Thin hardmask patterning stacks for the 22-nm node

Zhimin Zhu[a], Emil Piscani[b], Yubao Wang[a], Jan Macie[a], Charles J. Neef[a], and Brian Smith[a]

[a] Brewer Science, Inc., 2401 Brewer Drive, Rolla, Missouri 65401, USA,
zzhu@brewerscience.com
[b] Resist and Material Development Center, SEMATECH, 257 Fuller Road, Albany,
New York 12203, USA

ABSTRACT

This paper presents robust trilayer lithography technology for cutting-edge IC fabrication and double-patterning applications. The goal is to reduce the thickness of a silicon hardmask so that the minimum thickness of the photoresist is not limited by the etch budget and can be optimized for lithography performance. Successful results of pattern etching through a 300-nm carbon layer are presented to prove that a 13.5-nm silicon hardmask is thick enough to transfer the line pattern. Another highlight of this work is the use of a simulation tool to design the stack so that UV light is concentrated at the bottom of the trenches. This design helps to clear the resist in the trenches and prevent resist top loss. An experiment was designed to validate the assumption with 45-nm dense lines at various exposure doses, using an Exitech MS-193i immersion microstepper (NA = 1.3) at the SEMATECH Resist Test Center. Results show that such a stack design obtains very wide CD processing window and is robust for 1:3 line patterning at the diffraction limit, as well as for patterning small contact holes.

Key words: thin spin-on silicon hardmask, thin resist, UV distribution, foot exposure (FE), top exposure (TE), double patterning (DP)

1. INTRODUCTION

Semiconductor manufacturers are increasingly interested in spin-on hardmask technology due to its lower cost and higher throughput compared to hardmasks applied by chemical vapor deposition. Silicon-based hardmasks have very high resistance to oxygen plasma etching.[1] In a trilayer application, a very thin hardmask (13.5 nm) is sufficient to transfer a pattern into a thick (300-nm) spin-on carbon-based underlayer, and therefore the photoresist, or imaging layer, can in turn be very thin. The ability to use a thin resist has great advantages for a variety of IC patterning applications. First of all, a smaller line aspect-ratio requires less resist adhesion to the substrate to prevent collapse due to the lower capillary force torque, especially for patterning smaller feature sizes. In a double-patterning process where a 1:3 line:space pattern is obtained from the overexposure of a 1:1 aerial image, thinner resist would ameliorate line collapse to increase the processing window. On the other hand, thin resist lithography is challenging because top loss, layer intermixing, and photoacid leakage can become more pronounced. The goal of this study is to examine how far the process window can be improved through changes in both resist and hardmask thickness.

In the lithography process resist should adhere well to the substrate to prevent line collapse, and it should be easy to clear out in trenches to prevent footing and scumming problems. However, in most cases of immersion lithography engineers are struggling with footing and scumming issues. Many explanations exist for these issues, such as developer flow dynamics, photoacid diffusion, or substrate poisoning. Eventually it is the UV exposure that converts a resist from being highly adhesive to being easy to remove. Therefore, in the optical design, the UV intensity should be conducted onto the bottom of trenches. Conventional stack design is based on minimum substrate reflectivity. Consequently, the ever-increasing optical absorption (k-value) reduces the UV intensity at the resist bottom to cause the footing and scumming. In this work a Brewer Science internal simulation tool (OptiStack™ tool) was used for the stack design.[1-3] The tool takes the optical phase shift of the reflectivity into account and calculates the UV distribution at the bottom and top of the resist. A good stack design should allow a

Optical Microlithography XXII, edited by Harry J. Levinson, Mircea V. Dusa, Proc. of SPIE Vol. 7274,
72742K · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.813816

small amount of substrate reflectivity to obtain constructive interference at the resist bottom by controlling the amount of optical phase shift. When the resist thickness is reduced to less than one standing wave period, the standing wave is not visible in the line profile, and the profile is less important when the resist is thin.

