Experimental validation of a piezoelectrically driven photomask curvature manipulator

C.L. Valentin[1,2], J.P.M. Vermeulen[2], B.C.T. van Bree[3], R.H. Munnig Schmidt[1].
[1]*Delft University of Technology, Faculty 3mE, Department of PME, Delft, NL.*
[2]*ASML BV, Research Mechatronics, Veldhoven, NL.*
[3]*Janssen Precision Engineering BV, Maastricht, NL.*
c.l.valentin@tudelft.nl

Abstract

Photolithography is the critical step in realizing a smaller feature size of Integrated Circuits (IC). Manufacturing beyond the 30 [nm] node requires tighter focus budgets in ArF immersion lithography systems [1]. Wafer non-flatness and lens heating are main focus-budget contributors [2, 3]. Their contribution can be reduced by exposing the wafer with a curved instead of the conventional flat focal plane (Figure 1). This effect is achieved by manipulating the photomask curvature during the exposure process. A piezoelectric actuation system has been developed for this purpose which can control the photomask curvature [4]. This paper revisits the actuation principle and presents the experimental validation of the concept in a functional model.

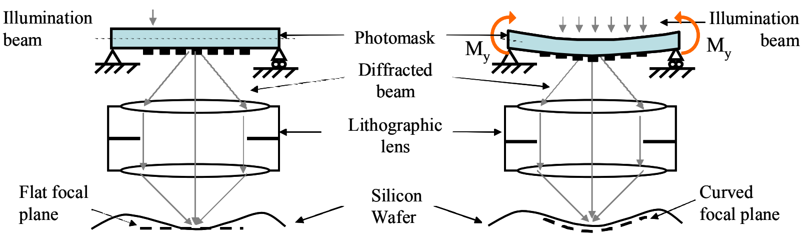

Figure 1: Focus strategy in lithography systems. Left: the conventional strategy fitting a flat focal plane through wafer topology data. Right: the strategy using a curved focal plane.

1 Design considerations and specifications

The photomask curvature manipulator was designed based on the following design considerations and specifications. It was first proven that the photomask can be approximated by a square glass plate with a direct relation between its curvature and applied external bending moment. Investigations showed that curvature amplitudes of 0.4 x 10^{-3} [m^{-1}] are required whilst a curvature tracking accuracy of 2.4 x 10^{-6} [m^{-1}] is desired up to a frequency of 100 [Hz]. Additional analysis proved that the induced pattern distortion by bending corresponds to a pure pattern magnification error which can be corrected by the lithographic lens. Finally, stress-birefringence levels in the photomask stay below the lithography limit of 5 [nm·cm^{-1}].

2 Mechatronic design of the manipulator

The desired bending moment is applied to the photomask using two arrays of seven bending actuators at each side of the photomask. This is shown in Figure 2. Each single actuator consists of an intermediate body that is attached to the optical element through vacuum preloaded interface rods. The piezoelectric actuator with serial compliance and horizontal leaf spring located between the intermediate body and surroundings create a local force loop. It generates a bending moment on the intermediate body during expansion or contraction of the piezoelectric actuator.

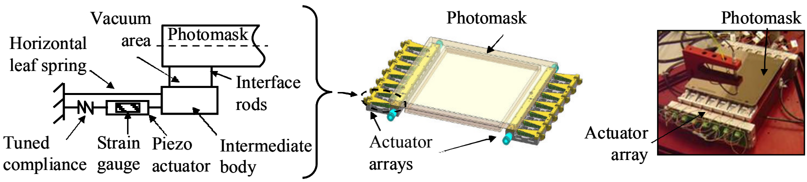

Figure 2: The curvature manipulator design. Left: a schematic representation of a single bending actuator. Centre and right: The design and realized hardware of the functional model.

Each piezoelectric actuator is equipped with a strain gauge for local feedback control to counteract disturbances as well as piezoelectric hysteresis and creep. The control architecture is provided in Figure 3. System identification confirmed the possibility to implement local SISO feedback loops because of little interaction between the loops (50dB gain difference). Each feedback controller consisted of a PID action, a low-pass and two notch filters. The loop gain is provided in Figure 3. A bandwidth of 100 [Hz] was achieved with sufficient phase margin.

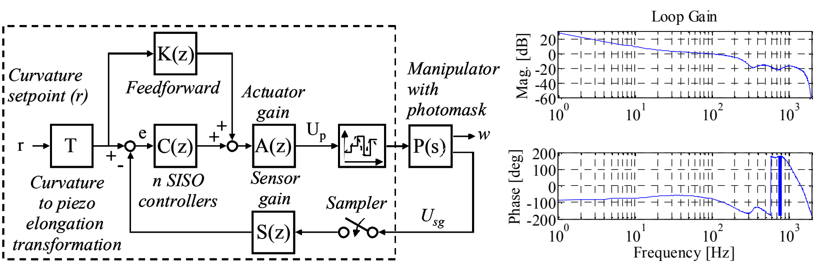

Figure 3: Implemented control strategy and open loop response of the curvature manipulator.

