thickness using the process described in Table 2. Polyimide thickness and uniformity were measured on a Nanometrics 8300X measurement system. All wafers used for this work were new. This was to prevent any adhesion problems from previous adhesion promoters or cleaning processes.

2.4 Data Analysis

All wafers were visually inspected after exposure 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 18,000X magnification. Multiple spacewidths were measured top-down on the S-7280H over the entire focus and exposure matrix. 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 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 Wafer Coating and Development

Two viscosities of the HD-8000X polyimide family were evaluated for coating 300 mm wafers. The standard viscosity of HD-8000 for 200 mm wafers is 1500 centipoise (cPs). However, this viscosity resulted in very thick films when spun at the slow spin speed required for 300 mm wafers. For example, at 1700 rpm the thickness was approximately 18 μm. In order to achieve thinner films it was necessary to use HD-8001 polyimide with a reduced viscosity. A spin speed curve for the HD-8001 is shown in Figure 3. It shows the standard logarithmic dependence on speed. A spin speed of 1000 rpm was used to obtain the desired thickness of 9.6 µm after coat.

The polyimide coating uniformity was measured at 49 points across the 300 mm wafer. A contour plot of the coating uniformity is shown in Figure 4a. The black contour lines represent 0.1 µm intervals. For this sample wafer the average thickness was 9.65 µm with a 3 sigma of 0.16 µm.This implies a coating uniformity of better than 2 percent.

The thickness uniformity of the same wafer was remeasured after the immersion develop process as shown in Figure 4b. The average thickness is 7.61 µm with a 3 sigma of 0.49 µm. The film retention is 79 percent which is within the desired range. However, the film uniformity has degraded to 6.4 percent. Most of this nonuniformity is probably due to the wafer cassette that was used for the immersion develop process. The contour plot shows three circular areas on the right side of the wafer which are thinner than the average. The cassette has three slots is the side which match these locations. Clearly the film uniformity could be improved dramatically by using a puddle develop on a 300 mm production track.

3.2 Linearity Analysis

Figure 5 shows the process linearity for the HD-8001 polyimide. 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 process bias is +0.447 µm and goodness of fit is 0.99998

The polyimide exhibits an excellent 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.

3.3 Polyimide Characterization

Wafers were imaged on the 300 mm stepper with exposure doses from 400 to 650 mJ/cm^2 with increments of 25 mJ/cm^2 and focus varied from -8 to +2 µm focus at increments of 1 µm. The HD-8001 demonstrated a 2 µm resolution for isolated spacewidths as shown in the cross sectional SEM micrographs shown in Figure 6. The sidewall angle is approximately 68 degrees and is independent of spacewidth down to 2 µm 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.

HD-8000 polyimide exhibits well behaved process characteristics. Figure 7a shows process window plots for 3 µm spacewidth features. The envelope region shaded in grey demonstrates a ten percent control limit for this spacewidth. The figure also shows the largest area rectangular process window that fits within the envelope. At the center of the process window the exposure energy is 465 mJ/cm^2 and the focus is -0.6 µm

Other rectangles can be drawn in the envelope region depending on exposure and focus latitude requirements for a given process. Figure 7b shows a curve that summarizes all of the rectangles. The maximum exposure latitude is 7.3 percent while the maximum focus latitude is 8.7 µm. However, they can not be achieved simultaneously. For example, if a 5 µm focus latitude is required, the resulting exposure latitude is 5.2 percent (same as box shown in Figure 7a).

3.4 Across Wafer Uniformity

The CD uniformity was measured at 238 points across the 300 mm wafer. A contour plot of the CD uniformity for 8 µm spacewidths is shown in Figure 8. The black contour lines represent 0.5 µm intervals. For this sample wafer the average CD was 8.59 µm with a 3 sigma of 1.25 µm. The actual CD closely matches the process bias determined in section 3.2. The across the wafer uniformity is 14 percent. The contour plot shows the same three circular areas on the right side of the wafer as seen in Figure 4b. Here the largest CD values correspond to the locations of the thin polyimide film after immersion develop. Again, it is expected that the CD uniformity could be improved dramatically by using a puddle develop process on a 300 mm production track.

