Dynamic Simulation of a Multichamber CVD Cluster Tool

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Abstract

Dynamic, physically based simulation has proved very effective in representing the time-dependent behavior of equipment, process, sensor and control systems. We have developed a system-level dynamic simulator for an 8” CVD cluster tool (ULVAC-ERA1000). The simulator incorporates models for equipment, process and control systems, representing time-dependent system level behavior through the imposition of equipment controller recipes for pump-down, process and venting cycles. Multistage pumping systems (Roots-mechanical and turbo-mechanical) are modeled using compression ratios, nominal speeds, and volumes to reflect actual behavior, validated against experiments on the Ulvac tool. The process simulator is derived from the work of Hsieh et al. The Ulvac simulator is applied to optimization of deposition rate and WF$_6$ utilization, analysis of experimental data for recipe improvement, and development and debugging of equipment controller software and operation.

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Introduction

The National Technology Roadmap for Semiconductors\textsuperscript{1} asserts strongly that continuing progress in integrated circuit technology is increasingly dependent on enhanced equipment productivity, involving costs of capital equipment, maintenance, and consumables, along with improved equipment reliability and short time-to-repair. The importance of these factors is underscored by the observations that equipment costs dominate the cost of new multi-billion dollar manufacturing plants, and that focus on these issues has been formalized and emphasized through the use of the concepts of cost-of-ownership (COO) and overall equipment effectiveness (OEE).

Stimulated by the successes of technology modeling at the process, device, and circuit levels, significant attention has been devoted to equipment or reactor modeling through approaches such as computational fluid dynamics\textsuperscript{2,3,4}. These have been coupled through explicit process models to reactor performance and the prediction of the evolution of microfeature profiles\textsuperscript{5,6,7,8,9,10}. However, the dynamics of equipment behavior through a process cycle has been treated in only isolated cases, most notably to meet the challenge of rapid thermal processing\textsuperscript{11,12}.

In this paper, we have studied the behavior of a multi-chamber cluster tool at the system level. System-level dynamic simulation provides a powerful technique for studying the time-dependant behavior of process, equipment, sensors and control systems of a manufacturing tool. This has been shown by Lu \textit{et al.}\textsuperscript{13,14} through simulation of polysilicon RTCVD processes. Their results demonstrate that system level simulation allows the evaluation of not only the deposition-related parameters, but also a broad range of system properties like equipment performance, gas and heat flow conditions and process cycle time. We have developed a similar model for a tungsten CVD cluster tool, which uses reduced order physical and chemical models to describe the gas transport, heat transfer and deposition kinetics in the reactor. The simulator captures the behavior of a full-scale manufacturing tool with multiple chambers (two reactors, a load lock and a central wafer handler), and a multi-pump vacuum system. The gas flow model for such a system must integrate the functioning of turbo and mechanical pumps in a methodology consistent with behavior of a sequential pump system. The individual elements representing equipment, process and control systems are integrated by the implementation of
process recipes which model the behavior of the cluster tool controller. The simulator has been validated with experimental results, and is being used to investigate the dynamics and control of deposition in tungsten CVD processes.

**Background**

System level dynamic simulation has been previously used by Lu *et al.* 8 to study the dynamics and control of polysilicon RTCVD. The RTCVD equipment consists of the gas handling system, a single wafer reactor and reactor pumping station and a two-stage differentially pumped QMS system. The simulator is composed of five elements. Since the present work builds upon this structure, it is useful to understand the purpose of these components in the polysilicon RTCVD simulator. The Process Recipe defines the status of the valves, mass flow controllers (MFC’s), power to the heating lamps and overall process conditions as a function of time. The Equipment Simulator uses the status of the valves, MFC’s etc to calculate the gas flow and heat flow conditions in the reactor. The mathematical models of the gas transport and heat transfer are based on reduced order mass and energy balance equations. The outputs of the Equipment Simulator are the reactor pressure and the wafer temperature. The Sensors and Control Systems simulator reads in this pressure and temperature and compares them to the process parameters preset in the deposition recipe. It then regulates the reactor pressure by changing the position of the throttle valve and the wafer temperature by varying the power to the heating lamp, and thus the nominal process conditions are established. The deposition kinetics are modeled in the Process Simulator which calculates growth rates and film thickness, which are the final output of the integrated model.

