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Automation and Integration in Semiconductor Manufacturing

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1. Introduction

Semiconductor manufacturing spans across many manufacturing areas, including *wafer manufacturing* where electronic circuitry is built layered on a wafer, *chip manufacturing* that involves circuit probing and testing, and *product manufacturing* from which the final IC (integrated circuits) products are assembled, and finally tested. Semiconductor manufacturing is well known as the most challenging and complicated production systems that involve huge capital investment and advanced technologies. Fabrication of semiconductor products demands sophisticated control on quality, variability, yield, and reliability. It is crucial to automate all the semiconductor manufacturing processes to ensure the correctness and effectiveness of process sequences and the corresponding parameter settings, and to integrate all the fab (semiconductor factory) activities to provide the efficiency, reliability, and availability of semiconductor manufacturing. Automation and integration are the keys to success in modern semiconductor manufacturing. This chapter deals with the automation and integration problems in semiconductor manufacturing.

Automation plays an increasingly important role in daily operations of semiconductor manufacturing. Like in the other industry, automation in semiconductor manufacturing originated from replacing human operators in tasks that are routine but tedious, or that should be done in dangerous, hazard environments. The ultimate goal of automation in semiconductor manufacturing is to eliminate the need of humans in fab operations. Depending on different degrees of operator attention and automatic control, fab operations are usually classified into three modes: *Manual*, *Semi-Automated*, and *Fully Automated*. Traditional manual mode of operations where fab tools (semiconductor equipment) are operated without computer assistance is very scarce to find in existing commercial fabs. Semi-automated operations are still quite popular in 6- and 8-in fabs where processing tools are automated and controlled by computers, but fab operators are responsible for the movement of materials from and to the tools. Fully automated mode is now well established in 12-in (300-mm) fab operations where there are complete computer-controlled processing and handling. Automation in semiconductor fabs has saved billions of dollars by eliminating and reducing misprocessed products, and improved operational efficiency by reducing human times and costs spent in data entry and product movement.

Automation in semiconductor manufacturing has to provide the intelligence and control to drive the operations of semiconductor fabrication processes, in which layers of materials are deposited on substrates, doped with impurities, and patterned using photolithography to generate integrated circuits. Automation in semiconductor industry adopts the hierarchical machine control architecture that allows for quick insertion into current fabrication facilities. In the architecture, the lower-level of the hierarchy includes embedded controllers to provide real-time control and analysis of fabrication equipment where sensors are installed for in situ monitoring and characterization. At the higher-level, more complex, context-dependent combination of process or metrology operations or materials movements is handled, sequenced, and executed.

Contemporary semiconductor manufacturing increasingly uses cluster tools, each of which consists of several single-wafer processing chambers, for diverse semiconductor fabrication processes, shorter cycle time, faster process development, and better yield for less contamination. To illustrate the automation in semiconductor fabrication equipment, we adopt a PDV (Physical Vapour Deposition) cluster tool as an example to convey the idea of hierarchical architecture and the associated communication protocols, intelligent job scheduler/dispatcher, as well as process modelling, monitoring, diagnosis and control.

Semiconductor manufacturing integration encompasses the allocation, coordination and mediation among system dynamics and flows of information, command, control, communication, and materials, in a timely and effective way. Because of the ever-increasing complexity of semiconductor devices and their manufacturing processes, computer or CIM (Computer-Integrated Manufacturing) systems are essential for the smooth integration of semiconductor manufacturing. However, CIM systems generally are loosely coupled, monolithic, and difficult to extend to support the new needs. Researchers and practitioners have been devoted to build an integration framework with a common, modular, flexible, and integrated object model to tackle the critical problems in semiconductor manufacturing integration: islands of automation, emergence of new applications, distributed systems, as well as data integrity.

Automatic Materials Handling System (AMHS) is considered as a must in modern semiconductor manufacturing environment. In a large-scaled AMHS, there are usually hundreds of OHT (Overhead Hoist Transport) vehicles running in dozens of loops. The management and control of even a single AMHS loop has proved to be crucial but difficult (Liao, 2005). The transport requirements of AMHS vehicles among different loops are usually changing from time to time, according to the dynamic WIP (Wafers in Process) distribution, process conditions, and equipment capacity. It is therefore needed an effective methodology to integrate AMHS with other CIM systems to cope with the dynamic changes on the material handling services. We propose an intelligent AMHS management framework to optimize and manage the integration of fab operations with AMHS.

Development of automation and integration usually requires the help of system definition, validation or verification techniques. To the large dynamic systems like semiconductor manufacturing, it is always difficult and challenging to define, validate, and verify their system dynamics, not to say, to consider their various and changing control and managerial policies. In this chapter, we adopt Petri-net techniques (Zhou & Jeng, 1998; Liao *et al*., 2007) to build models for a PVD cluster tool. Mathematical analysis and computer simulation are conducted to verify and validate the correctness of the automation and integration in the developed models.

This chapter is organized as follows: Section 1 describes the need of automation and integration in semiconductor manufacturing. In Section 2, automation in semiconductor manufacturing is detailed. Section 3 gives an illustrating example of automation of a representative cluster tool in semiconductor manufacturing. Section 4 discusses the integration problems and issues in semiconductor manufacturing. An intelligent, integrated framework is presented in Section 5. Section 6 deals with the modelling, validation and verification of processing and material handling systems in semiconductor manufacturing. Finally, Section 7 concludes this chapter with some visions and challenges to the automation and integration in future semiconductor manufacturing.

