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Modelling of Resolution Enhancement Processes in Lithography

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Abstract - This paper describes the modelling and simulation of two resolution enhancement techniques in lithography ; 1) phase shift mask (PSM) technology and 2) top surface imaging (TSI) with silylation and dry development. The effect of the duty ratio on the image contrast is computed. Simulated one and two dimensional rim shifters and attenuated PSMs are presented. The effect of the aerial image on the silylation profile for the top imaging processes, DESIRE and PRIME, is also presented. The effect of the first etch step on the final resist profiles is examined. The partial pressure and the presence of magnetic fields are also presented.

I. INTRODUCTION

For the last 30 years, optical lithography has evolved as the dominant competitor in the manufacture of VLSI semiconductor devices while electron beam lithography plays a role in the fabrication of optical masks, and the research and development of ULSI and GaAs devices. Top surface imaging combined with silylation and dry development has been demonstrated as an alternative technique for surmounting the constraints of conventional wet development lithography and allowing the achievable resolution to approach the Rayleigh limit [1]. In the past few years, the use of phase shift masks has resulted in drastically improved aerial image formation [2]. This paper describes the modelling and simulation of these two resolution enhancement techniques in lithography.

At the University of Limerick, a number of simulation programs have been developed for advanced processes in lithography; (1) SIMPHAD [3] (*Si*mulation *M*ethodology for *Pha*se Shift Mask *D*esign) which uses iterative techniques for designing various PSM schemes in one or two dimensions, (2) DESIM [4] (*DE*SIRE *Sim*ulation) for the simulation of silylation (in one-dimension) and dry etching, and (3) SLITS [5] (*S*imulation of *Li*thography on *T*opographic *S*ubstrates), the 2D simulator for modelling conventional lithography, DESIRE [1] (*D*iffusion *E*nhanced *Si*lylated *Re*sist) and the PRIME [6] (*P*ositive *R*esist *Im*age by Dry *E*tching) processes.

In this paper, simulated one and two dimensional rim shifters and attenuated PSMs are presented. The effect of the duty ratio on the image contrast is examined. The effect of the aerial image on the silylation profile for the DESIRE and PRIME processes is also presented.

Dry development is the final step in the DESIRE and PRIME processes. Two step dry etching at a pressure as low as 0.6mT with and without a magnetic field is examined. The effect of the first etch step on the final resist profiles is examined.

II. PSM AERIAL IMAGE FORMATION

Phase shift mask technology is regarded as a prominent candidate for the extension of i-line lithography further into the submicron range. Over the years there has been a number of phase shift mask techniques developed, i.e. alternating, chromeless, rim shifter and attenuated PSM [2,7,8]. Recently, the development of simulation tools for PSM technology has become a principal topic.

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The simulator SIMPHAD [3] has been developed which uses an iterative simulation technique to optimise the mask and the final resist patterns. Most of the reported work on PSM has been concentrated on equal lines/spaces for DRAM fabrication. However, simulations are presently been reported on relatively isolated and random structures for ASIC production. The two most acceptable PSM techniques are the rim shifter and the attenuated PSM principally due to their ASIC applications and the ease of manufacture. Figure 1 illustrates the effect of the duty ratio on the image contrast for both a conventional and a rim shifter mask. It can be observed that for a given period the image contrast decreases with an increase in the duty ratio for the conventional mask. In the case of the rim shifter mask, the image contrast increases rapidly up to a ratio of 1.5 and then at a slower rate up to a ratio of 4. This demonstrates that the rim shifter technique is suitable for high duty ratio patterns.

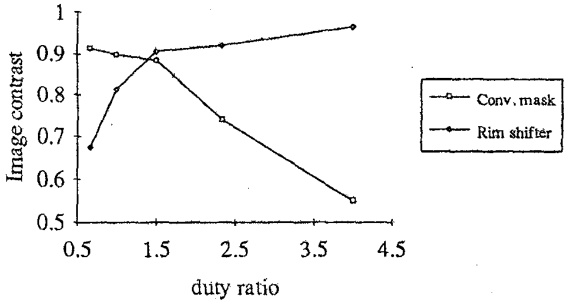

Fig. 1. image contrast versus line/space ratio (shifter width-0.12 μm, period-1μm).

