Using synchrotron light to accelerate EUV resist and mask materials learning

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ABSTRACT

As commercialization of extreme ultraviolet lithography (EUVL) progresses, direct industry activities are being focused on near term concerns. The question of long term extendibility of EUVL, however, remains crucial given the magnitude of the investments yet required to make EUVL a reality. Extendibility questions are best addressed using advanced research tools such as the SEMATECH Berkeley microfield exposure tool (MET) and actinic inspection tool (AIT). Utilizing Lawrence Berkeley National Laboratory's Advanced Light Source facility as the light source, these tools benefit from the unique properties of synchrotron light enabling research at nodes generations ahead of what is possible with commercial tools.

The MET for example uses extremely bright undulator radiation to enable a lossless fully programmable coherence illuminator. Using such a system, resolution enhancing illuminations achieving k1 factors of 0.25 can readily be attained. Given the MET numerical aperture of 0.3, this translates to an ultimate resolution capability of 12 nm. Using such methods, the SEMATECH Berkeley MET has demonstrated resolution in resist to 16-nm half pitch and below in an imageable spin-on hard mask. At a half pitch of 16 nm, this material achieves a line-edge roughness of 2 nm with a correlation length of 6 nm. These new results demonstrate that the observed stall in ultimate resolution progress in chemically amplified resists is a materials issue rather than a tool limitation. With a resolution limit of 20-22 nm, the CAR champion from 2008 remains as the highest performing CAR tested to date.

To enable continued advanced learning in EUV resists, SEMATECH has initiated a plan to implement a 0.5 NA microfield tool at the Advanced Light Source synchrotron facility. This tool will be capable of printing down to 8-nm half pitch.

Keywords: extreme ultraviolet, lithography, photoresist, mask roughness, mask cleaning, nanolithography

1. INTRODUCTION

While direct industry research efforts are focused on near term activities such as the development of extreme ultraviolet lithography (EUVL) pilot lines and associated infrastructure, the question of EUVL extendibility remains crucial. Extendibility questions are best addressed using advanced research tools such as the SEMATECH Berkeley microfield exposure tool (MET) and actinic inspection tool (AIT). Utilizing Lawrence Berkeley National Laboratory's Advanced Light Source facility as the light source, these tools benefit from the unique properties of synchrotron light enabling research at nodes generations ahead of what is possible with commercial tools. An example of the advanced capabilities afforded by the synchrotron implementation of the MET is its lossless fully programmable coherence illuminator. Using this system, resolution enhancing illuminations achieving k1 factors of 0.25 can readily be attained. Given the MET numerical aperture of 0.3, this translates to an ultimate resolution capability of 12 nm.

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In addition to high power sources and high resolution high sensitivity resists, defect free masks remain a major challenge for EUVL. Making progress in the near term and providing learning for the long term requires advanced metrology capabilities. Given the resonant reflective structure of EUVL masks, the use of actinic metrology is crucial. The use of synchrotron radiation enables metrology systems to be based on low-cost high performance diffractive optics. The AIT is an example of such a tool. The small size and low cost of the diffractive optics used in the AIT allow for a turret type of design whereby one can easily switch between aerial image modeling mode and higher resolution microcopy mode providing simultaneously for both lithographically relevant printability studies and defect characterization studies. Moreover, the high brightness of the source enables applications such as quantitative phase measurements of the mask.

In this paper we review some of the key learning in the areas of resist and mask materials obtained using the MET and AIT tools. Finally, the development of next generation advanced research tools addressing the learning needs out to the 8-nm node will also be presented.

2. BMET RESOLUTION ENHANCEMENT

With a variety of chemically amplified EUV resists now reaching resolution levels of 20 nm [1], the modified illumination capabilities [2] of the SEMATECH Berkeley MET are becoming more and more important for continued progress. Figure 1 shows the computed aerial image contrast for the SEMATECH Berkeley MET using its conventional annular 0.35-0.55 illumination as well as dipole illumination optimized for 18-nm half pitch. The performance cross-over is observed at a critical dimension (CD) of 23 nm half pitch. Although optimized specifically for 18 nm, the dipole case shows excellent performance in the 16-22-nm range. Forbidden pitches related to the MET optic central obscuration, however, degrade performance in the 25-nm to 50-nm CD range. The ultimate capabilities of the dipole illumination are demonstrated experimentally in Fig. 2 which shows a zoomed out image of a series of equal line-space patterns ranging from 100 nm down to 12 nm. The forbidden pitches are clearly seen as well as the small CD cutoff. Note that bright areas in the image do not necessarily imply quality printing but rather simply indicates the presence of the diffracted orders necessary to achieve printing; in practice, the actual printing performance will be limited by the resolution of the photoresist. Presence of the diffracted order intensity, however, as seen in Fig. 2, does provide information on the resolution limit of the mask. Figure 3 shows a plot of the modeled captured diffracted order intensity as a function of CD for the dipole illumination used in Fig. 2. Agreement between the modeled plot in Fig. 3 and the SEM image in Fig. 2 demonstrates that the dipole illumination is working as expected.