2. Automation in Semiconductor Manufacturing

2.1 Considerations of Semiconductor Manufacturing Automation

Reasons for fab automation are from many aspects, including lower costs, increasing fab performance, reliability and product quality. Very basically, fab automation should execute fab operations which are sequences or collection of the following activities:

- *Lot selection* (or *dispatching*) to determine which lot to process next
- *Transport* to locate and move the lot
- *Setting of process condition and recipe* to setup processing conditions
- *Process start* to initiate processing
- *Process data collection* to record and report measurement data during processing
- *Go/No-Go quality gating* to determine the acceptance of the processing results
- *Exception handling* to handle and solve production exceptions
- *Alarm handling* to handle and react predefined alarms

In addition to automate the above fab activities, automation in semiconductor fabs should also avoid or prevent frauds or problems in daily fab operations. Common problems in fab operations are listed as below:

- Wrong lot goes to the tool,
- Unable to get the lot when required,
- Unable to get the reticle (photolithography mask) when required,
- Wrong recipe is used,
- Inefficient recipe setting or tool setup,
- Errors or incomplete data are collected,
- Tools are not well monitored,
- Tool capacity is not fully utilized, and so on.

Semiconductor manufacturing automation usually involves business, technical, and economic issues. In addition, the following considerations must be addressed:

- Message sequencing standards between a tool and the host computer
- Load/unload port design
- Materials handling
- Wafer cassette/pod identification
- Recipe ID and recipe body check
- Process control
- Engineering review and control
- Manual override

For decades, semiconductor manufacturing operations have evolved from manual, semi-automation to fully automation. Considerations of automation are no longer on the issues in adoption of automation or not or full support from the management, because automation is considered as mandatory and must-have in contemporary fab operations. Semiconductor manufacturing arose from the interface and control of lot track in/out operations between processing tool and the host computer, MES (Manufacturing Execution System). Such centralized systems are proprietary, not flexible and very expensive to sustain the operations and reliability due to the weakness of single point of failures. Thanks to the advance of computer and network technology, modern fab automation moves toward a hierarchical and distributed architecture.

2.2 Hierarchical, Distributed Automation Architecture

Semiconductor manufacturing operations are inherently distributed. Most applications take place at physically separated locations where local decisions are made and executed. Modern distributed computing techniques enable semiconductor manufacturing to automate its processes in an open, transparent, and scalable way. The distributed automation architecture is drastically more fault tolerant and more powerful than stand-alone mainframe systems.

Due to the complexity of shop floor operations in semiconductor manufacturing, semiconductor manufacturing automation is hierarchically decomposed into three levels of control modules, each of which is linked by means of a hierarchical integrative automation system. In the automation hierarchy, flow of control is strictly vertical and between adjacent levels; however, data are shared across one or more levels. Each control module decomposes an input command from its supervisor into: (1) procedures to be executed at that level; (2) subcommands to be issued to one or more subordinate modules; and (3) status feedback sent back to the supervisor. This decomposition process is repeated until a sequence of primitive actions is generated. Status data are provided by each subordinate to its supervisor to close the control loop and to support adaptive actions.

In view of equipment functionality or process consistency, a fab can be considered as being composed of a series of manufacturing cells. Within each cell, there is a computer system for planning, controlling, and executing the production activities in the cell. Such manufacturing cells are autonomous, i.e., having the power to self-government. Each cell is capable of managing the fabrication of wafers within it, involving automatically distributing jobs to all workstations and equipment in the cell, monitoring the states of each workstation and equipment, and feeding back these states to its upper-level supervisor systems. Fig. 1 depicts the three-levelled hierarchical, distributed architecture of semiconductor manufacturing automation.

Automation in semiconductor manufacturing comprises three categories: *Tool Automation*, *Cell Automation*, and *Fab Automation*. Tool Automation includes automation of dry and wet atmospheric and vacuum wafer handling systems, integrated front-end modules, load ports, FOUP (Front Opening Unified Pod) tracking, alignment, calibration and e-diagnostics.

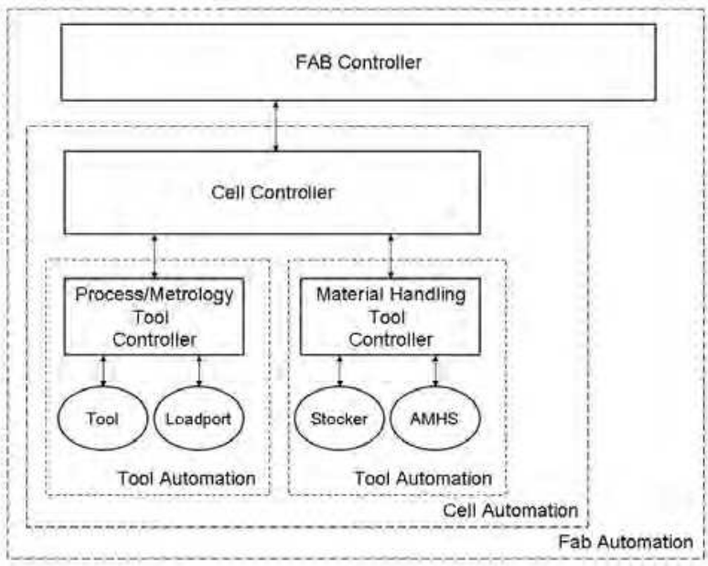

Fig. 1. The Three-levelled Hierarchical, Distributed Automation Architecture

Tool Automation also consists of wafer sorters, reticle inspection tools, reticle stockers, wafer stockers, and Automated Materials Handling Systems (AMHS). Cell Automation manages materials movement and control, tool connectivity, station control, and advanced process control (APC). Fab Automation covers system integration, manufacturing execution, scheduling and dispatching, activity management, and preventive maintenance.

