# Process Improvements for Ultra-Thick Photoresist Using a Broadband Stepper

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There are a number of new lithographic applications that require the use of ultra-thick photoresists. Extremely large structure heights and high aspect ratios are often necessary for electroplating processes. In this situation it is important for the height of the patterned photoresist to exceed the plating height. Two of the main applications for thick photoresist are micromachining and advanced packaging. Ultra-thick photoresists are used in packaging to define the size and location of the bonds for bump bonding, while in micromachining the photoresist is used to define fluidic chambers and electroforming molds.

At photoresist thickness greater than 15 microns, standard lithographic techniques become difficult in terms of performance and productivity. The bake, exposure and develop times increase dramatically as the photoresist thickness climbs. The estimated total process time for a 15 micron photoresist is approximately three times greater than that of a 1 micron photoresist. For thick films the develop time on the wafer track becomes the throughput limiter for the entire lithography cell. Therefore, reducing develop time for thick photoresist processes is critical to enhancing the lithography cell cost of ownership.

In this paper we will focus on the developer chemistry and process to improve both performance and productivity for a 15 micron thick photoresist. We evaluate process changes in both normality and surfactant level of the developer. Cross sectional analysis, contrast curves, process linearity and process windows are used to establish the lithographic capabilities. It is clear that a developer and process for a thin photoresist is not necessarily optimum for a thick photoresist process. The implementation of an ultra-thick photoresist becomes more feasible in a manufacturing environment after optimizing developer chemistry and process conditions.

**Key Words:** thick photoresist, developer, surfactant, normality, photoresist characterization, broadband stepper, productivity, advanced packaging, MEMS, plating

## 1.0 INTRODUCTION

Rapid growth is being experienced today in the areas of micro-mechanical systems (MEMS) and advanced packaging [1,2,3,4,5]. Additionally there have been very rapid technology changes in the magnetic head recording industry. All three of these market segments utilize thick photosensitive materials for electroplating. The largest upcoming market segment is wafer level packaging. The semiconductor manufacturing industry is converting to wafer level packaging to reduce cost and increase performance by replacing single chip wire bonding with bump bonding applications as the final step in chip manufacturing. Extending the microlithographic processes into these rapidly growing areas is placing new demands on both the photosensitive materials and the lithography equipment.

Electroplating metals for micro-scale features itself does not present new technical challenges. However, the fabrication of high aspect ratio linewidths for these applications is a new and challenging use of photolithography equipment and photoresists. The photolithography requirements for thick photoresists 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. Thick photoresists, 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 numerical aperture (NA) to maximize the illumination intensity at the wafer plane and to improve DOF.

Photoresist performance, like stepper performance, has generally been optimized over recent years for achieving the smallest geometries possible. Some newer photoresist formulations are available that have properties more tailored for making the high aspect ratio structures required for electroplating molds. The process operating conditions for thick photoresists are considerably different than for thin photoresists. In the case of thin photoresists the two issues are resolution and latitude [6]. With thick films the concerns are centered around aspect ratios, downstream plating performance, latitudes and productivity. As spin coated photoresist films become more popular for these applications, it becomes important to study thick photoresists for optimization of performance and productivity [7,8,9,10].

The cost of ownership of a lithography cell is driven primarily by the cost of the individual equipment and the effective throughput of the cell. Traditionally the exposure time is the limiting factor since the exposure system is the most expensive part of the cell. However, with thick photoresist films the track developer process can be the limiting factor with develop time in excess of 5 minutes. By improving the develop rate, the total exposure and develop time will decrease, reducing the total cost of ownership. This can be achieved by increasing the developer normality and optimizing the level of surfactant. However, simply changing develop conditions can impact the photoresist performance including critical dimension (CD) control, profile and aspect ratios.

Standard normality developer at 0.26N is used in the semiconductor industry for balancing photoresist performance and throughput. Since many thick photoresist applications don’t have as challenging of a CD requirement, it is possible that higher normality developers will be acceptable. The objective of this study is to find a faster photoresist/developer system (normality and surfactant) at the same time maintaining a process acceptable for thick photoresist applications.

## 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 1. The Saturn Spectrum 3 stepper is based on the 1X Wynne-Dyson lens design employing Mercury (Hg) g, h and i-line illumination from 350 to 450 nm and having a 0.16 NA [11]. 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 NAs and a relatively narrow bandwidth.

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 times were determined by measuring isolated space patterns at the specific linewidth of interest with a KLA-Tencor 8100 metrology SEM. 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 easy cross sectional SEM metrology for micromachining applications. 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 horizontal and vertical grouped line and space 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. All of the line structures are 7 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 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 Photoresist Processing

SEMI standard ultra-flat silicon wafers were used for this study. The 150 mm wafers were pre-treated according to recommendations by ShinEtsuMicroSi as described in Table 2. The ultra-thick photoresist used for this investigation was ShinEtsu SIPR® 9270M-12.0 positive photoresist. The photoresist coats to a nominal thickness of 12 µm at 3000 rpm. The ShinEtsu SIPR 9270M was coated to the 15 µm target thickness using the process and equipment described in Table 2. Photoresist thickness and uniformity were measured on a Nanometric 8300X measurement system.

ShinEtsu SIPR 9270M photoresist utilizes a bonded sensitizer to the novolak resin. Built into the PAC (photo active component) is a diazo group that pseudo-crosslinks when exposed to the $OH^-$ groups of the organic tetramethylammonium hydroxide (TMAH) developer. Effectively the dissolution rate of the photoresist decreases as the exposure to $OH^-$ increases. This is a valuable mechanism for thick photoresist application by decreasing unexposed photoresist loss and improving photoresist profiles at the top of the film stack where the exposure to developer can be on the order of 3 to 5 minutes depending on the photoresist thickness. The 3 to 5 minutes of develop time at the top of the resist is of great contrast to the bottom of the profile where the exposure to developer can be much less than one minute.