2. STACK DESIGN

The stack was designed with the help of the simulation tool, which provides highly accurate results calculated from a full vector diffraction model. Unlike commercial simulation tools, the output R% is an effective reflectivity that is calculated from the UV distribution 50 nm around a line edge, as shown in Figure 1. This method allows the standing wave smoothing of incoherent illumination to be taken into account. Two important parameters, foot exposure (FE) and top exposure (TE), are introduced as new design criteria. They are defined by equations (1) and (2), respectively, and are illustrated in Figure 1.

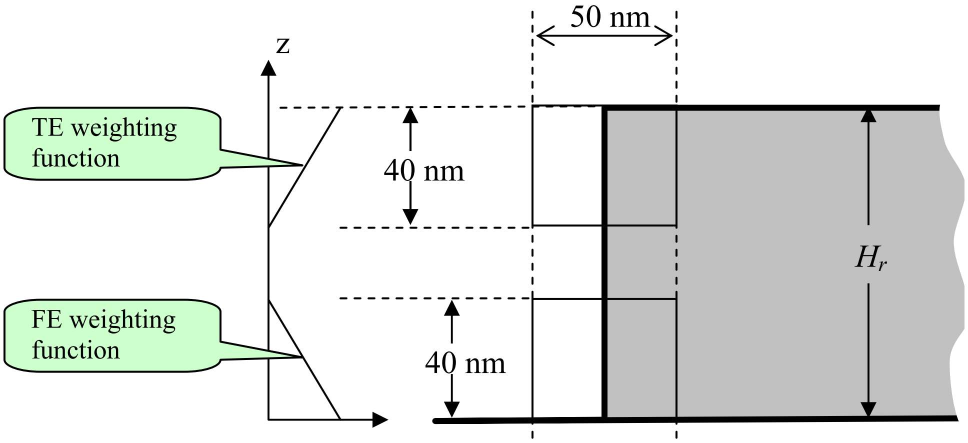


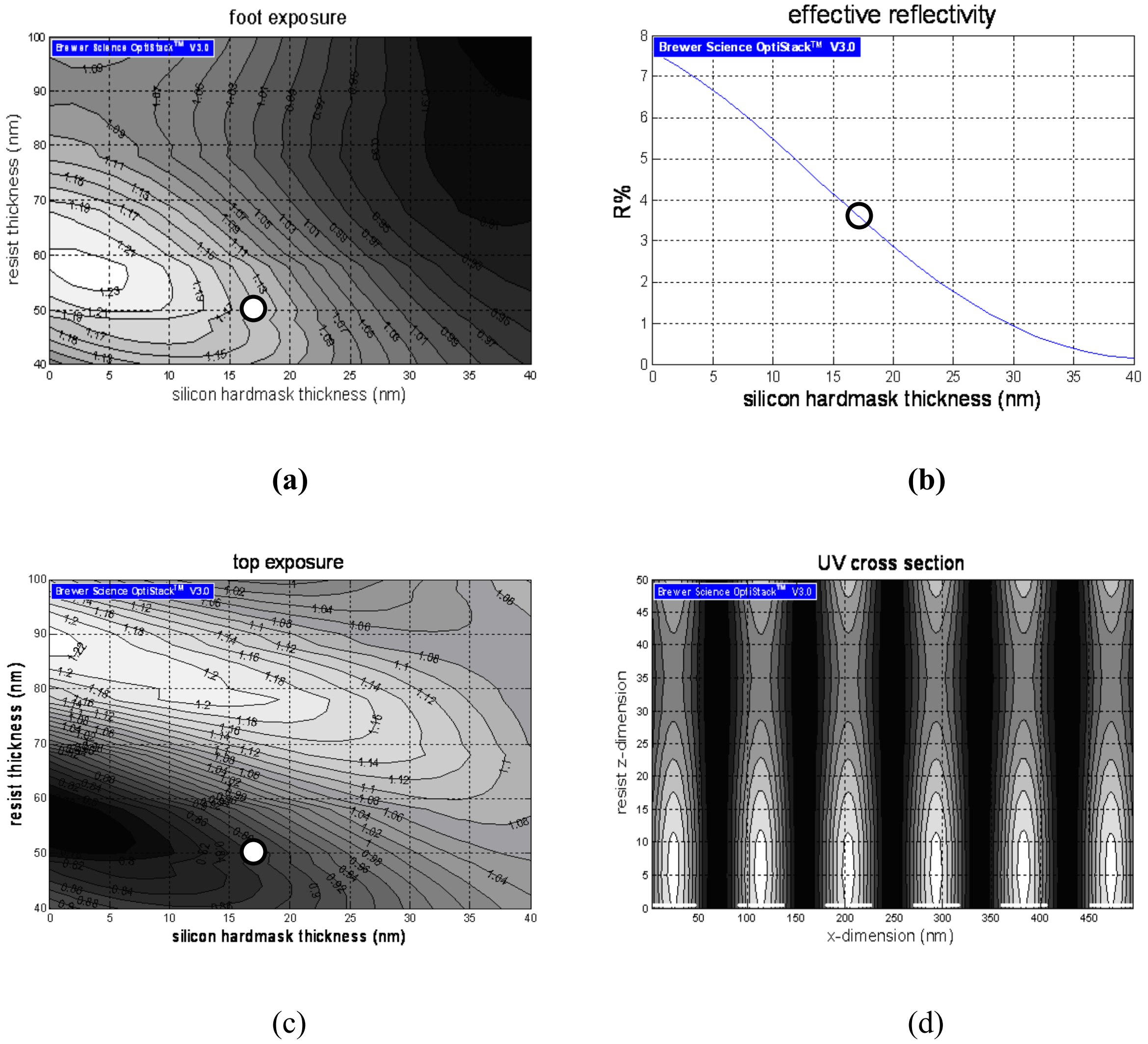
Figure 1. Simulation evaluates UV distribution at the line edge and 25 nm to each side.

