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In-line wavefront aberration adjustment of a projection lens for a lithographic tool using the dominant mode method

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Aberration adjustment is of great importance in the lithographic process of integrated circuit manufacturing due to the pressure variance, lens thermal effects, overlay correction, and 3D mask effects. With the objective of removing the crosstalk effect, as well as reducing computational complexity during in-line application, a dominant mode method is proposed to adjust the aberrations of the projection lens for a lithographic tool. Theoretical definitions and corresponding calculations of dominant modes are proposed to select the compensators of the projection lens and to build the control matrix for compensator settings. The proposed method is successfully applied in a practical aberration adjustment of the projection lens in a lithographic tool, and the results demonstrate its feasibility and performance.

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1. INTRODUCTION

In the lithographic process of integrated circuit (IC) chip manufacturing, the wavefront aberrations of a projection lens have significant impact on lithographic quality [1–3]. Common types of undesired impact include pattern distortion, critical size variance, depth of focus (DOF) degradation [4], and overlay error [5,6]. In high numerical aperture (NA) lithographic projection lenses, the wavefront aberrations should be controlled within 0.05–0.01λ, magnification error, and distortion should be controlled within 1–0.5nm. Modern optical manufacturing and assembly techniques are mature and reliable, and the lithographic projection lens could obtain required wavefront quality on the test bench [7]. However, in a practical lithographic process, due to the variance of air pressure and thermal effects [8–11] of the lens, the wavefront aberrations of the projection lens change significantly, and the lens must correct for these in-line errors. At the same time, the mask (object) and silicon substrate (desired image surface) are deformed in the process, so that it is necessary to adjust the magnification and distortion of the lithographic lens to compensate for the overlay error. Phase shift masks are a commonly used resolution enhancement technique in a low K1-factor process, but the three-dimensional structure of the mask phase-shifting layer produces equivalent spherical aberration [12–14], which should also be corrected with a lithographic projection lens.

A series of compensators is thus usually used to adjust aberrations, which includes the position of the wafer stage, reticle stage, exposure wavelength, and part of the movable elements in the projection lens. When the settings of these compensators change, the aberration of the projection lens changes at the same time. The aberration adjustment system of a lithographic projection lens is a typical multiple-input multiple-output (MIMO) linear system, and its control model can be expressed as $\mathbf{C} = \mathbf{M}\boldsymbol{\Phi}$. Here, the output $\mathbf{C}$ is the vector of all compensator setting values, the input $\boldsymbol{\Phi}$ is the vector of the desired aberrations to be adjusted, and the control matrix $\mathbf{M}$ is used to calculate the setting vector $\mathbf{C}$ of the compensators during aberration adjustment [15–17].

The aberration adjustment method for a lithographic projection lens consists of two steps: selecting the compensators and computing the control matrix $\mathbf{M}$. In the traditional aberration adjustment method, movable elements that work as compensators are selected empirically during the design process of a lithographic projection lens. This selection is subject to constraints of optical or mechanical structures and should satisfy the objective of aberration adjustment. Based on the selected compensators, the aberration sensitivity matrix $\mathbf{S}$ can be calculated by optical design software. The sensitivity matrix $\mathbf{S}$ maps the vector $\mathbf{C}$ of all compensator settings to the vector $\boldsymbol{\Phi}'$ of actual aberration variation. This mapping equation can be expressed as $\boldsymbol{\Phi}' = \mathbf{SC}$. The traditional adjustment method then straightforwardly adopts the Moore–Penrose inverse of the sensitivity matrix $\mathbf{S}$ as the control matrix $\mathbf{M}$, i.e., $\mathbf{M} = [\mathbf{S}^{\mathrm{T}}\mathbf{S}]^{-1}\mathbf{S}^{\mathrm{T}}$.

Because the sensitivity matrix $\mathbf{S}$ retains only the complete information of aberration variation without any mathematical constraints in the calculation process, **S** usually is a singular matrix, and its Moore–Penrose inverse **M** multiplied by **S** does not equal the unit matrix **U**. Therefore, the obtained compensator setting **C** is just the least square solution rather than the exact solution, i.e., $\mathbf{\Phi}' \neq \mathbf{\Phi}$, which means the actual aberration adjustment is not uniquely determined, and the result has crosstalk. When adjusting a particular form of aberration, this aberration is often not fully tuned into place, while at the same time producing a portion of aberrations that are not desired to be adjusted. However, the in-line aberration adjustment of the lithographic projection lens is an open-loop control process. The precondition of precise adjustment of aberration is that the control system should be fully decoupled in addition to the parameters in the control matrix **M** being accurate. Obviously, it cannot satisfy the above conditions directly using the Moore–Penrose inverse of the sensitivity matrix **S** as the control matrix **M**.

In order to avoid the crosstalk problem, some pioneering studies based on singular value decomposition (SVD) or similar methods have been proposed [18–21]. In these methods, the eigenvectors of the matrix $\mathbf{SS}^{\mathrm{T}}$ computed by the SVD-based method, as the orthogonal kernels of the input aberration space, are used to construct the desired aberration vectors $\mathbf{\Phi}$ by linear combination. The Moore–Penrose inverse of the sensitivity matrix **S** is still used as the control matrix **M**. Although the method can avoid the crosstalk problem mentioned above, because of the complex mathematical expression of the orthogonal kernels, the desired aberration vectors $\mathbf{\Phi}$ do not have obvious engineering application definitions in the lithographic process, such as magnification or constant spherical aberration terms. This method is suitable for off-line alignment of a lithographic projection lens, instead of the in-line rapid aberration adjustment application.

A dominant mode method for adjusting the aberration of a lithographic projection lens is proposed in this paper. This method also includes two parts: compensator selection and control matrix calculation. Different from other methods, the process of compensator selection and control matrix calculation depends on the dominant mode [22] of aberration variation in a projection lens.

