DESIGN OF AN AM FOR EUV LITHOGRAPHY

The high absorption of extreme ultraviolet (EUV) light causes thermal deformation of the mirrors in an EUV lithography machine, which in turn distorts the wavefront. This distortion deteriorates the imaging process in lithography. An adaptive optics correction strategy for counteracting these wavefront errors with sub-nm precision is studied. To achieve this precision, an active mirror (AM) is designed and validated in an experimental set-up. A comparison is presented between modelling and experimental results, as well as a feasibility experiment for PI control of the AM.

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Thermal issues in EUV lithography

The cost of integrated circuits can be reduced by miniaturising the size of their functional features and increasing the throughput of their production line. This miniaturisation is achieved by improving the resolution of lithography machines by decreasing the wavelength to an EUV of 13.5 nm and by using image enhancement techniques such as dipole illumination [1]. The throughput is increased, amongst other means, by more powerful light sources.

Since EUV light is highly absorptive, the projection optics of EUV lithography machines have mirrors instead of lenses [2]. Nonetheless, these mirrors heat up and therefore deform. This results in a wavefront error that is greater than the 0.33 nm RMS allowed [1]. A typical mirror deformation is shown in Figure 1. Exceeding this limit of 0.33 nm critically degrades the image, which in turn can lead to defective integrative circuits.

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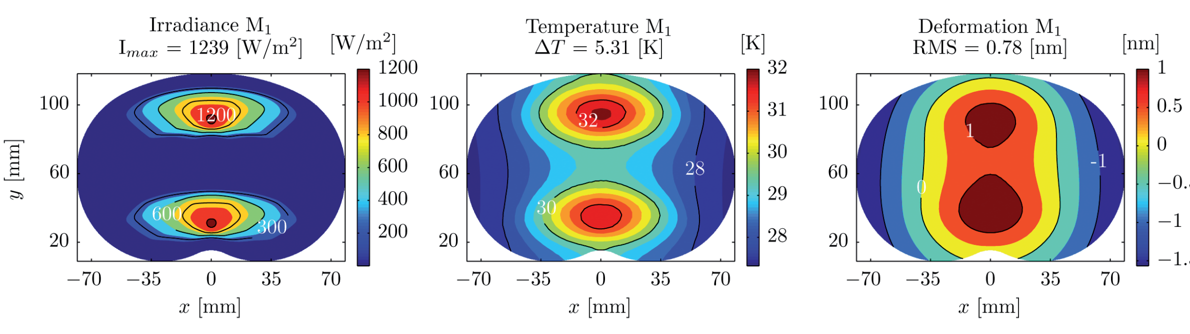
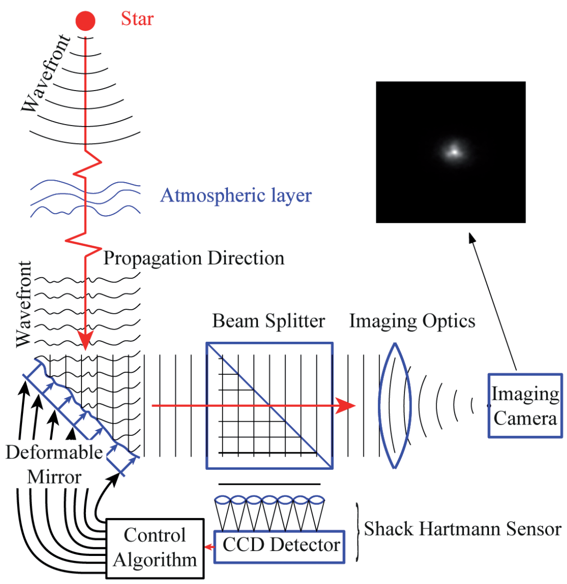
Current corrective methods

To prevent thermal aberrations, EUV lithography machines are equipped with mirrors made of low-thermal-expansion material. This material has zero thermal expansion for one specific temperature, i.e. the zero crossing temperature (ZCT), which is optimised to the lithographic process [3]. Furthermore, the mirrors have active positioning capabilities. To correct wavefront aberrations using these, the wavefront error is measured and minimised using a sensitivity matrix. This sensitivity matrix contains the



1 *Simulation results of the first mirror (M1) in the projection optical system. The simulation assumed a dipole illumination setting and a mask with horizontal dense lines and spaces.*
(a) Irradiance.
(b) Temperature profile.
(c) Deformation profile.