The developer used was Moses Lake 0.26N, 0.30N and 0.35N with two levels of surfactant. Moses Lake prepared the developer samples in order to facilitate the experiments. The lower level of surfactant had a surface tension of 43 dyne/cm while the higher level of surfactant had a surface tension of 40 dyne/cm. Immersion developing was used to process all wafers.

## 2.3 Data Analysis

After exposure all wafers were visually inspected and measured on a KLA tencor 8100 metrology SEM to determine the photoresist linearity over a range of linesizes. CD measurements of isolated spaces were taken at

9,400X magnification. Spacewidths of 10 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 10 percent CD control criteria. Cross sectional photographs are presented to illustrate masking linearity for isolated spaces and depth of focus for isolated spaces. The CD linearity data is also plotted. The results from the data analysis are discussed in Section 3.0.

## 3.0 RESULTS AND DISCUSSIONS

### 3.1 Normality Comparison

Figure 2 shows the contrast curves (normalized thickness versus exposure dose) for the 0.26, 0.30 and the 0.35 normality developers and two different times for the 0.30N developer. The ShinEtsu SIPR 9270M photoresist was exposed using an open frame reticle to allow measurement of residual film thickness. Both 3 and 4 minute immersion times were used for the 0.30N developer while the 4 minutes was used for the 0.26N developer. Any shorter times with the 0.26N developer resulted in complete scumming. It is evident by this graph that the 0.26N and the 0.30N developer give similar results. However the 0.35N developer resulted in a much faster falloff in thickness with exposure dose.

The exposure dose latitude was examined by plotting CD versus dose for 10 μm features (Figure 3) at the same developer normalities and developer times previously mentioned. The dashed lines show 10 percent CD latitude. Dose latitude for 10 μm features showed tremendous degradation for the 0.35N, 4 minute develop process. The dose latitude is around ±25 percent for the 0.26N and 0.30N while being approximately ±5 percent for the 0.35N.

Cross sectional photographs were used to determine the impact of the developer conditions on resolution and photoresist profiles (Figure 5). It is clear looking at the 0.35N for 4 and 2 minute develop times that the top loss of the smaller features is extremely large. The 0.30N developer shows excellent resolution and full photoresist retention even at 5 μm features. Based on these results it was determined that the 0.35 normal developer was not viable. The top loss and lack of process window made the very highest normality unacceptable.

Figure 6 shows cross sectional photographs of 10 μm features through focus for the 0.26N and 0.30N developers with a 4 minute develop time. At minus focus offsets the 0.30N developer shows more profile rounding than the 0.26N. This would reduce the effective DOF for the case were electroplating to the top of the photoresist thickness is required. However, the side wall angle at the base of the photoresist is comparable for both developer normalities through the focus range. Either developer would be acceptable for the case of electroplating up to 70 percent of the photoresist thickness.

A linearity analysis was used to more closely examine the 0.26 and the 0.30N developers (Figure 4). This plot was constructed using top down SEM data for isolated spaces and is a best fit plot of the data. The 0.26N developer shows excellent linearity across the range of sizes. The 0.30N developer shows some deviation from linearity for the small feature sizes. However, there is not a significant difference between the two develop times at 0.30N. It appears that with the 0.30N developer it is possible to reduce the develop time by 1 minute compared to the 0.26N developer. The shorter develop time with the 0.30N developer could be used to increasing lithography cell productivity and reduce total cost of ownership.

### 3.2 Surfactant Level Comparison

Figure 7 shows cross sectional SEMs of 10 μm features through DOF comparing low and high surfactant for the 0.30N developer using a 4 minute develop time. Low surfactant is defined as surface tension of 43 dyne/cm while high surfactant level is defined as surface tension of 40 dyne/cm. There is very little profile change between the two different surfactant levels. As a result it is necessary to perform a more comprehensive process capability analysis to determine the effect of the surfactant level.

Figure 8 shows process window plots for 10 μm features for low and high surfactant for the 0.26N at 4 minutes (a and b), the 0.30N developer for 3 minutes (c and d) and the 0.30N developer for 4 minutes (e and f). The shaded envelope on each plot defines the area with ten percent CD control limit for a 10 μm spacewidth. The largest rectangular process window that fits within the envelope is also shown. There is a significant difference between the process windows for the different surfactant levels. The lower surfactant level in all cases gave a larger process window in terms of exposure latitude with no difference in focus latitude. However, the higher surfactant level cut the optimum exposure by an average of 11 percent. Each graph shows the optimum focus position (marked F) and optimum exposure condition (marked E). Clearly the choice of surfactant level depends on the trade off between process requirements and increased throughput.

### 3.3 Wavelength Comparison

Cross sectional SEMs were used to determine the impact of the exposure wavelength on resolution and photoresist profiles. Figure 9 shows ghi-line and gh-line exposure for a CD range of 2 to 10 μm. The gh-line shows better resolution, sidewall angles and film retention than the ghi-line exposure. Traditionally very thick novolak photoresist performs better with just gh-line. At i-line the bulk absorption of the photoresist is so large that it requires higher exposures in order to clear out the base of the photoresist. This extremely high exposure causes top loss and general profile degradation. Also the exposure bias has a tendency to be higher. When the i-line component is removed the transparency improves throughout the entire thickness of the photoresist. Figure 9 clearly shows this phenomena especially for smaller feature sizes.

