Reduction of CD shift by optimizing incident angle and characteristics of absorber films

Minoru Sugawara, Takeo Hashimoto and Iwao Nishiyama

ASET (Association of Super-Advanced Electronics Technologies)
EUV process technology research laboratory
3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan

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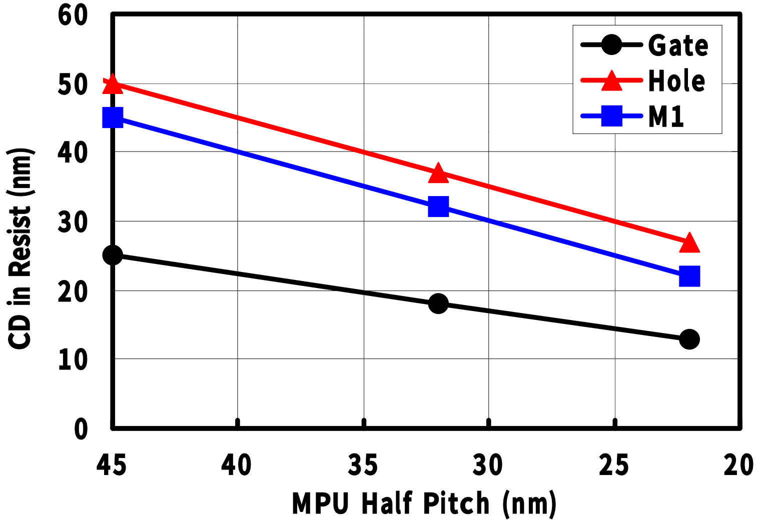
Scope and Contents

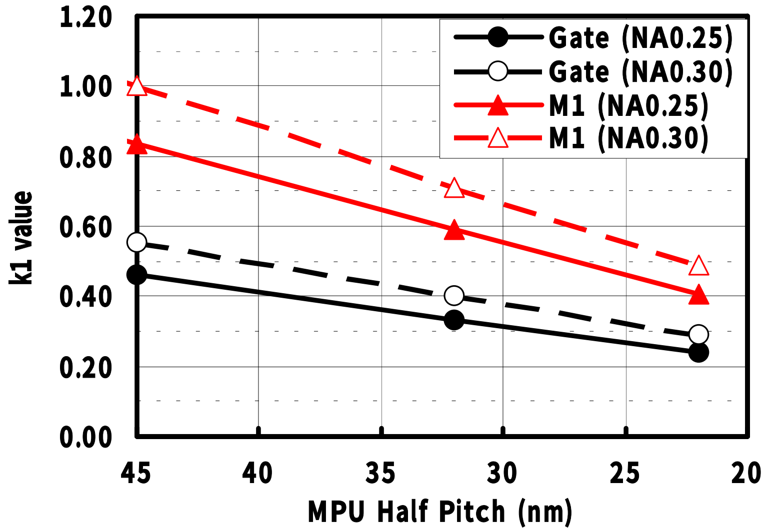
Scope: Reduction of CD shift of line pattern with linewidth of 22 nm.

- Evaluation model of CD shift by simulation.
- Correlation between CD shift and reflectance of absorber films.
- Criteria of incident angle, extinction coefficient and reflectance of an absorber films in order to satisfy CD shift below 1 nm.
- Consideration of CD shift due to energy loss by shadow.
- Correlation between CD mask bias and reflectance of an absorber film.
- Comparison of estimation of CD shift by a simple model with monochromatic light and by a practical model with broadband light.
- Conclusions.

Why is CD shift considered for line pattern with linewidth of 22 nm?



CD in resist vs. MPU half pitch



Process factor k_1 vs. MPU half pitch

Process factor k_1 which is described in Rayleigh's equation, $w=k_1(\lambda/NA)$, shows that CD control will be significantly strict in 22 nm node, because k_1 for NA 0.30 becomes 0.49 which is below 0.60. k_1 below 0.60 degrades considerably aerial image contrast in dense layout. Off-axis illumination light degrades further aerial image contrast due to shadow of absorber patterns. When k_1 below 0.60 is used with a binary mask, incident angle on a mask, extinction coefficient and thickness of an absorber film should be optimized for satisfying specification of CD shift.

Approach of decreasing CD shift caused by off-axis incident light

Problem 1:
Degradation of aerial image contrast in dense layout for perpendicular incidence.

Approach :
Small CD shift will be provided by
- smaller incident angle,
- larger extinction coefficient of absorber and buffer materials,
- appropriate thickness (appropriate reflectance) of an absorber film.

Problem 2:
Difference of CD between parallel and perpendicular incidence.

Approach :
Mask CD bias will be reduced by
- smaller incident angle,
- larger extinction coefficient of absorber and buffer materials.

Goal: Achieve small CD shift below 1nm in a practical exposure tool without any complicated corrections of mask patterns.

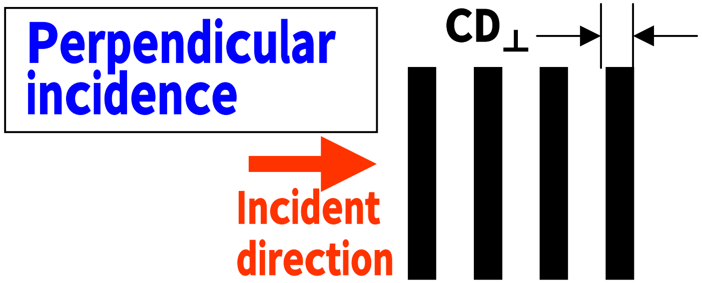
Definition of CD shift and CD mask bias

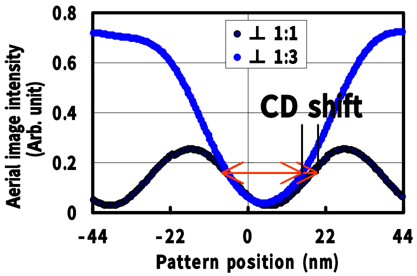
"CD shift" is defined as difference of CD between dense and semi-dense lines.