In ASIC fabrication, the contact hole is regarded as a critical masking level. Figure 2 illustrates the intensity profile of a 0.75μm square-aperture with a rim size of 0.3μm and an aperture centre to centre spacing of 3μm. From the figure it can be observed that the side intensity lobes are quite large due to the large rim size. Also, the image contrast and the edge slope have improved when compared to a 2D conventional mask.

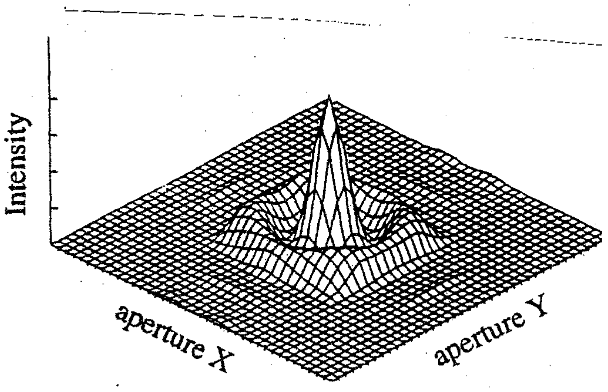

Fig. 2. intensity profile of a 0.75μm aperture (rim size-3μm, aperture centre to centre spacing-3μm).

In attenuated PSMs, the transmission of the phase shifter is adjusted to < 10% to prevent the creation of ghost lines. This technique can be applied to all type of features with a conventional mask layout. Figure 3 illustrates the intensity profile for 0.4μm lines/spaces for both a 1D conventional and a 1D attenuated PSM. In this figure, the contrast is 67% and 82% for the conventional and the attenuated PSM respectively. It can be observed that the contrast has improved by 15%. However, this technique also needs biasing to achieve the variety of feature sizes at different exposure doses.

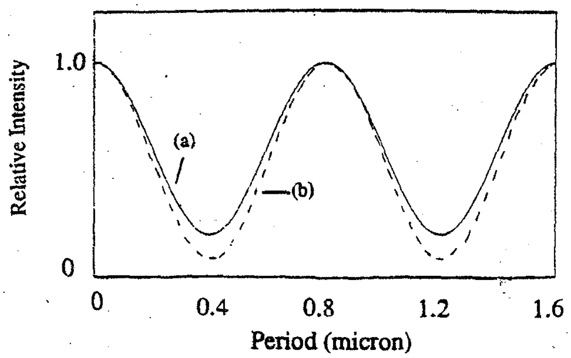

Fig. 3. aerial image profile of a) conventional mask and b) attenuated PSM for a 0.4μm line/space structure.

Figure 4 illustrates an attenuated PSM intensity profile for a 0.5μm aperture having 2μm centre to centre spacing. The edge slope is quite steep and the contrast near the edge is almost 100%. However, the intensity level in the dark regions is 10%, thus the exposure doses must be kept sufficiently low.

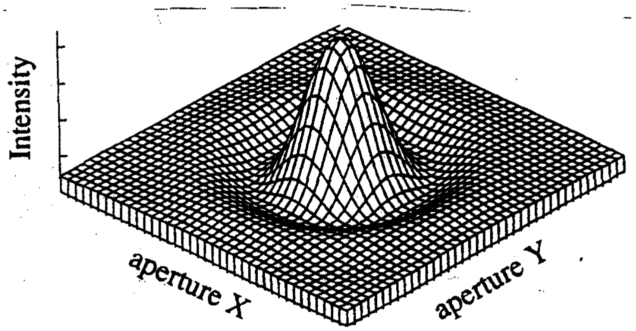

Fig. 4. intensity profile of a 0.5μm aperture (aperture centre to centre spacing-2μm).

