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# Aberration budget based on Zernike sensitivity for EUV lithography

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# 1-1. Motivation

EUV lithography will start at 22 nm node devices.

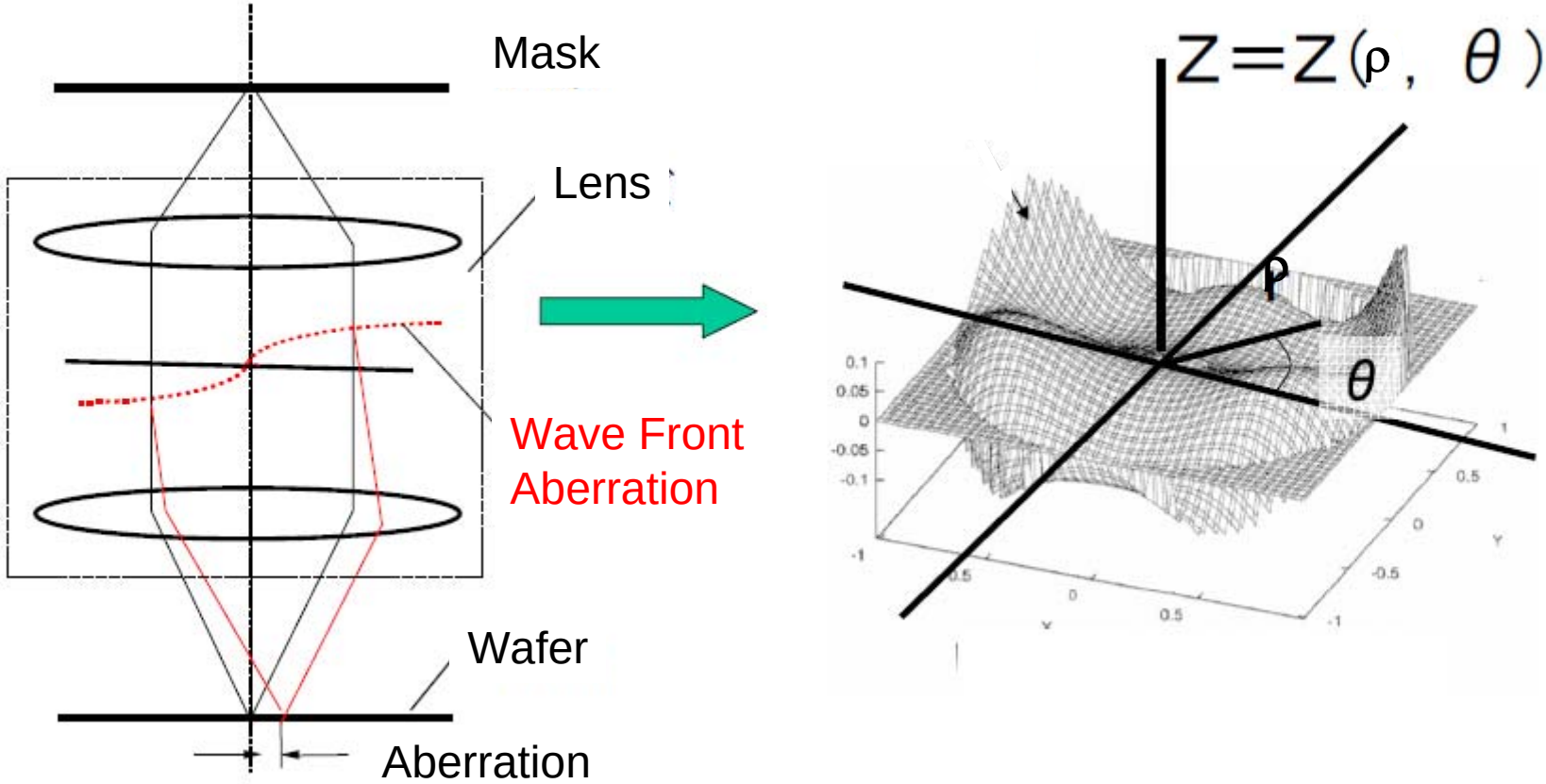
**1st generation EUV (NA 0.25, 2009~)**

Is it possible to form 22 nm node devices?
Key Points are the controllability of the aberration and the flare

22 nm dual-gate pattern needs high degree of accuracy in CD and position.
In this study, we estimate the aberration permissible for 22 nm dual-gate pattern using Zernike sensitivity based Design of Experimental (DOE) method.

# 1-2. Zernike polynomials

## Wave front aberration




$$W(x_0, \rho, \theta) = \sum_m C_m(x_0) \cdot Z_m(\rho, \theta)$$

*m*: Integer>0,
$C_m$: Aberration coefficient,
$Z_m$: Zernike polynomials

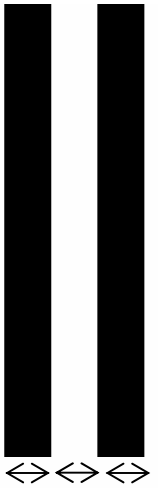
# 2-1. Calculation

## Calculation Condition

- Simulator : Solid-EUV
- Wavelength : 13.5 nm
- NA : 0.25
- Illumination : Circle
- Sigma : 0.7
- Flare :8% (Constant)

