Research on High Precision of Projection Exposure Imaging of Large-Scale Integrated Circuit Lithography Machine

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Abstract. The precision and work efficiency of the distributed repeat projection lithography machine (DSW) directly affect the special requirements of the large-scale integrated circuit production process. In order to improve the exposure and imaging accuracy of the large-scale integrated circuit lithography machine projection, the paper proposes the lithography machine projection object image difference in-situ detection (AMF) technology based on particle swarm optimization. The article analyzes the basic principles of this technology using special test marks to detect spherical aberration, astigmatism, and coma of the projection objective, and discusses the method of using the alignment position coordinates to calculate the imaging position shift caused by aberration. The experimental results show that the AMF technology can achieve accurate measurement of aberration parameters such as spherical aberration, coma, and astigmatism.

Keywords: Integrated circuit, lithography machine, projection accuracy, exposure imaging accuracy.

1. Introduction
The development of lithography technology has enabled the lithography resolution CD to reach 100nm or even below 100nm. With the improvement of lithography resolution, the requirements for CD uniformity are getting higher and higher. There are many factors that affect CD uniformity. For example, a series of photolithography processes such as glue coating, exposure, development, and etching will affect CD uniformity. Among them, the exposure dose is an important factor affecting the uniformity of CD. In the step-and-scan projection lithography machine (hereinafter referred to as the step-and-scan lithography machine), accurate exposure dose control is an indispensable and important link. Compared with the step and repeat projection lithography machine (hereinafter referred to as the step lithography machine), in the step and scan lithography machine with an excimer laser as the light source, the pulse characteristics and pulse energy fluctuations of the light source, the wafer stage and the The synchronous scanning movement of the mask stage makes the control of the exposure dose more complicated [1].

Based on this new technology, this paper proposes a new technology for in-situ detection of aberrations of lithography machine projection objects based on particle swarm optimization algorithm. Compared with commonly used technologies, this new technology can simultaneously detect spherical aberration, coma aberration and astigmatism. At the same time, the influence of photoresist and other process factors on the imaging position shift caused by aberrations is considered, and the dependence of
the original technology on the limitation of image quality parameters (such as defocus and image plane tilt) is effectively avoided.

2. TCP/AQM simplified model and its AQM control

V Misra et al. established a dynamic model of TCP on the basis of analyzing the continuous data flow and stochastic differential equations of the network, and described it with the following set of nonlinear differential equations.

\[ W(t) = \frac{1}{R(t)} - \frac{W(t)W(t-R(t))}{2R(t-R(t))} p(t-R(t)) \]

\[ \dot{q} = \frac{N(t)}{R(t)} W(t) - C(t) \]

Among them, \( \bar{q} \), \( \bar{W} \) and represent the cache capacity and the maximum window size respectively. The first equation in equation (1) describes the dynamic characteristics of TCP window control. The \( 1/R \) term at the right end of the equation simulates the additive increase of the window, and the \( W/2 \) term corresponds to the window size multiplication of the packet loss probability \( p \) reduce. The second equation describes the length of the bottleneck queue, which is equal to the difference between the packet arrival rate \( NW/R \) and the link capacity \( C \). Analyze the relationship between the parameters of the steady-state operating point, and mainly study the low-frequency performance [2]. When \( W >> 1 \), \( e^{-Rt} \approx 1 \), ignore the high-frequency performance, add AQM control, and finally get the simplified model AQM control system shown in Figure 1. block diagram.

![Fig. 1 Block diagram of AQM control system based on simplified model](image)

Let \( G_p(S) \) be the simplified model of the AQM system,

\[ G_p(S) = \frac{Ke^{-R_0s}}{(T_1s+1)(T_2s+1)} \]

\( k = \frac{(R_0C)^3}{4N^2}, T_1=R_0, T_2 = \frac{R_0^2C}{2N} \).

If the link capacity \( C \), the round-trip time \( R_0 \) and the number of connections \( N \) are 105packet/s, 0.03s and 30, respectively, then

\[ G_p(S) = \frac{7.5 \times 10^6 \times e^{-0.03s}}{(0.03s+1)(1.5s+1)} \]  

PID control is a closed-loop control system with negative feedback, which can respond quickly to the real-time state of the system. Therefore, it may be assumed that the AQM controller still has a PID form [3]. It introduces a differential link to enhance the rapid response capability of the system. Overcome the slow response of other control algorithms, adjust according to the change trend of the
deviation, have a leading effect, and have the ability to compensate for the time delay of the system. which is

\[ G_c(S) = K_p + \frac{K_i}{s} + K_{di} \] (4)

Among them, \(K_p, K_i, K_{di}\) are the proportional, integral, and derivative gain coefficients of the PID controller, and their discrete expressions are

\[ p(k) = K_pe(k) + K_i \sum_{j=0}^{k} e(j) + K_{di} \left( \frac{e(k) - e(k-1)}{T} \right) \] (5)

where \(e(k) = q(k) - q_0, q(k)\) is the sampled value of the queue length at time \(k\), \(q_0\)is the expected queue length, and \(p(k)\) is the packet loss probability at time \(k\). Its incremental form is

\[ \Delta p(k) = K_p \left\{ \left( 1 + \frac{T}{T_i} + \frac{T_d}{T} \right) e(k) - \left( 1 + \frac{2T_d}{T} \right) e(k-1) + \frac{T_d}{T} e(k-2) \right\} \] (6)

Where \(T_i = \frac{K_p}{K_i}, T_d = \frac{K_d}{K_p}\, T=0.00625s\)