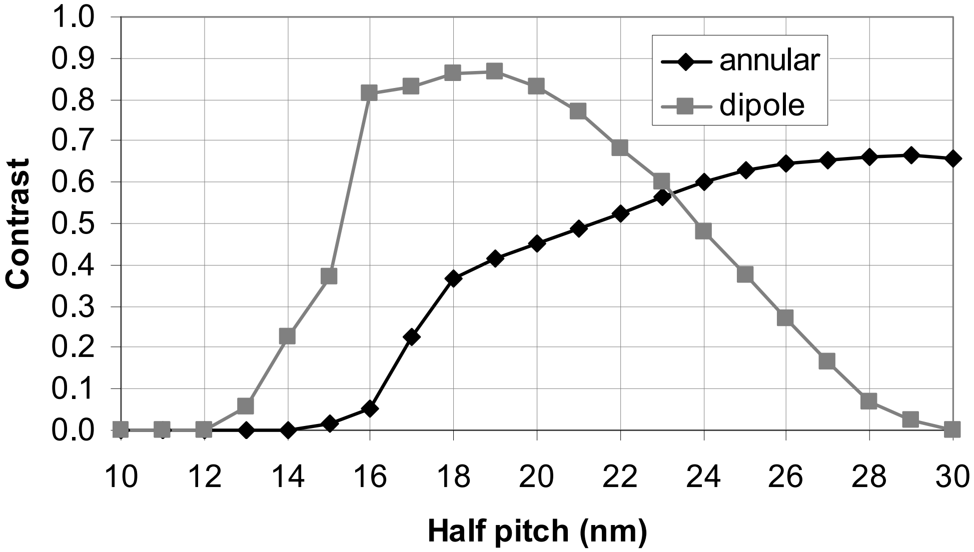


Fig. 1. Computed aerial image contrast for the BMET using its conventional annular 0.35-0.55 illumination as well as dipole illumination optimized for 18-nm half pitch.

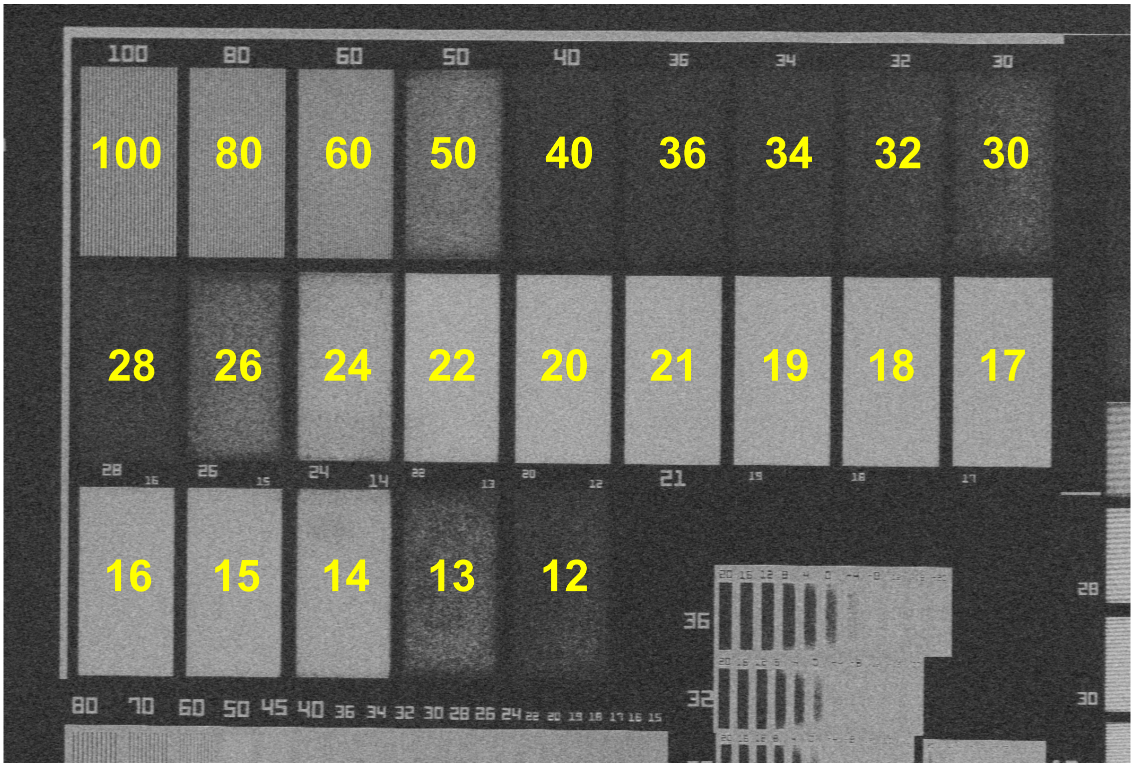


Fig. 2. Zoomed out image of a series of equal line-space patterns ranging from 100 nm down to 12 nm. The forbidden pitches are clearly seen as well as the small CD cutoff.

