[24] D. E. Widmann and H. Binder, "Linewidth variations in photoresist patterns on profiled surfaces," *IEEE Trans. Electron Devices*, vol. ED-22, p. 467, 1975.
[25] C. H. Ting, private communication.
[26] L. B. Rothman, "Properties of thin polymide films," *J. Electrochem. Soc.*, vol. 127, p. 2216, 1980.
[27] W. T. Scott, "Correlated probabilities in multiple scattering," *Phys. Rev.*, vol. 76, p. 212, 1949.
[28] J. J. Goldstein, J. L. Costley, G. W. Lorimer, and S.J.B. Reed, "Quantitative X-ray analysis in the electron microscope," *SEM*, vol. 1, p. 315, 1977.
[29] R. K. Watts, W. Fichtner, E. N. Fuls, L. R. Thibault, and R. L. Johnson, "Electron beam lithography for small MOSFET's," in *1980 IEDM Tech. Dig.*, p. 772, Dec. 1980.

Linewidth Control in Projection Lithography Using a Multilayer Resist Process

MICHAEL M. O'TOOLE, MEMBER, IEEE, E. DAVID LIU, AND MARK S. CHANG, MEMBER, IEEE

***Abstract*—Linewidth control using a tri-layer resist system on wafers with topography is investigated. An absorbing dye is incorporated in the bottom layer to improve the usable resolution. Resist patterns of 1-μm lines and spaces over aluminized topography are demonstrated using a projection aligner. The advantages of a multilayer system are investigated using an exposure and development simulation program for optical lithography. The relative contributions of planarization and reflection suppression are discussed.**

I. INTRODUCTION

IN OPTICAL lithography, the demand for small feature sizes has resulted in optical projection printers with higher numerical apertures, closer tolerances, lower imaging wavelengths, and better alignment capabilities. These improvements extend the theoretical resolution limit of projection lithography into the submicrometer range. However, the practical resolution limit has been considerably larger due to the difficulty in maintaining a constant resist linewidth over substrate topography. In an attempt to improve linewidth control over topography, several multilayer resist processes have recently been proposed and demonstrated [1]-[6]. In the multilayer system, the substrate topography is planarized by a bottom polymer layer. In addition, reflections from the underlying topography can be eliminated by choosing an absorptive material for the bottom polymer.

The technique outlined here extends the tri-layer scheme of Bell Laboratories [1], [2] by incorporating a selectively absorbing dye in the bottom polymer. The tri-layer structure is analyzed theoretically using an exposure and development simulation program for optical lithography [7]. The program assumes diffraction-limited optics and considers the numerical aperture of the imaging lens, the imaging wavelength, the partial coherence factor of the illumination system, and the focus error to generate an intensity pattern on the surface of the resist. The resist is then exposed and developed using the model described by Dill *et al.* [8]. The final output is a simulated line-edge profile in positive resist. The simulations in this paper are for Hunt positive resist developed nominally for 15 s in a mixture of two parts MF312 developer with one part water. The exposure and development parameters for the resist [9] were measured using equipment similar to Dill's for the exposure parameters and to Meyerhofer's [10] for the development parameters.

By using the exposure and development parameters of the resist in conjunction with the simulation program, the relative contributions of planarization and of reflection suppression to linewidth control are shown for 1-μm geometries. The simulation results provide an analytical understanding of the problem and aid in process optimization. Experiments with the tri-layer technique are conducted for 1-μm geometries over aluminized topography.

II. LIMITS OF CONVENTIONAL PROCESSING

The usable resolution of a projection system varies with the substrate topography and material. Current projection aligners can resolve submicrometer features with positive resist and conventional resist processing on a planar and nonreflective substrate. In device fabrication, however, the image is projected onto a nonplanar, reflective surface covered unevenly with resist. The resulting usable resolution degrades to approxi-

---

Manuscript received May 1, 1981; revised July 24, 1981.

M. M. O'Toole and E. D. Liu are with Hewlett Packard Laboratories, Palo Alto, CA 04304.

M. S. Chang was with Hewlett Packard Laboratories, Palo Alto, CA. He is now with Seeg Technology, Inc., San Jose, CA 95131.

0018-9383/81/1100-1405$00.75 © 1981 IEEE

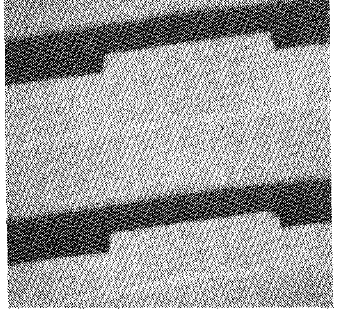


Fig. 1. Resist step coverage: 1-μm-thick resist pattern over 0.5-μm step.

