Contrast enhancement techniques for submicron optical lithography

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Contrast enhancement lithography (CEL), in which a bleachable film is deposited on a conventional photoresist, is studied theoretically and described mathematically. The resulting CEL model is used to understand the behavior of contrast enhancement lithography as well as the materials used. Effects such as resist sidewall angle improvement, exposure latitude, CEL thickness latitude, and CEL parameter optimization are studied. Other methods of "contrast enhancement" are explored.

I. INTRODUCTION

Geometries of production of very large scale integrated (VLSI) circuits have reached 1-μm feature sizes and are currently pushing into the submicron regime. Although techniques such as electron beam, ion beam, and x-ray lithography have demonstrated sufficient resolution to meet submicron lithography needs, poor throughput and other problems have precluded their use in production for the immediate future. Thus, optical lithography, long the workhorse of the microelectronics industry, will be called upon to satisfy the submicron requirements of production VLSI manufacturing through 1990, and probably beyond. The next generation of deep-UV optical lithography tools, currently under development, will have theoretical resolution limits down to 0.4 μm.[1] However, of more immediate importance is the practical resolution of a lithography process, i.e., the smallest feature that can be produced within specified linewidth tolerances with sufficient process latitude. The practical resolution limit is of course dependent on the theoretical limits of the tool, but also on the specific resist process used. Thus, an active area of research is the study of the resist process in order to improve the practical resolution.

One method which has been proposed to extend the practical resolution of current lithographic tools is called contrast enhancement lithography (CEL). The CEL process, in which a bleachable film is deposited on a conventional photoresist, improves the single-layer resist process by making the resulting resist sidewalls more vertical. This improvement, in turn, increases the process latitude of subsequent etching operations and thus extends the practical resolution of the pattern transfer process. In this paper, the theory of contrast enhancement lithography will be given and a model for CEL will be developed. This model, when combined with a model for the photoresist process, will be used to predict the effects of CEL and optimize processing and materials parameters.

II. THEORY OF CONTRAST ENHANCEMENT LITHOGRAPHY

Physical descriptions of the contrast enhancement effect have been given previously.[2-5] Here, the outline of a more rigorous mathematical treatment will be given. A typical CEL process is shown in Fig. 1. The contrast enhancement material (CEM), which is originally opaque to exposing radiation, bleaches as it is being exposed. As a result, the exposed regions become transparent allowing light to reach the photoresist. This bleaching reaction can be characterized by measuring the light transmitted by the CEM as it is being exposed (Fig. 2). The reaction of the bleachable material to form a (nearly) transparent product is first order and is governed by simple kinetics;

$$dx/dt = -CIx, \tag{1}$$

where x is the fraction of unbleached material remaining, I is the intensity of light within the material, and C is the exposure rate constant. For the simple case of CEM on a nonreflecting substrate (such as quartz), the intensity within the CEM is governed by the familiar absorption equation

$$dI/dz = -\alpha I, \tag{2}$$

where α is the absorption coefficient. The absorption coefficient, in turn, is dependent on the amount of unbleached material present:

$$\alpha = Ax + B, \tag{3}$$

where A and B are constants for a particular material at a

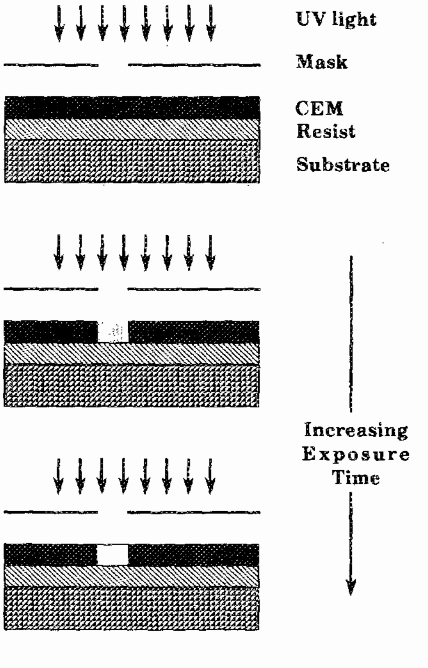

FIG. 1. Bleaching of contrast enhancement material (CEM).