The aberration of the lithographic projection lens can be characterized by a series of Zernike distribution coefficients (ZDCs). Here, the Zernike coefficients represent the phase difference distribution on the pupil corresponding to a certain position in the field of view (FOV), while the Legendre polynomial coefficients in ZDC are used to characterize the distribution of each Zernike coefficient in the FOV. In aberration adjustment, the ZDCs that are all elements of the aberration vector $\mathbf{\Phi}$ are arranged in a specific order in the vector. The dominant mode is a special type of aberration variance after the settings of each compensator are changed. The mathematical characteristics of the dominant mode embodied in the aberration vector $\mathbf{\Phi}$ are as follows: (1) the aberration vector $\mathbf{\Phi}_{\mathrm{d}}$ corresponding to any dominant mode is a sparse vector, i.e., only a small number of vector elements are non-zeros; (2) the non-zero elements in the aberration vector $\mathbf{\Phi}_{\mathrm{d}}$ corresponding to any dominant modes have a fixed ratio between non-zero elements numerically; (3) in aberration adjustment, the variance of aberration is only the scaling and linear sum of all dominant modes, and there is no other form of crosstalk. There, $\mathbf{\Phi}_{\mathrm{d}}$ is the aberration vector that characterizes the dominant mode. According to the mathematical properties of the dominant mode, a fast and effective iterative algorithm is presented to calculate the dominant mode of aberration variation in a projection lens.

Dominant mode is a representation of aberration control behavior of a projection lens. Although dominant mode is not the eigenvector of sensitivity matrix **S**, it has the advantage of non-crosstalk control. Based on the characteristic of dominant mode, this paper proposes a method of aberration adjustment for a projection lens. First, we calculate the dominant modes of all possible compensator combinations. According to the matching degree of dominant modes and aberration adjustment requirements, the optimal group of compensators is determined. Then, the control matrix **M** can be established based on the settings of the compensators of each dominant mode, and the corresponding aberration vectors $\mathbf{\Phi}$ are represented by a dominant mode coefficient (DMC). This method can not only realize fast optimization of the compensator, but also realize the non-crosstalk adjustment of aberration. It has been applied to the in-line aberration adjustment of a lithographic projection lens.

2. METHOD

A. Aberration Expression of Lithographic Projection Lens

The wavefront error (WFE) is adopted as the aberration evaluation parameter for the large NA projection lens. In the ideal lithographic lens, a segment of a divergent spherical wave has to be transformed into a segment of a convergent spherical wave. The deviation between the actual wavefront and the reference spherical wavefront is defined as the WFE. Shown in Fig. 1, the WFE can be expanded into Zernike polynomials [23,24] and expressed accurately with the Zernike polynomial coefficients as

$$W(r,\theta) = \sum_{i=2}^{37} z_i \cdot R_i(r,\theta), \tag{1}$$

where W is the WFE at the coordinate (r, θ) of pupil plane, $R_i(r,\theta)$ is the i-th term Zernike polynomial and normalized in the circular pupil domain, and z_i is the corresponding Zernike coefficient. In this paper, the Zernike coefficients can be represented as a vector:

$$\mathbf{z} = [\, z_2 \quad z_3 \quad z_4 \quad z_5 \quad \ldots \quad z_{37} \,]^{\mathrm{T}}. \tag{2}$$

The FOV of a lithographic lens is a rectangular domain larger than 20 mm size. In this area, the WFE in each location is different, and the variations of the WFE caused by the change of the compensation element setting are also different. In order to further describe the distribution characteristics of WFE in FOV, the single Zernike coefficients in all locations of FOV can be

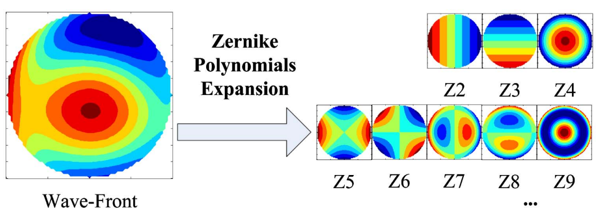

Fig. 1. Wavefront error expands into Zernike polynomials.

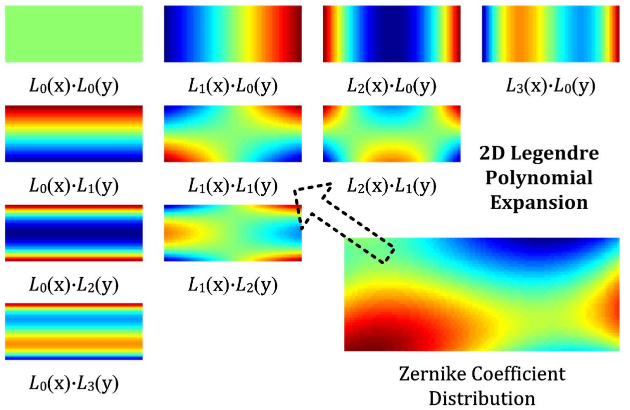

Fig. 2. Zernike coefficients expand into two-dimensional Legendre polynomials.

expanded into two-dimensional Legendre polynomial coefficients [25–27] by least square fitting (LSF) and normalized by the boundary of the FOV area, shown in Fig. 2.