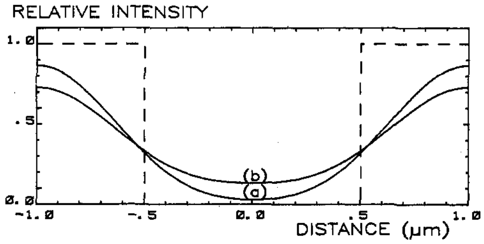


Fig. 2. The image intensity pattern of a periodic 1-μm line and space for the case of (*a*) perfect focus and (*b*) 3 μm of focus error. $\lambda = 436$ nm; NA = 0.28; partial coherence factor (σ) = 0.7; square aperture. (Dashed line is the intensity at the reticle.)

mately a 1.5-μm feature size for an aligner with a numerical aperture of 0.3 and an imaging wavelength of 436 nm. The nonplanar, reflective surface gives rise to two effects which limit the usable resolution of the aligner. The first effect is related to large thickness variations of the resist near steps, or the "bulk effect." The second effect is related to multiple reflections from the substrate, or the "standing-wave effect."

The bulk variation in the resist thickness as it covers a step is demonstrated in the micrograph of Fig. 1. If the resist on top of the step and the resist next to the step receive equal exposure, the resist on top of the step will clear first. The resist over the step may continue to develop while the thick resist next to the step clears, resulting in a narrowing of the resist line over the step. The narrowing is more pronounced for linewidths approaching the resolution limit of the aligner's objective lens and for areas slightly out of focus or influenced by scattered light. Fig. 2(*a*) is the calculated intensity of the image of a periodic 1-μm line and space pattern produced by a lens with a numerical aperture of 0.28 at a wavelength of 436 nm and a partial coherence factor [11] of 0.7. The curve is normalized so that large clear areas have an intensity of 1.0. The dashed line represents the ideal intensity profile, or that which exists at the reticle for a perfect chromium line. The nonzero intensity of the imaged line due to diffraction allows some exposure of the resist in an area where the resist should remain unexposed. Focus error, shown in Fig. 2(*b*), and scattered light further contribute to the undesirable exposure of the resist line. The undesirable exposure allows the resist lines in some areas to continue to develop and narrow, while areas having thicker resist or receiving less exposure have not yet cleared.

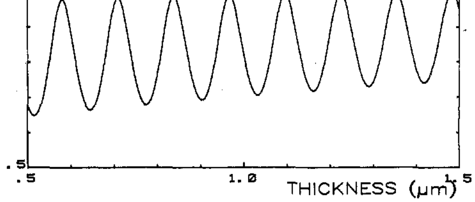


Fig. 3. The fractional intensity coupled into HPR 204 positive resist ($N = 1.69 - i0.12$) on a silicon substrate as a function of the resist thickness.

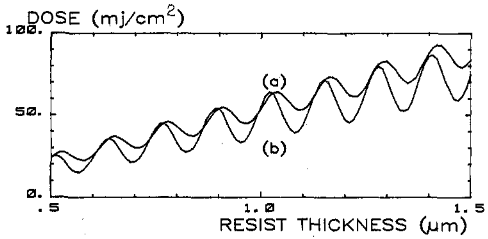


Fig. 4. The exposure energy density (dose) required at 436 nm to achieve 1-μm lines and spaces in HPR 204 on (*a*) silicon and (*b*) aluminum for $\lambda = 436$ nm, NA = 0.28, perfect focus, and partial coherence factor $\sigma = 0.7$.

Variations in exposure are due to nonuniform illumination of the mask and to the standing-wave effect. The exposure variation due to nonuniform illumination of the mask is generally less than 5 percent and much smaller than that due to the standing-wave effect. The standing-wave effect is related to multiple reflections of the electromagnetic waves [12] in the resist and in the underlying films. Small variations in the resist thickness or in the thin semitransparent layers under the resist can cause large variations in the energy coupled into the resist. Fig. 3 shows the fractional intensity coupled into a film of resist on a silicon substrate as a function of the resist thickness. For an exposure wavelength of 436 nm and a resist index $N = 1.69 - i0.012$, a 64-nm change in the resist thickness can cause a 50-percent change in the energy coupled into the resist. The energy coupled into the resist is periodic with period $\lambda/2n$. Essentially, random variations in resist thickness occur as the resist covers the substrate topography. In addition, changes in the reflectivity of the features under the resist cause additional variations in the amount of energy available for resist exposure. The exposure variations are most evident as the resist lines traverse steps. Resist features approaching the resolution limit of the projection lens show increased linewidth instability because of the nonzero intensity discussed previously.

