Mechatronics 39 (2016) 12–27

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Deformation control of a thermal active mirror

Rudolf Saathof[a,b,*], Martijn V. Wansink[a], Evert C. Hooijkamp[c], Jo W. Spronck[a], Robert H. Munnig Schmidt[a]

[a] TU Delft, Precision and Microsystems Engineering, Mechatronic System Design, Mekelweg 2, 2628 CD Delft, the Netherlands
[b] TU Wien, Automation & Control Institute, Gußhausstraße 27–29, 1040 Wien, Austria
[c] TU Delft, Precision and Microsystems Engineering, Structural Optimization and Mechanics, Mekelweg 2, 2628 CD Delft, the Netherlands

ARTICLE INFO

Article history:
Received 23 July 2015
Revised 10 July 2016
Accepted 12 July 2016

Keywords:
Adaptive optics
Deformable mirror
Active mirror
EUV lithography
Wavefront distortion

ABSTRACT

A demonstrator adaptive optics-system with a thermally actuated active mirror (AM) is presented to prestudy feasibility of sub-nm wavefront control in extreme ultraviolet (EUV) lithography. The AM is thermally actuated by selective heating using a spatial controllable heat source. Four different methods have been implemented to control the deformation of the AM. First thermal feedforward using estimated state feedback (ESF), second thermal feedback using proportional integral (PI) control, third their combination and fourth deformation feedback using PI control. To support ESF, a thermo-elastic finite element model is employed that describes the thermal deformation of the AM. ESF shows satisfying performance with a time constant of 10 s and a residual error of 0.7 nm. Thermal feedback shows large fluctuations of 12 nm for spherical aberrations of due to feedback of noise from the thermal camera. By applying deformation feedback the RMS-error is reduced to a satisfying 0.25 nm. This study shows that deformation control of this AM can be realised using thermal feedforward and deformation feedback to meet the requirements for EUV lithography.

1. Introduction

Extreme ultraviolet (EUV) lithography is an important step to make integrated circuits (ICs) smaller, faster and cheaper [1]. Since EUV light with a wavelength of 13.5 nm is absorbed by all materials, reflective instead of transmissive optics are used. These mirrors have special multi layer coatings with only 70% EUV reflectivity per mirror. This causes low optical transmission of the optical system, which demands increasing source power. Additionally, this absorption causes a local increase of temperature of the mirrors, which causes them to deform accordingly. Although low thermal expansion material (LTEM) is used for these mirrors, these deformations result in wavefront errors (WFEs). These deformations have time constants in the order of several minutes to one hour [2]. The fast flashing of EUV light for exposure does not play a role, as the EUV mirrors act like low pass filters for their thermal load. These errors can be partly removed by mirror position control [3,4]. Residual wavefront errors of more than $\sigma_{\max} = \lambda/20 = 0.65$ nm RMS cause image degradation like image blurring and distortion [5], for numerical apertures of 0.25.

1.1. Adaptive optics system for EUV lithography

In order to correct for these WFEs, adaptive optics (AO) is proposed, which is known from astronomy and microscopy [6,7]. AO is already suggested for argon fluoride (ArF) lithography (193 nm) to realise advanced wavefront engineering and correct thermally induced WFEs [8,9]. These references use thermal radiation to locally heat the active element, to locally change the refractive index for wavefront control. Applying AO in EUV lithography, is suggested by [10] and is explored in our previous work [2] (Fig. 1). The challenges for EUV-lithography to fulfil the requirements stated in Table 1 are the following.

First, the residual WFE should be less than $\sigma_{\max} = 0.65$ nm RMS compared to 10–50 nm RMS in conventional AO-systems [12,13]. Second, EUV mirrors are thick (50 mm) to provide stiffness during the manufacturing process. EUV mirrors should have a shape error of less than 0.1 nm RMS and surface roughness should below 1 nm [14]. Deforming thick substrates requires high actuator force. Third, in EUV-lithography the wavefront cannot be measured real-time. Conventional beam splitters will block the light and grazing incidence beam splitters [15] are not applicable. Because they would also decrease available optical power for the lithographic process, they would decrease the throughput and cost efficiency. "Wavefront sensor-less AO" [16,17] uses the projected image for wave-

---

[*] Corresponding author. Fax: +43(0)1 588 01 376 98.
E-mail address: saathof@acin.tuwien.ac.at (R. Saathof).

http://dx.doi.org/10.1016/j.mechatronics.2016.07.002

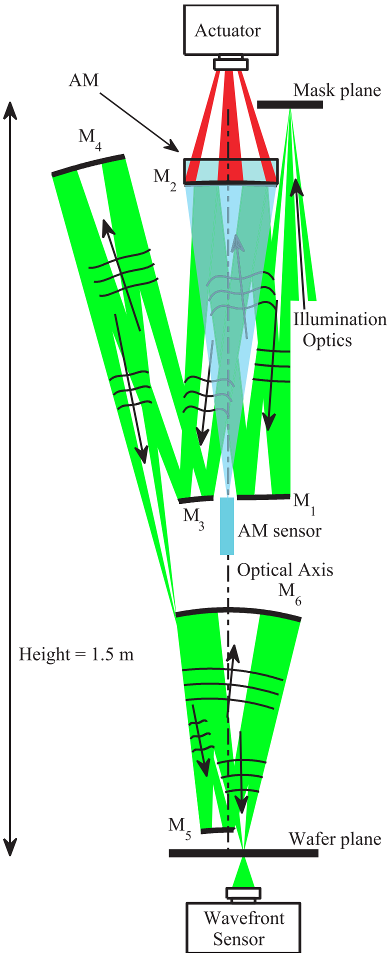

Fig. 1. Optical system for EUV-lithography [18], with the proposed AO system.