**Ulvac ERA-1000 Equipment Description**

The ULVAC-ERA 1000 at the Laboratory for Advanced Materials Processing, University of Maryland at College Park, is a CVD cluster tool designed for tungsten deposition. It consists of a gas handling system, the CVD reactor (including a load-lock, central wafer handler, two reaction chambers and heating lamps), reactor pumping system and equipment controls. Fig. 1 shows the schematic layout of the cluster tool.

The gas handling system consists of mass flow controllers, which regulate the flow of the reactant gases (WF$_6$ and H$_2$ for our deposition process) to the reaction chambers. The reaction chambers are cylindrical in shape and are located symmetrically on either side of the central wafer handler (CWH), which is then linked to a load-lock (LL). The load lock isolates the CWH
from the room ambient via a gate valve (V3). The CWH contains a robot arm, which takes the wafer from the LL and deposits it on a wafer lifter pin inside the reaction chamber via a gate valve (V1 or V2). The pressure in the reactor chamber is measured using a capacitance manometer. The pressure during deposition is controlled using a feedback loop to continuously adjust the throttle valve position on the reactor pumping station while maintaining a constant gas flow to the reactor. During deposition, the wafer chuck rotates at a speed of 5 rpm to ensure uniform heating.

The ULVAC cluster tool has a multistage pumping system. Each reactor is connected to two sets of pumps, which perform different function during the process cycle. One is used for chamber evacuation and consists of a turbo pump (TMP1 & 2) backed by a rotary vane pump (RP4). The second set of pumps, each consisting of a Roots blower (RBP1 & 2) backed by a rotary pump (RP1 & 2), is used to maintain constant pressure during the deposition process. Reactor pumping is switched from one pump stack to the other by the use of gate valves. The LL and the CWH are jointly connected to a Roots blower (RBP3) backed by a rotary vane pump (RP3).

**Overall Simulator Structure**

The CVD cluster tool is modeled in three sections: the gas handling system, the reactor (including LL, CWH and two process chambers), and the pumping stations. Each section is modeled in terms of three processes: gas flow, heat transfer and the reaction chemistry. Gas flow calculations for the ULVAC cluster tool are based on mass balance in each piece of the equipment. We have assumed ideal mixing between gases in the reactor to simplify our computations. The total number of molecules in each chamber must equal the molecules input to the chamber minus the molecules pumped out. For the reaction chambers the mathematical expression is

\[
P_{\text{fin}} = P_{\text{init}} + \frac{1}{V} \int \left( Q_{\text{in}} - Q_{\text{out}} + Q_{\text{reaction products}} - Q_{\text{reactant depletion}} \right) dt
\] (1)

where \( P_{\text{init}} \) is the initial (base) pressure of the reaction chamber in Torr, \( P_{\text{fin}} \) is the final pressure, \( Q_{\text{in}} \) is the total throughput of gas (in Torr-liter/sec) entering the reactor, \( Q_{\text{out}} \) is the throughput of
gas leaving the reactor, \( Q_{reaction\_products} \) is the throughput introduced due to product generation and \( Q_{reactant\_depletion} \) denotes the gas throughput removed from the chamber due to reactant depletion. The total and partial pressures of the reactor gases can thus be calculated at every iteration of the simulation.

**Equipment gas flow modeling**

Previous models developed for system-level simulation of CVD reactors have assumed a uniform pumping speed for the reactor pumping station, which is a good approximation of the vacuum system behavior when the reactor is evacuated by a single pump. However, the complexity of the pumping system on the ULVAC cluster tool necessitates a more detailed modeling of the mechanical and turbo pumps. Inclusion of factors like the pump start-up time or the gradual decay of pumping efficiency with decreasing pressure allows a better representation of the equipment state.

