Thermal control challenges in ASML wafer scanners

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Background 1st author Marc van de Wal

- MSc (1993) & PhD (1998) at TU/e, Mechanical Engineering

- 1998—2009: Philips Innovation Services:
  - 90% work for ASML:
    - Motion control research in co-operation with TUD & TU/e
    - First EUV machine for ASML: from research & development to shipment & servicing

- 2009—2021: ASML Research dept., Mechatronics & Control group:
  - 2009—2015: Advanced motion control
  - 2016—2021: Advanced thermal control

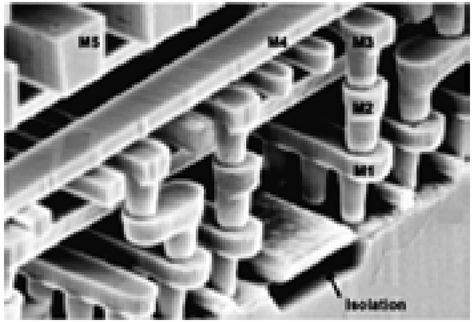
    ⇒ Topic today, with emphasis on recent academic co-operations.

The reason for ASML's thermal control challenges

Intro ASML & Thermal control challenges

Lithography as part of IC production process

- ASML scanners for microchip production.
- Principle: project DUV or EUV* light through a reticle (=mask), via a system of lenses (DUV) or mirrors (EUV), to expose a 2D image on a wafer (lithography).
    - *EUV machines trigger the main thermal control challenges for ASML. ⇒ Focus here.
- 3D structures are created by exposing multiple layers:



DUV=Deep Ultra-Violet; EUV=Extreme Ultra-Violet; IC=Integrated Circuit

Intro ASML & Thermal control challenges

The EUV wafer scanner in action (movie)

Intro ASML & Thermal control challenges

Thermal effects & main technical challenges

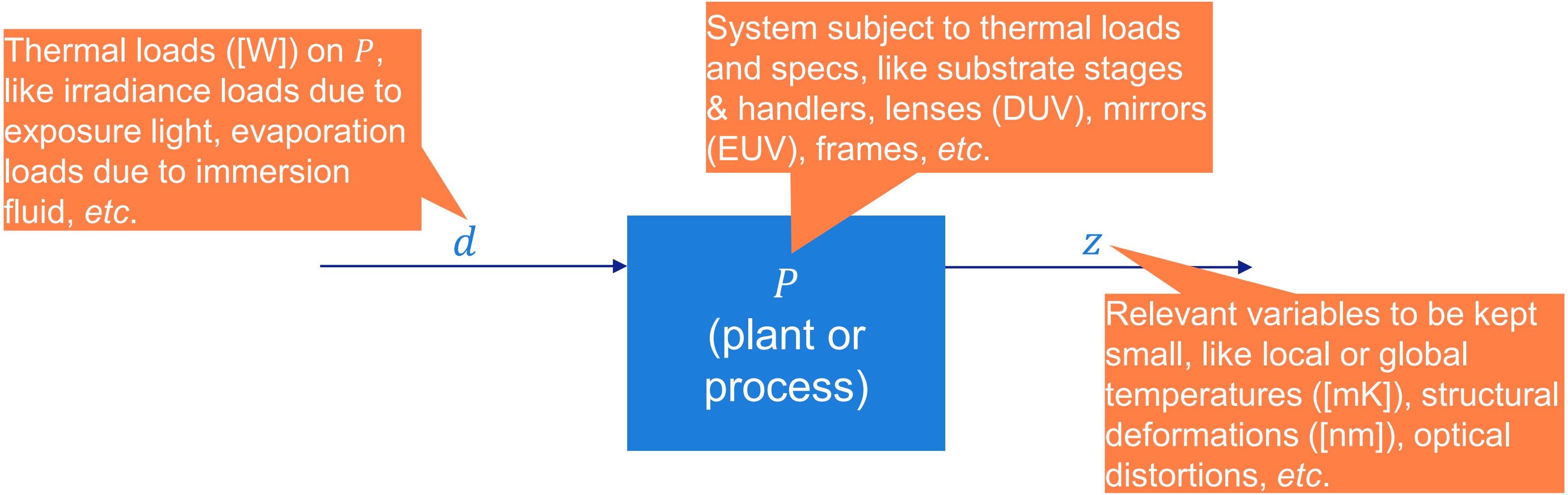
- **Thermal loads cause thermal gradients, causing structural deformations and distortions in the optical path.**
- Overlay error of future machines: <1 [nm], *i.e.*, <1e-9 [m] accuracy specs.
- To meet future demands, ASML needs:
  - mK-level temperature conditioning
  - sub-nm thermal deformations
- This imposes challenges on:
  - Thermal hardware design
  - Thermal measuring & actuation
  - Thermal modeling
  - Thermal controller design

