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DETAILED SIMULATION FOR SEMICONDUCTOR MANUFACTURING

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ABSTRACT

A factory model, ACHILLES, has been developed for detailed simulation of semiconductor manufacturing. Data for the model may be automatically collected from existing Computer Aided Manufacturing systems. Use of a model in factory control places stringent requirements on its accuracy and speed. ACHILLES is used to develop accurate factory-specific models which have the necessary rapid execution time on personal computers (386-type).

Another model called Thor performs detailed simulations of integrated processing tools. These very complex machines may incorporate several process steps into a single tool. They are currently being introduced into the semiconductor industry. There are many design and performance issues associated with production integrated processing equipment (PIPE) that can only be answered by detailed simulation.

Progress in factory modeling has been made in three areas. Validated simulation models are now being used to control factories. Factory models can now be used for all five factories from bare silicon to a finished computer. Performance models of integrated production equipment are being used to predict cycle time as a function of recipe.

1. INTRODUCTION

Semiconductor wafer fabrication is one of the most complex of modern manufacturing processes. A major process flow in a semiconductor factory may contain over 300 separate steps or operations. Examples of these steps include patterning (photolithography), thin-film etching, thin-film deposition, and oxidation. As a measure of the complexity of these factories, it is to be noted that describing one of these process flows may well require in excess of 1500 parameters. Typical semiconductor factories may have from four to ten major process flows and may process 20,000 or more wafers per month. [Glaseman, 1977]

Recent advances in electronics factory automation have widened the role and increased the importance of factory modeling. In conjunction with computer-aided manufacturing (CAM) systems, factory models are being used for on-line control of material movement. This use, in factory control, imposes stringent requirements for accuracy and computational speed. The development of models with the necessary accuracy and speed has required a fundamental reexamination of factory modeling. [Atherton et al. 1986, 1987, 1988, 1989,1990, Matsutama et al. 1990]

A second need for factory modeling results from the trend in electronics factories toward the complex integration of machines, material, and people. For example, in wafer fabrication factories (wafer fabs), equipment, instruments, and robots are being tied together to create workcells. Another example is the design of production integrated processing equipment (PIPE), containing multiple process chambers and material movement.

As manufacturing modules are connected to produce complex systems, the cycle-time performance of the overall system becomes difficult to predict. Simple spread-sheet calculations can no longer represent the variety of dynamic behavior exhibited by the system. In order to analyze, design, and control these new complex manufacturing systems, system-specific models are required for performance analysis.

Progress in detailed simulation in the semiconductor industry has been made in several areas. Validated factory models are making a direct impact on the factory floor. Factory models have been used to reduce cycle-time and to aid in scheduling [Atherton, 1989]. The complexity of the advanced integrated semiconductor-manufacturing equipment has required machine-specific models for effective equipment design, performance analysis, and control.

2. FACTORY CONTROL USING DETAILED-SIMULATION MODELS

Detailed-simulation models add the ability for factory control to computer-aided manufacturing (CAM) systems. In Figure 1, the factory is the physical system where lots interact with machines to produce products. Wafer fabs, in particular, generate a large volume of data describing this on-going production process. These data are generally collected, by the CAM system, for on-line reporting functions. While CAM system reports are useful, they provide limited capability for feedback and control. The CAM system simply builds an on-line database of factory measurements.

With the limits of the CAM systems in mind, the next block in Figure 1 shows the control loop provided by the ACHILLES factory model. ACHILLES is a detailed simulation model for factory operations. The model makes predictions of factory performance, based on current operating conditions. If the simulation results of the current factory operations do not meet production plans, ACHILLES may then be used for a variety of "what-if" scenarios. The results from these "what-if" simulations may then be used to provide management with the basis for seeking improved factory operation.