## 4.0 CONCLUSIONS

This paper has explored the performance of an ultra-thick photoresist for high aspect ratio micromachining and flipchip bump bond applications on the Ultratech Spectrum 3 stepper utilizing ShinEtsu SIPR 9270M photoresist and Moses Lake developers. Standard photoresist characterization techniques have been applied to evaluate the effects of developer concentration, surfactant levels and exposure wavelength. Features as small as 2 μm were observed in 15 μm thick films.

The use of 0.35N developer is not acceptable in terms of photoresist performance while the 0.30N and 0.26N gave acceptable performance. The 0.30N developer allowed the develop time to be reduced by 25% over the 0.26N, increasing the lithography cell throughput and reducing cost of ownership. The lower surfactant level in all cases gave a larger process window, however the higher surfactant level cut the optimum exposure by an average of 11%. The use of gh-line exposure for ultra-thick photoresist showed improved resolution and sidewall control as compared to ghi-line.

Over all, thick photoresist film processes can be improved dramatically with the use of higher level normality, a change in surfactant levels and a choice of wavelength. Follow up work can be done to further optimize the process by changing the softbake temperature/time, developer temperature, wait times and develop method (immersion verses puddle). Clearly the decision to implement a higher level surfactant depends on the trade off between process requirements and increased throughput requirements.

A summary of recommended developer conditions is given in Table 3.

## 5.0 ACKNOWLEDGEMENTS

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

**Table 1:** Optical specifications of the Spectrum 3 stepper used in this study.

| Process Step | Parameters | Equipment |
|---|---|---|
| Vapor Prime | HMDS 20 minutes | YES Oven |
| SIPR 9270M Coat | Static dispense; Spin: 2750 rpm for 20 seconds | MTI Coater |
| Softbake | 180 seconds at 110$^o$C, contact<br>1 hour wait time before exposure | MTI Hotplate |
| Develop | 1 hour wait time after exposure<br>Moses Lake Experimental developer at 21$^o$C<br>2 to 4 minutes immersion with agitation | Batch |
| Rinse | Dump Rinse with DI water; Spin rinse and dry | Batch |

**Table 2:** Process conditions for ShinEtsu SIPR 9270M for 15 µm thickness.

| Developer Type | 0.26N, Low Surfactant | 0.30N, Low Surfactant |
|---|---|---|
| Develop Time (minutes) | 4 | 3 |
| Nominal Exposure (mJ/cm$^2$) | 1210 | 1060 |
| Exposure Latitude (mJ/cm$^2$) | 400 | 300 |
| Focus Latitude (µm) | 16 | 16 |

**Table 3:** Recommended developer conditions for 15 µm Shin-Etsu SIPR 9270M on a Spectrum 3 stepper.

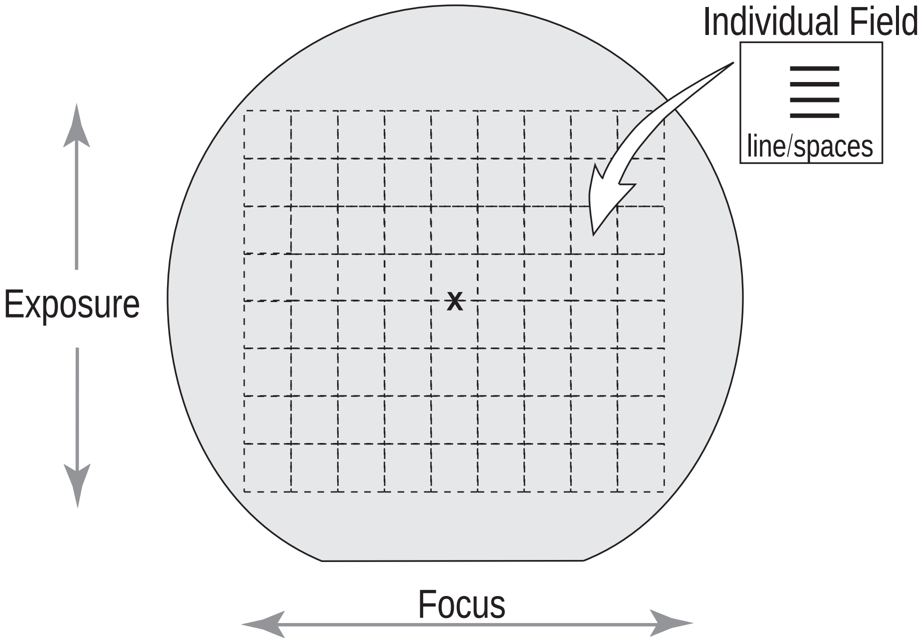


**Figure 1**: Wafer layout for the focus and exposure matrix. A nine by nine field array was exposed with focus varying in the horizontal axis and exposure dose varying in the vertical axis.

