Title
Resists for next generation lithography

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Resists for Next Generation Lithography

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Four Next Generation Lithographic options (EUV, x-ray, EPL, IPL) are compared against four current optical technologies (i-line, DUV, 193 nm, 157 nm) for resolution capabilities based on wavelength. Studies are also made comparing absorption characteristics and their role in polymer design for NGL Resists. EUV, x-ray, EPL, and IPL all have important, but distinct, requirements for resist sensitivity. EPL requires resists that are thirty times more sensitive than UV6™. Although the needs are less extreme, EUV and x-ray also require sensitivities that are beyond most conventional resists. IPL does not appear to have sensitivity issues. Quite often, increases in resist sensitivity can only be achieved at the cost of other important resist properties such as resolution, environmental stability and line edge roughness. This challenge must be met in order to properly design resists for NGL.

Keywords: NGL,LER, EUV, x-ray, EPL, IPL, resolution, resists, photoresists,

1. INTRODUCTION

The explosive growth in performance of semiconductor devices has been fueled in part by evolutionary and revolutionary advances in microlithography, which in turn fueled similar advances in photoresist technology. Lithographic technology has been based on projecting an optical image of a device onto a resist in order to record the image for subsequent processing steps. Evolutionary advances in optical lithography have improved imaging resolution from 1 μm to 0.25 μm using i-line (365 nm) light sources, and to sub-100 nm resolution using ArF (193 nm) lasers. Such advances are expected to continue using F_2 (157 nm) and EUV (13.4 nm) light sources.

Revolutionary advances in microlithography include the use of high-energy photons (13 to 0.5 nm) and projected high-energy particles (electrons or ions). These technologies have departed from optical approaches by using high-energy radiation with wavelengths that can be orders-of-magnitude smaller than any practical device structure. Each of these technologies requires new methods to project the device image onto resists, and therefore have been labeled Next Generation Lithography (NGL).

2. WAVELENGTH AND RESOLUTION

Figure 1 uses two approaches for comparing the challenges faced by each technology from i-line to EUV. Both types of interactions are shown as a ratio *vs.* the wavelength of interest. A line segment shows a ratio of each preceding wavelength to the wavelength of interest. This ratio gives a measure of how much resolving power is gained by switching from one technology to the next. The jump from 365 to 248 nm gave a relatively large jump, the consequences of which are the large success which DUV technology is currently enjoying. 193 and 157 nm technologies show much smaller gains in resolution due to wavelength and indicates that these technologies will require much higher NA steppers before manufacturing can begin. In contrast, EUV is at a wavelength that is 11.7 times smaller than 157 nm, and consequently, should have a large advantage in resolving power.

Also shown in Figure 1 is the range of features imaged (or expected to be imaged) by each technology. These data show that i-line and DUV benefited from coming in at features above their wavelengths and were capable of pushing resolution to below their wavelengths. In contrast, 193 and 157 nm technologies will be required to image feature sizes less than their wavelengths and push to even smaller features. The best predictions for EUV indicate that all features will be larger in size than 13.4 nm.

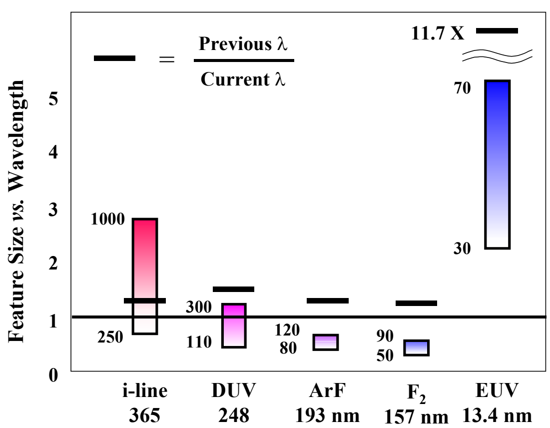


Figure 1. Wavelength *vs.* feature size for different technology generations.