**Heat transfer modeling**

Heat flow calculations in our simulation are based on reduced-order energy balance equations. The wafer is assumed to absorb power from the heating lamps primarily by radiation, with corrections for conductive and convective losses. Wafer temperature is regulated by controlling the power to the heating lamps. The energy balance for the wafer can be expressed as:

\[
aQA - 2eA \sigma T_w^4 - W_{cc} = mC_p \frac{dT_w}{dt}
\]

Where \( aQA \) corresponds to the power absorbed by the wafer, \( 2eA\sigma T_w^4 \) is the power radiated by the wafer, \( W_{cc} \) is the power lost by conduction and convection and \( mC_p (dT_w/dt) \) is the power consumed for heating the wafer; \( a \) is the wafer absorptivity; \( Q \) is the incoming lamp radiation; \( e \) is the wafer emissivity; \( A \) is the wafer area, \( \sigma \) is the Stefan-Boltzmann constant; \( T_w \) is the wafer temperature; \( m \) is the mass of the wafer; \( C_p \) is the specific heat of the wafer material and \( dT_w/dt \) is the rate of heating of the wafer. \( W_{cc} \) is modeled as a linear function of the difference between the wafer temperature and the ambient temperature.
**Chemical kinetics modeling**

The chemical kinetics for the film deposition are calculated by the Process Simulator, using as inputs the partial pressures of the process gases and the wafer temperature. Due to the cold wall configuration of the reactor, and the relatively low temperatures of operation (400-550 C), we have excluded gas phase reactions in the kinetic model. The surface reactions for tungsten deposition from WF$_6$ and H$_2$ gas have been adapted from Hsieh’s model$^9,10$ for the reduction of WF$_6$ by SiH$_4$ followed by H$_2$.

**Process recipe modeling**

Equipment operation and process dynamics are integrated by the implementation of a process recipe, which models the process sequence and the timing of the equipment controller. This helps to understand the complex dynamics of a manufacturing tool and to explain irregularities in equipment behavior by allowing one to study a broad range of system properties.

**Simulator development**

**Gas flow in a multistage pumping system**

Mechanical pumps like the rotary vane pump (RP1, 2, 3 & 4) operate in the low to medium vacuum region and reach full speed almost instantly on being turned on at atmospheric pressure. Fore pumps like Roots blowers (RBP1, 2 & 3) or turbo pumps (TMP1 & 2) have a longer start-up time because they do not reach their optimal speed unless the backing pressure is less than 10 mtorr. Thus they are typically backed by a mechanical pump (rotary vane pump in this case) to pump down the fore line to the mtorr range$^{15}$. We have taken into account this time delay by empirically modeling the ramp-up of pump speed with decreasing pressure in the foreline. The variation of pumping speed with pressure at the high end of the fore pump operation range is shown in Fig. 2.

At the low end of the pump operation range, all mechanical and turbo pumps (which use variations of rotating fans or turbine blades to pump gas molecules from one end of the pump to another) reach a limit in their pumping capacity before they reach their lowest pressure. The lowest pressure ideally achievable by such pumps is a called the base pressure (usually specified by the pump manufacturer) and is the parameter taken into consideration when designing vacuum systems. However, when the inlet of the pump reaches a low pressure, gas
particles start backstreaming from the pump exhaust towards the inlet. Once the flux of the backstreaming molecules equals the flux in the forward direction, a steady state pressure, which is the actual base pressure is established.

This backstreaming of gas particles is measured in terms of a compression ratio, which is defined as the ratio of the outlet pressure to the inlet pressure of a pump \(^{11}\). The compression ratio depends on the speed and design of the turbine blades, and varies with the size of the species being pumped, i.e. light gases like hydrogen and helium have much smaller compression ratios than heavy gases like argon, and are harder to pump on. If the compression ratio is constant for a pump for a given process, lower base pressures can be achieved by lowering the exhaust pressure, usually done by using a backing pump. In processes using a combination of gases, the ultimate pressure is determined by the compression ratio of the lighter gases.