3. Tool Automation

3.1 Interfacing to Semiconductor Tools

Escalating device complexity and cost have driven the demand for increased levels of automation and isolation in modern fabs. The goal of tool automation is to enable seamless integration among process control, auto identification (ID), load ports, environment control, data collection, and advanced robotics for wafer movement. However, the very challenge arose from interfacing the many and various semiconductor tools.

In 1978, Hewlett-Packard (HP) proposed to Semiconductor Equipment and Materials International (SEMI) to establish standards for communications among various semiconductor manufacturing tools (equipment). SEMI later published the SECS-1 standards in 1980 and the SECS-II standards in 1982. SECS is a point-to-point protocol via RS-232 communication. SECS is also a layered protocol consisting of three levels: Message Protocol, Block Transfer Protocol, and Physical Link (RS-232). The Message Protocol is used to send SECS-II messages between the host computer and the tool. Each SECS-II message, also referred to as a transaction, contains a primary message and an optional secondary reply message. SECS-II messages are referred to as *S*treams and *F*unctions. Each message has a *S*tream value (*S*x) and a *F*unction value (*F*y), where *S*treams are categories of messages and *F*unctions are specific messages within the category. The *F*unction value is always an odd number in a primary message, and even, or one greater, in the associated secondary reply. Fig. 2 illustrates the sequence diagram of an example of the message of *S*tream 1 *F*unction, *S*1*F*1 ("Are You There"). Note that in Fig. 2, the host computer sends the message

*S*1*F*1 to the tool to query the equipment status. The tool then replies to the host computer with a message of *S*1*F*2 after receiving the *S*1*F*1 message.

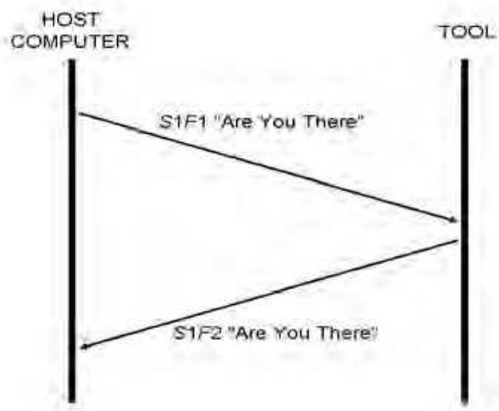

Fig. 2. Sequence Diagram of A *S*1*F*1 Transaction

The structure (or layout) of a SECS-II message defines all the data items for the message. The layout of a SECS-II message is what follows the *S*tream and *F*unction notation. An example of the message layout of *S*2*F*11 is given as below:

*S*2*F*11
<L
    <A "START">
    <L>
>.

Note that the above *S*2*F*11 message is represented in SML (SECS Message Language) format. Similar to the notation used in SEMI Standards, SML is a more precise and regular notation language for describing SECS-II messages and is often used in semiconductor tool manuals.
The Block Transfer Protocol (SECS-I) is used to establish the direction of communication and provide an environment for passing message blocks. Due to the data size limitation in the SECS-I protocol, a SECS-II message may not fit into one SECS-I transaction, i.e., over-sized. The SECS-II message is then divided into smaller blocks, and sent in one block at a time, which is referred as multi-block messaging. As general communication protocols, SECS-I defines four different timeouts during the handshaking process: T1 (inter-character timeout), T2 (protocol timeout), T3 (reply timeout), and T4 (inter-block timeout). No interleaved blocks are allowed from the tool to the host. That is, the tool always sends all blocks of one message before sending the first block of the next message. This simplifies the job of the host. However, the tool allows the host to send interleaved blocks, if it so chooses.
The tool may initiate several simultaneous outstanding SECS transactions by sending a secondary message before the host has sent the reply to a previous message. This occurs when the tool reports alarms and events.
Before SECS-II messages can be sent between the host computer and the tool, communications must be first established by a *S*1*F*13 (Establish Communications Request)

message, which is sent following an initial setup or after a long period of not communicating.

Contemporary semiconductor manufacturing adopts the Generic Model for Communications and Control of Manufacturing Equipment (GEM) standards so that fab host software can communicate with the manufacturing tool for monitoring and controlling purposes. The GEM standard, frequently referred to as the GEM or SECS/GEM standard, is formally designated and referred to as SEMI Standard E30. GEM defines messages, state machines and scenarios to enable fab software to control and monitor manufacturing tools.

SEMI Standard High Speed Message Service—Single Session (HSMS-SS) defines TCP/IP networking communication protocols for host software and a GEM tool. All GEM compliant manufacturing tools use a consistent interface to communicate with a GEM capable host either via TCP/IP (the HSMS-SS standard, SEMI E37.1) or RS-232 (the SECS-I standard, SEMI E4) protocols.

In order to facilitate the integration of automation of all the tools, contemporary semiconductor fabs demand single communication line between every tool to the host. The Equipment Front End Module (EFEM) must be integrated through the tool rather than connected directly to the host. Tool supplier must provide hardware on the tool to connect to the fab local area network (LAN). This communication connection must comply with HSMS protocol and be able to transmit and receive all SECS-II messages. Fig. 3 shows the idea of single communication link.