Packet loss probability

\[ p(k) = \begin{cases} 0 & c(k) < 0 \\ c(k) & 0 \leq c(k) \leq 1 \\ 1 & c(k) > 1 \end{cases} \] (7)

3. Multi-objective robust PID design and Pareto solution set

3.1. Multi-objective robust PID optimization model

In order to take into account the requirements of the system for fastness, stability and robustness, the overshoot, rise time and adjustment time of the system output are taken as the optimization goals, and the frequency domain robustness is the constraint (of course, it can also be taken as the goal [4]. Function processing), establish the following multi-objective optimization model:

\[ \begin{align*}
\min f &= \min(\sigma, t_r, t_a) \\
G_M &\geq G_{\text{min}} \\
P_M &\geq P_{\text{min}}
\end{align*} \] (9)

In the formula: \(\sigma\) is the overshoot; is the rise time (the time for the first rise from 2% of the final value to 98% of the final value); \(t_a\) is the adjustment time (the error band is 2%);GM and PM are the amplitude margin Degree and phase angle margin, the subscript min is the lower limit of constraint.

3.2. Pareto solution set

The multi-objective optimization problem can be defined by the function, which maps the decision vector to the target vector, and its mathematical description is:

\[ \begin{align*}
\min Y = f(X) &= (f_1(X), f_2(X), ..., f_n(X))^T \\
g(X) &= (g_1(X), g_2(X), ..., g_n(X))^T
\end{align*} \] (10)

Therefore, there is no absolute optimal solution that makes all the goals reach the optimal at the same time [5]. Only a satisfactory solution, namely the Pareto solution, can be obtained. For the minimum value multi-objective optimization problem \(\min f(X)\), the Pareto optimal solution is defined as: in the feasible region of the design variable, for the variable \(X\), if and only if there is no other variable \(G\).
4. Basic Principles of Exposure

The exposure dose is the light energy of a specific wavelength (or wavelength range) received on a unit area of the photoresist during the exposure process, namely

$$D = \int_0^t I(t) \, dt$$  \hspace{1cm} (11)

Where $D$ is the exposure dose (mJ/cm$^2$), $I(t)$ is the light intensity on the surface of the silicon wafer (mW/cm$^2$), and $t$ is the exposure time (s). In the case of a certain exposure dose, the greater the light intensity on the glue surface, the shorter the required exposure time and the higher the production efficiency. In a stepper lithography machine using an excimer laser, the exposure dose $D$ is determined by equation (2)

$$D = N \times \frac{EP_{\text{wafer}}}{A}$$  \hspace{1cm} (12)

Among them, $EP_{\text{wafer}}$ is the energy of a single pulse reaching the surface of the silicon wafer (mJ), $N$ is the number of pulses, and $A$ is the effective area of the projection objective's field of view (cm$^2$). In the step-and-scan lithography machine, inspect any image point on the surface of the silicon wafer, and this image point is only exposed during the time it passes through the exposure slit, as shown in Figure 2. The exposure process of this image point is the process of the point passing through the exposure slit, and the time that the point passes through the exposure slit, that is, the exposure time $t$ is calculated by equation (13)

$$t = \frac{N}{f} = \frac{D \cdot H \cdot L}{f \cdot EP_{\text{wafer}}}$$  \hspace{1cm} (13)

Considering the pulse working mode of the excimer laser, this pixel must get $N$ ($N$ is an integer) pulses during the process of passing through the slit. $H$ is the width (cm) of the scanning slit in the X direction. The exposure time $t$ can also be expressed as the optimal exposure dose in the photolithography process, which can obtain the best photolithography pattern. The optimal exposure...
dose is related to factors such as the type of photoresist and the specific structure of the exposed pattern. The exposure dose has a tolerance, and only when the exposure dose change is controlled within this tolerance, can the graphics that meet the requirements be obtained.

Based on the good linear relationship between the immersion lithography machine's projected objective lens and the Zernike coefficient, the specific process of the technology proposed in this study is shown in Figure 3. The method includes a rapid modeling process and aberration solving process. The image quality detection technology in Figure 3 is quoted from reference [6]

Fig. 3 High-order wave aberration solution process based on the technology proposed in this research

5. Analysis of experimental results
We find the example of pulse-by-pulse energy control algorithm. Without placing the mask and silicon wafer, the exposure dose is measured by a point energy sensor located on the silicon wafer stage. The point energy sensor scans the slit along the Y direction (the scanning direction of the wafer stage) at X=0 of the illumination slit, and measures the integrated energy of the slit. When the exposure dose settings are 5, 10, 20, 30, 40, 50, 100 and 500mJ/cm², the exposure dose test is performed. The measurement is repeated 100 times for each exposure dose. Exposure dose drift is inevitable, because in addition to pulse energy fluctuations, the system also has many other factors that cause dose drift, such as workpiece scanning speed error, illumination unevenness, laser wavelength drift, energy sensor calibration, and The calibration accuracy of the transmittance of the variable transmittance film. Analyze the experimental data. Under each exposure dose, the dose control accuracy and dose repeat accuracy are calculated respectively.
6. Conclusion
The exposure dose control in the step-and-scan lithography machine is affected by many factors, such as the scanning speed error of the workpiece stage, the uniformity of the illumination, the laser wavelength drift, the energy sensor and the transmittance calibration of the variable transmittance film. Therefore, the exposure dose will always drift. In order to achieve more precise control of the exposure dose, it is necessary to study the uniformity of illumination and the light intensity distribution of the scanning spot in the future.

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