Chapter 2. Computer-Integrated Design and Manufacture of Integrated Circuits

Academic and Research Staff

Professor Donald E. Troxel, Professor Dimitri A. Antoniadis, Professor Duane S. Boning, Professor James E. Chung, Professor Carl V. Thompson, Stanley B. Gershwin, Thomas J. Lohman, Michael B. McIlrath

Graduate Students

Yonald Chery, Keith M. Jackson, James T. Kao, Somsak Kittipiyakul, Jimmy Y. Kwon, Brian Lee, Zachary Lee, William P. Moyne, Joeseph E. Nemec, Manuel J. Perez, Christopher Peters, Nadir E. Rahman, Matthew D. Verminski, Chantal Wright

Technical and Support Staff

Francis M. Doughty

2.1 Advanced Modeling and Computational Prototyping

Sponsor

Defense Advanced Research Projects Agency
DABT 63-95-C-0088

Project Staff

Yonald Chery, Professor Carl V. Thompson, Professor Donald E. Troxel

2.1.1 Modeling of Interconnect Reliability

Recent research has demonstrated interconnect failure due to electromigration effect to be strongly dependent not only on current density but also on metal film crystal grain size distribution and geometries of interconnect patterns. This type of failure is manifest as a depletion of interconnect metal forming a "void" (open-circuit) or an accumulation possibly forming a "short" to neighboring interconnect.

Our research work focuses on:

1. Developing abstract, physically-based, microstructural interconnect failure models to more accurately predict electromigration induced failure.
2. Electromigration Reliability for Network Interconnect (ERNI): our prototype computer-aided design tool based on these abstracted microstructurally based models.

A release of ERNI 1.0 is expected during spring 1997 with extensions supporting hierarchical designs and utilizing higher-performance circuit simulation engines to be released by summer 1997.

2.1.2 Modeling of Advanced Device Structures

Project Staff

Zachary Lee, Nadir E. Rahman, Keith M. Jackson, Professor Dimitri A. Antoniadis, Michael B. McIlrath

As MOSFET dimensions are reduced to the submicron level, the electrical performance and characteristics are critically dependent on the two- and three-dimensional distribution of dopant concentrations in the semiconductor. Consequently, it has become essential to accurately characterize, predict, and control the diffusion characteristics of dopants during device fabrication.

The characterization of dopant distribution in the device is carried out through the use of an inverse modeling technique. Combining numerical optimization techniques with process and device simulation tools, through a careful choice of physical experiments, one is able to extract information of the process as well as device structures that are otherwise impossible or difficult to obtain through direct measurements. Using the super-steep retrograde devices fabricated at MIT as the starting point, we have been able to extract the one-dimensional dopant distribution, as well as some preliminary diffusion characteristics of indium, about which very little information is available. Experiments to obtain more complete and accurate information on the diffusion characteristics of indium are underway.

Inverse modeling techniques for obtaining channel doping profiles from device electrical measurements have been investigated. Constant current threshold voltage measurements and capacitance measurements were made on NMOS long channel devices and long channel super steep retrograde doped NMOS devices. Different representations of profiles were explored and simulation results obtained using these profiles were then converged to the output measurements using optimization algorithms. The best results were obtained using an optimizer which relies on a Levenberg Marquardt algorithm for profile variation.

On-going work involves the development of an accurate two-dimensional characterization technique that allows one to calibrate and subsequently predict with high accuracy the electrical characteristics of MOSFETs.

2.1.3 Thesis

Rahman, N.E. *Extraction of MOSFET Doping Profiles from Device Electrical Measurements.* M. Eng. thesis. Dept. of Electr. Eng. and Comput. Sci., MIT, 1996.

2.2 Distributed Collaborative Design and Prototyping Infrastructure

Sponsors

Defense Advanced Research Projects Agency
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Stanford University

2.2.1 Architecture for Distributed Design and Fabrication

Project Staff

Professor Duane S. Boning, Michael B. McIlrath, Professor Donald E. Troxel

The design and fabrication of state-of-the-art semiconductor devices and integrated circuits requires an increasingly diverse and expensive set of resources, including manufacturing equipment, people, and computational tools. Advanced semiconductor research activities can be even more demanding, frequently requiring unique equipment and processing capabilities.

