Mechanical system and dynamic control in photolithography for nanoscale fabrication: A critical review

Yi Song1 | Chengqun Gui1 | Zongliang Huo2 | S. W. Ricky Lee3 | Sheng Liu1

1The Institute of Technological Sciences, Wuhan University, Wuhan, China
2Yangtze Memory Technologies Co., Ltd., Wuhan, China
3Department of Mechanical and Aerospace Engineering, Hong Kong University of Science and Technology, Hong Kong, China

Abstract
As one of the most advanced and precise equipment in the world, a photolithography scanner is able to fabricate nanometer-scale devices on a chip. To realize such a small dimension, the optical system is the fundamental, but the mechanical system often becomes the bottleneck. In the photolithography, the exposure is a dynamic process. The accuracy and precision of the movement are determined by the mechanical system, which is even more difficult to control compared with the optical system. In the mechanical system, there are four crucial components: the reticle and wafer stages, the linear motor, the metrology system, and the control system. They work together to secure the reticle and substrate locating at the correct position, which determines the overlay and alignment performance in the lithography. In this paper, the principles of these components are reviewed, and the development history of the mechanical system is introduced.

KEYWORDS
control, dynamic, mechanical system, metrology, photolithography

1 | INTRODUCTION

Following Moore’s law, the integrated density of the transistors on a chip becomes double every 24 months, which means the critical dimensions (CDs) of the devices keep shrinking. As a key process in the chip manufacturing, photolithography determines the minimum CD of the devices. In the photolithography, one important parameter is CD. The frequently discussed 5 nm, 3 nm nodes refer to the minimum CD of a transistor gate. Another important parameter is the overlay, which defines the relative positioning between two adjacent layers. If two layers are misaligned, it will lead to a performance loss or even a failure of the device. In the photolithography, overlay is more difficult to control as compared to CD, because it is affected by not only the optical system but also the mechanical system. In the mechanical system of the photolithography, the dynamic control is always a big challenge.

In a photolithography tool, the reticle and wafer move at an extremely high speed and acceleration, which further increases the difficulty. In this situation, to realize a desired dynamic control, it needs a collaboration of the movement platform, motor, metrology and control system. The movement platform, which is also called the stage, is mainly classified into three types: mechanical guide, aerostatic guide, and maglev guide.1,2 The mechanical guide is a traditional guide, which suffers from friction and is not able to achieve very high accuracy. Aerostatic guide uses a air bearing to avoid direct contact, and can effectively reduce the friction. Maglev has been introduced in the recent decade for the nanometer-scale locating. Linear motors are applied to guide the movement, and make sure the stage moves in the correct direction, vertically or horizontally.
Iron-core and ironless linear motors are implemented for different applications, with respect to the cogging effect, thrust fluctuation, and dynamic response.\textsuperscript{3–12}

In a mechanical system, it is expected that the movement is always accurate. However, in reality, there always exists offsets between the design and the real operation. These offsets bring errors to the final devices, and the errors accumulate to cause failure. Proper metrology methods are needed to measure the offsets, and feedback could be applied to minimize the errors. Generally, interferometer is the standard metrology tool for the movement and locating.\textsuperscript{13–16} Two optical signals are collected by an interferometer. One is collected by a static light path and used as a reference signal. The other is collected from the moving stage as the measurement signal. Then the location can be decided by comparing the phase difference between the two signals. Based on the traditional interferometer, the grating interferometer was proposed, which is also called linear encoder. High precision gratings are utilized to program the optical signal, which can further improve the metrology resolution. Meanwhile, dual frequencies are applied by the interferometers for solving the $\pi$ phase shift issue in a broad measurement range. With the next step, the metrology result is treated as feedback to the photolithography, and the measured movement error can be compensated by the dynamic control of the stage.\textsuperscript{17–19}

2 | WAFER STAGE

Wafer stage is one of the core technological units of photolithography system, which has a long history of technical development. The accuracy and efficiency of the photolithography process are directly determined by the control precision and scanning speed of the wafer stage.

Mechanical guideways have been commonly used for early photolithography wafer stages. A typical structure of wafer stage fitted with a mechanical guide is shown in Figure 1.

The wafer stage mainly consists of a base, a cross structure, an X-Y table and a wafer clamping plate. As the X-Y table moves along the Y axis, the Y slider bar slides in a square channel along the Y guide plane, and then the X guide bar forces the X-Y table to move. For the movement along the X axis, the X plane in the X-Y table moves along the X guide bar.\textsuperscript{20}

Figure 2 shows the structure of Canon FPA-2000 photolithography system. In this system, movements in X-, Y-, and Z-directions are controlled precisely by double-layer mechanical guide, which has been used in the 0.5 $\mu$m process.\textsuperscript{21}

The performance of mechanical guideway workpieces are limited by the following factors. First, due to the gap between the die and the lead screw, the mechanical guide rail can only maintain the positioning accuracy at the sub-micron level. Second, the mechanical system has the inevitable friction, in which resulting particles can also contaminate subsequent processes. Finally, the mechanical guide is bulky and needs more complex processing techniques, for which the maintenance is costly.

With the upgrading of technology, the aerostatic guide gradually has replaced the mechanical guide and has become the main displacement device of the wafer stage. Aerostatic guide technology has been widely used in the major scanning photolithography systems, which is owned by the world’s three largest photolithography manufacturers: Canon, Nikon and ASML. The introduction of air bearing effectively isolates the actuator and rotor, and reduces the repeated friction between them. The zero-friction feature of the air floating guide almost does not generate additional heat, which can be integrated with the servo actuators and sensors to form a closed-loop system, and achieve high-precision displacement positioning.

Figure 3 shows a typical X-Y direction air-floating platform. The air floating platform consists of an X-direction platform and a Y-direction platform. The side of the platform was also equipped with a vertical guide rail and a laser diode for ranging. The gas
transmission adopts array distribution to ensure the uniformity of pressure.