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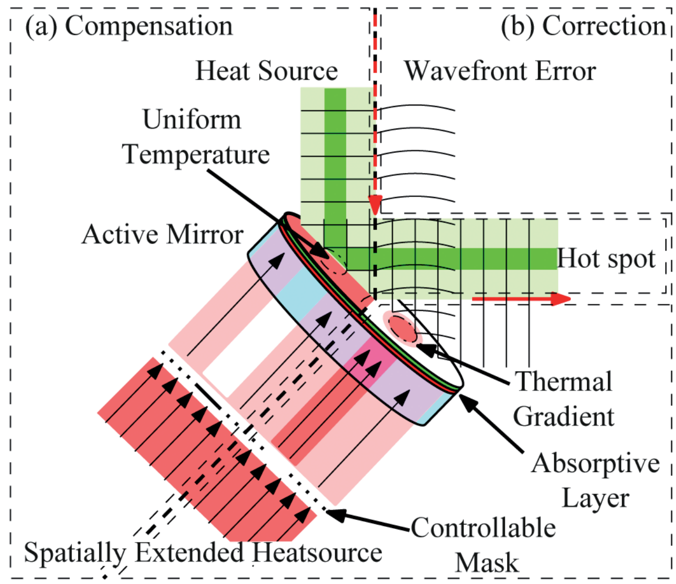

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2 *The working principle of an adaptive optics system; see text for explanation.*

3 *Active mirror design; see text for explanation.*

sensitivity between the displacement of the mirrors and the aberration coefficients, which are the amplitudes of orthogonal polynomials, which can be Zernike polynomials. As a result, the ideal placement of the mirrors can be determined [4].

Unfortunately, the variability of the imaging process does not allow the temperature of the mirrors to maintain the exact ZCT, and the computer-aided alignment procedure mainly corrects for defocus and spherical aberration, while dipole illumination for instance causes other aberrations as shown in Figure 1.

Adaptive optics system

To counteract the residual wavefront errors, an adaptive optics (AO) system is proposed. This system, which is known from its application in astronomy and microscopy [5], can be used to improve image quality as shown in Figure 2. The wavefront of light from a star is disrupted by turbulence in atmospheric layers, and corrected by the deformable mirror (DM). In order to do so, light is separated from the beam using a beam splitter and exposed to a Shack-Hartmann wavefront sensor consisting of a lenslet array and a CCD detector. The sensor signal is subjected to a control algorithm that obtains the necessary control signals for the DM. When the wavefront is properly corrected, the image on the imaging camera reveals the universe at the diffraction limit.

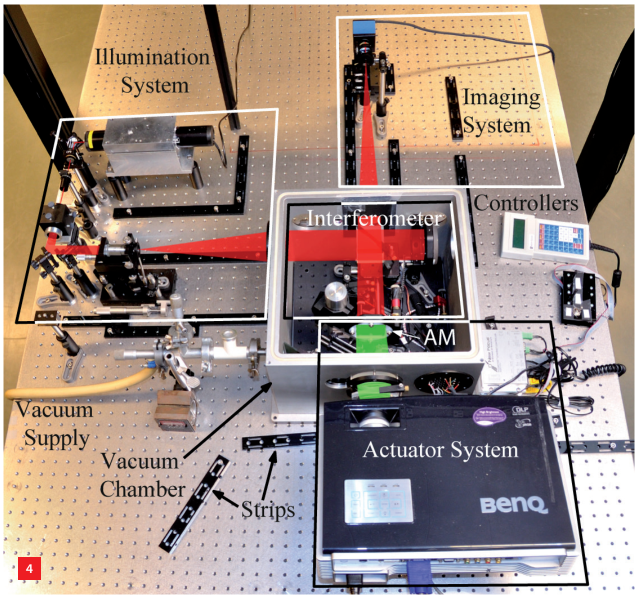
Unlike these AO systems, it is not possible to measure the wavefront in real time in an EUV lithography machine, i.e. during the illumination of wafers. It would decrease the available light for the lithographic process, which is not allowed. In addition, the required precision is 2-3 orders of magnitude better.

To anticipate these differences, an adapted compensation approach is proposed. A wavefront sensor measures the wavefront during the wafer exchange procedure, which is every 30 seconds. A control algorithm computes the actuator signal for the DM based on a real-time model predicting the thermal and deformation profile with support of the measurement signal. Instead of a conventional DM, which has a discretised actuation structure, an active mirror (AM) counteracts the predicted wavefront error. This AM needs sufficient stability to bridge the time gap between two individual measurements.

