Assessment of the Critical Dimension (CD) prediction accuracy of the Lumped Parameter Model (LPM) for resist lithography.

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Keywords

Lumped Parameter Model, simplified resist models, Bossung, Focus Exposure Matrix, Critical Dimension, CD prediction, simulation, lithography.

Abstract

Lithography modelling is widely used to predict the Critical Dimensions (CD) of patterned features after lithographic processing. A lot of full and simplified resist models are available. Previous works on full resist models have shown that the numerous model parameters are very difficult to set, and often have a poor range of validity outside the dataset that have been used to generate them [1,2]. Simplified resist models are an alternative solution, easier to set, and they often provide a good simulation accuracy [3,4]. Among simplified models, LPM is widely used for CD predictions.

In this article, we study the CD prediction accuracy of the Lumped Parameter Model, using a comparison between experimental and simulated data. A systematic method is applied for LPM parameters extraction (contrast γ, and effective thickness D_{eff}). This assessment shows that a single parameters set giving reasonable accuracy is not found. Moreover, the critical analysis of the model parameters shows that these LPM parameters have a poor physical meaning. We also point out that there is a fundamental disagreement between the LPM theory and experiments.

1. INTRODUCTION

The use of simulation for CD prediction is often mandatory to avoid heavy experimental work and to decrease the cost of R&D. These simulations can be conducted either using full or simplified resist models. Full resist models are very difficult to tune and the large number of required parameters is a major source of simulation to experiment mismatch. In practice, they often provide a questionable reliability for CD prediction, despite the fact that they are based on fundamental physical considerations.

Simplified resist models represent an alternative to full resist models. They rely on simpler physical considerations and use fewer model parameters. Among all the models available for CD prediction, the Lumped Parameter Model (LPM) is widely used.[5] In this paper, the CD prediction of the LPM as well as the physical meaning of the model parameters are analysed. The LPM simulation results are compared with experimental data using a large number of illumination conditions, wavelengths, mask designs, and feature types.

2. EXPERIMENTAL DATASETS

2D and 1D features have been used for our comparison, as well as two different wavelengths (248nm and 193nm). The available datasets for LPM prediction accuracy are listed below, and the detailed experimental conditions are summarized in Table 1.

<u>Contact holes @ 248nm:</u>

The features were obtained using 0.45µm thick JSR M79Y resist, conventional illumination and 6% attenuated PSM. The nominal CD of the holes on the mask is 200 and 220nm, with different Space to Line ratios L:S = 1:0.6 and 1:2.2. A 248nm Nikon S204B Scanner (numerical aperture (NA) of 0.68, and partial coherence (σ) of 0.6) and a Hitachi Critical Dimension Scanning Electron Microscope (Hitachi S9300 SEMCD) were respectively used for the exposures and for CD measurements. No mask correction has been applied in the simulations.

Lines @ 193nm:

The final features were obtained with 0.5µm thick Sumitomo PAR 707 resist on 75nm thick anti reflective coating AR19. For the exposure, we used an ASML/900 193nm stepper with conventional illumination and binary masks. The nominal CD of the lines on the mask are 120nm with a set of nested and isolated lines (line to space ratios L:S = 1:1.5, 1:1.75, 1:2, 1:3 and isolated), using 0.63 NA and two different partial coherences of 0.6 and 0.85. This provides a set of ten different settings on which the simulation is globally assessed.

3. LPM DESCRIPTION AND CRITICAL DISCUSSION

The Lumped Parameter Model (LPM) considered in this work is the enhanced LPM published by C. A. Mack in 1994 [5]. It takes as its input the aerial image of one or two-dimensional mask features and two lumped parameters. These parameters are the resist contrast γ and effective thickness D_{eff}, which are used to compute the developed resist feature size. The LPM uses a simple approach relating the development time to the exposure dose, while the aerial image simulation is derived in a classical way. The development model relies on the assumption of a constant contrast. The model is also based on the hypothesis of a segmented development process, with two steps: a vertical development down to a depth z, followed by a lateral development up to the position x. The CD for a given exposure energy E is found by solving equation 1:

$$\int_0^{CD/2} \left(\frac{I(x')}{I(0)}\right)^{-\gamma} dx' = \gamma . D_{eff} \left[\left(\frac{E}{E(0)}\right)^{\gamma} - 1\right] \quad (1),$$

where $\frac{I(x')}{I(0)}$ is the normalized image intensity and $E(0)$ is the dose to clear the resist.

More details on the derivation can be found in reference 5.