We are developing a flexible, distributed system architecture capable of supporting collaborative design and fabrication of semiconductor devices and integrated circuits. Such capabilities are of particular importance in the development of new technologies, where both equipment and expertise are limited. Distributed fabrication enables direct, remote, physical experimentation in the development of leading edge technology, where the necessary manufacturing resources are new, expensive, and scarce. Computational resources, software, processing equipment, and people may all be widely distributed; their effective integration is essential in order to achieve the realization of new technologies for specific product requirements. Our architecture leverages current vendor and consortia developments to define software interfaces and infrastructure based on existing and emerging networking, CIM, and CAD standards. Process engineers and product designers access processing and simulation results through a common interface and collaborate across the distributed manufacturing environment.

2.2.2 Labnet Software

Project Staff

Professor Duane S. Boning, Michael B. McIlrath, Thomas J. Lohman, Professor Donald E. Troxel

University microfabrication laboratories are facing many new challenges and opportunities: (1) facilities are becoming more expensive and difficult to manage; (2) resources and expertise need be shared and made available to a wider community; and (3) education and research are becoming more dependent on multi-institutional collaboration. Given the above challenges, there is a growing desire for a new distributed information infrastructure that will allow remote collaboration, access to remote sites' data and sharing of end-user software applications, in the face of differences between remote sites in computer platforms, operating systems, and technical resources. Past research has been done within this application domain but most working systems are too tightly coupled to their local facilities, suffer from portability problems, and have never addressed the issue of data distribution and remote site interaction.

The Labnet Software Project was initiated this year in recognition of the need for universities to share the effort needed to develop and maintain new distributed laboratory information systems. Over the course of the year, a series of meetings were held and joint development work was initiated between MIT, Stanford University, and the University of California at Berkeley. The main goals of the joint development effort are:

1. Assess the applicability of emerging technologies such as the Object Management Group's (OMG) common object request broker architecture (CORBA), OMG's interface definition language (IDL), Sun Microsystem's Java language, and object databases,
2. Explore developing an infrastructure to enable collaborative distributed design and fabrication (including object-oriented distributed programming interfaces and web-based user interface capability),
3. Develop abstract specifications for programming interfaces to both data and services, and
4. Explore developing standards to achieve software compatability such as the Sematech CIM application framework.

In order to explore the viability of using CORBA for distribution of data and services, Visigenic allowed us free use of their CORBA products (Visibroker for C++ and Visibroker for Java), and we developed a small prototype distributed equipment manager (DEM). This application allows a user, via a Java applet, to view the status of laboratory equipment located at a remote site. In addition, the user can change the status of a piece of equipment (if given the proper authority) and view its technical information and history. The application interface to DEM was defined using IDL and was based on the Sematech CIM Application Framework Specification 1.3.[1] Given the shared IDL definition, each site was able to implement its own DEM application server and link it to its existing back-end database servers. At MIT, the DEM server accessed laboratory data via the CAFE system,[2] using the Gestalt database interface. A successful demo of DEM was made at the Labnetwork meeting in San Francisco on December 9, 1996.

2.2.3 Distributed Process Control Architecture

Project Staff

Aaron Gower, Professor Duane S. Boning, Michael B. McIlrath

Semiconductor fabrication requires an increasingly expensive and integrated set of tightly controlled processes, driving the need for a fabrication facility with fully computerized, networked processing equipment. We have designed an integrated, open system architecture enabling distributed experimentation and process control for plasma etching. The system was developed at MIT's Microsystems Technology Laboratories and employs *in situ* CCD interferometry based analysis in the sensor-feedback control of an Applied Materials Precision 5000 Plasma Etcher (AME5000). Our system supports accelerated, advanced research involving feedback control algorithms and includes a distributed interface that utilizes the Internet to make these fabrication capabilities available to remote users.

The system architecture is both distributed and modular: specific implementation of any one task does not restrict the implementation of another. The low-level architectural components include a host controller that communicates with the AME5000 equipment via SECS-II and a host controller for the acquisition and analysis of the CCD sensor images. A cell controller (CC) manages communications between these equipment and sensor controllers. The CC is also responsible for process control decisions; algorithmic controllers may be integrated locally or via remote communications. Finally, a system server manages connections from Internet/Intranet (web) based clients and uses a direct link with the CC to access the system. Each component communicates via a predefined set of TCP/IP socket based messages. This flexible architecture makes integration easier and more robust, and enables separate software components to run on the same or different computers independent of hardware or software platform.

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[1] L. Eng, K. Freed, J. Hollister, C. Jobe, P. McGuire, A. Moser, V. Parikh, M. Pratt, F. Waskiewicz, and F. Yeager, "Computer Integrated Manufacturing (CIM) Application Framework Specification 1.3," *SEMATECH Tech. Trans. No. 93061697F-ENG* (Austin, Texas: SEMATECH, 1996).