※Calculated using aerial image

## Two-bars (Dual-gate)

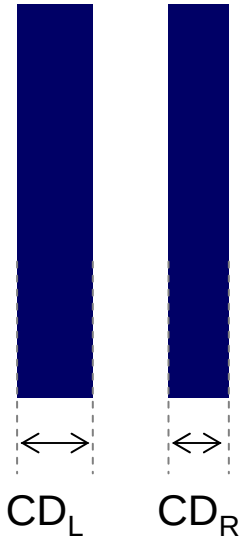


L/S = 22/22 nm


Thin mask

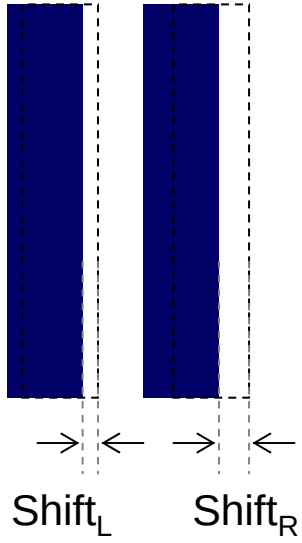
# 2-2. Requirements of 22 nm Two-bars

CD difference between left and right




CD difference = $CD_R$ – $CD_L$ < 2.2 nm

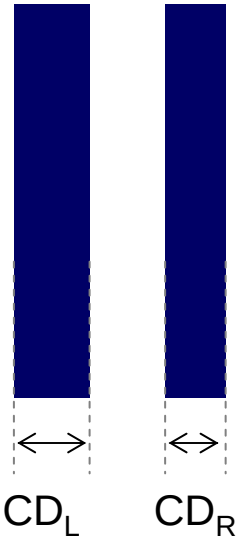
Positional shift




$Shift_L$ < 2.2 nm

$Shift_R$ < 2.2 nm

CD error



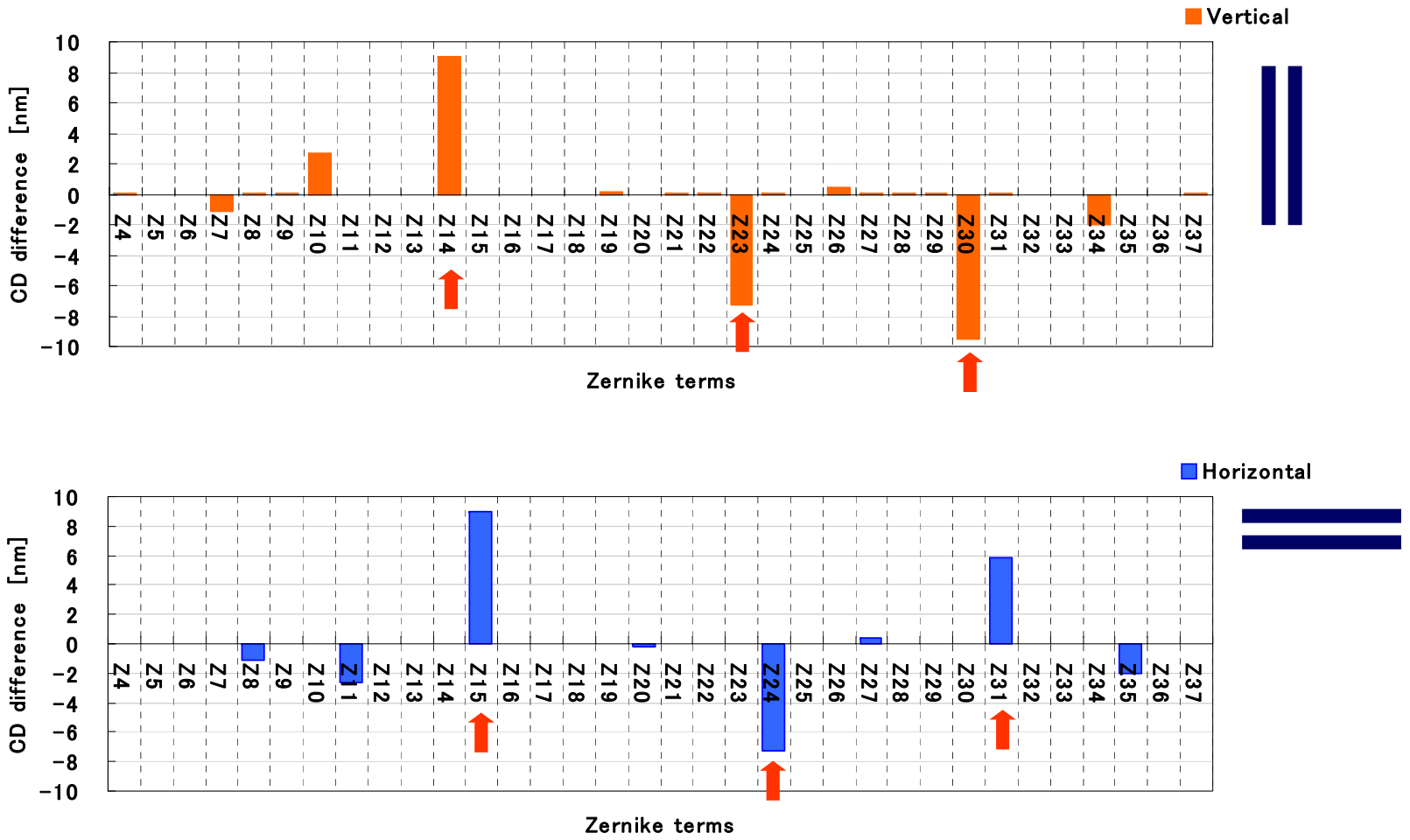

$CD_L$ = 22 nm ± 2.2 nm

$CD_R$ = 22 nm ± 2.2 nm

10% of target CD = 2.2 nm

# 3-1. CD difference of the two-bars

## 1. Zernike sensitivity (in the presence of 100 mλ rms)




Z14, Z23 and Z30 greatly affect on vertical two lines, and Z15, Z24 and Z31 affect on horizontal two lines.

# 3-1. CD difference of the two-bars

## 2. Calculated Effectiveness of each term

We calculated effectiveness of three Zernike terms using Design of Experimental (DOE).

$$\text{Total CD difference} = A \cdot a_{14} + B \cdot a_{23} + C \cdot a_{30} + AB \cdot a_{14}a_{23} + BC \cdot a_{23}a_{30} + AC \cdot a_{14}a_{30} + ABC \cdot a_{14}a_{23}a_{30} + \text{constant}$$

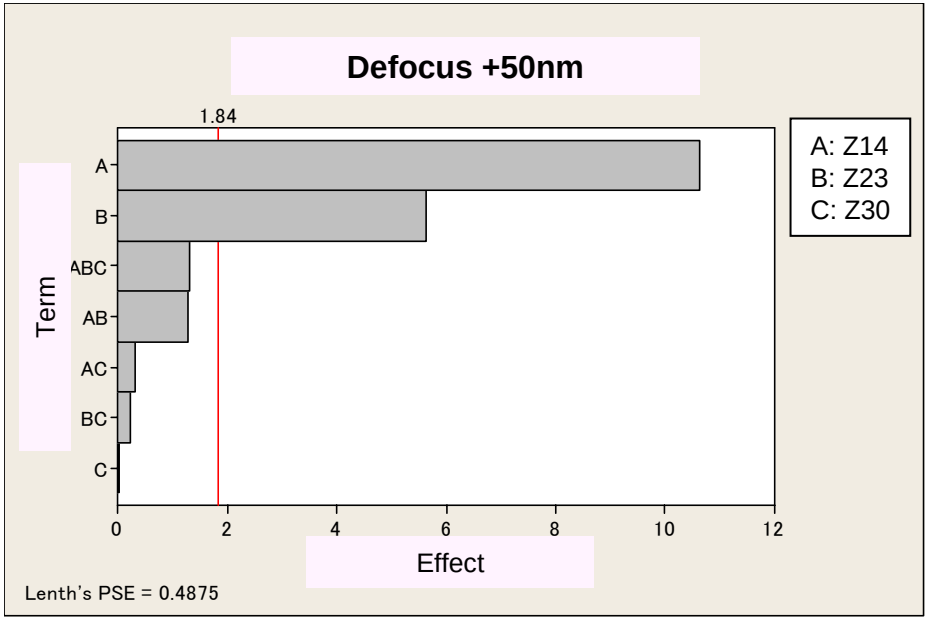
A: Coefficient of Error by Z14
B: Coefficient of Error by Z23
C: Coefficient of Error by Z30
AB: Coefficient of Error by Interaction of Z14 and Z23
BC: Coefficient of Error by Interaction of Z23 and Z30
AC: Coefficient of Error by Interaction of Z14 and Z30
ABC: Coefficient of Error by Interaction of Z14 , Z23 and Z30

$a_{14}$: aberration of Z14
$a_{23}$: aberration of Z23
$a_{30}$: aberration of Z30

# 3-1. CD difference of the two-bars

## 2. Calculated Effectiveness of each term

Pareto Chart of the Effects

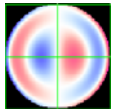
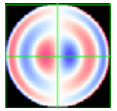
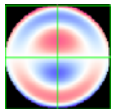
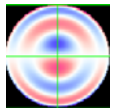




Z14 and Z23 occupy the greatly affect on CD difference of the two-bars

Total CD error $\fallingdotseq A \cdot a_{14} + B \cdot a_{23} + \text{constant}$

# 3-1. CD difference of the two-bars

## 3. Effective Zernike terms

| Direction | terms | function | pupil image | aberration name |
|---|---|---|---|---|
| Vertical | Z14 | $\sqrt{12}\,(10\rho^5-12\rho^3+3\rho)\cos\theta$ |  | 5th order x-coma |
| | Z23 | $\sqrt{16}\,(35\rho^7-60\rho^5+30\rho^3+4\rho)\cos\theta$ |  | 7th order x-coma |
| Horizontal | Z15 | $\sqrt{12}\,(10\rho^5-12\rho^3+3\rho)\sin\theta$ |  | 5th order y-coma |
| | Z24 | $\sqrt{16}\,(35\rho^7-60\rho^5+30\rho^3+4\rho)\sin\theta$ |  | 7th order y-coma |

The greatly affective aberrations on CD difference of the two-bar pattern are **Coma**.