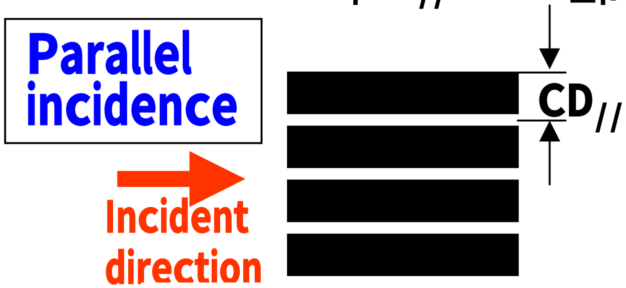
"CD mask bias" is defined as difference of CD between parallel (//) and perpendicular incidence (⊥).

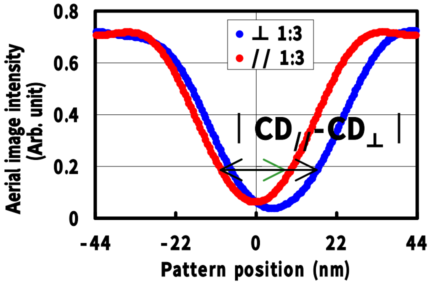
$$\text{CD shift} = \left|\text{CD}_{\text{dense}\perp} - \text{CD}_{\text{semi-dense}\perp}\right|$$

$$\text{CD mask bias} = 4\times\left|\text{CD}_{//} - \text{CD}_{\perp}\right|/\text{MEEF}$$





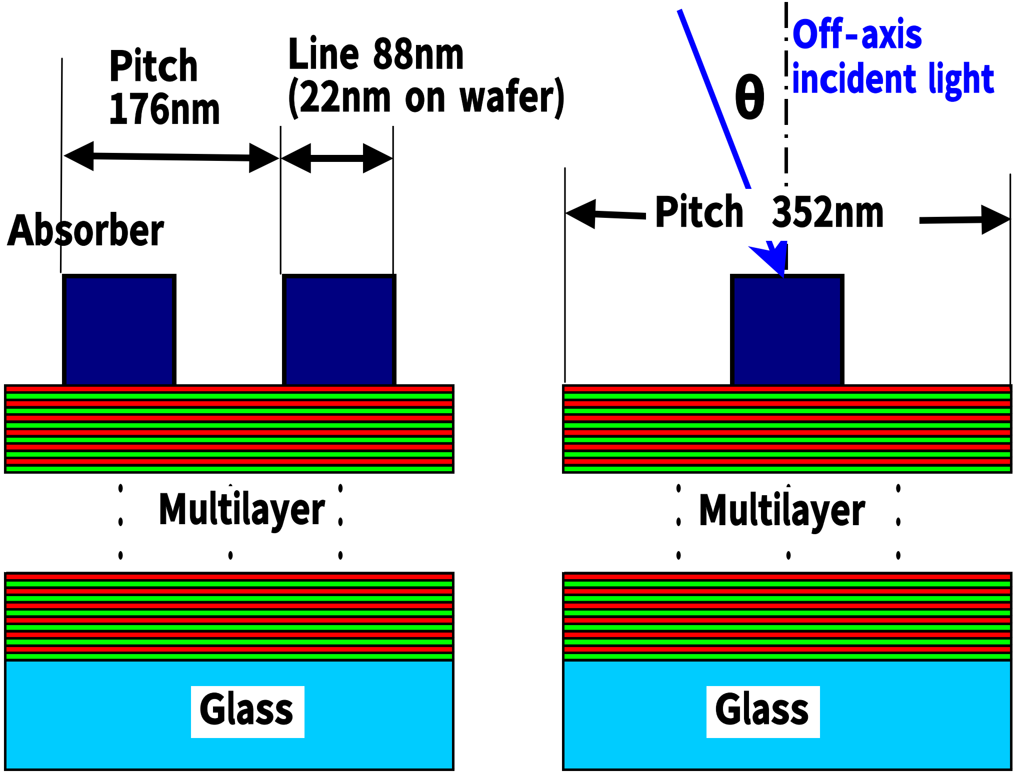




CD shift of CD between dense pattern and semi-dense pattern.
CD mask bias means amount of correction of mask patterns in order to decrease difference of CD between parallel and perpendicular incidences.

Absorber stack model for estimation of CD shift and CD mask bias

In order to obtain CD shift for line patterns with width of 22 nm on a wafer, a simple stack structure is used as a model for evaluation. Extinction coefficient (k) of absorbers are chosen from 0.025 to 0.040 so as to cover actual materials.



