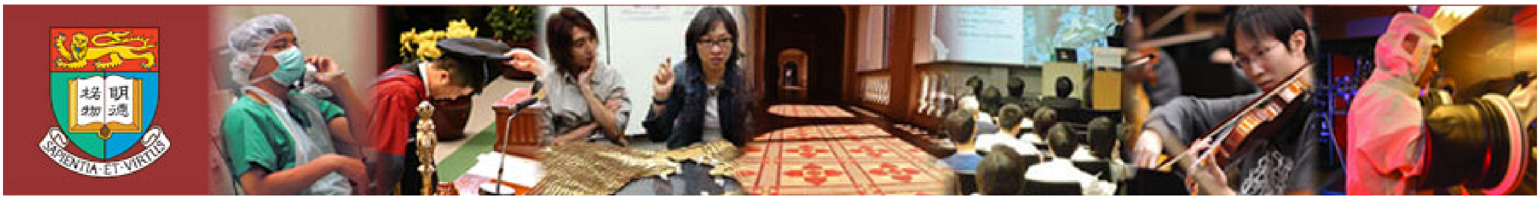

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# Feasibility of 50-nm device manufacture by 157-nm optical lithography: an initial assessment

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## ABSTRACT

The Normalized Process Latitude (NPL) is used to assess the feasibility of 50-nm device manufacture by 157-nm optical lithography. A first NPL quantification assuming steady improvement of processing technology shows that 157-nm optical lithography is infeasible. A second NPL quantification investigates the amount of technology acceleration required to make 50-nm manufacture possible. It is concluded that photolithography is a viable lithography technique for the 50-nm technology generation only with significant improvements in focus control, photomask making, photoresist contrast, as well as aberration levels.

## 1. INTRODUCTION

With the enormous effort of engineers and scientists, we are building integrated circuits with ever higher speed and lower power consumption. Components can be packed together with higher densities and each single chip can provide more functions. The critical dimension (CD) of devices keeps on shrinking according to Moore's Law [1]. The $k_1$ factor [2] has decreased from 0.75 in the mid-1980s to 0.45 nowadays and the 50-nm device generation is approaching soon. However, it is still controversial as to which technology is the most suitable for 50-nm device manufacturing. One of the possibilities is optical lithography. This paper investigates the feasibility of 50-nm device manufacturing by optical lithography.

Our approach is to make use of the quantification metric - Normalized Process Latitude (NPL) [3] to quantify the image of a 50-nm line feature of lithography. First, NPL quantification is performed to determine whether the normal rate of technology improvement is feasible to manufacture 50-nm devices. If not, we determine, again using the NPL, the needed rate of photolithography advancement that will enable the fabrication of 50-nm devices.

## 2. NORMALIZED PROCESS LATITUDE (NPL)

The NPL is a versatile metric for image quality quantification because it captures many sources of critical dimension error including dose variation, mask critical dimension error, focus fluctuation, and aberration; it can also be extended to consider other detractors such as placement error as well. Hence, the NPL is suitable for the study of future-generation lithography because of the growing importance of these detractors.

The NPL is computed first by calculating the sensitivity of the lithography image to each individual detractor:

**1. Dose sensitivity** –

$$NILS = \left| \frac{CD}{I_{threshold}} \frac{dI}{dx} \bigg|_{I_{threshold}} \right| \qquad (1)$$

- NILS stands for Normalized Image Log Slope [4,5]. It is inversely proportional to the dose sensitivity of the image edge position. It is closely related to exposure latitude and can be used to investigate how optical parameters affect image quality.

**2. Mask error sensitivity** –

$$MEF = \frac{1}{k} \times \frac{\partial CD_{wafer}}{\partial CD_{reticle}} \qquad (2)$$

- MEF stands for Mask Error Factor [6,7].