# 3-1. CD difference of the two-bars

## 4. Results

Coefficient table

| Term | | defocus | |
|---|---|---|---|
| Vertical | Horizontal | 0 | +50 nm |
| A(Z14) | A(Z15) | 0.103 | 0.106 |
| B(Z23) | B(Z24) | 0.057 | 0.056 |
| Constant | Constant | -0.46 | -0.54 |

Total CD error $\fallingdotseq A \cdot a_{14} + B \cdot a_{23} + \text{constant}$

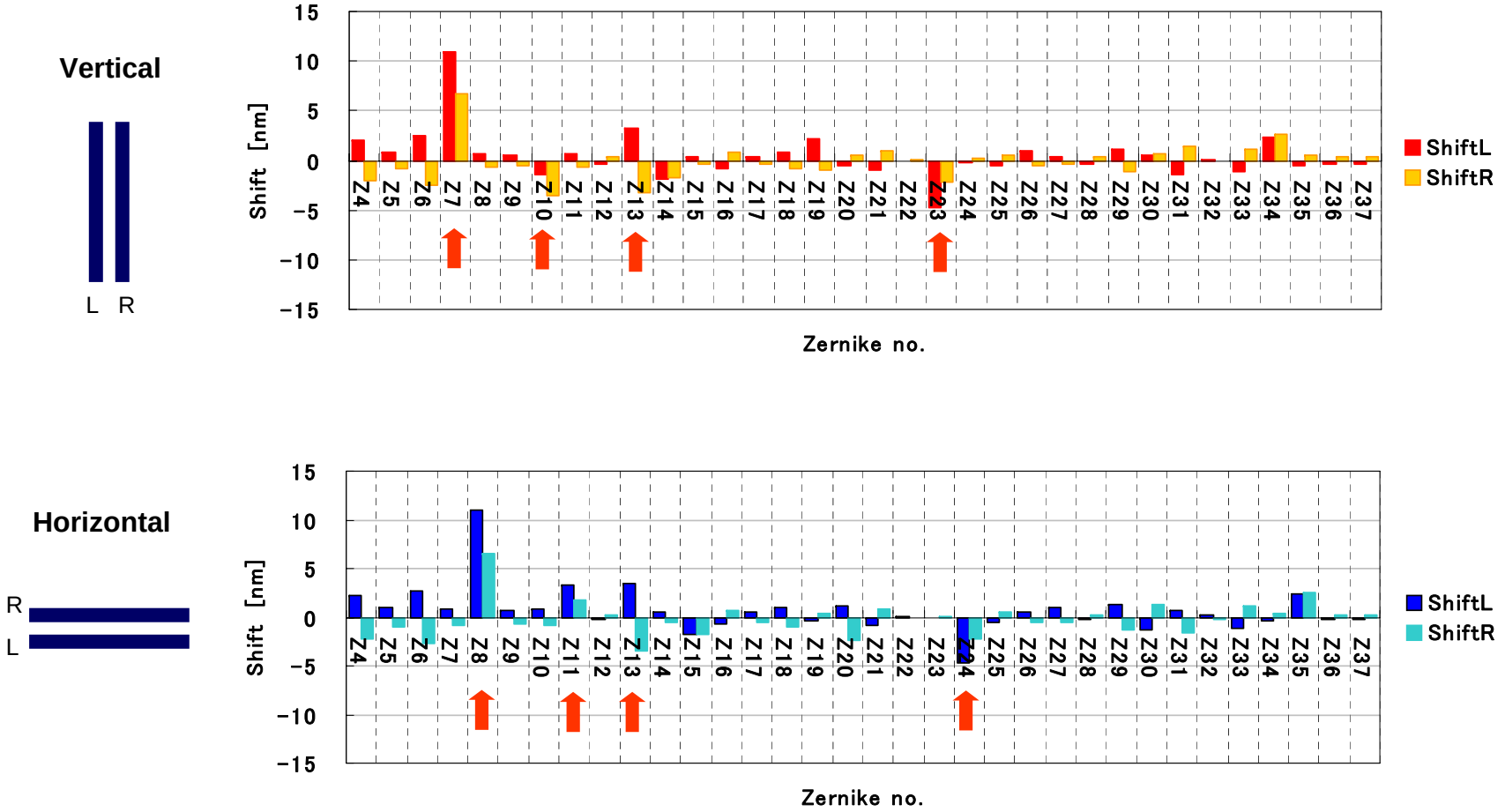
The aberration to control CD difference below 2.2 nm

| defocus | |
|---|---|
| 0 | +50nm |
| 25 | 24 |

[mλ rms]

# 3-2. Positional shift

## 1. Zernike sensitivity (in the presence of 100 mλ rms)

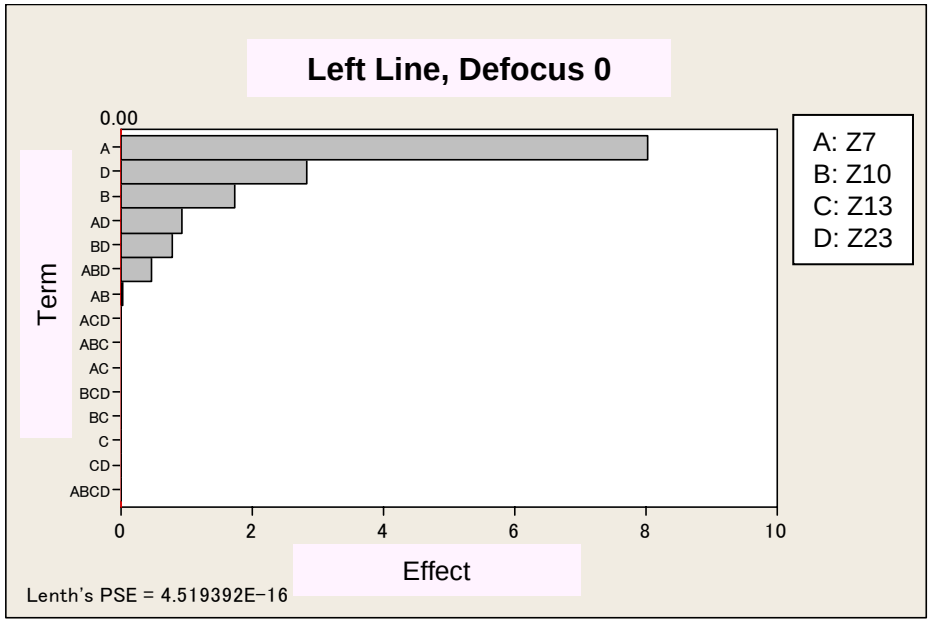


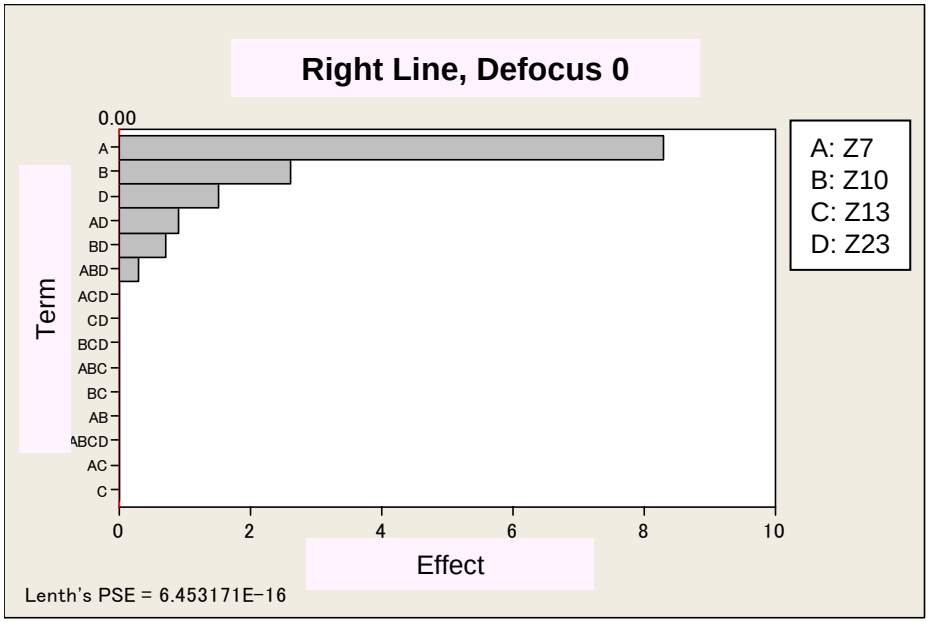

Z7, Z10, Z13 and Z23 greatly affect on vertical two lines, and Z8, Z11, Z13 and Z24 affect on horizontal two lines.

