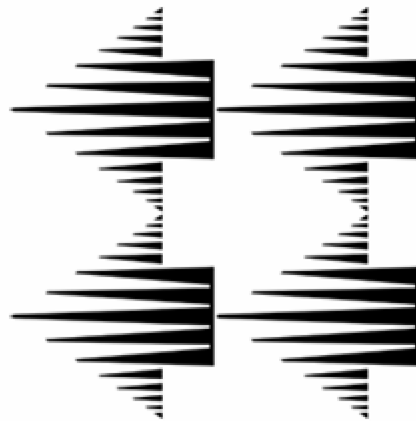

Chamber Conductance Modeling Using Transition Flow CFD and a Thermal Radiation Analogy to Free Molecular Flow

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Outline

- Introduction
- Background
  - Motivation
  - Modeling Approaches
- Models
  - 3D Geometries
  - Transition Flow Models
  - Free Molecular Flow Models
- Results
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Background
Motivation

- **What motivates the interest in this semiconductor modeling application?**
  - **Vacuum system conductance calculations always in use**
  - **We would like to avoid having to use specialty or non-commercial software in industrial applications**
    - Many operating conditions need Monte Carlo methodologies
  - **If calculations can be made simpler, that is a plus**
    - However, we need to model complex 3D geometries
    - We would like to use one modeling approach for all vacuum operating conditions (continuum to free molecular) if possible
    - Getting away from Monte Carlo models will speed up model run times significantly

Background
Motivation

- **What motivates the interest in this as a semiconductor processing application?**
  - **The chambers examined in this work are used in high density plasma CVD (chemical vapor deposition)**
    - In general, when these chambers deposit dielectric films in STI (shallow trench isolation) applications, the ability to fill gaps is improved at lower pressures
    - If the chamber pressure can be lowered easily and inexpensively, this is a marketplace advantage
    - If a smaller, cheaper pump can achieve the target process condition, it reduces tool cost and increases reliability
  - **Models can demonstrate the relative performance of chamber designs based on conductance differentials**

Background
Modeling Approaches

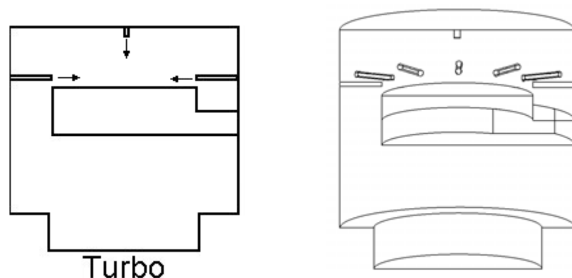
- **The idea of using an analogy between radiation heat transfer and free molecular flow is not new**
  - **However, it appears as though it is not well known in the semiconductor industry**
    - Bellcomm Memorandum (1968) on the World Wide Web
    - Peterson (1986) from Lockheed Martin presented the idea with validation in an aerospace application
    - Gantry et. al. (2001) from BOC Edwards discussed the idea in a short AVS presentation
    - Two software packages for aerospace use (MOLFLUX and NEVADA) mention this application in marketing materials
  - **The work being discussed here was presented last month at the 50th AVS Symposium in Baltimore**

Background
Modeling Approaches

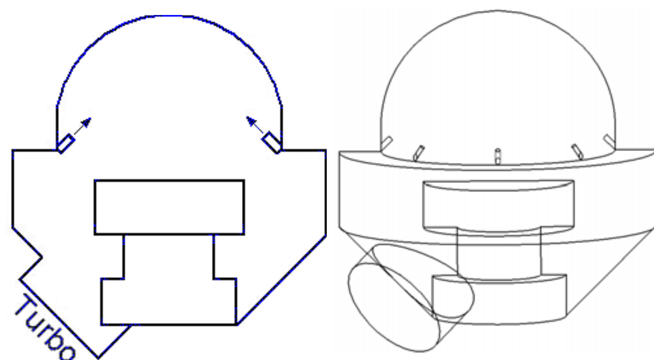
- **Near continuum transition flow is modeled here using Navier-Stokes CFD codes with slip BCs**
  - **Various transition flow models have been compared with pressure data from a Lam Research vacuum test cell**
    - Monte Carlo models
      - Shufflebotham, P. K., Bartel, T. J., Berney, B., JVST B, **13** (4) 1862 (1995)
    - CFD with no-slip BCs
      - Singh, V. Berney, B., Krishnan, A., JVST A, **14** (3) 1252 (1996)
    - CFD with slip BCs
      - Gochberg, L. A., Proceedings of the 23rd International Symposium on Rarefied Gas Dynamics, *Rarefied Gas Dynamics*, 1073 (2003)

