A revolutionary development in optical displacement metrology has been the transition from free-space laser interferometers to extreme-precision optical encoders for positioning measurements in semiconductor photolithography systems. An increasingly demanding error budget for stage motion control has mandated a dramatic reduction in sensitivity to air turbulence and refractive index changes that is only achievable with multi-dimensional sensors with intrinsically short air paths. Here we describe the design, implementation and performance of these new optical heterodyne encoder systems, which achieve sub-nm displacement measurements for stages moving at over 8 m/s.

The challenge

The history of the fabrication of semiconductor devices is characterised by astonishing breakthroughs in the number of transistors in a single data processor, now approaching 20 billion. The fabrication of circuits and memory at these densities relies on as many as 100 overlaying patterns created by high-speed lithographic exposure of photoresist, followed by chemical processing and reinsertion into a photolithography system for the next layer.

Each new pattern on a wafer in production is registered with the previous layers to a fraction of the 10-nm minimum critical dimension (CD) of individual transistors. The stage position measurement is only one part of the uncertainty budget, leading to demanding, sub-nm uncertainty allocation to stage metrology [1]. Wafer throughput requirements of 15 s per cycle on each wafer drive stage speeds to greater than 1 m/s, with displacements in the order of 0.5 m [2].

Until recently, stage metrology subsystems for semiconductor lithography consisted almost entirely of line-of-sight laser interferometers. These systems are highly-evolved versions of Michelson two-beam interferometers designed to monitor displacements and changes in stage orientation using heterodyne detection [3]. As CD values have decreased, the use of interferometers with long path lengths has reached a practical limit: fluctuations or turbulence in the air and environmental sensitivities related to variations in air index have proved to be the largest contributors to stage metrology error.

For extreme ultraviolet (EUV) systems working in a vacuum, this error source is less of an issue; but the majority of semiconductor exposure processes still take place in air and the resulting air turbulence from airflow, stage motions and other disturbances contribute as much as 80% of the error budget for the stage metrology [4].

In anticipation of the air-turbulence limit, serious attempts have been made to compensate for the refractive index of air using dispersion interferometry [3, 5, 6]; but these efforts have been overtaken by ever-tightening requirements. Another solution is needed.

The solution

The solution to the limitations imposed by air turbulence and environmental effects relies on the scaling of the magnitude of these sensitivities with the length of the air paths traversed by the interferometer beams. Shorter air paths result in a smaller contribution from these disturbances. Optical encoder systems replace the mirror with a diffraction grating (a substrate with periodic structures). Encoders shorten the air path from hundreds of mm in length typical of conventional interferometers to a constant length of just a few mm, significantly reducing air turbulence as an error source. Figure 1a and 1b contrast these two arrangements.

A long-standing limitation of encoders has been the inability to locate encoders in multi-degree-of-freedom (multi-DoF) stage systems in compliance with the Abbe principle, which requires that the line of measurement pass through the point of interest (POI) [7, 8]. Line-of-sight interferometers easily achieve this (Figure 1a), while a single 1-DoF encoder in a multi-DoF application must account for the Abbe offset $b$ and the stage rotation $\theta$ (Figure 1b).

As shown in the example in Figure 1c, multi-DoF encoders address this by providing displacement information in both the $x$ and $z$ direction that enables the measurement of the angular error motions of the stage for the compensation for the effects of the Abbe offset in the $x$ direction as well as...
Comparison of interferometer and encoder arrangements. Figures not to scale.
(a) Interferometer in compliance with the Abbe principle, but with a large air path length.
(b) 1-DoF encoder with ~mm scale air path, but in violation of the Abbe principle.
(c) Multiple 2-DoF encoders enabling compensation of Abbe errors while preserving a low sensitivity to air turbulence and environmental effects.

providing an effective line of measurement through the POI in the z direction. Using several multi-DoF encoders in conjunction with two-dimensional (2D) gratings enables extension of this principle to effectively eliminate Abbe errors in all measurement axes that result from rigid-body motions.

Encoders based on heterodyne interferometry
Encoders face another challenge in the intrinsically low light efficiency from a grating target. The net efficiency for a double-pass encoder with a 2D grating can be as low as 1%. It is a further system requirement that multiple encoders share the same light source, preferably at the familiar 633-nm Helium-Neon (HeNe) laser wavelength. The solution to this challenge is a proprietary light source combined with heterodyne signal detection – a combination that has fundamental advantages in achieving the high signal-to-noise ratio (S/N) that is essential for sub-nm performance at high speed [9].