Magnetic-levitation (maglev) guide is also one of the common technologies used in the wafer stage. With the increasing technological requirements, researchers put forward higher standards for the vacuum degree of the photolithography systems, where the floating rail technology was no longer applicable. Maglev guide is widely used in the wafer stage of the latest generation of photolithography systems. Figure 4 shows a wafer stage with maglev guide. In this model, the permanent magnets and the coils were arranged around the motor center in a circle. The magnet array was formed in the Halbach mode along the rotor circumference. Figure 5 shows the NXT:1950i photolithography system of ASML with maglev stages.

In addition, for the design and manufacture of advanced photolithography system, the modeling and simulation of the wafer stage system are particularly important. The wafer stage consists of a complex mechanical structure and dynamic characteristics, which have a great impact on its motion and measurement accuracy. Figure 6 shows a design framework supporting the dynamic design of nano-precision positioning stages. According to the system simulation, researchers get the relationship between the stiffness of the air floating and the thickness of the gas film, which is the basis to design the mass center of the actuator accordingly, as shown in Figure 7. Figure 8 shows the positioning errors of the stepper motion after the optimization of the system.

3 | LINEAR MOTOR

The motivations in lithography are mainly composed of behaviors in two categories: horizontal movements and vertical movements, which are activated by various motors. In other words, dynamic characteristics of motor in the lithography would determine the photolithography performance to a large extent.

The vertical movements in the photolithography are called the planar movements. Normally, the planar movements in the photolithography are driven by the planar motor. There are two types of planar motors with different driving forms usually implemented in the photolithography.
Air-core motor is a common driving device to support and control the movement in the Z-direction in photolithography. The photolithography with an air-core motor possesses the advantage of low vibrations, low acoustic noise, high precision and low power loss.\(^3\)–\(^{12}\)

Tanaka designed an air levitation (bearing) system, composed of Lorentz forced planar motors with three degrees of freedom (DOF). Dynamics test indicates that servo bandwidth is limited around 25 Hz due to a 75 Hz mechanical resonance frequency. The coupling between horizontal force and vertical force activated by the planar motor is less than 10%.\(^3\)

Chen et al. developed an ultra-precision drive machine with air bearing, as shown in Figure 9. The dynamic performances of the driving machines with short stroke motor and long stroke motor are compared. The results show that the vibration amplitude of drive machine with short stroke motor may decrease by 95.2% (from \(-2.8\) μm movement to 0.1 μm movement), compared with drive machine with long stroke motor.\(^6\) As a result, another disadvantage of air-core motor is that it is not suitable for photolithography with large stroke or large area. Alternatively, the magnetically levitated planar motor is more suitable for the photolithography with large stroke and large area.

To achieve a minimal fringing field influence on the working performance of photolithography system, Paul et al. investigated a maglev linear motor with a relatively short distance between the fringing fields and actuators. The dynamic characterization experiment shows that the photolithography system with this motor can realize high resonant frequency and high-precision movements.\(^26\)–\(^29\)

Zhang et al. developed a novel magnetically levitated planar motor for the photolithography system, as shown in Figure 10. The researchers used the scalar magnetic potential to investigate the magnetic system in a planar motor, with the differential equations simulated by the finite element method (FEM). Dynamic characterization experiment shows that the photolithography system with this motor can realize high resonant frequency and high-precision movements.\(^26\)–\(^29\)

With the demand for ultrahigh-precision lithography technology and 3D lithography technology, piezoelectric ceramic motors have
attracted the interest of researchers, due to their nanometer-level precision in the movement in Z-direction.30
Zhang et al. introduced a high-precision parallel positioning system with three identical limbs, as shown in Figure 11. It can realize six degree-of-freedom movements with nanometer accuracy via piezoelectric ceramic motors. Meanwhile, FEM analysis was employed to theoretically estimate dynamic characteristics of this parallel positioning system, with the experiments being carried out to validate the theoretical estimation. Dynamic simulation results show that output compliance and the input stiffness are predicted to be $7.436 \times 10^{-8}$ m/N and $1.041 \times 10^4$ N/m under the 1800 N force in Z-direction. Meanwhile, the result also shows the Z-direction stroke is about 30 μm with an accuracy of 10 nm.30
In addition to the movement in the Z-direction, the motor controlling the horizontal movement of the work piece table also determines the performance of the photolithography system.31–34
At present, long stroke motors used in the photolithography system can be classified into ironless linear motors and iron-core linear motors. The coreless permanent magnet linear synchronous motor has the advantages of no cogging effect, low thrust fluctuation, and high dynamic response. However, if it is applied to the double-workpiece stage of a photolithography system, some problems still need to be solved, such as achieving high thrust volume density, increasing thrust copper loss ratio, and thrust fluctuations. As a result, the horizontal movement in the photolithography system is usually realized by the iron-core linear motors.
To reduce the noise effect induced by the iron-core linear motors, Jun et al. presented a novel low-noise high-force linear motor for photolithography system, as shown in Figure 12. Usually, the spatial-frequency magnetic field is the main root cause leading to the vibration of the work piece. In that paper, the author reduces the spatial-frequency magnetic field by optimizing electromagnetic field design. The results show that this new type of motor can achieve 28% higher shear stress, compared to a common motor, and its output power can reach 500 W/mm.34
Although the iron-core linear motors can realize long stroke, to achieve a nano-level precision motion in a photolithography system, it requires linear motors combined with the advantages of other motors. Take ASML photolithography system Twinscan XT 1950i as an example, the maximum speed of the Y-direction long-stroke linear
motor of the mask table is greater than 2 m/s, the maximum acceleration is greater than 60 m/s², the peak thrust is greater than 1200 N, and the positioning accuracy is ±1 μm. Macro movement of Twinscan XT 1950i is realized by the iron-core linear motors.

