CONCEPTS AND GEOMETRIES FOR THE NEXT GENERATION OF PRECISION HETERODYNE OPTICAL ENCODERS

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A REVOLUTION IN STAGE METROLOGY

The fabrication of integrated circuits and solid-state memory relies on lithographic printing of overlaying patterns onto a semiconductor wafer. The manufacturing process may consist of more than 40 cycles, with each cycle defining a specific layer. Lithographic exposures require stage motions during a continuous projection, with the requirement that new patterns are registered with previous layers to much less than the minimum feature size or critical dimension (CD) of individual transistors, currently at 16 nm [1]. Double-exposure techniques permit an overlay error of no more than 15% of the CD, with about 20% of this number or 3% of the CD or 0.5 nm allocated for stage metrology [2].

As if the precision targets were not enough of a challenge, an additional requirement is stage speeds of greater than 1m/s, so as to achieve throughputs of 20s per wafer [3]. The wafer stage is continuously adjusted for tip and tilt through the exposure. These factors require closed-loop control with metrology feedback that continuously tests the limits of what is achievable.

A decade ago, stage metrology subsystems for photolithography equipment consisted entirely of line-of-sight laser interferometers. These systems, which still play a dominant role in stage positioning, are highly-evolved versions of Michelson two-beam interferometers configured to monitor displacements and changes in stage orientation using heterodyne detection [4].

As CD values have decreased, error analyses have revealed that 80% or more of the total error can be related to air fluctuation of the interferometer [1]. Serious attempts have been made to compensate for air-index using dispersion interferometry [4-6]; but these efforts have been overtaken by ever-tightening requirements.

Recognizing that optical encoders minimize the air turbulence contribution by reducing the air paths, the photolithography industry now uses high-performance encoders to monitor the critical stage motions during wafer exposure [3, 7-11].

DESIGN CONSIDERATIONS

For complete motion metrology, a 2-D grating replaces the traditional stage mirrors, and the encoder system is expected to monitor all six degrees of freedom. The multi-axis motion monitoring is not only a basic requirement for advanced stage control, but is essential for the calculation and compensation of Abbe error. Consequently, the basic geometry and ray paths within each individual encoder must allow for dynamic changes in tip, tilt and distance to the read head during data acquisition, with acceptable signal loss, systematic error and cross coupling between measurement axes. Assuming that this can be done, there remains the task of designing encoders with sub-nm precision at data rates in the MHz regime.

Traditional optical encoders familiar to precision engineers employ homodyne detection and measure the in-plane relative motion between the encoder head and a metal or glass scale [12, 13]. Linear and rotary encoders can be found in a wide range of machine tools and precision instruments. They can be viewed either as interferometric devices, with the two interfering beams generated by diffraction; or as optical systems that project an image of the grating onto a detector. The basic resolution unit is given by the spacing between the grating lines, with higher precision achieved by interpolation.

Traditional encoders vary from inexpensive to high performance; but typical systems that one can buy off the shelf have performance characteristics that fall well short of the demanding requirements of modern photolithography stage positioning systems. Hence the need in recent years to develop new encoders, including the invention of fundamentally new geometries.

NEW DESIGNS

A way to solve the problem of tip/tilt sensitivity is to redirect a measurement beam twice to the encoder grating, in a strategy analogous to the double-pass plane mirror interferometer [4]. This can be achieved by modifying a retro-reflector based linear encoder with the grating placed in the beam path. FIGURE 1 illustrates an efficient and compact approach that uses the encoder grating to fold a linear interferometer back onto itself, resulting in sensitivity to both in-plane and out-of-plane motions [14]. The double pass with a retroreflection compensates for tip and tilt of the encoder grating.

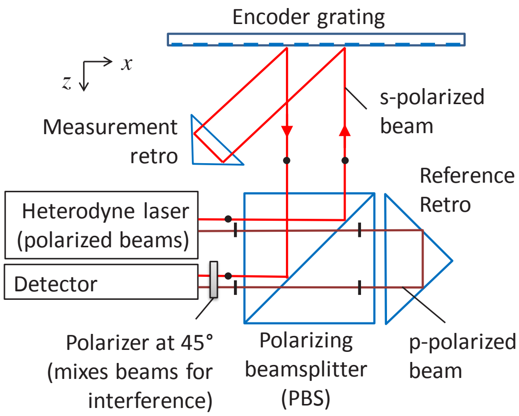

FIGURE 1: Basic encoder geometry using a linear interferometer.

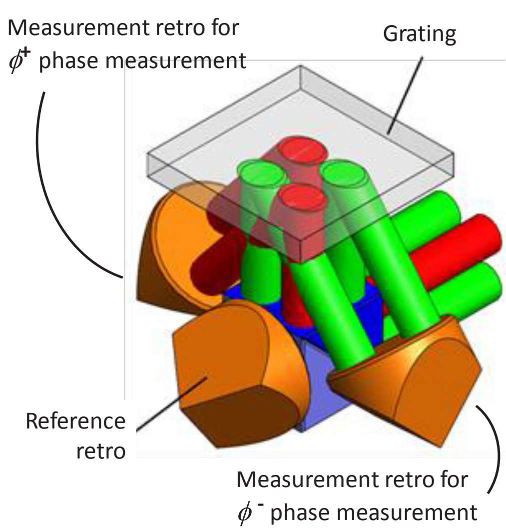

FIGURE 2: A two-axis encoder based on the concept shown in FIGURE 1.