3 Experimental validation

The experimental validation of the curvature manipulator was performed by placing it in the measurement setup of Figure 4. The setup consists of a stage with two capacitive sensors (w_1, w_2) which measure the distance between the optical element and the Zerodur® reference plane. The photomask deflection is obtained by subtracting the measurement data of the unloaded from the loaded configuration. The total surface deflection is obtained by repeating the measurement at a number of locations and stitching the data.

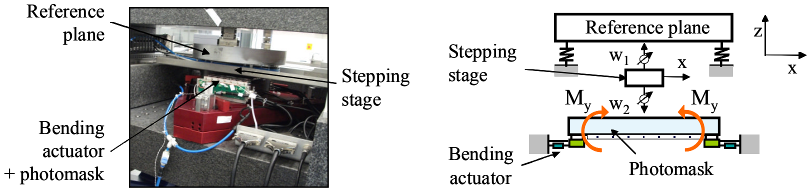

Figure 4: The measurement setup used for the validation. Left: the hardware in the lab. Right: A schematic representation of the setup where M_y is the applied bending moment.

Figure 5 shows the results of static photomask deflection measurements using eight repetitions. The average shape corresponds to the expected anticlastic shape when applying a bending moment along the two opposite edges of the photomask. Measurement repeatability is below 6 [nm] whilst the actuator behaves linearly across its range. The repeatability is largely limited by the noise of the measurement setup. The relation between the applied voltage and the photomask curvature was measured which showed to have a nice linear relation. The measurements also highlighted that the maximum achievable curvature is a factor four off the desired curvature value.

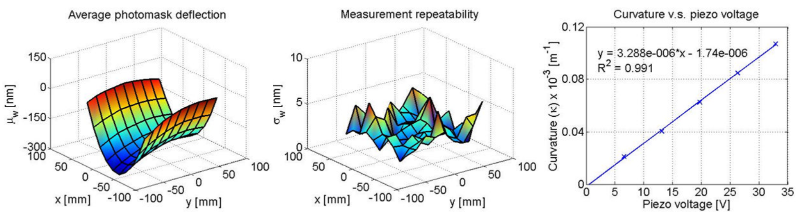

Figure 5: Results of the static deflection measurements using eight repetitions. Left and centre: The average deflection and the standard deviation. Right: The derived photomask curvature as a function of applied voltage.

Figure 6 provides measurement results for the dynamic curvature tracking performance of the system. It shows that it is able to follow the general trend of the curvature setpoint. The tracking error is approximately a factor 2.5 off the desired error bound however. Improvements in the feedforward and feedback path are currently under investigation to achieve the desired curvature tracking accuracy.

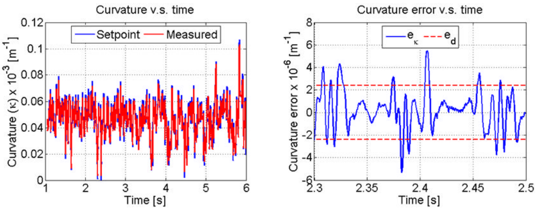

Figure 6: Measurement results of the dynamic curvature tracking with, left, the setpoint and measured curvature in time, and right, the achieved (e_κ) and desired (e_d) tracking error.

4 Conclusions and future work

This paper presented the experimental validation of a piezoelectrically driven photomask curvature manipulator for lithography systems in closed loop control. The results have shown that the desired curvature shapes are achieved and that the actuator behaves linearly across its range. Future work will focus on improving the dynamic curvature tracking performance of the curvature actuator.

5 Acknowledgements

The authors would like to thank ASML for their financial and technical support.

References:

[1] International Technology Roadmap for Semiconductors, *2010 ITRS Lithography Update*, www.itrs.net, 2010.

[2] C. Huang, *Bare wafer metrology challenges in microlithography at 45 nm and beyond*, In proceedings of SPIE, Volume 6827, 2007.

[3] M. Yasuda, *Stability and calibration of overlay and focus control for a double patterning immersion scanner*, Optical Microlithography XXIV, Proc. of SPIE, Vol. 7973, 2011.

[4] C.L. Valentin, J.B. van Wuijckhuijse, J.P.M. Vermeulen, B.C.T. van Bree, D.J. Rixen and R.H. Munnig Schmidt, *Prototype development of an optical element curvature manipulator with controlled piezoelectric actuator*, EUSPEN Conference, Como, 2011.