Active mirror (AM) design and realisation

This AM's design is based on the following obvious statement and is depicted in Figure 3. A mirror with a uniform temperature has no thermal gradients that are related to local mirror deformations. Hence, the temperature distribution is modified to achieve a uniform temperature to maintain an undistorted shape of the reflective surface. This is achieved by exposing this AM to a (radiative) heat source instead of using mechanical actuators.

This idea is composed of the following (see Figure 3): an absorptive layer absorbs radiation from a spatially controllable heat source. The *compensation* aspect of this actuation concept involves the exposure to an actuation profile opposite to the predicted irradiance profile, resulting in a net uniform irradiance profile. The *correction* aspect is based on the principle of thermal expansion; thermally



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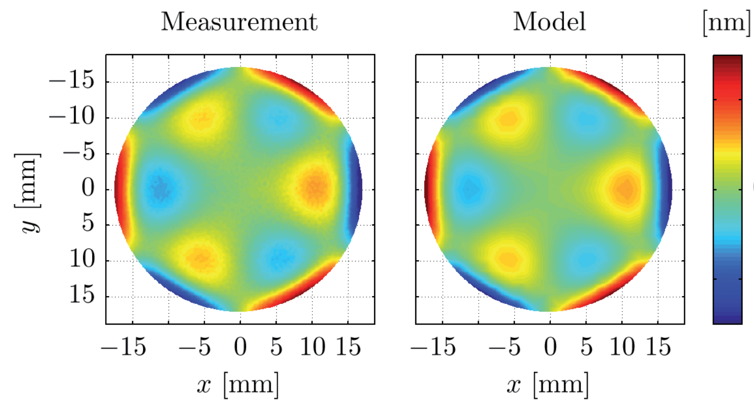

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induced deformations correct the wavefront error caused by other components in the optical system. These aspects are used simultaneously. Since this concept is significantly different compared to conventional deformable mirrors, we refer to this concept as AM.

A demonstrator AM is created by depositing an absorbing optical coating, which has an optical quality, on a mirror substrate. A normal reflective (aluminium) coating is deposited on this absorbing coating. The mirror substrate material is BK7, which is a conventional material for optics. This material also offers significantly more thermal expansion than the low-thermal-expansion materials, which makes the experimental procedure considerably easier with respect to measuring the deformation. Obviously, the difference in thermal expansion must be taken into account in the analyses of the experimental results. The spatially adjustable heat source for demonstration is provided by a commercial video projector with a relatively powerful lamp (BENQ 5000 ANSI Lumens).

Experimental set-up

Figure 4 shows the experimental set-up. The main parts are the interferometer and the illumination, the imaging and the actuator system. The photograph also shows the vacuum chamber and supply, strips for mounting the shielding against turbulence and the controllers, which are used for aligning the AM and shutters to block the reference and measurement for calibration purposes.

The set-up has to be sufficiently accurate, which is not an easy task given the required sub-nanometer precision. Instead of using a Shack-Hartmann wavefront sensor, which is the simplest choice for AO systems, a Michelson (surface) interferometer is built. Usually, surface interferometry uses a phase-stepping method, in which subsequent interferograms are recorded to extract the surface shape.
Instead, the built interferometer uses one interferogram for one measurement to facilitate the possibilities of closed-loop feedback control. This interferometer has a tilted reference mirror to create an interferogram consisting of (almost) straight interference fringes, which are demodulated using the Fourier transfer method [6], to obtain the phase difference between the reference and measurement beam.