Models
3D Geometries

- **Two different 200-mm chambers were modeled**
  - **Look at the relative differences between chambers designed for STI applications**



Centrally mounted turbopump with cantilevered pedestal



200-mm SPEED™ **with dual turbopumps at 45° and a centrally mounted pedestal**

Models
Transition Flow

- **Transition flow models done in commercial CFD software (CFD-ACE+)**
  - **Navier-Stokes continuum model at room temperature**
  - **Slip boundary conditions used to model flows at Knudsen numbers between 0.01 and 0.1**
  - **Inlet gas flows of 600 SCCM of argon with adiabatic chamber walls**
  - **Pumps initially modeled using constant pressure outlet boundaries consistent with 2200 l/s of total pumping**
    - The chamber with the 45 degree turbopumps uses two 1100 l/s pumps
    - The chamber with the single centrally mounted turbopump uses one 2200 l/s pump

Models
Free Molecular Flow

- Free molecular flow is modeled using a radiation heat transfer analogy ($P_{rad} \sim T^4$)
  - Models run in commercial Navier-Stokes software from Fluent and CFD-ACE+ using Discrete Ordinate Method

$$Q_{FM} = C\left(P_2 - P_1\right)$$

$$Q_{rad} = k_{rad}\left(T_2^4 - T_1^4\right) = k_{rad}\left(P_{rad,2} - P_{rad,1}\right)$$

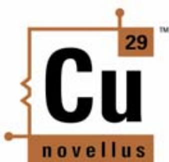
Variable	Symbol (Flow/Heat)	Free Molecular Flow Name (Unit)	Radiative Heat Transfer Name (Unit)
Flux	Q_{FM} / Q_{rad}	Throughput (pa-m^3/sec)	Heat Flux (Watts/m^2)
Driving Force	P_{rad} / T^4	Pressure (Pa)	Temperature (K^4)
Constant	C / k_{rad}	Conductance (m^3/sec)	Radiative Conductivity (Watts/m^2/K^4)

Models
Free Molecular Flow

- **Using the radiation heat transfer analogy, models are set up models in two manners**
  - **Fix the inlet and outlet boundaries identically, and make inlet flow areas identical in both chambers**
    - Look at system throughput
    - A higher value means a higher conductance
  - **Fix the outlet boundaries identically, make the inlet flow areas the same, and change the inlet boundary so the same system throughput is seen in both chambers**
    - Look at the driving force (pressure difference)
    - A smaller driving force means a higher conductance

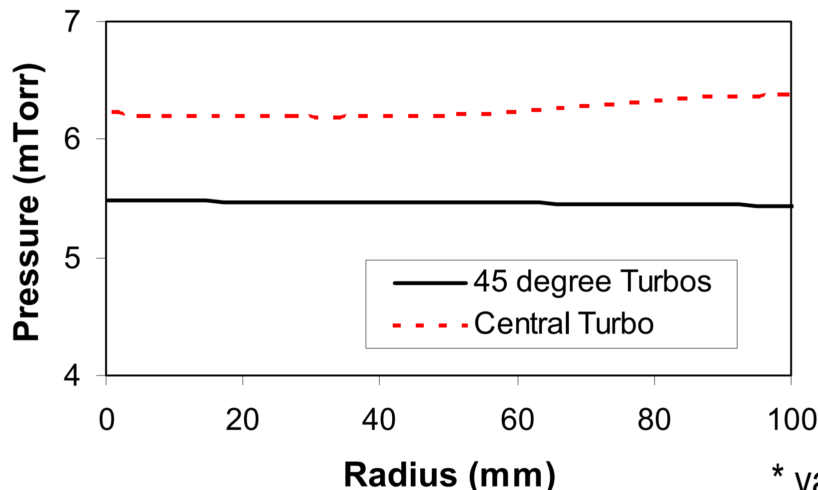
Models
Free Molecular Flow

- Inlets and outlets are modeled as isothermal boundaries with emissivity of one
  - Inlet and outlet temperatures chosen so local Kn $\geq$ 100
    - Local Kn (Knudsen number) is defined as the mean free path compared to a length scale based on local density gradients
- All other walls are modeled as adiabatic walls with emissivity of zero per Peterson (1986)
- There is no direct comparison between this approach and transition flow models
  - They have widely different operating conditions
  - Good for relative comparisons



