

2-D Self-Calibration for Scale Based Metrology in Nanolithography

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Abstract

Two-dimensional precision stages for semiconductor lithography require sub-nm-level accuracy. Current ultraprecision stage metrology based on heterodyne laser interferometers with a 632.8-nm HeNe laser and interpolation to $\lambda/2048$ provide resolution of 0.3 nm. Unfortunately, the refractive index of air varies with CO₂ and water vapor content, as well as with air turbulence. Without expensive atmospheric compensation, the actual accuracy may only be sub- μm for operation in air.

In our approach two scale based metrology system (OPTRA NanoGrid) are used. The NanoGrid greatly reduces possible effects from air turbulence and Abbe offsets from using separate X and Y scales. However, the metrology is based on a physical artifact, and the accuracy of the metrology is limited to the accuracy of the grid artifact itself: about 1 μm . Physical scales may provide greater precision, but not always greater accuracy. Real-time self-calibration is implemented to improve the accuracy of stage to the level limited by repeatability of stage.

Fourier transform is used to decouple the distortion of artifact metrology and stage metrology at sampling points from 3 measurement view. Based on feedback principle high accuracy translation and rotation is implemented to minimize misalignment error. Square reversal is used to calculate rotation error $\delta\gamma$. Iterative algorithm is developed to isolate the rotation error $\delta\gamma$ in self-calibration.

Keywords: Self-Calibration, Nanolithography, two-dimensional stage, scale based metrology

1. Introduction

The key issues in self-calibration is how to solve measurement equations. In other words, isolate the scale and stage distortion from measurement equations when there are misalignment errors during translation and rotation. In a previous approach, Ye, Pease et al. (1997) developed a discrete Fourier transform-based algorithm by approximating $A(x,y)$ and $S(x,y)$ with Fourier series, which is numerically robust to measurement noise. The alignment error is isolated in the statistical meaning by using least square method under several assumption, which is effective when the measurement noise has a normal distribution and required space sample interval is big enough. Second, translation and rotation error will affect the sample position. This will be problematic when space sample interval is small e.g sub- μm . Third, because the x and y translation and rotation values of the stage point set can not be given by the algorithm or known before the self-calibration, it is difficult to find the origin and the axis orientation which meet the assumptions. Thus the stage error map obtained from this method has an unknown coordinate system, which might not be directly related to the machine coordinate system.

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2. Testbed physical realization of an X-Y stage for Nanolithography

The testbed is an air-bearing, capstan drive interferometric lithography stepper, with HP laser interferometers for feedback. This stage is configured as a stacked-slide X-Y stage. The moving stage is supported by air bearings on the granite surface plate. Two scale based metrology systems are mounted on the same plane of moving stage to implement real-time self-calibration. The configuration in the plane is shown in Figure 1.

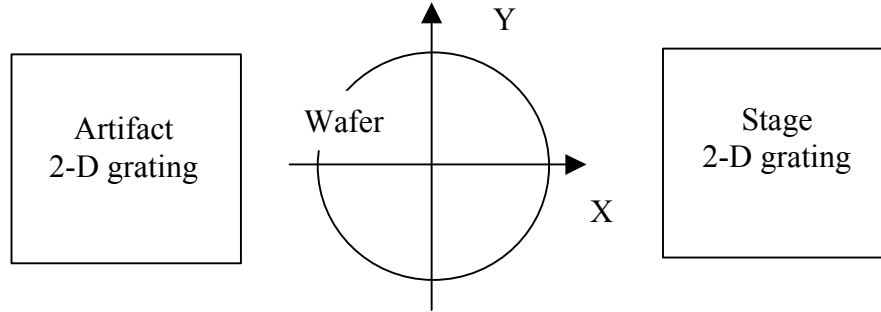


Figure 1 Configuration of 2-D real-time self-calibration

Scale based metrology system is a 2-D ultra-high resolution diffraction interferometer. It can measure X and Y plane motion simultaneously with 0.3 nm resolution and to detect small angle motion around Z axis.

One of the main error source in nanolithography come from the disturbance of guideway. The translation error of guideway in X and Y direction will be canceled by feedback of accurate stage metrology. The disturbance from the rotation error of guideway around Z axis will be minimized based on Abbe principle in X direction. For 1 nm accuracy, compare with traditional configuration, the tolerance of rotation error will increase from 1 μ rad to 80 μ rad. In Y direction the rotation error of guideway around Z axis will be measured by two scale based metrology system and compensated with software. So the accuracy of nanolithography mainly depends on the accuracy of metrology.