Refractive index used in a model

① n – ik = 0.94 – 0.025i
② n – ik = 0.94 – 0.030i
③ n – ik = 0.94 – 0.035i
④ n – ik = 0.94 – 0.040i

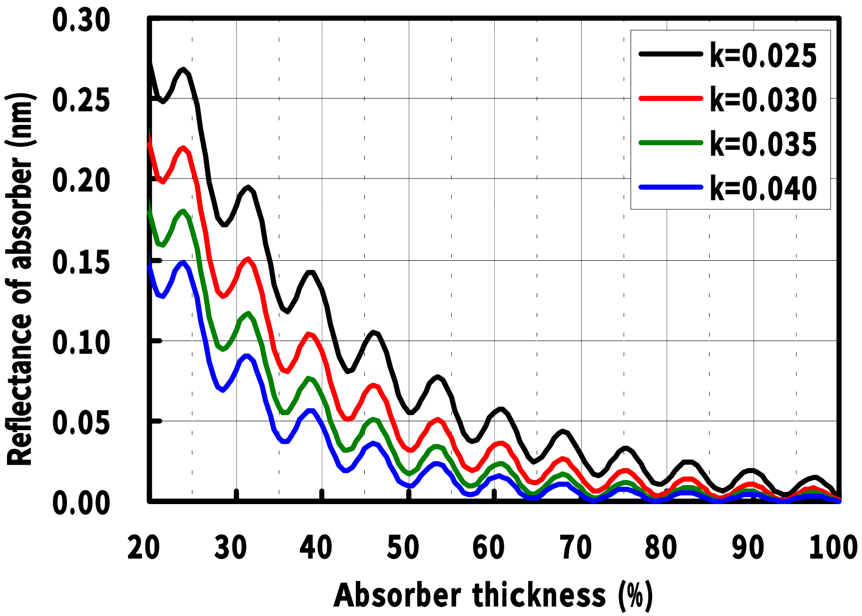
Extinction coefficient for actual materials

Absorber material	Extinction coefficient
Ta	0.0408
Cr	0.0389
TaN	0.0316
TaN70nm/Ru30nm	0.0273
TaN70nm/$SiO_2$30nm	0.0254

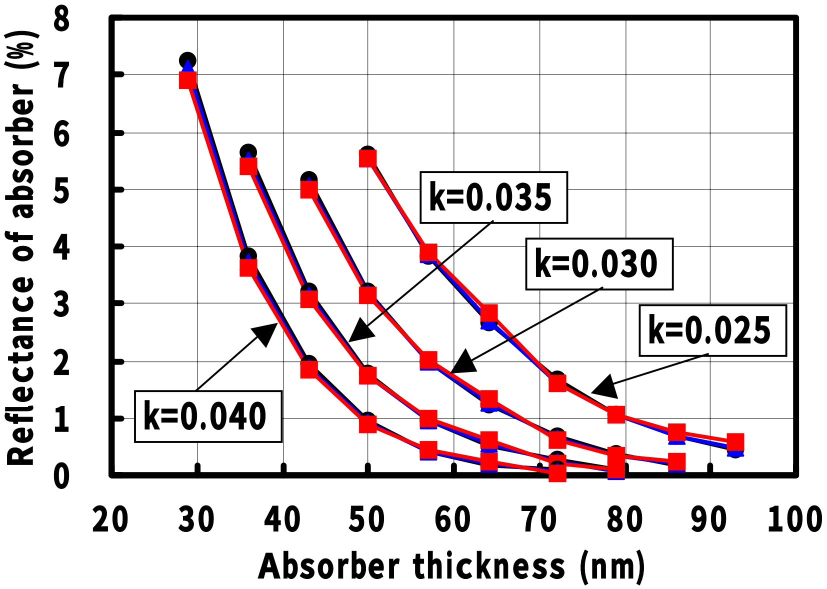
Simulation conditions

Width of line on a wafer: 22nm
Exposure wavelength: 13.5nm
Simulator: TEMPEST
Optical condition: NA0.30, σ 0.90
Polarization: TE and TM
Aberration and flare: None
Mask magnification: 4X

Reflectance vs. absorber thickness at wavelength of 13.5 nm for estimating CD shift



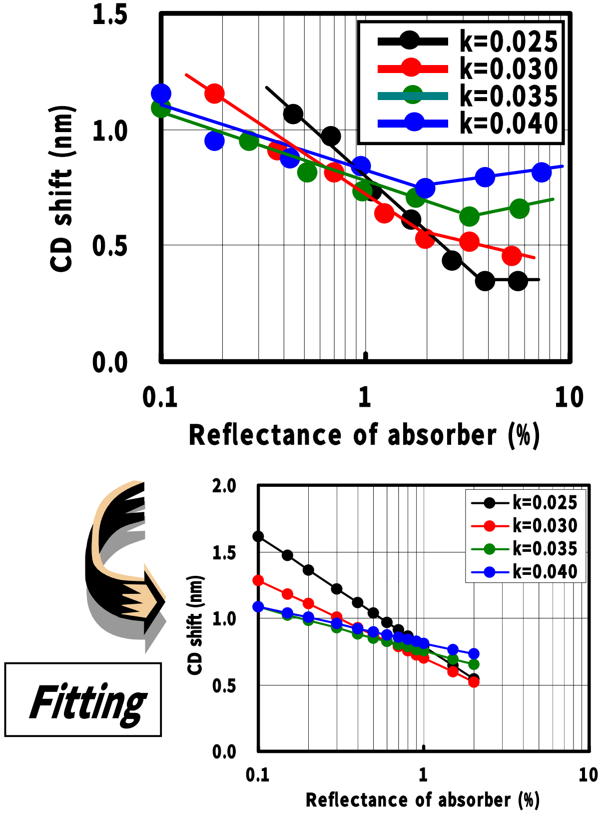
- Reflectance of absorber vs. absorber thickness



