Minimizing Linewidth Roughness for 22-nm node Patterning with Step-and-Flash Imprint Lithography

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ABSTRACT

Imprint lithography achieves high resolution patterning with low roughness by avoiding the tradeoff between pattern quality and process throughput – a tradeoff that limits the capability of photolithography with chemically amplified resists. This work demonstrates the use of ZEP520A electron-beam resist for fabrication of imprint masks (templates). It is shown that high resolution, low roughness patterns can be robustly transferred from imprint mask to imprint resist, and from imprint resist through etch transfer into the underlying substrate. Through improvements to the electron-beam patterning process, 22 nm half-pitch patterns are routinely achieved with linewidth roughness (LWR) of just 2.6 nm, 3σ.

Keywords: S-FIL, imprint mask, template, imprint lithography, linewidth roughness, LWR, LER

1. INTRODUCTION

Line Width Roughness (LWR) is the stochastic variation in width that occurs along the length of a resist line. This linewidth variation arises from a variety of sources, including exposure shot noise, diffusion of acid catalyst species, nanoscale phase separation, the finite molecular dimensions of the resist components, etc. The degree to which such factors influence LWR is determined by resist composition and processing parameters.[1,2,3,4] This relationship has been widely studied, particularly in the context of optimizing the resolution, sensitivity, and LWR performance of chemically amplified (CA) resists. Researchers have identified methods for enhancing the separate performance metrics of resolution, sensitivity, and LWR, but improvement in one metric generally worsens another metric.[5] As an example, the LWR of a CA resist can be reduced by incorporation of base into the formulation, but addition of base must be offset by generating more acid, thus reducing the sensitivity of the resist as well as the process throughput. Alternately, the LWR of a CA resist can be reduced by increasing the effective diffusion length of the acid species, which in turn reduces the resolution performance of the resist. This so-called "RLS trade-off" for CA resists[6] is particularly onerous because manufacturing constraints require the photolithography process to meet the specifications of resolution, LWR, and sensitivity simultaneously. As indicated by the 2007 ITRS Roadmap for Lithography[7] (Table 1), there is no known chemically amplified resist material that can demonstrate LWR lower than 2.7 nm, 3-sigma.

These limitations are avoided in imprint lithography because the factors that control the resolution and LWR of an imprinted resist pattern are separate from the manufacturing processes that determine throughput. Imprint lithography is a high fidelity replication process, so factors such as resolution and LWR are determined by the ability to create a master imprint mask (template) having the required dimensions. The imprint process itself adds no additional LWR to the patterning process and thus the burden of minimizing any roughness falls to the process that is used to fabricate the imprint mask. Fortunately, the mask fabrication process is not subject to the same throughput constraints as the wafer lithography process, and it is appropriate to employ electron-beam lithography with less sensitive non-chemically amplified resist materials that are capable of improved resolution with minimal linewidth variation.

Imprint lithography has been included on the ITRS Lithography Roadmap at the 32-nm, 22-nm, and 16-nm nodes. Step and Flash Imprint Lithography® (S-FIL®) operates in a step-and-repeat fashion: the processes of deposition of imprint resist, imprint with alignment, photocuring and release all occur sequentially as each die on a wafer is patterned. A critical aspect of S-FIL technology is the use of UV-curable liquids that are dispensed in a Drop-On-Demand™ fashion to meet the local pattern density requirements of the mask structures, thus enabling imprint patterning with a uniform residual layer regardless of pattern density variations.[8,9]

This paper characterizes the evolution of LWR through the Step and Flash Imprint Lithography (S-FIL) patterning process. It is shown that critical dimension (CD) and LWR is maintained from the imprint mask to the imprint resist, and from the imprint resist through etch transfer into an underlying oxide layer. The LWR of imprinted resist features is frequently less than 3.0 nm, 3-sigma; and in some cases it is possible to achieve LWR values less than 2.0 nm, 3-sigma. In an effort to understand the sources of LWR and other CD variations, the performance of an electron-beam resist was investigated for use in the fabrication of imprint masks. It is found that LWR values of 2.6 nm, 3-sigma can be routinely achieved in the electron-beam resist ZEP520A.

Table 1. ITRS Roadmap recommendations for linewidth roughness (LWR)

	2007	2008	2009	**2010**	2011	2012	**2013**	2014	2015	**2016**
DRAM half-pitch (nm)	**65**	57	50	**45**	40	36	**32**	28	25	**22**
LWR, 3σ (nm)	**3.4**	3.0	2.7	**2.4**	2.1	1.9	**1.7**	1.5	1.3	**1.2**

2. EXPERIMENTAL DETAILS

The imprint masks (templates) that were used for analysis in this work were supplied by both Dai Nippon Printing (DNP) and Hoya Corporation. The basic process used to fabricate the imprint masks has been previously described.[10,11] Electron beam exposures were performed with either 50 kV variable shaped beam (VSB) pattern generators or 100 kV Gaussian beam (GB) pattern generators. To compare resist performance, both a positive tone chemically amplified resist and a slower non-chemically amplified resist were employed on the VSB writers. ZEP520A was used in all cases when writing on GB systems. After exposure and development of the resists, the chromium and fused silica were etched using Cl_2/O_2 and fluorine-based chemistry, respectively. The imprint mask fabrication process was completed with mesa lithography and mesa etch processes, followed by a dice and polish step.[12]