The standing-wave and bulk effects may be simulated using a computer program for the simulation of optical projection printing. Fig. 4(*a*) simulates the nominal exposure required for a periodic 1-μm line and space pattern as a function of the resist thickness of positive resist on (*a*) a silicon substrate, and (*b*) an aluminum substrate. The nominal dose is defined as the exposure energy density required to obtain the mask linewidth in the resist. The bulk effect is evident by the gradual rise of the curve; and the standing-wave effect is evident by the periodic variation $\lambda/2n$, or 128 nm for an exposure wavelength of

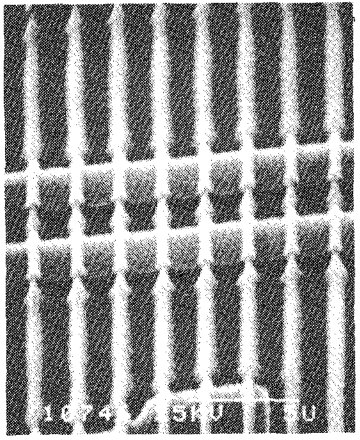


Fig. 5. 1-μm lines and spaces in 1 μm of resist over 0.5-μm polysilicon steps.

436 nm and a resist index of 1.69. A 25-percent exposure difference is required to compensate for the standing-wave effect for a 64-nm thickness variation in 1 μm of resist on a silicon substrate. A similar exposure difference due to the bulk effect requires a 250-nm resist thickness variation. Aluminum substrates (Fig. 4(*b*)) with their greater reflectivity demonstrate a larger standing-wave effect. From Fig. 4(*b*), a bulk thickness variation of about 420 nm is equal to a standing-wave thickness variation of 64 nm. Both effects can combine near a step to result in a significant variation in the nominal dose required and, therefore, severe linewidth control problems. Fig. 5 shows a micrograph of 1-μm lines and spaces patterned in 1 μm of resist over a 0.5-μm polysilicon step. The linewidth is very unstable near the edge of the steps.

III. TRI-LAYER RESIST WITH ABSORBING DYE

In order to realize the maximum resolution from an aligner, the surface of the wafer must approach that of a flat, nonreflecting substrate. The purpose of multilayer systems is to approximate the ideal surface conditions for exposure. Fig. 6 illustrates the multilayer structure used. An absorbing polymer, 1 to 3 μm thick, is used to planarize the substrate topography. The planarized surface enables the uniform dispense of the top resist layer and thus suppresses the bulk effect. The absorption of the bottom polymer eliminates reflections from the substrate topography and reduces the standing-wave effect. An intermediate silicon nitride layer serves as a reactive ion etch shield for the pattern transfer to the bottom layer. The silicon nitride has an index of approximately 1.8, which minimizes reflections from the nitride–resist interfaces. If the differential etch rate between the top and bottom polymers were sufficient, an intermediate layer would not be required.

Suitable materials for the bottom layer are polymers that have good planarization capabilities. Transparent polymers may be made absorbing with the addition of dye. The dye must dissolve in the polymer and absorb strongly at the exposing wavelength. In addition, processing is simplified if the dye is transparent at the alignment wavelength. Transparency at the alignment wavelength allows detection of the alignment mark through the thick bottom polymer. Many of the laser dyes meet these requirements. Fig. 7 shows the transmission spectra of several polymers measured with a spectrophotometer. Curve (*A*) shows the transmission spectrum of a 1.5-μm coating of Hunt 204 positive resist baked at 160°C for 30 min in a box oven. Curve (*B*) shows the transmission of a 1.7-μm coating of Hunt positive resist with the addition of a 1.5-percent concentration by weight of dye. The Hunt film absorbs 20–25 percent of the exposure light at 436 nm in a single pass, while the Hunt 204 with dye absorbs nearly 92 percent of the exposure light. Positive resist without dye may be made more absorbing by hardbaking at a higher temperature or for a longer time [14].