# 3-2. Positional shift

## 2. Calculated Effectiveness of each term

Pareto Chart of the Effects



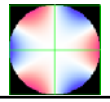
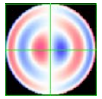
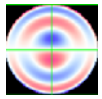




Z7, Z10 and Z23 occupy the greatly affect on CD difference of the two-bars.

Total Position shift $\fallingdotseq A \cdot a_7 + B \cdot a_{10} + D \cdot a_{23} + \text{constant}$

# 3-2. Positional shift

## 3. Effective Zernike terms

| Direction | terms | function | pupil image | aberration name |
|---|---|---|---|---|
| Vertical | Z7 | $\sqrt{8}\,(3\rho^3-2\rho)\cos\theta$ |  | 3th order x-coma |
| | Z10 | $\sqrt{8}\;\rho^3\cos3\theta$ |  | 3-foil x |
| | Z23 | $\sqrt{16}\,(35\rho^7-60\rho^5+30\rho^3+4\rho)\cos\theta$ |  | 7th order x-coma |
| Horizontal | Z8 | $\sqrt{8}\,(3\rho^3-2\rho)\sin\theta$ |  | 3th order y-coma |
| | Z11 | $\sqrt{8}\;\rho^3\sin3\theta$ |  | 3-foil y |
| | Z24 | $\sqrt{16}\,(35\rho^7-60\rho^5+30\rho^3+4\rho)\sin\theta$ |  | 7th order y-coma |

**Coma** and **3-foil** aberrations influence to Positional shift.

# 3-2. Positional shift

## 4. Results

Coefficient table

| Term | | Left line | | Right line | |
|---|---|---|---|---|---|
| Vertical | Horizontal | defocus | | defocus | |
| | | 0 | +50 nm | 0 | +50 nm |
| A(Z7) | A(Z8) | 0.080 | 0.0853 | 0.083 | 0.0893 |
| B(Z10) | B(Z11) | 0.017 | 0.0163 | 0.026 | 0.0248 |
| D(Z23) | D(Z24) | 0.028 | 0.0318 | 0.015 | 0.0183 |
| Constant | Constant | 1.163 | 1.388 | -1.15 | -1.363 |

Total Position shift $\fallingdotseq A \cdot a_7 + B \cdot a_{10} + D \cdot a_{23} + \text{constant}$

The aberration to control Positional shift below 2.2 nm

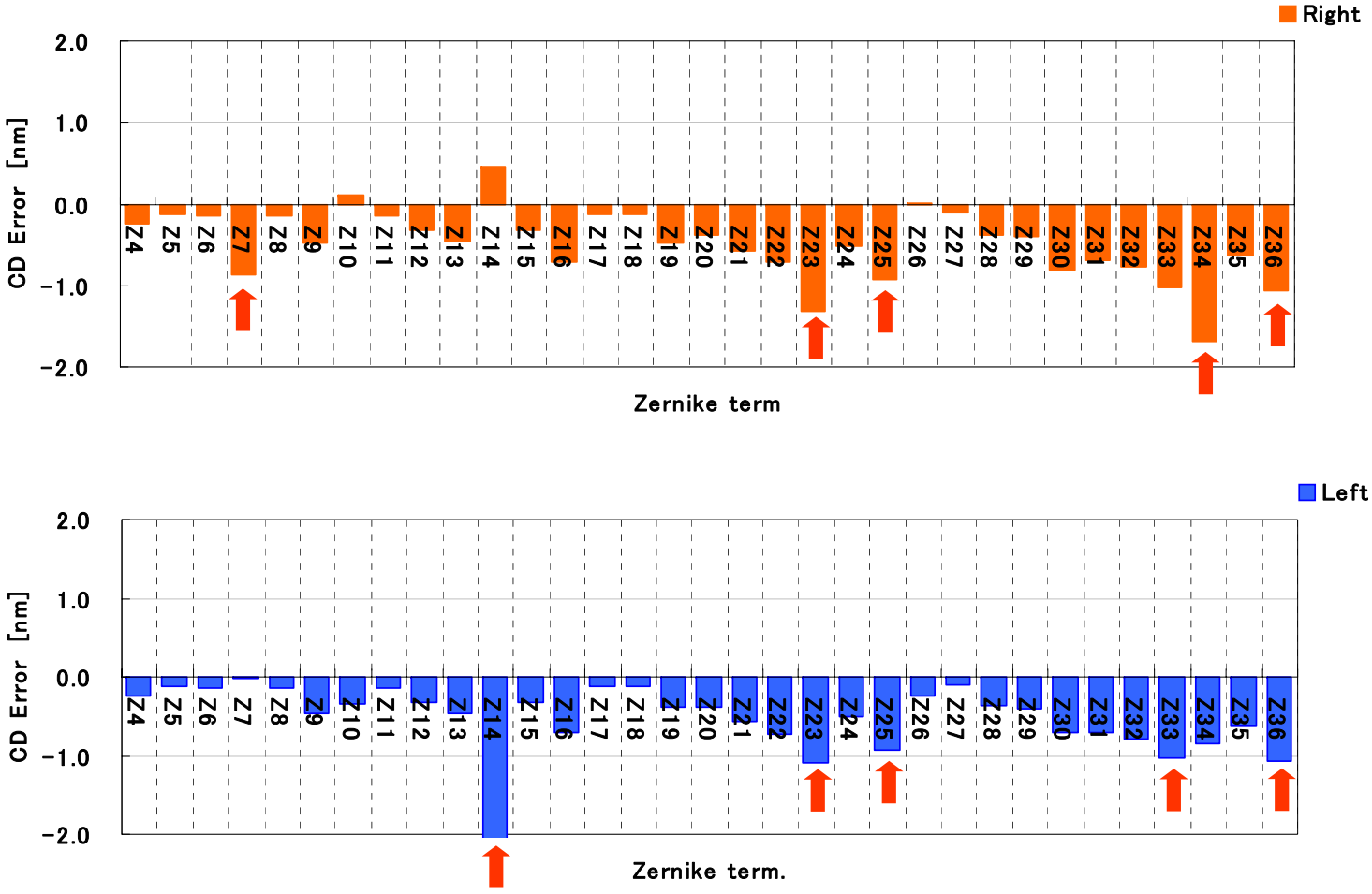
| | defocus | |
|---|---|---|
| | 0 | +50 nm |
| Left Line | 30 | 27 |
| Right Line | 44 | 42 |

[mλ rms]