The obtained coefficients of Zernike–Legendre expansion can be defined as ZDC:

$$z_i(x,y) = \sum_{m=0}^{3}\sum_{n=0}^{3-m} ZD_{i;m,n} \cdot L_m(x) \cdot L_n(y), \tag{3}$$

where z_i is the Zernike coefficient at the coordinate (x, y) of FOV, $L_m(x)$ and $L_n(x)$ are, respectively, the m-th and n-th terms of the Legendre polynomial and normalized in the rectangular FOV domain, and $ZD_{i;m,n}$ is the corresponding ZDC. In a lithographic projection lens, the Zernike coefficients are usually taken from the second to 37th order, in total 36 terms. The Legendre polynomial coefficients are usually taken from the zeroth to third order and $m + n \leq 3$, in total 10 terms. Therefore, the length of the aberration vector is 360. Through two strict correlated expansion operations, the aberration at all locations of FOV can be expanded into a series of ZDCs, and further be vectored as $\mathbf{\Phi}$:

$$\mathbf{\Phi} = [ZD_{2;0,0}\ \ ZD_{2;0,1}\ \ ZD_{2;1,0}\ \ \ldots\ \ ZD_{3;0,0}\ \ \ldots\ \ ZD_{37;3,0}]^{\mathrm{T}}. \tag{4}$$

This part is the preparatory work for the following design of the aberration adjustment system, especially for the calculation of dominant modes. Its purpose is to normalize the aberrations of the lithographic projection lens in a vector form for the subsequent matrix operation as

$$W(r,\theta;x,y) \Rightarrow \mathbf{z}(x,y) \Rightarrow \mathbf{\Phi}. \tag{5}$$

When the selection of compensators and calculation of corresponding dominant modes are completed, the aberration vector can be further constructed with the DMCs, which makes the mathematical expression of the control model more concise.

B. Dominant Mode Calculation for Aberration Variance

Dominant mode is a form of aberration variance with specific mathematical characteristics, which can be fully embodied in the aberration vector $\mathbf{\Phi}$. Therefore, the calculation of dominant mode is also based on the mathematical characteristics of $\mathbf{\Phi}$, which sets up the corresponding evaluation function and calculates by iterative method. The calculation method is as follows:

(1) Sort all sensitivity data $\partial ZD_{i;m,n}/\partial c_u$ of the designated compensators into the form of the sensitivity matrix $\mathbf{S}$; there, c_u is the normalized setting of the u-th compensator.

(2) Calculate the Moore–Penrose inverse of the sensitivity matrix as the control matrix $\mathbf{M}$ as

$$\mathbf{M} = [\mathbf{S}\mathbf{S}^{\mathrm{T}}]^{-1} \cdot \mathbf{S}^{\mathrm{T}}. \tag{6}$$

(3) Define the number d of non-zero coefficients in dominant mode. In order to make dominant mode more significant for application, d is suggested to be fewer than 6.

(4) Calculate dominant mode iteratively from an initial aberration vector $\mathbf{\Phi}_0$ with only one ZDC set to 1 and the remaining ZDC to 0, such as

$$\mathbf{\Phi}_0 = [1 \quad 0 \quad 0 \quad \ldots \quad 0]^{\mathrm{T}}. \tag{7}$$

(5) In each iteration, the aberration vector $\mathbf{\Phi}_{l-1}$ calculated in the previous iteration is multiplied by the control matrix $\mathbf{M}$ and the sensitivity matrix $\mathbf{S}$ sequentially, which is a simulated aberration adjustment process, and the aberration vector $\mathbf{SM\Phi}_{l-1}$ is screened by the operator $H_d(\mathbf{\Phi})$ and normalized. This intermediate process vector is multiplied by the weight w_1, and the iterative initial vector is multiplied by the weight w_2. Then, the two weighted vectors are added as the updated aberration vector $\mathbf{\Phi}_l$ for the next iteration as

$$\begin{cases} \mathbf{\Phi}_l = w_1 \cdot \frac{\mathrm{H}_d(\mathbf{SM\Phi}_{l-1})}{|\mathrm{H}_d(\mathbf{SM\Phi}_{l-1})|} + w_2 \cdot \mathbf{\Phi}_0 \\ w_1 + w_2 = 1 \\ w_2 \leq \frac{1}{d} \\ l = 1, 2, 3, \ldots, 10, \ldots \end{cases}, \tag{8}$$

where $\mathbf{\Phi}_0$ is the initial aberration vector, $\mathbf{\Phi}_{l-1}$ is the current aberration vector, and $\mathbf{\Phi}_l$ is the updated aberration vector; w_1 and w_2 are the modulating weights for the screened and normalized aberration vector and the initial aberration vector $\mathbf{\Phi}_0$, respectively, and l is the iteration number. In this calculation, $H_d(\mathbf{\Phi})$ is the specified operator in this method that screens the elements in the aberration vector $\mathbf{\Phi}$. Its role is to retain the d elements with larger absolute value in the aberration vector and set all the other elements to 0 as in Fig. 3.

(6) After about 10 iterations, if the normalized difference between the updated aberration vector $\mathbf{\Phi}_l$ and the current vector $\mathbf{\Phi}_{l-1}$ is less than the termination threshold T in the iterating loop, the vector $\mathbf{\Phi}_l$ calculated in this iteration is a dominant mode $\mathbf{\Phi}_{\mathrm{d}}$:

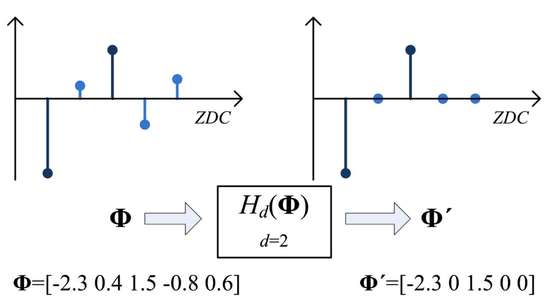

Fig. 3. Calculation process of screening operator.

$$\Phi_d = \Phi_l, \quad \text{if } \frac{|\Phi_l - \Phi_{l-1}|}{|\Phi_{l-1}|} < T, \tag{9}$$

where the iterative termination threshold T is usually set to 1/1000.

(7) Regardless of whether the dominant mode can be obtained, after no less than 10 iterations, the current round of calculation will be terminated, and the next round of iteration from another initial aberration vector will be carried out. Proceed back to step (4) and define a new aberration vector as the iteration initial value for which another element is set to 1 and the remaining elements are set to 0:

$$\Phi_0 = [0 \quad 1 \quad 0 \quad \ldots \quad 0]^{\mathrm{T}}. \tag{10}$$

As for the initial value, the element that is set to 1 needs to traverse all ZDCs from $ZD_{2;0,0}$ to $ZD_{i;m,n}$ to ensure that no dominant mode is omitted. In the above calculation process, step (5) is the key point of this method, and its core strategy is to make the output vector of iteration infinitely approach the dominant mode by continuous screening and comparison.

