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DEVELOPMENT OF GENERIC SIMULATION MODELS TO EVALUATE WAFER FABRICATION CLUSTER TOOLS

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ABSTRACT

This document presents the purpose, development and applications of generic simulation models used to design, evaluate and demonstrate the potential performance of semiconductor wafer fabrication cluster tools. The use of this type of highly integrated equipment is growing rapidly within the semiconductor manufacturing industry. Because of the complex interactions involved in cluster tools, analytical models and calculations have usually been inadequate for determining system performance. However, discrete-event simulation models have proven to be quite beneficial to cluster tool developers and owners. The models are used to simulate the performance of equipment integrating multiple process modules in a radial configuration. A menu-driven interface permits analysts to customize, develop and exercise the model for a variety of cluster tools.

1 INTRODUCTION

This paper describes the generic simulation models developed by SEMATECH to assist with the design, operation and promotion of cluster tool equipment used in semiconductor wafer fabrication. The use of cluster tool equipment is growing rapidly within the semiconductor manufacturing industry. Because cluster tools integrate multiple process chambers within a vacuum environment, they reduce particulates and contamination. This advancement has resulted in enhanced yields at critical processing steps. In addition, cluster tools reduce the number of distinct operational steps. This simplifies process flows and increases the benefit of using automated material handling systems. Semiconductor manufacturers are currently utilizing these tools for metal stacks, poly-metal dielectric depositions and several other multi-level processes that are driven by yield considerations (Seidel and Stark 1991). Annual cluster tool revenues were $954M in 1991 with a 1995 forecast approaching $3B (Holden 1991).

The first cluster tool model developed by SEMATECH was in conjunction with an Equipment Improvement Project for a particular multi-chamber cluster tool for chemical vapor deposition (CVD). The model provided analysts with accurate information regarding tool performance and proved quite successful in simulating this equipment. The model was not developed to be generic and was not flexible enough to simulate other cluster tools. Inexperienced programmers had difficulty modifying data and exercising the model. This resulted in the development of the specifications for the generic cluster tool models discussed in this paper.

2 MOTIVATING PROBLEM

The SEMATECH Operational Modeling group saw a need for a system that would analyze, characterize, and predict capacity, cost and performance with enough flexibility to satisfy cluster tool designers and owners. Because cluster tools are essentially mini-fabs integrating several process modules (as opposed to the typical stand-alone equipment configuration), the task of evaluating and operating these tools can be even more complex than that of examining typical manufacturing work cells. Cluster tools normally limit buffer sizes to one wafer, therefore when a queue occurs at a module chamber, it will block the preceding chambers. Likewise, the performance of a cluster tool or particular module is severely affected by the reliability of other system components.

Static analytical models such as spreadsheets were unable to produce valid information except in simple experiments that ignored temporal effects and random occurrences. In order to adequately represent cluster tool behavior, a dynamic and stochastic modeling approach was determined to be necessary (Law and Kelton 1991).

2.1 System Requirements

The system requirements for the generic cluster tool models evolved from specifications issued for the first SEMATECH CVD cluster tool model and from the need to simulate a variety of other pieces of processing equipment that have a radial configuration. Cluster tool components included up to six process modules, two load locks, a central wafer handler and one or two wafer loading robots. For the purpose of satisfying tool owners, a holistic approach encompassed an entire operation that included additional resources such as labor pools, WIP stockers and metrology stations. Information concerning cluster tool performance as well as system performance was needed. A menu interface or user-friendly data file was required to input or modify data that would easily configure tool and system components.

2.2 Object-Oriented Analysis

An extensive object-oriented analysis (OOA) was performed to thoroughly understand the interactions of cluster tools and to assist in code development. The Shlaer-Mellor notation (Shlaer and Mellor 1988) was used to produce OOA models for information, communication, state and process interactions. The object-oriented analysis proved quite successful in communicating the model design specifications. However, the model was coded in SIMAN, not an object-oriented language, and thus does not perform like an object-oriented design. This became apparent when modifying and enhancing the generic cluster tool model.