Imprinting of the mask patterns was performed with a Molecular Imprints Imprio 250 imprint tool. A Drop-On-Demand method was employed to dispense the photo-polymerizable acrylate-based imprint solution in field locations across a 200 mm silicon wafer. The imprint mask was then lowered into liquid contact with the substrate, displacing the solution and filling the imprint field. UV irradiation through the backside of the mask cured the acrylate monomer. The process was then repeated to pattern all fields on the substrate. Details of the imprint process have previously been reported. Dry etch pattern transfer of the imprint resist patterns was performed on both silicon-on-insulator (SOI) and thermally oxidized silicon wafers. SOI substrates were etched using an Applied Materials capacitively-coupled etch chamber. Thermal oxide wafers were etched in a Trion Oracle reactive ion etch chamber.

Electron-beam resist studies were performed using ZEP520A resist from Zeon Corporation. These resist studies were performed on 150 mm diameter, 0.7 mm thick fused silica wafers that were coated with 5.0 nm chromium. ZEP520A was diluted with anisole to create 25 weight percent solutions, which form a 40 nm thick resist film when spincoated at 2500 rpm. The substrates were baked at 180 °C for 300 s after spin-coating. Electron-beam patterning was performed using a VB300 lithography system from Vistec Semiconductor. The VB300 was operated at 100 kV accelerating voltage with 0.5 nA beam current, with a beam step of 2 nm. The resist patterns were developed for 120 s using an equal mixture solution of isopropyl alcohol and ZED-N50 developer from Zeon Corporation. (ZED-N50 is a standard high-resolution developer comprising filtered amyl acetate. We have observed that dilution of this standard developer with isopropanol results in increased patterning resolution; in future work we will report on the effect of developer concentration on patterning performance.) Development was performed in a static solution with ultrasonication. Following development, the substrate was rinsed in isopropyl alcohol for 60 s and dried under nitrogen.

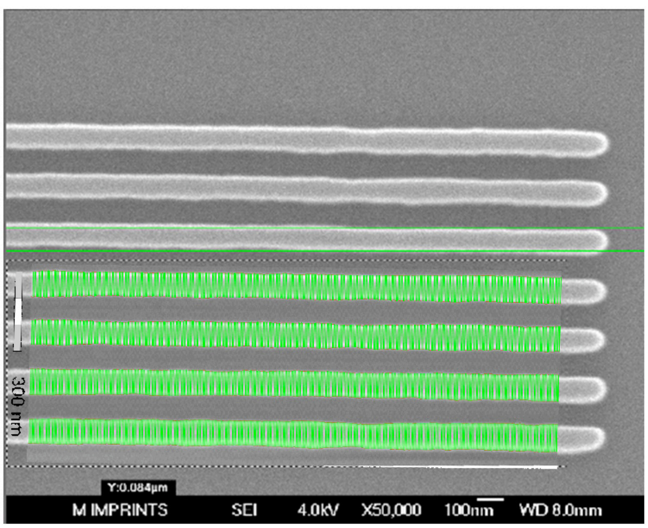
LWR characterization of all resist features was performed by software analysis of high-resolution SEM images. All SEM images of the imprint resist were obtained with a JEOL JSM-6340F field emission SEM at 4 kV and a working distance of ~8 mm. All imaging of ZEP520A electron beam resist was performed with a Zeiss Ultra 60 Field Emission

SEM operating at 2 kV and a working distance of ~3 mm. ZEP520A images were acquired with a resolution of ~1.0 nm/pixel with a pixel dwell time of ~6 µs. Image analysis was performed using the Simagis® software package from Smart Imaging Technologies. The image processing included normalization of image brightness and removal of angular tilt of the lines/spaces image, followed by a threshold function to locate the feature edge. All LWR measurements were obtained by analysis of at least 2.0 µm total line length, with a linewidth measurement performed every 4.0 nm or less, in accordance with the procedure recommended in the ITRS Roadmap. For SEM analysis of some of the etch work, an AMAT NanoSEM operating at 500 V was used to collect information on CD, LWR, and LER. 1200 pixels were used per scan line and 256 lines were scanned for each feature.

3. RESULTS AND DISCUSSION

3.1 Limitations of chemically amplified resists for imprint mask fabrication

The resolution and LWR limitations of CA resists have been well documented for photolithographic patterning on wafer substrates. CA resists have also been used in the fabrication of imprint masks using electron beam patterning, and previous publications have noted that resolution is typically limited to approximately 60 nm with this type of processing.[13] The LWR performance is also impacted when CA resists are used for fabrication of imprint masks. Figure 1 shows an example of resist lines that were imprinted from a mask patterned using a sensitive CA resist. The exposure dose was approximately 11 $\mu C/cm^2$, which equates to an incident electron dose of less than 1 electron per nm^2. Image analysis using Simagis software indicates an LWR performance of 11.3 nm, 3 σ. This relatively poor LWR performance is primarily attributed to shot noise during the exposure process as well as the associated statistics of acid generation and diffusion in CA resists. Fortunately, it is not necessary to employ fast CA resists for writing imprint masks.