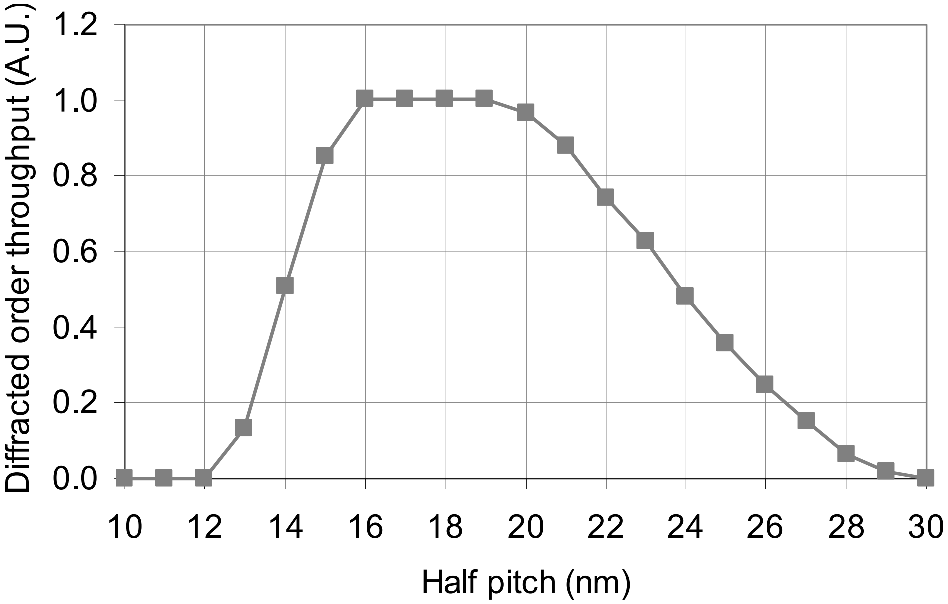


Fig. 3. Plot of captured diffracted order intensity as a function of CD for the dipole illumination. This data is directly comparable to the results visualized in Fig. 2.

3. RECENT RESIST TESTING RESULTS

With the focus on EUV resist development now at CDs of 20-nm and below, the 18-nm dipole illumination has been used to test a variety of leading resolution chemically amplified resists. Figures 4 through 6 shows results from three of the best performing chemically amplified resists tested to date on both the MET as well as commercial EUV lithography tools. Based on these printing results, the best performing (Fig. 4) is the SEMATECH Berkeley MET baseline material initially developed in 2008. The improvement we see in the 2008 material compared to results presented in the past, where an apparent resolution limit of approximately 22-nm was found, are due to a reduction in film thickness. The results in Fig. 5 are for a film thickness of 45 nm where we see a resolution improvement of approximately 2 nm compared to the 50-nm to 60-nm film thickness. We note that going even thinner with this same material formulation does not lead to continued improvement since the improvement in pattern collapse is outweighed by an increase in line-edge roughness.

Considering the optimized film thickness resolution limit, we find little, if any, absolute resist resolution gains in chemically amplified resists (CARs) in the passed few years. Figure 7 shows a plot of the ultimate resolution as a function of year in CARs. We see strong and consistent gains early on when the SEMATECH Berkeley MET was first brought online in 2004 enabling learning for the first time at resolutions of 50 nm and smaller, but these gains stagnated in 2008.

One might assume the lack of progress to be a limitation of the exposure tool rather than the resist, however, with its lossless programmable illuminator, modeling shows [1] that the SEMATECH Berkeley MET is easily capable of sub-16-nm printing. Modeling, however, is not absolute proof and without aerial image metrology, proof can only be obtained through actual demonstration in resist. To this end, we have explored non-chemically amplified resists. The ultimate resolution observed to date on the SEMATECH Berkeley MET [3] has been achieved using a directly imageable metal oxide hardmask. Since that time even further gains in resolution have been achieved in this material, but at the cost of sensitivity. Figure 8 shows printing results in such a material provided by Inpria [4]. The sizing dose in this material is approximately 70 mJ/cm^2 but significant improvements in speed are expected to be feasible based on an ongoing exploration of the material and process parameter space. The line-edge roughness in this material at 16-nm half pitch is 2.0 nm nm for spatial periods from 32 nm to 500 nm after correction for mask effects (Fig. 9). The line-edge roughness correlation length is 6 nm. We note that good 19 and 17 nm half pitch performance at 40 mJ/cm^2 was achieved in another variant of this same material (Fig. 10).