$$FE = \frac{\int_0^{40nm} I(z)(40-z)dz}{\frac{1}{H_r}\int_0^{H_r} I(z)dz \int_0^{40nm}(40-z)dz} \quad (1)$$

and

$$TE = \frac{\int_{H_r-40nm}^{H_r} I(z)(H_r-z)dz}{\frac{1}{H_r}\int_0^{H_r} I(z)dz \int_{H_r-40nm}^{H_r}(H_r-z)dz} \quad (2)$$

where *I*(*z*) is the average intensity at resist z points over 50 nm in the horizontal direction, and H_r is the height of the resist. Calculations are made in nanometers. The formulas present a weighted-average UV exposure at the bottom or at the top. The trilayer patterning system under investigation consisted of the following layers: a thick spin-on carbon layer (Brewer Science OptiStack™SOC110D) was applied onto a silicon substrate, and then a silicon hardmask (Brewer Science OptiStack™HM710) was applied on top. Diluted photoresist (TARF-Pi6-001 ME from TOK) was then applied, along with a topcoat (TCX041 from JSR), as shown in Figure 4. The simulation results are shown in Figure 2.



(a) **(b)**

(c) (d)

Figure 2. Simulation results: (a) foot exposure, (b) effective reflectivity, and (c) top exposure. (d) is the UV distribution at wafer cross-section for the chosen design point. The white thick line at the bottom in (d) is the ideal trench location along the x-axis. The illumination setup: NA = 1.3, 45 nm 1:1 pattern, dipole sigma= 0.67/0.97 with TE polarization. The stack in the simulation is (from top down) the topcoat, the resist, the silicon BARC hardmask, the thick spin-on carbon layer, and the silicon substrate, as shown in Figure 4.

The stack design was based on these contours and material processing commitments. Although an even thinner silicon BARC would give higher FE and lower TE, higher substrate reflectivity would be needed. Therefore, to compromise, we chose 17 nm as the hardmask thickness, as indicated by the white circle in Figure 2. At this thickness, the maximum FE at low TE is found at a resist thickness of 50 nm, where FE = 1.164, TE = 0.847, and R% = 3.62, respectively. Figure 2(d) is the UV distribution for this design point and is close to an optimum design. For this type of simulation, a fine tuning may required based on the experimental results. FE may need to be increased or reduced to eliminate footing or line collapse. The silicon content of the BARC hardmask was 39%. To make sure the silicon hardmask has enough etch resistance, an even thinner hardmask layer was used. Figure 3 shows the etch results with a 13.5-nm thick BARC hardmask layer. The line pattern was transferred all the way through the 300-nm carbon layer. The etch work was done with an Oxford PlasmaLab 80Plus reactive ion etcher.