4.0 CONCLUSIONS

This study has shown the feasibility of processing photosensitive polyimides on 300 mm wafers. HD Microsystems HD-8001 positive acting, aqueous developable polyimide was patterned using an Ultratech 300 mm stepper. The polyimide can easily be coated to better than 2 percent uniformity across the 300 mm wafer. The film uniformity after develop and the CD uniformity are highly dependant on the development process. A manual immersion process resulting in three hot spots on the right side of the wafer which adversely impacted film uniformity and CD control. It is expected that the CD uniformity could be improved dramatically by using a puddle develop process on a 300 mm production track.

Cross sectional SEM analysis and process window analysis were used to establish the lithographic capabilities of the HD-8001. A 9.6 µm thickness at coat produced a resolution of 2 µm features with wall profiles of 68 degrees. The Ultratech 300 mm stepper offers significant process latitude and short exposure times for this polyimide. A summary of recommended lithographic process for the HD-8001 is given in Table 3.

5.0 ACKNOWLEDGEMENTS

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Parameter	300 mm Stepper
Reduction factor	1X
Wavelength (nm)	390 - 450
Numerical aperture (NA)	0.32
Partial coherence (σ)	0.56
Wafer plane irradiance (mW/cm^2)	1250

Table 1: Optical specifications of the lithography system used in this study.

Process Step	Parameters	Equipment
Polyimide Coat	Static dispense; Spin: 1000 rpm for 30 seconds	Suss RC-13 Coater
Softbake	150 seconds at 126^{o}C, contact	Blue-M Oven
Develop	PD523AD developer at 21^{o}C 70 seconds immersion with agitation	Batch
Rinse	Rinse with DI water for 30 seconds then gently air dry	Batch

Table 2: Process conditions for HD-8001 polyimide for 9.6 μm thickness.

Polyimide	9.6 microns
Stepper Model (wavelength)	300 mm (gh)
Resolution (μm)	2.0
Nominal Exposure (mJ/cm^2)	465
Exposure Latitude (mJ/cm^2)	25
Focus Latitude (μm)	5.2
Reticle Bias (μm)	0.45

Table 3: Recommended process application for the HD-8001 on 300 mm wafers.

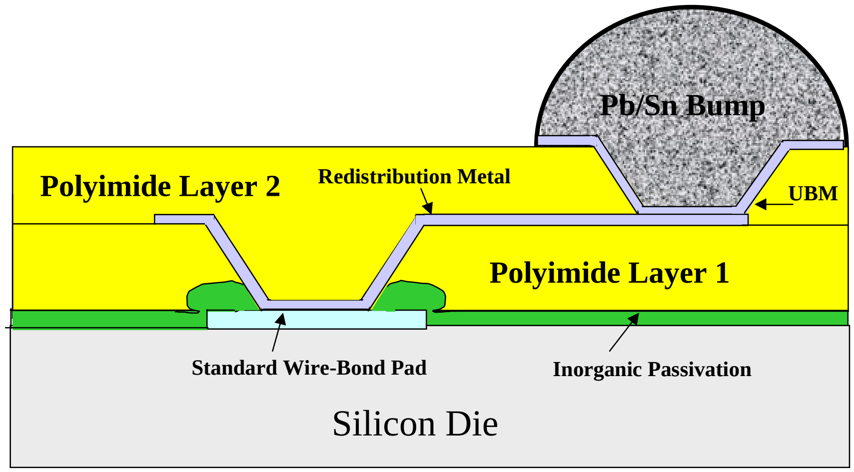


Figure 1: The bond pad redistribution layer (polyimide 1) and the under bump metallization layer (polyimide 2) for a solder bump interconnect structure.