3.1 Experimental CD behaviour through doses

Previous works [3,6] have shown that experimental Focus Exposure Matrix (FEM) data can be simply represented as an expansion of the feature dimension around the isofocal CD. A representation (Figure 1) of the experimental CDs behaviour as a function of the aerial image intensity thresholds (or inverse of experimental dose [3]) for fixed defocus, gives an accurate insight into the experimental CD behaviour. This representation shows that all constant defocus curves are odd functions of intensity threshold. A major observation on the experimental CD behaviour is that the inflection points of each constant defocus curve are all located at the same CD position, namely the *isofocal CD*. (More precisely, all defocus curves cross at the same point, which is located at the *isofocal CD* and at the *isofocal* intensity threshold). The following polynomial expression of experimental FEM can represent this fact [3]:

$$CD_{\exp} = \left[\sum_{k\in\mathbb{N}} a_k . (f - f_0)^{2k} \right] . \left[\sum_{n\in\mathbb{N}} b_n . (t - t_0)^{2n+1} \right] + isofocal\ CD \qquad (2)$$

(where f is the defocus, f_0 the defocus at best focus, t the image intensity threshold, t_0 the image intensity threshold at *isofocal CD*. f_0, t_0, *isofocal CD*, a_k and a_n are constants. A good fitting expression is obtained using only k=[0,1,2] and n=[0,2].[3]) This expression takes into account that *isofocal CD* is constant for $t=t_0$, and that all inflection points of defocus curves are located at the same isofocal CD for a given defocus f.

3.2 The simulated CD behaviour for LPM

Figure 2 uses the representation of the previous section (Figure 1) to illustrate the computed LPM CD behaviour as a function of the Log exposure dose, for various defocus. This plot shows that there is a fundamental disagreement between experimental FEM and the LPM theory, because LPM isofocal CD is no more at the same location than the inflection point of the curves. The mismatch between the *isofocal CD* and the inflection point is a strong indication of the inability of LPM to provide accurate simulation of experimental data for which these two points always match. Since we deal with monotonic and continuous functions, the fact that the log exposure dose is plotted (whereas inverse of dose is plotted on Figure 1) does not change this conclusion.

4. ASSESSMENT OF THE LPM CD PREDICTIONS CAPABILITIES

4.1 Method

In this section, we will assess the LPM CD prediction accuracy. The experimental datasets (expressed as a function of experimental doses and defocus) are compared to Focus-Exposure Matrices computed using the LPM (expressed as a function of Log exposure doses and defocus). To compare the FEMs, the experimental doses must match the Log exposure doses for each Bossung curve. Since the experimental doses and the dose to clear of the resist are not exactly defined, we modified the original expression $\ln\left(\frac{E(x)}{E(0)}\right)$ of reference 5 into $\ln\left(\frac{d-\Delta E}{E(0)}\right)$, where d represents the experimental dose, $E(0)$ represents the dose to clear and ΔE represents a potential dose offset. Thus, a general relation between the experimental dose d and the log exposure dose d_{LPM} can be written as $d = E(0).\exp\left(d_{LPM}\right) + \Delta E$, where $E(0)$ and ΔE are two adjustable parameters of the model. This does not change the basics of the Lumped Parameter Model but adds one more parameter to tune the model.

The LPM that we use here requires the determination of five resist parameters, which are assumed of general use for a given resist process (resist thickness, layer stack, baking and development conditions) and a given metrology procedure. These coefficients should be the same for all illumination conditions (all masks types, all features types, all optical settings, etc.) and this process can be represented by the expression:

$$CD_{simul} = CD_{LPM}\left(\ln\left(\frac{d-\Delta E}{E(0)}\right), \gamma, D_{eff}\right) + \Delta CD, \quad (4)$$

where: CD_{LPM} is the CD provided by the LPM calculation at a given Log exposure dose. The contrast γ and the effective thickness D_{eff} are parameters of the rough LPM.

A fifth coefficient ΔCD is added as an additional degree of freedom accounting for a possible offset between experimental and simulated CDs. To find out these five coefficients, an optimisation procedure is performed using a Levenberg-Marquardt algorithm. The coefficients are extracted at the same time for all conditions or features for a given resist process. This way, we obtain two sets of LPM coefficients for each set of previously described 248nm and 193nm data.

4.2 Results of LPM CD predictions

The results of the model parameters determination are gathered in Table 2. Figure 3 and Figure 4 show respectively two examples of superimposition of the best simulated CD predictions on experimental data for both contact holes and lines respectively printed at 248nm and 193nm. These figures illustrate that, with the LPM coefficients giving the best CD prediction, the accuracy can at the same time be good for some features (e.g. 120nm isolated lines @ 193nm on Figure 3b, or 220nm semi isolated contacts @ 248nm on Figure 4a) and can give poor match for others (e.g. 120nm nested lines (L:S=1:1.5) @ 193nm on Figure 3a, or 200nm semi isolated contacts @ 248nm on Figure 4b). This shows that for these sets of data, LPM does not provide very accurate results.

