REVIEWS

DIRECTIONS FOR SEMICONDUCTOR WAFER-FABRICATION FOR TWENTY FIRST CENTURY

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ABSTRACT

Research work carried out in the last decade on the Microelectronics Manufacturing Science and Technology (MMST) program sought to address a need for increased flexibility in IC manufacturing through single-wafer processing, with in-situ sensors and real-time process/factory control has lead to a successful demonstration of a novel approach to IC manufacturing based on flexible process.

To make it possible for modern industry to utilize MMST program, one can make use of programmable process-tool with technology of computer-aided design (T-CAD) and Process Synthesis.

Computer-Integrated Manufacturing (CIM) links equipment, people, and products in a manufacturing facility. Today's manufacturing requires "agility" - the ability to thrive in a continuously changing, unpredictable environment [1], which can be achieved by using advanced monolithic CIM systems.

This article presents an overview of strategies employed in the MMST program to build a flexible, distributed, CIM system-framework, with applications that exploit new hardware, process-technologies, and Process-Synthesis for agile and cost-effective wafer fabrication.

PROCESS-SYNTHESIS FRAMEWORK (PSF)

The Microelectronics Science and Technology (MMST) approach has successfully demonstrated a novel approach to IC manufacturing, based on flexible process equipment [2]. The next step is to make it possible for modern industry to make use of these developments, applying "Process Synthesis", making use of programmable process-tools with technology of computer-aided designs (T-CAD) and process-models, within a framework called "Process Synthesis".

This will allow designers to prepare a manufacturing process-flow and to produce an IC in which performance, reliability, manufacturability, life-cycle cost, and cycle-ti me have been optimized.

The architecture is shown in Figure-1, as envisaged for semiconductor manufacturing facility of the future.

The most important part is the tight integration of a virtual (simulated) factory and a programmable production-facility. The actual production-line would follow the MMST model, with flexible, microprocessor-equipped process-tools, linked to a host-computer-integrated manufacturing (CIM) computer, which would generate an optimized use of equipment for each device.

The first step is to create a PSF, so as to simulate and optimize a virtual product from a design. A PSF might include the following:

- Integrated process and equipment models for each tool;
- Unit process-specification and product-description data-base;
- Product simulation;
- Manufacturing rule checker;
- Process sequence optimizer.

The output of the PSF would then be passed on to the MMST production-line for execution. T-CAD tools, which provide a model of the unit-process steps and process-integration, need to be integrated with the programmable factory. Companies will therefore use these T-CAD models to develop standard and reusable process-libraries, which will provide the fundamental "building blocks" of a manufacturing-sequence. Once these technologies are developed, the integration of manufacturing-process and circuit-design can begin.

PROCESS SYNTHESIS—ITS DESIGN AND WORK

A central data-base of unit process specifications would provide general parameters for a given process;

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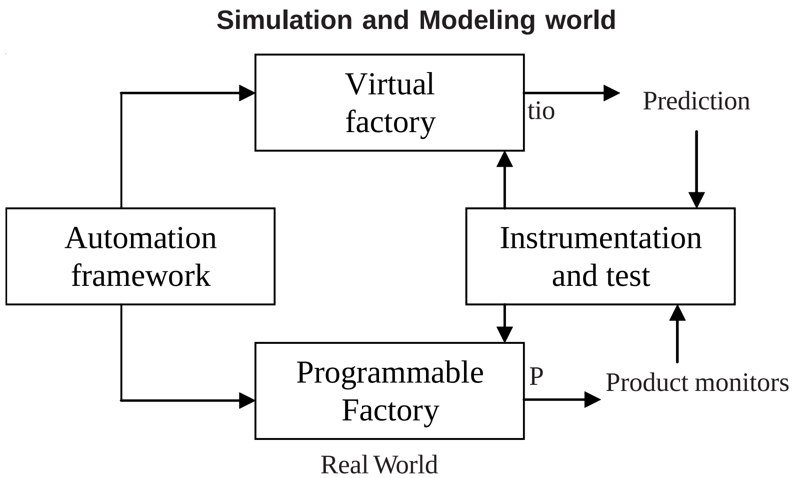

Figure - 1: Semiconductor manufacturing in the 21st century, with a Process Synthesis framework

these parameters would be obtained from a complete product-simulation in the PSF. Rule-checker would check the product-simulation against the process-capability of each tool, taking process-interaction into account. The database of the checker would be automatically updated when tools with improved processing-capability are inserted into the line.