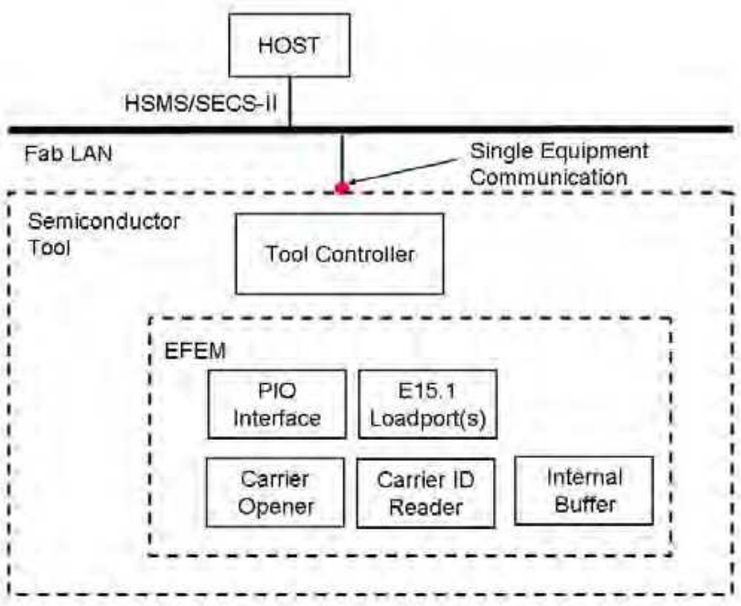

Fig. 3. Single Communication Link

3.2 Automation in Cluster Tools

Semiconductor manufacturing operations are inherently distributed. Most applications take place at physically separated locations where local decisions are made and executed.

Modern distributed computing techniques enable semiconductor manufacturing to automate its processes in an open, transparent, and scalable way. The distributed automation architecture is drastically more fault tolerant and more powerful than stand-alone mainframe systems.

Contemporary semiconductor manufacturing increasing uses cluster tools, each of which consists of several single-wafer processing chambers, for diverse semiconductor fabrication processes, shorter cycle time, faster process development, and better yield for less contamination. To illustrate the automation in semiconductor fabrication equipment, we adopt a PDV (Physical Vapour Deposition) cluster tool as an example to convey the idea of hierarchical architecture and the associated communication protocols, intelligent job scheduler/dispatcher, as well as process modelling, monitoring, diagnosis and control.

PVD cluster tools are used for vacuum film deposition on semiconductor wafers and are widely used in the fabrication of modern VLSI (Very Large Scaled Integration) circuits. The films provide conducting regions within the device, electrical insulation between metals, and protection from the environment. As PDV techniques provide more precise controls such as uniform film thickness, better crystal structure especially for compound semiconductor, PVD clusters are widely applied in contemporary fabs.

A PVD cluster tool is a fully automated system using a single wafer processing, multi-chambered design. Each single-wafer processing chamber performs a unique process without chamber redundancy. After being process, a wafer will be held by the process chamber for further pickup by a transporter. Wafer input and output are through cassette loadlocks. Integration among different process modules and allowing simultaneous processing of different routes significantly increase the operational complexity and cost. Wafer operations of different process flows compete for the use of functional modules of a PVD cluster tool such as robot transporters, buffer space and processing chambers.

The multi-chambered design of the PVD cluster tool allows for precise control over all process parameters to enhance consistency and uniformity among wafers. Major components of a PVD cluster tool include mainframe, process, transport, and cassette modules. Each module has its specific function and is mechanically linked together to form an integrated environment to execute a defined sequence of flows. Fig. 4 demonstrates an example of 300-mm PVD cluster tool configuration.

The mainframe module consists of two major chambers: transfer chamber and buffer chamber, each of which is with a robot of transfer modules. Each process module performs a unique process. Each process chamber has a wafer lid to facilitate wafer exchange with the wafer handling robot. A chamber must be at the atmospheric pressure level before the lid can be opened. Recipe change within a process chamber is allowed and it takes time to setup. A chamber can be switched to various processes, but sometimes the required setup time is significant and usually need to do some testing after switching. Therefore, a process chamber is usually fixed to some specific process only. Cassette modules include cassette loadlocks that provide access to the cluster tool system while isolating wafer process routes from atmosphere. A PVD cluster tool is usually equipped with two cassette loadlocks. The cassette loadlock provides a storage and indexing capability for programmable wafer processing sequences. Two loadlocks can operate independently to increase system throughputs and flexibility. Integration among various process modules has advantages such as cycle time reduction, footprint reduction, and so on. However, along with the flexibility, the operational complexity increases significantly.

The PVD cluster tool is a single-wafer processing tool where each chamber can accommodate at most only one wafer. Wafer movement is done mechanically by one robot in the transfer chamber and one robot in the buffer chamber. After a FOUP arrives at a loadport of the cluster tool, the cassette is loaded into a cassette loadlock which is then pumped down to vacuum. The buffer chamber robot picks a wafer from the cassette and places it in the degas chamber where the wafer is re-oriented and degassed. After being degassed, the buffer chamber robot then takes the wafer from the degas chamber and places it in a preclean chamber for preclean with plasma etching. After completing the preclean process, the transfer chamber robot picks the wafer from the preclean chamber and places it on one process chamber for deposition of aluminium (Al), titanium (Ti), or titanium nitride (TiW), as specified by the processing recipe of the wafer. After completing the deposition process, the wafer is carried by the transfer chamber robot again from the process chamber and places it in a cooldown chamber in which the wafer is cooled down.

