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EXTENDING NAVIER-STOKES EQUATIONS FOR EUV LITHOGRAPHY GAS FLOWS

Erik Arlemark[1]
erik.arlemark@asml.com

KEY WORDS

Transition regime, Slip shear heat load, Sherman-Lee conductive heat load.

ABSTRACT

ASML is market leading supplier of photolithography systems for the semiconductor industry. ASML manufactures machines for the production of integrated circuits such as CPUs, DRAM memory and flash memory. The new generation of lithography machines are capable to produce line features of about 10 nanometer by utilizing extreme ultraviolet light source (EUV) projected onto a mask and then exposing a resist on top of the target wafer. Thereafter by etching away material from the light-exposed-pattern, features can be produced. However EUV light easily get absorbed by all medium including gases. As a consequence lenses have to be exchanged with mirrors and environment has to be maintained at low pressure consisting of light weight gas type. Chips mare composed by stacking single layer exposure features which are correctly aligned within about 1 nanometer (called overlay). One of many challenges in this scope is to limit uncertainty caused by thermal expansion of the wafer. As the EUV light exposes the wafer resist, molecular contaminants are made volatile, which reduce light transmission if deposited on optics, illustrated in Fig 1. To hinder contaminates from obscuring sensitive optics, carefully designed gas purging is introduced with aim of convecting contaminates to the pumps. The risk of overlay is an effect of thermal expansion of the wafer. The expansion is mainly caused by EUV heat exposure and gas flow induced heat loads. The latter can be induced by 3 effects:

1. Center heat load: gas purged onto the wafer impinges and stagnates on wafer, obtaining higher temperature than surface causing heat load.
2. Gas expansion: gas purged with large pressure drop will expand and cool causing extraction of heat from surrounding solids.
3. Sheer heating: in low pressure domains heat can be induced to surface by slip-sheer heating.

The work in this paper will be addressing points 2 and 3 above, while predicting flow induced heat loads over the wafer with Navier-Stokes equations and DSMC. However, DSMC applied in comparisons above is not able to simulate the true geometry due to high computational cost, which is also impacted by inadequate parallelization possibilities.

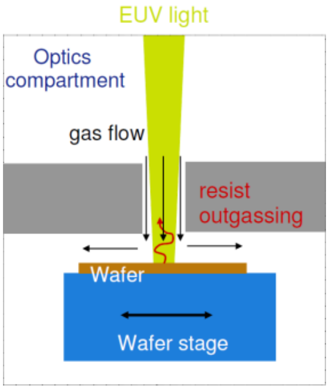
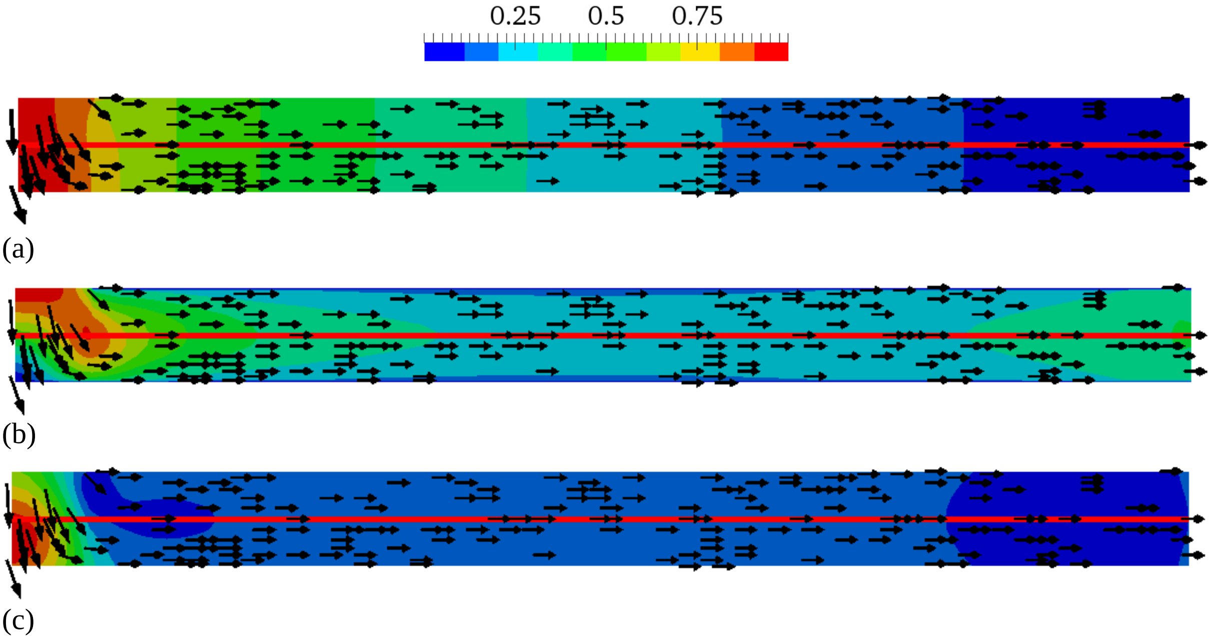