Moreover, Table 2 shows that the best CD prediction for lines can be obtained using several values of contrasts ranging from 1 to 2. We also notice that the effective thickness D_{eff} is always very low (almost 0). These two LPM parameters exhibit a poor physical meaning here in comparison with the 8±1 experimentally measured contrast and the experimental 0.5µm resist thickness. For contacts, the contrast (10 to 15) and effective thickness D_{eff} (0.7 to 0.9µm) show values closer to real ones (contrast of 5±1, experimentally measured, and resist thickness of 0.45µm on 0.05µm Bottom Anti-Reflective Coating).

5. CONCLUSION

We have shown that the LPM simulated CDs do not follow the behaviour of experimental CD. The generated LPM Focus-Exposure Matrix are fundamentally different from the experimental reality. The assessment of CD prediction shows as well that LPM provides generally poor accuracy. In addition, the LPM coefficients set giving the best CD prediction could generally not provide information on the resist process because the values given by the model parameters have no realistic physical meaning (best fits are obtained for lines with low contrast γ and zero effective thickness D_{eff}). For these reasons, the LPM can hardly be considered as a reliable predictive model for CD.

One explanation of the disappointing results provided by this widely used model can be the following: the basic LPM is a rather old model [5] and was performing well in a range of features sizes where resist diffusion was almost negligible. This is not the case anymore and the LPM, which is a development model, cannot account for that. Including diffusion effects into the model would certainly help the LPM to increase its accuracy.

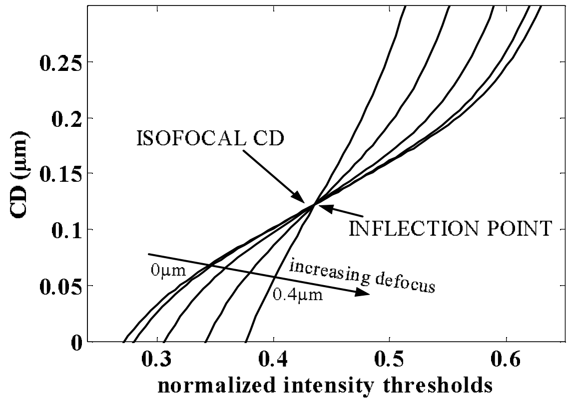

0.25
0.2
0.15
0.1
0.05
0
CD (µm)
ISOFOCAL CD
INFLECTION POINT
0µm
increasing defocus
0.4µm
0.3
0.4
0.5
0.6
normalized intensity thresholds

Figure 1

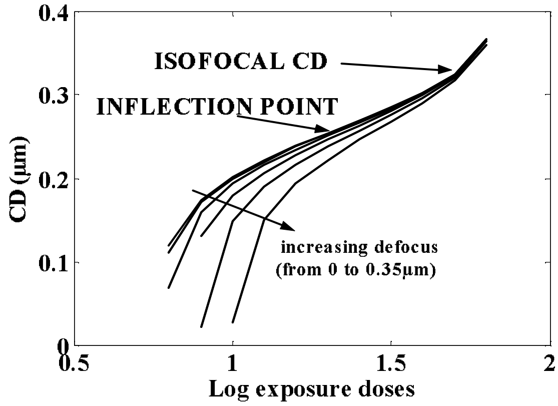
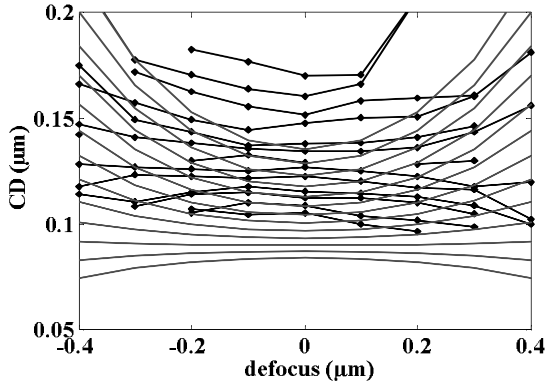
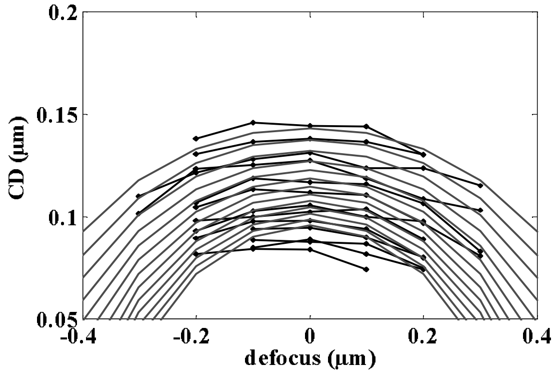