Heterodyne detection
Our heterodyne encoder systems use a proprietary 20-mW, frequency-stabilised, single-mode HeNe laser [10]. The output beam is split into two collinear, orthogonally polarised beams that have a fixed optical frequency difference (the split frequency) between them by means of an acousto-optical modulator. Within the encoder, these two polarised beams play the role of measurement and reference beams of an interferometer, with the grating being an integral part of the measurement path.

The beams interfere after passing through a mixing polariser at the output. The frequency split between the two beams creates a continuous sinusoidal beat signal, even with a stationary target. As the target moves, this changes the optical path length, and the receiver electronics detect a time-varying phase change at the split frequency that is proportional to the displacement.

Heterodyne detection provides important advantages over homodyne detection, the chief being a significantly improved S/N thanks to the shift in the operating point of the interferometer away from the high 1/f noise background in the low-frequency region of the spectrum. A further reduction in noise follows from using fewer detectors per measurement channel when compared to homodyne interferometers.

Encoder design
A fundamental challenge of encoder designs is to achieve high-resolution measurements of in-plane and out-of-plane motions while accommodating tip and tilt of the grating. Figure 2a shows one of our interferometric encoder designs where a retroreflector reverses the measurement beam’s path after its encounter with the grating [11]. The reversal via a retroreflector makes the final beam angle independent of grating rotation about x, y and z, thereby maintaining adequate signal strength over realistic rotations. The double-pass beam geometry doubles the sensitivity to grating motion, at the expense of radiometric efficiency.

The basic configuration of Figure 2a is sensitive to displacements both in the in-plane x and out-of-plane z directions, i.e. the measured phase change \( \Delta \varphi \) is a linear combination of the two displacements. A second measurement channel as shown in Figure 2b provides an additional phase change \( \Delta \varphi \), that allows the electronics to separate these two motions. Solving for displacements \( \Delta x \) and \( \Delta z \) from the two measured phase changes \( \Delta \varphi \) and \( \Delta \varphi \) results in:

\[
\Delta x = c_x (\Delta \varphi_1 - \Delta \varphi_2)
\]

\[
\Delta z = c_z (\Delta \varphi_1 + \Delta \varphi_2)
\]
Here, $c_x$ is derived from the grating pitch and $c_z$ is derived from the wavelength and the grating pitch. Combining multiple encoders oriented in different directions and viewing different areas of a 2D grating provides full 6-DoF sensing with Abbe offset compensation.

**Advanced configurations**

Although stages in lithography applications nominally move within the $xy$ plane, encoders also monitor out-of-plane $z$ motions over a range that can sometimes reach 1 mm as the stage tips, tilts and translates to accommodate variations in wafer flatness and focus position. Figure 3 demonstrates how the grating's motion in $z$ creates a beam shear between the orange reference and the red measurement beam in the basic encoder design of Figure 3a. Excessive beam shear of the order of the beam radius or larger reduces the signal significantly.

Depending on the encoder location in the photolithography system, accommodation of the required stage motions may warrant more advanced optical designs.

Choosing a larger beam to increase the $z$ range would be an obvious solution; but the need for compact designs usually rules out this otherwise straightforward option. Figure 3b shows a superior beam geometry for extending the $z$ range, which – during the second diffraction – fully compensates the shear created during the first diffraction. As long as the internally sheared beam clears limiting apertures, this advanced design maintains full signal strength over a wide range of $z$ positions [12].

For encoders to provide accurate measurements, the effects of unintended beam paths through the optical system need to be minimised. So-called ghost beams that pollute the
encoder’s optical signal arise from polarisation leakage or unwanted reflections from various components. While advanced signal processing can reduce the effects (as described below), prevention of ghost beams in the first place is always preferable. A variety of strategies can be applied that separate the ghost beams from the desired beams spatially or angularly, e.g., by means of glass wedges or birefringent prisms [13]. While the exact heterodyne encoder head designs and specifications depend on the particular application, Table 1 provides a general sense for the key performance specifications.

### Design for repeatability

Successful registration of features between the various layers of an integrated circuit requires consistent, repeatable stage positioning. Good encoder design therefore places a premium on repeatability, and seeks to minimise noise and drift that would otherwise compromise consistent results in the stage metrology. Here we consider a few of these potential error sources and their mitigation.