A complete calculation process of dominant mode is shown in Fig. 4. After the above calculation steps, the corresponding dominant modes of the selected compensators can be obtained. Figure 5 shows the process of these operations, and it can be seen that if the ZDC of the initial aberration vector is one of the coefficients in the dominant mode, the dominant mode can be obtained accurately through about 10 iterations. In this example, the initial vector Φ_0 of this iteration is $ZD_{8;0,1} = 1$ and other ZDCs are zero. In each iteration, the updated aberration vectors Φ_l of this iteration are calculated according to the initial vector Φ_0 and the current aberration vector Φ_{l-1} as Eq. (8). After each iteration, the aberration vector Φ_l is much closer to the final dominant mode with $ZD_{7;1,0}$ increasing and $ZD_{8;0,1}$ decreasing. During 12 iterations, the dominant mode is determined, and its expression is $ZD_{7;1,0} = 0.712$, $ZD_{8;0,1} = 0.288$, and the other ZDCs are zero. That means the projection lens can accurately adjust the first-order coma without any other form of crosstalk aberration. In this dominant mode, the ratio of $ZD_{7;1,0}$ and $ZD_{8;0,1}$ is exactly the aspect ratio of rectangular FOV.

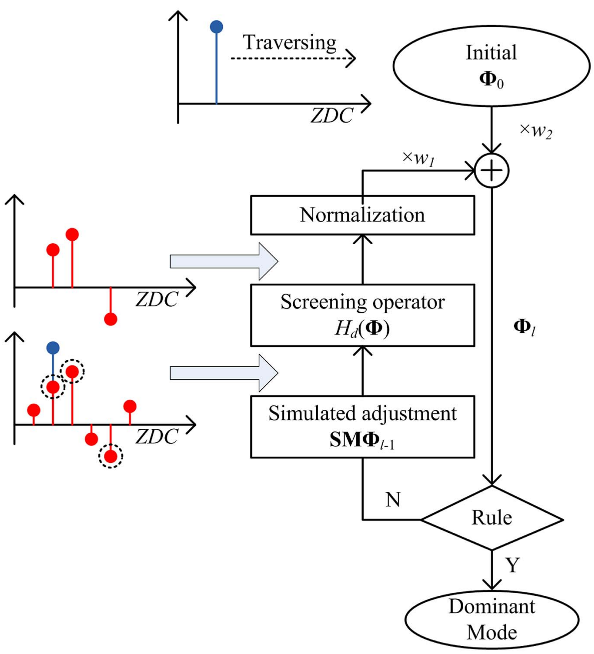

Fig. 4. Flow chart of dominant modes calculation.

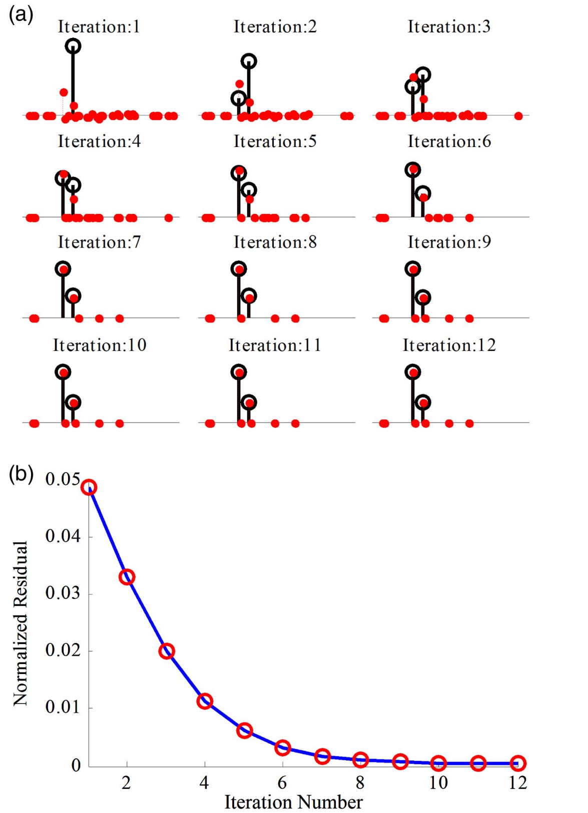

Fig. 5. Iteration process data of dominant modes searching: (a) iteration process in which the aberration vector of the system is closer to final dominant mode in each iteration; black mark is the Φ_l, and red mark is the Φ_{l-1}. (b) Residual curve, and the residual error is convergent after 10 iterations.

From the above calculation results, it can be seen that adjusting aberration by the dominant mode method will not cause crosstalk. For example, the first-order coma is an aberration form that needs to be adjusted frequently for a lithographic projection lens. In the traditional method, $ZD_{7;1,0} = 1$ is taken as the adjustment target. There are some deviations in the adjustment result in that $ZD_{7;1,0}$ is not adjusted in place, but some other forms of aberration are produced. Nevertheless, using the dominant mode method and taking the dominant mode corresponding to the first-order coma as the target of aberration adjustment will not cause similar problems. The comparison of adjustment results between the two methods is shown in Fig. 6.