ISOFOCAL CD
INFLECTION POINT
increasing defocus
(from 0 to 0.35µm)
CD (µm)
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
Log exposure doses

Figure 2


0.2
0.15
0.1
0.05
CD (µm)
-0.4
-0.2
0
0.2
0.4
defocus (µm)

(a)


0.2
0.15
0.1
0.05
CD (µm)
-0.4
-0.2
0
0.2
0.4
defocus (µm)

(b)

Figure 3

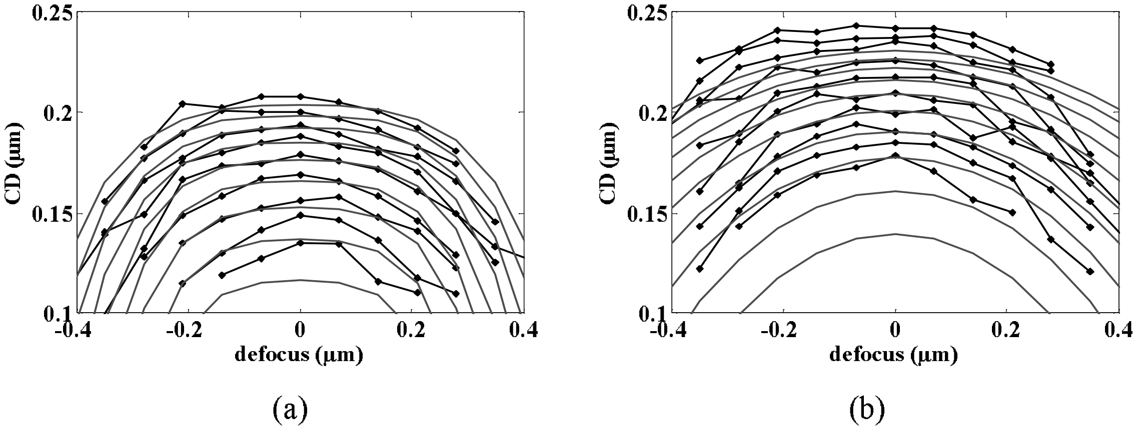


Figure 4

Exposure tool	ASML /900	Nikon S204B Scanner
Wavelength	193 nm	248 nm
Illumination	Conventionnal	Conventionnal
Numerical Aperture	0.63	0.68
Partial coherence σ	0.6 and 0.85	0.6
Mask	Binary mask	6% attenuated PSM
Features	120 nm lines	200 and 220 nm contacts
Line to Space ratio L:S	1:1.5, 1:1.75, 1:2, 1:3 and isolated	1:0.6, 1:2.2
Resist	Sumitomo PAR 707	JSR M79Y
Thickness	0.5 µm	0.45 µm

Table 1

	120nm lines @ 193nm (Whole dataset)	**200 & 220nm contacts @ 248nm (Whole dataset)**
resist contrast γ	1 to 2	10 to 15
effective thickness D_{eff}	<0.2µm	0.7 to 0.9µm
***E(0)* coefficient**	4.05mJ.cm^{-2}	8.2mJ.cm^{-2}
***ΔE* coefficient**	-0.05mJ.cm^{-2}	-3mJ.cm^{-2}
ΔCD	0nm	5nm
CD prediction accuracy	8.9%	4.9%

Table 2

Figure caption

Figure 1: CD as a function of normalized intensity threshold for various defocus (ranging from 0 (best focus) to 0.3µm), for 120nm nested lines (L:S=1:1.5), λ=193nm, NA=0.63 and σ=0.6.

Figure 2: simulated CD as a function of the log exposure doses for various defocus (ranging from 0 (best focus) to 0.42µm), for 200nm dense contacts (pitch=320nm), λ=248nm, γ = 6, D_{eff} = 0.2, *E(0)* = 8.2, *ΔE* = -3 and *ΔCD* = 5nm.

Figure 3: Superimposition of simulated LPM FEM (dashed lines, using the best parameters extracted from whole dataset) on experimental data (solid lines + diamonds) for λ=193nm, 120nm lines with L:S=1:1.5 (a) and with isolated lines (b).

Figure 4: Superimposition of simulated LPM FEM (dashed lines, using the best parameters extracted from whole dataset) on experimental data (solid lines + diamonds) for λ=248nm, using 200nm contact holes and 640nm pitch (a) and 220nm contact holes and 720nm pitch (b).

Table caption

Table 1: Summary of the experimental datasets.

Table 2: LPM parameters giving the best CD prediction for the whole dataset.

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