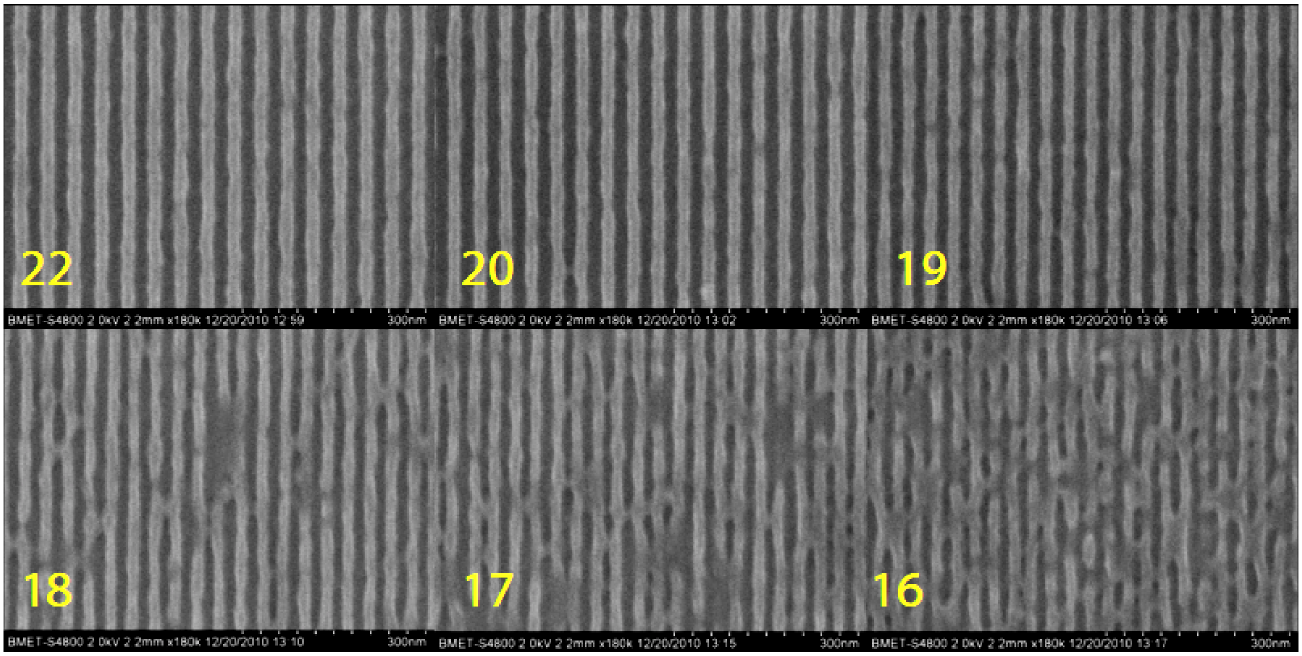


Fig. 4. Imaging results for chemically amplified resist A using the 18-nm dipole illumination.

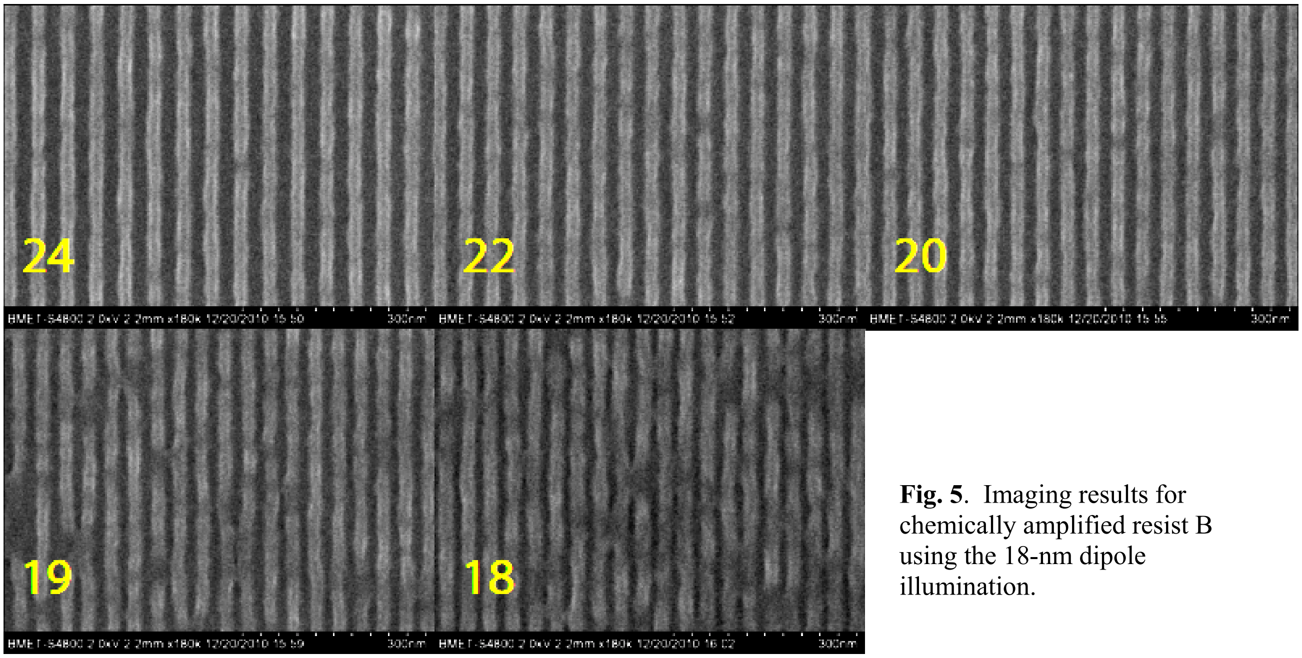


Fig. 5. Imaging results for chemically amplified resist B using the 18-nm dipole illumination.