"Thermal control"

High-level abstract view on thermal control at ASML

Abstract view on thermal control

Passive thermal control



Thermal loads ([W]) on P, like irradiance loads due to exposure light, evaporation loads due to immersion fluid, *etc*.

System subject to thermal loads and specs, like substrate stages & handlers, lenses (DUV), mirrors (EUV), frames, *etc*.

Relevant variables to be kept small, like local or global temperatures ([mK]), structural deformations ([nm]), optical distortions, *etc*.

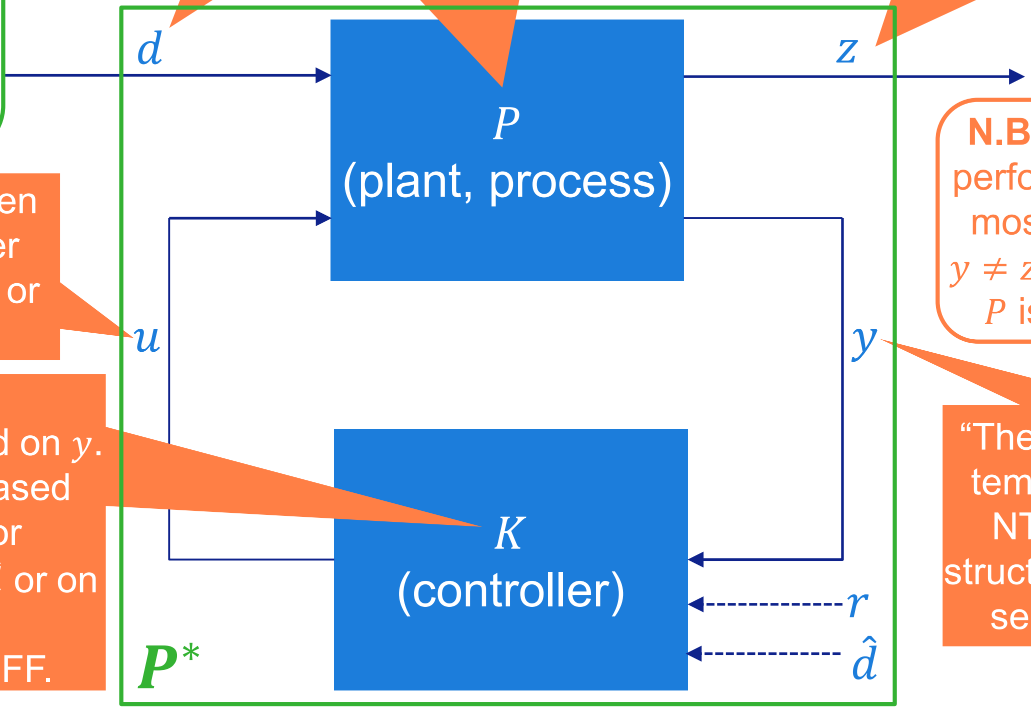
Passive thermal control: keep effect of thermal loads d on performance variables z small, by proper thermal design of hardware in P (materials, shape/geometry, heat sinks, *etc*.) and minimizing the thermal loads d:

- Passive thermal control still very important at ASML, but *not sufficient* anymore.
- Also “**active thermal control**” and “**error correction**” needed. ⇒ Next slides.