**3. Focus sensitivity** – Focus curvature [3] **4. Aberration sensitivity** – Aberration slope [3]

These image sensitivities are then normalized to be within the range of zero and one by using the sigmoid function [3]:

- For dose sensitivity:

$$R = \frac{1}{1 + e^{-(\frac{x-c}{\eta})}} \qquad (3)$$

- For mask error, focus and aberration sensitivity::

$$R = 1 - \frac{1}{1 + e^{-(\frac{x-c}{\eta})}} \qquad (4)$$

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A critical parameter in the NPL is the discrimination point [the parameter c in Eq. (3) and Eq. (4)]. Each detractor has a distinct discrimination point. It can be perceived as the threshold which separates images that are sensitive to the detractor from the ones that are not. In other words, the discrimination point is the average value of image sensitivity to the corresponding detractor in a lithography process. For example, if the discrimination point for the mask error sensitivity is one, then the average MEF in the lithography process is one. Another critical parameter in addition to the discrimination point is the spread [the parameter $\eta$ in Eq. (3) and Eq. (4)]. Each detractor also has a distinct spread. It is generally equal to six times the difference between the average and the best or worst value of an image sensitivity and it measures how rapidly an image turns from good to poor as the image sensitivity varies. These normalized sensitivities are called the robustness of an image.

The NPL is then found by combining the individual robustness values by the following equation:

$$NPL = \left(\left|R_{dose}\right| \times \left|R_{mask}\right| \times \left|R_{focus}\right| \times \left|R_{aberrations}\right|\right)^{\frac{1}{4}} \qquad (5)$$

## 3. 50-NM DEVICES

In this study, we investigate the feasibility of 50-nm device manufacture using optical lithography at 157 nm with a numerical aperture (NA) of 0.95, a partial coherence factor of 0.8, and a demagnification of 4X. To gain an initial understanding without the complication of full lithography optimization, no resolution enhancement techniques (RET) [8] are used in this study. Representative aberrations considered include spherical aberration, coma, astigmatism, curvature, and distortion.

### 3.1 FEASIBILITY WITH STEADY IMPROVEMENT

For 180-nm devices with an exposure wavelength of 193 nm and a NA of 0.75, the discrimination points and spreads from a prior study [3] are shown in Table 2. Since the NPL takes process improvement into consideration by the use of normalized quantities such as percentage of CD change for dimensions and Rayleigh's unit (lambda/2NA$^2$) [9] for focus variations, the same parameter for the 50-nm generation represents the case of steady improvement of lithography capabilities.

Using these parameters, 50-nm devices with periodicities from 100 nm to 200 nm are quantified, and the results are shown in Table 1. From Table 1, we can observe that the NPL is generally small and its average is close to zero. Since the NPL extracts image sensitivities to quantify image quality and it already takes technology improvement into consideration, the first NPL quantification result in Table 1 implies that the steady rate of manufacturing improvement will not be possible to produce 50-nm device because the process latitude is inadequate. That means steady process improvement at the rate of scaling with the wavelength and NA, i.e., aberration level reduces with the wavelength, focus control improves with (lambda/2NA$^2$), mask error control scales with the reduction of CD, and 157-nm photoresists have the same contrast as 193-nm photoresists, cannot make 50-nm device manufacturable.

Table 2: Normalization parameters for the first NPL quantification

| Type of sensitivity for normalization | Discrimination point, c | Spread, $\eta$ |
|---|---|---|
| Dose sensitivity | 3 | 0.6 |
| Mask sensitivity | 1 | 0.3 |
| Focus sensitivity | 18 | 1.5 |
| Aberration sensitivity | 2 | 1.5 |

### 3.2 FEASIBILITY WITH ACCELERATED IMPROVEMENT

If steady improvement is not enough, we need accelerated improvement. We attempt to determine the needed rate of improvement by changing the critical parameters of the NPL, i.e., the discrimination point and the spread, such that the NPL shows an acceptable value. Then we determine the corresponding process requirements from the discrimination points and spreads.