When the adjustments to factory operation, suggested by ACHILLES, are made on the factory floor, subsequent factory operations are tracked, and the control cycle is repeated. Since conditions in the factory change from shift-to-shift (i.e.,

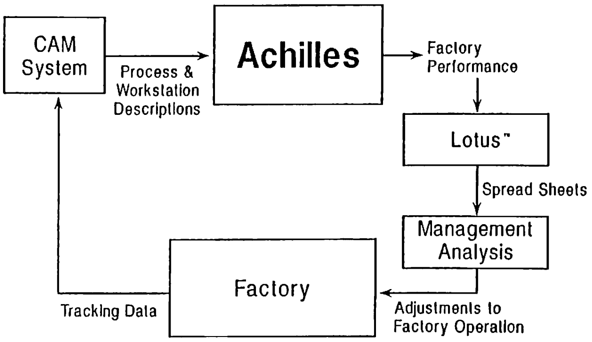

Figure 1. Factory Control

equipment failure), the initial conditions for the factory model need to be updated prior to each set of performance predictions.

In addition to control, the CAM system and the detailed-simulation model interact in a variety of ways to provide initialization of the model, and calibration and validation of both the model and the CAM system.

The CAM system makes detailed-simulation modeling easier because it automates collection of the ten-of-thousands of parameters necessary to initialize the factory description contained in the model. The parameters in the factory description are natural and basic to manufacturing operation. In fact, they were chosen because of manufacturing personnel's familiarity with them. (It is not necessary to derive artificial parameters such as the characteristics of queueing distributions in order to develop a factory description.) Parameters for a factory description include such fundamental entities as the number of machines, the batch size of the machine, process and setup times for an operation, and a sequence of process steps.

2.1 Calibration

A calibration exercise establishes that the factory has been accurately represented to the detailed-simulation model. The calibration exercise is especially important when the initial factory description is taken from a CAM system, since the CAM system contains an implicit, and often simplistic, factory model. The CAM factory description is used primarily for establishing tracking points, not performance analysis and factory control. Much of the information in the CAM system has not been evaluated since its initial input.

In calibration, the values of the parameters describing the factory are carefully evaluated for accuracy. In practice, the calibration exercise applies as much to the CAM factory data as it does to the factory description for the detailed simulation model. Process times, set-up times, and loading rules are parameters undergoing close scrutiny. Simulation results with the revised parameters are compared to operating data in a repetitive process of calibration.

Many minor inaccuracies in CAM system data are encountered, ranging from typographical errors to misplaced decimals. Other, more serious, errors have often been uncovered, such as workstation misassignments, inaccurate process times, and misreported equipment quantities.

2.2 Validation

Validation involves establishing that the model accurately describes the factory's behavior. In practice, a set of simulation cases are developed to predict well-characterized factory operating conditions. The detailed-simulation model's predictions are then compared to measurements of factory performance for cycle-time, throughput, equipment utilization, and bottlenecks. Because of the descriptive power of the detailed-simulation model, validation to an accuracy of 95+% may be expected. This level of accuracy is required for models used in factory control.

3. DYNAMIC CAPACITY PLANNING

Once validated, the factory-specific model provides an effective tool for establishing the dynamic capacity of the factory. Like every physical system, the capacity of a factory is finite. In addition, the capacity is not constant over time; it changes with production demands (product mix) and availability of equipment. Thus, factory capacity is a dynamic variable which is constantly changing. Knowing the dynamic capacity, as it changes in time, is imperative for effective factory management and control. If the production plan for the factory exceeds its dynamic capacity, then following the plan will build inventory and increase congestion. It will not, however, increase output.

With accurate initial conditions, the detailed simulation model may be used to predict lot completions by shift, or by workday. This prediction of production (lots out) is accurate because it is based on the actual dynamic capacity of the factory. The dynamic capacity for that shift (or workday) reflects the current equipment availability, work in progress (WIP), and the process or product mixture.

4. DETAILED-SIMULATION METHODOLOGY

In detailed-simulation models, the factory is treated as a physical system. These models deal in a very literal manner with the interactions of lots and machines, or more generally, with materials and resources. The factory operations are modeled in terms of fundamental events and their interactions. Specific lots enter the factory and then follow process flows moving from work area to work area. (See Figure 2.) In each work area, the lot may spend time in a queue waiting for processing. Eventually, the lot is loaded into a specific machine according to the loading, batching, and dispatching rules. Finally, the lot completes its manufacturing sequence with a cycle time that sums its individual processing times, setup times, and wait times. The detailed-simulation model mimics each, and every one, of these events.