Abstract view on thermal control

Active thermal control

Active thermal control: keeping effect of d on z small by proper *closed-loop* control system design K.



Thermal loads

System subject to thermal loads and specs

Relevant performance variables to be kept small

N.B.: Directly measuring performance variables z is mostly not possible, *i.e.*, $y \neq z$. $\Rightarrow$ Often a **model** of P is required to infer z.

"Thermal actuators", often heaters, but also Peltier elements (= TEM's [W]) or piezo actuators.

"Thermal sensors", mostly temperature sensors like NTC's ([mK]), but also structural sensors like strain sensors ([pico-strain]).

Controller:

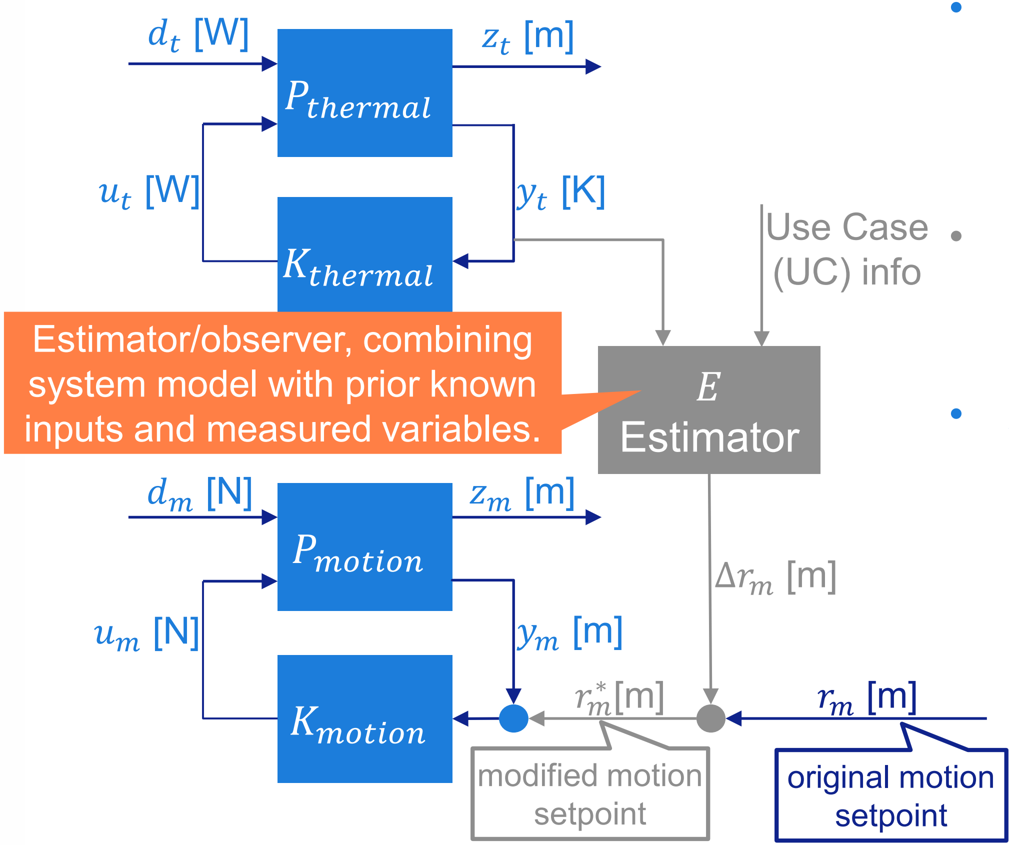
- FeedBack (FB) based on y.
- FeedForward (FF), based on measurable or prior known part of loads $\hat{d}$ or on setpoints r.
- Combination of FB & FF.