3 MODEL DEVELOPMENT

The original Multi-Cluster Tool Model (Pierce 1991) has evolved into several application-specific models. The Multi-Cluster Tool Model integrates two cluster tools via a pipeline using a buffer robot. The Dual Cluster Tool Model contains two separate cluster tools with independent systems. This model essentially performs two experiments simultaneously, but offers users the ability to visually evaluate each tool's performance. Both of these models allow and animate one to six wafers per process chamber. The Batch Cluster Tool Model allows batch sizes of one to two hundred wafers per chamber. This model does not animate the wafers in the system, but does provide wafer counters at each resource. These models were created by Systems Modeling Corporation under contract to SEMATECH over a two year period.

3.1 Model Description

The simulation model developed to capture the interactions of a generic cluster tool was constructed using the SIMAN IV simulation language and several sets of FORTRAN modules. The FORTRAN modules are used primarily for a menu-driven user interface and for the complex robot movement calculations. The user interface contains a multiple level menu system that allows users to define a cluster tool's configuration. Menu system default parameters and changes made by the user are saved to an external file for recall by later simulation runs. This option allows the user to save several cluster tool configurations without having to reenter cluster tool options for every simulation run.

The generic nature of the cluster tool effort required a SIMAN experiment frame that is considerably larger than would be required for a specific cluster tool model. Over eleven hundred variables and parameters and five hundred distributions are provided in the experiment. Most of these system variables may be changed through the menu system. The initial effort required development in the OS/2 operating system with 8514 graphics. Reduced capability models execute under the DOS operating system with EGA graphics.

External data files were also included to define up to ten process plans and to assign process plans to wafers entering the system. Users have the option of either running an animation with the simulation model, one that details cassette and wafer flow through the system, or running a model-only execution. Animation screens are provided to detail critical system statistics.

3.2 Model Features

The generic cluster tool system was defined to contain six process modules, a central wafer handler robot, two load locks, buffer positions, a buffer robot and a metrology station. Figure 1 displays the animation layout of the Dual Cluster Tool Model. Additionally, each cluster tool model has up to three classes of operator pools for system tasks. The pools include transport operators for delivery of cassettes, technicians for system maintenance and repair, and super operators who are capable of performing all tasks.

Cassettes of wafers are transported into the cluster tool system by one of the operators. The system restricts the number of cassettes entering the system to a user-defined number. Prior to entry into the system, each wafer in a cassette is assigned a process sequence to follow through the cluster tool. Restrictions on wafer sequence assignment include only