Some of the features of the detailed-simulation model include process and product flows, batching and loading rules, dispatch rules, set-up rules, and models of maintenance and equipment reliability. As an example of the degree of detail, the model can simulate the time-varying partial loading of diffusion furnaces [ACHILLES 1987,1988,1989].

The detailed model exists as an algorithm, and thus, is independent of any implementation in software. Starting from this fundamental model, implemented as a discrete-event simulation in Fortran, an accurate representation of semiconductor factories has been achieved by adding successive levels of detail. This accuracy has been verified by comparing

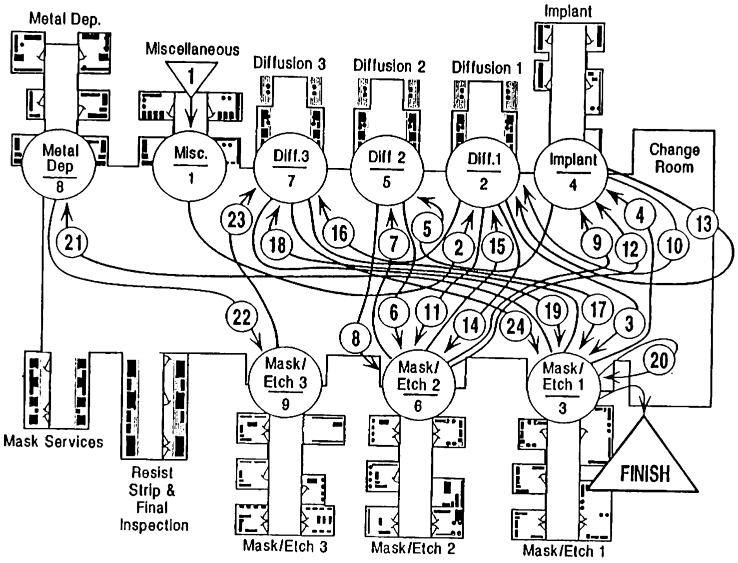

Figure 2. Simplified Factory Floor With Process Flows

the model's predictions of factory-performance variables, such as throughput, cycle times, capacities, equipment utilization, and bottlenecks, with measurements of actual factory operation.

By completely describing the factory, the detailed model becomes site specific for each factory. An illustration of the inputs and outputs of the ACHILLES model is given in Figure 3. The inputs, the factory description, are given in terms of tables of parameters specifying the properties of machines, process flows, inventory, and equipment availability. These tables and parameters provide a very natural description of the factory, and are immediately familiar to manufacturing personnel. Furthermore, these tables can be easily generated from the factory description residing on the CAM system.

In both the U.S. and Japan, detailed-simulation models of real factories are being run on advanced personal computers [Matsuyama, 1990]. These models are being used for factory design, factory performance analysis, and factory control. The speed of these models makes it possible to make mid-shift corrections based on actual factory occurrences. Furthermore, because the model provides detailed schedules of the time and order of lots completing, the model may be used for short-interval scheduling. Finally, the speed makes it possible to gain decades of synthetic factory experience in days.

An example of the speed is discussed below. A performance analysis, performed by a Japanese semiconductor company, required a three-month simulation of a medium-scale wafer fab. This factory was characterized in terms of 290 process steps and 20,000 wafers out per month. Using ACHILLES, this case was simulated in 1.75 hours on a Compaq 386, without a math co-processor. (With a math co-processor, this case was simulated in less than 30 minutes.)

In extending factory models to integrated production equipment, it was necessary to extend the theoretical understanding of buffer dynamics associated with finite storage in electronics factories. When finite storage capacity at a resource is considered, qualitatively different phenomena arise in modeling. Buffer dynamics may become dominant. While the classic linear chain-line problem has been well-studied, buffer dynamics for the hub structures (multiple process returns to a work area) of semiconductor manufacturing are much more complex. The major difficulty at this point is to establish criteria for avoiding lockup.