C. Compensator Selection

In the design process of the lithographic lens, the compensators used for in-line aberrations adjustment must be assigned high priority. The exposure wavelength and the height setting of the wafer stage and mask stage can be used as the compensators for aberration adjustment. In addition, some movable elements in the projection lens must be selected as compensators to adjust other types of aberrations. The typical lithographic projection lens

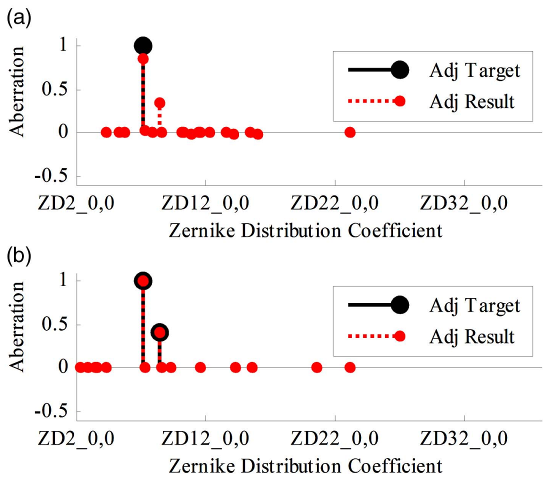

Fig. 6. Adjustment results comparison of two methods: (a) adjustment result of traditional method in which there are some deviations between the adjustment target and the adjustment results; (b) adjustment result by dominant mode method in which the adjustment target and the adjustment results are almost consistent.

usually consists of 20 to 30 elements, but due to the mechanical and vibration constraints, the number of lens compensators used in-line is usually limited to fewer than five. So in this section, the problem to be solved is how to select a few elements from these 20 to 30 elements as compensators. This problem is mathematically equivalent to which one is the best in all possible combinations C_p^q, where p is the total elements number of the projection lens, q is the elements number used as compensators, and C_p^q is the number of all possible combinations.

Based on the calculation of dominant mode, the aberration adjustment effect of all lens element combinations can be calculated quickly. The optimal combination is used as the result of compensators selection, which is based on the comparison of dominant mode and aberration adjustment requirement under each combination and some other engineering factors, such as the motion range of the compensator. The detailed calculation steps are as follows, and the flow chart of this calculation is shown in Fig. 7:

(1) Define the number q of lens compensators.
(2) All possible combinations C_p^q in p elements of the projection lens are listed.
(3) Calculate the dominant modes of each combination of compensators in turn.
(4) The dominant mode of each combination is compared with the requirements of the aberration adjustment, and the combination with the highest degree of satisfaction is screened out as the designed compensators.

If the requirements satisfaction is insufficient, the number q of compensators can be increased appropriately, and repeat the operations above. Correspondingly, if the requirements are over satisfied, the number q of compensators can be reduced to lower the design redundancy.

Once the selection of compensators and the corresponding dominant modes are determined, the first part of the aberration adjustment system is designed. The dominant modes of this compensator combination will be used for the establishment of control matrix $\mathbf{M}$.

D. Control Matrix Calculation

Another part of this aberration adjustment method is calculation of the control matrix $\mathbf{M}$. The calculation results of the dominant modes show that when the aberration vector is a linear sum of the dominant modes, the Moore–Penrose inverse of the sensitivity matrix $\mathbf{S}$ can be straightforwardly used as the control matrix $\mathbf{M}$, and no crosstalk will occur during the aberration adjustment process. The aberration vector is

$$\mathbf{\Phi} = \sum_{j=1}^{k} \varphi_j \cdot \mathbf{\Phi}_{\mathrm{d}j}, \tag{11}$$

where $\mathbf{\Phi}_{\mathrm{d}j}$ is the j-th dominant mode, φ_j is the corresponding DMC that represents the scale of this dominant mode in the aberration vector, and k is the total number of the dominant modes. Although the control method fully meets the need of non-crosstalk aberration adjustment, the control matrix $\mathbf{M}$ is large with $(q+3)$ rows and 360 columns, which needs to be further simplified. There, $(q+3)$ is the total number of compensators, including q movable elements in the projection

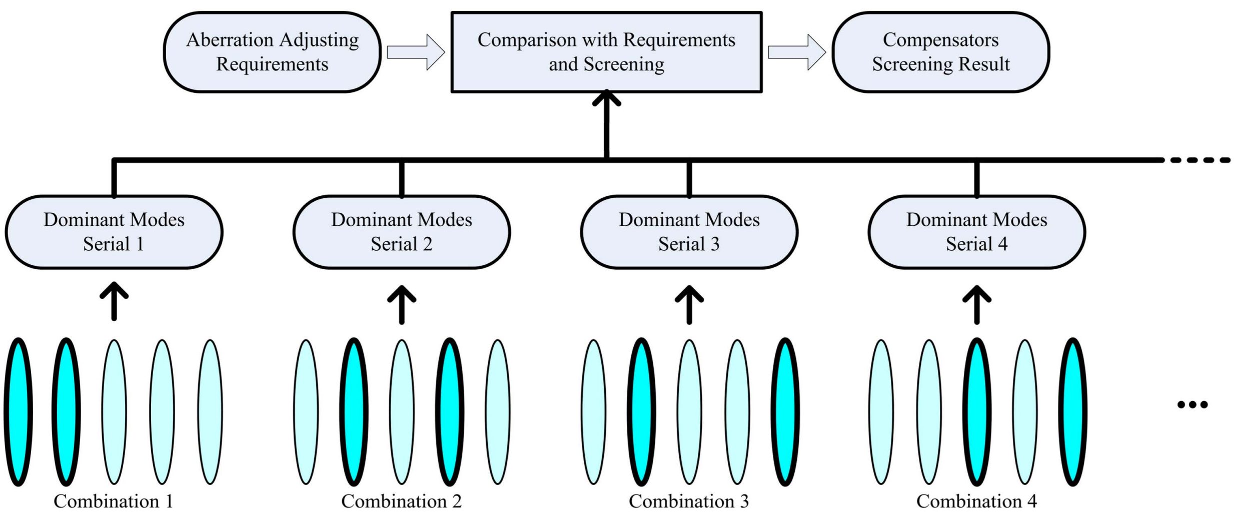

Fig. 7. Calculation process of compensators selection.

lens, and the other three compensators are laser wavelength, reticle stage height, and wafer stage height. The number 360 corresponds to the total number of ZDCs and is the same as the length of the aberration vector $\mathbf{\Phi}$.