3. Mathematical model and Self-Calibration Algorithm

3.1 Decouple 2-D grating distortion when there is no alignment error

Two scale based metrology system are used to generate measurement view. One is stage metrology. The other is artifact metrology. The distortion $s(x,y)$ of stage grating and distortion $a(x,y)$ of artifact grating at sampling points (x_m, y_n) can be expressed as

$$\begin{aligned} s(x_m, y_n) &= s_x(x_m, y_n)e_x + s_y(x_m, y_n)e_y \\ a(x_m, y_n) &= a_x(x_m, y_n)e_x + a_y(x_m, y_n)e_y \end{aligned} \quad (1)$$

We need 3 measurement views to solve $s(x_m, y_n)$ and $a(x_m, y_n)$. In View 0 or home view, two metrology system is aligned with the air bearing of the stage by minimizing the angle between the moving direction of air bearing and X-axis of the metrology. $s(x_m, y_n)$ and $a(x_m, y_n)$ is compared at sampling points, so

$$v_x 0(x_m, y_n) = s_x(x_m, y_n) - a_x(x_m, y_n) \quad (1a)$$

$$v_y 0(x_m, y_n) = s_y(x_m, y_n) - a_y(x_m, y_n) \quad (1b)$$

In View 1, the sensor head is translated from View 0 by one sample site interval relative to the artifact grating, yield the measurement equations

$$x_x 1(x_m, y_n) = s_x(x_m, y_n) - a_x(x_{m+1}, y_n) \quad (2a)$$

$$v_y 1(x_m, y_n) = s_y(x_m, y_n) - a_y(x_{m+1}, y_n) \quad (2b)$$

Based on translation property of 2-D discrete Fourier transform to solve $A_x(u, v)$ from equation (1) and (2)

$$A_x(u, v) = \frac{V_x(u, v)}{1 - e^{j2\pi \frac{u}{M}}} \quad (3)$$

where

$$A_x(u, v) = \frac{1}{MN} \sum_{x_m=-\frac{N-1}{2}}^{\frac{N-1}{2}} \sum_{y_n=-\frac{M-1}{2}}^{\frac{M-1}{2}} a_x(x_m, y_n) e^{-j(\frac{2\pi}{M}ux_m + \frac{2\pi}{N}vy_n)} \quad (4)$$

$$V_x(u, v) = \frac{1}{MN} \sum_{x_m=-\frac{N-1}{2}}^{\frac{N-1}{2}} \sum_{y_n=-\frac{M-1}{2}}^{\frac{M-1}{2}} (v_x 0(x_m, y_n) - v_x 1(x_m, y_n)) e^{-j(\frac{2\pi}{M}ux_m + \frac{2\pi}{N}vy_n)}$$

Equation (3) only gives solution at $u \neq 0$. Based on the rotation property of 2-D Fourier transform $A_x(0, v)$ will be solved from equation (5) in View2 where artifact grating is counterclockwise rotated 90° relative to View 0.

$$V_x 2(x_m, y_n) = s_x(x_m, y_n) - ROT90(a_y(x_m, y_n)) \quad (5a)$$

$$V_y 2(x_m, y_n) = s_y(x_m, y_n) - ROT90(a_x(x_m, y_n)) \quad (5b)$$

where ROT90 denotes “ 90° rotation.”

3.2 Minimize the misalignment error based on feedback and iterative algorithm

The sensor head is mounted on 6 degree kinematics stage. The direction and location of sensor head relative to the 2-D grating are determined by the 6 balls on the kinematics stage. A picomotor is used to drive the relative movement of sensor head relative to the 2-D grating with 30 nm resolution. The sensor head is aligned with the 2-D grating stage by minimizing the angle between the moving direction of 6 degree kinematics stage and X-axis of the metrology. The relative translation between sensor head and 2-D grating will be measured by 2-D metrology system itself. The feedback is used to guarantee required one sample site interval translation accuracy determined by sampling requirement.