Results
Transition Flow Models

- **This model approximates the STI operating condition in pressure and volume flow rate (600 SCCM argon, no chemistry or deposition)**
- **We look at processing conditions (i.e. pressure) over the wafer (conductance changes with pressure)**



***Pressure over the wafer is 20% lower with the *Novellus SPEED™* design (two 1100 l/s turbos at 45°)**

* van Schravendijk, et al., SEMI Conference (1999)

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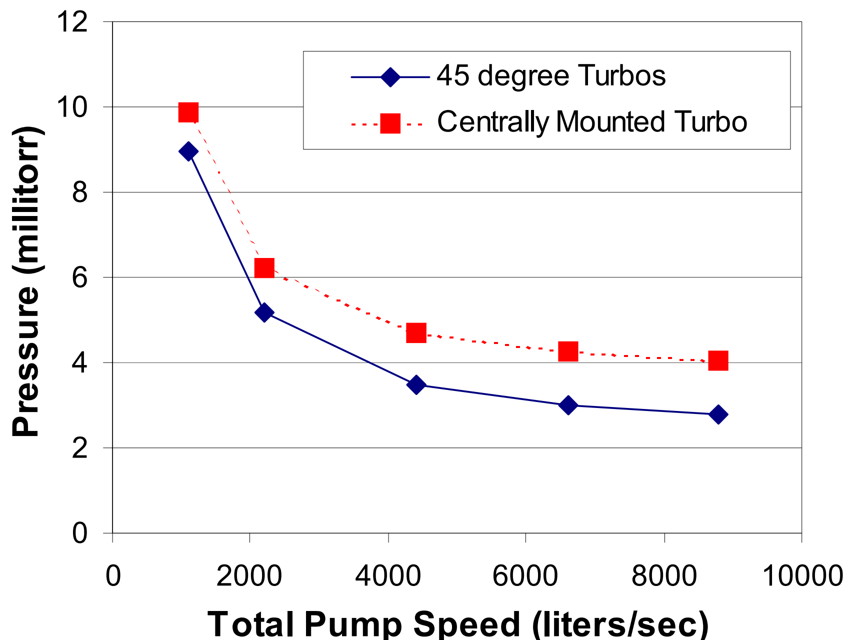
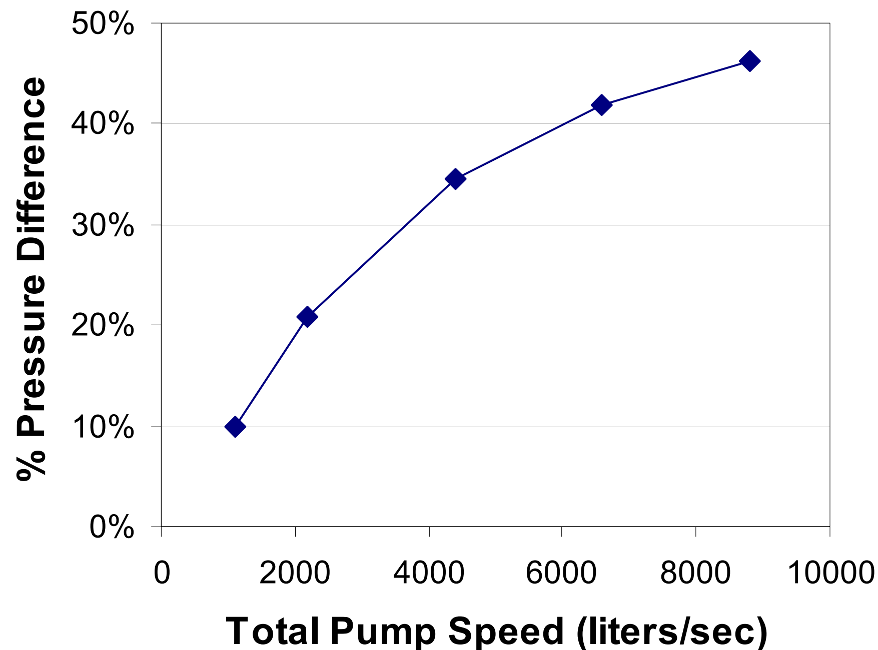
Results
Transition Flow Models