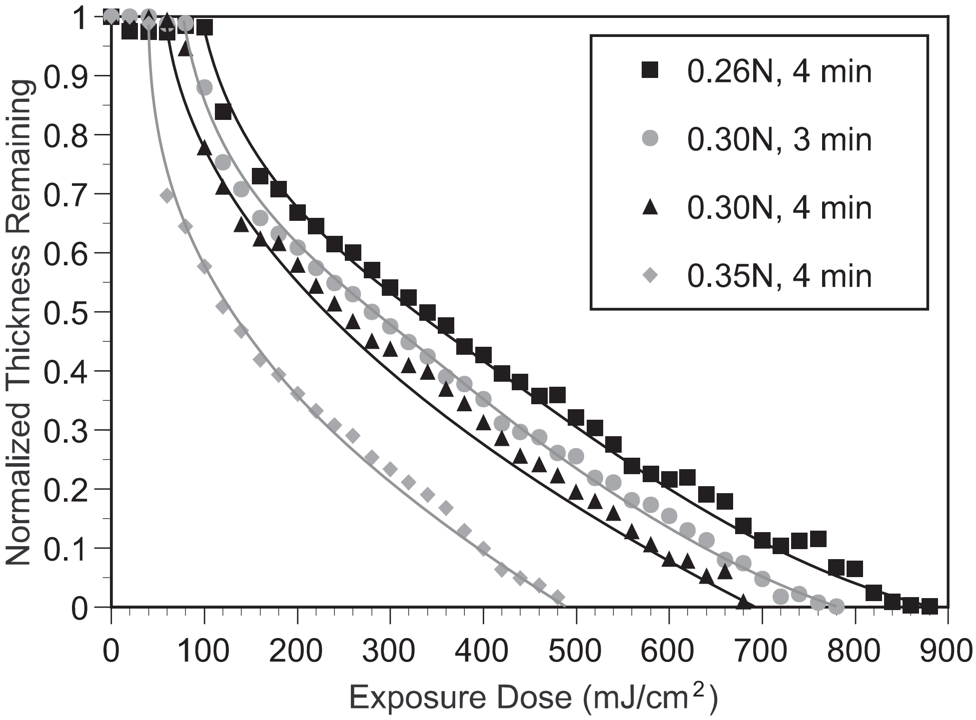


**Figure 2**: Contrast curves for 0.26, 0.30 and 0.35N developer concentrations. The surfactant level is low for all cases.

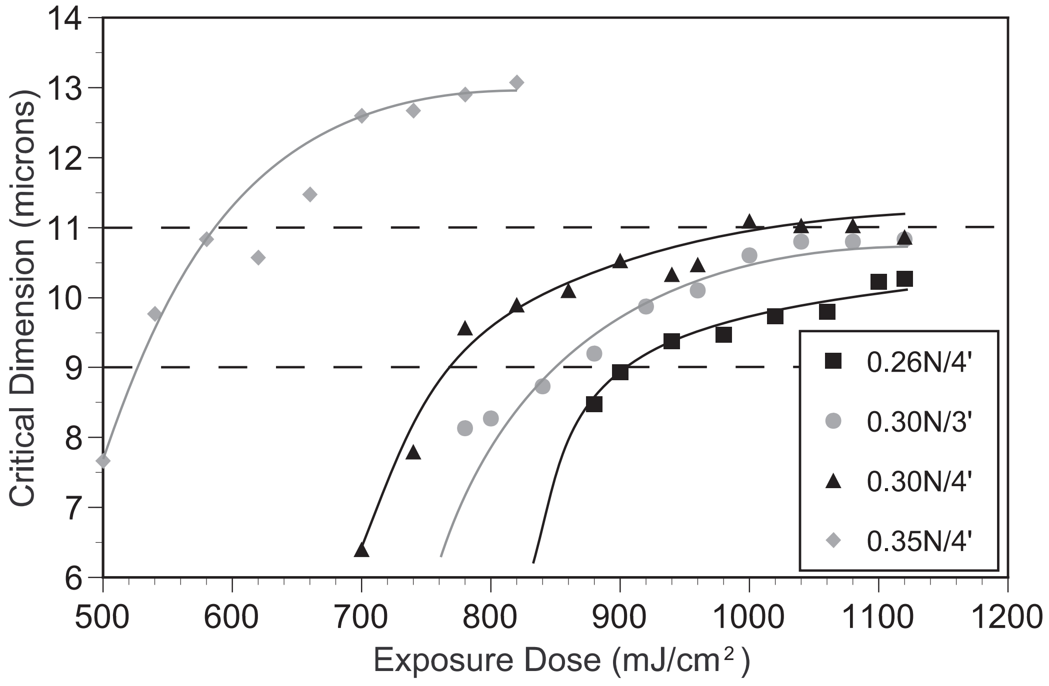


**Figure 3**: Exposure latitude for 10 µm spacewidths at 0.26, 0.30 and 0.35N developer concentrations. The surfactant level is low for all cases.

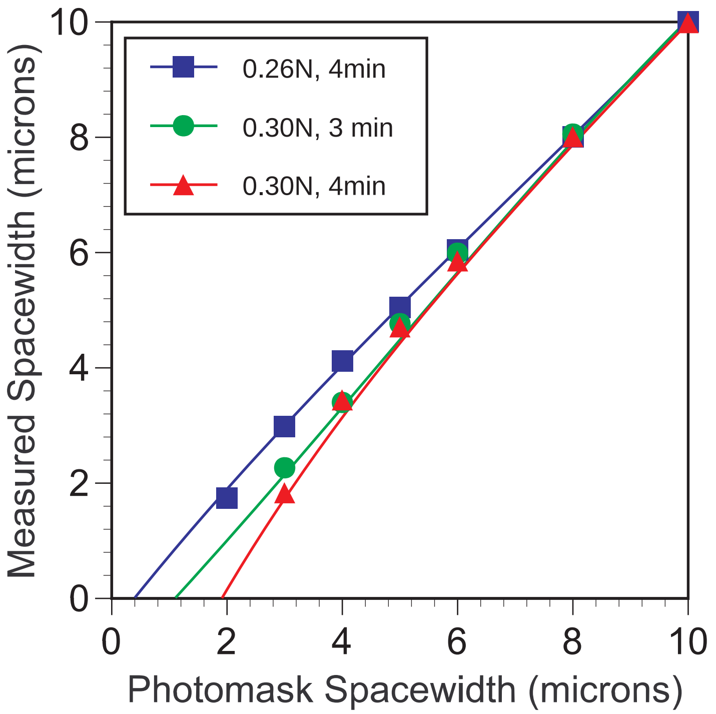
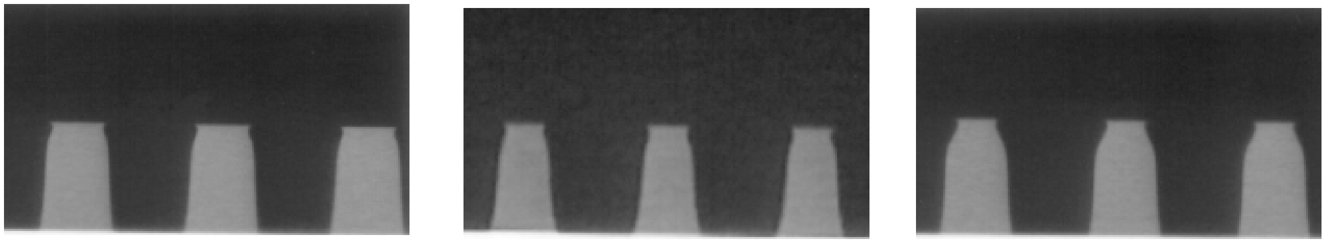