NTC=Negative Temperature Coefficient; TEM=Thermo-Electrical Module

Abstract view on thermal control

Error correction

Error correction: keeping effect of d_t on z_t small by proper *estimator* design.

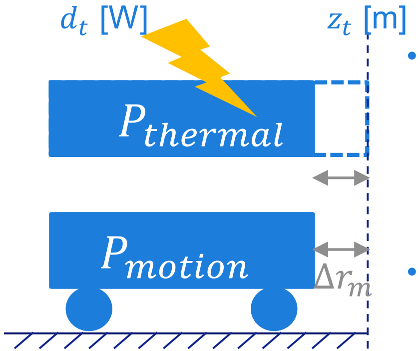


Estimator/observer, combining system model with prior known inputs and measured variables.

modified motion setpoint

original motion setpoint

- **Error correction** combines the slow ([hours]) & relatively ineffective thermal control domain with the fast ([seconds]) & highly effective motion control domain.
- Principle: Thermal-induced structural deformations are *estimated* and corrected in motion control setpoints.
- Artist impression:



- Thermal load causing thermal expansion and point-of-interest z_t at different location.
- ⇒Addressed by setpoint modification in motion system.

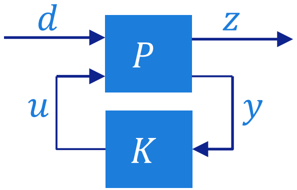
Abstract view on thermal control

Overview of main thermal control challenges for ASML

Passive thermal control:

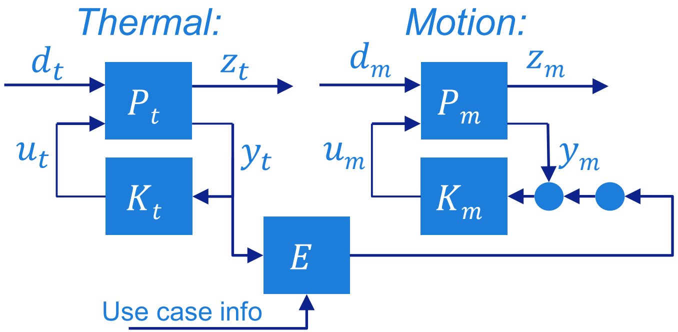
- d: Physical & experimental **disturbance** modeling, *e.g.*, radiation, time-varying disturbances.
- z: Systematic error budgeting: quantification of effect of individual disturbances in d on performance in z.
- P: Structural design, *e.g.*, multi-physical topology optimization, heatsink design, advanced materials.

Active thermal control:



- P: Physical & experimental **plant** modeling, *e.g.*, high-order dynamics, order reduction, multi-physics, nonlinearities.
- y: Sensor development, *e.g.*, contactless temperature.
- u: Actuator development: fast, high-power, 2-sided actuation (joint heating & cooling), reliable.
- y & u: Optimal sensor & actuator configuration/layout design.
- K: Control design: optimal, multivariable, constrained, FB/FF.

Error correction:



- E: State & parameter estimator (observer) design: accurate modeling of P_t is prerequisite (multi-physical, high-order, nonlinearities).

Selected thermal control advancements in some PhD projects 2016—2021

Advanced Thermal Control consortium (ATC)

2016—2021

- Industrially driven consortium on thermal control challenges:
- Industry partners:

ASML
PHILIPS Innovation Services
ThermoFisher SCIENTIFIC
SIOUX LIME
IBS Precision Engineering
SEGULA TECHNOLOGIES
VDL VDL Enabling Technologies Group

- University partners:

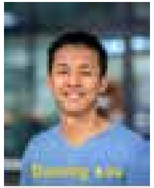
TU Delft Delft University of Technology
TU/e Technische Universiteit Eindhoven University of Technology