Other software components would include a process-sequence optimizer, to ensure maximum utilization of equipment and a product-description database to evaluate each product for performance, reliability, and cost. This integrated tool-set would be able to simulate the complete design, evaluation, and manufacturing-process before starting with silicon.

An example of a PSF is shown in Fig.2 Assume that a design-framework has been used to define the architecture, circuit-implementation technologies, and some physical characteristics of an IC. This information forms the virtual product-description, linked to a device-engineering framework for checking. Here, consistency with design-rules is checked; performance, reliability, etc., could be estimated. Design-data passed on by the device engineering-framework is used by PSF for an initial attempt at process-development. A process-sequence is then determined, simulated, and optimized. Depending on the results, a new virtual product could be defined and fed into the device-engineering framework for further refinement or simulation.

The process would continue until an acceptable product-design and manufacturing-process are generated and passed on to the factory for production, as shown in Fig.2.

MMST PROGRAM

In the fourth decade of the IC business, manufacturers are looking for new ways to add value through product-differentiation. Comparison of MMST vs conventional processing is shown in table 1 below.Two possible differentiators are custom-processing and very short delivery-time for new application-specific IC designs. But fast turn-around for new designs is difficult to achieve with today's high-volume wafer-fabs. Another problem is the huge minimum investment

The MMST program is a solution for increased flexibility in IC manufacturing, through research on single-wafer processing with in-situ sensors and real-time process/factory control. Advanced CIM, including real-time process-control, should also help the semiconductor industry.

Modular Single-Wafer Equipment:

MMST's impact on the cost elements is mainly due to a transition from unique, standalone batch-tools to modular single-wafer plasma, vapor-phase, or boatless wet-process, and rapid thermal processing (RTP).

The MMST vision for equipment includes the greatest practical degree of modularity (see fig 3). Ideally, most

Table - 1: MMST vs. conventional processing

Current technology	MMST technology
Large, fixed, 20,000-Wafer capacity	Modular, 100- to 1000-wafer/month capacity
Factory costs>$500M	Factory costs $30M-$50M
Silicon only	Generic manufacturing (HgCdTe, GaAs, etc.)
Class 1 cleanroom	Class 1000 cleanroom
30% of processes use liquids	Liquid-free processing
25- to 50-wafer batches	Single-wafer processing
Batch sampling	Real-time process control
Long cycle time, 1-3 months	Short cycle-time, 5-15 days
Mixed equipment-configurations	Modular vacuum-processing equipment