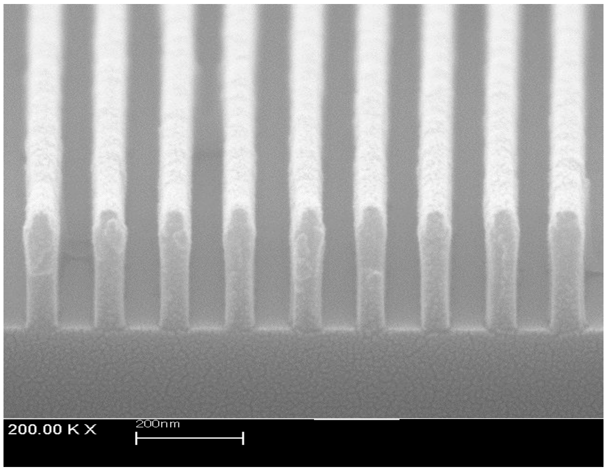


Figure 3. Preliminary etching results of the trilayer patterning system with a 13.5-nm silicon hardmask on top of a 300-nm spin-on carbon layer. The line width is 64 nm, and the substrate is silicon.

3. LITHOGRAPHY RESULTS

Figure 4 shows the stack from the design point in Figure 2. To obtain 22.5-nm 1:3 lines by overexposure for double-patterning applications, 45-nm dense lines were targeted using a 6% attenuated phase shift mask. Exposure was done with the Exitech MS-193i immersion microstepper (NA = 1.3) at the SEMATECH Resist Test Center using their standard 45-nm dense line illumination setup, sigma=0.67/0.97. For the preliminary results the measured Bossung curves are shown in Figure 5(a), which presents a very wide range of exposure latitude and depth-of-focus (DoF). The minimum line width obtained is 19 nm, for which the top-down CD SEM micrograph is shown in Figure 5(b). The line edge roughness is qualitatively excellent for a feature having such a small CD. Figure 6 shows the cross-section of a 45-nm dense line pattern generated with an Amphibian™ interferometer stepper. As the TE is very low, very little resist top loss occurred. With ProDATA to fit the measured data the Bossung curves and CD processing window (for CD=35nm) are given in Figure 7 (a) and (b) where the depth of focus for 10% CD and 10% exposure latitude tolerance is as wide as 330 nm. This window was further improved by reducing the sigma diameter from 0.3 to 0.24. The results are shown in Figure 7 (c) and (d), where the DoF extended to 450nm.

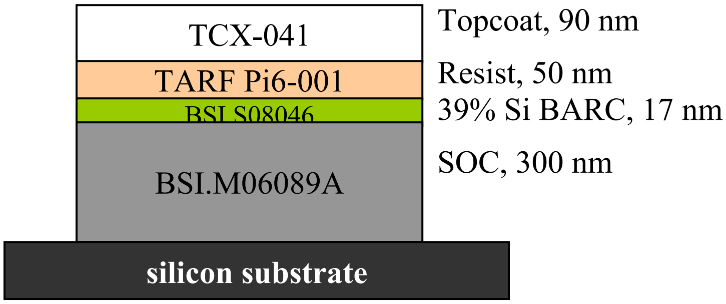
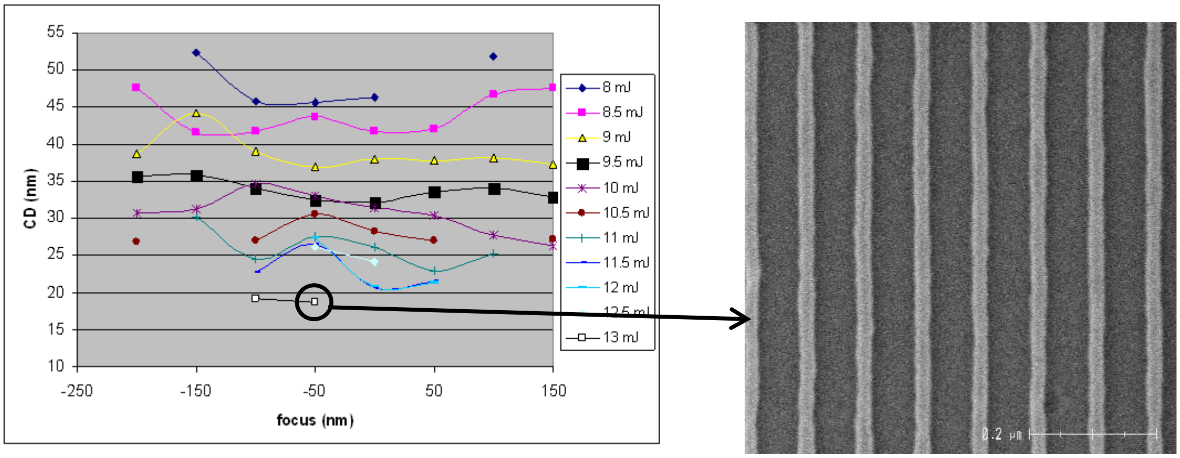