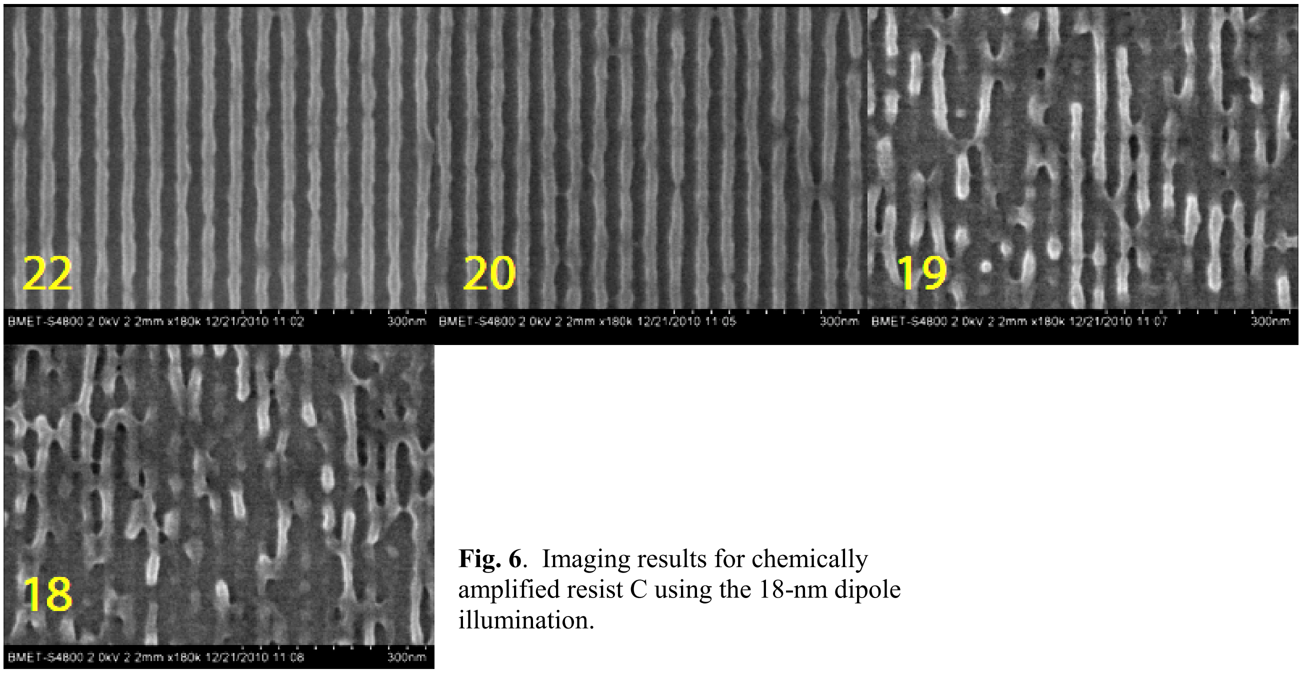


Fig. 6. Imaging results for chemically amplified resist C using the 18-nm dipole illumination.

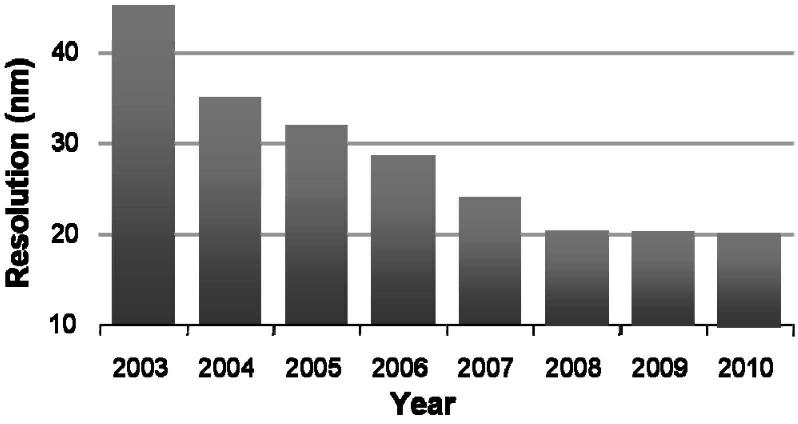


Fig. 7. Ultimate resolution as a function of year in EUV chemically amplified resists.