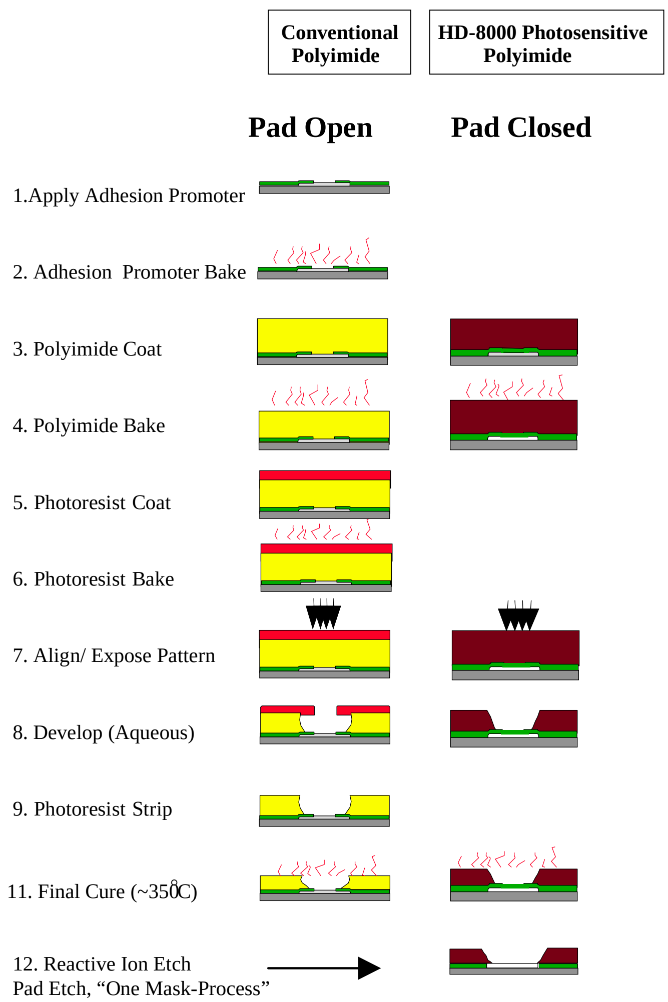


Figure 2: Comparison of conventional polyimide process and positive acting photosensitive polyimide process. The photosensitive polyimide process eliminates multiple steps and decreases cycle time.