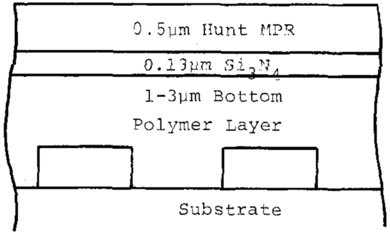


Fig. 6. Tri-layer resist system.

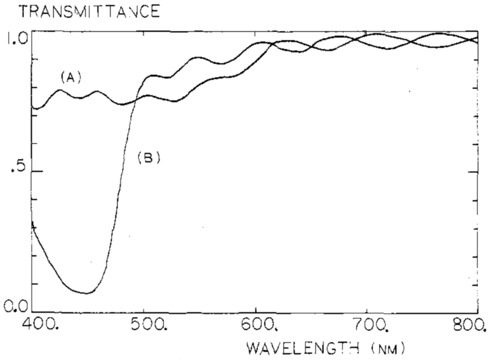


Fig. 7. Transmittance spectra of (*A*) 1.5-μm HPR 204 and (*B*) 1.7-μm HPR 204 with 1.5-percent concentration of dye by weight in solution after hard bake in a box oven at 160°C for 30 min.

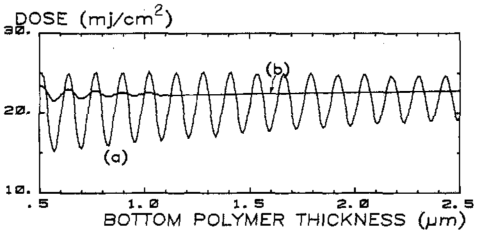


Fig. 8. Nominal dose versus bottom polymer thickness for the tri-layer system of Fig. 6 on an aluminum substrate for (*a*) HPR 204 for the bottom polymer and (*b*) HPR 204 with 1.5-percent dye. Simulations are for 1-μm lines and spaces under perfect focus.

Fig. 8 shows the simulated nominal dose required to print 1-μm lines and spaces as a function of the thickness of the bottom polymer for the tri-layer system of Fig. 6. Curve (*a*) assumes the absorption given for the Hunt resist of Fig. 7(*A*), and curve (*b*) assumes the absorption for Hunt resist with dye in Fig. 7(*B*). The addition of dye significantly reduces the variation in the nominal exposure dose due to the standing-wave effect. From Fig. 8(*b*), a 1.1 μm of positive resist with dye should suppress reflections from the underlying topography. In other words, the highest point on the substrate topography must be

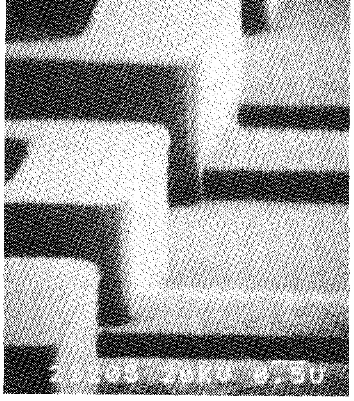


Fig. 9. Edge profile of 2.0 μm of HPR 204 on 0.5-μm polysilicon steps after reactive ion etching.

covered with at least 1 μm of Hunt resist with dye in order to suppress reflections and scattered light from the topography.

In the experiments that follow, a resolution test mask was used to print lines and spaces over aluminized substrates with 0.5-μm steps. A number of bottom polymers were tried. Positive resist was used because of its superior planarization properties [13]. The intermediate layer was 130 nm of silicon nitride deposited by plasma-enhanced CVD at room temperature. The top layer of resist was approximately 0.5 μm of Hunt MPR. A GCA DSW4800 stepper was used to expose the top layer of positive resist. The wafers were then developed in a spray developer with a 2:1 solution of AZ MF312. Pattern transfer from the top resist to the silicon nitride was achieved by plasma etching with CF_4 at 4 mtorr. An oxygen reactive ion etch process was used to transfer the pattern to the bottom polymer. A 0.1-W/cm^2 RF power density at 4-mtorr pressure resulted in a 70-nm/min etch rate. Undercut was minimal as shown in the micrograph of Fig. 9.

IV. Results

A. Simulation

Computer simulations were used for analysis and process optimization. In addition to the optical parameters of the aligner and the exposure–development parameters of the resist, the simulation of the tri-layer system considers the indices of the materials and thicknesses of the various layers. Steps on the substrate are simulated as a variation in the bottom polymer thickness. The resist linewidth for 1-μm lines and spaces traversing steps and the nominal dose required were investigated. The simulations demonstrate the bulk and standing-wave effects associated with the thickness variation of the layers and with the absorption of the bottom polymer.