Figure 4. The spin-coated patterning stack from the design point in Figure 2.



(a) (b)

Figure 5. (a) Measured Bossung curves of the lithography results; (b) top down SEM picture for the narrow line.

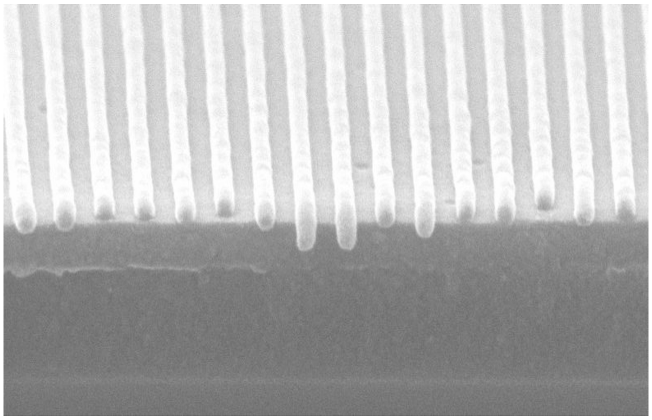
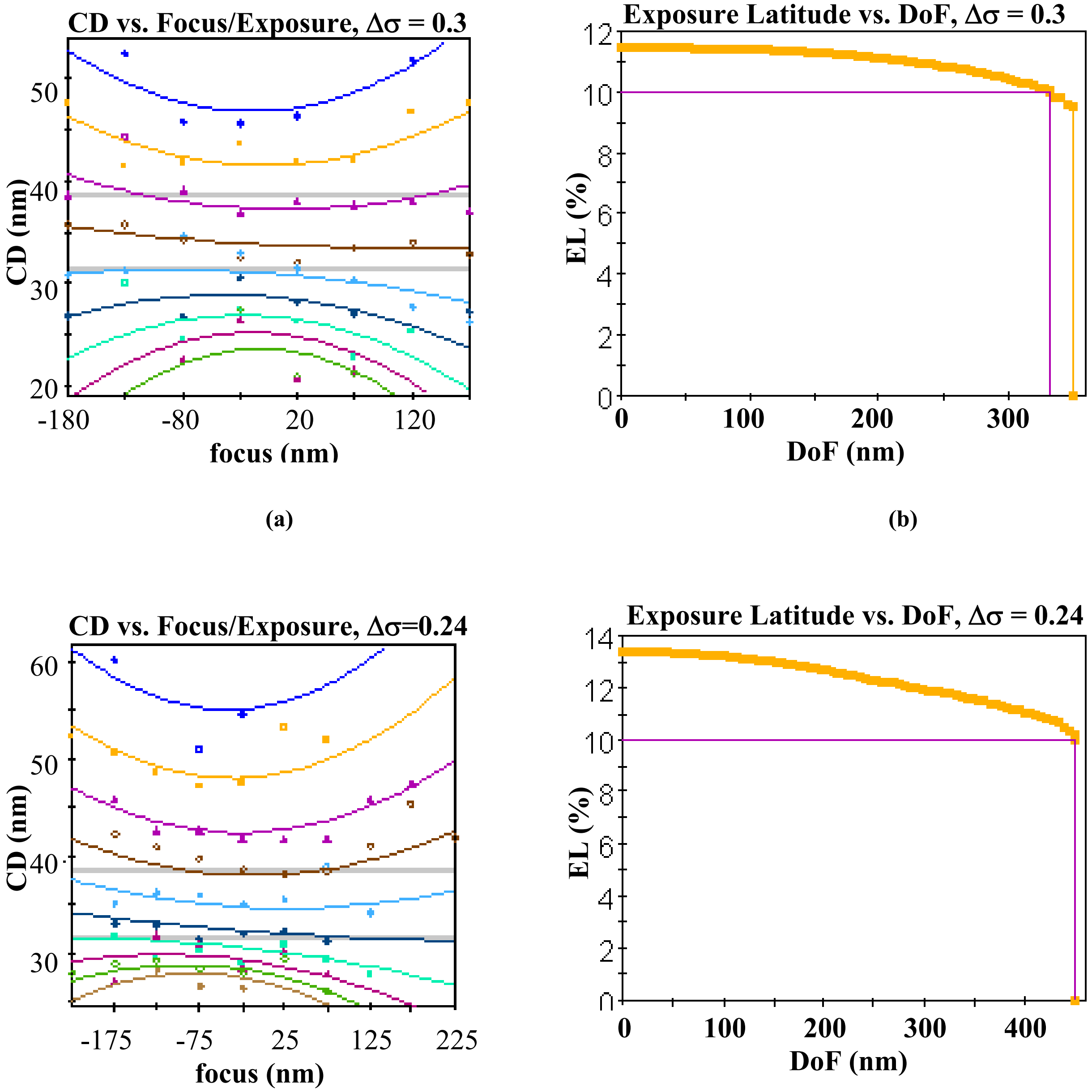