Furthermore, with the development of high-precision laser direct writing photolithography systems, such as a two-photon laser direct writing equipment, researchers directly used piezoelectric ceramics as actuators to complete the photolithography process.35–40

Brussel et al. designed a work piece with the piezoelectric ceramics, as shown in Figure 13, and the work piece possesses the advantage of high-speed positioning, high precision. Dynamic characterization experiment shows the maximum speed of prototype linear motor can exceed 100 mm/s with the movement range within 3 μm.39

On the premise of maintaining accuracy, Gao et al. designed a dual mechanism multimodal linear motor to enlarge the movement range. Besides a piezoelectric motor, an electromagnetic motor can also be found in the linear motor. Dynamic characterization test experiment prototype shows that the nanomotor can reach 2 nm under the high speed of 50 mm/s.38

In addition to the electromagnetic motor and piezoelectric ceramic motor, pneumatic motor is also a new development direction for the photolithography system. Worktable driven by pneumatic motor in laser direct writing photolithography system, as shown in Figure 14, developed by 4pico company could achieve 2 nm accuracy with good dynamic characteristics.41

The dynamic characteristics of the above motor and its component are mainly obtained through experiments or finite element analysis. However, these methods restrict effective explorations, especially in dynamic design of complex systems such as photolithography system and their iterative optimization.

Wu et al. proposed a method named rigid multibody modeling strategy (RMMS), as described in Figure 15, to simulate the dynamic characteristics of components in the complex systems. Compared with the traditional FEM, RMMS would regard a complex flexible component as a few rigid finite elements connected by spring-damping elements (SDE). Finally, by solving the dynamic characteristics of a few rigid finite elements connected by SDE or multibody systems, the dynamic characteristics of the original model can be obtained.42

4 | STAGE POSITION MEASUREMENT

Stage positioning is the alignment accuracy of the wafer stage and reticle stage, which can be well positioned to each other. An independent measurement system is needed to control the stage movement precision. Therefore, it is important to establish a precise method to measure the position and orientation of the stage directly.

As the solutions, heterodyne laser interferometers and grating interferometers are widely used as metrology tools for ultra-precision displacement measurements.43

Interferometers have been applied in the industry as the stage position measurement system for more than 20 years.13–16 The typical principle of an interferometer is to measure an optical path difference between two beams, which are separated by a Wollaston prism or

![Figure 12](image1.png) Figure 12  A linear stage testbed with a fine-tooth motor. A magnet track is mounted on the bottom surface of the moving stage. Reproduced with permission.34 Copyright 2021, The Authors, published by IEEE

![Figure 13](image2.png) Figure 13  (left) Actuator lay-out, (right) picture of actual piezo motor. Adapted with permission.39 Copyright 2021, The Authors, published by Elsevier
other optical splitters. One is an external beam reflected by a stage mirror, and another one is an internally beam reflected by a mirror inside the interferometer. As shown in Figure 16A, these two reflected beams will produce interference fringes composed of bright and dark bands. The optical path change of the external beam can be calculated by counting the number of fringes. To further enhance the resolution, a new design was proposed based on the traditional laser interferometer. As illustrated in Figure 16B, a mirror in front of the detector input gate is added, and it switches to the model with the same gate for input and output beams. As a result, a twofold enhanced measurement resolution was obtained, but the maximum velocity of the measured target was reduced to half.

To apply this method on stage position measurement of a photolithography system, it is necessary to know the frequency of the external beam propagating in the air. If the changes in the refractive index of the air are not compensated, they will cause measurement noise and errors, especially in the region 0.5–50 Hz. Even in a system with a very stable environment, these noise and errors will...
detected by a photodetector (PD) module. The single PD is shown in Figure 18B. It can realize only homodyne interference displacement measurements, but not able to distinguish the direction of motion.\textsuperscript{56} To achieve the direction measurement, a quadratic phase detector module and a quadrature phase detector module are implemented, as shown in Figure 18C,D. The movement of the measuring grating generates the diffraction beams on the surface. Due to the optical Doppler effect, the movement will cause a frequency shift of diffraction beams, causing a phase difference between the reference beam and the measuring beam.\textsuperscript{57} When the interference beam is formed by these two beams with a phase difference, the actual motion phase can be acquired from interferential phase signals, from which the length and direction of the grating displacement can be calculated. Now, there is an issue for this structure, the sensitivity of the homodyne GI. To achieve a high sensitivity, the phase sensitive detector requires a more complex optical structure, including multiple PDs for the phase-sensitive detection.\textsuperscript{56}

To solve the sensitivity issue of the homodyne GI, a heterodyne GI with a dual-frequency laser source has been proposed. A Michelson-type interferometer can also be formed by a heterodyne GI, as shown in Figure 19.\textsuperscript{55} A polarized laser beam with two frequencies $f_1$ and $f_2$ is produced by a dual-frequency laser. The light is split into two beams by a NPBS, one beam is detected by the PD$_r$ to form a reference signal, the other beam is divided into two parts by a polarized beam splitter (PBS) and enters the reference grating and the measuring grating respectively. Then the interference light formed in the beam splitter is collected by the PD$_m$. For a heterodyne GI, the frequency difference ($f_1 - f_2$) contains displacement information, which makes it possible to use a single PD to determine the direction.\textsuperscript{56}