Figure 2 considers the resolution ability of eight lithographic technologies from i-line to IPL in three ways. First, the open circles show what the resolution would be if the equations "$R = k_1\lambda/NA$" and $k_1 = NA = 0.5$ were true for each technology. In this case, the predicted resolution would be equal to wavelength. Although this simplistic approach gives a reasonable approximation of resolving capability from i-line to EUV, the predicted resolution capability of x-ray, e-beam and ion beams are very far off the mark. X-ray lithography would be predicted to have resolving capability less than the typical polymer diameters, and e-beam and ion beam technologies would be predicted to have resolution capability smaller than the length of a C-H bond. The solid circles in Figure 2 show resolution capability using realistic k_1 and NA values for five technologies.[1] The solid squares show demonstrated resolution.[2]

The demonstrated resolution appears to be fairly flat from EUV to IPL. In addition to resolution limitations caused by polymer size, and the current state of maturity for each technology, each NGL may have additional factors limiting their resolution such as proximity imaging (x-ray) and electro-magnetic optics (e-beam and ion beam).

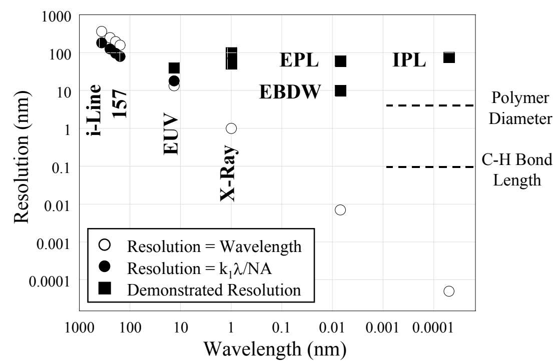


Figure 2. Wavelength *vs.* resolution for different technology generations.

3. TRANSPARENCY

Resist transparency has been a dominant factor in the choice of resist materials from i-line to 157 nm. Typically, polymers and other components (PAGs, PACs, etc.) have been developed to be as transparent as possible to the wavelength of interest to enable the imaging of high aspect ratio features with straight sidewalls.

Table I shows the optical density of four prototypical polymers (i-line → 157 nm) as well as optical density of the polymer in UV6™ for NGL EUV → IPL.[3] This definition has to be modified for high-energy particles since, unlike photons, electrons lose energy in small amounts and can continue traveling through the resist.[4]

As the radiation wavelength used for each lithography generation reduces, the interaction changes from molecular state excitations, to molecular ionizations and then atomic level ionizations and plasmon generation. In Figure 3, the ODs of the polymer structures illustrated in Table I are plotted as a function of the radiation energy. The polymers developed for i-line, DUV and 193-nm lithography exhibit relatively high transparency. While, near the molecular ionization potential (157 nm), the OD is very sensitive to molecular structure. As the wavelength decreases and the photon-polymer interaction shifts from molecular to atomic, the OD becomes less sensitive to molecular structure. In practical terms, this means that optical density will play a diminished role in selecting polymers for use in EUV, EPL and x-ray lithography.

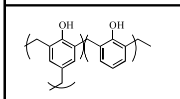
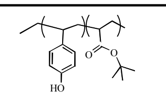
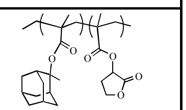
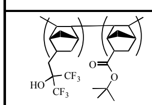
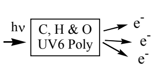
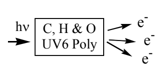
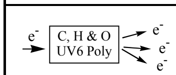
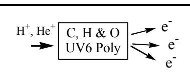
i-line 365 nm	**DUV 248 nm**	**ArF 193 nm**
		
0.02 /µm	**0.18 /µm**	**0.22 /mm**
F_2 157 nm	**EUV 13.4 nm**	**X-ray 1 nm**
		
2.35 /µm	**1.55 /µm**	**0.12 /mm**
100 kV E-Beam	**75 kV H^+, He^+ Ion Beam**	
		
0.02 /µm	**3.7 /µm**	

Table I. Optical density for typical polymer structures used in different lithographic techniques.

4. SENSITIVITY

Resist sensitivity plays a very important role for NGL technologies. For this NGL overview, we assembled the sensitivity requirements from various researchers working on NGL technologies to develop a qualitative comparison of resist sensitivities (Table II).[5] In the interests of simplicity, all target sensitivity goals are referenced to a well known DUV resist, UV6. EUV requires resists that are ten times more sensitive than UV6 in order to target 80 wafers/hour. Despite the relatively high OD of the UV6 polymer at 13.4 nm, the current EUV sources are weak and 75-90% of the light is lost in the aspheric mirrors.[6] A highly sensitive resist could allow an EUV stepper to meet throughput goals while permitting the use of a low power source.