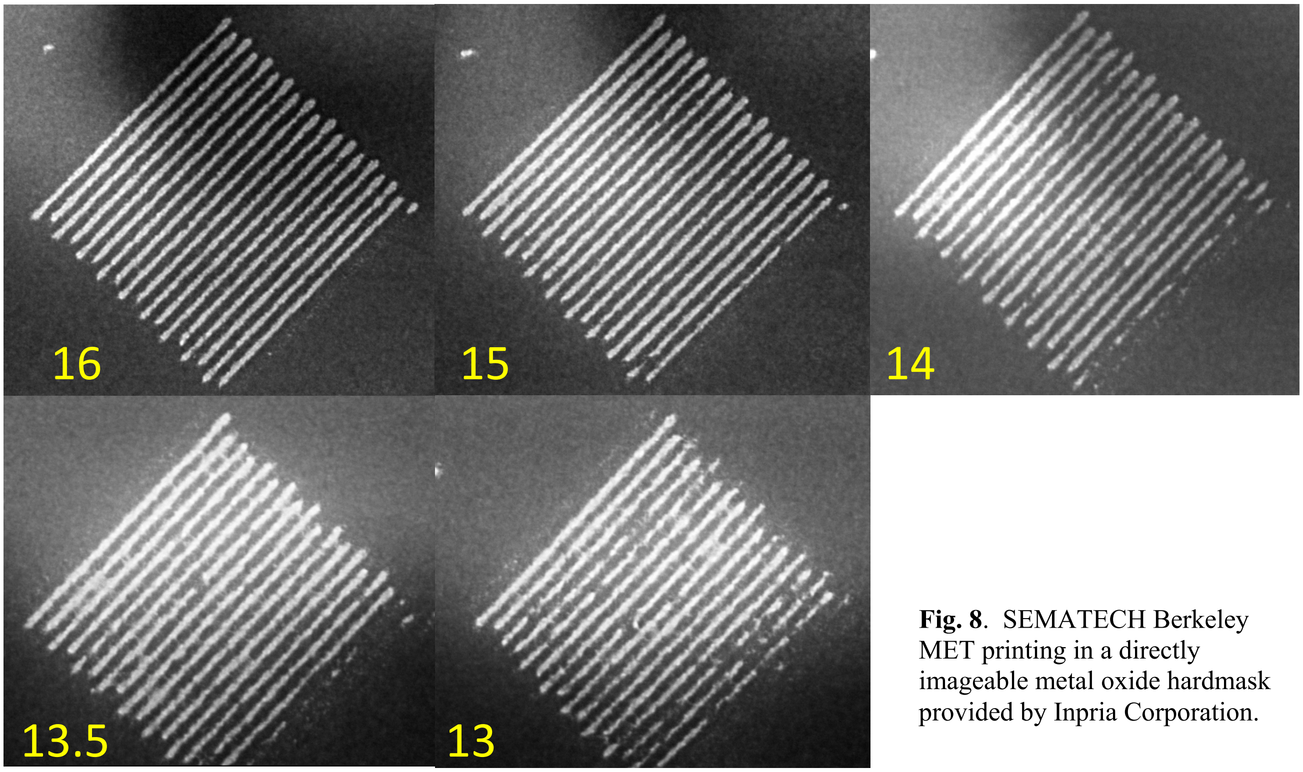
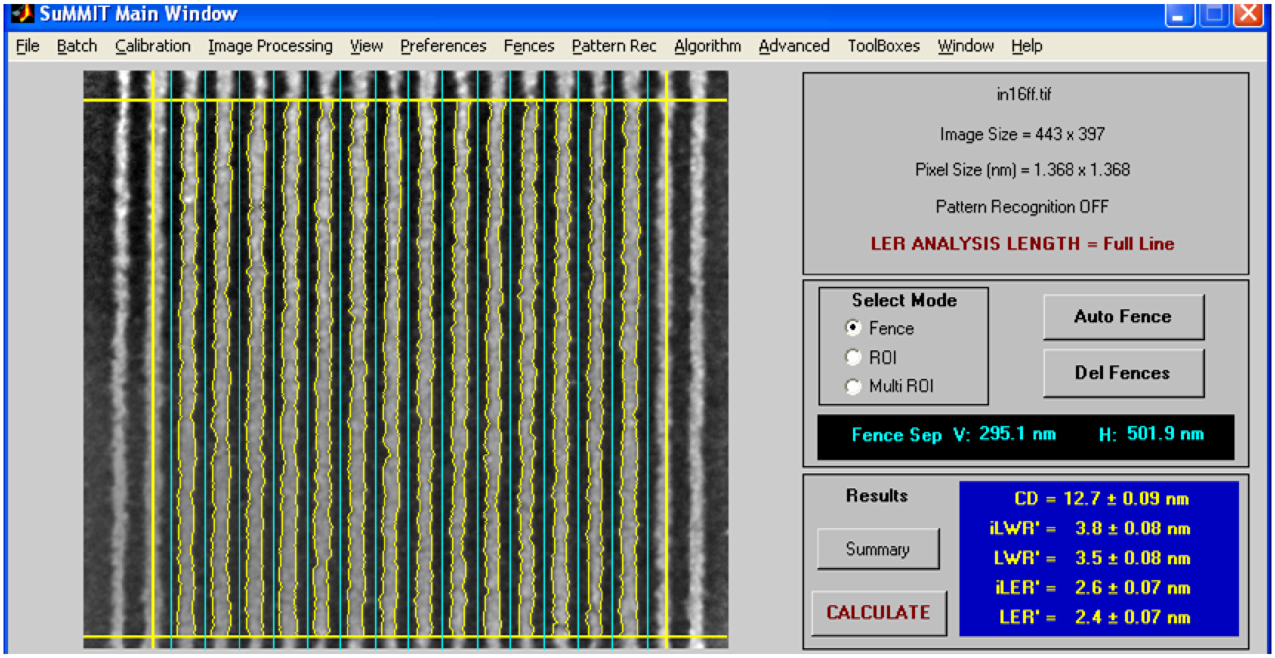


Fig. 8. SEMATECH Berkeley MET printing in a directly imageable metal oxide hardmask provided by Inpria Corporation.



in16ff.tif

Image Size = 443 x 397

Pixel Size (nm) = 1.368 x 1.368

Pattern Recognition OFF

LER ANALYSIS LENGTH = Full Line

Select Mode
● Fence
○ ROI
○ Multi ROI

Fence Sep V: 295.1 nm H: 501.9 nm

Results
CD = 12.7 ± 0.09 nm
iLWR' = 3.8 ± 0.08 nm
LWR' = 3.5 ± 0.08 nm
iLER' = 2.6 ± 0.07 nm
LER' = 2.4 ± 0.07 nm

Fig. 9. LER analysis of the 16-nm lines and spaces printed in the resist from Fig. 8. The actual printed CD is 12.7 nm and the LER is 2.4 nm for spatial periods from 32 nm to 502 nm. The correlation length is 6 nm.

