Near-field distribution in light-coupling masks for contact lithography

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We discuss the potential and limitations of light-coupling masks for high-resolution subwavelength optical lithography. Using a three-dimensional fully vectorial numerical approach based on Green's tensor technique, the near-field distribution of the electric field in the photoresist is calculated. We study the dependence of the illuminating light and the angle of incidence on polarization. Furthermore, we investigate the replication of structures of various sizes and separations. It is predicted that the formation of features in the 60 nm range is possible using light with a 248 nm wavelength. However, with decreasing separation among the features, crosstalk limits the ultimate resolution. © *1999 American Vacuum Society.* [S0734-211X(99)04606-5]

I. INTRODUCTION

Hard-contact lithographies can, in theory, replicate features below the wavelength of the incident light.[1] Substrate topography and ubiquitous dust particles prevent the hard chrome mask from establishing a close contact with the substrate, thus limiting the maximal resolution by the minimally attainable gap size. Projection lithographies have replaced hard-contact lithographies because excellent optics in conjunction with step and repeat exposure are able to direct and focus light with an accuracy close to its vacuum wavelength on slightly uneven resist surfaces.[2]

Recently a new approach to high-resolution optical lithography based on light-coupling masks (LCMs) was introduced.[3] The surface of a polymer mask is topographically patterned such that the areas to be exposed in the photoresist form protrusions on the mask surface. The ability of a rubber elastic polymer to adapt to the substrate topography allows the formation of a uniform ''conformal'' contact with the photoresist over large areas. Placing the mask in intimate contact with a resist-coated substrate, mechanical contact between mask and resist layer occurs only in the region to be exposed (Fig. 1). When the LCM is illuminated through its backside, the light is differentially guided by the structure and coupled into the photoresist. This technique, called soft lithography, exploits the virtues of contact lithography and avoids its weaknesses. Soft lithography, on the other hand, is limited by the mechanical stability of protrusions—especially as lateral dimensions shrink and the ratio of lateral to vertical dimensions (aspect ratio) becomes large.[4] Using this approach, Schmid *et al.* demonstrated the formation of features in the 100 nm range with a wavelength of 256 nm.[5]

Rodgers *et al.*[6] focused on the effects of the phase delay between the light beam crossing the air gap and the beam guided within the polymer. By means of this phase-shift lithography, Aizenberg *et al.*[7] demonstrated the fabrication of line structures with a 50 nm linewidth. However, this approach is only suitable for the replication of low-density lines.

In this article we test the limits of the LCM approach when the protrusions guide light into the photoresist. We study numerically the dependence of the near-field distribution in LCMs on typical experimental parameters. The model for our calculations based on the solution of the vectorial wave equation is presented in Sec. II. In Sec. III the results of our simulations are shown. First, we investigate the effects

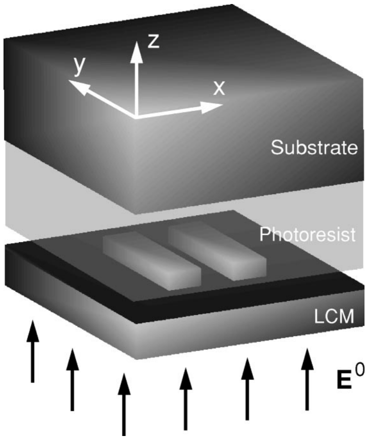

FIG. 1. Schematic view of a LCM and its operation using a normal incident field $\mathbf{E}^0$ through the backside of the LCM. The simulated structures with a width d and a length $4d$ are identical and parallel. In the z direction a fixed protrusion height of 60 nm was chosen. In order to suppress light leaking through the noncontacting sections of the mask, a 15 nm gold absorber was added in recessed parts.