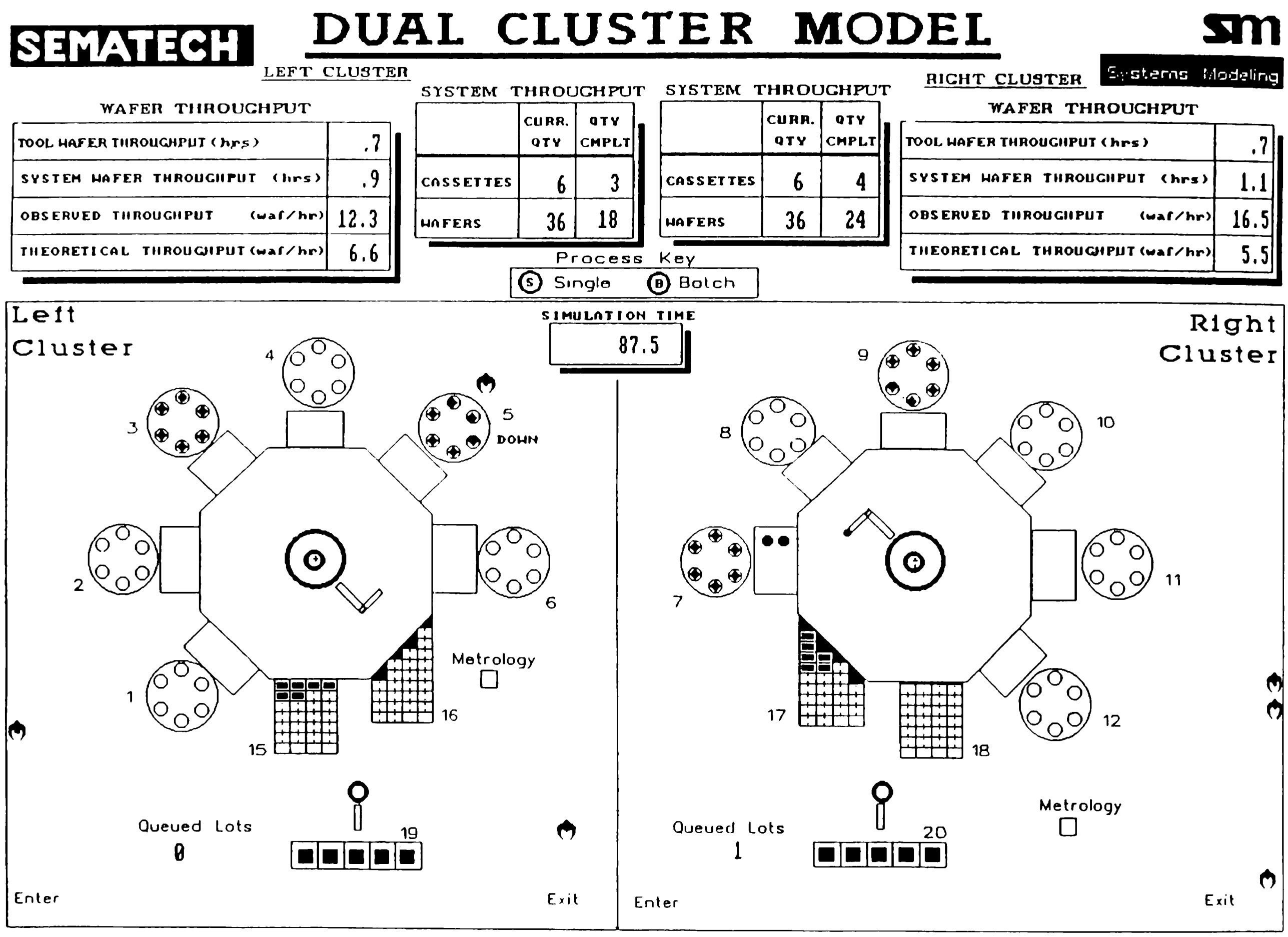

Figure 1: Dual Cluster Tool Model Animation Screen

the requirement that wafers in a cassette enter a load lock together and exit a load lock together. This maintains cassette or lot integrity.

Cassettes are placed in a buffer position and transferred by lot or by individual wafer to the entry load lock by the buffer robot. Once the lot has entered the load lock, processing begins on the wafers. Up to twelve user-defined delays may occur while wafers are entering the system at the load lock. Load lock processing prepares wafers for processing in the cluster tool's modules.

Transfer of the wafers to individual modules is accomplished via the central wafer handler robot. Each robot movement delay time is calculated in the FORTRAN subroutines to determine a precise delay that is dependent on the robot status. The robot delay time is determined from current robot location and destination and robot movement status (with or without wafer). The delay is calculated by determining the number of degrees the robot has to move and using user-defined values for angular sluing velocity, robot ramp up/down time and arm loading/unloading time.

Wafers delivered to the modules are processed either in a batch or as a single wafer. Each module may be configured to represent one of several different types of processes. Thirty-two options may be defined by the user in the menu system for each of the process modules. Many of these options define the distributions and parameters for equipment failures and repairs. Wafers can be processed at secondary modules when the primary module is busy or in a state of failure. System failures for all resources are incorporated into the simulation and may occur randomly or with a pre-defined number of process cycles. Technicians or Super Operators are requested when failures or maintenance requests occur. Thus, a failed resource will be unavailable until personnel respond and complete the repair.