- Continuation ATC being discussed

Three PhD projects:

1) Thermal design & **topology optimization** (TUD; Max van der Kolk)

2) Model reduction for complex systems (TU/e; Daming Lou)



3) Advanced **identification** & control (TU/e; Enzo Evers)

ATC PhD 1: Thermal design & topology optimization

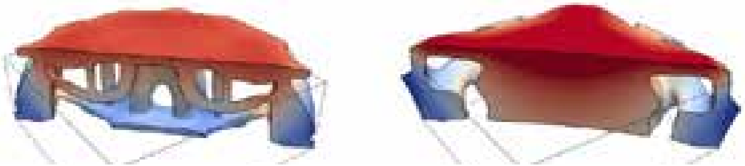
- **Topology Optimization (TopOpt)**: Optimize the material distribution in a given design domain for given loads and boundary conditions.
- Key ingredients TopOpt:
  - Objective function
  - Constraints
  - Parametric (FEM) models

$$\min_{x} f(x)$$
subject to:
$$g(x) \leq 0, h(x) = 0$$
$$x \in X \subseteq \mathbb{R}^n, (\underline{x} \leq x \leq \overline{x})$$

- **PhD project**: Improve opto/fluid/thermo/mechanical (*i.e.*, multi-physics) transient (i.s.o. steady-state) performance, by improving 3D (i.s.o. 2D) geometry, placement of cooling channels, and properties & usage of materials.
- **Remaining TopOpt challenges:** manufacturability, computational feasibility, multi-physics, nonlinearities, meta-/multi-materials, multi-component (*e.g.*, in optical path), multi-disciplinary (*e.g.*, joint optimization of hardware P and controller K in *active* thermal control).

Example: wafer-stage-like structure (bottom view) obtained with TopOpt & Additive Manufacturing (AM) in IMSYS3D project (link).

Example: opto-mechanical 3D TopOpt for optical mirror mount, for steady-state *vs*. transient performance objectives:



1) Steady-state

2) Transient

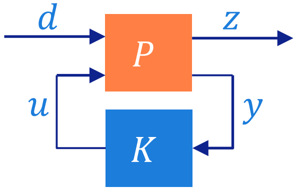
⇒ Clearly different structures for different performance objectives

FEM=Finite-Element Method; IMSYS3D=Integrated 3D Motion System Synthesis

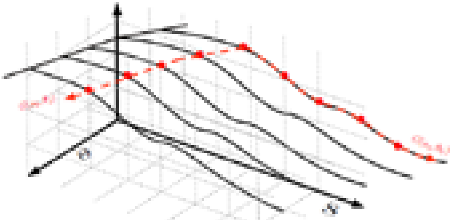
ATC PhD 2: Model reduction for complex systems

- **parametric Model Order Reduction (pMOR)**: Reduce dimension of *state* vector x and/or physical *parameter* vector θ of plant model P, while maintaining the essence (*e.g.*, input-output behavior) of the model and the physical interpretation of the parameters. Important for:
  - **Thermal design**: Fast iteration on system parameters (*e.g.*, material properties), when designing new system.
  - **Thermal modeling**: Data-based calibration of parameter values (identification), *i.e.*, "model updating" to better match the hardware.
  - **Thermal controller design**: Feasibility of optimal model-based estimator and/or controller design $\min_K ||M(P,K)||$.
- **PhD project**: Enable practical pMOR for large-scale industrial models ($n_x \approx 10^6$, $n_\theta \approx 100$) in Matlab.
- **Remaining pMOR challenges**: Computational feasibility for even larger systems ("digital twins"), nonlinearities, more general classes of parametric entries in system matrices of P.