The tri-layer simulation results for a 1-μm line and space pattern traversing an aluminum step patterned on an aluminum substrate are shown in Fig. 10. A 130-nm nitride intermediate layer and a 0.5-μm top resist layer are assumed for simulation purposes. The bottom polymer is Hunt 204 positive resist, baked at 160°C for 30 min. Fig. 10(a) shows the simulated linewidth for a 1-μm line and space pattern versus the thickness of the bottom polymer for a nominal exposure of the top resist of 21 mJ/cm^2 at 436 nm, the average exposure of Fig. 8(a). The optical parameters are those of the caption of Fig. 4.

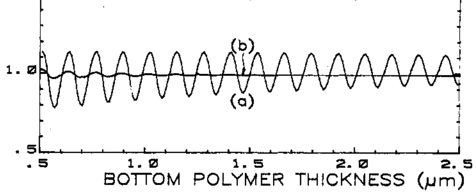


Fig. 10. Simulated linewidth versus bottom polymer thickness for 1-μm lines and spaces for a bottom polymer of (a) HPR 204 and (b) HPR 204 with 1.5-percent dye.

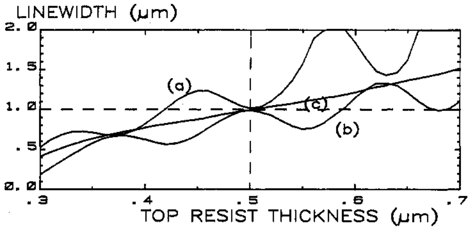


Fig. 11. Simulated linewidth versus top resist thickness for 1-μm lines and spaces for (a) 0.95-μm bottom layer of HPR 204 and dose of 16 mJ/cm^2 for the top layer; (b) 1.03-μm bottom layer of HPR 204 and dose of 25 mJ/cm^2 for the top layer; (c) 1.0-μm bottom layer of HPR 204 + dye and 21-mJ/cm^2 dose for the top layer of resist.

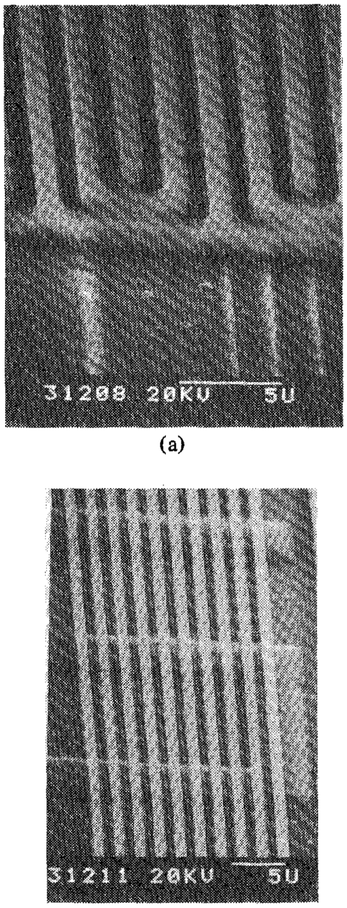
The periodic linewidth variation results from multiple reflections from the substrate topology, or the standing-wave effect. Since the bottom resist is somewhat absorbing, a thicker bottom resist partially absorbs the reflections and reduces the standing-wave effect. Bulk effects are not directly observed with thickness variation of the bottom polymer, since the top layer of resist was assumed uniformly thick by the simulation.

If the bottom polymer does not sufficiently planarize the surface, the top layer of resist will dispense nonuniformly. Fig. 11(a), (b) shows the simulated linewidth as a function of top resist thickness for the bottom polymer thicknesses of 1.03 and 0.95 μm, representing two extremes of Fig. 8(a). In both cases, the exposure dose has been adjusted to produce a 1-μm line for a 0.5-μm-thick top resist. Both the bulk and standing-wave effects are clearly seen. If the top resist were uniformly 0.5 μm thick, the nominal exposure required to maintain 1-μm features would change from 16 mJ/cm^2 for a bottom layer of 0.95 μm to 25 mJ/cm^2 for a 1.03-μm bottom layer. The exposure variation is too great to achieve linewidth control over the entire wafer.