Number of lines analyzed	4
Total analyzed length (nm)	8177
Line orientation (degrees)	-90.8
Profile sampling step (nm)	3.79
Image scale (nm/pixel)	1.89
Line width, mean (nm)	94.93
Line width, std dev (nm)	2.02
Line pitch (nm)	185.9
LWR, 3σ (nm)	11.27
LER, 3σ (nm)	7.06

Figure 1. LWR analysis for 90 nm half-pitch resist lines, imprinted from an imprint mask that was fabricated using a fast chemically amplified resist.

The remainder of the paper will discuss patterning of imprint masks using ZEP520A, a high-resolution positive-tone electron beam resist from Zeon Corporation. This material is a chain-scission resist; electron exposure breaks bonds in the polymeric resist film, which reduces the polymer molecular weight and thereby increases the solubility of the exposed material in an organic solvent. Depending on the exposure and development conditions, the patterning dose can vary from 100 $\mu C/cm^2$ to over 300 $\mu C/cm^2$ for exposure at 100 kV (approximately 50 $\mu C/cm^2$ to 150 $\mu C/cm^2$ for 50 kV exposure). Due to the improved exposure statistics and the absence of any roughening due to chemical amplification, it is expected that the LWR of ZEP520A patterning would be significantly reduced relative to CA resists.

3.2 Imprint patterning and etch transfer of 30nm and 40nm semi-dense features for memory devices

As an example of high resolution imprint patterning, analyses were performed on 30 nm and 40 nm semi-dense designs that are being considered to test addressing schemes for ultra-high density memory.[14] The imprint masks for this prototyping effort were fabricated using ZEP520A, non-CA resist. Portions of a typical test structure are shown in Figure 2. Figure 2a is a top-down SEM image of the imprint mask for the 30 nm test designs. Figure 2b shows the corresponding imprint of the test structure on an SOI substrate. The etched SOI fins, with apparently very smooth sidewalls, are shown in Figure 2c.

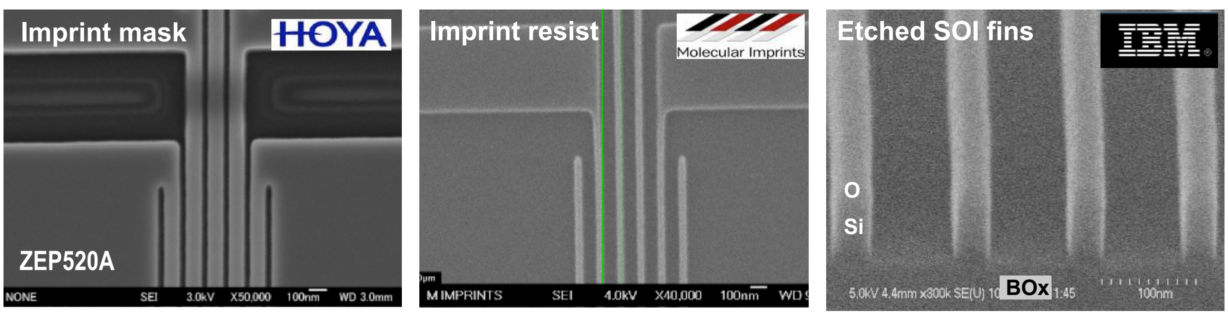


Figure 2. 30 nm semi-dense design: a) imprint mask, b) imprinted resist, and c) etched SOI fins.

SEM image analysis of the imprinted resist indicated an LWR of 2.43 nm, 3σ. A lot of 25 200-mm SOI substrates was imprinted with 37 fields per wafer, followed by etch transfer into the underlying SOI. Wafers 1 and 25 were analyzed via CD-SEM to obtain a more complete view of the patterning variations within a field, from field to field, and from wafer to wafer. Figure 3 shows the LWR and LER results for a single set of 30 nm and 40 nm designs. In general, the LWR was comparable to the starting imprinted LWR, and LER was less than 2.0 nm. The average LWR was measured at 2.61 nm, 3σ for the 30 nm design structures, and 2.62 nm, 3σ for the 40 nm design structures. Measurements of individual lines reveal small deviations from the average values for both CD and LWR. Fifteen distinct lines from 30 nm design structures, plus fifteen distinct lines from 40 nm design structures spread across five fields were measured on wafers 1 and 25, and the results are plotted in Figure 4. Although the measured CDs on these imprint masks are larger than the target values, it is observed that both the CD and the LWR are accurately replicated from wafer 1 to wafer 25. For the 30 nm designs, the correlation between wafer 1 and 25 is 0.928 for CD and 0.528 for LWR. For the 40 nm designs, the correlation between wafer 1 and 25 is 0.907 for CD and 0.954 for LWR. The highly reproducible CD and LWR from field-to-field are indicative of the high precision with which the imprint process replicates the structures on the imprint mask.