# 3-3. CD error

## 1. Zernike sensitivity (in the presence of 25 mλ rms)

Vertical lines

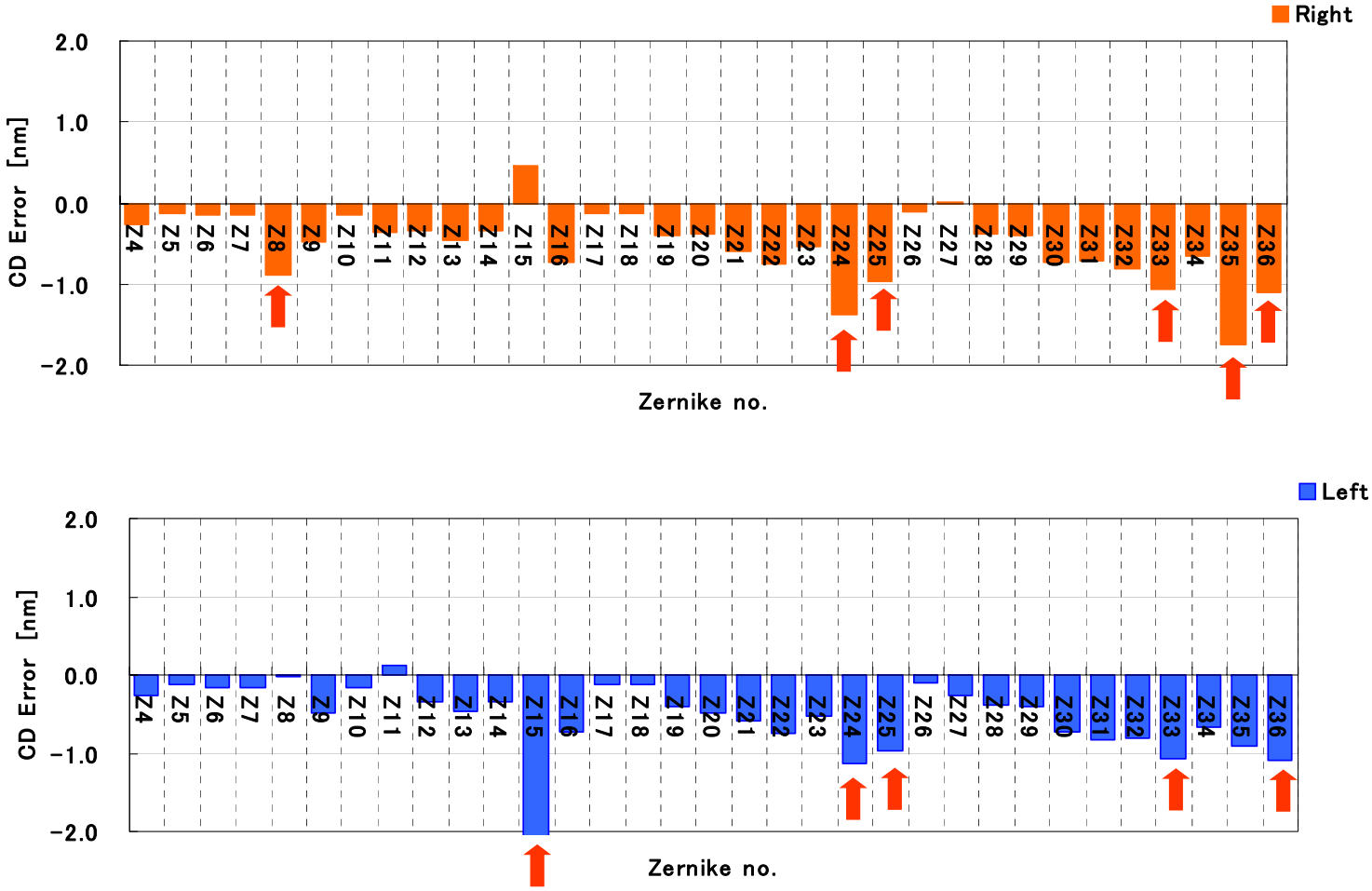

Z7, Z14, Z23, Z25, Z33, Z34 and Z36 greatly affect on vertical two lines.

# 3-3. CD error

## 1. Zernike sensitivity (in the presence of 25mλ rms)

**Horizontal lines**

R
L

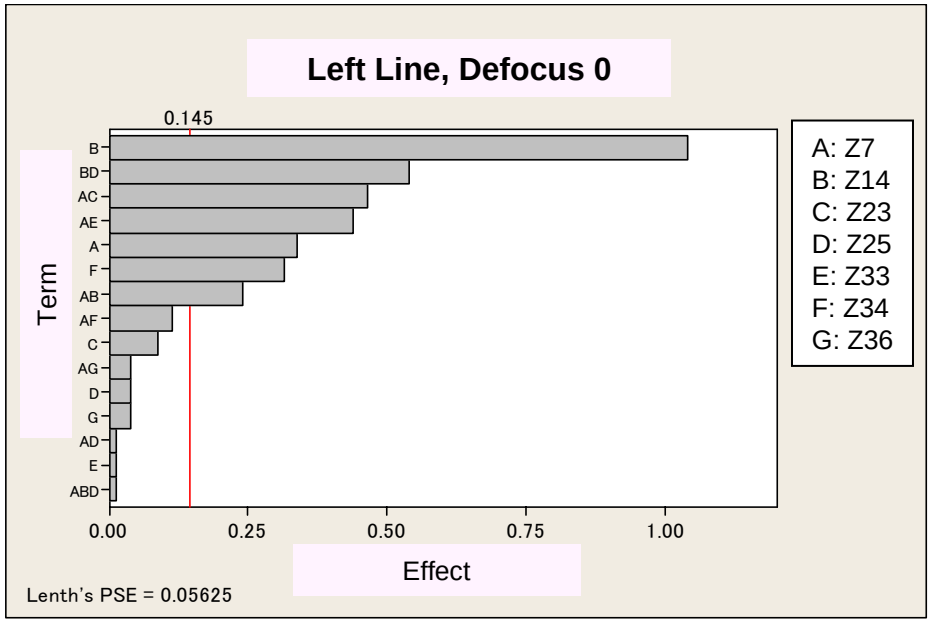


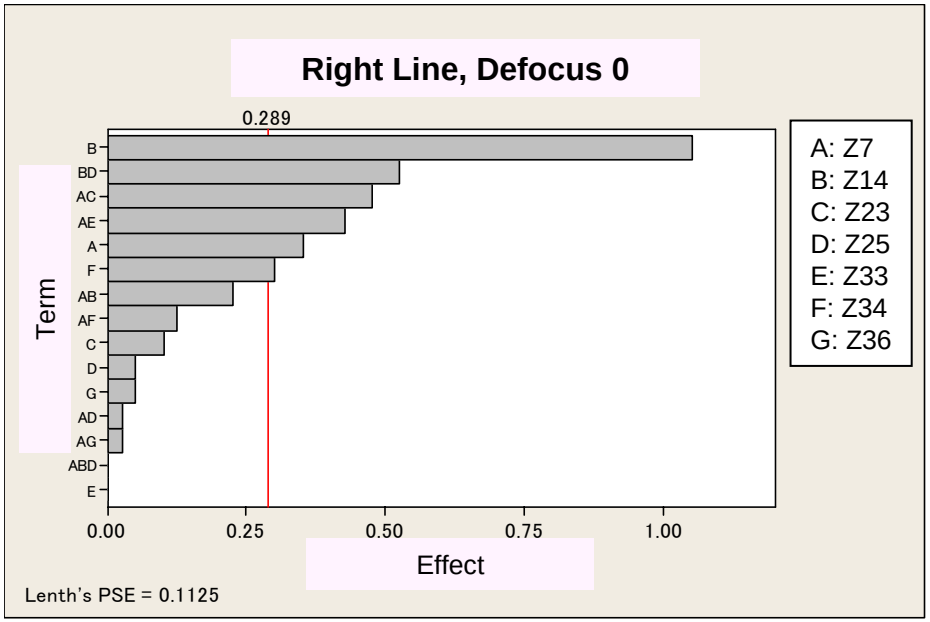

Z8, Z15, Z24, Z25, Z33, Z35 and Z36 greatly affect on vertical two lines.