**Figure 4:** Mask linearity plot for 15 µm thick ShinEtsu SIPR 9270M. The exposure dose for the 0.26N developer was 1500 mJ/cm$^2$. The exposure dose for the 0.30N developer was 1200 mJ/cm$^2$ for 3 minutes and 1100 mJ/cm$^2$ for 4 minutes. The surfactant level is low for all cases.

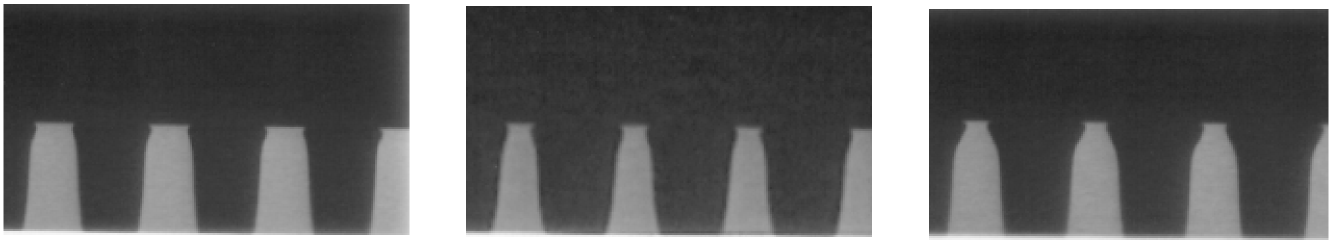
0.30 N, 4 minute develop
Exposure = 1000 mJ/cm$^2$

0.35 N, 4 minute develop
Exposure = 800 mJ/cm$^2$

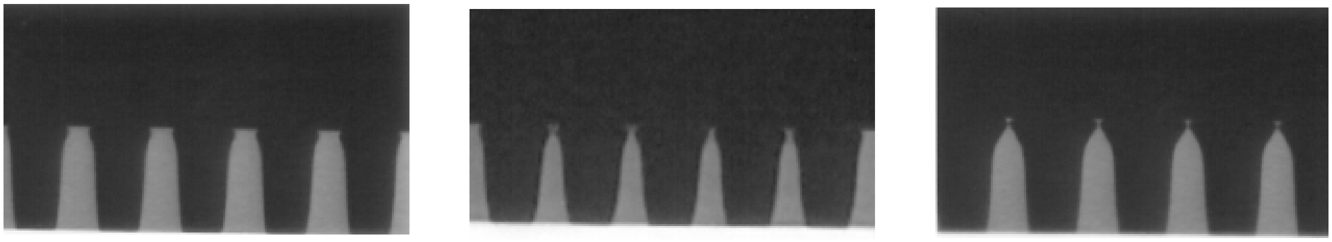
0.35 N, 2 minute develop
Exposure = 1200 mJ/cm$^2$



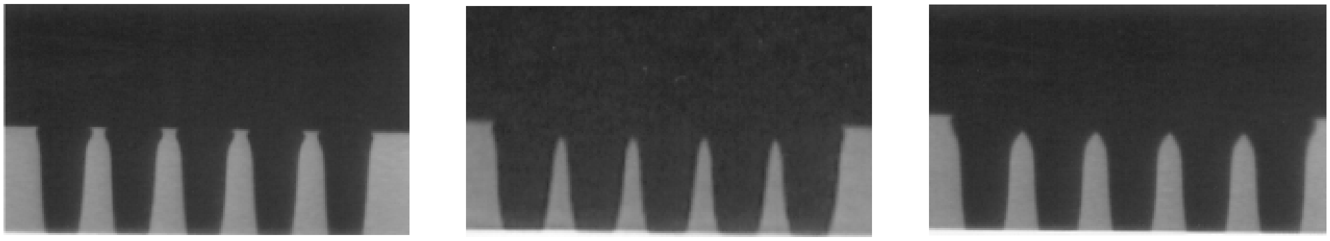
10 micron line/space



8 micron line/space



6 micron line/space



5 micron line/space

**Figure 5**: Cross sectional photographs for 15 μm thick ShinEtsu SIPR 9270M showing a linearity for 0.30 and 0.35N developer concentration levels. The 0.35N is shown for both 2 minute and 4 minute develop times. The surfactant level is low for all cases.