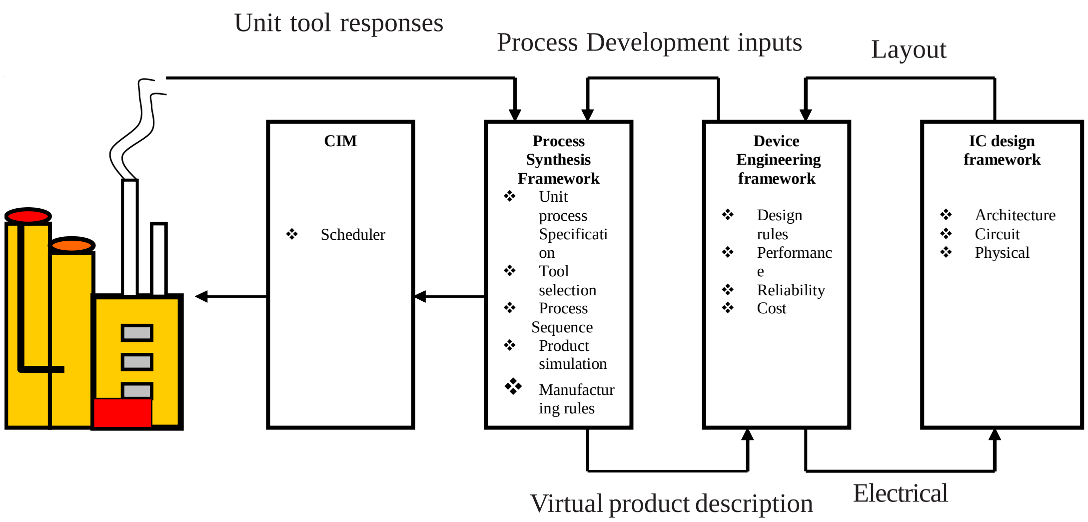

Figure - 2: Design and process synthesis integration

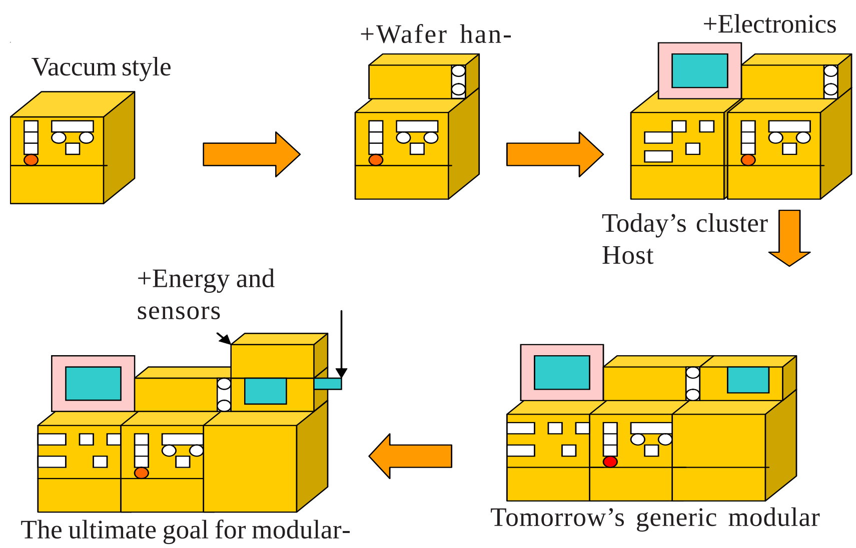

Figure - 3: Process-tool equipment should be standardized around basic subsystems to achieve a high degree of modularity for flexible manufacturing.

tools would look almost identical physically and would be distinguished only by the specific energy-sources and sensors that were attached to the process-chamber. All wafer-handling, gas-distribution, vacuum, computer, etc, subsystems, as well as the process chambers would be identical.

Figure 4 shows the results of a factory-level analysis of relative wafer cost vs cycle time. It is apparent that the single-wafer fade exhibits less sensitivity of cost over a wider range of cycle times. Another alternative way is to employ an appropriate CIM system for such analysis. For example, a commercial CIM software system evolved from the MMST programs that it should be able to predict fab cost/performance changes associated with adding or changing a particular piece of equipment without having to input a complete fab description into a stand-alone Factory-simulation program.

Computer-Integrated Manufacturing (CIM)

Requirements of a CIM system for agile semiconductor fabrication in the MMST program [2] were derived, analyzing the objectives of the manufactory.

Capabilities, cost, and other characteristics of current IC manufacturing technology versus those for flexible, low-volume MMST technology are compared in table 1. As shown, typical factory cost based on MMST technology range from $30-50 million, whereas traditional large-volume wafer-fab facility now costs atleast $500 million, and some even $ 1 billion or more. Furthermore, a low-volume MMST-like facility allows cycle times less than two weeks for new devices, compared to about three months in large-volume factory.

CIM offers great hope for dealing with the future IC production, by providing the flexibility, full integration, functionality, cost-effectiveness, maintainability, and ease of use that would encourage widespread adoption by IC industry.