Table 1
Requirements for the AO system [11].

Requirements	Value	Unit
Maximum residual WFE σ_{max}	<0.65	nm
Feedback sampling time	30	s
Stroke, (fourth order Zernike)	7	nm
Deformation speed	>0.1	nm/min
Surface roughness	<1	nm
Mirror thickness	50	mm
Surface shape determined by optical design		
Vacuum compatibility	10	mTorr

front reconstruction, and is thus not real-time applicable. Instead, the wavefront can only be measured at the wafer exchange procedure each 30 s, for a throughput of 120 wafers per hour (wph), see Table 2.

To overcome these challenges, a strategy similar to ArF lithography [19] is proposed, which is mainly based on the deterministic character of the lithographic process.

1. Predict the irradiance profiles, deformations of the EUV mirrors and WFE at the exit pupil.
2. Carry out a computer aided alignment procedure, to minimise the WFE [3,4].
3. Derive and apply a control action to realise the correction to counteract the WFE.
4. Measure the WFE during the wafer exchange procedure.
5. Adjust the model prediction of the irradiance profiles and the WFE based on this measurement.

Sequence 1 can be done by accurate models [2,10,20], and initial measurements such as the pupil irradiance profile [21]. The pupil irradiance profile is mainly determining the spatial profile of the deformation. As it is adjusted to the mask for maximum resolution, it will change at the mask exchange procedure. The predictions should have a precision of better than $\sqrt{\sigma_{max}^2 - \sigma_{AO}^2}$, in which σ_{AO} the achievable RMS error of the AO system. For Sequence 3, the wavefront can be measured using integrated lens interferometer at scanner (ILIAS) [22,23], which uses shearing interferometry. Other references propose a Hartmann array [24] and phase retrieval [25] for wavefront measurements in EUV lithography. Sequence 2 and 3 can be executed at a relative fast rate (e.g. 1 Hz), Sequence 4 and 5 can be repeated at a maximum of the wafer exchange rate. During this wafer exchange procedure there is less than 1 sec time for wavefront measurements.

1.2. Deformable mirror technology

To support this sequence a deformable mirror (DM) is needed that fulfills the requirements stated in Table 1. Conventional DMs consist of a thin membrane actuated by push pull actuators or shearing actuators. Actuation is applied using piezo electric [26], electrostatic, Lorentz [27–29] or thermal actuators [30]. These DMs have a correction bandwidth from 100 Hz to 10 kHz, a stroke of 1 to 100 μm, an open loop precision of maximum 10 nm [12], or a feedback controlled uncertainty of 0.6 ± 0.3 nm [31]. Microelectromechanical system (MEMS) DMs [32], have a flat surface of only a few cm^2, which cannot replace an EUV mirror. In astronomy, customised secondary DMs have large, non-flat membranes [26,28,29] with insufficient precision for EUV application. X-ray adaptive optics [33,34] have grazing incidence [35], instead of required normal incidence. Due to their thin membrane, all these DMs cannot be manufactured with sufficient precision and surface finish. They also are limited in precision due to actuator print-through [36] and lack thermal stability.

DMs for synchrotrons [37] are actively cooled, and pneumatic actuation is proposed for high power lasers [38]. However, the supply of a fluid medium is undesirable, due to vacuum compatibility and transfer of vibrations, through the cooling supply to the DM. Vibration isolation is a generic difficulty, as the actuator provides stiffness between a reference frame and the deformable mirror [39]. An alternative DM for AO for EUV lithography [40] avoids this by using a floating support frame. AO for laser interferometer gravitational-wave observatorys (LIGOs) [41,42] provide sufficient accuracy using thermal actuation. These systems provide sufficient accuracy, but are applied on transparent optics and only control defocus, coma and astigmatism [41,42].

1.3. Active mirror for EUV lithography

In our previous work we introduced an AM design to circumvent these limitations [11]. This AM comprises a thermal actuation principle of selective heating to compensate and correct for the thermally induced errors [43] (Fig. 2).

The *compensation aspect* as depicted Fig. 2(a) is realised by applying an actuation profile which opposes the estimated irradiance profile (Sequence 1). To support this, the AM is preheated to reach an equilibrium point prior to the lithographic process to allow positive and negative compensation. In this fashion it generates a spatial uniform heat input by preventing thermal gradients. These gradients are related to local mirror deformations [44].