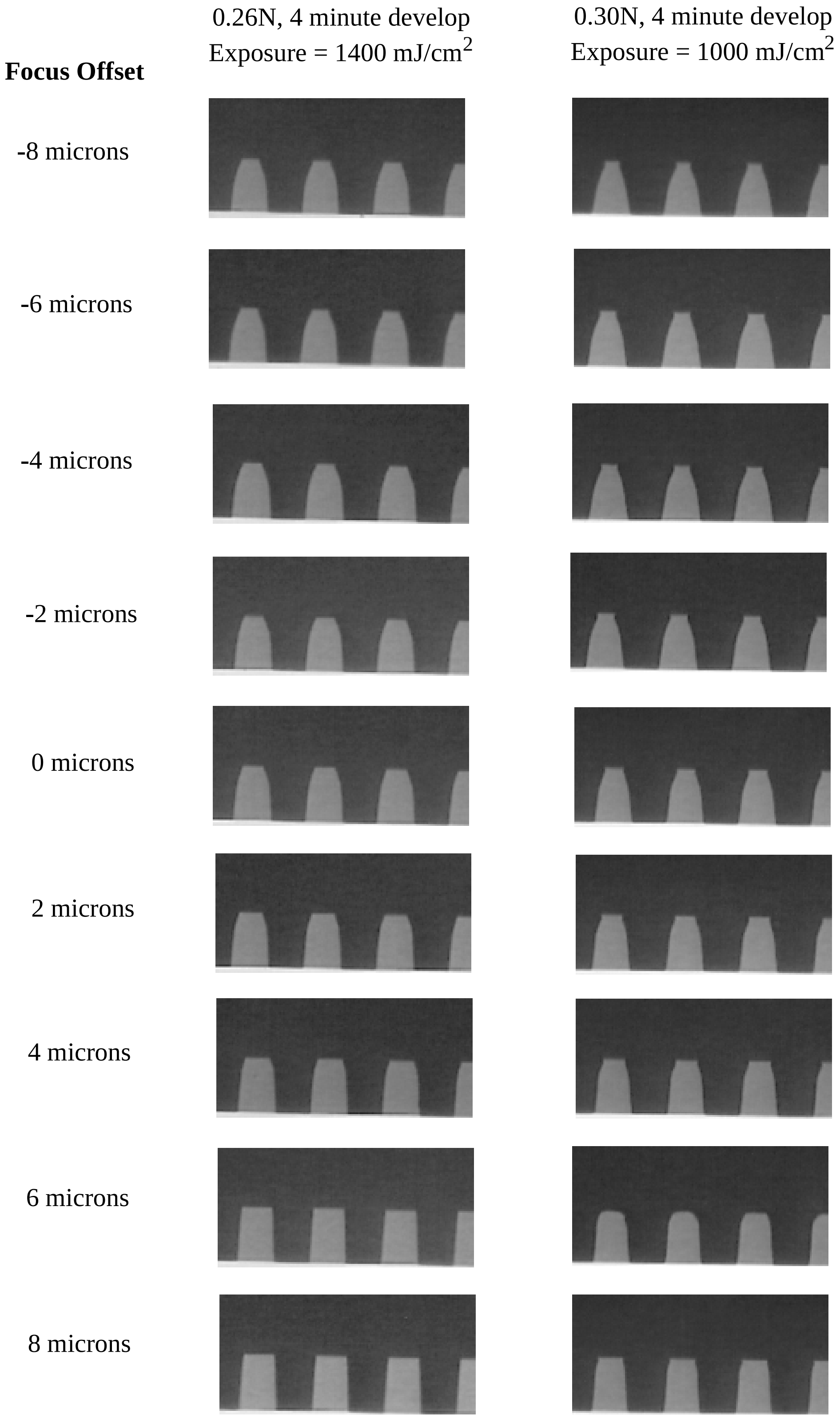


**Figure 6**: Cross sectional photographs of ShinEtsu SIPR 9270M showing 10 µm line and space patterns for 0.26 and 0.30N developer concentrations at 4 minute develop times. The surfactant level is low for both cases.