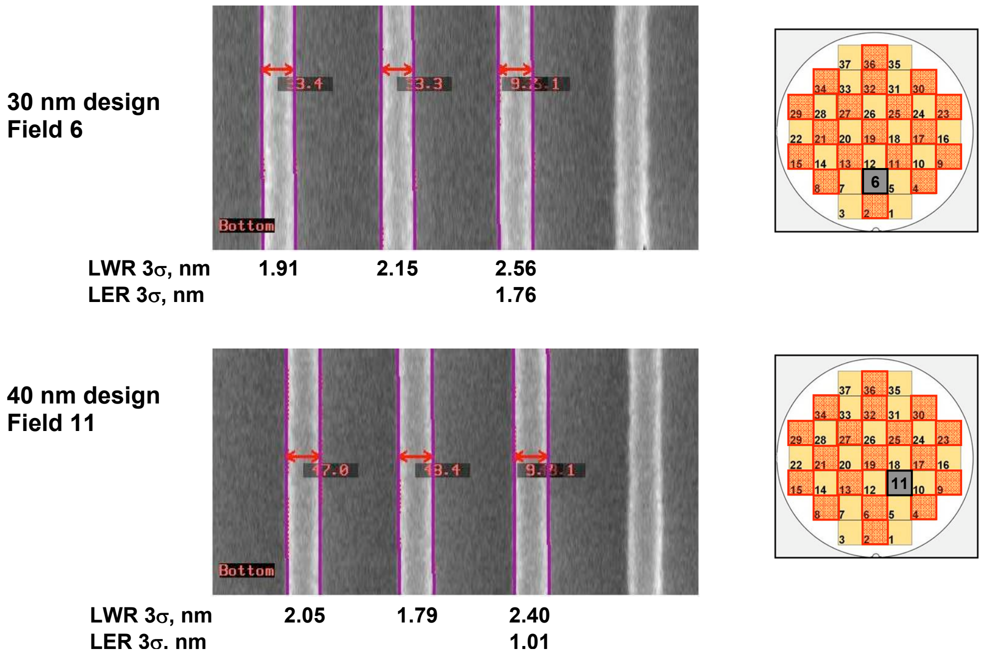
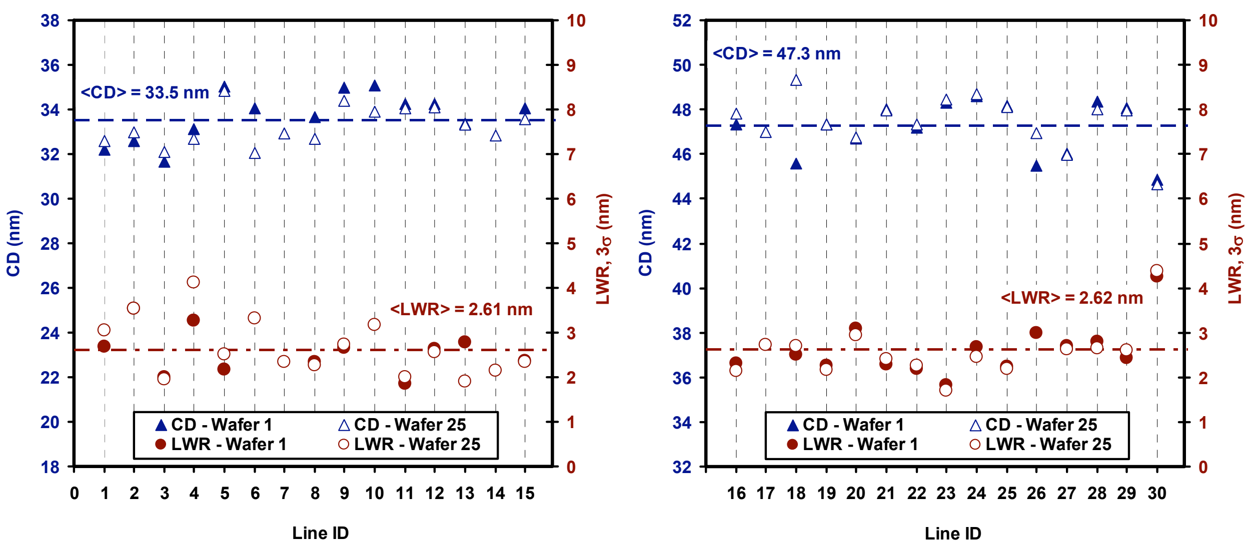


Figure 3. LWR and LER measurements of the 30nm and 40nm semi-dense features after etch.