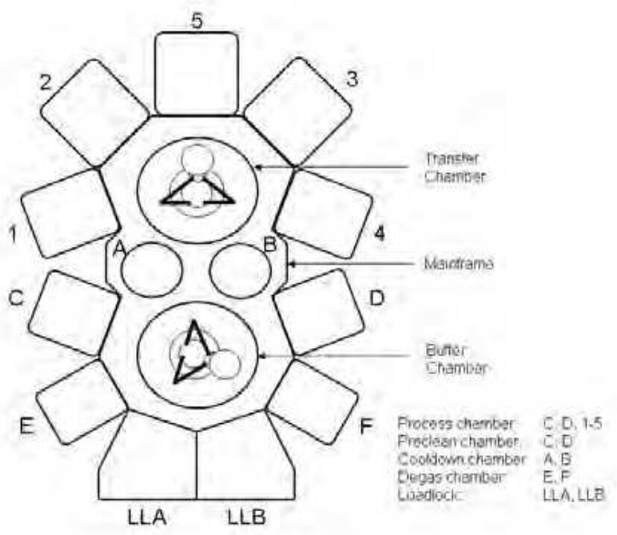

Fig. 4. An Example of 300-mm PVD Cluster Tool Configuration

Once the temperature of the wafer reduces to the specific degree, the buffer chamber robot brings the wafer from the cooldown chamber and places it back to the same cassette from which the wafer is removed. After all wafers in the cassette complete the processing and return to the cassette, the loadlock chamber raises its pressure to atmospheric pressure and returns the cassette to the FOUP in the loadport. This then completes the entire process. Arrows in Fig. 5 indicates an example of the process flows executed in the PVD cluster tool, where the process starts at s1 (arrival at the loadlock), then goes to s2 (degassed), s3 (cooling), s4 (deposition), s5 (cooling), and then return to the loadlock to complete the process.

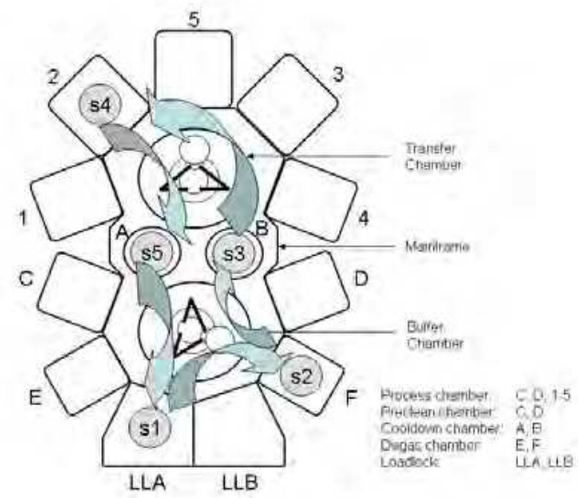

Fig. 5. An Example of Process Flows in the PVD Cluster Tool

The configuration of a PVD cluster tool allows itself to execute multiple process flows simultaneously. This capability of parallel processing of multiple process flows facilitates better utilization of tool capacity. However, operational complexity and difficulty in its tool automation become increased and challenging. Due to the potentially circular wait of shared resources (for example, a wafer is a process chamber is waiting to be transferred to a cooldown chamber where there is another wafer waiting to be the process chamber), the cluster tool system is inherently subject to deadlocks, which may cause the entire system to halt and thus ill-functioned. Tool automation in such a system is no longer simply the implementation of a predefined sequence of logics, code, or programs. It involves the knowledge and techniques from operation research, optimization, system engineering, and so on.

4. Computer-Integrated Semiconductor Manufacturing

Semiconductor manufacturing integration encompasses the allocation, coordination and mediation among system dynamics and flows of information, command, control, communication, and materials, in a timely and effective way. According to the definition of ITRS 2007 Roadmap (ITRS 2007), semiconductor fab integration is divided into five thrusts: *Fab Operations*, *Production Equipment*, *Materials Handling*, *Fab Information & Control Systems*, and *Facilities*. Among these five thrusts, Fab Operations is the key driver of requirements and actions for the other four thrusts, while Fab Information & Control Systems is the facilitator to the integration in semiconductor manufacturing.

Because of the ever-increasing complexity of semiconductor devices and their manufacturing processes, computer or CIM (Computer-Integrated Manufacturing) systems are essential for the smooth integration of semiconductor manufacturing. However, CIM systems generally are loosely coupled, monolithic, and difficult to extend to support the

new needs. Researchers and practitioners have been devoted to build an integration framework with a common, modular, flexible, and integrated object model to tackle the critical problems in semiconductor manufacturing integration: islands of automation, emergence of new applications, distributed systems, as well as data integrity.

SEMATECH (1995, 1998) created a CIM Framework based on the Microelectronics Manufacturing Science and Technology (MMST) Project in Texas Instruments (TI), a member company of SEMATECH. The CIM Framework intends to promote integration on the shop floor, reduce costs, and increase reuse through object-oriented technology. Based on the definition of SEMATECH, a framework is a *software infrastructure* that creates a common environment for integrating applications and sharing information in a given domain. The CIM Framework is a framework of components that provide the functionality common across applications (programs consisting of a collection of interoperating objects). The CIM Framework also enables integration of those applications.

A set of functional components are defined and designed in the SEMATECH CIM Framework Specification to work together to form an integrated manufacturing system. The functional components of the CIM Framework Specification are grouped by application areas. The CIM Framework adopts CORBA (Object Management Group, 1999) as the common interface that defines the object-oriented architecture of an object request broker, which enables and manages interoperability between objects and applications across heterogeneous computer boundaries. The functional components in each application area are tabulated in Table 1. Fig. 6 demonstrates the integration of the SEMATECH CIM Framework.