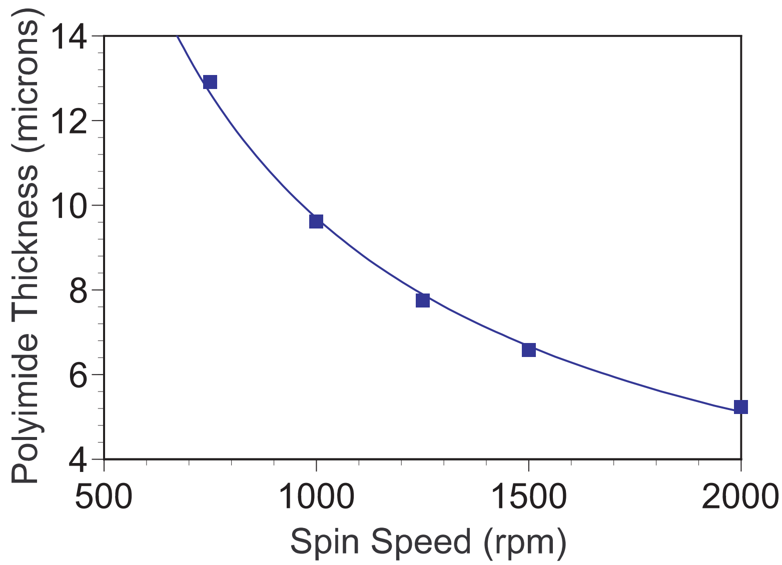
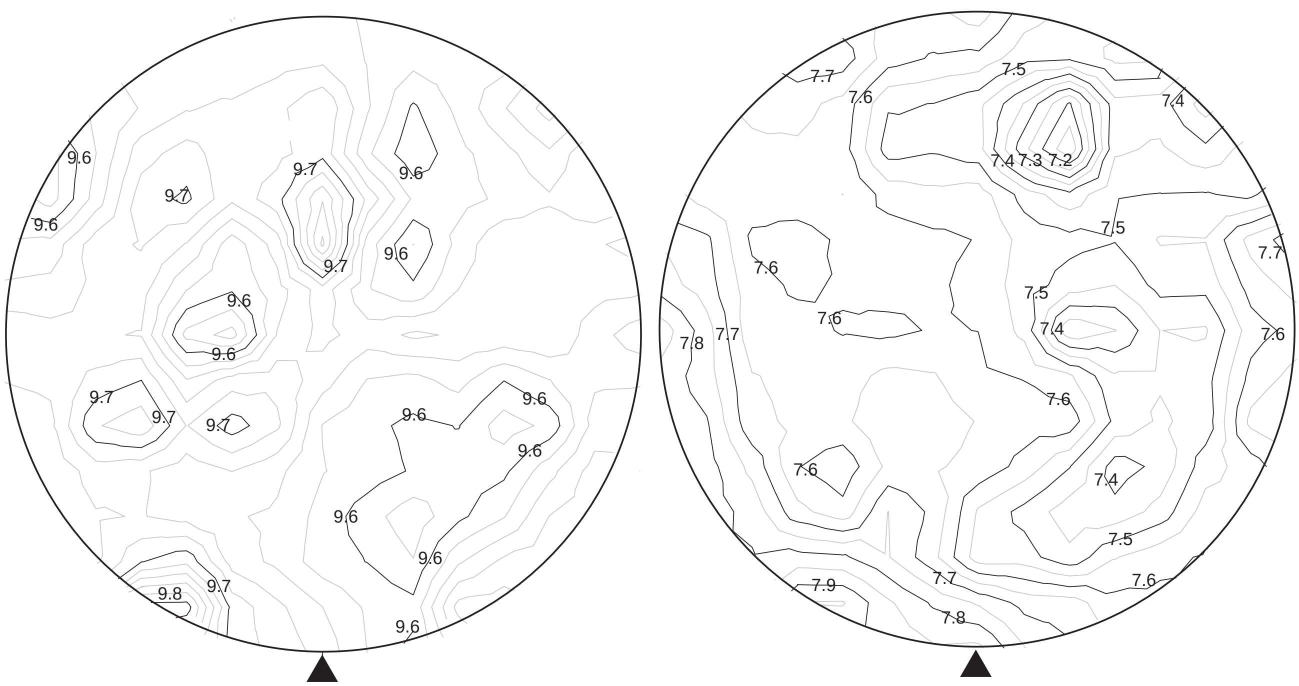


Figure 3: Spin speed curve for the HD-8001 polyimide on 300 mm wafers.



(a) After prebake
Mean = 9.65 µm 3σ = 0.16 µm

(b) After development
Mean = 7.61 µm 3σ = 0.49 µm

Figure 4: Coating uniformity for HD-8001 polyimide on a 300 mm wafer after prebake and after development. The dark contour lines are at 0.1 µm intervals. The three thin spots on the right side of the wafer after development (b) match slots in the wafer cassette used for immersion development.