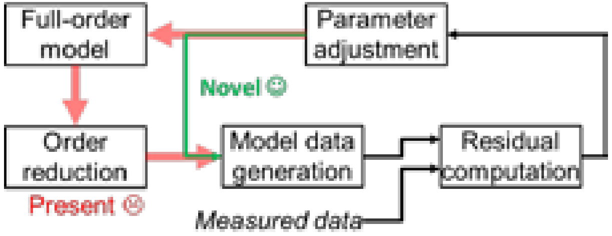
$$P\begin{cases} E(\theta)\dot{x} = A(\theta)x + B(\theta)\begin{bmatrix} d \\ u \end{bmatrix} \\ \begin{bmatrix} z \\ y \end{bmatrix} = C(\theta)x + D(\theta)\begin{bmatrix} d \\ u \end{bmatrix} \end{cases}$$



PhD project: pMOR method based on multi-frequency (S) and multi-parameter (θ) "moment matching."



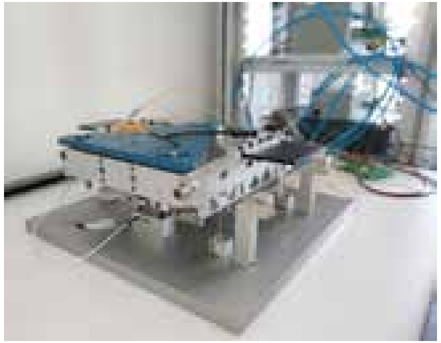
Application of pMOR: avoid time-consuming iterative numerical order reduction in parameter calibration:



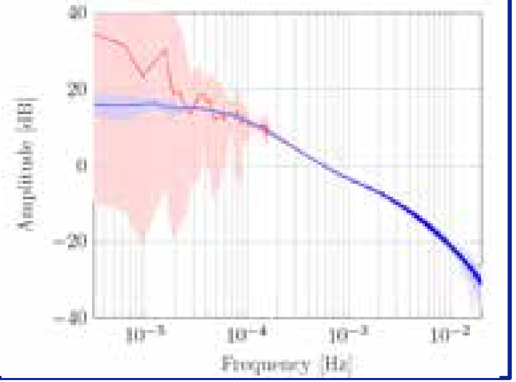
ATC PhD 3: Advanced identification (& control)

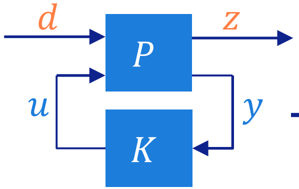
- **Advanced identification**: Develop fast & accurate tools for experimental modeling (identification) of thermo-mechanical dynamics of existing hardware, for high-quality dynamic analysis and model-based controller & estimator design.
- **PhD project**: Handle transient (i.s.o. stationary) data (reducing machine time) & environmental disturbances, Frequency Response Function (FRF) identification (i.s.o. time response, for improved dynamic accuracy), FRF-based parameter calibration & FRF fitting tools to obtain parametric models for Multi-Input Multi-Output (MIMO) systems.
- **Remaining identification challenges**: Exploiting mixture of different data types/sources (*e.g.*, strain & temperature in y), optimal identification experiment design, parameter calibration for partly inaccessible inputs d & outputs z.

Clarification:
Identification is accurate modeling (“black/grey-box”) of existing hardware, different from, *e.g.*, FEM modeling in design phase.