The pressure-dependent pumping speed for each pump in the lower pressure regime has been modeled in terms of the compression ratio of the pump. The effective gas throughput for a pump is a combination of flow in the “forward” or inlet-to-exhaust direction and the flow due to backstreaming particles.

Throughput in the forward direction: 
\[ Q_f \text{ (Torr-liter/sec)} = (P_{\text{pump inlet}} - P_{\text{base}}) \times PS \]  

Throughput due to backstream: 
\[ Q_b \text{ (Torr-liter/sec)} = (P_{\text{outlet}} - P_{\text{pump inlet}}) \times PS / CR \]  
(in the reverse direction)

Effective throughput: 
\[ Q_{\text{eff}} = [(P_{\text{pump inlet}} - P_{\text{base}}) - (P_{\text{outlet}} - P_{\text{pump inlet}}) \times 1 / CR] \times PS \]

where \(P_{\text{pump inlet}}\) is the pressure at the chamber being evacuated. For the fore pumps (RBP and TMP), \(P_{\text{pump inlet}}\) is the pressure at the reaction chamber, and for the rotary vane backing mechanical pump (RP), it is the pressure at the outlet of it’s fore pump. \(P_{\text{outlet}}\) is the pressure at the exhaust of the pump. The fore pumps exhaust into the inlet of the backing pumps, which in turn pump out to atmosphere. \(P_{\text{base}}\) is the theoretical base pressure of the pump, which would have been in the absence of backstreaming gas. \(PS\) is the maximum speed of the pump, which it achieves at its optimal pressure range. \(CR\) is the compression ratio, which is usually specified by the manufacturer for a particular gas.
Thus the effective pumping speed in the low pressure end of the pump’s operating range is not PS but is given by

\[
PS_{\text{eff}} \text{ (liters} / s) = [1 - \left( \frac{P_{\text{outlet}} - P_{\text{pump in}}}{P_{\text{pump in}} - P_{\text{base}}} \right) \times \frac{1}{CR}] \times PS
\]

Modeling the transient behavior of process pumps has a significant impact on the total process cycle time in a multi-pump setup. Because of the sequential operation of the pumps, the start-up time for the fore pumps depends on the lowest pressure achieved by the mechanical backing pumps. Secondly, the conductance of the process pumps is limited by the fact that during tungsten deposition, the bulk of the reactor gas is composed of hydrogen, which has a very small compression ratio. This could affect the time response of the throttle valve to pressure changes during the process.

**Chemical Kinetics Model for W CVD**

We consider here the Hsieh model \(^9,10\) for the surface reduction of WF\(_6\) by (SiH\(_4\) + H\(_2\)), which has three competing reaction pathways of the Eley-Rideal type. The first pathway describe the SiH\(_4\) reduction of WF\(_6\), the second pathway the Si reduction of WF\(_6\), and the third the H\(_2\) reduction of WF\(_6\).

We have modified the Eley-Rideal mechanism to obtain a three step kinetic model for the surface reduction of WF\(_6\) by H\(_2\). In the first step, WF\(_6\) gas is reduced by surface silicon to form an initial seed layer of tungsten. In the next step, WF\(_6\) gas adsorbs on to active tungsten sites. Finally, adsorbed WF\(_6\) is reduced by H\(_2\) to deposit W metal. The relevant equations are given below:

Nucleation: \[ WF_6 + 3/2 \text{Si}^* \rightarrow W^* + 3/2 \text{SiF}_4 \text{ (g)} \] \hspace{1cm} \text{R1 = 0.3 } J_{WF_6} \theta_{Si} \hspace{1cm} (7)  

Adsorption: \[ W^* + WF_6 \rightarrow WF_6^* \] \hspace{1cm} \text{R2 = 0.48 } J_{WF_6} \theta_{W} \hspace{1cm} (8)  

Reduction: \[ WF_6^* + 3H_2 \rightarrow W(\text{s}) + 6HF \] \hspace{1cm} \text{R3 = } k_{H_2}[P_{H_2}]^{0.5} \theta_{WF_6} \hspace{1cm} (9)  