Figure 1: Schematic of EUV lithography where light hits the wafer causing molecular contaminants to diffuse in direction of light path, hence threatening light transmission by depositing on optical hardware.

Predicting peripheral heat load with Navier-Stokes equations in the transition regime

The geometry of the "over the wafer" flow case is radially expanding and illustrated in Fig. 2 where axi-symmetry occurs on the far left. The flow source is inserted on the top left of geometry and exit on the far right. It should be noted that the aspect ratio of the case is made arbitrary. The flow methods used are of Openfoam where rhoCentralFoam solves the Navier-Stokes equation's and dsmcFoam is the DSMC method. Both methods are modified for purpose of addressing flow case described here.



(a)

(b)

(c)

Figure 2: Normalized flow results over the wafer of (a) pressure, (b) speed and (c) temperature. The red center line between the two walls indicates where flow profiles will be extracted and compared.

By using the density profile of the flow results the Knudsen number is calculated as in Fig. 3, it can we seen that flow regime is in Knudsen regime between slip to mid transitional.

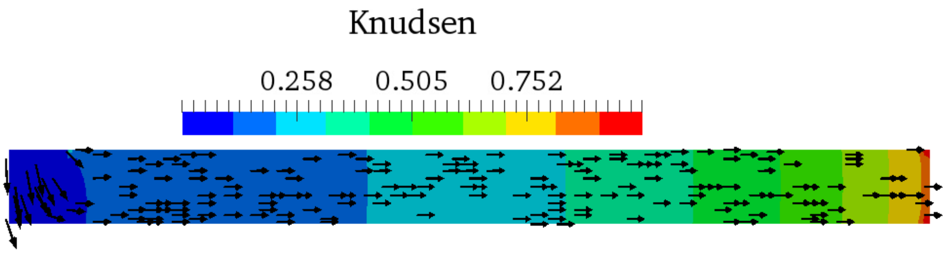


Figure 3: Calculated Knudsen number from the simulation where length scale is taken as the wall to wall spacing (not arbitrarily scaled).

As indicated in literature the Navier-Stokes equations with slip boundary conditions are not valid beyond Knudsen of about 0.1 [1], this abstract investigates an approach to extend applicability to larger rarefaction by:

1. Scale viscosity, μ, as:

$$\mu_{eff} = \frac{\mu}{1 + 2.5Kn^{1.6}} \tag{1}$$

   similar as described in [2] using different coefficients.

2. Include free-molecular slip-sheer term in wall heat transfer (derived from [3].):

$$q_{FM}^{\tau} = \frac{\alpha_1}{2\sigma}\rho\sqrt{\frac{k_B T}{2\pi m}}U^2 \tag{2}$$

   Where $\alpha_1, \sigma, \rho, k_B, T, m, U$ are thermal accommodation coefficient, tangential momentum accommodation coefficient, density, Boltzmann’s constant, temperature, molecular mass and velocity respectively. In addition to free molecular slip sheer term the slip regime slip-sheer term can expressed:

$$q_s^{\tau} = \sigma\rho\frac{C_m + 1}{C_m}\sqrt{\frac{k_B T}{2\pi m}}U^2 \tag{3}$$

   where $C_m = {}^{2-\sigma}/_{\sigma}$. The free-molecular and slip terms are combined as transitional slip-sheer

$$q^{\tau} = \frac{q_s^{\tau}}{1 + {}^{q_s^{\tau}}/_{q_{FM}^{\tau}}} \tag{4}$$

The flow results from comparisons are illustrated in Fig 3, where improvement on speed is mostly due to viscosity scaling and on temperature due to inclusion of free-molecular slip-sheet heat transfer.