[2] M.B. McIlrath, D.E. Troxel, M.L. Heytens, P. Penfield, Jr., D.S. Boning, and R. Jayavant, "CAFE—The MIT Computer-Aided Fabrication Environment," *IEEE Trans. Comp., Hybrids, Manuf. Tech.* 15(2): 353-360 (1992).

2.2.4 Remote Microscope for Collaborative Inspection of Integrated Circuits

Project Staff

James T. Kao, Brian Lee, Somsak Kittipiyakul, Manuel J. Perez, Professor Donald E. Troxel

The Internet remote microscope was developed to enable users to inspect a microscope specimen remotely by using an ordinary workstation computer connected to the Internet. The remote microscope is a distributed system that consists of one or more graphical client interfaces running on UNIX workstations that communicates over the Internet with a microscope server unit consisting of the hardware and software needed to automatically control an inspection microscope. The client interface presents the user with a graphical microscope control panel and two image panels that show static images of the microscope specimen that can be updated upon request.

Because it is not important to have live video when examining many types of specimens, especially in the context of inert semiconductor wafers, this approach gives acceptable performance while requiring only limited bandwidth. From the control or instrumentation panel, the user may select a new magnification, pan position, and focus setting (manual or automatic) and can then instruct the system to capture a new image at the specified coordinates. The new image can be placed in one of the two arbitrary display windows, allowing the user to keep a previous image for reference. Typically, one would actually use one window to show a global or panoramic view of the specimen at low magnification, while using the other window to show a more detailed region of interest at high magnification.

The server system consists of a Zeiss microscope, an automated stage accurate to 0.4 microns for X-Y translation and 0.1 microns for Z direction, a video camera, and an ordinary personal computer running OS/2 that services requests over the Internet from clients. The PC contains a framegrabber board that can capture an ordinary NTSC video signal from a CCD camera that is mounted on top of the microscope and is responsible for controlling the stage, turret, and focus settings for an automated Zeiss microscope. Except for the initial placement of a wafer on the stage, this system is fully automated and controllable from the client control panel. Essentially, the remote microscope allows users at a distance to access and view a specimen remotely as if they were controling the microscope themselves. An additional capability of the Internet remote microscope is that multiple clients can view the microscope simultaneously during a conference inspection mode. This enables any number of experts anywhere on the Internet to simultaneously view the microscope images collaboratively. However, only one person at a time is in control and allowed to change the system settings.

Manual focusing options have been added to the client program. This option gives clients a second alternative for producing a focused image, as well as provides a basis for a potentially more robust automatic focusing algorithm. This is important because there may be times when the client wishes to have complete control over the focusing of the microscope, i.e., to focus on different layers or areas on the wafer. There are two manual focusing options which have been added. Both are based on the concept of allowing the client to adjust the focus axis position and transmitting back to the client a small amount of image data which represents a measure of focus quality of an image. The client, by interpreting the data received, can adjust the focus axis position to produce the desired image.

For one of the options, the image data relayed to the client is a measure of focus quality used by the microscope server when performing an autofocus attempt. The client can attempt to scan the focus axis range quickly and spot the area of maximum focus quality. For the second manual focusing option, the image data relayed to the client is a horizontal scan line of pixel values (displayed on a graph). In a well focused image, there will be sharp transitions and edges because in such an image the pixel values will differ greatly from one pixel to the next. The client may scan the focus axis range and observe the graph for these sharp transitions.

To aid the client in determining the area of maximum focus, a measure of focus quality is computed by taking the first derivative of the horizontal scan line and returning this value to the client. The client then has the option of either inspecting the graph for transitions or maximizing the value of focus quality which was returned. The client is able to determine the point of maximum focus quality for a specific region on the image simply by looking for sharp transitions within the desired area. This would be of great benefit if the wafer under inspection could not produce a sharply focused image for all regions on the image. The value of focus quality can also be used as a basis for a more robust automatic focusing algorithm, thus allowing the user to select an autofocus method, or perhaps dynamically to select the optimal autofocus method based on the current situation.

The original C and Tcl/Tk based remote microscope client has been implemented in Java in both the application and applet form. Users can now use the remote microscope to retrieve the client applet from a web server, residing on the same system as the remote microscope server application. This design has made the client program platform independent, allowing the use of the client program on any machine which supports Java applets. The Java client currently includes all the functionality of the original client, as well as many of the new manual focusing options currently being designed.