Due to ellipticity and nonorthogonality of the light source and misalignment or imperfection of the PB,\textsuperscript{56} periodic nonlinear errors exist in the practical GIs. As shown in Figure 20, the spatially separated heterodyne GI has been proposed to reduce these errors.\textsuperscript{59} This configuration avoids the frequency mixing with two acoustic optic modulators, which modulates the two beams by using two different frequencies, $f_1$ and $f_2$ separately. To implement a GI on the stage position measurement in a photolithography system, the measurement resolution needs to be further enhanced. There are mainly two ways to enhance the optical resolution, decreasing the grating pitch or increasing the optical fold factor. However, the decrease of the grating pitch is limited by the fabrication capability. Therefore, the efficient way to improve the optical resolution is increasing optical fold factor. Multifold diffraction has been applied to achieve a high optical resolution by using a differential optical structure, where the diffracted beams are reflected onto the grating and diffract each time.\textsuperscript{60,61} In addition to a high optical resolution, a multi-DOF measurement of the stage position is also needed in a photolithography system. Many optical structures for multi-DOF measurements have been proposed, based on different types of GIs. It includes in-plane displacement measurement,\textsuperscript{62,63} out-of-plane displacement measurement,\textsuperscript{64,65} and rotational measurement.\textsuperscript{66,67}

The GI system is implemented onto the ASML NXT platform with a signal error of 0.22 nm (3σ), as shown in Figure 17(bottom).\textsuperscript{26} Compared with a laser interferometer, the encoder has many benefits, including no
influence to the turbulence problem, more compact, less sensitive to Abbe errors, and much cheaper. Meanwhile, it has short, vertical, fixed beam path lengths (as short as 15 mm) while traveling in the operational plane within a few hundred millimeter range. This type of GI system is similar to small beam interferometers. Signal generation and interpolation are completed based on the interference of two interacted light beams. The two beams propagate close to each other, securing the refractive index of the air they travel through extremely similar. This makes it less susceptible to the change of the air refractive index. In addition, the small size of the encoder head allows local purging of the critical area.

One encoder head measures 2 DOF: the translation in the grating plane, and the distance between the encoder head and grating. An encoder head is place on the corner of each chuck. A grating plane

**FIGURE 17** Schematic views of a traditional interferometer system with long variable beams (top) and the encoder system with short fixed beam interferometers and grid-plates (bottom). The left plotting is the noise levels of both systems. Reproduced with permission. The Authors, published by SPIE.

**FIGURE 18** A homodyne grating in a Michelson-type interferometer: (A) an optical structure of reading head; (B) a single photodetector; (C) a quadratic phase detector module; (D) a quadrature phase detector module with a non-polarized beam splitter (NPBS). Reproduced with permission. Copyright 2021, The Authors, published by Springer.

**FIGURE 19** A heterodyne grating interferometer within a Michelson-type structure. PBS, polarized beam splitter. Reproduced with permission. Copyright 2021, The Authors, published by Springer.

**FIGURE 20** Spatially separated heterodyne grating interferometer structures. PBS, polarized beam splitter. Reproduced with permission. Copyright 2021, The Authors, published by © The Optical Society.
consisting of a 2-dimensional grating is used as the reference for the encoder measurement, as shown in Figure 21.57 Due to the thermal expansion effect of the chuck, the measurement direction is selected tangent to the center of the chuck, which improves the thermal stability of the position measurement. Finally, ASML points out that the new bidirectional encoder-design is an improvement of the uni-directional encoders, which has been used in the reticle stage for more than 5 years.

5 | CONTROL OF OVERLAY

With a continuous development of the integrated circuits, the CD of the semiconductor manufacturing continues to shrink. In this situation, there are many challenges in the photolithography technology, and a crucial issue is the distortion of wafer patterns.68

The quality of the wafer pattern is determined by many factors, including but not limited to the light source quality, reflective reticle, reflective optics and vacuum environment.69 Meanwhile, the synchronization errors caused by the scanning and projection modes of the exposure module also greatly impact the wafer pattern fidelity. In particular, the synchronization between the wafer stage and the reticle stage is a key factor of the exposure.70

Here the reticle stage is defined as the master stage, holding the reticle with a pattern on a quartz plate. And the wafer stage is defined as the follower stage, holding the wafer covered by the photo resist. In an ideal condition, the reticle stage and the wafer stage keep a precise synchronization during the scanning exposure. However, the external disturbance and the dynamic performance may introduce a relative error between the reticle stage and the wafer stage at the scanning direction.71 In addition, the response speed of the wafer stage and the reticle stage may differ due to the weight difference, and it further increases the difficulty of the control system.72

To secure the precise synchronization for both long and short distances,73 a feedback control strategy has been applied. It solves the synchronization problem by compensating the positioning errors during the movement process.17-19

Figure 22 shows the structure of a photolithography scanner. The reticle stage and the wafer stage are located at the high and the low levels of the base frame. The coarse stage is driven by a linear motor, which responses for the fast and long distance motions; and the fine stage is driven by a voice coil motor (or Lorenz plane motor), which responses for the fine motion.

The structure of a synchronized control system is shown in Figure 23, in which two stages move with a fixed velocity while maintaining a synchronized position.72 The synchronization error is minimized with the assistance of a position close loop and feedback synchronization. Then a flexible and efficient control can be realized.

Here $P_R$ and $P_W$ define the models of two stages, $C_R$ and $C_W$ define the feedback controllers of two stages, and ILC defines the synchronization controller. $e_s(t)$ defines the synchronization error. $y_R(t)$ and $y_W(t)$ define the position outputs of the two stages. For the control effort (N) of the reticle stage, $u_R(t)$ is a sum of the feedback control input $u_f(t)$ and the feed-forward control input $u_s(t)$.

$$u_R(t) = u_f(t) + u_s(t).$$

where $u_f(t)$ is realized by the PID method, and $u_s(t)$ is the synchronization control input with the use of ILC method.

The synchronization error $e_s(t)$ can be calculated by

$$e_s(t) = y_W(t) - \frac{1}{\beta} y_R(t).$$

During the exposure, the performance of synchronization in lithography is evaluated by two parameters, moving average (MA) and the moving standard deviation (MSD):

$$MA = \frac{1}{T} \int_{-T/2}^{T/2} e(t)dt,$$

$$MSD = \frac{1}{\sqrt{T}} \sqrt{\frac{1}{T} \int_{-T/2}^{T/2} (e(t) - MA)^2 dt},$$

where $T$ is the exposure time and $e(t)$ is the position error as a function of time $t$.