Object-Oriented CIM System Architecture

Architecture of a distributed object-oriented CIM system is multidimensional. Two important dimensions, the logical and the physical, are shown in fig .5 .The physical architecture is shown on the right side of fig .5. Objects are grouped by many "using" or "containing" relationships and distributed to the various computing-nodes throughout the factory. For example, a machine (object) contains many other objects (e.g.; chambers, valves, robots, pumps etc). These are instantiated on the various computers within specific machines, such as the host user-interface computer and one or more process-control computers.

The logical architecture is represented by the object class-inheritance hierarchy. At the top of the hierarchy stand the most abstract and generic classes (e.g., Document, Plan, Resource, and Material). At the bottom of the class hierarchy lie the most concrete and specialized classes [e.g.Process Spec, Wafer Start Plan, Advanced Vacuum Process (AVP), and wafer].

The services provided by CIM system are portioned into eight major applications-Factory Manager, Factory Planner, Factory Scheduler, Factory Simulator, Specification Manager, Generic Equipment Model (GEM Software), Machine Control, and Process Control.

The highest-level application in the CIM system, the Factory Manager, contains many factory-level abstractions (e.g.Factory, Area, Material, User, Material Transporter) that tie all the applications together. The Factory-Manager application provides services for starting up and shutting down the factory and for coordinating the activities of operation-management personnel while the factory is running. Fab-performance monitoring (e.g.throughput, cycle time) and work in progress (WIP) tracking facilities are provided.

The Factory Planner is the focal point for accepting factory-orders and generating a production-plan that pinpoints which wafers are to be processed by the fab during each time-period. This model works hand-in-hand with the Factory Scheduler, with the scheduler being responsible for driving the factory to meet delivery-schedules, specified by the Planner. Collaboration between the Planner and the Scheduler controls material-release into the factory; the Scheduler controls when the material is released and the Planner controls what material is released. The Planner, also, continuously take care of any changes to the plans or resources, and the output can be used

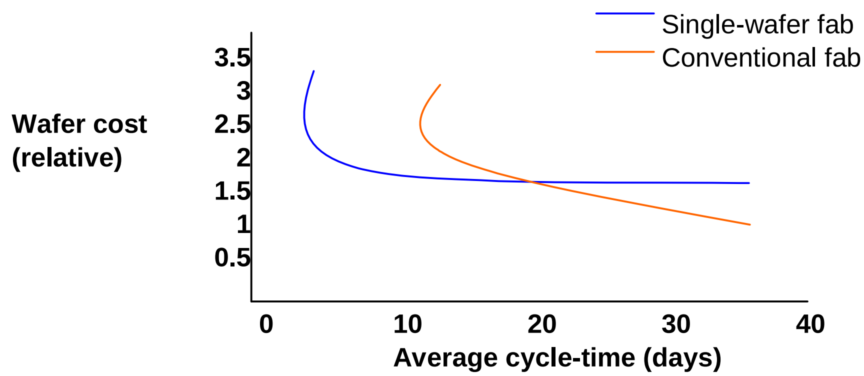

Figure - 4: An example of cost vs. cycle-time for wafer fabrication.
Total single-wafer processing offers shorter cycle-times than today's mix of both batch and single-wafer Processing. There is also less variation in wafer-costs over a wider range of cycle-time

