HIGH-FIDELITY LITHOGRAPHY

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ABSTRACT

Of primary importance in lithography is understanding internal molecular forces, characterized by chemical contrast, which, when uncontrolled, can lead to pattern uncertainty and line edge roughness/line width roughness (LER/LWR). Another key to achieving high-fidelity lithography is to control resist and substrate interaction (or nanoscale affinity), which can be characterized by chemical contrast at the base of the resist. Both of these factors are important in determining ultimate resolution capability. Because these forces are difficult to model, the effectiveness of matching performance to simulation becomes more complicated. As a result, the cost of optical proximity correction (OPC) is increasing to match the requirements for pattern accuracy. This paper will review how these factors relate to advanced lithography concepts, and experimental results of trilayer immersion lithography of high foot contrast will be presented to show striking improvement over conventional minimum substrate reflection stack.

INTRODUCTION

With feature size aggressively shrinking in the IC industry, lithography fidelity becomes more and more critical. Major efforts in the industry are aimed at pattern prediction for guaranteeing overlapping alignment accuracy within a few nanometers. While prediction requires incorporating inverse lithography, 3-D mask calculation, resist characterization, and imaging aberration calibration, these approaches do not take into account the effects of molecular forces that deform patterns via resist settling during develop and drying processes (e.g., line-end pullback).[1]

As pattern sizes continue to shrink, new approaches must also be able to solve pattern uncertainty issues that are encountered in cutting-edge lithography, including pattern uniformity, overlay alignment, and LER/LWR. Modeling efforts are limited in this instance because semi-empirical modeling—such as optical proximity correction (OPC) algorithms and design-for-manufacture (DFM) processes—depend on fitting chemical and physical properties to experimental results[2-3] and are not suitable for predictive computation.

Understanding and control of molecular interactions are substantially important in improving the patterning process. This paper will discuss using contrast at the resist foot (foot contrast) to control substrate affinity and will introduce an innovative application for bottom anti-reflective coatings (BARCs): While also eliminating standing waves, a BARC can serve as a foot-contrast-enhancement and adhesion-control layer.

RESIST DYNAMICS

During the resist development process, a gel interface is theorized to form between the liquid developer and the undissolved resist, as shown in ***Figure 1(a).*** When feature size is small, the volume of the gel phase will be significant compared to the volume of the remaining undissolved resist, leading to pronounced gel effects. The thickness of the gel interface will depend on resist chemical design. The principal gel effect results from surface tension, which helps smooth the pattern surface, reduce LER, and stabilize the pattern profile against the distractive forces of the substrate, ***Figure 1(b)***.

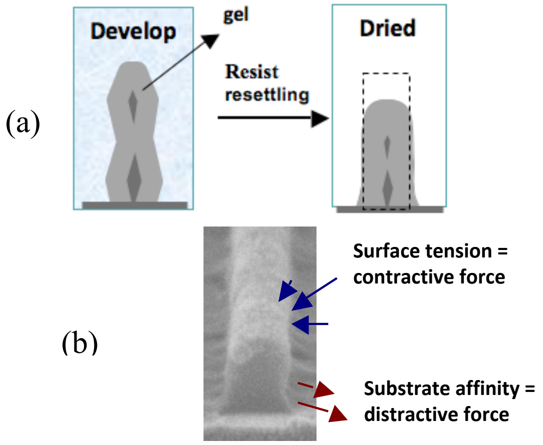
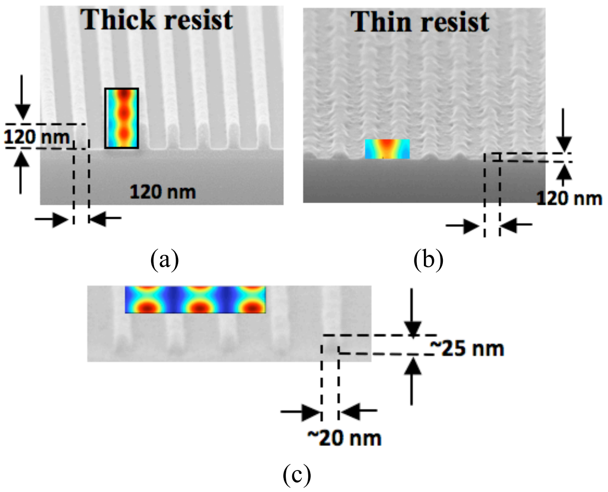