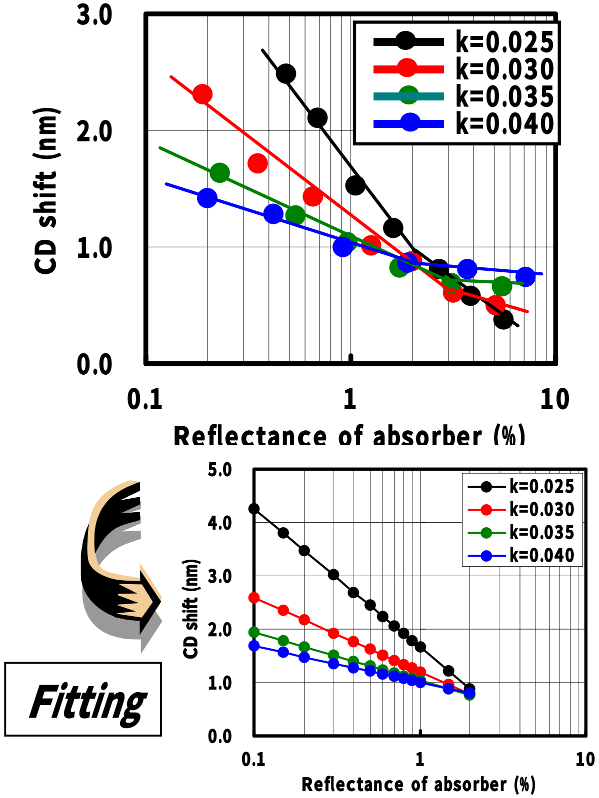
- Reflectance of absorber and absorber thickness that are used.

Reflectance of absorber decreases periodically with increasing absorber thickness as shown in left figure. Absorber thicknesses that are used for estimating CD shift are shown by marks in right figure. The absorber thicknesses are chosen at the minimum points of reflectance curves.

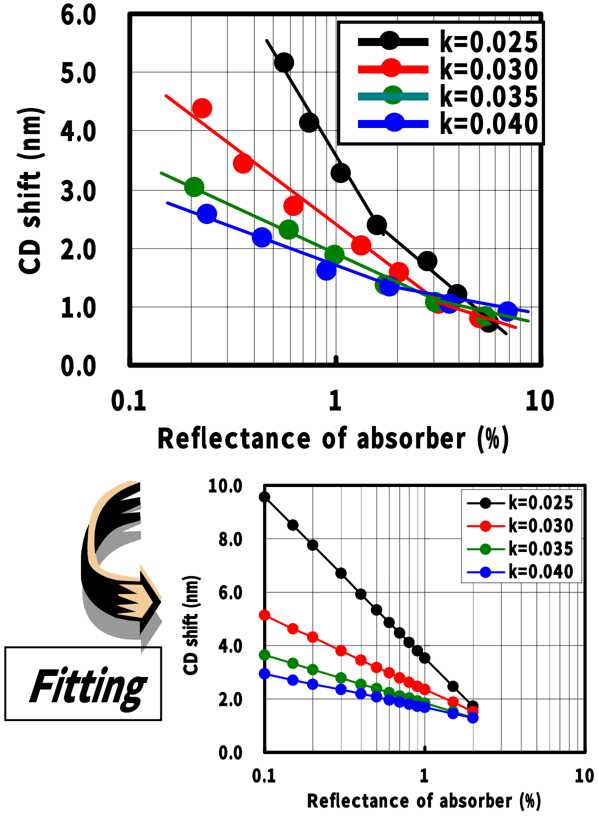
CD shift with respect to reflectance of absorber films



(a) 5.50 degrees



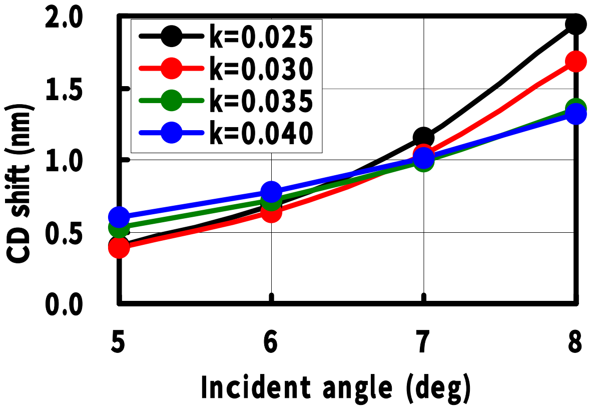
(b) 6.61 degrees



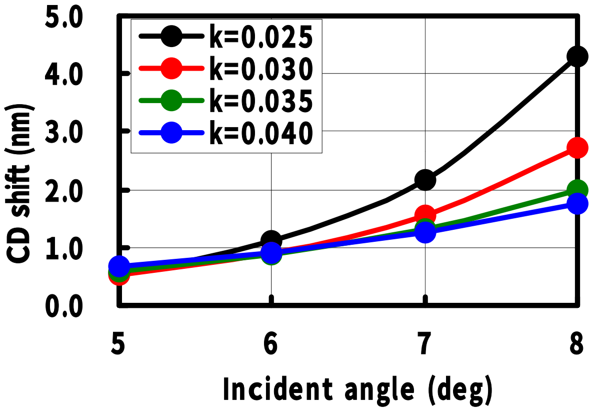
(c) 7.71 degrees

CD shift correlates well with reflectance of absorber below 2.0%. It is suggested that the reflectance of absorber below 2.0% could be feasible. Fitting curves are useful to determine incident angle, reflectance and extinction coefficient of absorber film.