Figure 6. Cross-section view of 45-nm 1:1 pattern generated with an Amphibian™ interferometer stepper. Very little resist top loss occurred.



(a) **(b)**

(c) **(d)**

Figure 7. Bossung curves and EL/DoF curve obtained from ProDATA; (a) and (b) are the results from the first design described in Figure 2; the processing window is improved by reducing the illumination aperture from 0.3 to 0.24, of which the results are shown in (c) and (d).

4. DISCUSSION

This work demonstrated the advantage of thin resist lithography made possible by the use of new materials for the patterning stack. The preliminary experimental results are very promising. The resulting processing window is very large and could be improved by a few means. The sigma area has been reduced to improve DoF as shown by Figure 7 (c) and (d). The TE should be increased to obtain larger CD (or smaller trenches). The problem is that the photoacid generated at the trench bottom does not diffuse sufficiently to the top to fully open the resist until the exposure level is high enough. However, at this exposure level the stack is overexposed for the desired CD target. This effect will be worsened for resists having a low diffusion rate. The FE value may also need to be reduced to extend the CD window down to narrower trenches.

5. ACKNOWLEDGEMENTS

This work was supported by SEMATECH Resist and Material Development Center personnel including Dominic Ashworth, Sandy Finkey, Paula Yergeau, Khurshid Anwar, David Amedure, Rob Gantt, Scott Wright, and Warren Montgomery.

REFERENCES

1. Weimer, M., Wang, Y., Neef, C.J., Claypool, J., Edwards, K., and Zhu, Z., "Materials and performance of multilayer lithographic schemes," *Proceedings of SPIE*, vol. 6519, 65192S-1 - 65192S-8 (2007).
2. Zhimin, Z., Emil, P., Kevin, E., and Brian S., "Reflection control in hyper-NA immersion lithography," *Proceedings of SPIE*, vol. 6924, 2008, pp. 69244A-1 - 69244A-7.
3. Brewer, T., Carlson, R., and Arnold, J., "The Reduction of the Standing-Wave Effect in Positive Photoresists," *Journal of Applied Photographic Engineering*, vol. 7, no. 6, 184-186 (1981).