With the parameters shown in Table 3, the NPL of 50-nm features at intermediate periodicities (about 130 nm to 160 nm) are acceptable. Note that although the very dense (period less than 120 nm) and the rather sparse (period greater than 170 nm) features still have nearly zero NPL, their NPL can be improved with the using of RET such as off-axis illumination [10] and assist features [11]. The discrimination points of dose sensitivity, mask sensitivity and focus sensitivity are changed from three to 1.3, one to two, and 18 to 64 respectively. That means the average NILS for a process is now 1.3 instead of three. The average MEF is now two instead of one while the average focus curvature is now 64. All of these imply that the manufacturing condition has less process latitude and the limitations on various detractors are now more severe. Less parameter variations are allowed. By comparing the normalization parameters of the first and second quantification, we can estimate the necessary improvement in photoresist, mask manufacturing, focus control and lens aberration.

Table 3: Normalization parameters for the second NPL quantification

| Type of sensitivity for normalization | Discrimination point, c | Spread, η |
|---|---|---|
| Dose sensitivity | 1.3 | 0.2 |
| Mask sensitivity | 2 | 0.4 |
| Focus sensitivity | 64 | 1.5 |
| Aberration sensitivity | 2 | 1.5 |

### 3.2.1 PHOTORESIST

Corresponding to the decrease of the discrimination point of NILS from three to 1.3 is the further limitation on the dose variation. Referring to the columns of NILS and EL (exposure latitude) in Table 1 of the reference [3], the average exposure latitude of a 50-nm device manufacturing process is found to be about 7%. This is smaller than the approximately 15% requirement for a manufacturable process in the 193 nm and 0.75 NA exposure system of existing lithography technology. Therefore, the decrease in the average NILS leads to the reduction of exposure latitude in 50-nm manufacturing process. Furthermore, since the NILS is reduced, the photoresist contrast must be higher to compensate for the deteriorated image quality. One point to note is that the spread of dose sensitivity decreases significantly from 0.6 to 0.2. As the spread is decreased, the distinction between good and poor images becomes smaller. Therefore the amount of image quality variation that can be tolerated becomes smaller.

### 3.2.2 MASK MANUFACTURING

The discrimination point of the MEF is increased from one to two. Since the MEF is the ratio of the CD change on wafer to the CD change on reticle, so in the manufacturing process of 50-nm device, the CD error on the reticle will be doubled on the wafer. To handle this magnification effect of CD error, we need to control the manufacture of photomasks more tightly. In fact, it needs to be twice more tightly than that would be expected from steady improvement of the mask-making process. For example, supposed that mask CD error can contribute at most 5% of the printed CD variation. For the 180-nm generation, the mask error can be 180x0.05x(4/1) nm= 36 nm, where (4/1) is the ratio of (demagnification/MEF). For the 50-nm generation, we expect the mask control to improve, giving an error of 50x0.05x(4/1) nm= 10 nm. But since the discrimination point of the MEF is 2, we actually need to control the mask to 50x0.05x(4/2) nm= 5 nm. This is a challenge to the current mask manufacturing technology.

### 3.2.3 FOCUS CONTROL

As for the focus, its curvature discrimination point is increased from 18 to 64. With reference to the columns of DoF (Depth of Focus) and focus curvature of Table 1, this corresponds to about 60 nm or 0.7 R.U. depth of focus. Therefore, only 0.7 R.U. (60.9 nm) of depth of focus can be provided to the 50-nm device manufacturing process and it is much smaller than the 2 R.U. (343 nm) of depth of focus in 180-nm generation. The variation of focus in the process will cause the CD fluctuation. For 180-nm generation, the focus variation can be as large as 2 R.U. (343 nm) before the printed dimension goes beyond the ±10% of the specification. For 50-nm generation, if the focus of the 50-nm manufacturing process varies beyond 0.7 R.U. (60.9 nm), the CD of the generated device will be outside the ±10% CD tolerance. Therefore, much effort has to be made on the focus control of the system to ensure the focus varies within the range of 0.7 R.U. (60.9 nm) depth of focus in 50-nm manufacturing.