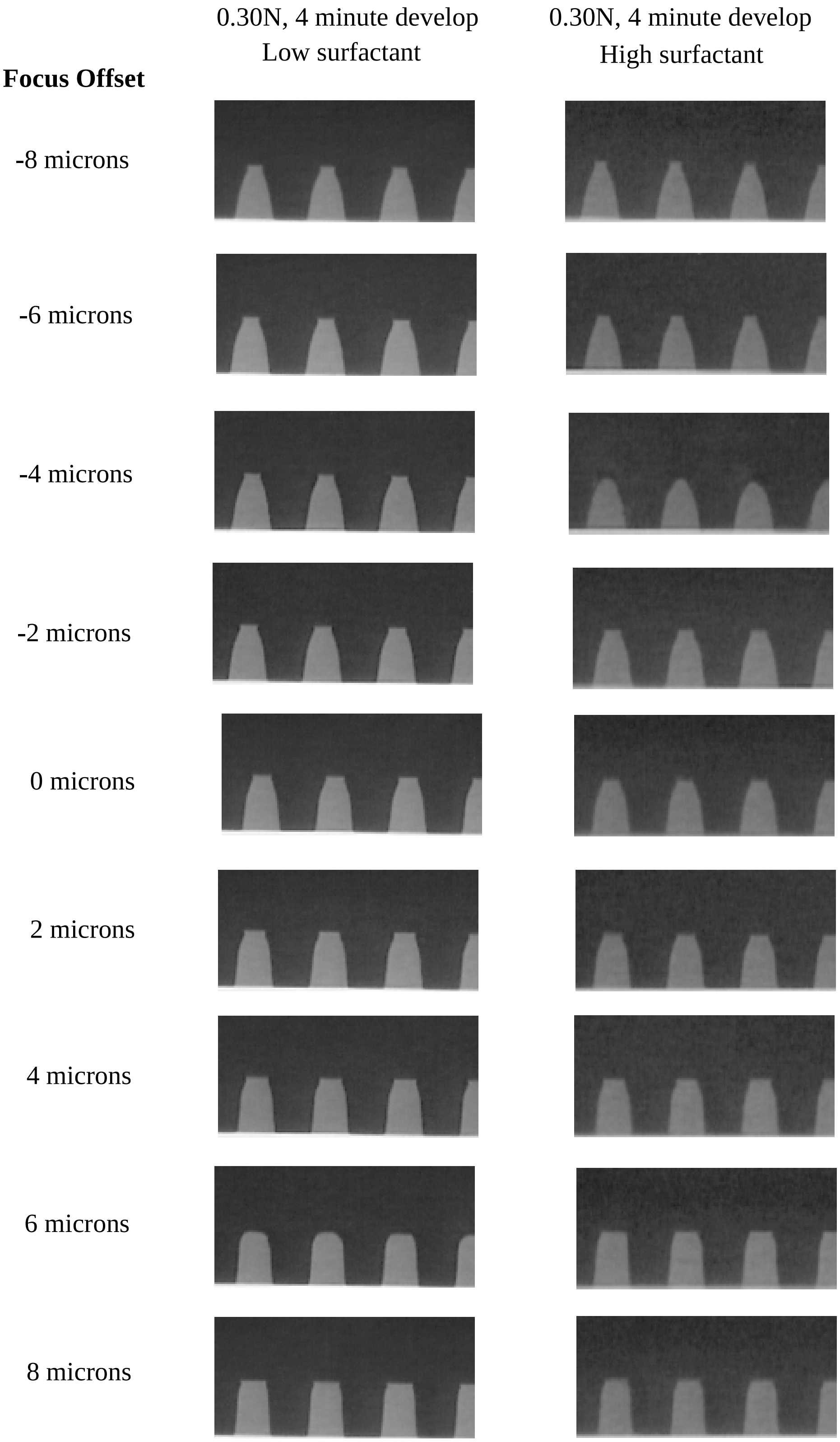
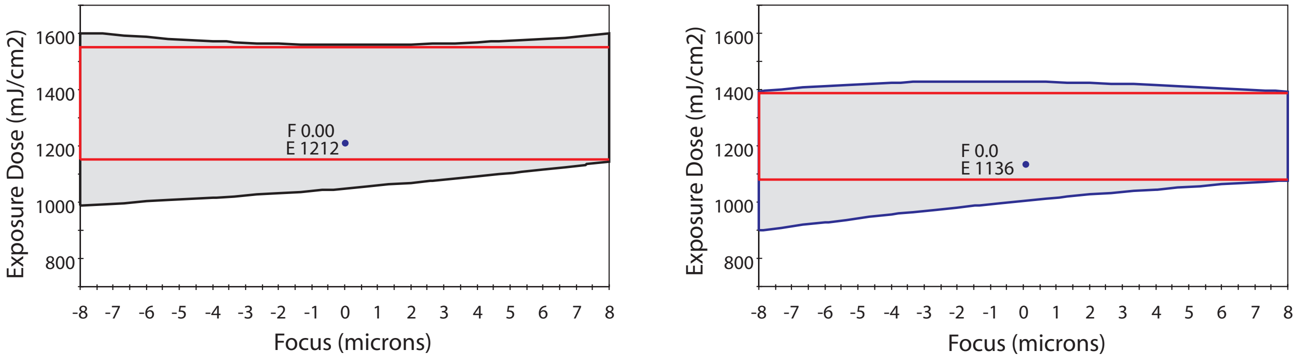
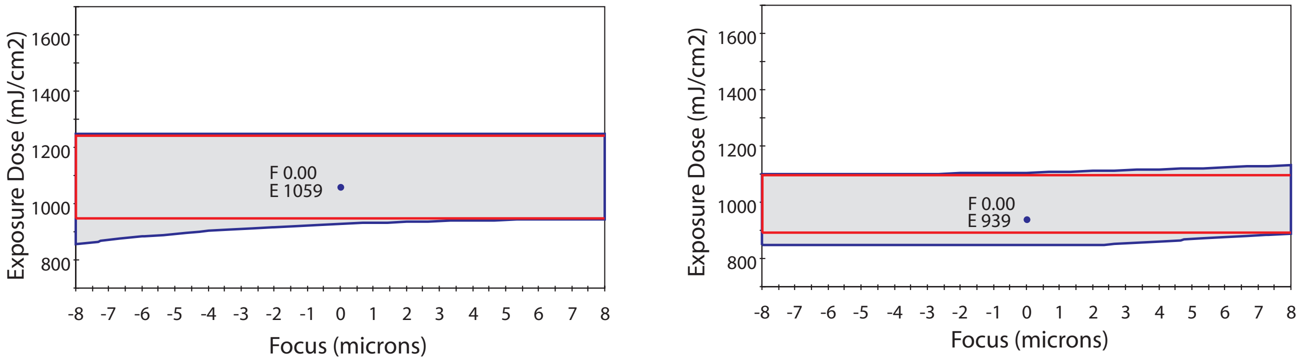