Site conservation: \[ \theta_{Si} + \theta_{WF_6} + \theta_{W^*}=1 \hspace{1cm} (10) \]

where \( k_{H_2} \text{ (mol/cm}^2\text{/s.Torr}^{0.5} = 0.0083 \exp[-8800/T(K)] \) is an equipment dependent empirical constant depending on the process temperature. \( J_{WF_6} \) is the molar flux of WF\(_6\) gas, \( [P_{H_2}] \) is the
partial pressure of H₂ in the reactor and θ_{Si}, θ_W and θ_{WF6} are the fractions of the total surface active sites covered by Si*, W* and WF₆* respectively. The rates of the first two reactions are proportional to the sticking probabilities (0.3 and 0.48 respectively) of the impinging gas on the active site.

The dynamic rates of the reactions are calculated in terms of the instantaneous concentrations of the reactant gases and surface sites. In turn, the surface coverage of Si, W and WF₆ can be calculated by integrating over time the rates of all the reaction steps that produce or consume the particular species, at each iteration step. The net deposition rate R_{net} equals (R1+R3), since both reactions deposit tungsten metal on the surface. The total film thickness is obtained by integrating the growth rate over time.

Initially, the surface coverage (θ_{Si}) of the Si sites is 1. Due to low activation energy, the nucleation reaction takes place at a very high rate and rapidly drives θ_{Si} to zero. For simplicity, diffusion of Si atoms through the W film is not included in the simulator. Once the initial seed layer of W* is deposited covering all available Si sites, R1 becomes zero. Shortly after, R2 and R3 reach a steady-state equilibrium, i.e. R2=R3, and the bulk of the W film is deposited.

The deposition of W films using H₂ reduction of WF₆ has traditionally been regarded as a slow and inefficient process. According to the simulator, in the pressure range of 0.1-0.5 Torr and temperatures around 400-500 C, less than 10% of the WF₆ is deposited on the wafer. It is known that the deposition rate as well as the WF₆ conversion rate can be significantly enhanced with the introduction of small amounts of silane (SiH₄).

**Process Recipe for Model Integration**

The various elements for gas and heat flow, deposition kinetics etc. have been integrated into a coherent unit in order to achieve a system-level representation of the cluster tool. This has been done in two steps. First, the controller command sequence and interlocks were duplicated in as much detail as possible, to allow us to simulate the functioning of a full-scale manufacturing tool. Thus the Process Recipe module defines valve states and interlocks and MFC states, which represent equipment states, such as venting the load lock and wafer handler to load the wafer, pumping down all chambers prior to deposition, opening up mass flow controllers and turning on the heating lamp to begin deposition. The status of valves, MFC’s and heating lamps is used to compute gas and heat transport in the system.
Secondly, to simulate a deposition process, a number of process parameters must be entered by the user. Numerical values for the flow rates of the process gases, process pressure, temperature and timing for each step of the deposition recipe (if it is a multi-step recipe) form the complete set of inputs. Once the simulation is initiated, the wafer is loaded into the reactor via the load lock and the central wafer handler. When the reactor is ready for deposition, the gas flow, pressure and temperature control systems implement a series of actions to achieve and maintain the set values of deposition parameters. A detailed modeling of the equipment controller aids significantly in understanding and analyzing the dynamics of the cluster tool at every step of its operation.

Validation

The various modules of the ULVAC cluster tool simulator have been validated independently to create a tool which can be directly used for experimental design and process control strategies.

To validate the simulation results for equipment dynamics we developed a data acquisition system (using DAQ cards from Computer Boards) to read relevant analog and digital voltage signals (for process pressure, valve status and conductance, wafer temperature etc) from the equipment controller. Once the voltage signals were scaled to range of the respective parameter, they were directly compared to the simulation results. Fig. 3 presents simulation results for the reactor pressure and the status (on/off) for valves V11 and V41 (see Fig. 1) as a function of time. Data is shown for the wafer loading part of the process cycle. The valve connecting the reactor to the process pumps (V11) is closed when the wafer is being loaded in through the load lock and central wafer handler. Once the wafer is loaded the reactor is pumped down using the turbo pumps (V41) to the $10^{-6}$ Torr range to remove all contaminants. After the successful completion of this step, valve V11 opens up as deposition commences. This detailed modeling of equipment behavior has been instrumental in analysis and optimization of system behavior.