5. INTEGRATED EQUIPMENT

Highly complex integrated processing equipment is now being used in the semiconductor industry. Like the factory, this complex equipment requires detailed-simulation models in order to provide the accuracy necessary for performance analysis, design enhancement, and control.

Integrated processing equipment is also known as

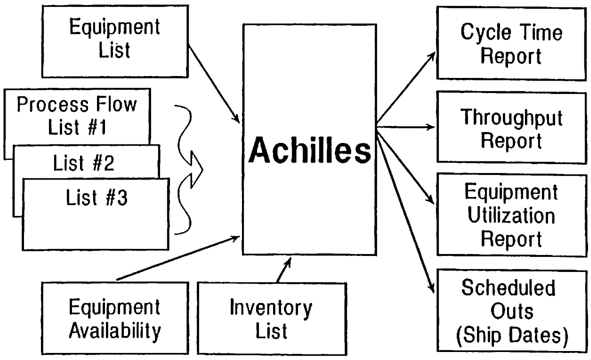

Figure 3. Factory - Specific Model : Inputs and Outputs

modular equipment, cluster tools, or production integrated processing equipment (PIPEs). PIPEs are capable of performing multiple, independent processing steps without leaving a controlled environment. By performing sequences of processing steps in a single machine, substantial yield improvements may be achieved. This automated processing reduces contamination and unnecessary human handling. The complexity of this integrated equipment, however, introduces new problems in equipment performance analysis.

Performance analysis predicts the throughput and cycle time of the machine as a function of equipment design, process recipe, and operating conditions. The process recipe that is being performed can strongly affect the cycle time of a cassette of wafers. Integrated processing equipment has complex, and often poorly understood, internal material movement. For example, a four-step process recipe may require nearly 30 operational steps, each having a time element associated with it. (See Figure 4.) Thus, the cycle time for a cassette may be over twice the cycle time expected from processing times alone. This operational complexity means that spreadsheet calculations are approximate at best, and may be misleading. Yet, it is the cycle time per cassette that determines the throughput of the machine.

6. THE MINI FACTORY

In performing multiple process steps, the PIPE is no longer a simple machine, but is in reality a mini-factory. Like a factory, the cycle time of individual wafers, and consequently of lots and cassettes, has time components that include transport, wait, and process. This simple observation explains why performance analysis of the PIPE is so much more complicated than for conventional processing equipment. When the wafer completes its operation sequence in the PIPE, its cycle time is a sum of its processing time, transport time, and wait time.

Since PIPEs are in reality mini factories, the same modeling techniques used in ACHILLES, the detailed factory model, are used in THOR, the detailed-simulation model for PIPEs. In extending factory models to integrated equipment, it was necessary to extend the theoretical understanding of buffer dynamics associated with finite storage in production systems. When finite storage capacity at a resource is considered, qualitatively different phenomena arise. Buffer dynamics often becomes dominant, and lockup may occur.

Thus, in order to design effective PIPEs, engineers must develop an understanding of buffer dynamics and of the competition for processing resources. In one PIPE design, wafers may spend time in the process chamber waiting for the next processing step. In a second design, an internal buffer may be provided, and wafers may move to this internal buffer if no processing resource is available. In a third design, multiple process chambers may be capable of performing the same process step. This last design may be used in conjunction with either waiting in the chamber or in the internal buffer.

Further complexity in analysis of PIPEs results if the path of the wafer through the machine (mini factory) is dependent on the dynamic condition of the machine. For example, in the design with an internal buffer, a wafer may spend additional time in the buffer if the next processing chamber is unavailable. However, use of the buffer will also acquire additional transport time in addition to the wait time. Thus, the additional transport times in the PIPE can be critical in establishing cycle-time performance.