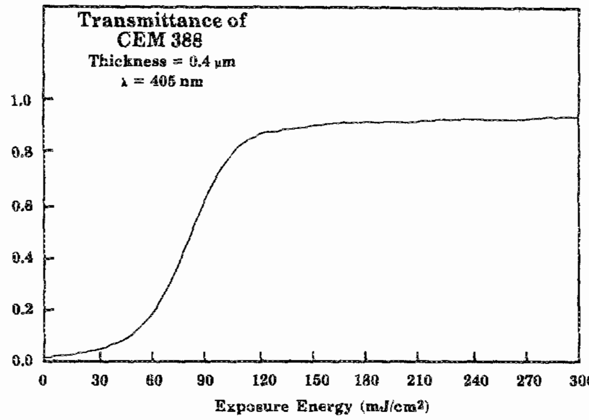

FIG. 2. Light transmitted through CEM-388 as it is exposed.

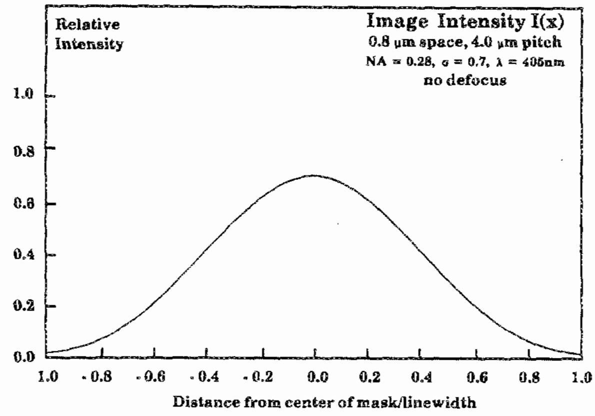

FIG. 3. Image intensity distribution used to expose CEM/resist in modeling studies.

given wavelength. The solution of these three equations will allow the prediction of the light transmitted by the CEM as it is being exposed. By comparing predicted and measured transmittances, the parameters A, B, and C can be determined. This has been done for two commercial contrast enhancement materials with the results shown in Table I.

The simple model above, which applies only to CEM on a nonreflecting substrate, can now be used to predict the effects of the CEM on an aerial image projected onto its surface. A typical image intensity distribution for a 0.8-μm space is shown in Fig. 3. Applying the above model, one can determine the transmitted intensity as a function of the lateral position as well as exposure time. The result is a transmitted image which varies with time as shown in Fig. 4.

This simple model can now be expanded to include the effects of other than a nonreflecting substrate. An analytical expression for the electrical field within an arbitrary absorbing material (such as a CEM) on top of any number of arbitrary materials (such as resist on silicon) has been previously derived[6];

$$E_2(x,y,z) = E_I(x,y)\tau_{12}\frac{\exp(-ik_2z) + \rho'_{23}\tau_D^2\exp(ik_2z)}{1+\rho_{12}\rho'_{23}\tau_D^2}, \quad (4)$$

where $E_I(x,y)$ = the incident wave at $z=0$; $\rho_{ij} = (n_i - n_j)/(n_i + n_j)$, the reflection coefficient; ρ' = the effective reflection coefficient (defined in Ref. 6); $\tau_{ij} = 2n_i/(n_i + n_j)$, the transmission coefficient; $\tau_D = \exp(-ik_2D)$, the internal transmittance of the resist film; $k_j = 2\pi n_j/\lambda$, the propagation constant; $n_j = n_j \pm i\kappa_j$, the complex index of refraction; and λ = vacuum wavelength of the incident light. The intensity can be determined easily from Eq. (4). Thus, solving this equation with Eqs. (1) and (3), an accurate model of CEM bleaching is obtained. Note that the above expression assumes that the light exposure the CEM/resist is a plane wave. Thus, the shape of the aerial image is not affected by substrate reflectance and the curves of Fig. 4 are still valid. This model has been combined with models for the exposure and development of conventional positive photoresists to form an overall model called PROLITH (the positive resist optical lithography model).[7,8] This model will be used now to simulate the performance of the CEL process.

TABLE I. Measured parameters for commercially available contrast enhancement materials.