# 3-3. CD error

## 2. Calculated Effectiveness of each term

Pareto Chart of the Effects



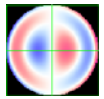
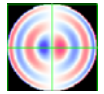
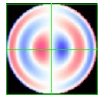
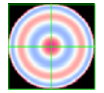

Z14 is most effective term.
In addition, there are alternately effects between Z14 and Z25, Z7 and Z23, Z7 and Z33, Z7 and Z14.

$$\text{Total CD accuracy} \fallingdotseq B \cdot a_{14} + BD \cdot a_{14}\, a_{25} + AC \cdot a_7\, a_{23} + AE \cdot a_7\, a_{33} + A \cdot a_7 + F \cdot a_{34} + AB \cdot a_7 a_{14} + \text{constant}$$

# 3-3. CD error

## 3. Effective Zernike terms

Direction: Vertical Line

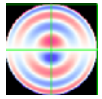
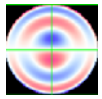
| effects | terms | function | pupil image | aberration name |
|---|---|---|---|---|
| Independently | Z7 | $\sqrt{8}\,(3\rho^3-2\rho)\cos\theta$ |  | 3th order x-coma |
| | Z14 | $\sqrt{12}\,(10\rho^5-12\rho^3+3\rho)\cos\theta$ |  | 5th order x-coma |
| | Z34 | $\sqrt{20}\,(126\rho^8-280\rho^6+210\rho^4-60\rho^2+5)\,\rho\cos\theta$ |  | 8th order x-coma |
| alternately | Z23 | $\sqrt{16}\,(35\rho^7-60\rho^5+30\rho^3+4\rho)\cos\theta$ |  | 7th order x-coma |
| | Z25 | $\sqrt{9}\,(70\rho^8-140\rho^6+90\rho^4-20\rho^2+1)$ |  | 7th order Spherical |
| | Z33 | $\sqrt{18}\,(56\rho^6-105\rho^4+60\rho^2-10)\,\rho^2\sin2\theta$ |  | 7th order 45 deg. astigmatism |

The greatly affective aberrations on CD error are **Coma**.

# 3-3. CD error

## 3. Effective Zernike terms

Direction: Horizontal Line

| effects | terms | function | pupil image | aberration name |
|---|---|---|---|---|
| Independently | Z8 | $\sqrt{8}\,(3\rho^3-2\rho)\sin\theta$ |  | 3th order y-coma |
| | Z15 | $\sqrt{12}\,(10\rho^5-12\rho^3+3\rho)\sin\theta$ |  | 5th order y-coma |
| | Z35 | $\sqrt{20}\,(126\rho^8-280\rho^6+210\rho^4-60\rho^2+5)\,\rho\,\sin\theta$ |  | 8th order y-coma |
| alternately | Z24 | $\sqrt{16}\,(35\rho^7-60\rho^5+30\rho^3+4\rho)\sin\theta$ |  | 7th order y-coma |
| | Z25 | $\sqrt{9}\,(70\rho^8-140\rho^6+90\rho^4-20\rho^2+1)$ |  | 7th order Spherical |
| | Z33 | $\sqrt{18}\,(56\rho^6-105\rho^4+60\rho^2-10)\,\rho^2\sin2\theta$ |  | 7th order 45 deg. astigmatism |

The greatly affective aberrations on CD error are **Coma**.

# 3-3. CD error

## 4. Results

### Coefficient table

| Term | | Left Line | | Right Line | |
|---|---|---|---|---|---|
| | | defocus | | defocus | |
| vertical | horizontal | 0 | +50 nm | 0 | +50 nm |
| A(Z7) | A(Z8) | 0.0169 | 0.0207 | -0.0175 | -0.0213 |
| B(Z14) | B(Z15) | -0.0519 | -0.0544 | 0.0525 | 0.055 |
| F(Z34) | F(Z35) | 0.0156 | 0.0156 | -0.015 | -0.0163 |
| AB(Z7xZ14) | AB(Z8xZ15) | 0.00119 | 0.00131 | 0.00113 | 0.00113 |
| AC(Z7xZ23) | AC(Z8xZ24) | 0.00231 | 0.00131 | 0.00238 | 0.0025 |
| AE(Z7xZ33) | AE(Z8xZ33) | 0.00219 | 0.00131 | 0.00213 | 0.00213 |
| BD(Z14xZ25) | BD(Z15xZ25) | 0.00269 | 0.00306 | 0.00263 | 0.0025 |
| Constant | Constant | -1.0688 | -1.619 | -1.063 | -1.625 |

The aberration to control CD error below 2.2 nm

| | defocus | |
|---|---|---|
| | 0 | +50 nm |
| Left Line | 137 | 63 |
| Right Line | 32 | 24 |

[mλ rms]

# 4. Comparison of estimated aberrations

The permissible amounts of aberration to form 22 nm two-lines

CD difference

| defocus | |
|---|---|
| 0 | +50nm |
| 25 | 24 |

Positional shift

| | defocus | |
|---|---|---|
| | 0 | +50 nm |
| Left Line | 30 | 27 |
| Right Line | 44 | 42 |

CD error

| | defocus | |
|---|---|---|
| | 0 | +50 nm |
| Left Line | 137 | 63 |
| Right Line | 32 | 24 |

[mλ rms]

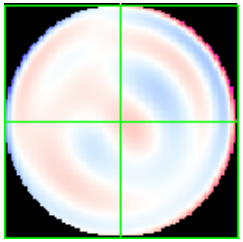
CD difference and CD error needs severe aberration conditions.
Vertical lines and horizontal lines needs 24 mλ rms respectively.
The aberration specification to 22 nm-node-dual gates estimated as follows.

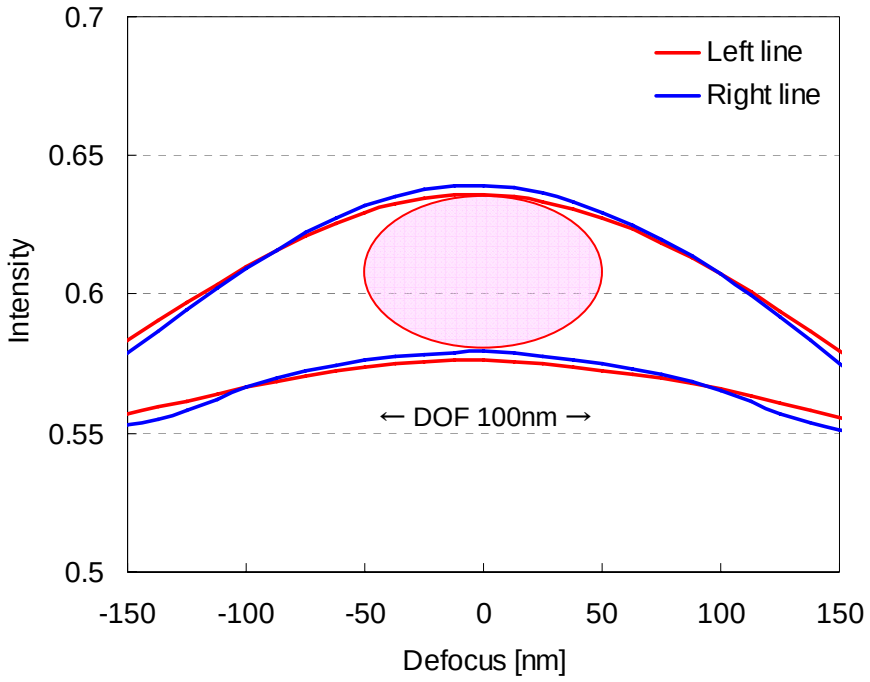
$$\Delta\Phi rms = \sqrt{\sum_{j>1} C^2{}_j}$$