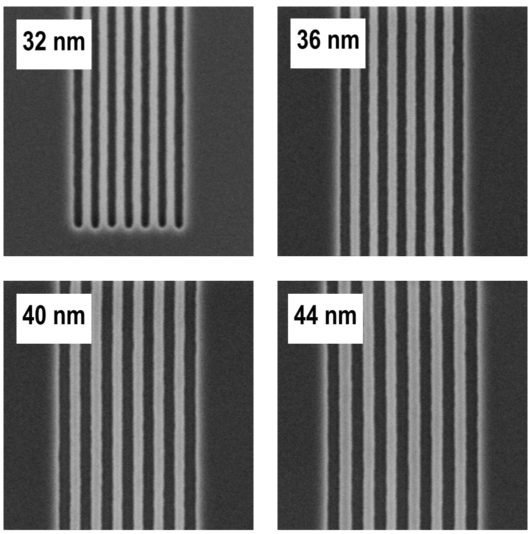
a) 30 nm semi-dense design measurements

b) 40 nm semi-dense design measurements

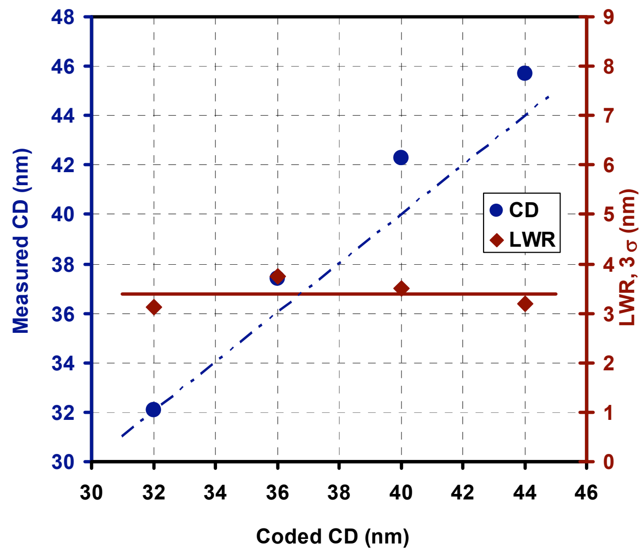
Figure 4. Critical dimension (CD) and LWR for the 30nm (left) and 40nm (right) designs after etch for two different wafers. A high degree of correlation is observed for both CD and LWR; see the text for details.

3.2 Fidelity of 32 nm imprint pattern transfer from mask to resist

To further evaluate the fidelity of pattern transfer from imprint mask to imprint resist, another study was performed that included direct inspection of mask features ranging in size from 32 nm to 44 nm half-pitch. Figure 5 contains SEM images of an imprint mask provided by DNP. The chromium hard mask was left intact after fused silica etching to facilitate charge dissipation during SEM inspection. CD (space width) and LWR measurements are plotted as a function of target CD. The CD on the imprint mask remained linear (to within 5 percent) across all feature sizes. The mean CD for all fifteen lines was 34.72nm, with a 3σ variation of only 1.62nm. LWR was measured to be approximately 3.4 nm and was essentially independent of feature size. Imprint results from this mask are shown in Figure 6. Three imprints of the 32nm patterns had a mean LWR of 2.73nm, closely tracking what was observed in the imprint mask. These results confirm that it is possible to pattern with high resolution and low LWR if the features are properly formed on the imprint mask.

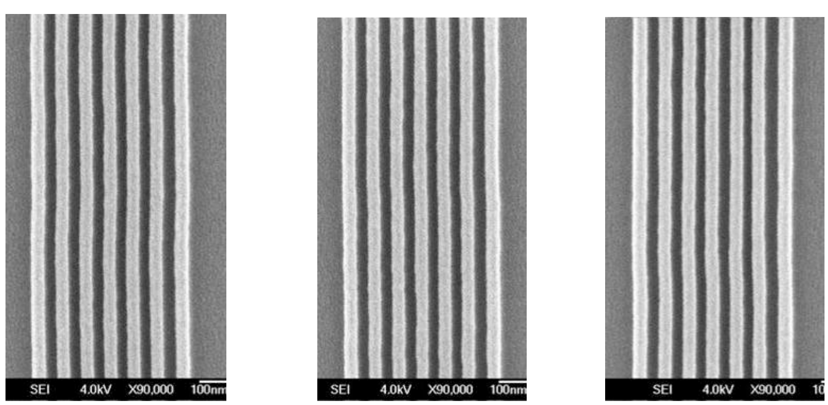


a) Top-down SEM images from imprint mask



b) CD and LWR measurements from imprint mask

Figure 5. a) Imprint mask SEMs for CDs ranging from 32nm to 44nm; b) CD and LWR as a function of target CD. CD response is observed to be linear, while LWR is independent of feature size.



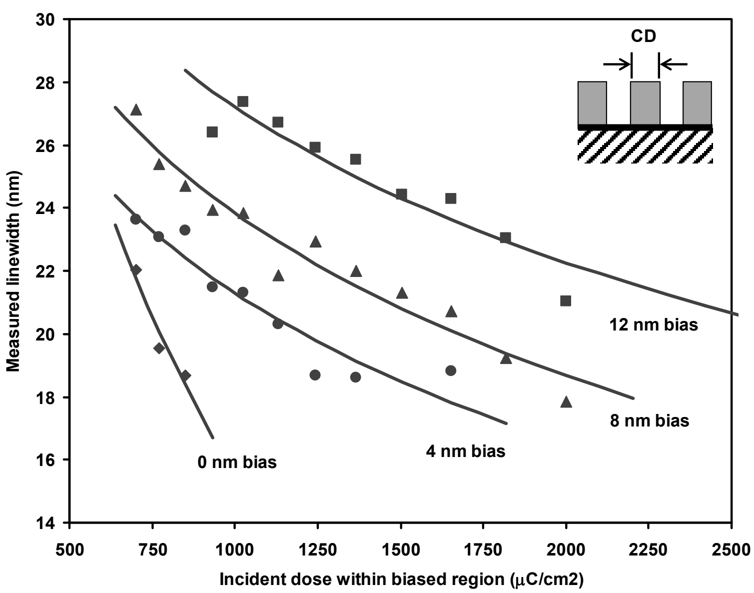
a. b. c.