Application Area	Functional Component
Factory Services	▪ Document Management ▪ Version Management ▪ History Management ▪ Event Broker
Factory Management	▪ Factory ▪ Product Release ▪ Factory Operations ▪ Product Request
Factory Labour	▪ Person Management ▪ Skill Management
Process Specification Management	▪ Process Specification ▪ Process Capability
Schedule Management	▪ Dispatching
Machine Control	▪ Machine Management ▪ Recipe Management ▪ Resource Tracking
Material Management	▪ Product Management ▪ Durable Management ▪ Consumable Management ▪ Inventory Region ▪ Product Specification ▪ Bill of Material
Material Movement	▪ Material Movement
Advanced Process Control	▪ PlugIn Management ▪ PlugIn Execution ▪ Control Management ▪ Control Execution ▪ Control Database ▪ Data Collection Plan

Table 1. Functional Components by Application Area in SEMATECH CIM Framework

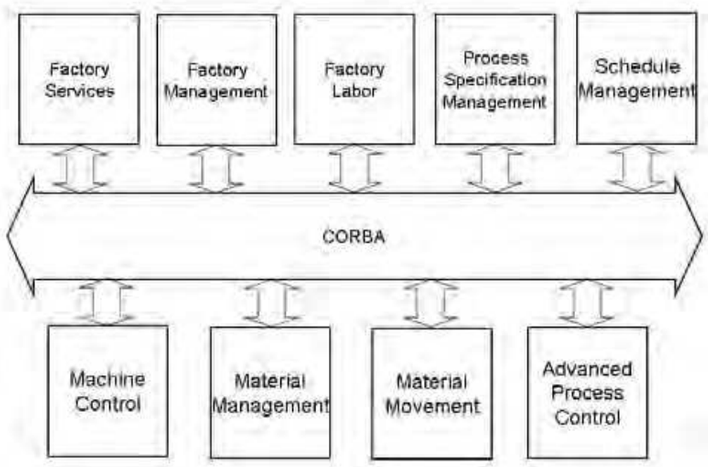

Fig. 6. SEMATECH CIM Framework

5. Intelligent and Computer-Integrated Framework for Prioritized Manufacturing Services

Automatic Materials Handling System (AMHS) is considered as a must in modern semiconductor manufacturing environment (International SEMATECH, 1999). There are usually hundreds of vehicles running in dozens of loops in an AMHS. The transport requirements of AMHS vehicles among different loops are usually changing from time to time, according to the dynamic WIP distribution, process conditions, and equipment capacity. It is therefore needed an effective methodology to integrate AMHS with other CIM systems to cope with the dynamic changes on the materials handling services. We propose an intelligent AMHS management framework to optimize and manage the integration of fab operations with AMHS.

Daily fab operations are usually differentiated to several levels of priorities to cope with frequent process changes, engineering experiments, or pilot production. In a fab, a lot is granted as high priority (named as Hot Lot or Super Hot Lot) if either it is going to execute several operations for experiments or inspections on process conditions; or it was borne as a pilot or risk lot for process characterization or design validation before releasing a new product for production (Liao & Tsai, 2006). Hot lots are given to higher priority to reduce their cycle time. Operations of high priority lots can be either pre-emptive against normal operations, or capacity-reserved for no-wait services (Liao & Wang, 2004; Liao & Wang, 2006). The introduction of high priority lots has the potential to shuffle the regular production and should be well managed (Ehteshami *et al*., 1992). The AMHS management framework should be effective to minimize the transport time of hot lots while optimizing the use of underlying resources for regular production.

In order to support prioritized automated materials handling services in semiconductor manufacturing, Liao proposed a management and control framework (Liao, 2002) as

depicted in Fig. 7, where there are four main modules in the framework: Service Level Agreement Management (SLAM), AMHS Traffic Forecast (AMHSTF), Dynamic OHT Allocation (DOHTA), and Dynamic OHT Dispatching (DOHTD). Several QoS (Quality of Service) levels are first defined to provide differentiated automated materials handling services to transport jobs. Service-level specifications (SLS) are used to describe the appropriate QoS parameters which the AMHS should take into account when transporting prioritized jobs. The SLS also specifies or guarantees an upper bound of a performance measure, such as average delivery time. In order to achieve QoS guarantees, the framework plans and manages the requirements for service subscription according to available resources. The dynamic OHT allocation and dispatching modules of the framework is responsible for managing the allocation of OHT vehicles and for controlling the transport sequence to meet the SLS demands provided by the SLA management. With the integration of dynamic OHT allocation and dispatching functions, the proposed framework ensures that agreed-upon SLS are adequately provisioned.

In the prioritized AMHS service framework, SLAM receives transport service requests from lot dispatching/scheduling function of fab CIM systems. Assessments are then made with traffic forecast to evaluate the impact on transport performance due to these requests for high priority materials handling services. A SLA is negotiated and contracted to the lot dispatching/scheduling functions (Liao *et al.*, 1996) to provide a guaranteed service. With this precise prediction on wafer transport times, lot dispatching/scheduling functions are more effective to cope with the real-time fab dynamics. SLS are then interpreted according to the SLA and are translated into commands to dynamic OHT allocation and dispatching to meet the fluctuating requirements specified in the SLS. A simulation model (Liao & Fu, 2004) based on the dispatching policies and the allocation method is used for fab traffic forecast.