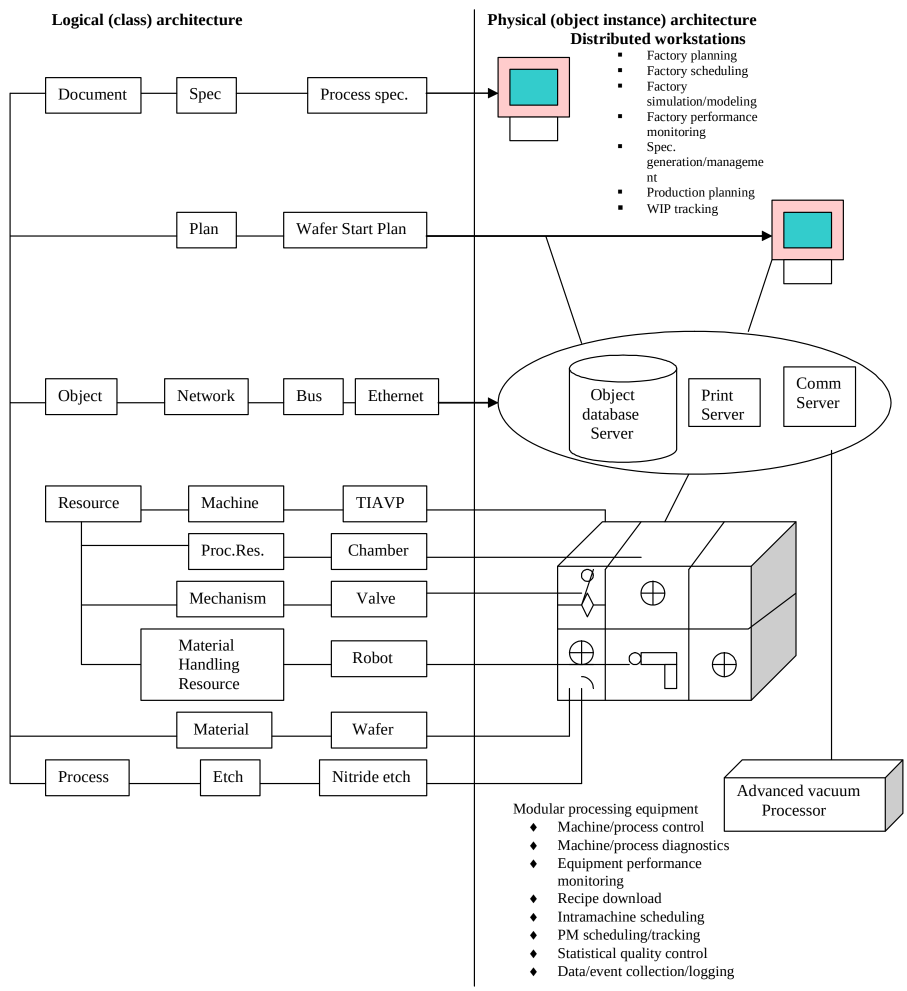

Figure - 5: System-architecture for the object-oriented CIM software.
Architecture can be visualized in the logical domain (left) or physical domain (right)

with the Factory Simulator to verify the plan via simulated production.

Scheduling of production-operations is controlled by the Factory Scheduler. The Scheduler decides when material is to be processed by each machine and directs the factory-resources (people and machines) to effect those decisions. Scheduling-decisions are based upon the production strategy, the real-time factory status, machine-performance history, while machine failures and preventive maintenance (PM) actions are accommodated.

Mechanisms required to conduct discrete-event simulations of factory-operations are provided by the Factory Simulator. The Simulations are controlled by user-defined experiments, specifying the factory-configuration and any starting and terminating condition. A computer-aided process-engineering environment is provided by the Specification Manager, to generate and manage various CIM system-specifications. The Specification Manager includes editors (for entering and modifying new process-steps, sequences, and flows) and an engineering change notice management-system.

GEM includes all aspects of common machine-operation, including material-transfer, intramachine scheduling, material-processing, data-collection, performance-monitoring, and preventive maintenance (PM).

Machine Control is responsible for controlling sequencing and settings of the various machine-resources, in response to external commands for processing. Any specialization of GEM required for a specific type of machine is also provided by Machine Control. This can include specialized sensors, calibration procedures, maintenance-instructions, and programs for controlling unique machine operations.

Ensuring consistency and quality of processing for a specified machine is the responsibility of Process Control. This requires translation of the desired effects, as specified by the machine-independent process-specifications, into actual machine settings.

CONCLUSION

Intelligent and flexible process equipment *of the future* could enable a process synthesis framework for simulating and optimizing virtual products from design. There is a need for agile manufacturing calls for more-flexible CIM systems, allowing economic production of smaller lots and the ability to adapt to advances in hardware and process-technology. This Object-oriented CIM software for the Microelectronics Manufacturing Science and Technology (MMST) program is required. It is also important to explore the extension of present models to flexible, shorter cycle-time manufacturing, using modular, single-wafer processing tools, such as those developed for the MMST project.

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