Figure 6. Top-down SEM images of resist features created using the imprint mask shown in Figure 5. a) CD = 34.55 nm, LWR = 2.55 nm; b) CD = 34.43 nm, LWR = 3.05 nm; c) CD = 35.24 nm, LWR = 2.60 nm

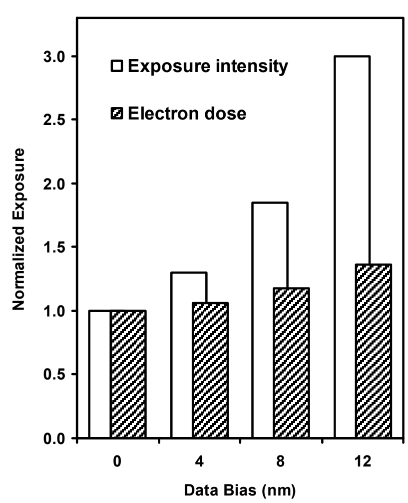
3.4 Resolution and LWR performance of ZEP520A electron-beam resist

The experiments just described demonstrate that S-FIL technology is capable of replicating with high resolution and low LWR, provided that a high quality imprint mask can be fabricated. It is concluded that minimization of LWR for imprint patterning should be accomplished by minimization of LWR of the structures on the imprint mask. Imprint mask structures are created in a series of steps including electron-beam resist exposure and development, descum etching, chromium etching, and fused silica etching. Each of these steps can have a significant effect upon the CD and LWR of the imprinted resist pattern. This work examines the formation of high resolution patterns in ZEP520A resist; evolution of CD and LWR during etch transfer of the mask will be examined in future work.

One method that has been widely used to improve resolution and process latitude of electron beam lithography is to employ data bias of the exposed patterns.[11] When exposure data bias is used, the size of the exposed area is intentionally different from the target feature size. For high resolution patterning of dense lines and spaces in a positive-tone resist, a negative data bias is often used, such that the width of the exposed line is less than the target CD (trench width). Patterning with this data bias allows exposure at a higher intensity within the exposed region and thus provides higher exposure contrast. This provides a significant increase in dose latitude for fine patterns, an effect that can be seen in Figure 7a for patterning of 22 nm half-pitch lines and spaces. Figure 7b plots the dose-to-size at 22 nm, measured as the dose of electrons (per length of line) required to achieve equal lines and spaces after the pattern is developed. For 12 nm data bias (corresponding to exposure of a 10 nm wide region for a 22 nm line/space pattern), it is observed that a 30 percent increase in electron dose is required, which allows a threefold increase in exposure intensity within the exposed area of the resist. Exposure with 12 nm data bias was evaluated for patterning from 24 nm half-pitch down to 18 nm half-pitch resolution; some typical results are shown in Figure 8.



a) Exposure latitude of 22 nm half-pitch lines with varying data bias



b) Dose-to-size

Figure 7. Electron-beam patterning of 22 nm half-pitch lines in ZEP520A. a) Dose latitude with varying amount of exposure data bias; b) electron dose-to-size and the corresponding exposure intensity with varying data bias.