Given the low diffraction efficiency of 2D gratings, signal to noise requirements point to a preference for heterodyne interferometry, which benefits from coherent amplification and a measurement frequency offset to frequencies above thermal noise. The optics are fed with orthogonally polarized measurement and reference beams having a heterodyne frequency difference of 20 to 80MHz [15]. A polarizing beam splitter directs the light along reference and measurement paths, and a polarizer mixes the recombined beams at the detector.

Although the folded linear interferometer is compact and efficient, the in-plane x and out of plane z measurements are confounded in this elemental geometry. The solution is to employ two encoders sharing a common entrance beam and beamsplitter, providing two simultaneous phase measurements, ϕ^{+},ϕ^{-}, as in FIGURE 2. The displacement measurements follow from straightforward math, where Λ is the grating pitch:

$$x=\frac{\left(\phi^{+}-\phi^{-}\right)}{8\pi}\Lambda$$

$$z=\frac{\left(\phi^{+}+\phi^{-}\right)}{8\pi}\frac{\lambda}{1+\sqrt{1-\left(\lambda/\Lambda\right)^{2}}}.$$

An important consideration in polarized interferometer design is the control of beam mixing. The cyclic error commonly encountered with interferometric displacement sensors can easily surpass several nm even with the best PBS optics [16]. To suppress these errors, angled beam geometries such as the one shown in FIGURE 3 combine with advanced firmware for the suppression of residual errors [17, 18].

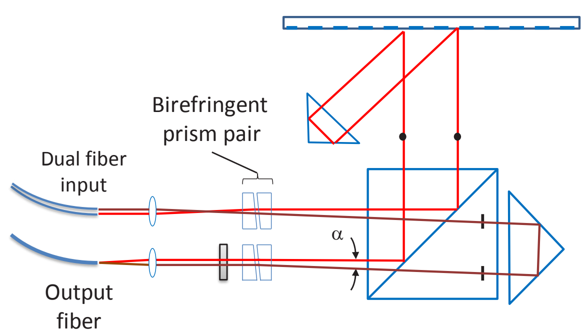

FIGURE 3: A technique for reduced polarization mixing uses separated-beam light delivery and angled beams.

Heterodyne encoders based on the folded linear interferometer solve the basic problem of tip/tilt compensation, but they have their limitations. Out-of-plane motion along the z axis has an undesirable side effect of laterally shearing the measurement beam with respect to the reference beam, which reduces signal strength. The result is a restriction in the allowable z displacement, which can be an issue if the metrology system must allow for a large range of motion in this direction.

The recirculating double-pass geometry shown in FIGURE 4 compensates for beam shear as the encoder head's distance to the grating changes [19]. After a first diffraction from the moving grating on the stage, the measurement beam diffracts from a fixed grating and reflects from a small roof prism back to the moving grating. A second cycle of diffractions from the two gratings compensates not only for tip and tilt, but also for beam shear caused by stage motion in the z direction.

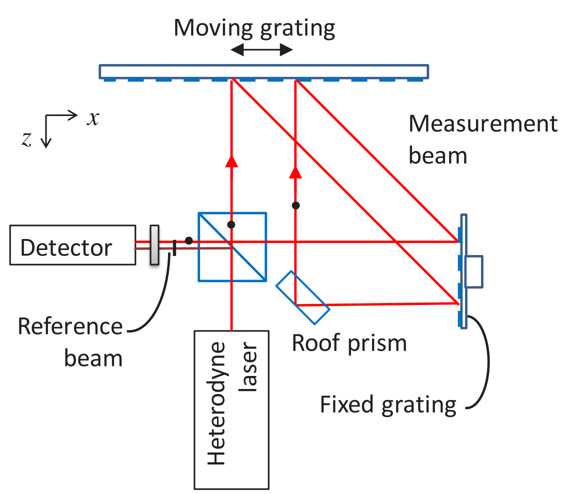

FIGURE 4: Simplified, conceptual drawing of a double-pass heterodyne encoder compensated for beam sheer over large z-axis motions.

PERFORMANCE

The conceptual elements described in this abstract have been incorporated into advanced photolithography systems. In actual product designs, the optical components are rearranged so as to provide passive thermal compensation as well as dimensional stability [20]. Many of these design details are currently proprietary, as are the procedures and results of system-level testing to verify the sub-nm uncertainty requirements of semiconductor lithography stage positioning.

Some pre-shipment testing is nonetheless an expected step in the manufacturer of OEM encoder systems. The example spectral signal analysis in FIGURE 5 for a laser displacement interferometer shows the main signal as well as parasitic signals that are the result of polarization mixing, uncontrolled reflections, and other harmonic errors [4]. Tests of this kind performed for encoder heads in production confirm that cyclic errors are less than 0.05 nm RMS and the random noise is 0.06 nm for a 10 kHz bandwidth.