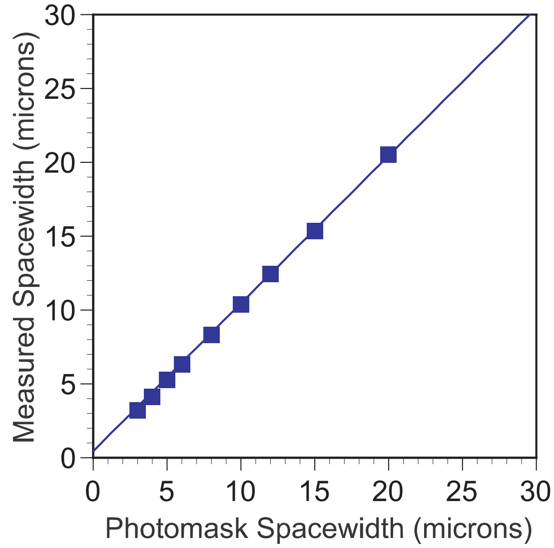
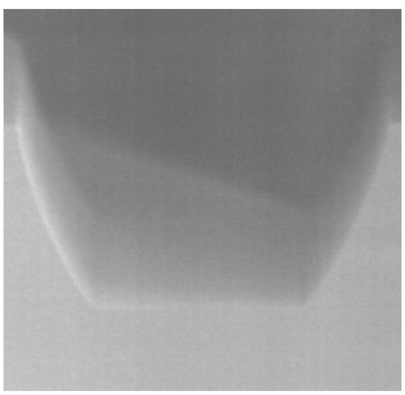
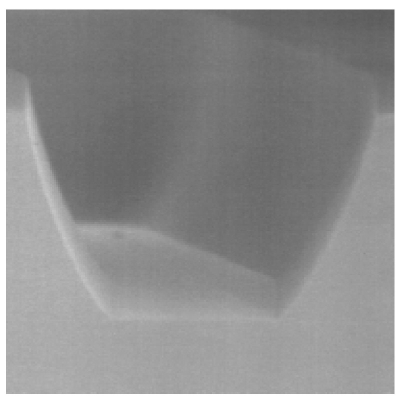


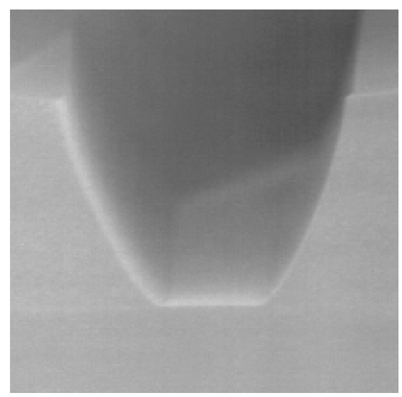
Figure 5: Mask linearity plot for 9.6 μm thick HD-8001 polyimide. The reticle bias was determined to be +0.45 μm.