However, the positioning accuracy also depends on some nonlinear factors, such as the cogging force and force ripple,74 while the driven motor is involved in the control model. Considering the behavior of the linear motor, the control process can be approximated as a second-order dynamic system. With a rigorous modeling, the reticle stage system can be expressed as

$$M \ddot{x}_R(t) + b \dot{x}_R(t) = K u_R(t),$$

where $M$ is the effective mass, $x_R$ and $\dot{x}_R$ are acceleration (m/s²) and velocity (m/s) of the stage position, $b$ is the damping coefficient.
As a result, the law of synchronization control during each iteration can be expressed as

$$u^{k+1}(t) = u^k(t) + \alpha e^k(t),$$  \hspace{1cm} (7)$$

where \( k \) is the iteration number and \( \alpha \) is the step size.

The compensation of the position synchronization is executed in the direction of the minimal error. The synchronization errors of MA and MSD are shown in Figures 24 and 25. The synchronization performance can be improved substantially, in terms of the 15.6% MA and 56.7% MSD reductions. Consequently, the exposure precision can be ensured with the synchronization control of the reticle and wafer stages.

In addition, the dynamic reliability and precision reliability of the motor are important factors affecting the motion control. The dynamic performance influences the performance and efficiency of production directly.\cite{74,75} Thus, the theories of reliability analysis based on structural statics and dynamics\cite{76-78} are investigated, to achieve better dynamic performance and reliability assurance. For the study of dynamic precision reliability of 6 DOF micro displacement mechanism in the reticle stage,\cite{79} the coordinate system and the layout of motors are shown in Figure 26. The motions in the X-direction and the Y-direction are realized by stepping direction motors and scanning direction motors, respectively. Cylindrical motors are used for the motion in the Z-direction.

With the modeling of dynamic error based on the global coordinate system and the modeling of dynamic precision reliability, the motor error data have been recorded during the motor performance test and are given in Figures 27–30. It is noted that the blue star points are output error data while the dashed line is the corresponding normal distribution.\cite{79} The experimental results show the output errors obey normal distribution in each direction.

To further reduce the position error, a system with feedback and feedforward control has been developed, and the experimental setup is shown in Figure 31.\cite{80} It has a H-type precision air floating platform with two DOF in the X-Y direction. It is driven directly by a single permanent magnet linear synchronous motor (PMLSM), and the position signal is measured by a GI. The position errors between the reference position and the feedback position can be obtained by the feedback controller. The position errors with and without the time-delay feedforward control signal are shown in Figure 32. It shows that the position error caused by the impact of jerk segment can be further reduced under the time-delay feedforward, and the maximum error is reduced from \( 4.028 \times 10^{-6} \) to \( 2.057 \times 10^{-6} \) m.

A similar feedback control experiment of the motor has demonstrated the superiority of PID control system. The feedforward forces are calculated by multiplying the set-point reference acceleration by the stage's mass and inertia.\cite{81}

The time response trend of the stage position change is shown in Figure 33. In Figure 33A, the green curve shows a 20 mm stage motion set-point and actual position, with a scaled acceleration by the red curve which is limited by a value of 10 m/s². In Figure 33B, the corresponding imaging error is plotted, which is constrained in a
±50 mm range during the movement and approached the target position gradually.

MA and MSD trends of the position error to time are shown in Figure 34. In Figure 34A, the raw servo error and acceleration of set-point are shown. In Figure 34B, the MA and MSD values with different vertical scales are shown. It is worth to note that, the first relevant MA and MSD value can be calculated after $t = 100 \text{ ms}$. This value is located at $t = 50 \text{ ms}$ in Figure 34 due to the MA and MSD.

In addition, during the lithography process, the accuracy of the image transfer from the reticle to the wafer is also impacted by the optical elements. Then an optical element, such as a high precision phase detector, is applied to ensure the phase measurement accuracy of interference fringes.82

The accuracy of a homodyne detector is constrained by three factors: the DC offsets, the unequal AC amplitudes, and the quadrature phase-shift error in the detected quadrature signals.82,83 Thus, the signal correction of the detector is crucial. For example, the least...
The square fitting method can be used to correct the periodic non-linearity in the interferometer, the analog circuitry method can be used to correct the two signals with quadrature phase-shift in real-time, and the Kalman filter method can be used to correct time-varying nonlinearity. As a real-time correction method, Kalman filter includes the numerical model establishment of the homodyne detector and the extended filter design, so it can remove the time-varying nonlinearity error effectively.

Figure 35A shows the correction of phase error, which dramatically decreases from 45.5 to 8.1 nm. However, the corrected phase signal is still not perfect, mainly due to the residual phase locking error. The eliminated nonlinearity error is given in Figure 35B, with the value of 39.0 nm. Figure 35C shows the results of the spectrum analysis. The amplitudes of the first and the second-order periodic errors are attenuated by 27.8 and 46.5 dB.
6 | SUMMARY AND FUTURE OUTLOOKS

In photolithography, the mechanical system and the dynamic control play very important roles. They determine the final performance of the fabricated devices. Several technologies have been implemented to improve the capability of the working platform, the linear motor, the metrology and the control system. The combination of a maglev guide working platform and a grating interferometer based linear encoder pushes the photolithography capability to the range below 10 nm resolution and locating, which also requires a less-than-1 nm CD control and a less-than-3 nm overlay control.