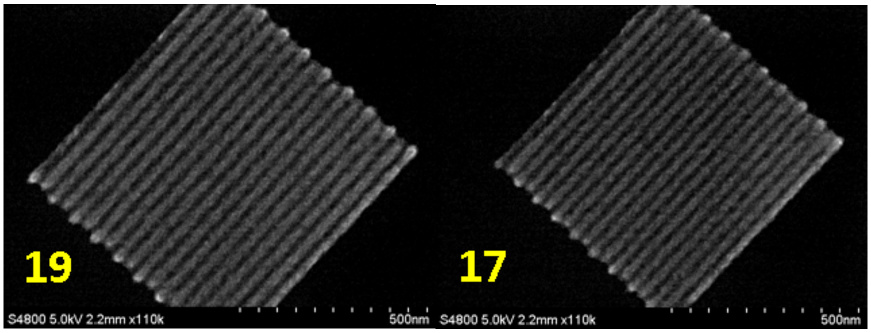


Fig. 10. SEMATECH Berkeley MET printing in Inpria material with a sensitivity of 40 mJ/cm^2.

3. LINE-EDGE ROUGHNESS

Although EUV resist resolution remains a significant challenge at feature sizes of 18 nm and smaller, the resolution issue is arguably solved for the 22-nm half pitch node. That being said, line-edge roughness (LER) is still a critical problem even at 22-nm half pitch. Figure 11 shows a scatter plot of the LER as a function of resist sensitivity. The plot is comprised of data collected as far back as 2004 through the present. The point at 70 mJ/cm^2 corresponds to the resist material in Fig. 8. The data has also been corrected for mask sources of LER [5-8] and thus represents the LER of the resist alone. We note that what is missing from the plot is any information on the resolution of the various resists and LER was measured for features sizes safely above the resolution limit for each resist. Nevertheless, the trend is clear: LER increases with increased sensitivity.

The plot also shows the predicted photon-noise limited LER using a stochastic resist model [9,10]. The model assumes a resist blur of 10 nm, resist absorptivity of 0.0042 nm^{-1}, a thickness of 80 nm, a quantum efficiency of 2, a PAG concentration of 0.1 nm^{-3}, and a deprotection rate of 4 nm^3/sec. These values were chosen based on measured and expected values for typical EUV CAR materials. The sensitivity in the model was changed by varying the base loading while keeping all other parameters the same. We note that the base-loading method for varying sensitivity is often used in experimental studies as well [11-13]. The modeling results show that resist improvement relative to the photon noise limit is indeed possible. We also note that the modeling results should not be viewed as an absolute limit since the predicted LER values can be further reduced by changing resist parameters. For example, the curve can be readily lowered by increasing the absorptivity of the resist.

As mentioned above, mask contributors to LER are no longer negligible and must be accounted for. The largest contributor from the mask arises from phase roughness on the mask rather than absorber LER which can readily be measured using conventional metrology. The AIT serves as the ideal tool for directly measuring the impact of the phase roughness in terms of speckle [14] and even for the measurement of the phase roughness itself [15]. Figure 12 shows AIT measured speckle through focus on a programmed roughness clear field mask. This speckle, which is simply random intensity variations, is what couples to LER in the printed image of lines. The through focus behavior in Fig. 12 can be fit to extract the rms phase roughness of the mask given the imaging conditions of the system. An even more quantitative procedure can be used as described in Ref. 18, to deterministically measure the aerial image phase roughness from the mask. The process is essentially an iterative Gerchberg Saxton phase retrieval process [16].

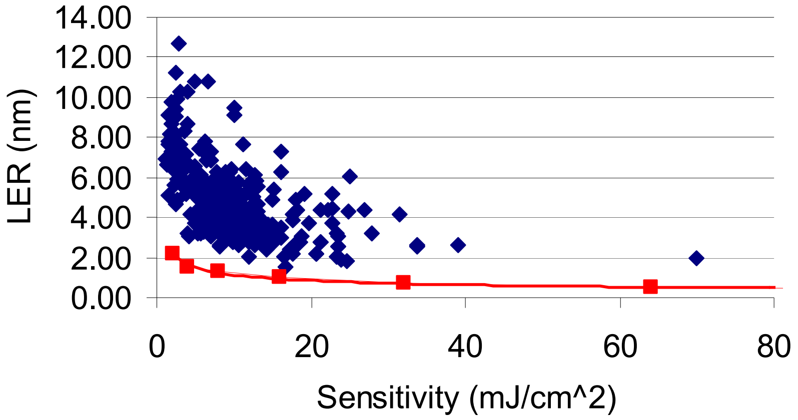


Fig. 11. Scatter plot of LER as a function of resist sensitivity and prediction of photon noise induced LER based on stochastic model.

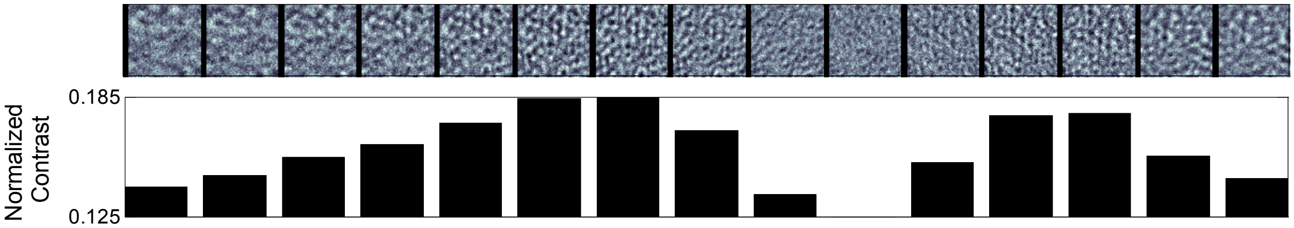


Fig. 12. AIT measured speckle through focus on a programmed roughness clear field mask.