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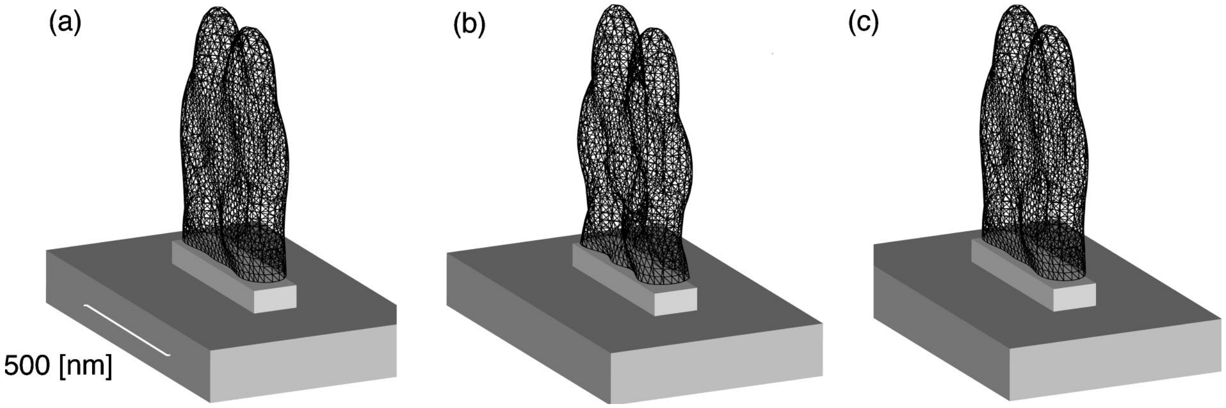

FIG. 2. Illumination of an isolated linelet with $d=120$ nm. The isosurface representing 75% of the incident light intensity is shown. The polarization of the incident light is (a) linear in the y direction, (b) linear in the x direction, and (c) circular. The extension of the isosurface in the photoresist is approximately 650 nm.

of the polarization of the incident field and discuss near-field distributions for various feature sizes. Then, we concentrate on the interaction between neighboring structures and, finally, we examine the consequences of oblique incidence on the resulting intensity profiles.

II. MODEL

We calculate the electric field distribution inside the resist layer caused by the guiding and scattering processes in a LCM illuminated by an incident field $\mathbf{E}^0$. Our calculations are based on Green's tensor technique and take the vectorial character of the electromagnetic field into account. This approach delivers a three-dimensional, self-consistent, and accurate description of the optical processes in the LCM resist system. Thus, it even allows the simulation of structures with dimensions far smaller than the wavelength. For details about the formalism please refer to Ref. 8. It should be emphasized that our approach is different from the in depth projection of the aerial image on the resist surface, since it provides the electric field distribution in the entire structure. One could use our calculated three-dimensional intensity distribution in conjunction with a sophisticated resist model to exactly predict the profile of the developed photoresist.[9,10] However, it has been previously shown that for this particular nanolithography technique, surfaces of constant intensity (or isosurfaces) of the electric field distribution do correspond to the resist profile that is measured experimentally.[3]

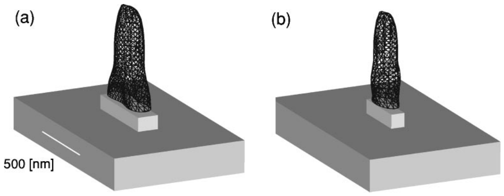

FIG. 3. Isosurfaces of the electric field intensity (75%) in the photoresist using isolated linelets with (a) $d=90$ nm and (b) $d=60$ nm. The incident light is circularly polarized. The extension of the isosurface in the photoresist is approximately 400 nm.

For our simulations we selected short, densely packed lines of width d and length $4d$ because these ''linelets'' are known to be difficult to replicate optically owing to line shortening effects and neighbor interference.[2] We use the term ''design rule'' for the width because in a technological environment the smallest replicable feature width determines the design of an electronic circuit based on this lithographic feature.

The results presented here refer to a vacuum wavelength of the incident light of 248 nm. The optical properties of the simulated resist are linear and isotrop, the refractive index of LCM and photoresist at this wavelength is assumed to be 1.6. Thus, we do not investigate possible reflections on the LCM/photoresist or photoresist/substrate interfaces due to a mismatch of the dielectric constants. In order to suppress the leaking of light through the noncontacting sections of the mask, a 15 nm gold absorber was added in the recessed parts.[11]

III. RESULTS

A. Polarization effects

The direction of polarization of light strongly affects the replication by LCM of features elongated in one dimension.