### 3.2.4 LENS ABERRATION

The aberration slope discrimination point remains unchanged at two. That means aberration control in exposure systems needs to progress with wavelength reduction. For an aberration control of 0.01 wavelength, the optical path difference control for a 193-nm wavelength needs to be 193x0.01 nm = 1.93 nm and that for a 157-nm wavelength is 157x0.01 nm= 1.57 nm. This atomic order surface finish is nontrivial especially since the NA is expected to be as high as 0.95. One point to note is that if the focus error gains additional improvement in the 50-nm device manufacturing process, the requirement on aberration error may become less strict because aberration sensitivity in general reduces with decreasing focus error [12].

Table 1: The 1st and 2nd quantification results

Exposure conditions: Wavelength = 157nm Sigma = 0.8 NA = 0.95

| CD (um) | Period (um) | NILS | EL(%) | MEF | DoF(R.U) | Focus curvature | Aberration slope | Total window (%R.U.) | 1st NPL quantification | 2nd NPL quantification |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.050 | 0.100 | 0.271 | 0.000 | 15.410 | 0.000 | 0.2858 (iso) | 0.016 | 0.000 | 0.000 | 0.000 |
| 0.050 | 0.110 | 0.624 | 2.427 | 5.055 | 1.384 | 27.680 | 0.027 | 2.836 | 0.002 | 0.041 |
| 0.050 | 0.120 | 0.880 | 5.161 | 3.030 | 1.307 | 32.350 | 0.048 | 6.214 | 0.007 | 0.240 |
| 0.050 | 0.130 | 1.052 | 6.774 | 2.256 | 1.154 | 42.390 | 0.073 | 7.369 | 0.003 | 0.447 |
| 0.050 | 0.140 | 1.163 | 7.598 | 1.901 | 0.962 | 48.020 | 0.099 | 7.449 | 0.001 | 0.548 |
| 0.050 | 0.150 | 1.226 | 8.242 | 1.739 | 0.808 | 62.620 | 0.126 | 7.300 | 0.000 | 0.539 |
| 0.050 | 0.160 | 1.253 | 8.457 | 1.685 | 0.654 | 65.070 | 0.153 | 7.048 | 0.000 | 0.453 |
| 0.050 | 0.170 | 1.242 | 8.136 | 1.717 | 0.423 | 69.930 | 0.182 | 6.070 | 0.000 | 0.219 |
| 0.050 | 0.180 | 1.183 | 8.301 | 1.843 | 0.269 | 100.300 | 0.215 | 5.783 | 0.000 | 0.001 |
| 0.050 | 0.190 | 1.137 | 7.479 | 1.949 | 0.000 | 100.900 | 0.236 | 0.000 | 0.000 | 0.001 |
| 0.050 | 0.200 | 1.137 | 7.285 | 1.952 | 0.000 | 100.800 | 0.236 | 0.000 | 0.000 | 0.001 |

(iso) The image falls into the iso-focal point and has abnormally small focus curvature

## 4. CONCLUSION

In this paper, we use the Normalized Process Latitude to quantify the image quality of 50-nm features produced by optical lithography. Two sets of normalization parameters of NPL are used to perform the quantification. The first quantification result shows that steady lithography advancement to 157 nm wavelength and 0.95 NA exposure systems is not sufficient to make 50-nm devices manufacturable. The second quantification result tells us that to manufacture 50-nm device by 157-nm optical lithography, the photoresist contrast has to be higher, the control of the manufacture of photomasks need to be twice more tightly than the steady improvement, focus control should ensure the focus variation to be within the range of 0.7 R.U. (60.9 nm), and the aberration level has to progress with the reduction of wavelength. In conclusion, 50-nm device manufacture by 157-nm lithography is feasible with significant improvements in photoresist contrast, mask making, exposure system tolerances, and process control.

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