Figure 1: *(a) Gel interface in resist development process. Pattern profile is determined by resist resettlement. (b) Two important molecular forces build a pattern profile. Surface tension is the "beneficial force" that smooths and holds a pattern, while the distractive force caused by substrate affinity pulls the resist away from the pattern profile.*

Conversely, the distractive molecular force is due to residual resist and its affinity for the substrate. In ***Figure 2(a) and (b)***, lithography results are compared for two resist thicknesses. Thick resist, ***Figure 2(a)***, produces more preferable patterns due to the dominating effects of surface tension. When the resist layer is thin (low aspect ratio), as in ***Figure 2(b)***, the surface tension is less significant and the line pattern is pulled by distractive force from the substrate. However, thin resist can produce a



(a) (b)

(c)

Figure 2: *Surface tension plays an important role in lithography. In thick resist, (a), surface tension dominates to yield a clear line profile; in thin resist, (b), the uncontrolled substrate distractive force pulls the resist away from the profile. Thin resist, (c), gives a clear line profile when the substrate distractive force is controlled through high optical foot exposure. The colored insets show optical distribution across the trench profile.*

better pattern if the substrate distractive force is controlled, as shown in ***Figure 2(c)***. Strong foot exposure (FE) is applied to enhance contrast at the foot, resulting in evenly distributed substrate forces along the line edge. The dominance of surface tension should be evaluated by aspect ratio, substrate affinity, and profile undercut/footing situation. Although the evidence of the LER increase with thinner resist has been discussed and investigated with different approaches,[4] the evaluation of the molecular force interactions yields a reasonable explanation for the observed behavior.

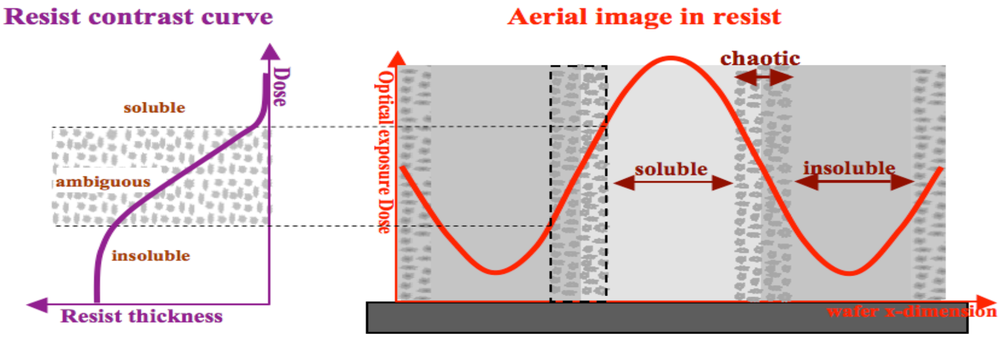
Photoacid contrast in resist

Figure 3 is a schematic diagram of positive-tone photoresist exposure, where the resist has low UV absorption without standing waves. The aerial image is plotted uniformly along the vertical direction. By projecting the UV dose (intensity) onto the resist contrast curve, it can be divided into three regions of solubility: trench (soluble), line (insoluble), and line edge (varying solubility). The region of varied solubility can be considered as an undefined region that causes LER/LWR, pattern collapse, and poor pattern resolution. Because contrast is the only way to reduce the undefined region, high-contrast resist and an optical design having a high normalized image log-slope (NILS) are highly desirable. Increasing photon count in EUV lithography serves the same purpose—to reduce the size of the undefined region; some resist venders supply low–acid diffusion materials to retain a narrow undefined region.

Optical foot contrast enhancement

Figure 4 shows a UV intensity cross-section in resist. Typically, the resist base receives less intense UV exposure than the top due to optical absorption, which leaves a larger undefined region at the substrate. To reduce the size of the undefined region, foot exposure can be increased by constructive interference, using a small amount of substrate reflection (R~1%), as shown in ***Figure 4(b)***. In this case, substrate molecular forces will be more evenly distributed along the line edge, while the larger uncertain solubility region on the top of the resist would be smoothed by surface tension. This concept of high foot exposure has been experimentally validated and published previously,[5-9] where a tested matrix shows that pattern printability is improved at higher foot exposure (rather than at lower substrate reflectivity).