Once the dominant mode is fully determined, aberration vectors can be constructed with all the DMCs as

$$\mathbf{\Phi} = [\varphi_1 \quad \varphi_2 \quad \cdots \quad \varphi_j \quad \cdots \quad \varphi_k]^{\mathrm{T}}, \tag{12}$$

where φ_j is the j-th DMC. Compared with the aberration vector represented by ZDCs, although the physical meaning of each element in these aberration vectors is different, the information contained in the whole vectors is identical, and the length of the vectors is greatly shortened. Therefore, we need only all dominant modes, and the corresponding control matrix $\mathbf{M}$ can be composed of the settings of all the compensators corresponding to each dominant mode as

$$\mathbf{M} = [c_{\mathrm{d}1} \quad c_{\mathrm{d}2} \quad \cdots \quad c_{\mathrm{d}j} \quad \cdots \quad c_{\mathrm{d}k}], \tag{13}$$

where $\mathbf{M}$ is a $k \times (q+3)$ matrix, k is the number of dominant modes, and $(q+3)$ is the number of compensators. The column vector $c_{\mathrm{d}j}$ corresponds to the j-th dominant mode, in which the $(q+3)$ elements are the compensator settings corresponding to this dominant mode. Each matrix element is obtained in the process of calculating the dominant mode. Through the above calculation, we can obtain the control model $\mathbf{C} = \mathbf{M\Phi}$ of the aberration adjustment system based on the dominant mode.

3. RESULTS

The aberration adjustment method proposed in this paper is applied to a lithographic projection lens, and the effect of aberration adjustment is verified. The NA of this projection lens is 0.75, the nominal exposure wavelength is 193.368 nm, and the size of FOV is 26 mm × 10.5 mm.

In the design process of this projection lens, we use the optical design software to calculate the changes of the Zernike coefficients in each position of the FOV after all possible compensators change certain settings, such as the position of the lens elements, exposure wavelength, and positions of the image plane and object plane. After regression to the Zernike distribution coefficients, the data will be used as the sensitivity coefficients for compensator selection and dominant modes calculation.

In accordance with Section 2.C, we have selected five movable elements, together with exposure wavelength, object plane height, and image plane height, with a total of eight compensators, which are listed in Table 1 and shown in Fig. 8. The selected five movable elements are located near the surface of the object and pupil, which can change the constant spherical aberration and the distribution of odd-order aberrations, in accordance with the general optical design experience.

In the selection process of the compensators, we can simultaneously calculate the dominant modes of aberration variance and the corresponding compensator settings. Under the action of the above eight compensators, the identified dominant modes are listed in Table 2 and further shown in Fig. 9.

Table 1. Selected Compensators for Aberration Adjustment

	Compensator	Setting Value
C1	Laser	Wavelength (pm)
C2	Reticle stage (object plane) position	Height (μm)
C3	Wafer stage (image plane) position	
C4	No. 4 lens element	
C5	No. 12 lens element	
C6	No. 13 lens element	
C7	No. 14 lens element	
C8	No. 17 lens element	

Table 2. Identified Dominant Modes and Optical Meaning

Dominant Mode	Optical Aberration	*ZDC* Combination
$\mathbf{\Phi}_{\mathrm{d}1}$	Defocus	$ZD_{4;0,0} = 1$
$\mathbf{\Phi}_{\mathrm{d}2}$	0th-order spherical	$ZD_{9;0,0} = 1$
$\mathbf{\Phi}_{\mathrm{d}3}$	Magnification	$ZD_{2;1,0} = 0.712$ $ZD_{3;0,1} = 0.288$
$\mathbf{\Phi}_{\mathrm{d}4}$	1st-order coma	$ZD_{7;1,0} = 0.712$ $ZD_{8;0,1} = 0.288$
$\mathbf{\Phi}_{\mathrm{d}5}$	3rd-order distortion	$ZD_{2;3,0} = 0.459$ $ZD_{2;1,2} = 0.124$ $ZD_{3;0,1} = -0.105$ $ZD_{3;2,1} = 0.311$
$\mathbf{\Phi}_{\mathrm{d}6}$	Image plane deviation	$ZD_{4;2,0} = 0.284$ $ZD_{5;0,0} = 0.115$ $ZD_{5;2,0} = 0.270$ $ZD_{6;1,1} = 0.330$

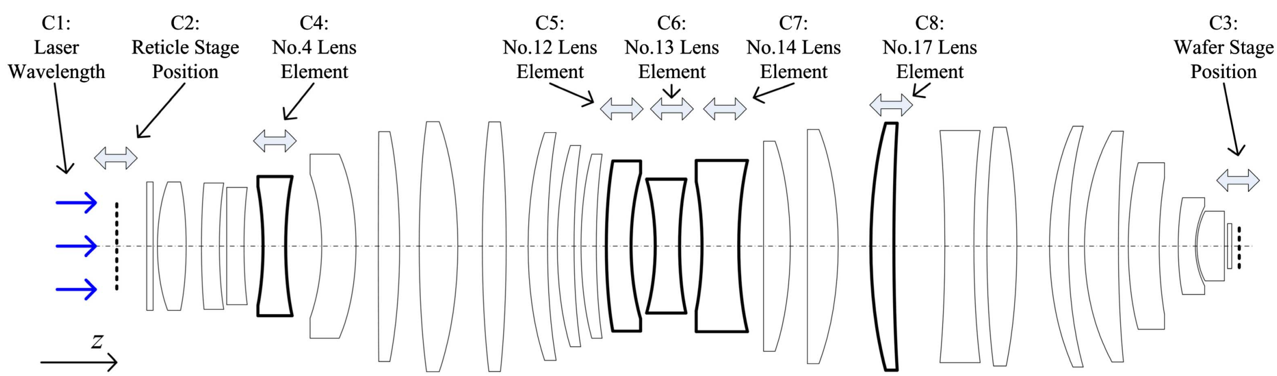

Fig. 8. Selected compensators for in-line aberration adjustment.

Since the number of Zernike distribution coefficients has been limited in the dominant modes calculation process, most of the dominant modes have a physical meaning that is consistent with or close to common optical aberrations. Here, the dominant modes include defocus, constant spherical, magnification, first-order coma, third-order distortion, and image plane deviation. This characteristic is very convenient for engineering application of aberration adjustment.