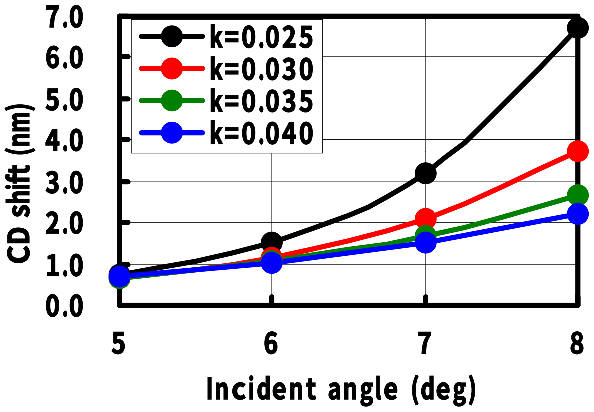
CD shift with respect to incident angle



(a) Absorber reflectance of 2.0%



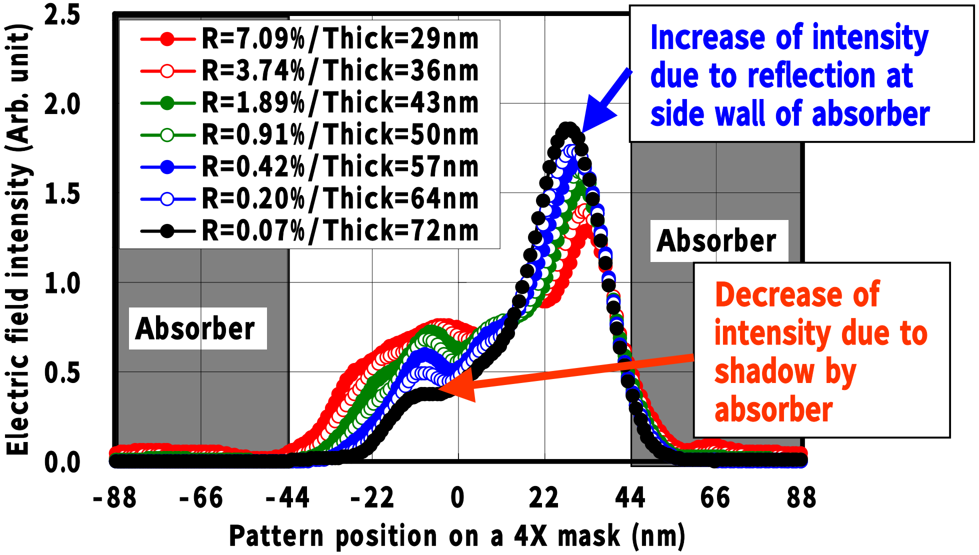
(b) Absorber reflectance of 1.5%



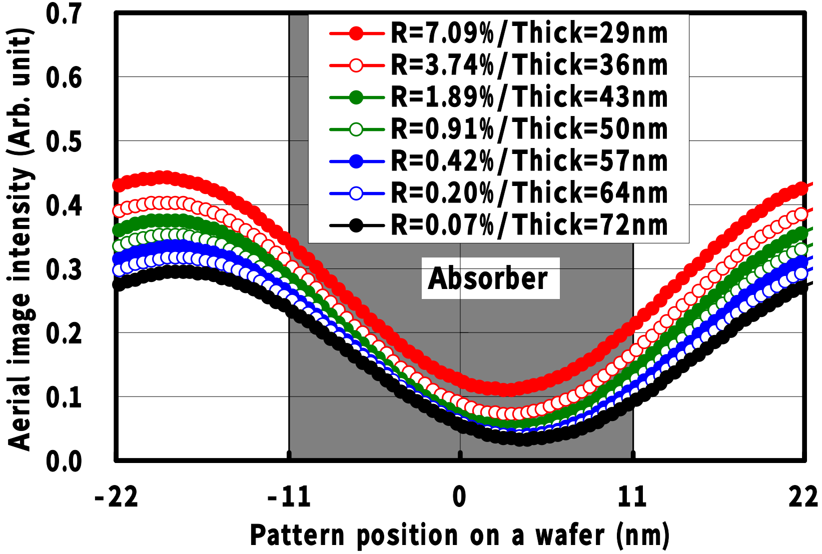
(c) Absorber reflectance of 1.0%

CD shift as a function of incident angle provides the criteria of incident angle, extinction coefficient and reflectance of an absorber film in order to satisfy the CD specification on a wafer. When CD shift specification below 1.0 nm is assumed, reflectance of an absorber film of 2.0% restricts incident angle to 7 degrees or below for absorber material with extinction coefficient of 0.040. When an exposure tool requires larger incident angle over 6 degrees, extinction coefficient of an absorber film should be more than 0.035. Figures are another expressions of fitting curves that are shown in the preceding page.