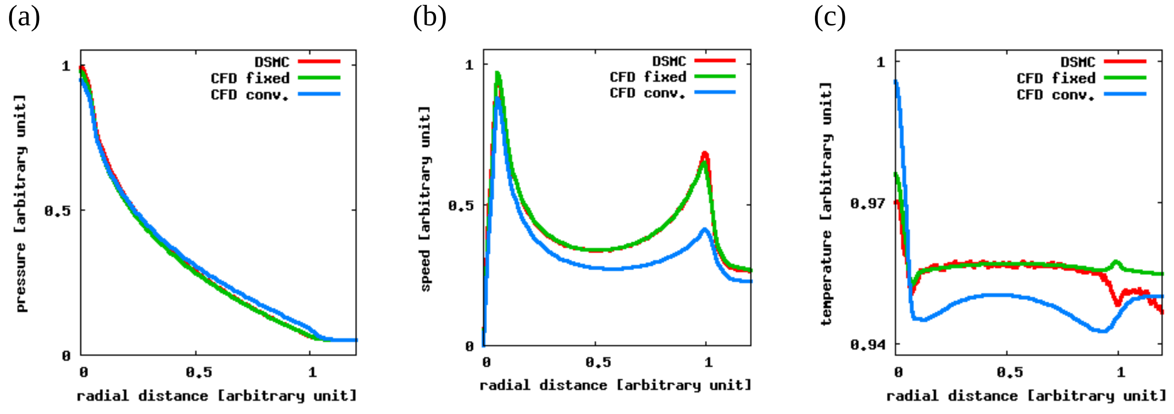


Figure 3: The flow results from Navier-Stokes equations (CFD conv.), Navier-Stokes equations with proposed correction (CFD fixed) and DSMC are compared for pressure (a), velocity (b) and temperature (c).

The heat load on the bottom surface (which would represent the wafer) is calculated by in post processing calculating the conductive and slip-sheer heat loads as:

$$q = q^{\tau} + q^{cond} \tag{5}$$

Where $q^{cond}$is the conductive heat load such as can be predicted from Sherman-Lee's relation:

$$q^{cond} = \frac{q_s^{cond}}{1 + q_s^{cond} \big/ q_{FM}^{cond}} \tag{6}$$

Where $q_s^{cond} = -k\frac{Twafer - Tgas}{gap/2}$ which is Fourier's Law and

$$q_{FM}^{cond} = -\frac{1}{2}\left(\frac{pc}{T}\right)\left(\frac{a_1\alpha_2}{a_1 + \alpha_{2-}a_1\alpha_2}\right)\left(1 + \frac{\xi}{4}\right)(Twafer - Tgas) \tag{6}$$

Where $p, c, \alpha_2, \xi$are pressure, average molecular speed, artificial wall accommodation coefficient (set to 1) and internal degree of freedom respectively.
In Fig. 4 the flow induced peripheral heat loads are compared with a good match for proposed CFD fix, while the conventual CFD results solved by rhoCentralFoam showed even negative cumulative heat load.

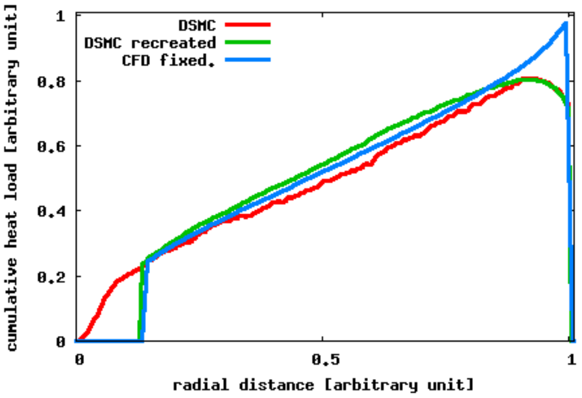


Figure 4: Shows calculated cumulative heat load for DSMC, DSMC recreated from flow profiles and Navier-Stokes equations with correction (CFD fixed) of this abstract.

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References and Citations

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