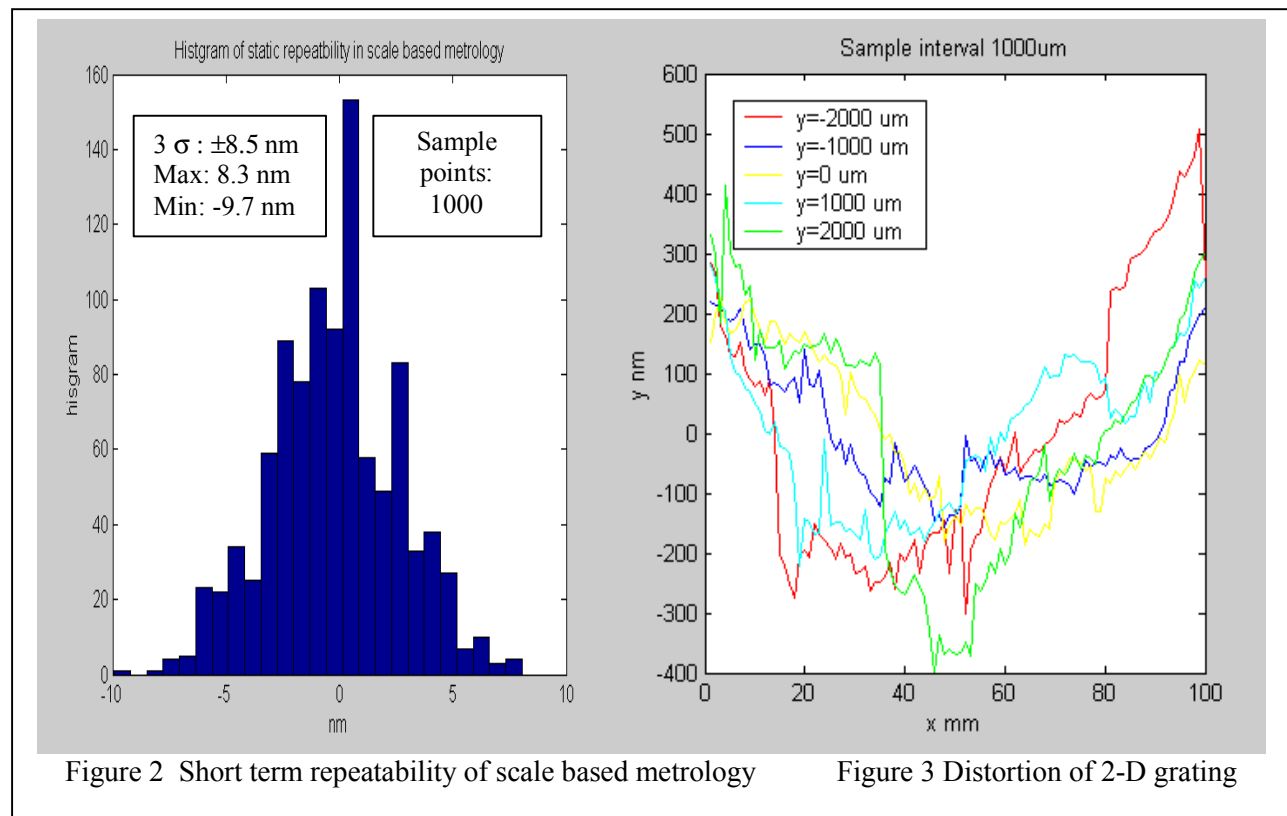
A 2-D grating is mounted on the bearing and rotation can be driven by a picomotor with $30''$ resolution. Square reversal is used to measure the 90° rotation error $\Delta\gamma$ which will be reduced by feedback to the level limited by the picomotor resolution.

The accuracy to implement translation and rotation depends on the accuracy of 2-D grating. The translation error can be minimized by implement 1-D self-calibration in X axis first.

The 2-D self-calibration error due to 90° rotation error $\Delta\gamma$ can be compensated if $\Delta\gamma$ is accurately measured when $\Delta\gamma$ is tiny. From experiment and computer simulation the measurement accuracy of $\Delta\gamma$ is insensitive to the accuracy of metrology which means error transfer coefficient is less than 1. This will guarantee that an iterative algorithm will be convergent. So an iterative algorithm is developed to minimize disturbance from measurement accuracy of rotation error $\delta\gamma$.

4. Experiment results and summary

Real-time calibration was implemented on the Nanolithography testbed. Dynamic data sampling methodology was developed to minimize effects of quasi-static disturbance from measurement environment change, such as temperature. The repeatability of scale based metrology is about 8.5 nm (see Fig 2). The initial calibration result is shown in Fig 3. The distortion of 2-D Grating is about 1 μ m. Real time self-calibration will increase the accuracy of scale based metrology from 1 μ m to the level limited by the measurement noise.



References

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