New features being added include a text chat tool, on-line help files, a mini tools window, and a layout based navigation tool. The text based chat tool will allow users to send small text messages to one another, while inspecting a wafer. The online help will contain a complete users guide, trouble shooting tips, and other remote microscope related material. These help files will be directly available through the web server. The mini tools window will allow for quick zoom, move, and grab commands, as well as include some measurement functions. A Java based MAGIC file viewer, being developed in our group, will also serve as the basis for an easy and quick navigation tool.

2.2.5 Process Repository

Project Staff

William P. Moyne, Chantal Wright, Professor Duane S. Boning, Michael B. McIlrath

The goal of this research task is to create a system to facilitate distributed process research and design. Such a system will allow users to retrieve and examine process flows from multiple process libraries across the network.

We have completed the implementation of a prototype system which allows users to design and edit process flows through the interface of a web browser. The system demonstrates the potential of the Java programming language to enable researchers to share processing information among any number of distributed sources.

Communication of information from multiple databases or libraries among a distributed community of researchers requires a common data representation; the proposed standard is the Semiconductor Process Representation (SPR). We have implemented the SPR information model in Java, and our system stores and presents information in this format. By using the standard data representation, we demonstrate that the tool could access data from separate sources across the network. However, since the SPR is not yet in use in the research community, conversion from the representations used by local systems (such as MIT's CAFE) will be necessary.

Our prototype system focuses on making SPR process objects from MIT's CAFE database available for viewing and editing. A user can load a flow into the Java applet running in a web page. The user may edit the process flow or a step's SPR view information. The user may also spawn another Netscape client to browse the information associated with steps in the CAFE process library. This SPR browser is supported by Tcl scripts which perform a rudimentary translation from the CAFE process flow representation to SPR. The user may add information found in the repository browser to the process flow currently in the tree editor. Finally, a user may save an edited flow. (Netscape imposes security resrictions on the Java applet so this save is limited to the web server which provided the applet.)

The MIT Semiconductor Process Repository has been made publicly available on-line. Fabrication processes provided by the repository are those supported by the staff of the MIT Microsystems Technology Laboratories.

The MIT Common Lisp Hypermedia Server[3] has been installed and is currently used to serve the process repository. Process objects are retrieved directly from the GESTALT database of CAFE, the CIM system used to operate the MIT fabrication facilities. HTML presentations for these process objects are created dynamically by the server. These web pages present different process views (e.g. effects, equipment, simulation) to the web client. Hypertext links to related objects in the CAFE database (e.g. fabrication equipment, laboratory users, other processes) are available only to clients with local access permissions. An experimental searching capability is also under development. The on-line repository was described and demonstrated at the Semiconductor Research Corporation (SRC) TechCon '96 Conference.

We have begun work on a distributed object programming interface for the process repository. The interface is described in the Object Management Group interface definition language (OMG IDL). The implementation uses the CAFE database and the

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[3] J.C. Mallery, "A Common LISP Hypermedia Server," *Proceedings of the First International Conference on The WorldWide Web*, CERN, Geneva, Switzerland, May 1994.

