Efficient CFD Modeling Of Single Wafer Semiconductor Fabrication Systems For Closed-Loop Evaluation*

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Abstract

General finite element models of single wafer systems that describe the dynamics of both solids and gas flow are usually unsuited for quick design iterations, because of computational complexity. In this paper a more efficient alternative is proposed. Solids can be modeled efficiently and with sufficient accuracy using a finite volume approach, and the gas flow can be modeled by finite element CFD software. The gas flow model can then be coupled to the solids model by iterating on the heat transfer coefficients at the interface.

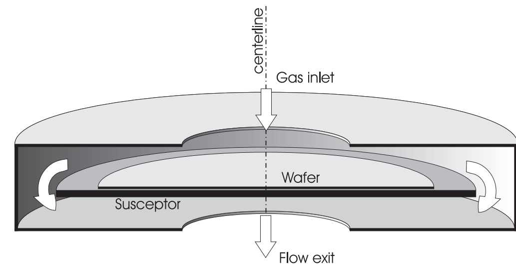

Figure 1: Generic single wafer system

1 Introduction

Computer models of single wafer semiconductor fabrication processes can be used for design and evaluation of the chamber and related components such as control laws. To allow for quick design iterations one must have a computationally efficient, yet accurate, description of the system dynamics. Unfortunately, straightforward application of finite element methods quickly leads to large and computationally intensive models, especially when the dynamics of solids as well as gases are taken into account simultaneously.

This paper will develop an alternative to this modeling approach, by considering the separation of the dynamics of the solids and the gases, combining finite element CFD models with low order finite volume models of the solids. This separation is possible because the fluid dynamics can be approximated as a static map. Hence, the proposed approach can lead to an efficient yet reasonably accurate model of the total system dynamics.

2 Thermal Dynamics Modeling of Solids

Consider the chamber as depicted in Figure 1. At high temperatures the thermal dynamics of the chamber solids is dominated by radiative and conductive heat transfer. At lower temperatures the influence of convective heat transfer becomes increasingly important. Convection can added to the model by including heat transfer coefficients of the boundary layer at the free surfaces. These coefficients can be provided by the CFD model. The resulting system can be modeled efficiently using a finite volume approach, using general graphical nonlinear modeling and simulation software, such as MATRIXx SystemBuild [4].

The required model order (the number of elements, or volumes) can be fairly low, typically 100 to 300, where most of the elements are used to describe the wafer, which is generaly the most important component. Typical simulation runs take from several seconds to a few minutes on a powerful PC. Additionally, these models allow nonlinear model reduction [2], for an even larger reduction in complexity.

3 CFD Modeling of Gas Flow

Modeling the flow of gas through the chamber is a relatively complicated task, that is commonly solved by running large finite element CFD models. Given a temperature profile of the chamber solids (included as boundary conditions) and an inlet flow rate, it is possible to compute the flow field, and related properties, such as the convective heat transfer coefficient at the boundary layer. Generally a relatively large number of elements (several thousands or more) is required to yield an accurate solution. Consequently, running dynamic CFD simulations will require a large amount of time to run (hours to days), but steady-state solutions can be computed fairly quickly.

4 Coupling Solid and Fluid Models

By virtue of the fluid dynamics being significantly faster than the dynamics of the solids, it is possible to approxi-

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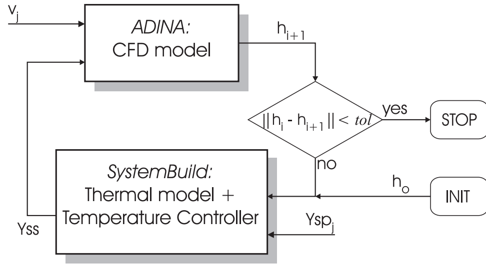

Figure 2: Procedure for obtaining steady-state solutions

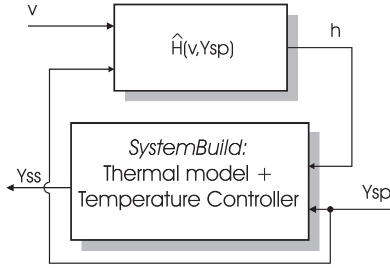

Figure 3: Resulting fast simulation model

mate the fluid dynamics as a static map, and use that map in the thermal dynamics model of the solids. The key coefficient that relates the fluid dynamics to the thermal dynamics of the solids is the heat transfer coefficient at the boundary h, which is a function of the inlet flow rate v and the temperatures of the free surfaces Y_{SS}.

Using the results from a number of runs with the finite element model it is possible to construct a fairly accurate (nonlinear) static map $\hat{H}(\cdot)$ between h and the inputs v and Y_{SS} that is valid for a range of operating conditions of interest. This map can now be used for fast computation of an approximate value of h.

5 Example: Generic Single Wafer System

The approach will be illustrated using a generic model of a single wafer system, see Figure 1. The thermal dynamics (under closed-loop conditions) of the solids is modeled in MATRIXx SystemBuild, using a finite volume modeling approach [3]. The gas flow is modeled in the finite element modeling software package ADINA [1].

A number of cases are computed, covering several operating temperatures and gas flow rates, using the procedure as depicted in Figure 2. As a first step, only the steady-state solutions are considered. In this case h simply depends on v and the refence temperature Y_{SP}. The use of the map $\hat{H}(v, Y_{SS})$ is depicted in Figure 3.

Figure 4 shows the convergence for one set of iterations as depicted in Figure 2. The top left figure shows the predicted wafer temperature profile Y_{SS} assuming closed-loop operation; the top right figure shows the incremental error, clearly indicating quick convergence of the procedure in

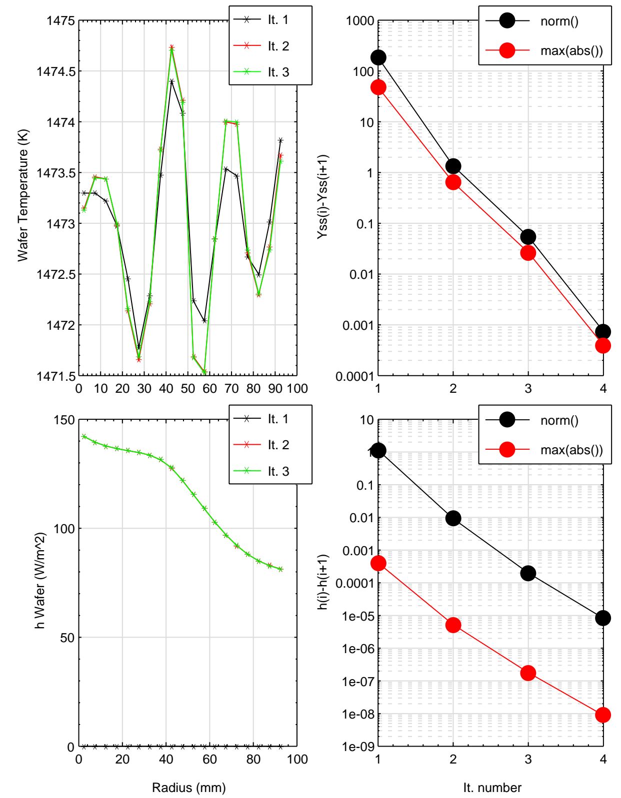

Figure 4: Convergence to steady-state solution (wafer)

3–4 iterations. Similarly, the bottom two figures show the results for h.

6 Future work

In the work presented here only steady-state temperature results were considered when computing the map. Future work may focus on extending this to include more temperature conditions, e.g., during ramp-up. Furthermore, the model can be extended to include Chemical Vapor Deposition (CVD), which is of considerable interest.

References

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