Precision Engineering 37 (2013) 353–363

Contents lists available at SciVerse ScienceDirect

Precision Engineering

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

# Deformable mirrors with thermo-mechanical actuators for extreme ultraviolet lithography: Design, realization and validation

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ARTICLE INFO

*Article history:*
Received 19 April 2012
Received in revised form 7 October 2012
Accepted 11 October 2012
Available online 23 October 2012

*Keywords:*
Adaptive optics
Optical lithography
Deformable mirrors
Mirror heating

ABSTRACT

In lithographic illumination systems, a nonuniform light distribution causes local deformations on the mirrors used. Active mirrors are a solution to correct these deformations by reshaping the surface. This paper presents the deformation of a mirror with thermo-mechanical actuators placed perpendicular to the surface. Two deformable mirrors are modeled, realized and validated: one with seven and one with 19 actuators. By placing the actuators on a thin back plate, the force loop is localized and therefore a lower actuator coupling is achieved. The thermo-mechanical actuators are free from mechanical hysteresis and therefore have a high position resolution with high reproducibility. Extensive Finite Element Analysis is done, to maximize actuator stroke and minimize input power. The mirrors are tested and validated with interferometer surface measurements and thermocouple temperature measurements. A mirror deflection of 0.68 nm/K is realized and no hysteresis is observed. Thermal step responses are fitted and both heating and cooling characteristic time constants are 2.5 s. The thermal actuator coupling from an energized actuator to its direct neighbor is 6.0%. The total actuator coupling is approximated around 10%, based on the good agreement between simulated and measured inter-actuator stroke.


## 1. Introduction

In the production of integrated circuits (e.g. computer chips), optical lithography is used to transfer a pattern onto a semiconductor substrate (wafer). For lithographic systems using light in the ultraviolet band (EUV) with a 13.5 nm wavelength, only reflective optics with multi-layers can reflect that light by means of interlayer interference, but these mirrors absorb around 30% of the incident light [1]. Depending on pattern and beam shape, there is a nonuniform light distribution over the surface of the mirrors. This causes temperature gradients and therefore local deformations, due to different thermal expansions [2–4]. To improve the throughput (wafers per hour), there is a demand to increase the source power, that will increase these deformations even further. Active mirrors are a solution to correct these deformations by reshaping the surface [5].

### 1.1. Challenges to accurately deform a mirror

This publication addresses the challenges to accurate deform a mirror with high repeatability, meeting the requirements for implementation in a lithographic illumination machine. The main design criteria are vacuum compatibility, actuator stroke and the distance between actuators.

### 1.2. Mirror requirements

The specifications for the projection mirrors are derived, based on simulations and measurements on current EUV systems. These are formulated by the semiconductor industry and form the basis for this research. Preferably, the concepts are applicable to current mirrors with little effort and only small adaptations. The desired spatial frequency, determined by the actuator spacing, is 20 mm. These actuators should deform the surface by 1 nm over 1 min, 5 nm over 1 h and 10 nm over the lifetime (7 y), with a hysteresis below 5% at full stroke. Typical desired actuator coupling is 10–15%, meaning that an adjacent actuator translates with that percentage of the energized one. In conventional deformable mirrors, this coupling results in the desired optical performance (influence function) and control performance. Since the illumination is done in vacuum, (potential) compatibility is required.

To control such mirrors, the surface deformation must be determined. This is outside the scope of this publication, but possibilities are measuring off axis at another wavelength and/or using the actuator inputs.

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0141-6359/$ – see front matter 
http://dx.doi.org/10.1016/j.precisioneng.2012.10.004

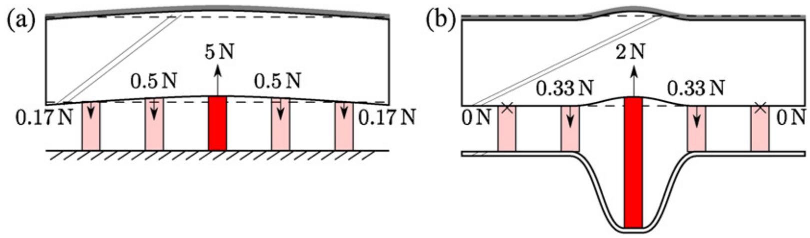


**Fig. 1.** Comparison between a mirror on (a) an infinite stiff back-structure, and (b) a flexible back-plate. Both are a schematic cross section of an FEA result, so the central actuator has 6 direct neighbors.

## 2. Actuation principle

In most conventional deformable mirrors (DMs), the actuators are placed perpendicular to the mirror surface. Mainly three different actuator technologies are used:

- micro machined electro static actuators:
  - Boston Micromachines Corporation [6], with application [7],
  - Iris AO [8],
  - Alpao [9],
  - Flexible Optical B.V. (Okotech) [10],
- stacked piezo ceramic actuators:
  - Cilas [11], with applications [12–14],
  - Xinetics [15], part of the Northrop Grumman group, with application [16],
- reluctance actuators:
  - Eindhoven University of Technology and TNO [17,18].