	Wavelength (nm)	A (μm^{-1})	B (μm^{-1})	C (cm^2/mJ)
CEM-388	436	7.4	0.07	0.029
	405	13.0	0.23	0.070
	365	11.1	0.82	0.066
CEM-420	436	2.9[a]	0.41	0.024
	405	4.1	1.04	0.018
	365	0.55	2.9	···

[a] Material problems may have caused this abnormally low value.

III. SIMULATIONS

For the purposes of this study, a nominal process is defined by the parameters given in Table II. These values are used in all modeling runs except where noted. A matched substrate was used in order to eliminate the effects of standing waves and simplify the measurement of sidewall angle. In all cases (except the ΔCD curves), the exposure energy was adjusted to give the nominal linewidth at the bottom of the resist pattern. With these guidelines in mind, a series of

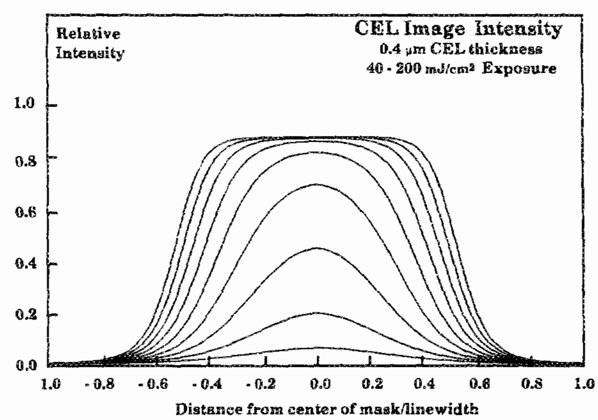

FIG. 4. Image intensity transmitted through CEM for various exposure energies (20 mJ/cm² increments).

TABLE II. Nominal parameters used with PROLITH for CEL modeling studies.

Projection system:	Resist parameters:
Wavelength = 405 nm	$A = 0.6\ \mu m^{-1}$
$NA_0 = 0.28$	$B = 0.1\ \mu m^{-1}$
$\sigma = 0.7$	$C = 0.020\ cm^2/mJ$
Linewidth = 0.8 μm	Refractive index = 1.65
Pattern = space	Thickness = 0.8 μm
CEL parameters:	Developer conditions:
$A = 12.0\ \mu m^{-1}$	Develop time = 60 s
$B = 0.10\ \mu m^{-1}$	$R_{max} = 200$ nm/s
$C = 0.10\ cm^2/mJ$	$R_{min} = 1$ nm/s
Refractive index = 1.70	$mTH = 0.5$
	$n = 5$
Exposure energy:	
Variable	

modeling studies was undertaken to better understand the behavior of contrast enhancement lithography.

The first modeling study examines the effects of contrast enhancement material thickness on exposure energy required and resulting resist sidewall angle. The proper exposure dose is defined as that which gives the nominal linewidth in the final resist image. The outcome of this study is well known: resist sidewall angle is improved at the expense of increased exposure energy (Figs. 5 and 6). It was also observed that the CEL exposure penalty varies linearly with CEM thickness. Thus, once the exposure penalty is known for one thickness of CEM, one can predict the energy required by any other CEM thickness. Note that for CEM thicknesses greater than 400 nm there is very little further improvement in sidewall angle. All simulations were performed assuming a matched substrate so that the conditions represented are idealistic. It is the trends, however, not the absolute numbers that are the subject of this study.

A very interesting question arises when the properties of contrast enhancement lithography are examined. For a given CEL material, is there an optimum resist material to be used with this CEM? To look into this question, the resist parameter C (the bleaching rate constant) was varied in order to determine its effect on sidewall angle. The results, for various CEM thicknesses, are shown in Fig. 7. There is quite definitely an optimum range of values for C. Conventional