In accordance with Section 2.D, the settings of each compensator for all dominant modes are extracted and the following control matrix $\mathbf{M}$ is formed:

$$\mathbf{M}=\begin{bmatrix} 0.000 & -1.843 & -0.014 & 0.629 & -0.258 & -0.247 \\ 0.000 & -0.792 & 0.003 & -0.373 & -0.990 & 0.362 \\ 1.372 & -14.492 & -0.023 & -3.800 & -10.708 & 9.159 \\ 0.000 & 1.780 & 0.010 & -0.206 & 0.286 & 0.123 \\ 0.000 & 0.534 & 0.008 & 0.150 & 0.093 & -0.160 \\ 0.000 & 0.603 & 0.006 & 0.160 & 0.096 & 0.295 \\ 0.000 & 1.377 & 0.012 & -0.500 & 0.203 & 0.167 \\ 0.000 & 0.043 & -0.006 & 0.081 & -0.027 & 0.037 \end{bmatrix}, \tag{14}$$

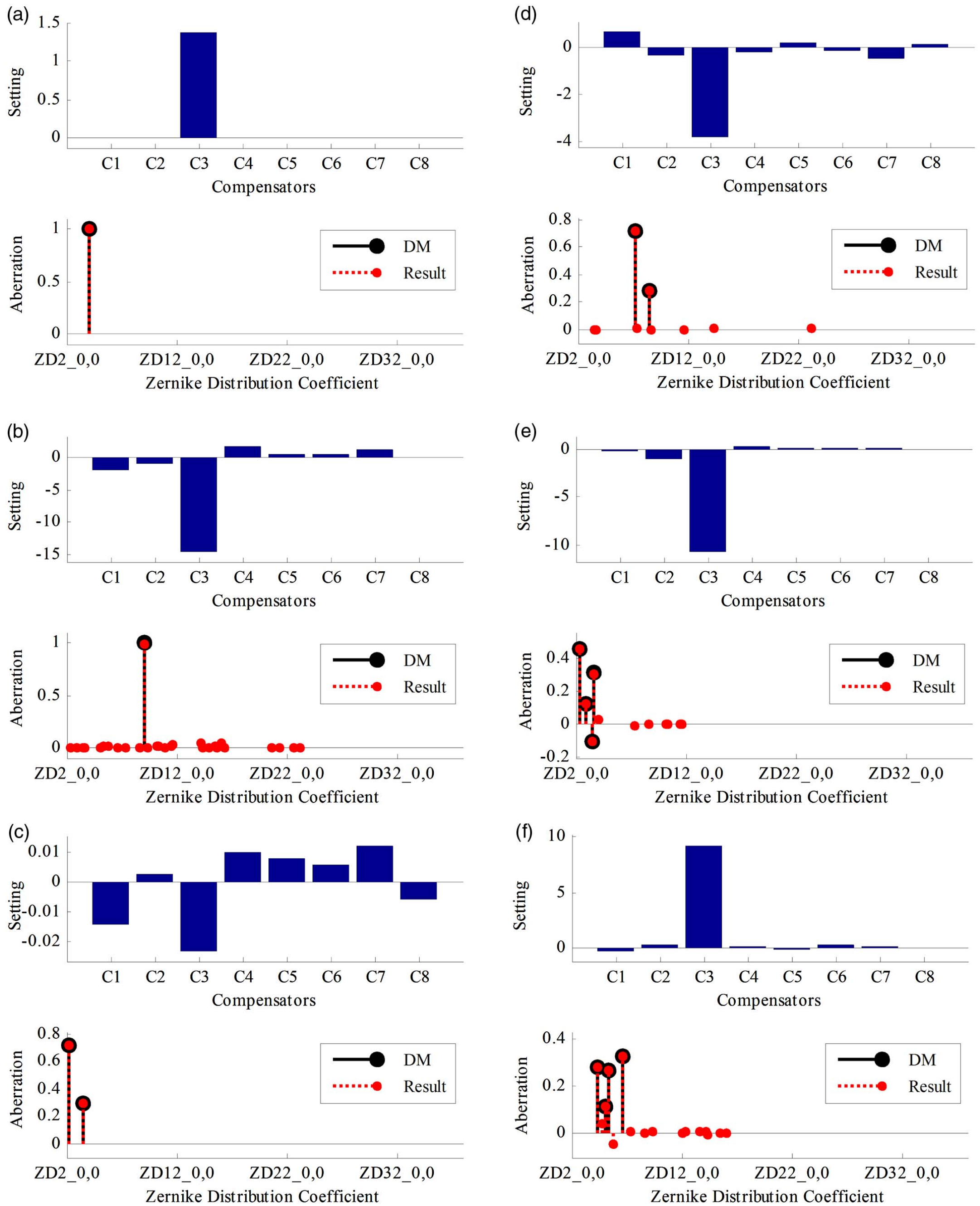

Fig. 9. Dominant modes of in-line aberration adjustment; DM is the dominant mode and the result is the actual adjusting effect. (a) Defocus, (b) zeroth-order spherical, (c) magnification, (d) first-order coma, (e) distortion, and (f) image plane deviation.

Table 3. DMCs of Aberration Variance Caused by Temperature and Pressure Changes

Optical Aberration	DMC	DMC Caused by Temperature Changes	DMC Caused by Pressure Changes
Defocus	φ_1	13.9756	–29.9493
0th-order spherical	φ_2	1.1692	–2.1038
Magnification	φ_3	10.0417	–10.1009
1st-order coma	φ_4	0.1296	–0.3274
3rd-order distortion	φ_5	0.1110	–0.1136
Image plane deviation	φ_6	–0.4147	0.2785

where **M** is a 6×8 matrix, the six column vectors correspond to six dominant modes of aberration change, and the eight row vectors correspond to eight compensators that include laser wavelength, reticle stage position, wafer stage position, and five moveable elements of the projection lens, successively. Each matrix element is the conversion coefficient from the corresponding DMC to the compensator setting value.