III. Resist Silylation Modelling

The modelling of the silylation step in the DESIRE and PRIME processes has been reported in the literature [4,9-13]. Some of these models [10-12] are inconsistent since they do not contain any parameters that depend directly on the silylation baking or the exposure energy. These models only solve the vertical diffusion of the silylating agent into the resist. The DESIM and the SLITS models [4,9] account for the exposure energy, the silylation baking and the selective silylation rates. The SLITS model also predicts the lateral diffusion mechanism during silylation [14], i.e. the silylation thickness at the mask edge, which is essential to accurately control resist linewidths in the DESIRE and PRIME processes. Figure 5 illustrates a typical silylation profile and resist swelling for a 0.5μm line/space as predicted by SLITS.

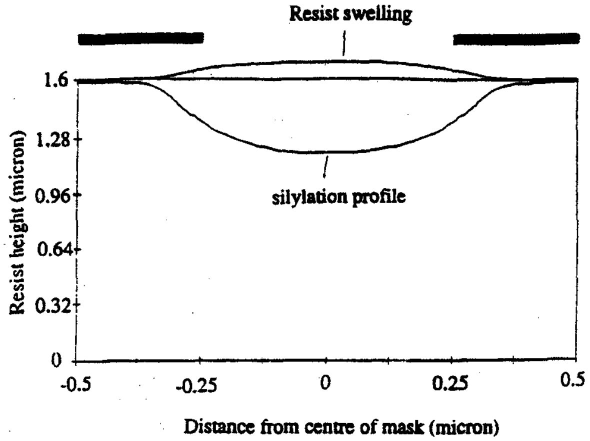

Fig. 5. the silylated and resist swelling profiles for a 0.5μm line/space as predicted by SLITS (silylation time-120s).

The silylation time was 120s at a temperature of 180°C. The silylation thickness at the mask edge is used to determine the amount of resist that must be removed in the first dry development step in order to attain the desired linewidth. It can be noticed from the figure that the swelling profile is a scaled replica of the silylation profile (25%). From the figure it can be observed that the silylation profile is quite smooth and is comparably close to experimental work by Husiken *et al.* [15]. Figures 6 and 7 illustrate the silylation thickness at the mask centre and the edge for 0.35 to 2.0μm lines/spaces as predicted by SLITS, DESIM, Philips simulation [15] and experimental results in 1.6μm thick PLASMASK 200G resist. It can be observed from figure 6 that the Philips simulations are quite inaccurate when compared to the experimental results. The SLITS simulations are the closest to the Philips experimental results over the feature range followed by the DESIM simulations. Also the SLITS results are much closer to the experimental results for feature sizes below 0.7μm which is the region of most importance for production-line lithography. The SLITS and DESIM simulators use the same silylation model to predict the silylation profiles while the Philips simulations are based on the aerial image and empirical data.

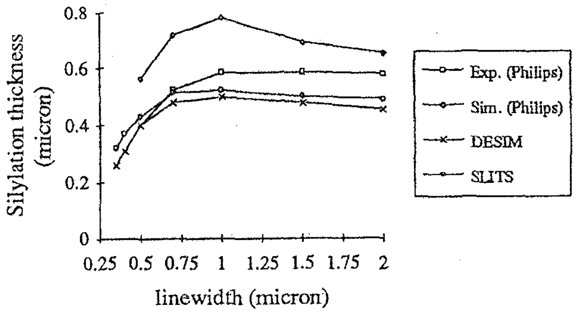

Fig. 6. silylation thickness at the centre of the mask as predicted by SLITS, DESIM, Philips simulation and experimental results for 0.35 to 2 μm lines/spaces.

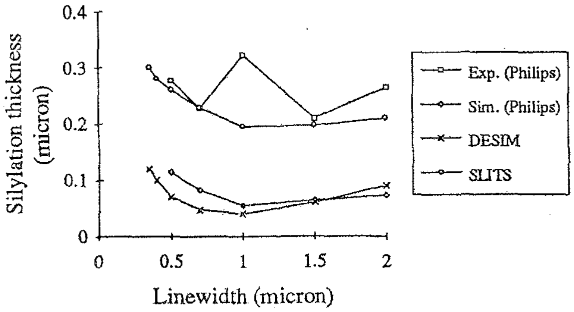

Fig. 7. silylation thickness at the mask edge as predicted by SLITS, DESIM, Philips simulation and experimental results for 0.35 to 2 μm lines/spaces.