6.1 Pipe Performance Analysis

The detailed-simulation models that have been used for PIPE performance analysis accurately simulate, in detail, the complex interactions of wafers and the interconnected modules for processing, transport, and storage. Wafers enter the PIPE and then attempt to follow a process recipe. However, the process steps in the recipe are only a fraction of the total steps necessary in the overall operations sequence to complete that wafer. Hence, one requirement of the PIPE model is that it account for all operations steps (Atherton, 1990).

The detailed-simulation models for PIPEs are defined in terms of rules that are given by logic tables, if-then constructs, and formulas. The rules define the dynamic interaction of wafers and the PIPE modules. These dynamic interactions may be represented graphically by the operations graph (Figure 4). The technique of discrete-event simulation is used to derive numerical results from the model of material movement.

These detailed-simulation models have been used to analyze the performance of a variety of integrated equipment. Processing applications include: photolithography, sputtering, plasma etching, and CVD. The simulated cycle time results have been compared to measurements of machine performance. The agreement between the model's predictions and actual machine performance is 95+%.

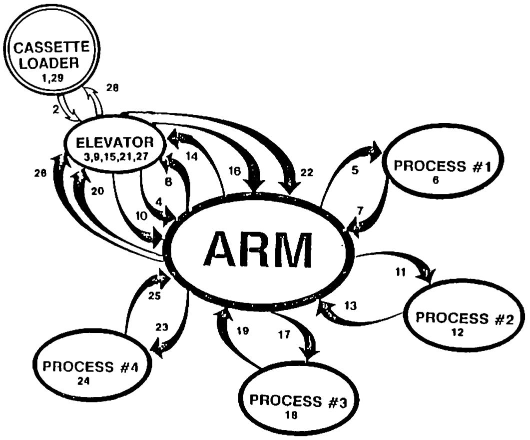

Figure 4. OPS Graph for PIPE

7. PIPE WORKSTATION ANALYSIS

Some performance analysis problems may require the use of both the factory-level detailed-simulation model and the PIPE detailed-simulation model. For example, consider the introduction of PIPEs into the factory environment. The PIPE may replace two or more stand-alone machines. (A workstation is a set of one or more identical machines.) Thus, the capacity of the PIPE workstation needs to be evaluated in terms of the capacity of the factory with conventional processing equipment.

The equipment-performance model provides the cycle time per cassette for a single PIPE. This parameter, in turn, is used as a process time in the factory-level model to determine overall factory performance. This factory performance with the PIPE(s) may then be compared to the factory performance with conventional equipment.

8. SUMMARY AND CONCLUSIONS

Detailed simulation models are required for high accuracy and speed in industrial applications such as factory control. The ACHILLES factory model has been developed for detailed simulation of semiconductor manufacturing. It is capable of handling factory descriptions and initial conditions involving tens of thousands of parameters. In factory applications, almost all of these parameters are already stored in computer-aided manufacturing (CAM) systems. Factory-specific models can be initialized by down-loading the parameters from the CAM system.

The CAM system and ACHILLES interact in a variety of ways that enhance their usefulness in factory management. Operating data on the CAM system provides for improvement of model accuracy through calibration and validation. The validated factory-specific model can then be used to provide factory control in conjunction with the CAM system. Validated factory-specific models are 95+% accurate in predicting factory performance. The execution speed on 386-type computers is sufficiently fast that mid-shift factory corrections are possible.

Highly complex integrated processing equipment in now being used in the semiconductor industry. Since this equipment is in effect a mini factory, it exhibits most of the complexities of the dynamics of a full factory. Key issues in the detailed modeling of such production integrated processing equipment (PIPE) are dealing with buffer dynamics and lockup. Detailed simulation of integrated equipment is performed using the THOR simulation model. It has been applied to integrated equipment for sputtering, photolithography, plasma etching, and CVD.

In evaluating the performance of integrated equipment in the factory environment, both detailed models are useful. The THOR simulation can determine the cycle time of the PIPE for a cassette of wafers as function of the PIPE process recipe. The ACHILLES simulation can then evaluate the performance of a PIPE workstation in the factory environment.

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