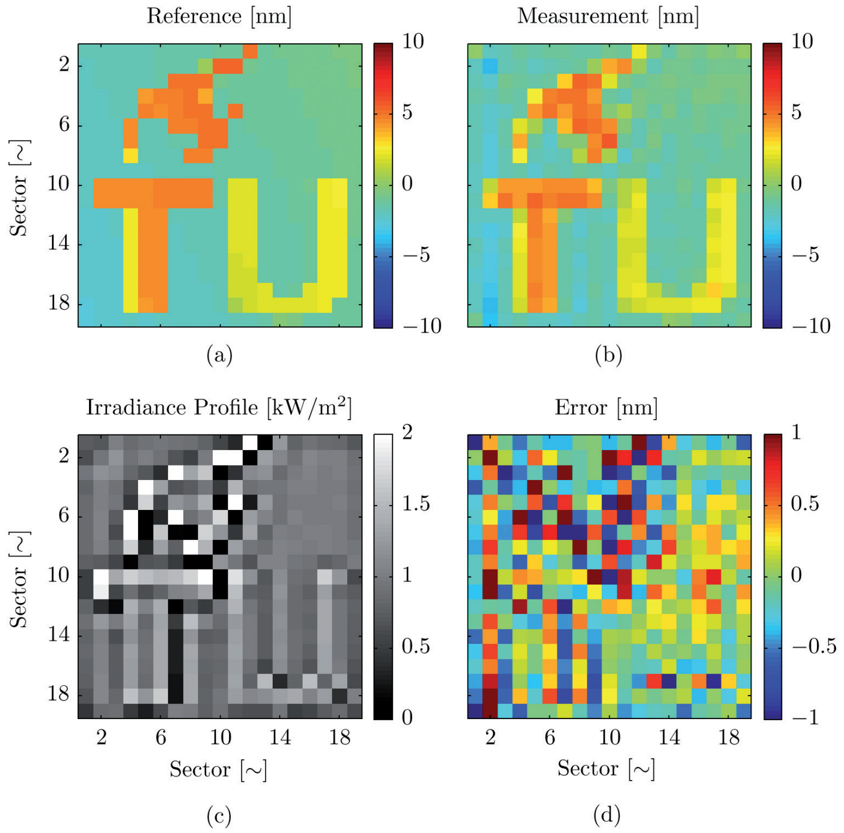
Experimental results

Our research demonstrated that this AM fulfils the requirements, even though they were 2-3 orders of magnitude more strict than conventional systems. In addition, other functional aspects were investigated and carried out, such as the active control of the AM. Here, the results of predetermined actuation profiles using active feedback control are presented.

Predetermined actuation profiles

Wavefront correction is often done by decomposing the wavefront error into orthogonal shapes. To correct the error requires knowledge of the actuation signals to create these orthogonal shapes and superimposing them according to the decomposed wavefront error. Using the FEM (finite element method) package COMSOL Multiphysics, actuation profiles are determined. The approach is an optimisation procedure with the actuation profile as the

4 *The experimental set-up; see text for explanation.*
5 *Exposure of the AM to an actuation profile.*
(a) Experimental set-up.
(b) Model; a curvature with a peak-to-valley (P-V) amplitude of 2.5 nm is subtracted.



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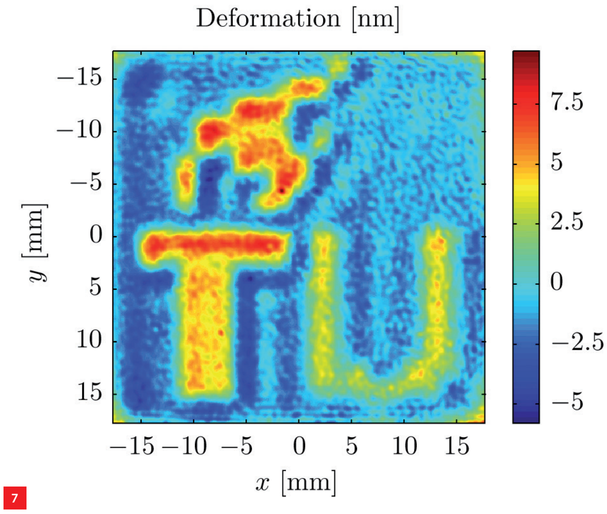

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6 *The feedback control strategy: the reference profile is a TU Delft logo; see text for explanation.*

7 *The raw measurement data, which is the (differential) mirror shape when applying feedback control, with a spatially resampled TU Delft logo as reference.*

input variable and the squared error between desired shape and obtained shape as the minimisation criterion. Using the video projector, the demonstrator AM has been exposed to these profiles. The modelling and experimental results are shown in Figure 5; these results show no significant differences.

Active mirror control

To check feasibility for control, PI feedback is applied to the AM. To this end, the AM is partitioned in 19x19 sections, which are all independently controlled with the PI feedback controller. Before the control action is applied, a reference shape is obtained that is subtracted from all successive measurement samples to remove the nominal mirror shape. The control strategy is shown in Figure 6 and consists of a TU Delft logo as a reference profile (setpoint), a measurement that is partitioned and an error map with the difference between the measurement and the reference. The control action, which is exposing the AM to an irradiance profile, is derived from the error map. This results in a (differential) mirror shape as shown in Figure 7, clearly displaying nanometer precision.

Conclusions

In EUV lithography, the absorption of EUV light could lead to thermally induced wavefront errors that degrade the image quality. This article presents the development and verification of an AM concept that can be used in EUV lithography. Experimental results show that predetermined actuation profiles result in mirror shapes that resemble the expected shape. Furthermore, the results show that feedback control can be applied to obtain mirror shapes with high spatial fidelity. Both experiments show that sub-nm precision can be achieved using an AM. ■

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