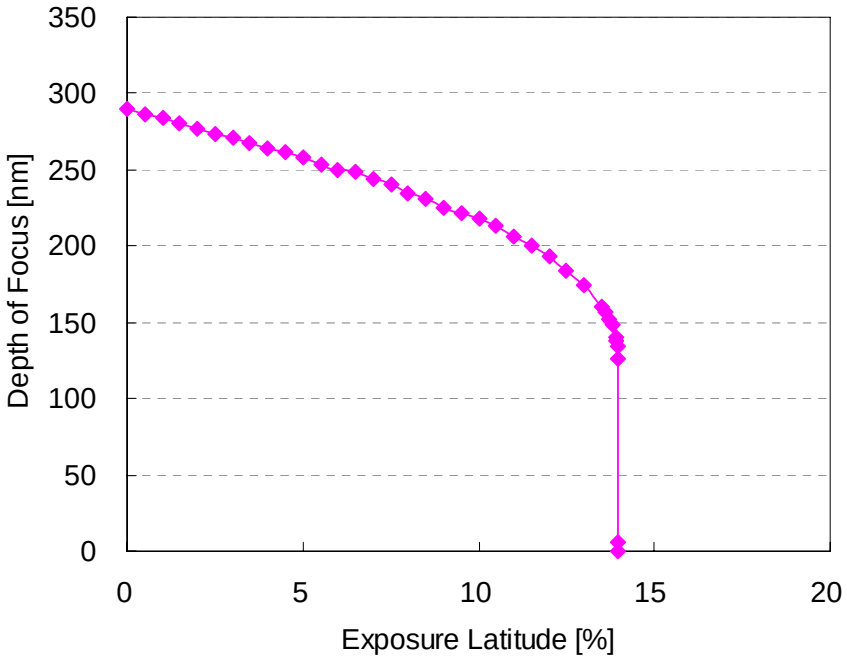
$$= \sqrt{24^2 + 24^2} = \textbf{34 m}\lambda\textbf{ (0.46 nm rms)}$$

# 5. Process Window Calculation

5-1. Process window of vertical lines in the presence of 24 mλ aberration evenly allocates Z7, Z14, Z23, Z25, Z33 and Z34.



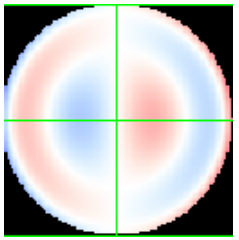


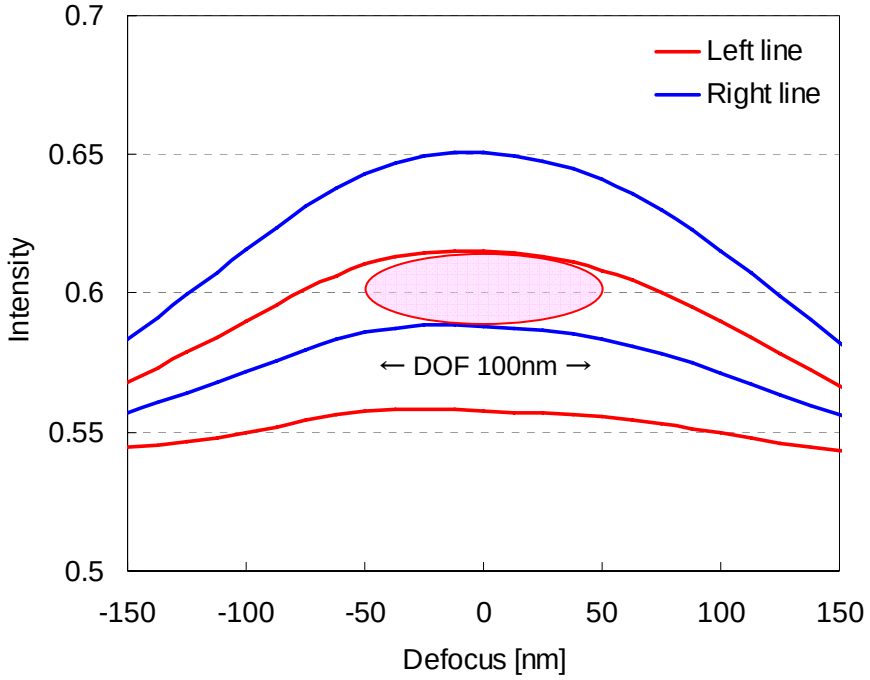



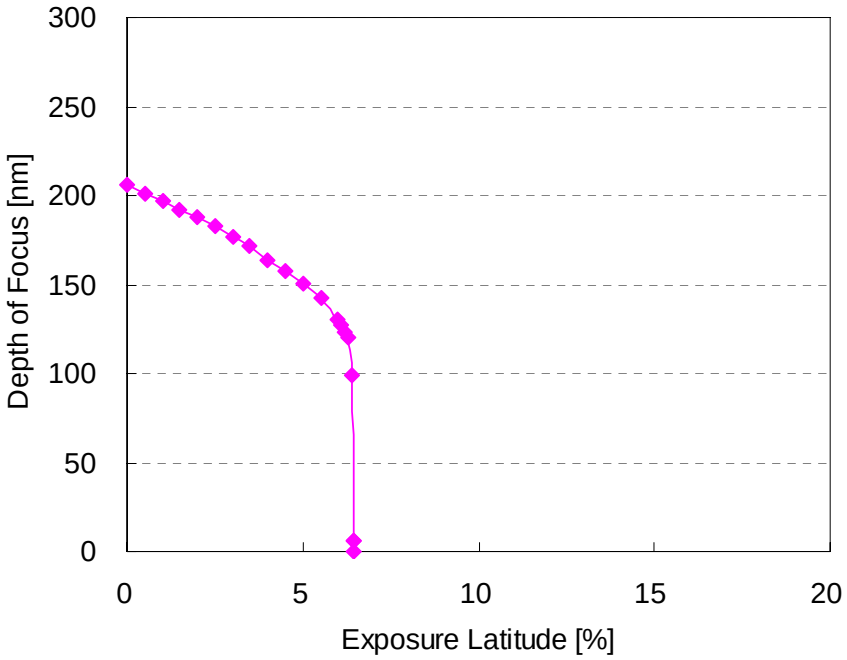

If the aberration is 24 mλ (to vertical lines), an enough lithography margin can be taken for 22 nm-dual gate.

# 5. Process Window Calculation

5-2. Process window of vertical lines in the worst case.
All 24 mλ aberration allocates to Z14.






If the aberration is 24 mλ (to vertical lines), lithography margin of 6 % or more can be expected even in the worst case.

# 6. Conclusions

- We have studied about the aberration specification of 1st generation EUV tool to form 22 nm dual gates.

  - ✓ Effective Zernike terms to CD difference are coma.
  - ✓ Effective Zernike terms to positional shift are coma and 3-foil.
  - ✓ There are interaction effects of coma and spherical on CD error.
  - ✓ The aberration to form 22 nm dual gate pattern is below 34 mλ (0.46 nm rms).

| Vertical | Horizontal |
|---|---|
| 24 mλ | 24 mλ |
| 34 mλ (0.46 nm rms) | |

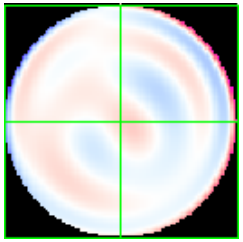
- It was confirmed to be able to take lithography margin of 22 nm dual gates in the presence of the above aberration.

- The aberration specification of 1st generation EUV tool should be settled within the above value.