In the near future, as the technical node of the integrated circuits approaches 3 nm and below, and the wide application of 3D stacking, new technologies will be required to further improve the mechanical system and its dynamic control. Multiple frequency optical interferometer or even X-ray interferometer can increase the metrology precision and reliability. High order calibration models will be applied to the control per exposure, with both inter and intra field optimization.
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CONFLICT OF INTEREST
The authors declare that there are no conflict of interest.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID
Yi Song http://orcid.org/0000-0001-9632-404X

REFERENCES
1. Wronosky JB, Smith TG, Darnold JR. Development of a wafer positioning system for the Sandia extreme ultraviolet lithography tool: 1995.
2. Lan H, Ding Y, Liu H, Lu B. Review of the wafer stage for nanoimprint lithography. Microelectron Eng. 2007;84:684–648.
3. Tanaka K. Feasibility of air levitated surface stage for lithography tool. J Adv Mech Des Syst Manuf. 2010;4(6):1119-1132.
4. Chen X, Yu X, He X, Yan T. Dynamic characteristic analysis of precise long stroke linear motor with air-bearing in optical lithography. Chin J Mech Eng (English Ed). 2008;21(02):17.
5. He X, Chen X. The dynamic analysis of the gas lubricated stage in optical lithography. Int J Adv Manuf Technol. 2007;32:978–984.
6. Chen X, Lei J. The dynamic modeling and dynamics response analysis of ultra-precision drive machine. 3rd IEEE Int Conf Nano/Micro Eng Mol Syst NEMS. 2008;828–833.
7. Onda H. Development of a unique, high precision linear motor integrated air slide table, and its application to laser beam writers. Opt Rev. 1999;6:88–92.
8. Yoon JY, Lang JH, Trumper DL. Double-sided linear iron-core fine-tooth motor for low acoustic noise and high acceleration. IEEE/ASME Trans Mechatronics. 2019;24(5):2161-2170.
9. Wu ZH, Zhang M, Jiang W, Jin JX. Pitching vibration analysis of precision motion stage with air-bearings. Mach Electron. 2012;2:5–9.
10. Chen XD, Xie DD, He XM, Jiang W, Zhang LL. Structure dynamic modeling and analysis of precision linear motor with air-bearings. J Wuhan Univ Technol. 2008;184:117–121.
11. Yu XZ, Chen XD, Ye YX, Jia WC. Dynamic response analysis of precision double-layer air-floating linear motor. China Mech Eng. 2008;7:761–765.
12. Chen XL, Liu C, Geng CQ, Xu JY. Perfect tracking control for linear motor in wafer stage of lithography. J Central South Univ. 2015;46(9):3238–3244.
13. Zhang J, Yamaguchi T, Iwata K, Kikuta H, Park CS. Measurement by multidirectional interferometers of the position and orientation of a positioning stage. Opt Appl. 2003;42(28):5661–5669.
14. Henshaw PD, DeGloria DP, Kelly SA, Dillon RF. Real-time stage position measurement with nanometer-scale accuracy. Opt Microlithogr X. 1997;3051:913-921.
15. Lazar J, Habina J, Šery M, Klapecek P, Cip O. Multiaxis interferometric displacement measurement for local probe microscopy. Cent Eur J Phys. 2012;10(1):225-231.
16. Lin ST. A laser interferometer for measuring straightness. Opt Laser Technol. 2001;33(3):195-199.
17. Norrlöf M, Gunnarsson S. Experimental comparison of some classical iterative learning control algorithms. IEEE Trans Rob Autom. 2002;18(4):636-641.
18. Lee JH, Lee KS, Kim WC. Model-based iterative learning control with a quadratic criterion for time-varying linear systems. Automatica. 2000;36(5):641-657.
19. Gunnarsson S, Norrlöf M. On the design of ILC algorithms using optimization. Automatica. 2001;37(12):2011-2016.
20. Tsuyuzaki H, Shimazu N, Fujinami M. High speed flat guide ceramic stage for electron-beam lithography system. J Vac Sci Technol B Microelectron Process Phenom. 1986;4:280–284.
21. Kuniyoshi S, Komoriya S, Sekiguchi K, Katoo T. Stepper stability improvement by a perfect self-calibration system. Optical/Laser Microlithography VII. 1994;2197:990-996.
22. Mo DY, Ma P, Lian H, Gong MF. Optimal design for the structure parameters of long raster engraving air-floating platform. Mechanika. 2020;26(1):55–63.
23. Zheng T, Xu X, Lu X, Hao LY, Xu F. Learning adaptive sliding mode control for repetitive motion tasks in maglev rotary table. IEEE Trans Ind Electron. 2021;1.
24. Castenmiller T, de van der M, de Kort T, et al. Towards ultimate optical lithography with NXT:1950i dual stage immersion platform. Opt Microlithogr. XXIII, 2010;7640.
25. Liang C, Yuan F, Chen X, Jiang W, Zeng L, Luo X. Comprehensive analysis of the influence of structural and dynamic parameters on the accuracy of nano-precision positioning stages. Front Mech Eng. 2019;14:255–272.
26. Zhang L, Kou B, Xing F, Jin Y, Zhang H, Zhu J. A magnetically levitated synchronous permanent magnet planar motor with concentric structure winding used for photolithography system. J Appl Phys. 2015;117:17B525.
27. Gehring R, Demmg S, Mertens A, Ponick B. Investigations on a micro linear stepping motor supplied by a DC-DC converter. Proc IEEE Int Electr Mach Drives Conf. 2007:1096–1101.
28. Konkola PT, Trumper DL. Electromagnetic design of a low-fringing-field magnetic bearing stage for electron beam lithography. JSME Int J Ser C Mech Syst Mach Elem Man. 2003;46(2):370–377.
29. Lu QF, Shen YM, Ye YY. Development of permanent magnet linear synchronous motors structure and research. Proc Chinese Soc Electr Eng. 2019;039:2575–2588.
30. Zhang D, Li P, Zhang J, Chen H, Guo K, Ni M. Design and assessment of a 6-DOF micro/nanopositioning system. IEEE/ASME Trans Mechatronics. 2019;24(5):2078-2107.
31. Tang YB, Li LY, Liu JX, Pan DH. Thrust analysis of air-core permanent magnet linear synchronous motor with fractional slot concentrated windings. Electron Mach Control. 2013;17(8):1-8.
32. Li LY, Tang YB, Liu JX, Pan DH. Application of multi-population genetic algorithm in optimal design of air-core permanent magnet linear synchronous motor. Proc Chin Soc Electr Eng. 2013;033(15):49-77.
33. Wang YG, Chen XL, Li JX. Three degrees of freedom modeling and adaptive neural network control for the long-stroke wafer stage. Opt Precis Eng. 2015;23:132–140.
34. Yoon JY, Lang JH, Trumper DL. Fine-tooth iron-core linear synchronous motor for low acoustic noise applications. IEEE Trans Ind Electron. 2018;65(12):9895–9904.
35. Wang JP, Zhou HP, Shi YL. Displacement resolution of precision stage driven by linear ultrasonic motors. J Vib Shock. 2015;34(22):178–182.
36. Kunioka T, Takeda Y, Matsuda T, Shimazu N, Nakayama Y. XY stage driven by ultrasonic linear motors for the electron-beam X-ray mask writer EB-X3. J Vac Sci Technol B Microelecron Nanom Struct Process Meas Phenom. 1999;17:2917–2920.
37. Egashira Y, Kosaka K, Iwabuchi T, et al. Sub-nanometer resolution ultrasonic motor for 300 mm wafer lithography precision stage. Jpn J Appl Phys. 2002;41(99):5858-5863.
38. Gao X, Li Z, Wu J, et al. A piezoelectric and electromagnetic dual mechanism multimodal linear actuator for generating macro- and nanomotion. Research. 2019:8232097.
39. Van Brussel H, Van De Vijver W, De Voilder M, Devos S, Reynaerts D. A fast, high-stiffness and high-resolution piezoelectric motor with integrated bearing and driving functionality. *CIRP Ann Manuf Technol.* 2006;55(1):373-376.