The SLITS and DESIM simulations are quite close since the vertical diffusion of the silylating agent is dominant at the mask centre. The close matching of the silylation profiles with the experimental results at the mask centre is not as critical as for the mask edge for features below 0.5μm. From figure 7, it can be noticed that the Philips and the DESIM simulations are quite inaccurate when compared to the experimental results while the SLITS simulations predict the silylation thickness quite well at the mask edge especially for features below 0.7μm. The Philips and DESIM simulators assume vertical propagation of the light source and vertical diffusion of the silylating agent, while the SLITS simulator solves the exposure using the 2D wave equation and the silylation process using both vertical and lateral diffusion. The prediction of the silylation thickness at the mask edge is critical since this information controls the first dry development step and hence the linewidth obtained. From figure 7, it can be observed that the experimental result for the 1μm feature size seems to be quite high and was not explained by Huisken *et al.* [15]. This silylation thickness is ill-defined and may be attributed to an inaccurate measurement conducted by Huisken *et al.* All the simulation results presented in figure 7 apparently have the same shape and can be explained in terms of the aerial image and the silylation mechanism.

In figure 7, the silylation thickness increases rapidly as the feature size decreases below 1μm for all the simulations and experimental results. As a consequence, the silylation thickness at the edge is approaching the silylation thickness at the centre of the mask, therefore reducing the silylation profile contrast. Hence, it is not possible to pattern features below 0.35μm with the resist using a wavelength of 365nm. Figure 8 illustrates the silylation profiles for a 0.3μm line/space using an i-line (365nm) and an attenuated PSM/i-line exposure source.

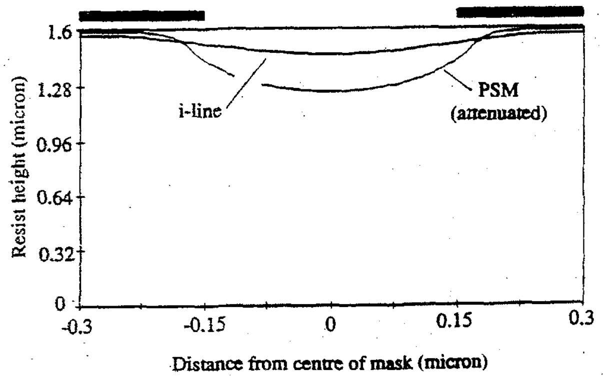

Fig. 8. silylation profiles for a 0.3μm line/space using an i-line and attenuated PSM/i-line source.

From the figure it can be noticed that the silylation profile using the i-line source is quite poor with a silylation contrast of 0.65. The silylation thickness at the mask edge and the centre are almost the same (0.08). The silylation profile has improved drastically when a PSM/i-line source is used. The silylation contrast of this profile is 0.935.

IV. RESIST DRY DEVELOPMENT MODELLING

The dry development or etching system that has been modelled is a modified Balzer BA510A system. It has been noticed that little has been published on the modelling of RF coupled plasma systems with axial magnetic fields like the BA510A system. Hence, a new empirical model was proposed to predict the resist profiles under low or high pressures [4]. Also a new analytical model based on the solution of Boltzmann's equation coupled with Poisson's equation was developed [16]. This model included the enhancement in the glow of the bulk plasma due to the magnetic field under low pressure.

The first step of the dry development is performed at high power (200-400W) and pressure (< 30mT), and acts as a resist stripping process removing the top layer from the surface. It also controls the silylation thickness at the mask edge and the subsequent linewidth. This can be realised by a uniform non-directional etching of the resist. Figure 9 illustrates the effect of the resist stripped in the first development step on the simulated final linewidth for various mask lines/spaces. For 0.5 and 0.4μm lines/spaces, a rapid decrease in linewidth is achieved which brings the linewidth near the desired critical dimension (CD). The 0.35 and 0.3μm lines/spaces were patterned using an attenuated PSM with an i-line source. It can be observed that imaging with the PSM requires less resist stripping than conventional imaging.