4. FUTURE PLANS

Although modified illumination can push the resolution of the 0.3 NA SEMATECH Berkeley MET down below 20 nm, the benefits are quite restrictive in terms of the required high coherence illumination conditions and pattern flexibility. These restrictions have significant impact on resist learning that can be done in areas such as iso-dense bias, through-pitch performance, contact printing, etc. The restrictions are even more important in the area of mask development significantly limiting learning in the areas of defect printability, optical proximity correction, mask architecture, etc. Clearly, more generalized EUV learning and development at the 16-nm half-pitch node and below will require a higher NA system. To this end, SEMATECH has initiated a plan to implement a 0.5 NA microfield tool at the Advanced Light Source synchrotron facility. A diagram of proposed two mirror optical system [17] is shown in Fig. 13. The system has a magnification of 5, a field of view of 200×30 μm, and a mask angle of incidence of 6°. With modified illumination, the system has a resolution limit of 8 nm (Fig. 14), and with conventional illumination the system can easily resolve 12-nm features as depicted in Fig. 15.

In addition to a new microfield exposure tool, the SEMATECH plans further include the development of a new EUV mask microscope also relevant down to the 8-nm half pitch node.

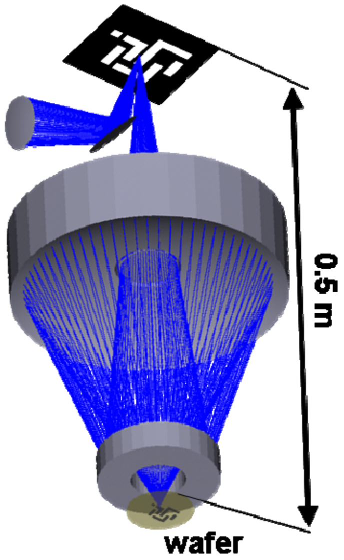


Fig. 13. Model of proposed 0.5-NA microfield lithography optic.

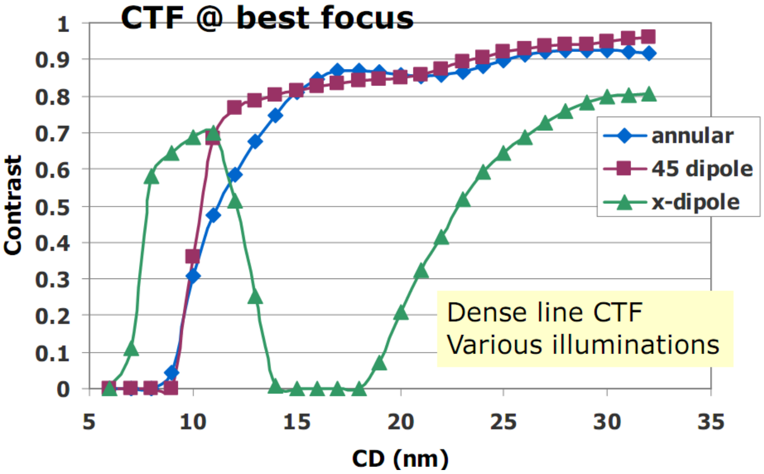


Fig. 14. Modeled performance of 0.5-NA system in imaging equal lines and spaces under three different illumination conditions.

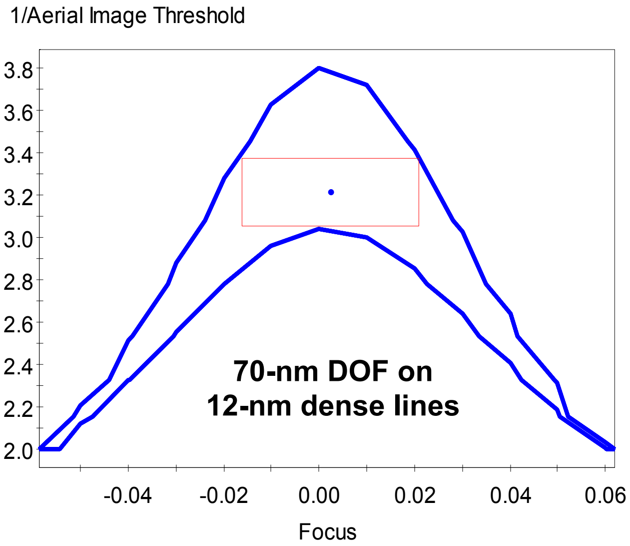


Fig. 15. Modeled process window performance of 0.5-NA system in imaging 12 nm equal lines and spaces using conventional annular illumination.

5. SUMMARY

As we enter the realm of sub-22-nm EUV development, resolution enhancing illumination capabilities are becoming increasingly important. Using such methods, the SEMATECH Berkeley MET has demonstrated resolution to 16-nm half pitch and below in an imageable spin-on hard mask. These new results also demonstrate that ultimate resolution progress in chemically amplified resists has indeed stalled at about 20-22 nm. The CAR champion from 2008 remains as the highest performing CAR tested to date.

To enable continued advanced learning in EUV resists, SEMATECH has initiated a plan to implement a 0.5 NA microfield tool at the Advanced Light Source synchrotron facility. This tool will be capable of printing down to 8-nm half pitch. Additionally SEMATECH is also planning the development a new mask inspection microscope at Berkeley also relevant down to the 8-nm node.

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