In Fig. 2 we show isosurfaces of the field intensity distribution in the photoresist created by an isolated linelet for three incident polarizations. The design rule is $d=120$ nm. The best results are achieved with a polarization in the y direction, i.e., parallel to the linelet. In that case, the structure shape is reproduced accurately within the first 250 nm of photoresist, steep edges providing approximately a 1:1 image of the linelet in the resist layer [Fig. 2(a)]. On the other hand, using a polarization in the x direction leads to an irregular field distribution with intensity variations along the sides of the feature as well as in the depth [Fig. 2(b)]. As a complete mask possesses structures in both directions, circular polarization provides a homogeneous illumination. Actually, the field distribution for circular polarization turns out to be close to the ideal parallel polarization case, independent of

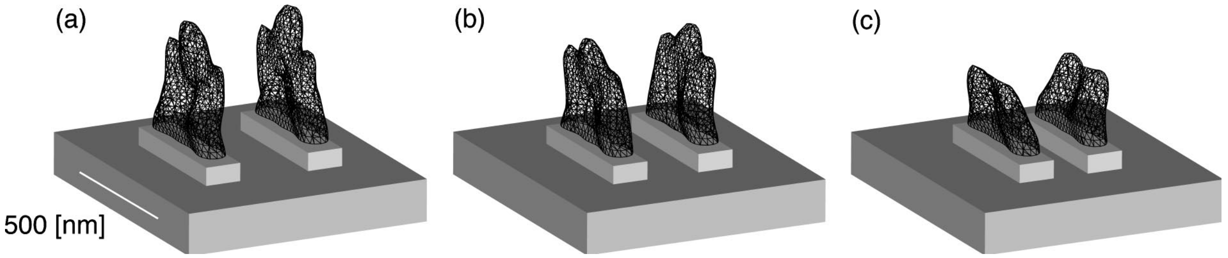

FIG. 4. Isosurfaces of the electric field intensity (75%) in the photoresist using two linelets with $d=120$ nm and separations of (a) $2d$, (b) $1.5d$, and (c) d. The incident light is circularly polarized. The extension of the isosurface in the photoresist in (a) is approximately 400 nm.

the linelets' orientation [compare Figs. 2(a) and 2(c)]. The shape of the structure is well replicated within the first 250 nm of photoresist.

B. Resolution limit for isolated linelets

Figure 3 shows isosurfaces of the field intensity distribution in the photoresist created by an isolated linelet, but with smaller design rules, $d=90$ and $d=60$ nm. In both cases it is still possible to reproduce the structure shape in the photoresist, even for features smaller than 1/4 of the vacuum wavelength of the illuminating light [Fig. 3(b)]. Note that for $d=60$ nm the aspect ratio of the isosurface no longer corresponds to the aspect ratio of the linelet, the field distribution being more constrained. The length of the isosurface $d=15$ nm below the mask in the photoresist is 190 nm, the width 90 nm. This corresponds approximately to an aspect ratio of 1:2, leading to a strong line shortening. However, this figure also shows that structures in the 50 nm range are amenable to this technique. For $d=90$ nm, line shortening increases with the depth in the photoresist, so that 100 nm below the mask the aspect ratio is reduced to 1:3.

C. Two linelets, variation of separation

A realistic mask is not composed of isolated structures but contains a high density of patterns. For increasing density the mutual interactions between neighboring structures become more and more important.

Figure 4 shows isosurfaces of the field intensity distribution in the photoresist for two linelets. The design rule is $d=120$ nm, and the separation is $2d$, $1.5d$, and d. In all cases the crosstalk between neighboring features is relatively small, especially within the relevant resist depth, where the field distribution replicates the mask structure accurately. However, for small separations, the distance between the isosurfaces of the two field distributions increases as light propagates into the photoresist [Fig. 4(c)].