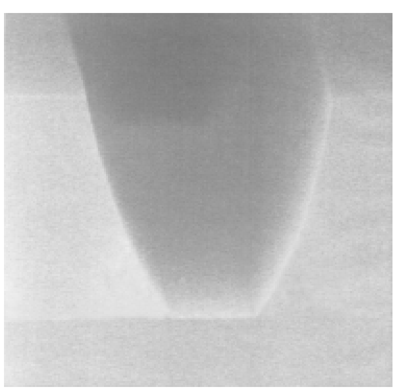
(a) 8 μm Spacewidth



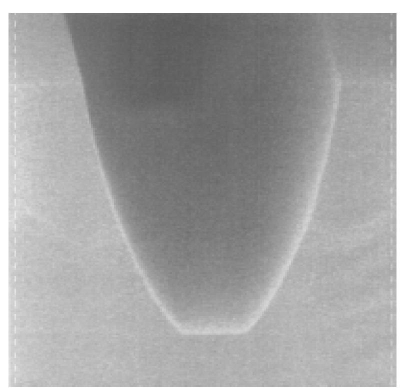
(b) 6 μm Spacewidth



(c) 4 μm Spacewidth

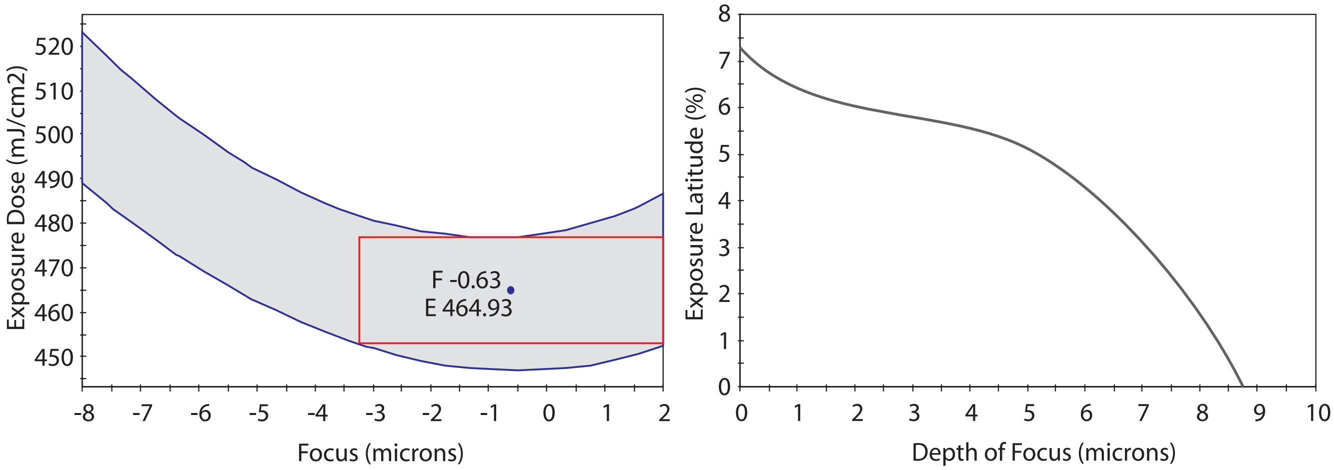


(d) 3 μm Spacewidth



(e) 2 μm Spacewidth

Figure 6: Spacewidth linearity for 9.6 μm thick HD-8001 polyimide exposed with an Ultratech 300 mm stepper. The exposure dose is 450 mJ/cm^2 and the focus offset is -1 μm.



(a) Process Window

(b) Process Latitude

Figure 7: Process window for 3 μm spacewidth in 9.8 μm of HD-8001 polyimide. The process envelope shows ±10 percent CD control limits.

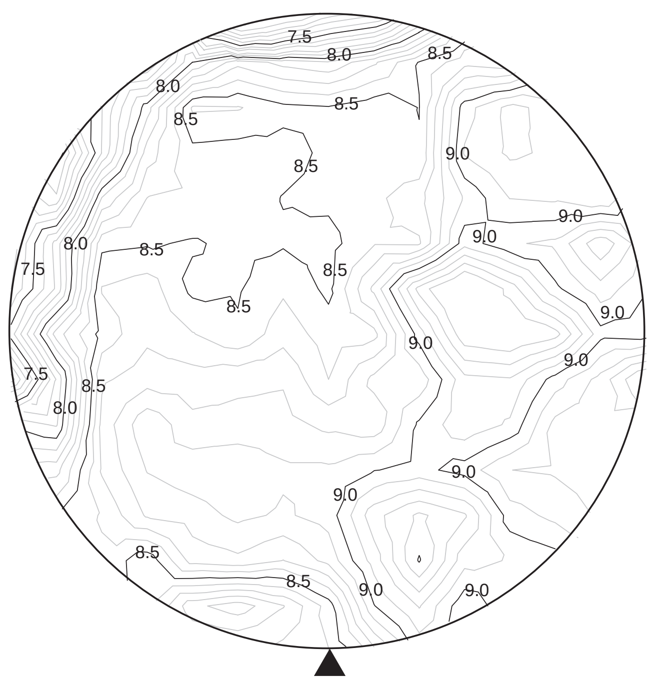


Figure 8: CD uniformity for 8 μm spacewidths in HD-8001 polyimide on a 300 mm wafer. The average size is 8.59 μm with 3σ of 1.25 μm. The dark contours are at 0.5 μm intervals. The three larger CD spots on the right side of the wafer match the thin polyimide spots seen after development (Figure 4b).