Near field intensity and aerial image for analyzing CD shift



(a) Near filed intensity

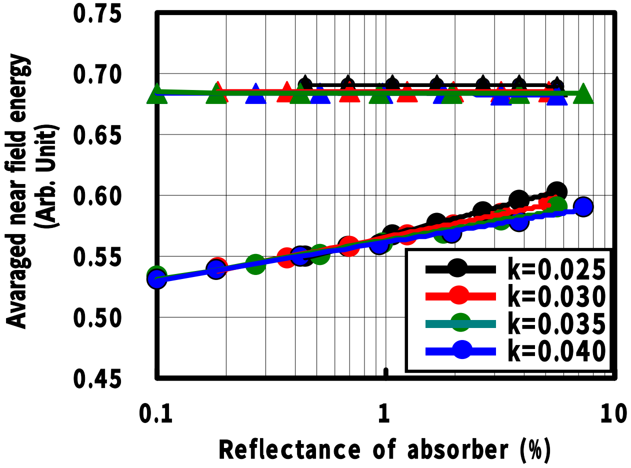


(b) Aerial image intensity

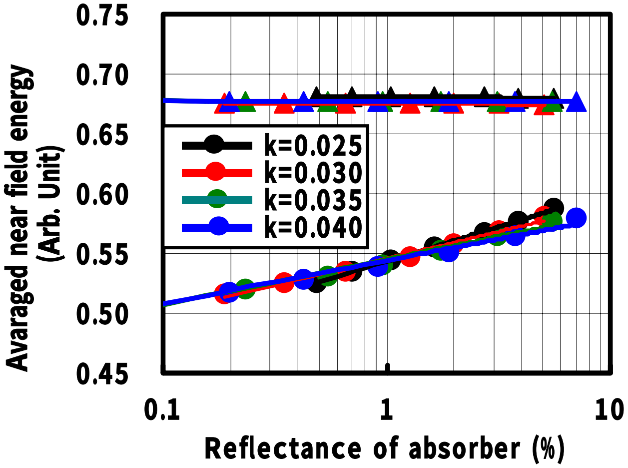
CD shift of dense lines is attributed to the degradation of energy due to shadow which is created by absorber patterns and off-axis illumination on a mask. Fig. (a) shows near field intensity at extinction coefficient of 0.040 and incident angle of 6.61 degrees, as an example. Near field intensity becomes small due to shadow with decreasing reflectance of absorber (increasing absorber thickness). Decrease of intensity by shadow overcomes increase of intensity due to side-wall reflection. Aerial image contrast degrades with decrease of near field intensity. Smaller contrast of aerial image enlarges CD shift.

Averaged near field energy vs. reflectance of absorber

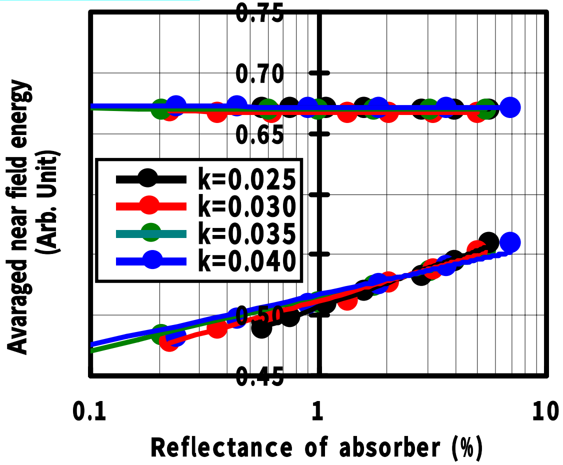
Averaged near field energy is defined as $$E_{ave} = |1/(x_2 - x_1)| \int_{x1}^{x2} E_{near}\, dx$$



(a) 5.50 degrees



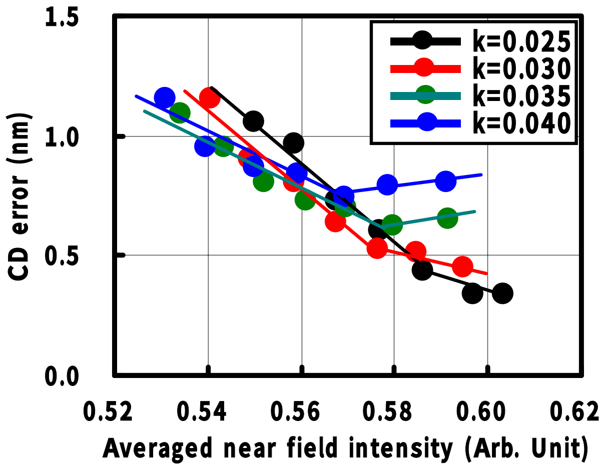
(b) 6.61 degrees



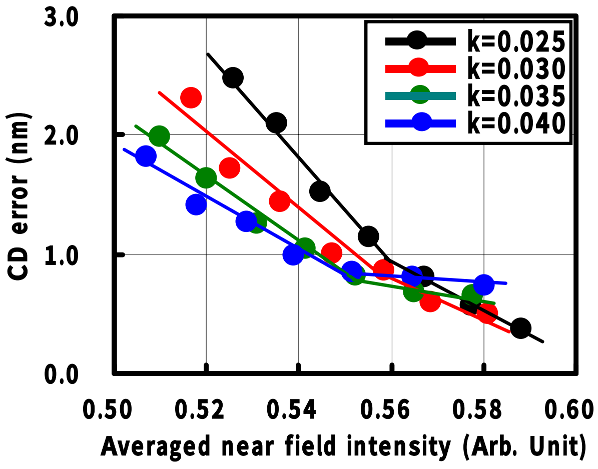
(c) 7.71 degrees

For dense lines (line and space = 1:1), the averaged near field energy becomes small with decreasing reflectance of absorber (increasing absorber thickness). For semi-dense lines (line and space = 1:3), the averaged near field energy becomes flat. These results mean that shadow influences on dense lines. Semi-dense line has been used for fixing aerial image threshold so far, because the averaged near filed energy is independent of reflectance of absorber. For dense lines, reflectance of an absorber film correlates linearly with CD shift as shown in the next page.

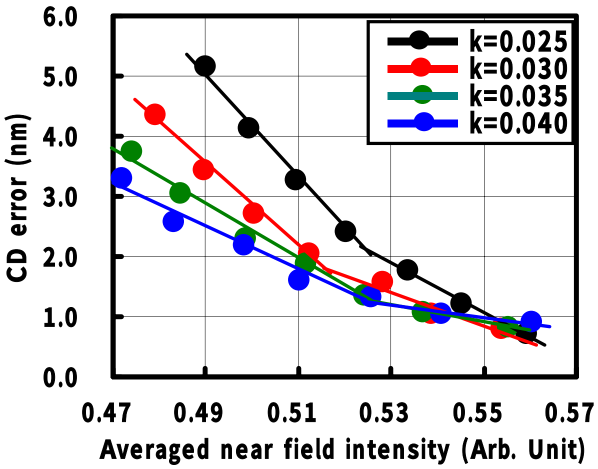
CD shift and averaged near field intensity



(a) 5.50 degrees



(b) 6.61 degrees



(c) 7.71 degrees

CD shift is attributed to degradation of the averaged near field intensity, since CD shift correlates linearly with the averaged near field intensity which corresponds to reflectance of absorber films below 2.0%. It can be summarized that:

Decrease of reflectance (increase of absorber thickness) →Energy loss due to degradation of near field intensity → Degradation of contrast of aerial image → CD shift

Degradation of near field intensity is strengthened by increasing incident angle.