The following is an implementation example of this aberration adjustment system. The aberration of the lithographic projection lens is very sensitive to environmental factors. Slight changes of internal temperature or pressure may lead to significant variance in wavefront aberrations of the projection lens. Therefore, aberration adjustment must be adopted to compensate for the wave aberration caused by environmental changes. In this projection lens, when the internal temperature changes 0.02 K or the internal pressure changes 0.001 bar, which are typical environmental changes in a lithographic projection lens, the Zernike coefficients of each FOV are significantly changed. As shown in Table 3, the variation of the above wavefront aberration is regressive to the DMCs by LSF method, and the values of each column constitute an aberration vector $\mathbf{\Phi}$ as the input of the aberration adjustment system.

The variance of the temperature and pressure leads to the change in defocus, magnification, and spherical aberration of the projection lens. Although the produced aberrations are different, the same adjustment strategy can be used to compensate for the aberrations caused by different factors. In this aberration adjustment system, the compensators and the control matrix **M** are uniquely determined, and the setting value of each compensator is obtained through the control matrix transformation. It means that under the same adjustment strategy, the setting values of each compensator are often quite different for different aberration adjustment objectives. Similarly, this method can be used to adjust the magnification and distortion caused by overlay matching, and equivalent spherical aberration caused by the mask 3D effect.

As shown in Fig. 10, when all the compensators are set in place, the WFE caused by temperature and pressure variance can be completely compensated for. The black mark in Fig. 10 is the target aberration to be adjusted, and the red mark is the actual adjustment result. Although there are slight differences between the adjustment objective and obtained result, the residual aberration is small enough to satisfy the image quality requirements of the lithographic process. From this result, the dominant mode method can accurately compensate for the aberration changes caused by temperature or pressure changes.

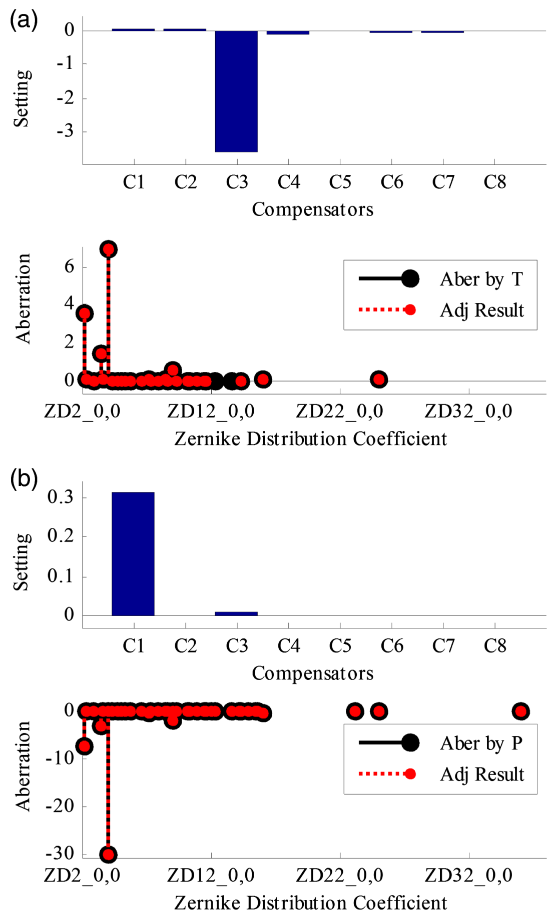

Fig. 10. Aberration adjustment for lithographic application. (a) WFE caused by temperature variance (red mark) and the compensation result (black mark); (b) WFE caused by pressure variance (red mark) and the compensation result (black mark).

4. CONCLUSION

The aberrations adjustment of the projection lens is important and necessary in the lithographic process of IC chip manufacturing. The adjustment is needed to compensate for pressure change, lens thermal effects, overlay errors, and 3D mask effects. In the traditional method, there is a problem of crosstalk, and the aberrations adjustment cannot be determined accurately.

In this paper, the method based on the aberrations dominant modes of lithographic projection lens has been proposed to establish the aberration adjustment system. The establishment process of the aberration adjustment system includes the calculation of dominant modes, selection of compensators, and calculation of the control matrix. This method has been well applied to the practical lithographic projection lens design and in-line aberration adjustment. After a moderate expansion, this method can be applied in the alignment and regular maintenance process of the lithographic projection lens, and can be further extended to the application of image quality compensation in the field of adaptive optics.

This paper presents the study of the dominant mode method in aberration adjustment for a lithographic projection lens. Although the application example is a 0.75 NA projection lens, the method presented in this paper is also applicable to an immersion projection lens with NA up to 1.35. It is similar to the 0.75 NA projection lens in that the immersion projection lens also needs to equip multiple compensators to compensate for the aberration caused by various factors. In essence, the aberration adjustment system of the immersion projection lens is still a MIMO linear control system that operates in open-loop mode. The control behavior of this aberration adjustment system can still be characterized by dominant modes. In addition to movable elements, 1.35 NA immersion projection lenses are usually equipped with pressure or thermal driven adaptive elements to compensate the high-order thermal aberration caused by freeform illumination. Therefore, the method proposed in this paper needs to be modified appropriately in the application of 1.35 NA immersion projection lenses. A feasible method is to use Zernike coefficients to characterize the surface shape or refractive index distribution of the adaptive optical elements and define them as the setting parameters of the compensator. Based on this modification, the dominant mode method can still be used to adjust aberration for an immersion projection lens, including dominant mode calculation, compensators selection, and control matrix calculation. There, the control matrix transforms the Zernike distribution coefficients of wavefront aberration into the Zernike coefficients of each compensator. In addition, the relationship between the control parameters of actual drive mechanism, such as voltage, pressure, etc., and the Zernike coefficient of the compensators must be calibrated at off-line phase accurately.

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