Example: Initial and improved FRF by accounting for environmental disturbances





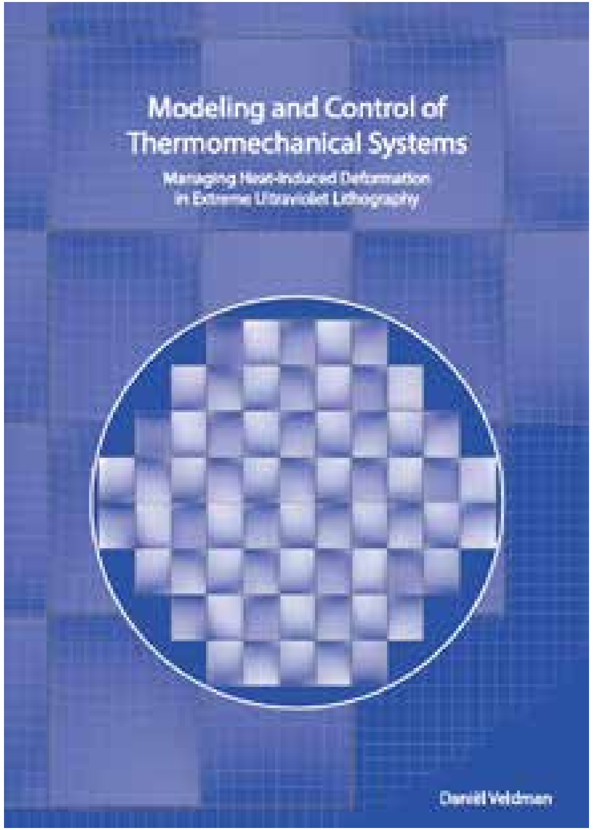
PhD project Daniel Veldman

2016—2020

- PhD project financed by ASML.
- Performed at TU/e, Dynamics & Control group.
- Supervision: Henk Nijmeijer, Hans Zwart, Rob Fey.

Daniel Veldman

- **Topics**:
  - Modeling of moving heat source problems (*e.g.*, exposure light on reticle and wafer)
  - Optimal distributed actuator layout design for feedforward control
  - Discrete actuator & sensor placement for feedback control

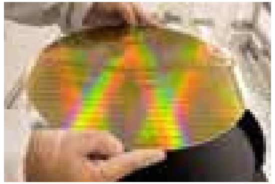


Modeling and Control of
Thermomechanical Systems
Managing Heat-Induced Deformation
in Extreme Ultraviolet Lithography

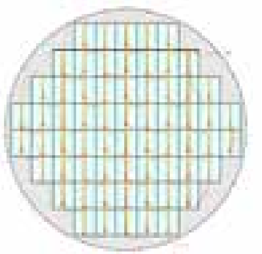
Daniël Veldman

Modeling of moving heat source problem

Silicon wafer, ∅=300 [mm]:



Sequential exposure of the fields (IC's) on the wafer ("meandering"):



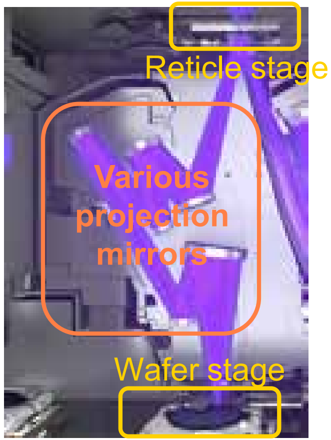
Time-varying wafer temperature due to moving exposure light:

Heat induced by EUV light → Temperature increase → Thermal expansion → Malfunctioning chips

- **PhD project**: Develop effective & efficient methods for the modeling and simulation of thermo-elastic dynamics, due to time-varying fast moving heat loads on substrates, for subsequent analysis and design, *e.g.*, of Error Correction (EC) methods (estimators).
- **Remaining challenges**: Modeling realistic systems with complex geometries, nonlinearities (*e.g.*, material properties, surface tribology), modeling uncertainties in heat loads, integrating model order reduction methods.

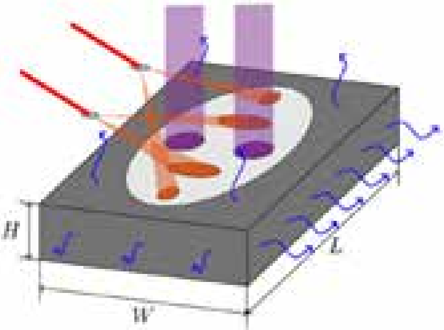
Optimal distributed actuator layout design

- **PhD project**: Develop a method to design optimal actuation profiles and actuation signals u, for a given set of irradiance shapes, mirror characteristics, and actuation constraints, where "optimal" is in terms of a steady-state temperature objective.
- **Remaining challenges**: Optimizing for transient performance, designing for minimal deformation & wavefront errors, addressing multiple mirrors (i.s.o. single mirror), addressing robustness against uncertainty in irradiance shapes.