Lower extinction coefficient of absorber material enhances CD shift, because it needs thicker absorber film. The thicker film enlarges energy loss and CD shift due to shadow.

CD mask bias vs. reflectance

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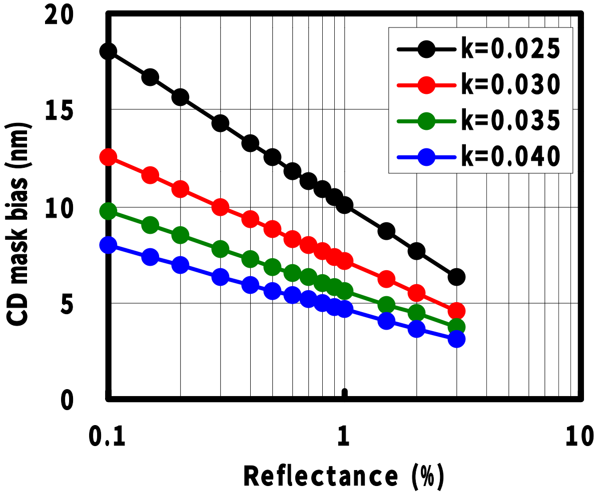
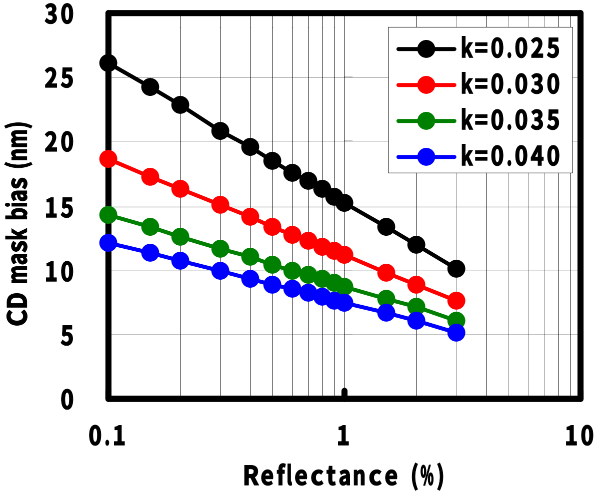
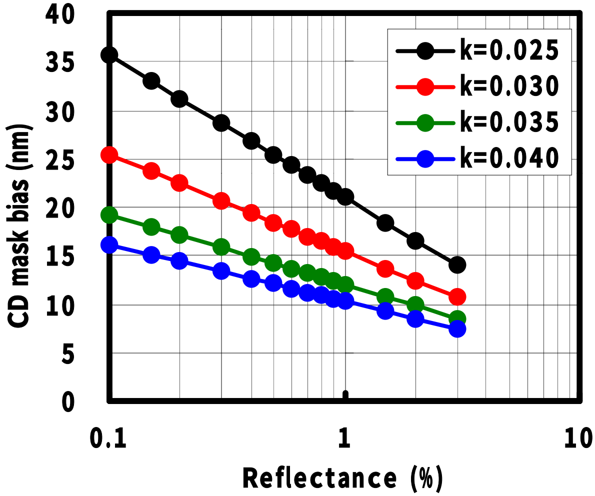
$$\text{CD mask bias} = 4\times|CD_{//} - CD_{\perp}|/\text{MEEF}$$



(a) 5.50 degrees



(b) 6.61 degrees

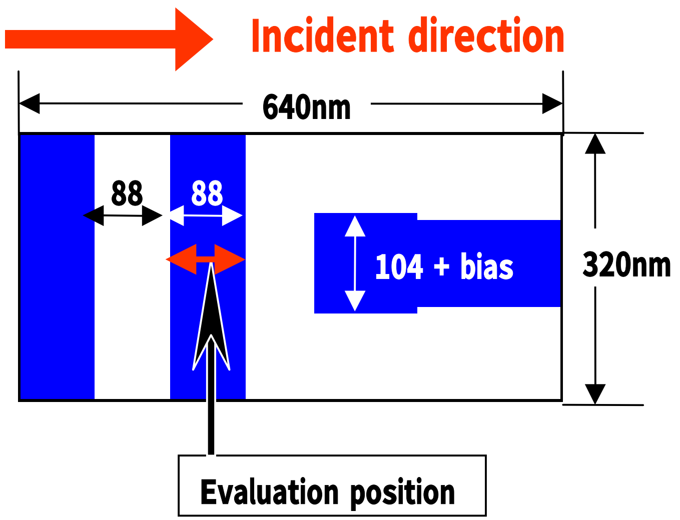


(c) 7.71 degrees

CD mask bias (4X) is also correlated with reflectance of absorber film. Small extinction coefficient of absorber films and large incident angle increase CD mask bias. Small CD mask bias is preferable to achieve enough contrast of aerial image to print patterns for parallel incidence.