A thin reflective facesheet is connected to an actuator grid. This introduces out of plane forces or displacements to reshape the mirror surface. The grid is supported by a stiff back-structure, normally a few orders stiffer compared to the facesheet. Main advantages of this type of DMs compared to bending moment mirrors, is higher spatial frequency (meaning more actuators per surface area) and a symmetrical actuator influence function with more design freedom in actuator coupling.

There are some challenges when using such a conventional grid of actuators under an EUV mirror: the back-structure and the actuator stiffness. A significantly stiffer back-structure is needed to obtain the desired spatial resolution of 20 mm in combination with the desired stroke of 10 nm. Since this support structure is part of the mirror, it also needs to be isolated from its surroundings, and therefore is undesirably a substantial part of the (in this case: magnetically levitated) mirror mass. The limitations of the actuator stiffness are described below, with an example.

Assume an infinitely stiff back-structure and an $h_M = 20$ mm thick fused silica mirror. In conventional DMs the mechanical actuator coupling is around 10%, meaning that adjacent actuators displace with 0.1 times the displacement of an energized actuator (for discussion see Section 3.2). This requires in this case an actuator stiffness above $5 \times 10^9$ N/m, using the analytical mirror model described in Section 3.1. Theoretically, a piezo actuator with that stiffness is 16 mm in diameter and has a length of 1 mm. (Young's modulus is 27 GPa, based on the power actuator product range of PI [19].) This actuator stiffness is the result of the flexural rigidity of the mirror in combination with the actuator pitch (20 mm).

Using aluminum actuators with a diameter of $D_A \approx 3$ mm and length $l_A \approx 10$ mm (with a stiffness in the order of $2 \times 10^7$ N/m), results in a surface deformation given in Fig. 1(a). This figure is a cross section of a 3D Finite Element Analysis (FEA), where the central actuator in a hexagonal grid has 6 direct neighbors. Equilibrium of the vertical forces is given by $5\,\text{N} \approx 6 \times 0.5\,\text{N} + 12 \times 0.17\,\text{N}$. A high actuator coupling is observed: neighbors displace with 0.6 times the displacement of the central actuator, using zero displacement at the outer actuators as boundary condition.

By using the same actuators on a more flexible back-structure compared to the mirror, the force loop is limited to the neighboring actuators. This result in a local influence of a single actuator as shown in Fig. 1(b). Equilibrium of the vertical forces is given by $2\,\text{N} \approx 6 \times 0.33\,\text{N}$. A drawback of this geometry is the large displacement of the back-structure. So, only a percentage of the actuator displacement is used for deforming the mirror surface. On the other hand, this can be used to measure the surface deformation with a lower accuracy on the back-structure, and obtain the mirror surface by a conversion.

Patent number US5986795 [20] claims almost the same features including a flexible back-structure and axial actuators. This back-structure can have a constant thickness or a variable thickness, matching the stiffness of the reflecting mirror. Also the correction of EUV light for lithographic purposes is claimed. However, it is decided to continue research on the feasibility and applicability, manly due to the age of this patent (it is filed on June 15, 1998).

## 3. Analytical mirror model

In this section an analytical thin plate model [21] is derived to support the design process. Also some design considerations are explained for choosing the ratio between mirror and back-plate thickness [22] and choosing the actuator dimensions [23].

### 3.1. Thickness balance between mirror and back-plate

To analyze the relation between actuator stiffness and out of plane stiffness of a plate, an analytical plate model is derived, based on [24].

Assume a facesheet (with thickness $h$) placed on discrete actuators with a given pitch $p_A$ and stiffness $c_A$, see Fig. 2(a). Each actuator covers a given plate area $A$, as shown for a hexagonal configuration in Fig. 2(b). The plate theory assumes isotropic material, a constant thickness and small out of plane displacements ($<0.5h$) based on flexural deformation.

The deflection $\delta(r, \phi)$ of a plate on an elastic foundation with load $F$, is described by the biharmonic plate equation [21, p. 260]:

$$\nabla^4 \delta(r,\phi) = \frac{F(r,\phi) - \kappa\delta(r,\phi)}{\mathcal{D}}. \tag{1}$$

Using the biharmonic operator ($\nabla^4 = \nabla^2 \nabla^2$, the Laplacian $\nabla^2$ squared) in polar coordinates and using axial symmetry ($\delta(r, \phi) = \delta(r)$) with a central load $F(r = 0)$, the above equation becomes

$$\left(\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr}\right)\left(\frac{d^2\delta}{dr^2} + \frac{1}{r}\frac{d\delta}{dr}\right) = \frac{F(r) - \kappa\delta(r)}{\mathcal{D}}. \tag{2}$$

The flexural rigidity of the plate is given by

$$\mathcal{D} = \frac{Eh^3}{12(1-\nu^2)}, \tag{3}$$