Figure 5 is another comparison of low and high foot exposure. Cases (a) and (b) use the same resist and similar trilayer BARC materials, but with different optical reflection designs. Both sets of SEM pictures were taken at center dose. The exposure image is a 13-line bright-field mask, and the cross-sections of UV distribution in the resist are shown by the insets, where (a) has higher foot exposure than (b). Because higher foot exposure was



(a) (b)

Figure 3*: (a) Resist contrast curve (purple); (b) resist solubility diagram after optical exposure where solubility in spotted area is uncertain; red curve is aerial image across the resist.*

used, stack (a) has strikingly better performance. At the best focus, 15 lines (including 2 ghost lines with very low image contrast) can be printed, while the lower foot exposure gives only 11 lines—a loss of 2 edge lines. The edge and ghost lines have lower image contrast, which gives a larger undefined region at the substrate. Only high foot exposure is capable of reducing this undefined region and forming patterns from the poor image contrast. Clear line profiles are achieved by using high foot exposure to enhance foot contrast and reduce undefined forces in the substrate.

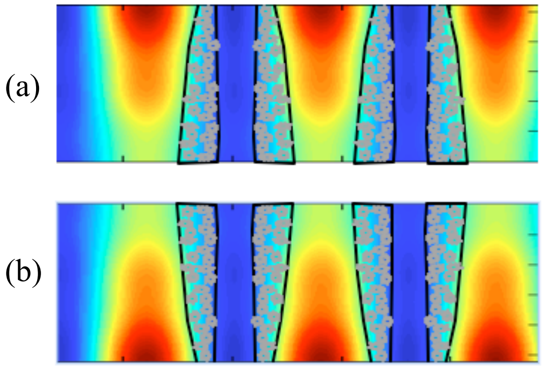


Figure 4: *UV cross-sections. (a) Resist receives lower UV intensity at the bottom, due to optical absorption. (b) High foot exposure is used to enhance foot contrast to reduce the size of the undefined region, ensuring that the substrate forces are evenly distributed along the line edge.*

Chemical foot contrast enhancement

Foot contrast means chemical contrast at foot. In chemically amplified resists, photoacid generators (PAGs) and quenchers are included; the function of the quencher is to neutralize the background photoacid to give sharp resist contrast and reduce the uncertain solubility region. The higher the quencher loading, the sharper the resist contrast curve, and the clearer the line profiles, but at the cost of exposure dose. At the higher exposure dose, there is a higher photon count; hence, less optical noise (size of the undefined region) forms in the resist. From the resist dynamics discussion above, foot contrast is more important in controlling the distractive substrate force; therefore, PAG and quencher loading in the BARC have the potential to enhance chemical foot contrast. With more photoacid generated from the BARC and more background photoacid consumed by the quencher, the chemical foot contrast will be increased. In this way, resist function is extended into the BARC layer without significantly increasing average exposure dose. Because high foot contrast is capable of printing patterns from poor image contrast, we refer to it as robust lithography,[5] which can print narrow lines, narrow trenches, or small vias of low NILS.

DISCUSSION

Contrast, specifically foot contrast, is the basic criteria for achieving clear lithography patterning. As the contrast is initiated from the optical image, high contrast results in patterns that are formed under strong optical control, referred to as high-fidelity patterning. Controlling foot contrast also indicates that pattern footprints are well-defined by the optical image, which is critical for pattern overlay alignment accuracy. Regardless of the contemporary industry patterning road map, EUV, or DSA, high-fidelity patterning is essential.