Heterodyne encoders receive the light from the two-frequency laser source via optical fibres. Temperature- and strain-induced phase changes between the two frequencies as they propagate through the fibres manifest themselves as erroneous displacements. Specialised optics within the encoder head interferometrically measure and compensate these phase changes in real-time.

While the in-plane measurements are independent of the wavelength, any wavelength instabilities affect the measurement repeatability through unequal measurement and reference paths. Specialised high-power, frequency-stabilised HeNe laser sources with stabilities of a few parts per billion (ppb) in combination with the small path imbalances provide sub-nm stabilities over times commensurate with lithographic cycle times [10].

Interestingly, the traceability path to the unit of length for encoder systems is through the grating calibration, rather than directly to the wavelength of light. On balance, this turns out to be an advantage, as reliance on a material artifact (the grating) reduces sensitivity to short-term environmental changes in temperature and pressure thanks to the thermal and mechanical stability of the grating material. This is a distinct advantage in the arena of microlithography, where stability and precision far outweigh the need for accuracy.

A source of non-repeatability common to many interferometers and encoders are cyclic or periodic errors (also referred to as interpolation errors) [14]. These errors have periods that are related to the wavelength or the grating pitch and lead to periodic deviations of the measured displacement from the true displacement as shown in Figure 4.

**Table 1**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range in (x) and (y) direction</td>
<td>Determined by length of grating</td>
</tr>
<tr>
<td>Range in (z) direction</td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Max. velocity (with 1 (\mu)m grating pitch)</td>
<td>8.1 m/s</td>
</tr>
<tr>
<td>Typical grating tilt range</td>
<td>± 10 mrad</td>
</tr>
<tr>
<td>Cyclic error</td>
<td>&lt; 50 pm</td>
</tr>
<tr>
<td>Digital resolution</td>
<td>7.6 pm</td>
</tr>
<tr>
<td>Data rate</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Operating wavelength</td>
<td>633 nm</td>
</tr>
<tr>
<td>Data interface</td>
<td>sRIO</td>
</tr>
</tbody>
</table>

![Cyclic or periodic error.](image)

(a) Encoder response with the deviation of the measured displacement from the actual displacement.
(b) Residual error magnitude after optical correction of 0.4 nm.
(c) Residual error after optical and electronic correction reduced to 0.04 nm.
The mitigation of these errors includes both optical measures [15] and the detection and removal of residual parasitic signals electronically [16, 17], with the electronic reduction affording an additional order of magnitude reduction over the already sub-nm cyclic error after optical correction as shown in Figure 4c.

The sensitivity of the encoder head to changes of temperature can be an important source of measurement drift. These contributions arise from deformations of the encoder structure, bulk changes in the refractive index of glass components, birefringence from thermal stresses and thermal deformation of the adhesive bonds within the encoder assembly. The largest of these contributors is often the temperature-induced motion of the effective measuring point of the encoder relative to the encoder mount.

A combination of low-CTE materials, careful design of the constraint system to accommodate thermal expansion and strategic location of thermal centres (Figure 5) produce sub-nm contributions in the temperature environments typically found in lithography machines [18]. The choice of adhesives and the design of joints requires careful consideration to accommodate differential expansion between optics with different CTE values while also preventing excessive stresses from developing – stresses which result in birefringence and localised index changes.

**Summary**
As we have seen, the basic problem posed by photolithographic stage positioning reflects the global technology and manufacturing trends towards ever more demanding requirements, with a current requirement for controlling the position of a stage moving at up to 8 m/s to sub-nanometer precision. Turbulent airflows and the environmental sensitivity of the air index have made traditional long-path interferometric solutions untenable for the latest generation of wafer fabrication systems in the majority of photolithography systems, leading to the introduction of short-path, 2D grating encoders – an enabling technology that until recently simply was not up to the task.

The heterodyne optical encoder solution is an excellent example of interdisciplinary precision engineering in action. Every aspect of the development of encoders over the last decade has required significant advances, starting with innovative optical designs to accomplish multi-dimensional sensing, to the mechanical design for thermal insensitivity, temporal stability and manufacturability.

The laser-heterodyne system involves new light sources, advanced optical and electronic cyclic error reduction, fibre-optic delivery, and highly complex assemblies of precision-fabricated optical components. Far from being demonstration experiments of the state-of-the-art, these revolutionary designs are purpose-built, practical implementations that must satisfy daunting space, cost and performance constraints on a routine production basis. It perhaps goes without saying that these requirements are not stationary – they will continue to challenge us to precision engineer creative solutions going forward.
REFERENCES