Wafers follow their individual process plan and are grouped back into their cassette upon arrival at the exit load lock. Processing at the exit load lock is followed by a transfer to the buffer robot, a transfer to the buffer position, and a request for the operator to test the cassette at a metrology station or deliver the completed cassette to an exit point. Statistics are then collected for throughput and cycle time characteristics of the system.

One hundred and fifty time-persistent statistics are kept during simulation runs to detail equipment performance. Each module's characteristics are reported, including statistics for productive time, down time, idle time, time seized but not productive, and time spent waiting for the central wafer handler robot.

Validation and testing of this model uncovered several unique characteristics of cluster tools and the process plans they required. Of particular note was the fact that the system could be easily "deadlocked" with certain process plans. For example, a deadlock occurs when wafer #1, (occupying module #1) requests module #2 while wafer #2, (occupying module #2) requests module #1. Testing of secondary options for process modules revealed an increase of the frequency of deadlocks. Thoughts of adding exception policies under deadlock situations were dismissed due to the wide range of policies that might be implemented by various users. No single policy was agreed upon nor could any be adequately defined to allow for inclusion in the simulation model. Additionally, it was determined that most supplier applications would require a single process plan for all wafers processed through the cluster tool.

4 MODEL APPLICATIONS

The wide variety of cluster tool systems available in the semiconductor manufacturing industry prompted SEMATECH to direct this effort toward improving cluster tool design. This endeavor is part of SEMATECH's overall mission to create fundamental change in manufacturing technology and the domestic infrastructure to provide U.S. semiconductor companies with the capability to be world-class suppliers. The integration of modeling and simulation into the design of new manufacturing equipment reduces the development time required as well as providing a software tool to assist equipment owners with operational analysis.

4.1 Cluster Tool Systems

The generic cluster tool simulation models are used to design, develop, improve and operate a variety of cluster tool systems. Cluster tool developers are designing equipment with the following general formations; Multi-Process using different dedicated chambers, Multi-Process using the same chamber, and Multi-Chamber where each chamber performs the same process. Although modules are typically single wafer process chambers, batching or mini-batch modules are also available. These design decisions and combinations certainly affect performance indices such as lot cycle time and wafer throughput. The simulation models enable cluster tool developers to analyze these designs.

4.2 Instrument for Design and Promotion

These models are successfully being used to design and promote cluster tool equipment. The advantages of improved yields and the reduction of operation steps are significant to this competitive, technology-driven industry. Comparisons and contrasts between conventional stand-alone work cells and cluster tools are conducted by examining cycle time, throughput and capacity.

A wide variety of experiments can be conducted using the models. A typical experiment would include establishing the quantity, capabilities and basic sequence of module chambers. Redundant chambers may be included to counter the impact of modules with long processing times or poor reliability. Experiments may also include the analysis of wafer handlers and deadlock detection. Statistics concerning the operation activities such as labor, metrology and lot movements would then be used in evaluating the effect of cluster tools in a manufacturing environment. SEMATECH has used the generic cluster tool models to simulate eleven cluster tools from eight suppliers.

Although these models do not need to be animated in order to be effective, they are easier to communicate and configure if the movements and interactions are viewed on a monitor. Due to this feature and the attraction it creates with potential cluster tool buyers, these models are enabling SEMI/SEMATECH suppliers to promote as well as design their equipment. Representatives from these cluster tool suppliers are using these models to simulate their equipment with customers at trade shows and on sales visits.

5 SUMMARY

Because of the complex interactions involved with cluster tools and the proliferation of this kind of processing equipment within the semiconductor manufacturing industry, the generic simulation models have proven valuable for the purpose of designing, operating and promoting cluster tools. These models are exclusively available to SEMATECH and SEMI/SEMATECH member companies.

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