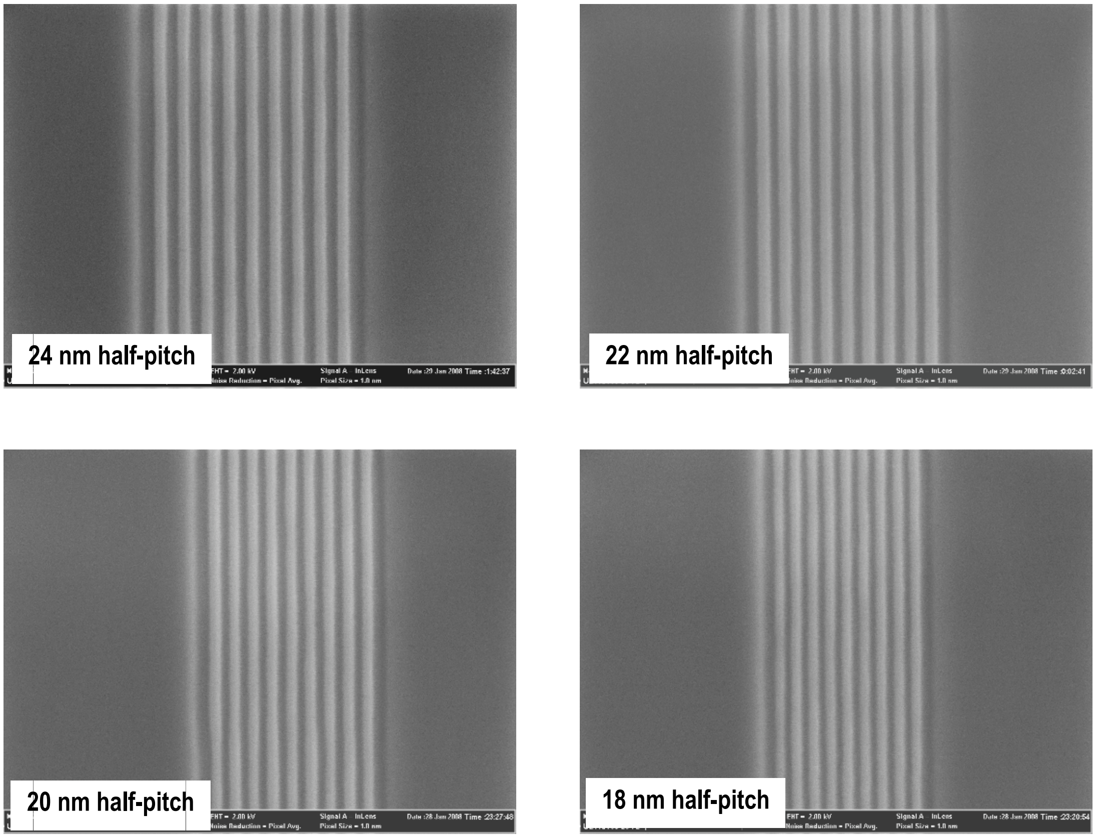
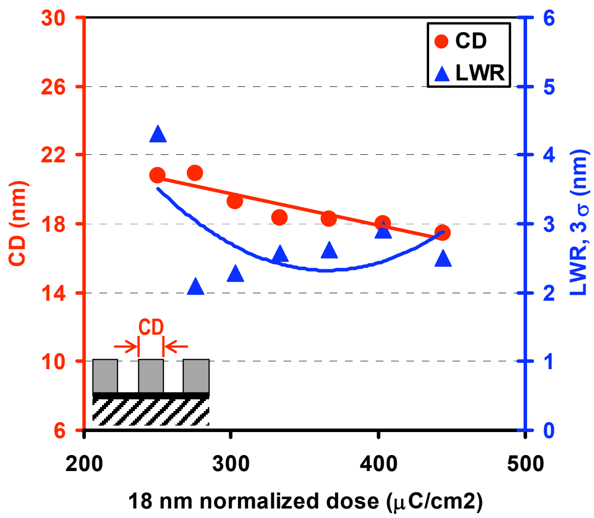
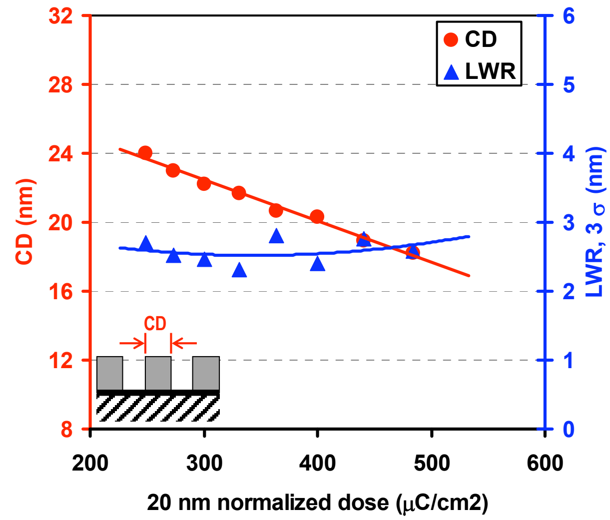


Figure 8. Top-down SEM images of ZEP520A resist patterns on an imprint mask.

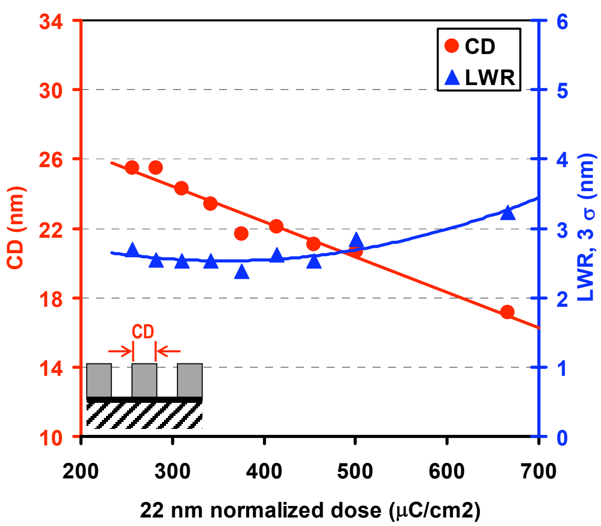
The data presented in Figure 7 are useful for targeting a particular CD by varying the exposure dose and data bias. Additional measurements were performed to investigate the variation of LWR and CD with exposure dose for constant negative data bias of 12 nm; these data are presented in Figure 9. Each LWR data point was calculated as the geometric mean of measurements from 3 – 7 individual SEM images; CD data was averaged with an arithmetic mean. Significant process latitude was observed over the full range of 18 nm to 24 nm half-pitch patterns, with the measured CD varying linearly with dose over the indicated range. As expected, under-exposure of the line/space pattern results in a narrow trench in the positive-tone resist, corresponding to a large line-width CD. Extreme under-exposure results in bridging of the resist lines, while slight under-exposure is observed to result in larger LWR values. Similarly, over-exposure of the line/space pattern results in a wide trench in the positive-tone resist, corresponding to a narrow line-width CD. Extreme over-exposure results in very narrow lines that are prone to collapse and/or pinching, while slight over-exposure leads to increased LWR. The effects of under- and over-exposure are exemplified in the images shown in Figure 10. It can be seen from the plots in Figure 9 that the LWR measurements exhibit a broad minimum that coincides with the dose-to-size.