- Models were also run for various pumping speeds
  - Pressure at wafer center 10-46% lower for 45° turbo design for pump speeds between 1100 and 8800 liters/sec





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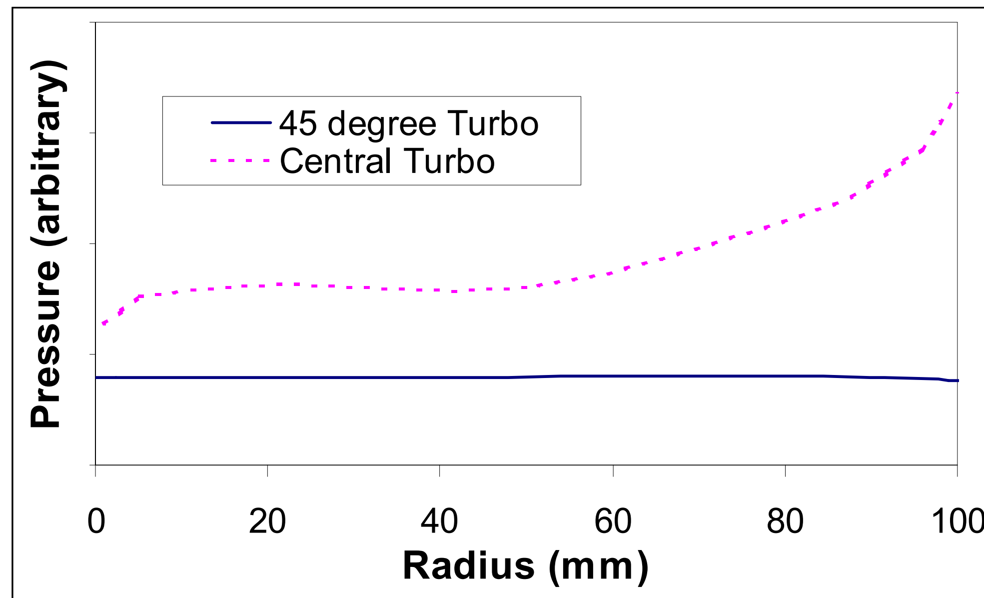
Results
Free Molecular Flow Models

- **Both boundary condition set-ups the same results**
  - **Free molecular flow models provide a single conductance value for each design**
  - **Transition flow models have variable conductances as operating conditions change**

Summary of Results		
Performance Improvement with 45° Turbopumps	**Transition Flow Models (pressure gain over wafer)**	**Free Molecular Flow Models (conductance gain)**
% Gain	10-46%	24%

Results
Free Molecular Flow Models

- Using a “radiative pressure” equal to T^4, we examine pressure over the wafer in free molecular flow
  - Direct correlation between "radiative pressure" and actual chamber wall pressures is not clear



Conclusions

- Models were run in 3D for realistic semiconductor processing vacuum chambers
  - Transition flow using Navier-Stokes with slip BCs
  - Free molecular flow using analogy to radiation heat transfer (Discrete Ordinates Method)
- The *Novellus SPEED™* design with two turbopumps at 45° performs better than competing designs
  - Competing design has a single centrally mounted turbo
  - Transition flow models show 10-46% lower pressure at wafer center with constant pump speeds in both systems
  - Free molecular flow conductance is 24% higher

Conclusions

- Both modeling approaches show the same design trends and qualitative improvement levels
  - Only one model per design need be run using the free molecular flow approach
  - The radiation heat transfer analogy allows the user to model free molecular flow without Monte Carlo methods within commercial codes already in widespread use
  - Complex 3D geometries can be modeled easily
  - Such models can be used to quickly optimize conductance in chamber designs early in the development stage

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