The addition of 1.5-percent dye to the bottom polymer of the tri-layer system suppresses the standing-wave effect of Fig. 10(a). Fig. 10(b) shows that a 1-μm film of Hunt resist with dye essentially eliminates the nominal exposure variation due to reflections from the aluminum topography. Fig. 11(c) shows the linewidth variation versus the top resist thickness for a 1-μm-thick bottom resist with dye. The linewidth variation is entirely due to the bulk effect. Since positive resist as a bottom polymer has been shown to planarize well, the top resist thickness can be held to close tolerance, and good linewidth control is expected.

B. Experiment

A resolution test mask was used to print 1-μm lines and spaces over 0.5-μm topography using the tri-layer system and a GCA



(a)

(b)

Fig. 12. 1-μm lines and spaces in tri-layer resist with 2.0-μm HPR 204 + 1.5-percent dye as the bottom polymer over 0.5-μm aluminum steps after reactive ion etching. (a) Side view to show planarization. (b) Top view to show linewidth control.

DSW4800 stepper. In order to consider the worst case, the topography was coated with highly reflecting aluminum before laying down the three-layer system. HPR 204 resist with and without dye was used as the bottom polymer. The dye absorbs strongly at the exposure wavelength and is transparent at the alignment wavelength. An exposure–focus matrix was used to determine optimum exposure conditions for the top resist. The image in the top resist is transferred to the silicon nitride with a plasma etch. The bottom layer is etched using reactive ion etching.

Fig. 12(a) and (b) shows SEM micrographs of 1-μm features patterned in the 2.0-μm HPR 204 bottom resist containing 1.5-percent dye over 0.5-μm aluminum topography. Since the 2.0-μm bottom resist planarizes the topography well, the thickness of the top resist layer is controlled to about 0.03 μm. The bulk effect of Fig. 11(*c*) is minimized. The standing-wave effect due to the topography is eliminated by the absorbing dye, as indicated by Fig. 10(*b*). Because the wafer surface appears planar and nonreflective, excellent linewidth control of 1-μm features over steps is achieved.

Fig. 13 shows a SEM micrograph of 1-μm features in a 2.6-μm bottom resist layer without dye over 0.5-μm aluminum steps. Although the bottom resist is partially absorbing without the addition of dye, the standing-wave effect due to reflections from the topography is not completely eliminated, as indicated by Fig. 10(*a*). Increasing the thickness or intensely hardbaking the bottom resist would reduce the standing-wave effect.

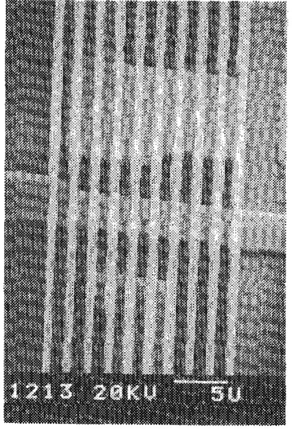


Fig. 13. 1-μm lines and spaces in tri-layer resist with 2.0-μm HPR 204 as the bottom polymer over 0.5-μm aluminum steps after reactive ion etching.

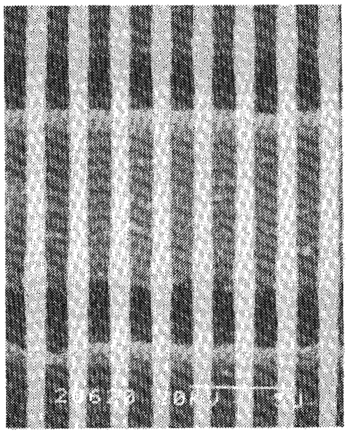


Fig. 14. 1-μm lines and spaces in tri-layer resist with 2.0-μm HPR 204 + 1.5-percent dye as the bottom polymer over 1.0-μm aluminum steps after reactive etching.

Thicker topography inhibits planarization. Fig. 14 shows a SEM micrograph of 1-μm features of 2.0-μm bottom layer of HPR 204 resist with dye over 1.0-μm aluminum steps. The linewidth variation is caused by insufficient planarization of the bottom layer polymer.

V. CONCLUSIONS

The tri-layer resist system incorporating an absorbing dye in the bottom polymer improves the usable resolution of projection aligners. One micrometer features over topography are achievable. Since the effect of the topography are eliminated, the exposure for each masking layer is essentially constant. The dye concept offers flexibility for the material selection of the bottom polymer and for the exposure system. Simulations of the tri-layer system provide an analytical explanation of the experimental results and aid in process optimization.

ACKNOWLEDGMENT

The authors wish to thank D. Ilic and P. Marcoux for their help with the PECVD nitride and G. Rankin for useful discussions on plasma etching.

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase®
Smarter legal research.