Figure 10 illustrates the effect of the oxygen pressure on the resist etch rate with and without a magnetic field. At low pressure and without the magnetic field the etch rate is low.

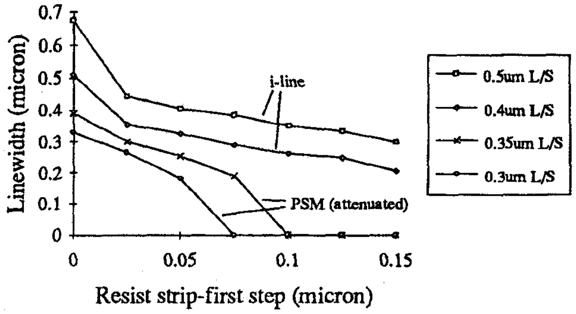

Fig. 9. effect of the resist stripped in the first step on the simulated final linewidth for various mask lines/spaces.

For sub half-micron and nanometer structures, low pressure (below 5mT) is required to reduce the effect of bowing and undercutting in the resist profiles but the plasma is difficult to maintain. The only alternative is to increase the ionisation efficiency in the plasma which in turn increases the etch rate. The increase in the ionisation efficiency can be achieved by applying a magnetic field. In the presence of the magnetic field the wall losses are reduced, hence the number of ions and electrons are greatly increased for the same density of oxygen molecules.

The SEM micrograph of figure 11 illustrates 0.5μm lines/spaces after a two step dry development process. The partial pressure was 0.6mT at an RF power of 100W with a magnetic field of 120 Gauss. It is clear from the micrograph that the equal lines and spaces show no undercutting or bowing in the side walls.

V. CONCLUSIONS

The modelling of advanced processes in lithography such as aerial image formation with phase shift masks (PSMs), the silylation and dry development of the top imaging processes, DESIRE and PRIME, have been presented. It has been observed from the results that i-line lithography coupled with PSMs can be used to extend the resolution down to 0.3μm and lower which is required for the fabrication of 256Mb DRAMs. The application of TSI processes, like DESIRE and PRIME, with PSMs and DUV lithography may achieve the 0.18μm design rule for the 1Gb generation.

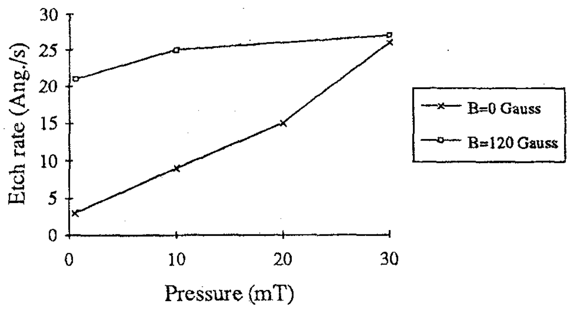

Fig. 10. oxygen pressure vs resist etch rate at 100W RF power (without and with a magnetic field of 120 Gauss).

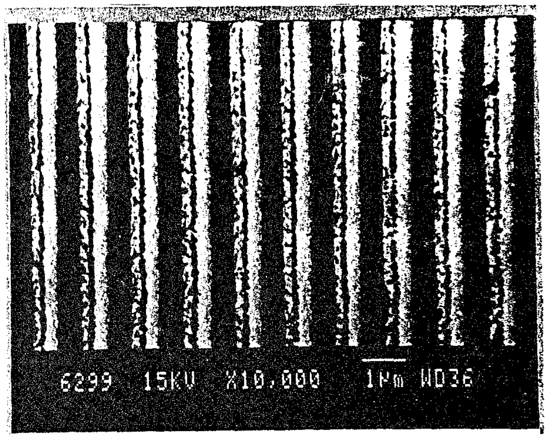

Fig. 11. micrograph of 0.5μm lines/spaces in PLASMASK 301U (samples etched at 0.6mT, 100W RF power and a magnetic field of 120 Gauss).

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