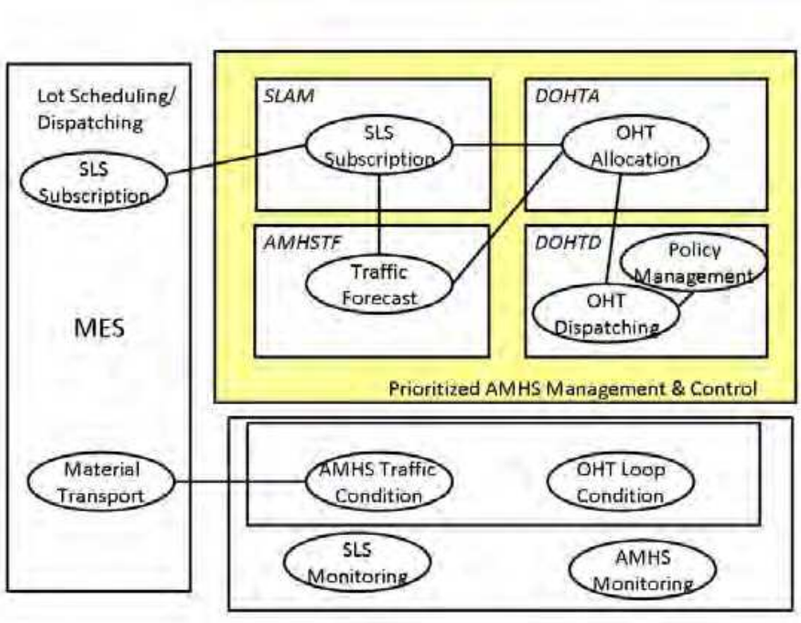

Fig. 7. The Management and Control Framework for Prioritized AMHS Services

Although the average (or static) loading of the AMHS has been optimized in the stage of fab layout design, the transport loadings of different interbay/intrabay loops are usually various and changing from time to time. For an interbay/intrabay loop, its transport requirements are dynamic according to the varying WIP distribution and the fluctuating processing capacity of tools within the loop. Such requirements are usually local and urgent. They demand timely and flexible autonomous responses and actions immediately, which now can be achieved with the help of intelligent agents (Jennings & Wooldridge, 1998). Exploiting the agent-based technology, we implement the Prioritized Management and Control Framework with agents for OHT dispatching, resource management, traffic monitoring, and policy management applications, that completes the intelligent, computer-integration framework for prioritized semiconductor manufacturing services. Fig. 8 depicts the integration of the agent-based components with the other fab CIM systems.

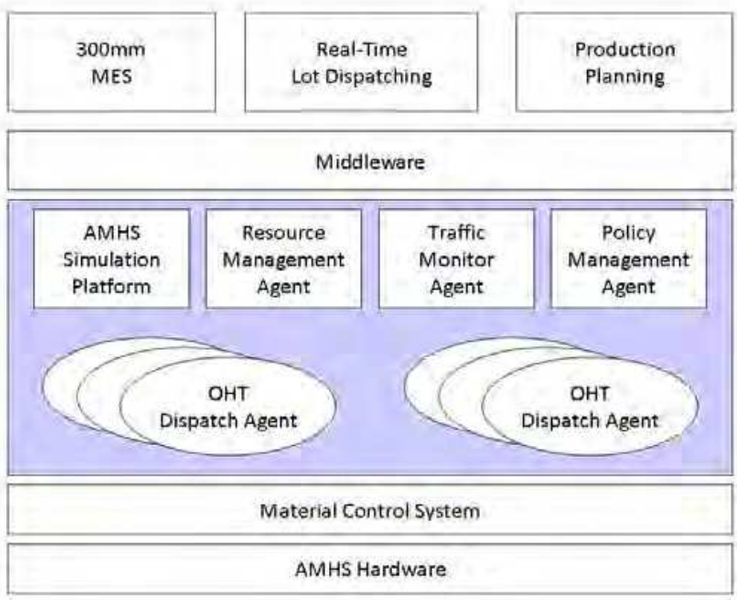

Fig. 8. Intelligent, Computed-integrated Framework for Prioritized Services

6. Design of Automation and CIM Systems

Systematic design and analysis methodologies, like system definition, validation or verification techniques, are always needed in the design of automation and CIM systems. During the design phase, the most tedious job is to implement the dynamic behaviours between system components and objects for all manufacturing applications involved. To the large dynamic systems like semiconductor manufacturing, it is always difficult and challenging to define, validate, and verify their system dynamics, not to say, to consider their various and changing control and managerial policies. In this Chapter, we adopt Petri-net techniques to build models for both PVD cluster tool and AMHS. Mathematical analysis and computer simulation are conducted to verify and validate the correctness of the automation and integration in the developed model.

A Petri net (PN) (Peterson, 1981; Murata, 1989) is a special kind of directed bipartite graph that consists of nodes as places and transitions. Directed arcs in a PN are either from a place to a transition or from a transition to a place. Each place may hold either none or a positive number of tokens. In a place, tokens are used to represent the number of available resources or to check whether a condition is satisfied or not. When all the input places of a transition hold enough number of tokens, the transition is enabled. A transition is firing at an enabled transition if firing conditions are satisfied. Such a firing changes the token distribution in places of the PN, which are usually to model the change in system states (markings). Pictorially, places in a PN are depicted by circles and transitions by bars. A TPN is a PN where either zero or positive time delays are associated with places, transitions, and/or arcs. Mathematically, a TPN *C* is defined as follows:

$$C = (\mathbf{P}, \mathbf{T}, I, O, m)$$

Where

$\mathbf{P} = \{p_1, p_2, \ldots, p_i\}$ is the finite set of places, where $i > 0$;

$\mathbf{T} = \{t_1, t_2, \ldots, t_j\}$ is the finite set of places, where $j > 0$; with $\mathbf{P} \cup \mathbf{T} \neq \varnothing$ and $\mathbf{P} \cap \mathbf{T} = \varnothing$;

$I : \mathbf{P} \times \mathbf{T} \rightarrow N$ is the input function defining the set of directed arcs from **P** to **T** with $N = \{0, 1, 2, \ldots\}$;

$O : \mathbf{T} \times \mathbf{P} \rightarrow N$ is the output function defining the set of directed arcs from **T** to **P** with $N = \{0, 1, 2, \ldots\}$;

$m : \mathbf{P} \rightarrow N$ is the marking representing the number of tokens in the places.