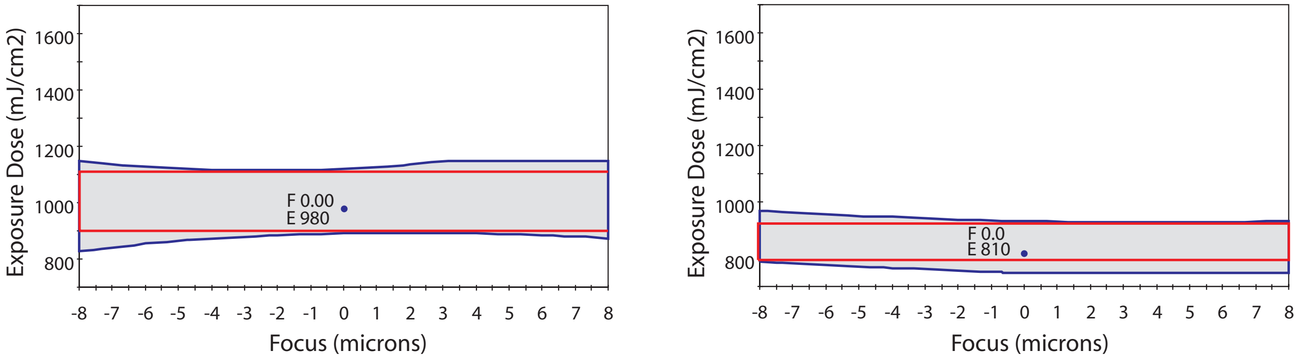
**Figure 7**: Cross sectional photographs of ShinEtsu SIPR 9270M showing 10 μm line and space patterns for 0.30N developer with low and high surfactant levels. The exposure dose is 1000 mJ/cm$^2$ for both cases.



(a) 0.26N, Low surfactant, 4 minute develop (b) 0.26N, High surfactant, 4 minute develop



(c) 0.30N, Low surfactant, 3 minute develop (d) 0.30N, High surfactant, 3 minute develop



(e) 0.30N, Low surfactant, 4 minute develop (f) 0.30N, High surfactant, 4 minute develop

**Figure 8**: Process window for 10 µm spacewidth in 15 µm thick ShinEtsu SIPR 9270M exposed with ghi-line. The process envelope shows ±10 percent control limits.

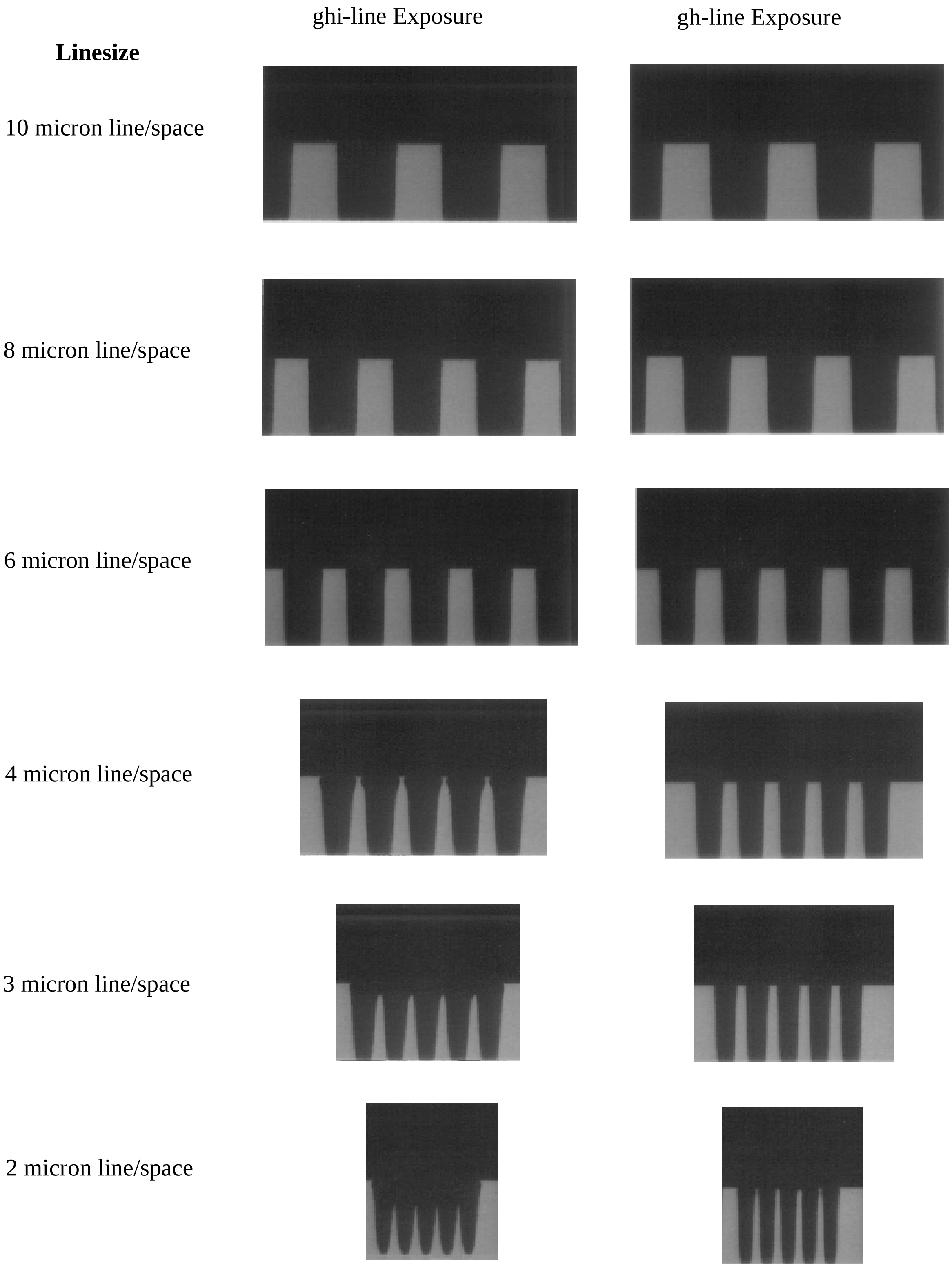


**Figure 9**: Cross sectional photographs of ShinEtsu SIPR 9270M showing linearity at 1100 mJ/cm$^2$ for ghi-line and gh-line exposure wavelengths. The focus offset is zero for all cases. The developer time was 3 minutes at 0.30N concentration with low surfactant level.