EUV light causes mirror heating & deformation, counteracted by thermal actuator profiles.

<u>Problem</u>: Huge variety of irradiance shapes $B_d \Rightarrow$ **How to design actuation profile(s) B_u and actuation signal(s) u?**

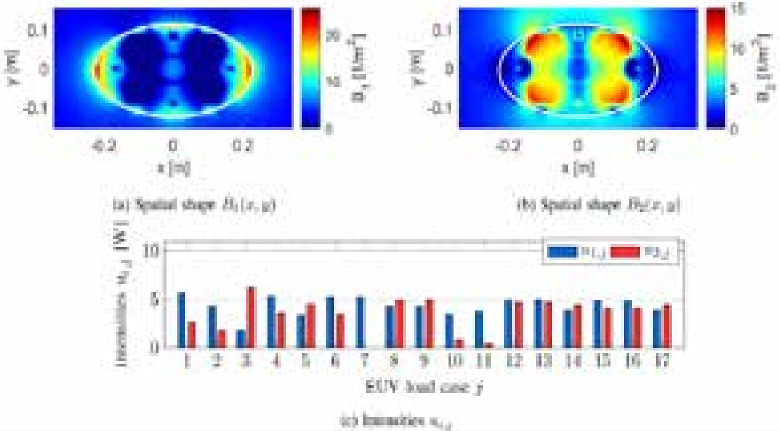


$$\dot{x} = Ax + B_d(x,y)d + B_u(x,y)u$$

Optimal design for 17 irradiance shapes in B_d and 2 thermal actuators in B_u.

<u>Top</u>: actuation profiles $B_{u_{1,2}}$.

<u>Bottom</u>: actuation intensities $u_{1,2}$



(a) Spatial shape $B_1(x,y)$

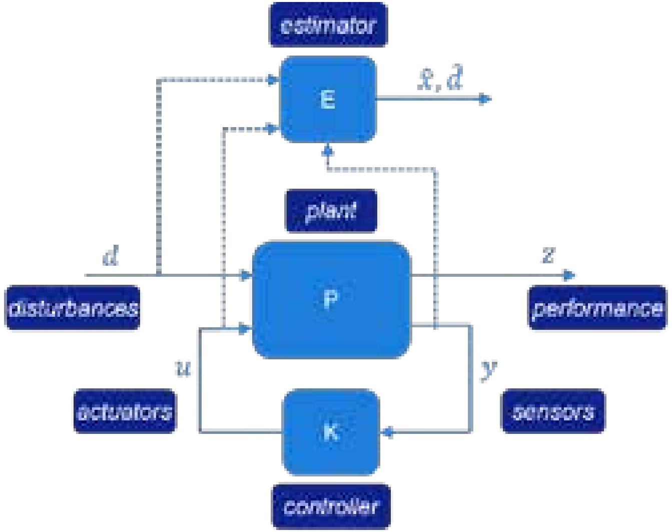
(b) Spatial shape $B_2(x,y)$

(c) Intensities $u_{i,j}$

Summary

Summary

- Counteracting thermal effects in ASML wafer scanners increasingly important to meet <1 [nm] overlay specs.
- In particular crucial for EUV machines, mainly due to the EUV exposure light itself, causing heating & deformation of the reticle, projection mirrors, and wafer.
- Numerous challenges on “thermal control” in a broad sense, developed internally at ASML *plus* in co-operation with academia:
  - Thermal hardware design
  - Thermal measuring & actuation
  - Thermal modeling
  - Thermal controller design



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