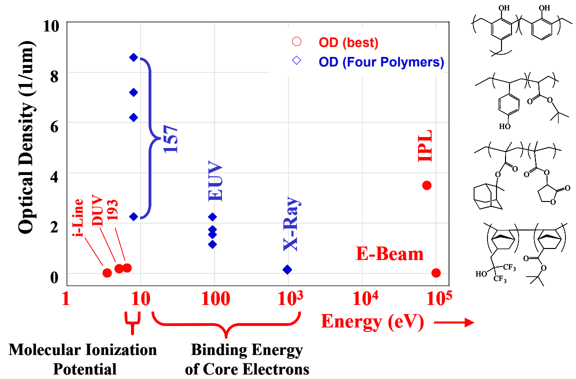


Figure 3. Optical density *vs.* excitation energy.

	EUV	**X-Ray**	**EPL**	**IPL**
Target Sensitivity vs. UV6	**10 X**	**5 X**	**30 X**	**≤ 1X**
Reason	Low source power, 70% mirror reflectivity	Low OD	Minimize space charge effect, Low OD	Relatively high OD

Table 2. Required resist sensitivity relative to current UV6 resist exposure sensitivity.

X-ray photons interact ten times less strongly with the UV6 polymer than do EUV photons (OD = 0.12 *vs.* 1.55, respectively). Although the OD is less, the x-ray throughput goals are less ambitious. Nonetheless, sensitivity is still an issue. EPL requires resists which are thirty times more sensitive than UV6.[7] This high sensitivity is required because the interaction of 100 kV electrons is very low (OD = 0.02 /µm), throughput goals are ambitious, and electron-electron repulsion causes a trade-off between beam current and resolution. Currently, researchers working to develop IPL require resists that are less sensitive than UV6. The high level of interaction between H^+ and He^+ ions with phenolic polymers account for the low sensitivity requirements.

Chemically amplified resists systems will, no doubt, be required to meet the sensitivity goals of EUV, x-ray and EPL. These systems work by generating protons in the exposed regions from the decomposition of photoacid generators (PAGs). These protons then catalyze chemical transformations with 10-300 turnovers.[8] The amplification potential of these systems give them a very large sensitivity advantage over non-catalytic systems (e.g. Diazo i-line, PMMA). However, pushing chemically amplified systems to higher sensitivities can cause degradation in other lithographic properties.

Figure 4 shows the sensitivity and LER of three resists prepared with three different base levels. In this case, a trade-off is established between sensitivity and LER. Pushing the sensitivity of resists too far, can cause additional problems such as, degradation of resolution, post-exposure delay sensitivity and shelf life. Nonetheless, careful design can produce faster resists, with minor impact on other properties. Figure 5 shows the increase in EUV sensitivity can be achieved with minimal impact on LER.[9] and Figure 6 shows that highly sensitive e-beam resists can also be developed with good resolution and low LER.[10]

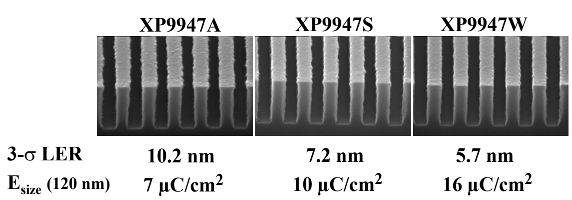


Figure 4. LER *vs.* resist sensitivity at 50 kV.

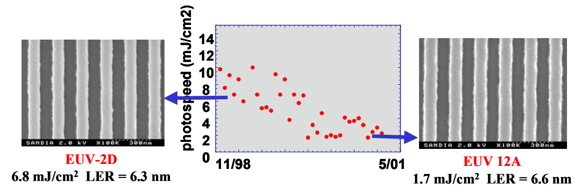


Figure 5. Improvement of resist sensitivity with LER under control for EUV resists.