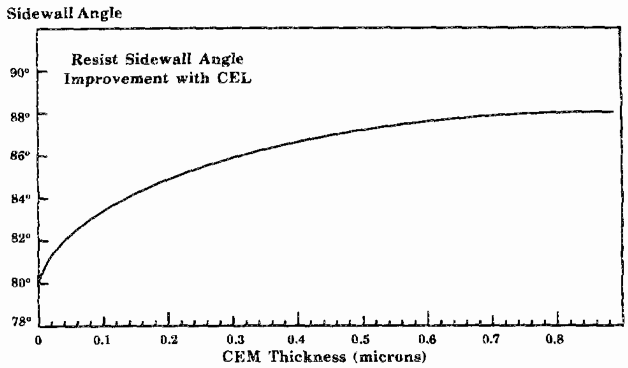

FIG. 6. Resulting resist sidewall angle for various CEM thicknesses.

photoresists, which have values of C of 0.025 to 0.030 cm^2/mJ at 405 nm, are near the optimum value for CEM-388. However, one can see that for CEM thickness greater than 200 nm, resists which are two to three times faster (larger values of C) can be used without significantly degrading the sidewall angle, thus improving throughput. In a similar fashion it is possible, through a series of simulations, to find the optimum CEL parameters for a given resist material. This could be a very important tool in the development of future CEL systems. This type of study is easily accomplished via an appropriate model, but is virtually impossible to perform experimentally.

There has been some question as to whether contrast enhancement lithography has better exposure latitude than a single-layer photoresist process. To help answer this question, the linewidth of a nominal 0.8-μm space was simulated for various exposure energies. This was then repeated for different CEM thickness. The resulting curves are plotted on a scale so that the energy required to give the nominal dimension is normalized to 1. The result, given in Fig. 8, shows that the use of a contrast enhancement material does improve process latitude somewhat. An interesting result of this study is that a CEM thickness of 200 nm offers the best exposure latitude and that thicker CEL layers do not cause any further improvement.

There has been some concern that the CEL process is so sensitive to changes in CEM thickness as to make it imprac-

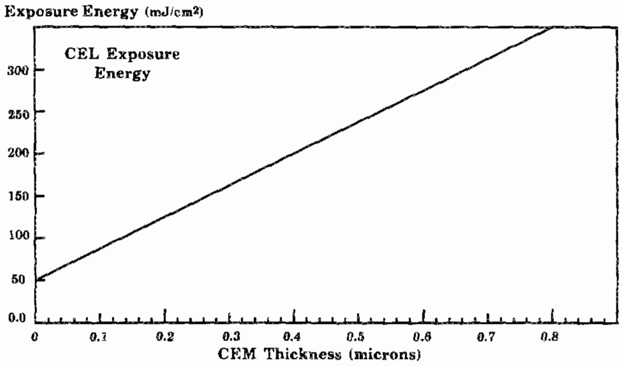

FIG. 5. Exposure energy required for various CEM thicknesses.

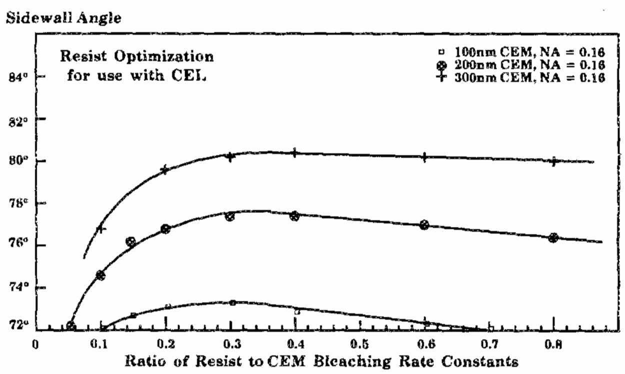

FIG. 7. Optimization of the resist bleaching rate constant C in terms of sidewall angle for use with a CEM.

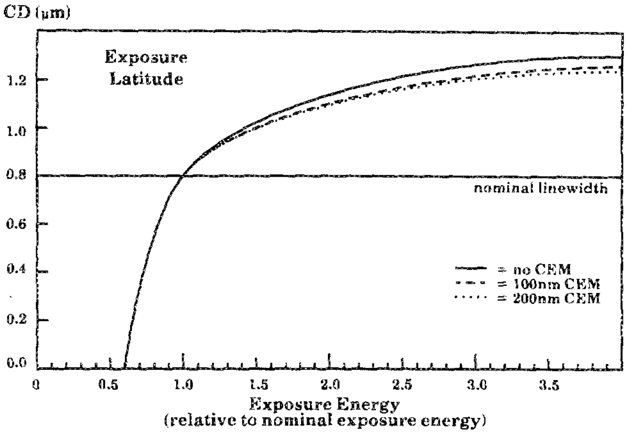

FIG. 8. *CD* variation with exposure energy for different CEM thicknesses.