Consider the PVD cluster tool described in Section 3.2. Each process chamber (C, D, E, F, 1-5) can be in one of the following states:

- *Idle*: chamber is free to be accessed
- *Move In*: chamber is reserved to move in wafer
- *Processing*: chamber is reserved to process wafer
- *Wait/Move Out*: chamber is reserved to move out wafer

Based on the definition of chamber states, each process chamber can be modelled as a Petri net. The chamber state could become *Move In* only when it is in the state of *Idle*. After the specific duration of move-in time, the chamber changes its state from *Move In* to *Processing*. After the processing time elapses, the chamber again changes its state from Processing to *Wait/Move Out*, where physically wafer is wait for Transport Chamber to move out the wafer from the process chamber. Finally, the process chamber becomes *Idle* after the wafer is moved out. In a process chamber Petri net, the places represent states of the chamber and the transitions represents the change of states with associated time delays. The token in the Petri net represents the availability of state and there is only one token in the Petri net, i.e., m=1.

Different to the Petri net model for process chamber, the Petri net model for wafers is determined by the process flow of the wafers, which is specified in the recipe and received from fab MES systems via tool automation. Each process flow involves a sequence of

operations as well as processing requirements. A Petri net model for the process flow in Fig. 5 is shown in Fig 9, where the Petri net models of process chambers F and 2, preclean chamber B, cooldown chambers A, are all combined as an integrated model. Mathematically, the process flow Petri net is the union of these Petri nets of chambers F, 2, B and A.

The graphical presentation of Petri nets helps not only modelling a system, but also validating the system. It is easy to trace all the possible states of the PVD cluster tool when wafers are processed in the tool. The Petri model can be verified with the analysis of its reachability, liveness, safeness, and so forth (Srinivasan, 1998). Mathematically, it can be proved that the process flow Petri net in Fig. 9 is live and safe. That is, for any wafer lot to go with the process flow will complete the entire process.

Automation and integration in semiconductor manufacturing usually involve discrete event systems that exhibit sequential, concurrent, and conflicting relations among the events and operations. The evolution is dynamic over time. A formal approach such as Petri nets enables one to describe complex discrete event systems precisely and thus allows one to perform both qualitative and quantitative analysis, scheduling and control of the automation and integration systems.

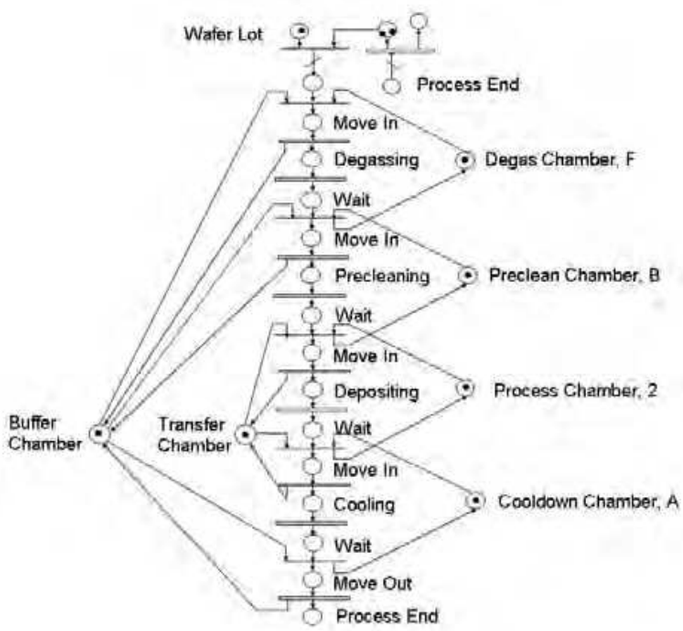

Fig. 9. Petri Net Model of Process Flow in Fig. 5

7. Conclusion

Semiconductor automation originates from the prevention and avoidance of frauds in daily fab operations. As semiconductor technology and business continuously advance and grow, manufacturing systems must aggressively evolve to meet the changing technical and business requirements in this industry. Semiconductor manufacturing has been suffering pains from islands of automation. The problems associated with these systems are limited

flexibility and functionality, low level of integration, and high cost of ownership. Thanks to the recent technological advances that can provide significant approaches in dealing with these problems, we are able to realize the promise of semiconductor manufacturing with sound automation and integration.

In this Chapter, we have reviewed the need of automation and integration in semiconductor manufacturing. Some considerations in fab automation are addressed. The three-levelled hierarchical, distributed automation architecture is discussed, where automation in semiconductor manufacturing is classified into tool, cell, and fab automation. Three popular protocols, SECS, GEM, and HSMS, for interfacing to semiconductor tools, are reviewed. In addition, the concept of single communication link is highlighted due to its importance in the design of modern tool automation. Specially, we take the PVD cluster tool as the study vehicle for tool automation. We have reviewed the SEMATECH CIM Framework. We have proposed an intelligent and integrated CIM framework for prioritized manufacturing services, where the management and control to AMHS services are discussed and intelligent and autonomous agents are used to facilitate the prioritized services in modern semiconductor manufacturing. Finally, we adopt the Petri net technology to go through the modelling, validation, and verification in the design of automation and integration systems in semiconductor manufacturing.

This Chapter adopts Petri nets to demonstrate the techniques for system modelling, validation and verification of automation and integration in semiconductor manufacturing. Some useful approaches like Unified Modelling Language (UML), computer simulation, queueing network analysis, mathematical programming, and so on, are also frequently used in system analysis of fab automation and integration applications.

The automation and integration in semiconductor manufacturing must continue to evolve to meet the needs of the competitive and vital industry.

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