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Finite element and semi-analytic modeling of the temperature field of a wafer with moving heat loads

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1 Introduction and problem statement

In ASML's lithography scanners, a pattern is projected on a silicon wafer with the precision of a few nanometers. The light used to project the image causes the wafer to heat up and expand, which leads to a degraded image quality. Therefore, methods to model and control the thermal expansion of the wafer must be developed. In this work, we focus on the computation of the temperature field $T(x,y,t)$, which is the first step in the computation of the induced deformation.

The wafer is modeled as a circular plate which is connected to a heat sink at the bottom. This leads to the following PDE

$$\rho c \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} - \frac{1}{R_t}T + Q \qquad (1)$$

where ρ, c, and k are the mass density, heat capacity, and thermal conductivity of the wafer, respectively, R_t is the thermal resistance to the heat sink, and Q is the heat load. Figure 1 shows the heat load that moves with high velocity v in a straight line over a rectangular area, called a field. After the scanning of one field is completed, the heat load moves in the oppositie direction over the next field, which results in a meandering path. About 100 fields fit on one wafer. We consider (1) with perfectly insulated boundary conditions.

To avoid spurious oscilations in the solutions of a finite element model of (1), the element size should not exceed [1]

$$L_{e,max} = \frac{2k}{\rho c v}. \qquad (2)$$

This makes solving (1) for high velocities v time consuming. We therefore propose a more efficient method to compute T.

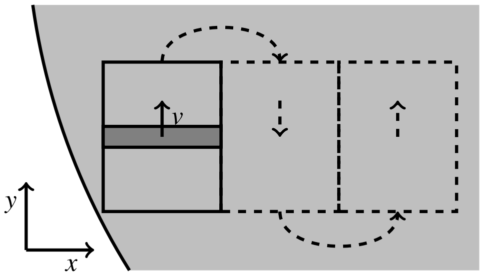

Figure 1: A part of the circular wafer (light grey) with the moving heat load (dark grey) following a meandering path

2 More efficient FE and semi-analytic modeling

The proposed method consists of three steps:

1a. Solve (1) using FE for the exposure of one field on the infinite domain $(x,y) \in \mathbb{R}^2$
1b. Alternatively, a semi-analytic approximation can be used. Now only one PDE similar to (1) in one spatial dimension is solved.
2. Shift the solution obtained in step 1. in space and time and make use of superposition to obtain the temperature field resulting from the complete path of the heat load on $(x,y) \in \mathbb{R}^2$.
3. Convert the solution from step 2. on $(x,y) \in \mathbb{R}^2$ to the solution on the considered circular domain using a reflection argument.

The proposed method provides a significant reduction in the computational effort. A FE model which uses the element size in (2) for the whole wafer is practically impossible to solve on a normal computer, whereas the above procedure takes about 5 minutes with step 1a. and only a few seconds with step 1b. Using step 1b. instead of step 1a. introduces an error of 8% in temperature, which leads to a 2% error in the resulting deformations. A temperature profile resulting from the method above (with step 1b.) is shown in Fig. 2.

References

[1] O. C. Zienkiewicz and R. L. Taylor, "The Finite Element Method," Volume 2, McGraw-Hill, 1991.

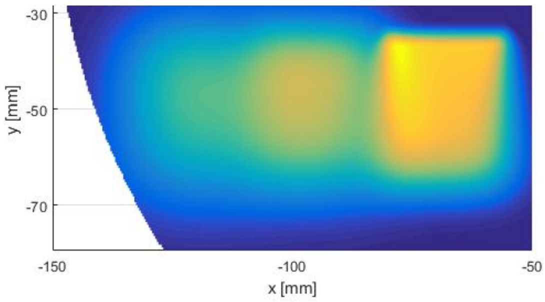

Figure 2: Temperature after the scanning of the fields in Fig. 1 (blue = low temperature, yellow = high temperature)