In Fig. 5 the design rule is reduced to $d=60$ nm. For such small structures, crosstalk turns out to be much more important. In the case of a separation equal to d the field distribution no longer reproduces the individual mask features, and a collective scattering behavior is observed: the incident light is focused by the structure such that a single spot appears between the linelets [Fig. 5(a)]. Note, however, that an isolated structure with a design rule of $d=60$ nm can be replicated satisfactorily [Fig. 3(b)]. By increasing the separation to $1.5d$ and $2d$ one recovers the individual features in the near field [Figs. 5(b) and 5(c)]. With a separation of $1.5d$ the isosurface has a length of 100 nm and a width of 40 nm, whereas for a separation of $2d$ the isosurface length is 140 nm and the width 60 nm. This corresponds to the same line shortening as for the isolated linelet.

Working with such small structures, therefore, requires special care to suppress crosstalk. Furthermore, the resist depth seems to be a particularly important issue in that case.

D. Dependence on the angle of incidence

A further important experimental parameter is the dependence of the field intensity distribution on the angle of incidence. Therefore, we also performed calculations for oblique illuminations.

Figure 6 presents lines of equal field intensity for a cut in the x direction of the structure shown in Fig. 2(c). The angles of incidence are 0°, 5°, and 10°; circularly polarized light is used. These graphs emphasize the steepness of the edges, which guarantees the accurate reproduction of the mask features in the photoresist. With increasing angle of incidence the orientation of the isolines follows the direction of the

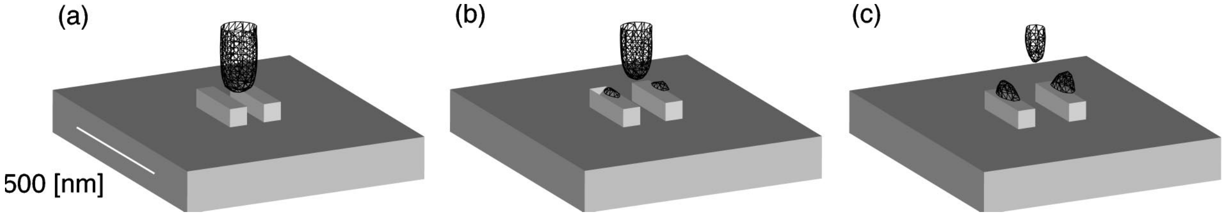

FIG. 5. Same situation as in Fig. 4, but with $d=60$ nm linelets and separations of (a) d, (b) $1.5d$, and (c) $2d$. The extension of the isosurface in the photoresist is in (b) 35 and in (c) 65 nm.

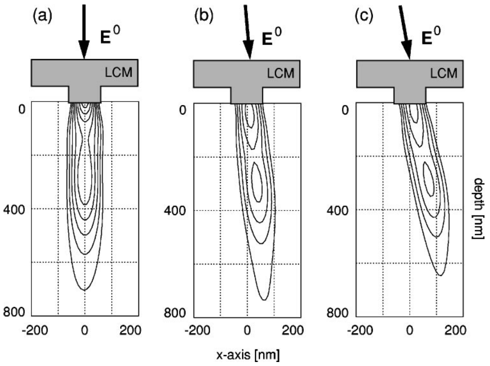

FIG. 6. Isointensity lines for a cross section in the *x* direction of the structure shown in Fig. 2(c), $d = 120$ nm. The illumination directions investigated are: (a) normal incidence, (b) 5° tilt, and (c) 10° tilt. The line spacing corresponds to an intensity increment of 10%, where the outer isoline represents the value of 75% compared to the incident light intensity.

illuminating field. Furthermore, the entire image in the resist layer is slightly shifted in this direction [Figs. 6(a) and 6(b)]. However, for a thin resist layer, the field distribution within the photoresist does not differ much from that at normal incidence, so that a 5° tilt seems tolerable.

IV. SUMMARY

We presented three-dimensional calculations for the near-field distribution in light-coupling masks. It was shown that using an illumination with circularly polarized light, structures can be replicated accurately with steep edges in the photoresist, independent of their orientation on the mask. Even features in the 60 nm range can be reproduced using a 248 nm wavelength. Although crosstalk between neighboring structures appears to be negligible for features of 120 nm, it can become dominant when the size shrinks to 60 nm. Finally, it was illustrated that the process is not very sensitive to small deviations of the angle of incidence.

The numerical results emphasize the suitability of light-coupling masks as a lensless alternative for high-density, high-resolution optical lithography in the subwavelength regime.

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