In order to validate the accuracy of implementation of Hsieh’s model in the simulator, the simulated results for film growth rate have been compared to the experimental results reported by Rosler and co-workers. Fig. 4 shows our simulation results for the tungsten deposition process, which seem to be in good agreement with experimentally measured growth rates.
Applications of Dynamic Cluster Tool Simulator

Optimization of Deposition Processes

An experimentally validated dynamic simulator proves to be an invaluable tool for process recipe improvement and optimization. A primary application of the ULVAC cluster tool has been in defining a process regime for tungsten deposition, which would optimize both the growth rate and reactant consumption. To target an optimal process pressure and reactant composition which would generate improved process recipes, we simulated deposition processes for different H₂:WF₆ flow rate ratios and process pressures (0.2 and 0.5 torr), for the temperature range 350-600 °C. In each case the flow rate of H₂ is kept fixed at 200 sccm, and the results are shown in Fig. 5.

Simulation results showed that although the conversion rates for WF₆ are better for high ratios of H₂:WF₆, deposition rates can be enhanced by moving towards a hydrogen limited regime (low H₂:WF₆ ratio), which is also in favor of uniform W thin film. Increasing the process pressure benefits both the film growth rate and the conversion ratio. This behavior can be understood as arising from a longer residence time for the reactant gases in the reactor. For the same reactants inlet rates, if the process pressure is increased, the throttle valve conductance must decrease to reach the set-point pressure. This means that the gas molecules remain in the reactor for a longer time, increasing the probability of their impinging on the wafer surface and thus increase the growth rate and the conversion ratio as well. Once simulation results have been used to define the desired process regime, smaller and better-focused sets of actual experiments may be designed for optimal process conditions.

Equipment Diagnostics and Fault Detection

A dynamic simulator can generate the time-dependent response of all the process and equipment related parameters through the process cycle. This can be compared against the signals from the equipment sensors to detect and analyze dynamic details of system operation. We have used this capability explicitly to debug and better understand the subtleties of the cluster tool, particularly the relative timing of actuation events involving valves, flow controllers, etc. The integration of multiple equipment state signals, and their time-synchronous combination with chemical sensor signals, has revealed important but subtle feature in the equipment dynamics, while the dynamic tool simulator has been the primary vehicle which enables interpretation and understanding of the system dynamics.
An example of this simulator application is illustrated in Fig. 6. The experimental data showed that at the end of the deposition process (when the wafer was being transferred from the reactor back to the central wafer handler through the slit valve) the pressure in the reactor shot up briefly in a sharp spike. This seemed abnormal since there should have been no pressure gradient between the reactor and the CWH during wafer transfer. In an attempt to explain this phenomenon, we modified the Process Recipe module to simulate the following sequence: during the removal of the wafer from the reactor, the mass flow controllers would simultaneously open up completely for a second to flush out all the process gases. The resulting brief pressure spike in the reactor corresponded closely to experimental data obtained from the cluster tool, as seen in Fig. 6. Thus it is the combination of sensor integration and dynamic simulation, which provides a powerful tool for system analysis and potential improvement.

**Test-bed for Equipment Controller Development**

Finally, we have begun to exploit the dynamic simulator as a vehicle for equipment controller development. In order to enhance the versatility of equipment control for implementing various approaches to advanced process control, we have been bringing up a new tool control system based on a Brooks Automation™ platform. Just as in the design of any new equipment control system, a major challenge is to develop and validate the software recipes in the control system. If the real equipment must be the test-bed for control software debugging, significant cost and delay in equipment usage will result. The object here is to exploit the dynamic simulator for validating and debugging control software, rather than requiring dedication of real hardware to the task.