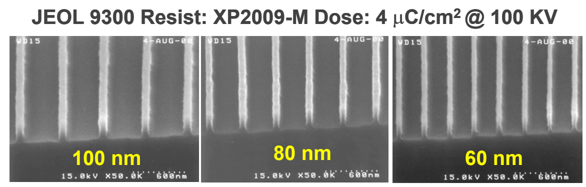


Figure 6. Sub-100 nm lithography at 100 kV with high sensitivity and low LER.

5. Line Edge Roughness.

As feature sizes continue to decrease, so will the performance goals for line edge roughness (LER). The ITRS roadmap,[11] lists the critical dimension control goals for the 50 and 30 nm nodes at 3 and 2 nm (3σ). These LER objectives are near the radius of gyration of the polymer used in resists (Figure 7). Clearly, the molecular weight of the polymers will play an important role in determining LER.

Other factors are important in determining LER, such as, the aerial image contrast, and resist contrast and dissolution uniformity. EUV LER has been shown to decrease with increasing contrast[12] (Figure 8). Similarly, the LER of three resists exposed at DUV were shown to decrease with increasing feature size (180 to 250 nm), but flattened out at larger feature sizes. The LER of the resists was plotted *vs.* image contrast or image log slope (Figure 9) upon imaging with DUV and EUV exposure. The DUV images at high image contrast can be used to predict EUV LER performance. These results show that there are at least two factors involved in determining LER. When the image contrast is low, it is the primary factor in determining LER. When the image contrast is large, it is much less important in determining LER, and resist properties become important.

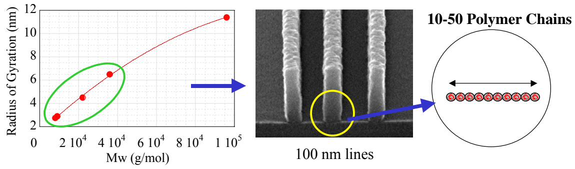


Figure 7. Molecular dimensions of resins in resist are getting closer to required feature size.

Figure 10 shows how low image contrast and low resist contrast can combine to create a condition that could result in poor LER. A high image log slope can combine with a high resist contrast to generate a low "chemical contrast", or a gradually changing distribution of soluble and in soluble polymers. Similarly, a low contrast image can combine with a high contrast resist leading to a low chemical contrast. An interface with gradually changing distribution of soluble and insoluble polymers may cause swelling and uneven development leading to line edge roughness.

Although much work is required to define LER test methods and to understand how LER effects device performance before realistic LER goals can be set, significant breakthroughs in resist design will be needed to meet targets which are near the size of polymer molecules.

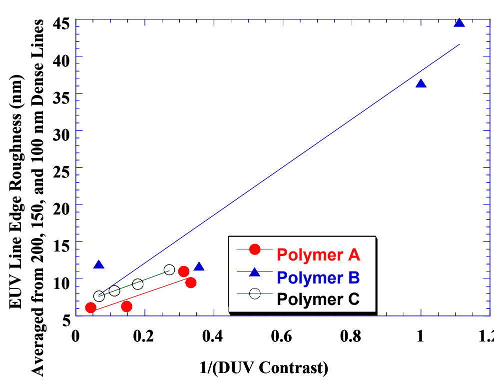


Figure 8. LER *vs.* DUV image contrast.

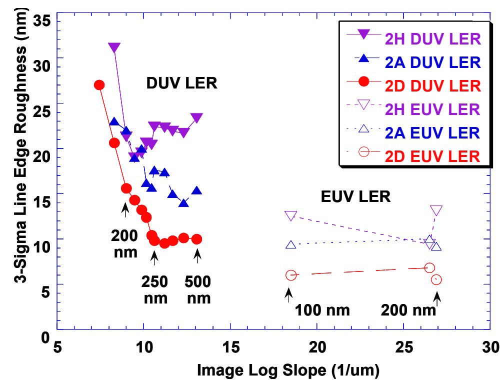


Figure 9. LER *vs.* image contrast for DUV and EUV exposures.