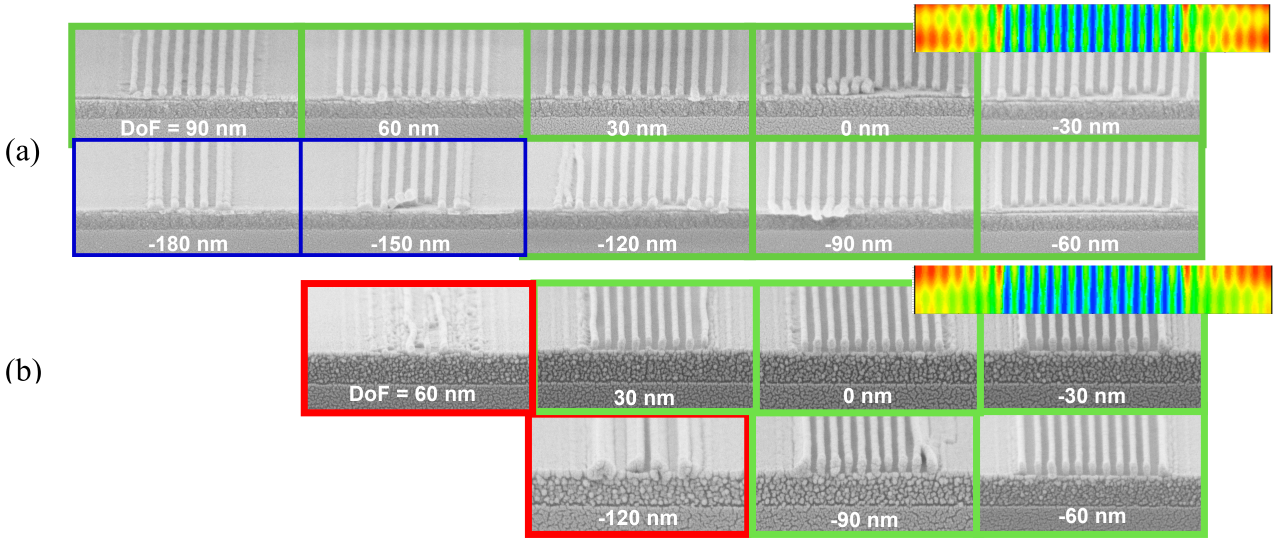


Figure 5: *Immersion trilayer lithography of 40-nm dense lines with dipole illumination. (a) High–foot exposure stack (FE = 0.92, R = 0.8%) gives clearer line profiles than low–foot exposure stack. (b) High–foot exposure stack (FE = 0.86, R = 0.2%) is capable of printing edge and ghost lines of low image contrast, while low–foot exposure is not able to print the edge line.*

In addition, surface tension plays an important role in lithography. It allows for consistent critical dimension (CD) size against dose variation, explaining the improvement of exposure latitude (EL) with the use of a thicker resist. Low adhesion or undercut profiles encourage the dominance of surface tension over substrate adhesion and help to improve LER/LWR and EL. However, surface tension effects are independent from the optical image, violating patterning fidelity and leading to patterning issues such as line-end pullback; therefore, conventional methods of evaluating pattern robustness and fidelity, such as CD process window and LER, should be expanded. The performance criteria, in addition to depth of focus (DoF) and LER, should also reflect foot contrast, which could indicate the printability of narrow lines/trenches or edge vias.

Substrate adhesion is required to prevent pattern collapse and displacement, though size of the undefined substrate is proportional to the substrate affinity and inversely proportional to chemical foot contrast. In this instance, the proposed recommendation is use of the minimum necessary affinity. The question of affinity uniformity at the nanometer scale may also be important. Material design and additive loading may be subject to uniformity issues, and as such, Poisson statistical fluctuation could be a possible source of error. Additionally, the bonding behavior for surface tension and substrate adhesion could be characterized with computational chemistry methods for varying types of molecular bonding forces.

Resist thickness is an important factor in lithography. Thick resist has stronger surface tension effects that give smooth line profiles, but it also increases resist film lateral tension, which has the potential for pattern displacement. Simulations show that increasing resist thickness also reduces foot exposure and further degrades lithography fidelity. When choosing resist thickness, there is a trade-off between LER and fidelity. To reiterate, high foot contrast is the primary factor needed to support adequate substrate affinity that could tolerate higher surface and lateral tension.

In two-beam immersion lithography, the best NILS is at 1:1 line/space patterns, but the preference is for higher exposure dose, as it gives a higher photon count. Therefore, for positive-tone development (PTD) applications, it is recommended to apply this theory for narrow patterns to logic and double-patterning applications. With this same logic, benefits would be seen in narrow trenches and vias patterning schemes for negative-tone development (NTD).

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