The ULVAC simulator has been designed so that the Process Recipe module can be isolated and/or disconnected from the equipment and process modules, thereby allowing the simulator to be operated in a fully manual way, i.e., one actuator (valve, flow controller, etc.) at a time. This makes the simulator a "virtual tool" operable by an external agent (i.e., a user or some other control system). We added a real-time interface (hardware interface cards and their software support) to the VisSim™ simulator, so that simulator PC could sense and respond to electrical actuation signals from the Brooks controller, and also return electrical signals from the simulator to the controller. We were then able to use the Brooks controller, and its software for process recipes, to control the ULVAC dynamic simulator, and thereby to see how the system - represented faithfully by the dynamic simulator - behaved under the control system process recipes in the Brooks controller.
Summary and Conclusions

We have developed a system level simulator for the deposition of tungsten in a multi-chamber CVD cluster tool. The overall architecture provides for the incorporation of manufacturing equipment dynamics as well as reduced order process models in a coherent manner. The individual modules have been integrated through the imposition of equipment controller recipes for the cluster tool operation. The Process Recipe determines the state of the valves, flow controllers, and heating lamps at each step of the process cycle, and defines a sequence of actions for the equipment to achieve them. In this way, the dynamics of a manufacturing process tool have been simulated at the system level. Validation of the dynamic simulator has been accomplished by comparison with experimental data for individual simulator components and more complex system-level behavior.

This dynamic simulator extends previous work by providing a more sophisticated representation of pumping systems, specifically multistage pumping arrangements, and by representing a full multichamber cluster tool. In this work, we have seen its applications to initial process optimization, interpreting important subtleties of equipment dynamics, and testing of control system software and operation. Given the manufacturing importance attributed to the details of equipment behavior - and particularly dynamics - this research direction appears of substantial promise to impact a variety of equipment-centered manufacturing issues.

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References


Figure Captions

Figure 1. Schematic draws of the Ulvac ERA-1000 CVD cluster tool. Reactors 1 and 2 are pumped by Roots pumps RBP1 and RBP2 backed by mechanical pumps RP1 and RP2 during processing, while they are pumped to base pressures prior to process by turbopumps TMP1 and TMP2, backed by mechanical pump RP4. Mechanical pump RP3 is used to evacuate the load lock. The various chambers are isolated from each other by slit (gate) valves V1, V2, and V3.

Figure 2. Variation of pumping speed with system pressure for turbo and mechanical pumps.

Figure 3. Comparison of reactor pressure and valve state signals during the initial part of the process cycle, i.e., wafer loading into the reactor for deposition. Data points are from dynamic simulation, while solid lines are experimental measurements using equipment state signal integration under LabView. Voltage signals for valve states (~3.0V) are scaled up by 100X for clarity. Valve state data from the simulation is scaled vertically to match amplitude of experimental signals.

Figure 4. Comparison of simulated deposition rate with experimental results reported by Rosler et. al. 16.

Figure 5. Analysis of deposition rate and WF6 conversion vs. temperature for different reactant ratios (H2:WF6 flow rate ratio = 20:1, 10:1, 5:1) for process pressures (a) 0.2 Torr and (b) 0.5 Torr.

Figure 6. Dynamic simulation (triangles) and experimental data (smooth curve) for pressure burst observed in reactor during post-deposition wafer unload.
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*A representative plot of the pumping speed as illustrated in ALCATEL ATP Catalog
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Figure 4. Comparison of simulated deposition rate with experimental results reported by Rosler et. al. \(^\text{16}\).
Figure 5 (a). Analysis of deposition rate and WF6 conversion vs. temperature for different reactant ratios (H₂:WF₆ flow rate ratio = 20:1, 10:1, 5:1) for 0.2 Torr pressure.
Figure 5 (b). Analysis of deposition rate and WF6 conversion vs. temperature for different reactant ratios (H₂:WF₆ flow rate ratio = 20:1, 10:1, 5:1) for 0.5 Torr pressure.
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