Comparison of CD shift by the simple model and by a practical model

Practical T-shaped model



Incident angle
4.84, 6.05, 7.27 and 8.49 degrees

Configurations

Thickness (nm)		Reflectance (%) for broad-band
Ta	Cr	
23	21	1.143
36	21	0.617
43	21	0.351

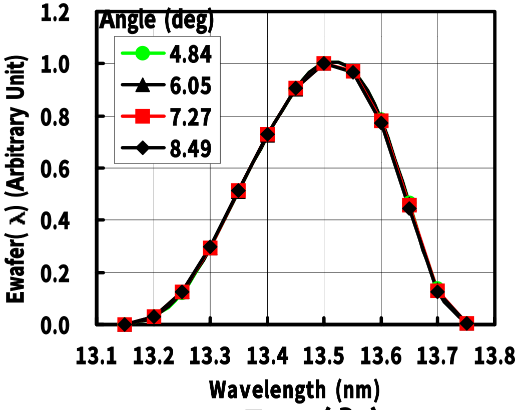
Aerial image for broad-band exposure light

$$I\,(x,y\,) = C^{-1}\int E\,(\lambda) J\,(x,y,\,)d\lambda$$

E(λ) is the energy distribution on a wafer.

$$E_{wafer}(\lambda) = R_E(\lambda)^{12} R_M(\lambda)$$

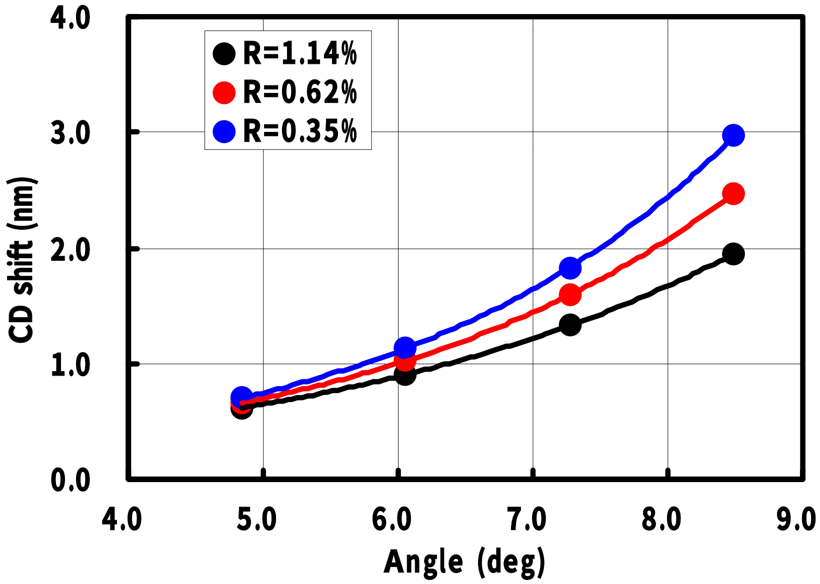
where $R_E(\lambda)$ and $R_M(\lambda)$ are the reflectance of the mirrors and of a mask blank, respectively.



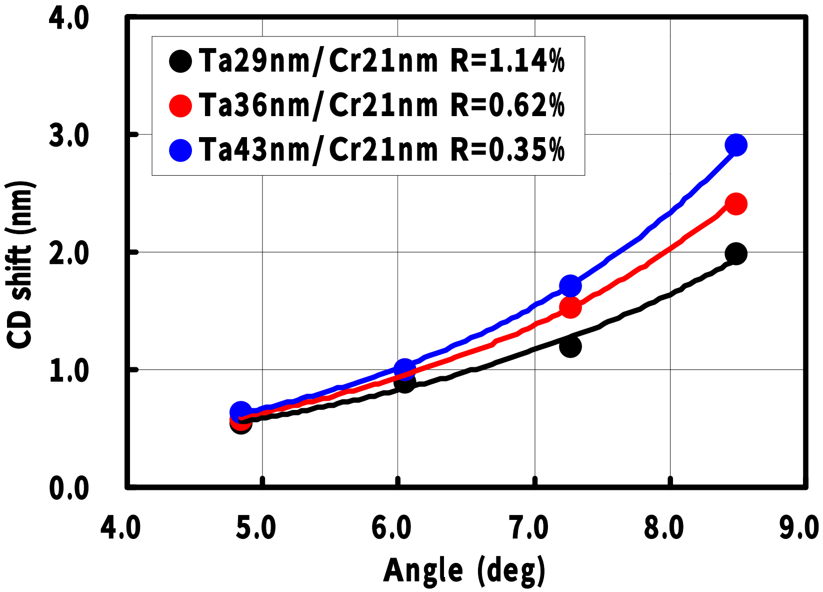
$E_{wafer}(\lambda)$

So far, CD shift has been estimated by line pattern with monochromatic exposure light. Here, the simple approach is compared with broadband exposure of light and a practical T-shaped layout with Ta absorber and Cr buffer.

Estimation of CD shifts by the simple model and by the practical model



(a) CD shift by dense line pattern



(b) CD shift in T-shaped pattern

CD shift due to the simple approach in Fig. (a) coincides with CD shift of the T-shaped pattern by broadband exposure light as shown in Fig.(b). The simple approach provides sufficient estimation of CD shift for a practical layout and broadband exposure.

Conclusions

- Optimization of incident angle and, extinction coefficient and reflectance of absorber are indispensable for decreasing CD shift of line patterns with linewidth of 22 nm. When CD shift specification below 1.0 nm was assumed, reflectance of an absorber film of 2.0% restricted incident angle to 7 degrees or below for absorber material with extinction coefficient of 0.040.

- CD shift was caused by energy loss due to degradation of near field intensity.

- Smaller mask CD bias was obtained by large extinction coefficient of absorber films and smaller incident angle.

- The simple approach of estimating CD shift by using lines and monochromatic exposure light provided sufficient estimation of CD shift for broadband exposure light and for the practical T-shaped layout with Ta absorber and Cr buffer.