40. Chen PY, Jywe WY, Wang MS, Wu CH. Application of blue laser direct-writing equipment for manufacturing of periodic and aperiodic nanostructure patterns. *Precis Eng.* 2016;46:263-269.

41. Gui C, Ding X, Zhou S, Gao Y, Liu X, Liu S. Nanoscale Ni/Au wire grids as transparent conductive electrodes in ultraviolet light-emitting diodes by laser direct writing. *Opt Laser Technol.* 2018;104:112-117.

42. Wu J, Zeng L, Han B, Luo X, Chen X, Jiang W. Inverse eigenvalue theory-based rigid multibody modeling method of complex flexible structures in large-scale mechanical systems. *Math Probl Eng.* 2020:8329935.

43. Ye W, Zhang M, Zhu Y, et al. Real-time displacement calculation and offline geometric calibration of the grating interferometer system for ultra-precision wafer stage measurement. *Precis Eng.* 2019;60:413-420.

44. Baldwin R. Interferometer system for measuring straightness and roll. 1974; U.S. Patent No. 3,790,284.

45. Chaney RJ, Mcmurtry DR. Straightness interferometer system. 1991;EP, EP033783 A1.

46. Cheng Z, Gao H, Chai X, Ning Z, Huang H. Study on high-accuracy displacement interferometer for lithography application. *Fifth Int Symp Laser Precis Microfabr.* 2004:5662:395–399.

47. de Jong F, van der Pasch B, Castenmiller T, Vleeming B, Droste R, van de Mast F. Enabling the lithography roadmap: an immersion tool based on a novel stage positioning system. *Opt Microlithogr. XXII,* 2009:7274.

48. Gao Z, Hu J, Zhu Y, Duan G. A new 6-degree-of-freedom measurement method of XY stages based on additional information. *Precis Eng.* 2013;37(3):606–620.

49. Gao W, Kimura A. A fast evaluation method for pitch deviation and out-of-flatness of a planar scale grating. *CIRP Ann.* 2010;59(1):505–508.

50. Guan J, Kôchert P, Weichert C, Tutsch R. A high performance one-dimensional homodyne encoder and the proof of principle of a novel two-dimensional homodyne encoder. *Precis Eng.* 2013;37(4):865–870.

51. Zhang M, Zhu Y. Review of ultra-precision optical interferential grating encoder displacement measurement technology for immersion lithography scanner. *Opt Precis Eng.* 2019;27(9):1909–1918.

52. Yang C, Lei T, Yuan X. Micro-grating array-enabled power efficiency improvement for a DMD-based optical switch. *IEEE Photonics Technol Lett.* 2017;30(3):145–148.

53. Cosijns SJAG, Jansen MJ, Haitjema H. Advanced Optical Incremental Sensors: Encoders and Interferometers. *Smart Sensors MEMS.* 2nd ed. Elsevier; 2018:245-290.

54. Du H, Zhang W, Xiong X, et al. Influence of installation error of grating interferometer on high-precision displacement measurement. *Opt Eng.* 2021;60(4):45102.

55. Hu P, Chang D, Tan J, Yang R, Yang H, Fu H. Displacement measuring grating interferometer: a review. *Front Inf Technol Electron Eng.* 2019;20:631–654.

56. Ellis JD. Field guide to displacement measuring interferometry. Society of Photo-Optical Instrumentation Engineers (SPIE); 2014.

57. Wise S, Quetschke V, Deshpande AJ, et al. Phase effects in the diffraction of light: beyond the grating equation. *Phys Rev Lett.* 2005;95:13901.

58. Xie J, Yan L, Chen B, Zhang S. Iterative compensation of nonlinear error of heterodyne interferometer. *Opt Express.* 2017;25(4):4470–4482.

59. Xing X, Chang D, Hu P, Tan J. Spatially separated heterodyne grating interferometer for eliminating periodic nonlinear errors. *Opt Express.* 2017;25(25):31384–31393.