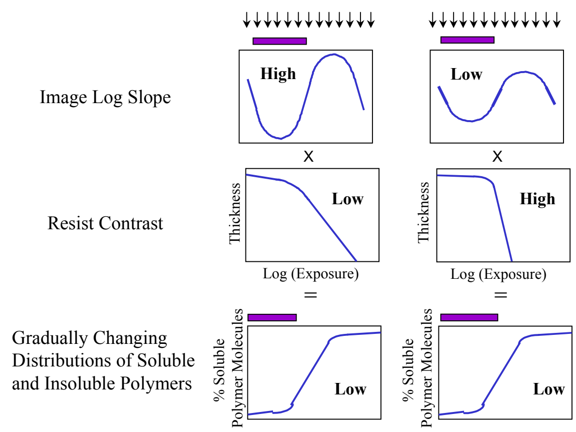


Figure 10. Interpretation of effect of image and resist contrast on final chemical image.

6. SUMMARY AND CONCLUSIONS

Four Next Generation Lithographic options (EUV, x-ray, EPL, IPL) are compared against four current optical technologies (i-line, DUV, 193 nm, 157 nm) for resolution capabilities based on wavelength. As the wavelength of the incident radiation decreases, the nature of the interaction with the resist changes. At high energies, optical density is less sensitive to molecular structure then at 157 nm. This leaves other parameters, such as resist sensitivity, contrast and dissolution characteristics as important properties that must be understood and controlled to get the best performance from NGL resists.

Most NGL technologies require more sensitive resists. Although several advances have been made in increasing the sensitivity of resists, the increased sensitivity can come with lithographic penalties in other performance factors (LER, PED, profiles). As these NGL technologies push to smaller and smaller feature sizes, the demand for commensurately smoother lines will follow. In this paper, we have shown that polymer size, image contrast and resist contrast will be among several factors that will need to be controlled to reach these LER objectives.

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NOTES AND REFERENCES

1. The k_1 and NA values used for each technology were: i-line, 0.4 and 0.8; DUV, 0.4 and 0.8; 193 nm, 0.4 and 0.8; 157 nm, 0.4 and 0.8; EUV, 0.4 and 0.3.
2. Resolution capability of each NGL technology came from the following references. EUV: D. O'Connell, et. al., EUV Workshop, 2000. X-Ray: L. Ocola, et. al., XEL Workshop 1995. EPL: Nikon, 2001 NGL Workshop. EBDW: H. Namatsu, et. al., EIPBN, 2001. IPL: R. Kaesmaier, H. Loschner , 2001 NGL Workshop.
3. Optical density (OD) in units of 1/μm is defined as a function of transmittance (*T*) as OD = $-\log_{10}(T)$.
4. OD for charged particles is not widely used. It has been adapted for comparison purposes only. Transmission (*T*) was calculated using Monte Carlo simulations for 100 KV electrons traveling through 1 μm of resist. Transmitted electrons are considered those with < 1% energy loss after passing through the resist film. OD for ions was calculated from data provided by Stefan Hirscher (Infineon).
5. These values were based on requirements given to Shipley by workers in each technology area. Since each NGL has different challenges and are at different stages of development, the throughput goals are different. For example, although EUV is targeting 80 wafers/hour, IPL probably isn't.
6. EUV Workshop references.
7. UV6™ sizing energy is ~30 $\mu C/cm^2$ at 100 kV and Nikon has published their sensitivity goal of $1\mu C/cm^2$ at 100 kV. K. Okamato, K. Suzuki, H. Pfeiffer, M. Sogard, Solid State Tech., May 2000, pp 118-122.
8. J. Cameron, A. Orellana, M. Rajaratnam, R. Sinta, Proc. SPIE, 1996, 2724, 261-272; J. Thackeray, M. Denison, T. Fedynyshyn, J. Georger, M. Mori, G. Orsula, J. Vac. Sci. Technol., B (1993), 11(6), 2855-61; T. Sakamizu, H. Yamaguchi, H. Shiraishi, F. Murai, T. Ueno, J. Vac. Sci. Technol., B (1993), 11(6), 2812-17.
9. D. O'Connell, et. al., EUV Workshop, 2000.
10. L. E. Ocola, M. I. Blakey, P. A. Orphanos, W.-Y. Li, R. J. Kasica, A. E. Novembre, Journal of Photopolymer Sci. and Technology, 14, 547, (2001)
11. ITRS 2000 Update: Lithography, 2001 International Technology Roadmap for Semiconductors
12. R. Brainard, et al, J. Vac. Sci. Technol., B 17, 3384, (1999)