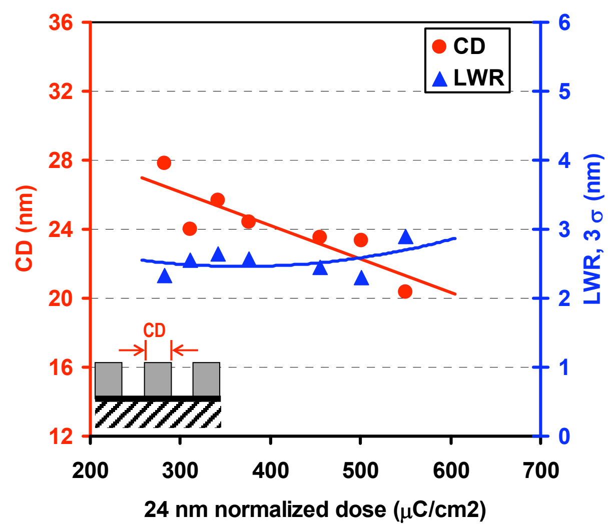
a. Process latitude for 18 nm half-pitch lines



b. Process latitude for 20 nm half-pitch lines

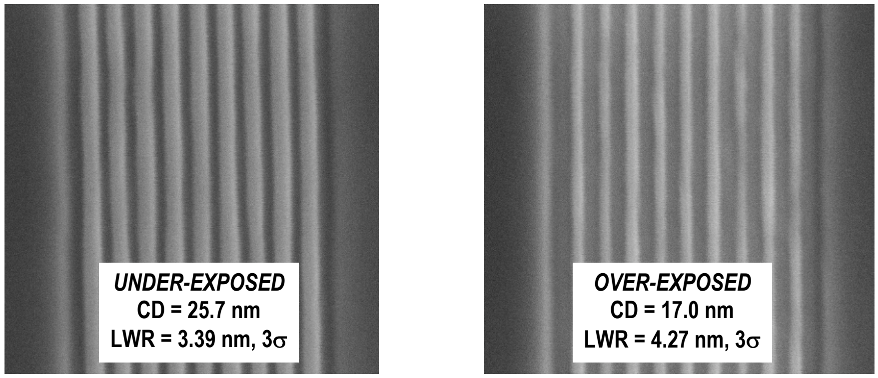


c. Process latitude for 22 nm half-pitch lines



d. Process latitude for 24 nm half-pitch lines

Figure 9. CD and LWR performance as a function of exposure dose for high resolution ZEP520A patterning. CD data is shown with a best-fit line; LWR data is shown with a best-fit quadratic curve.



a) b)

Figure 10. a) Under-exposure and b) over-exposure of ZEP520A 22 nm half-pitch line/space patterns.

3.5 VSB patterning with ZEP520A resist

The resist processes described in Section 3.4 were developed using a GB pattern generator, but the same processes can be applied with the commercial VSB pattern generators that are commonly employed in the photomask industry. The use of ZEP520A for fabrication of 38 nm half-pitch patterns across a full device field is reported in these proceedings.[15] Measurements from the imprinted resist indicate an LWR value of approximately 3.7 nm, 3 σ. The VSB write time for the full field (~18 mm x 30 mm) imprint mask was approximately 10 hours, which is comparable to the write time for a 4x photomask for the same pattern.

4. CONCLUSIONS

LWR, a critical parameter for determining device performance, has been characterized for the S-FIL process. Significant improvements in resolution and LWR performance have been achieved on the imprint mask through use of ZEP520A, a non-chemically amplified resist material. LWR was characterized on the mask (template), after imprint, and after etch into SOI substrates; the LWR values were observed to be consistently low. Improvements in ZEP520A patterning on the imprint mask have been achieved through use of a dilute development process in conjunction with exposure data bias. Patterning of 22 nm half-pitch lines with LWR values of 2.6 nm, 3 σ is routinely achieved. The ZEP520A process has also been shown to be extendible to patterning of 18 nm half-pitch lines with GB pattern generators. Recent reports demonstrate that it is possible to achieve 38 nm half-pitch patterning with 3.7 nm, 3σ LWR using VSB pattern generators with write times that are comparable to 4x photomasks.

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