60. Lee J-Y, Jiang G-A. Displacement measurement using a wavelength-phase-shifting grating interferometer. *Opt Express.* 2013;21(21):25553–25564.

61. Zhao B, Wang L, Xu M, Zhao H, Liu X. A displacement measuring system based on grating double diffraction. *Ninth Int Symp Precis Eng MeasInstrum.* 2015:9446.

62. Renkens MJM, Struyckpen AM, Kok RJ, Verhagen MCM. Lithographic apparatus, measurement system, and device manufacturing method; 2006:US7102729 B2.

63. Baselmans JJM, Mertens JJS, Donders SNL, Hoogendam CA, Jansen H, Mulkins JCH, et al. Lithographic apparatus, device manufacturing method and device manufactured thereby. 2006; U.S. Patent No. 7,034,917.

64. Lin C, Yan S, Du Z, Wang G, Wei C. Symmetrical short-period and high signal-to-noise ratio heterodyne grating interferometer. *Chin Opt Lett.* 2015;13(10):100501.

65. Ito S, Aihara R, Kim WJ, Shimizu Y, Gao W. Three-axis vibration measurement by using a grating-interferometric vibrometer. *Adv Opt Technol.* 2014;3:435–440.

66. Kim J-A, Kim K-C, Bae EW, Kim S, Kwak YK. Six-degree-of-freedom displacement measurement system using a diffraction grating. *RevSci Instrum.* 2000;71:3214–3219.

67. Bae EW, Kim J-A, Kim SH. Multi-degree-of-freedom displacement measurement system for milli-structures. *Meas Sci Technol.* 2001;12:1495-1502.

68. Wong AK. Resolution enhancement techniques in optical lithography. 2001. SPIE -The International Society for Optical Engineering; 2001.

69. Silverman PJ. Extreme ultraviolet lithography: overview and development status. *J Micro/Nanolithogr MEMS MOEMS.* 2005;4(1):011006.

70. Zhu T, Li Y. Study on control strategy of wafer stage and reticle stage of EUV/L. *2nd Int Symp Adv Opt Manuf Tech Test Technol Adv Opt Manuf Technol.* 2006;6149.

71. Li L, Hu S, Zhao L, Ma P. Iterative learning control for synchronization of reticle stage and wafer stage in step-and-scan lithographic equipment. *Int Symp Photoelectron Detect Imaging 2013 Micro/Nano Opt Imaging Technol Appl.* 2013:8911.

72. Wang C, Yin W, Duan G. Cross-coupling control for synchronized scan of experimental wafer and reticle stage. *IET Conf Publ.* 2006.

73. Hong Li, Zhou YF. The design of stage for 100nm photolithography. *Microelectron Technol.* 2003;4:2–6.

74. Lei J, Luo X, Chen X, Yan T. Modeling and analysis of a 3-DOF Lorentz-force-driven planar motion stage for nanopositioning. *Mechatronics.* 2010;20(5):553-565.

75. Zhu Y, Yin WS, Duan GH. Research on ultra-precision stages of lithography. *Echiptron Prod Manuf.* 2004;33(2):25–27.

76. Yimin Z, Xianzhen H, Xiangdong H, Wei G. Reliability sensitivity design of the kinematic accuracy of a planar linkage mechanism with arbitrary distribution parameters. *Mech Sci Technol Aerosp Eng.* 2008;5:130–133.

77. Chong YL, Bai GC, Jiao JT, Gao Y. Research on deformation dynamic response reliability analysis of flexible mechanism. *J Astronaut.* 2006;27:1039–1043.

78. Lu Z, Yue Z, Zhang W. Numerical simulation method for random-fuzzy reliabilityanalysis of elastic linkage mechanism stiffness. *Chin J Comput Mech.* 2004;1:62-66.

79. Luo D, Wang K, Zhang L, Li J, Wang Z, Huang HZ. Dynamic precision reliability analysis for six degrees of freedom micro-displacement mechanism of reticle stage in photolithography system based on Monte-Carlo. *2013 Int Conf Qual Reliab Risk, Maintenance Saf Eng.* 2013:250-252.
80. Sun Y, Li X, Luo Y, Chen X, Zeng L. Iterative tuning of feedforward controller with precise time-delay compensation for precision motion system. *Math Probl Eng*. 2020:9391526.

81. Butler H. Position control in lithographic equipment [applications of control]. *IEEE Control Syst*. 2011;31(5):28-47.

82. Keem T, Gonda S, Misumi I, Huang Q, Kurosawa T. Removing nonlinearity of a homodyne interferometer by adjusting the gains of its quadrature detector systems. *Appl Opt*. 2004;43(12):2443-2448.

83. Hu P, Wang Y, Fu H, Zhu J, Tan J. Nonlinearity error in homodyne interferometer caused by multi-order Doppler frequency shift ghost reflections. *Opt Express*. 2017;25(4):3605-3612.

84. Fitzgibbon A, Pilu M, Fisher RB. Direct least square fitting of ellipses. *IEEE Trans Pattern Anal Mach Intell*. 1999;21(5):476-480.

85. Eom TB, Kim JY, Jeong K. The dynamic compensation of nonlinearity in a homodyne laser interferometer. *Meas Sci Technol*. 2001;12:1734.

86. Wang C, Burnham Fay ED, Ellis JD. Real-time FPGA-based Kalman filter for constant and non-constant velocity periodic error correction. *Precis Eng*. 2017;48:133-143.

87. Lu S, Cheng R, Yang K, Zhu Y, Wang L, Zhang M. Real-time correction of periodic nonlinearity in homodyne detection for scanning beam interference lithography. *Opt Eng*. 2018; 57(10), 104107.

88. Yu Zhu YZ, Leijie Wang LW, Ming Zhang MZ, et al. Novel homodyne frequency-shifting interference pattern locking system. *Chin Opt Lett*. 2016;14(6):061201.

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