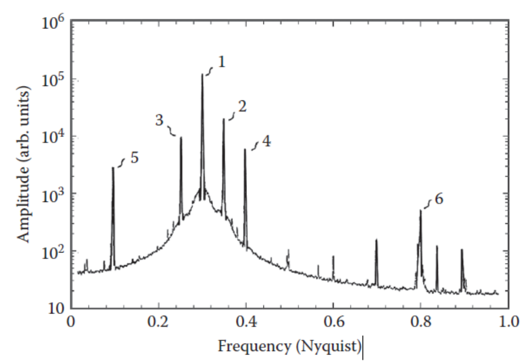

FIGURE 5: Graph showing the frequency content of a laser displacement interferometer signal. Data of this kind allows for the detection and correction of residual cyclic errors.

CONCLUSIONS

The demands of modern precision engineering exemplified by semiconductor photolithography systems have propelled encoder technology to a performance level surpassing that of line-of-site interferometry. The key advantage in these systems is the nearly complete suppression of air turbulence. This advance has come at the price of increased demands on calibration and compensation systems, as well as on the encoder design itself. Here we have reviewed the basic concepts and geometries underlying the current and future generation of optical encoders. Driven by ever decreasing critical dimensions, there will continue to be demands on developers for new designs with even higher precision.

REFERENCES

[1] Yoda, Y., Hayakawa, A., Ishiyama, S. *et al.*, Next-generation immersion scanner optimizing on-product performance for 7nm node. in *Optical Microlithography XXIX*, Proc. SPIE. 2016; 9780: 978012-978012-10.

[2] Schmidt, R.-H. M. Ultra-precision engineering in lithographic exposure equipment for the semiconductor industry. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences. 2012; 370: 3950-3972.

[3] Butler, H. Position Control in Lithographic Equipment [Applications of Control]. IEEE Control Systems. 2011; 31: 28-47.

[4] Badami, V., and de Groot, P. Displacement Measuring Interferometry. In Handbook of Optical Dimensional Metrology, Chap.4. Taylor & FrancisBoca Raton 2013

[5] de Groot, P. J., and Badami, V. G., Revelations in the Art of Fringe Counting: The State of the Art in Distance Measuring Interferometry. in *7th International Workshop on Advanced Optical Imaging and Metrology*, Proc. FRINGE Springer Verlag. 2014; 785-790.

[6] Minoshima, K., Nakajima, Y., and Wu, G., Ultra-precision optical metrology using highly controlled fiber-based frequency combs. in *Optical Measurement Systems for Industrial Inspection IX*, Proc. SPIE. 2015; 9525: 952502-952502-7.

[7] Shibazaki, Y., Kohno, H., and Hamatani, M., An innovative platform for high-throughput high-accuracy lithography using a single wafer stage. in Proc. SPIE. 2009; 7274: 72741I-72741I-12.

[8] Hercher, M., and Wijntjes, G. J., Interferometric measurement of in-plane motion. in Proc. SPIE. 1991; 1332: 602-612.

[9] Kimura, A., Gao, W., Arai, Y. *et al.* Design and construction of a two-degree-of-freedom linear encoder for nanometric measurement of stage position and straightness. Precision Engineering. 2010; 34: 145-155.

[10] Wang, J. L., Zhang, M., Zhu, Y. *et al.*, A novel heterodyne grating interferomter system for in-plane and out-of-plane displacement measurement with nanometer resolution. in *29th Annual Meeting of the American Society for Precision Engineering*, Proc. ASPE Annual Meeting ASPE. 2014;

[11] William R Trutna, J., Owen, G., Ray, A. B. *et al.* Littrow interferometer. US patent number 7,440,113. 2008.

[12] Slocum, A. H. Optical Encoders. In Precision Machine Design, Chap.4.3. Prentice HallEnglewood Cliffs 1992

[13] Kunzmann, H., Pfeifer, T., and Flügge, J. Scales vs. laser interferometers performance and comparison of two measuring systems. CIRP Annals-Manufacturing Technology. 1993; 42: 753-767.

[14] Deck, L. L., de Groot, P. J., and Schroeder, M. Interferometric encoder systems. US patent number 8,300,233. 2012.

[15] Holmes, M. L., Shull, W. A., and Barkman, M. L., High-powered, stabilized heterodyne laser source for state-of-the-art multi-axis photolithography stage control. in *euspen's 15th International Conference & Exhibition*, Proc. EUSPEN. 2015; 135-136.

[16] de Groot, P., Jones matrix analysis of high-precision displacement measuring interferometers. in *Topical Meeting on Optoelectronic Distance Measurement and Applications*, Proc. ODIMAP IEEE LEOS. 1999; II: 9-14.

[17] Demarest, F. C. Cyclic error compensation in interferometric encoder systems. US patent number application 20120154780. 2012.

[18] de Groot, P., and Schroeder, M. Interferometric heterodyne optical encoder system. US patent number 20120194824. 2012.

[19] de Groot, P., and Liesener, J. Double pass interferometric encoder system. US patent number 9,025,161. 2015.

[20] Badami, V. G. Thermally stable optical sensor mount. US patent number 9,200,892. 2015.