tical. The fact that CEL processes are currently being used successfully might indicate otherwise. For this reason, a study was performed to investigate the linewidth change due to CEM thickness changes for various nominal CEM thicknesses. The results are shown in Fig. 9. The exposure energy was fixed so as to give the nominal linewidth when the nominal thickness of the contrast enhancement material was used. The result is very similar to an exposure latitude curve in mirror image. This is to be expected since an increase in CEM thickness by a set amount is equivalent to a decrease in exposure energy by a set amount. A recent study of the coating properties of CEM-388 showed that when this material was coated over steps of height 0.55 μm and width greater than 10 μm, CEM thickness variations of ± 0.5 to ± 0.9 μm occurred for a nominal 0.4-μm CEM film.[9] Further work should be done to determine the CEM thickness variations over smaller feature size steps. This information, along with the data of Fig. 9, can be used to estimate linewidth variations over steps due to CEM thickness changes.

IV. CONCLUSIONS

The modeling studies performed show that CEL techniques can improve resist sidewall angles, thus improving the process latitude of subsequent pattern transfer operations. The price paid for this improvement is in throughput. Also, there is a slight improvement in exposure latitude when a CEL process is used. In terms of sidewall angle, exposure latitude, and exposure penalty, the optimum CEM thickness is about 200–400 nm for CEM-388. To generalize for any CEL material, the thickness should be set such that the product of thickness and the CEM parameter A is about 3–4. Thus, CEM-420 at 436-nm exposure requires a thickness of about 1 μm.

When examining the aerial image transmitted through a CEL material, one can see a marked improvement in the image contrast (Fig. 4). However, this image changes with exposure time making the actual contrast improvement much less. It seems likely that if one could somehow expose the CEM in one step then expose the resist in a second step, one could fix the transmitted image and eliminate the problem of a changing image. Two approaches are the built on mask (BOM)[10] and the photochemical image enhancement (PIE)[11] processes. In these techniques, the CEL material is exposed at a wavelength to which the resist is not sensitive. Then the resist is flood exposed through the contrast enhancement layer at a wavelength to which the CEM is not sensitive. The difficulty is in finding a material with the desired properties at the two different wavelengths used.

The major drawback with the above methods is the use of a flood exposure to expose the resist. Thus, the CEM is used to improve the contrast of an image with no contrast (the flood exposure), rather than improving the contrast of an image with already good contrast. A better approach would be to expose the CEM and the resist in two sequential exposures at two different wavelengths in a machine with multiple-wavelength capabilities, such as a scanning projection printer or a broad band stepper. For example, the contrast enhancement material can be exposed through the mask at 310 nm forming a mask of bleached and unbleached areas. Then, without moving the wafer, the resist is exposed at 436 nm, through the same mask, simply by changing a filter in the exposure tool. Such a process, if a suitable material can be found, will result in considerable improvement over the standard CEL process, as well as the PIE and BOM processes.

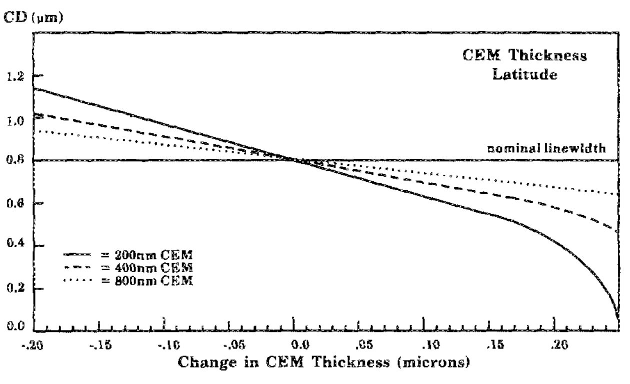

FIG. 9. *CD* variation with CEM thickness.

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