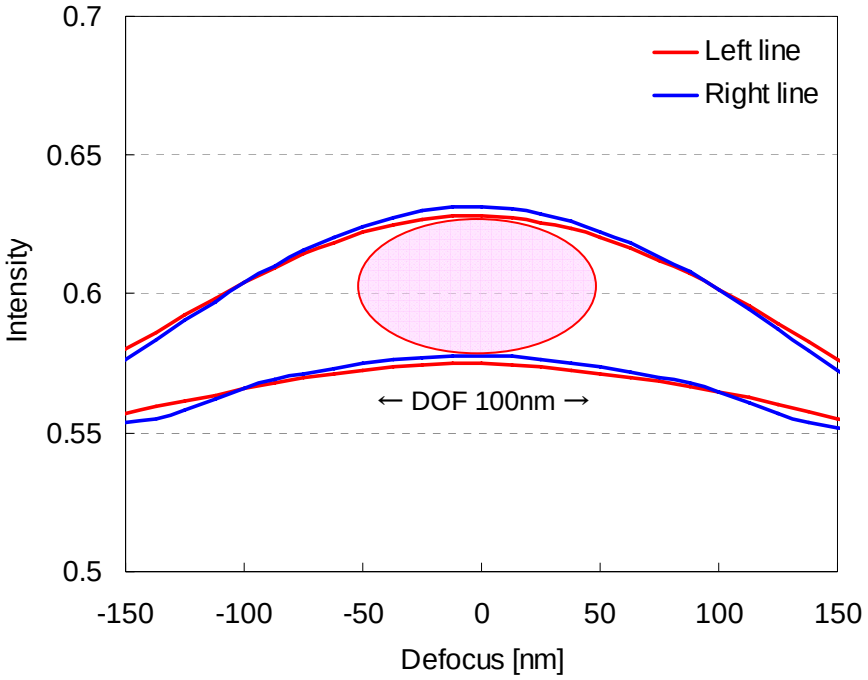
# Appendix

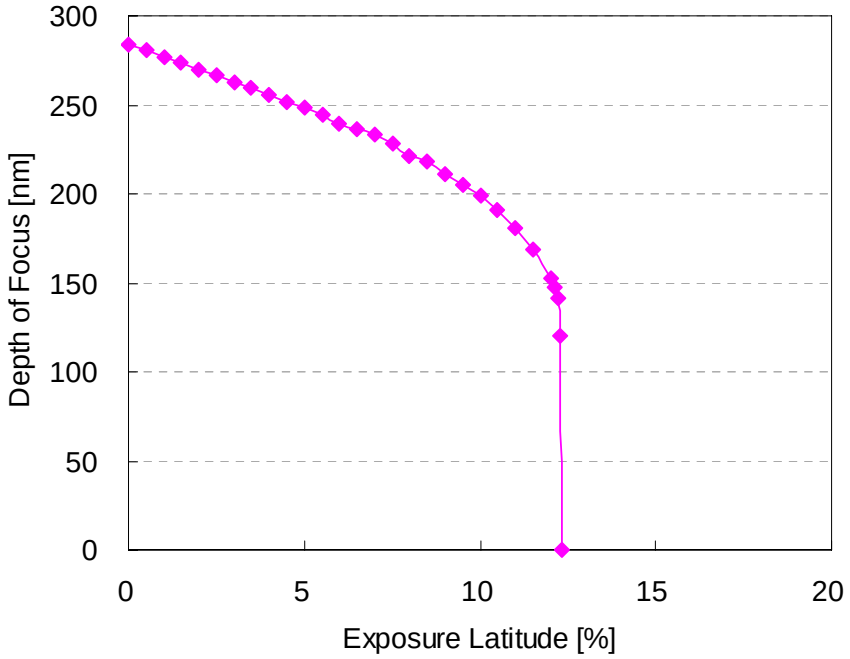
# Process Window Calculation with ΔL

1. Process window of vertical lines in the presence of 23 mλ aberration evenly allocates Z7, Z14, Z23, Z25, Z33 and Z34.



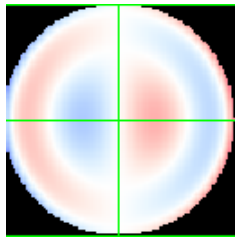
The process factor ΔL = 5 nm



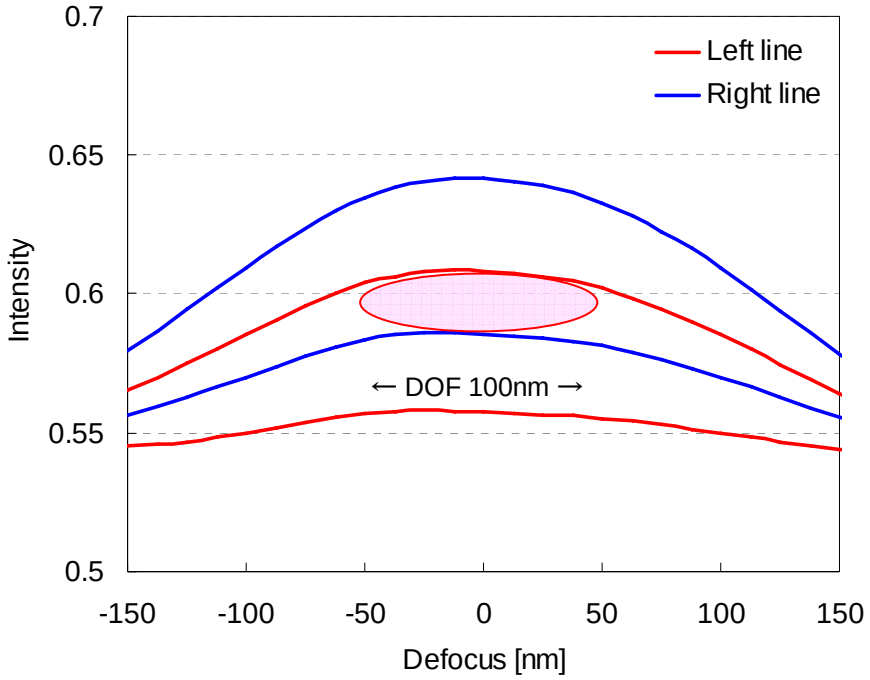



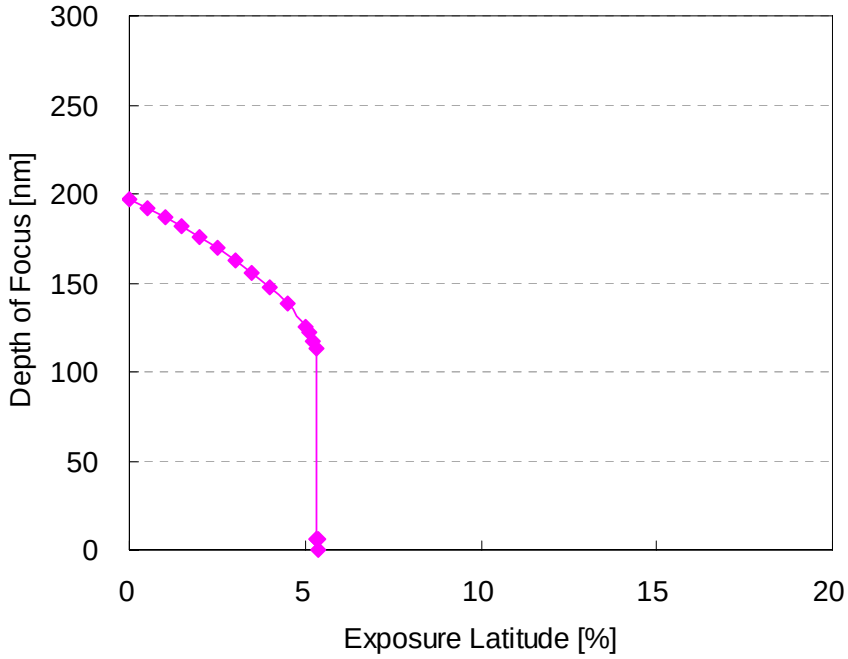
# Process Window Calculation with ΔL

1. Process window of vertical lines in worst case.
   All 24 mλ aberration allocates to Z14.



The process factor ΔL = 5 nm



# Aerial image intensity contours for 22nm dual gates