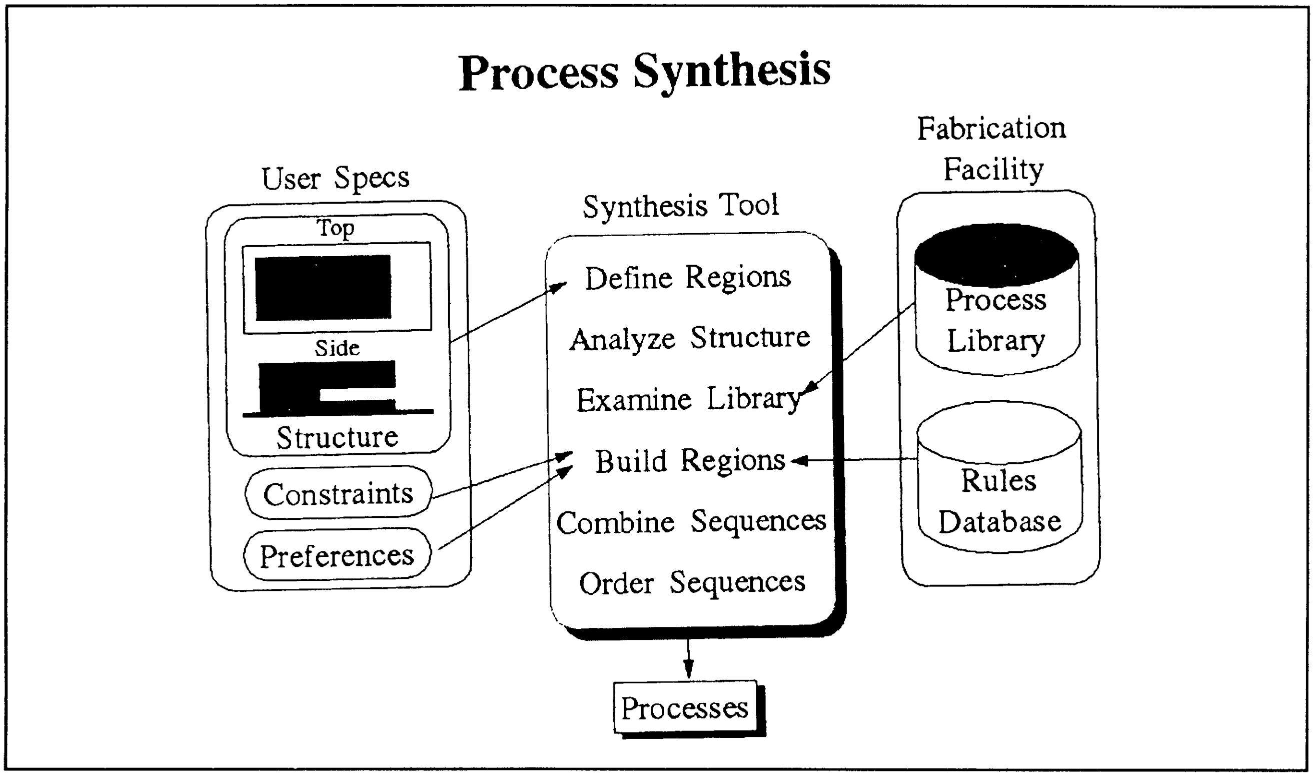

Figure 1

Xerox Interlanguage Unification (ILU) system.[4] ILU is a multilanguage distributed object interface system that can be used to implement OMG CORBA Object Request Brokers (ORBs). Test client programs for the repository have been implemented in C++ and Java.

The goal of process synthesis (see figure 1) is to automate and optimize the process steps needed to realize a given three-dimensional structure. This project touches a number of areas including process representation, process step optimization, and process parameter optimization. Work has begun in the area of process representation since it is the underlying data structure used for the tool. SPR (Semiconductor Process Representation) is being implemented using CORBA (Common Object Request Broker Architecture) to aid its integration with existing process repositories.

In addition to the SPR effort, a prototype version of the tool is being developed to gauge the complexity of the problem and determine what components are essential for its eventual operation. Once these components have been identified, work will begin on a fully functional tool that takes user specifications and site-specific process information and generates optimal process flows.

2.2.6 Networked and Distributed CAD Tools

Project Staff

Yonald Chery, Christopher Peters, Matthew D. Verminski, Duane S. Boning, Professor James E. Chung, Professor Donald E. Troxel

The rapid growth of computer networks has changed the way applications can be made available. The Internet provides a framework with which to distribute and share tools among many users. One of the various methods used to integrate applications with the Internet is the use of CGI (Common Gateway Interface) programming. This, complemented with HTML (Hypertext Markup Language) form based entry for inputs, allows users with a standard web browser to access applications.

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[4] B. Janssen and M. Spritzer, *ILU Reference Manual*, (Palo Alto, California: Xerox Corp, Palo Alto Research Center, 1996).

Electromigration Simulator CGI User Interface

EmSim[5] was developed by the Submicron Materials Group of the Department of Materials Science and Engineering to simulate the the effects of electromigration along the length of an interconnect. The program takes a set of user-defined conditions for a population of interconnects and it yields statistical data on the time to failure of the set of lines. EmSim has been encapsulated by a CGI program to make it available via the Internet and can be accessed at the URL *http://nirvana.mit.edu/emsim/.* The creation of the CGI user interface to EmSim is the first application from the SubMicron Materials Group to be obtainable on the Internet, with other applications expected soon.

Networked CAD Tool for Integrated Circuit Manufacturability Variation Decomposition

The fabrication of integrated circuits suffers from systematic spatial variation introduced at several points in the process.[6] Understanding the nature of this variation is important in order to identify and reduce that variation, or to design circuits and layouts that are robust against those specific varation sources. In this project, a web-based CAD tool has been developed to identify the wafer level trends in a parameter of interest and to separate this from the die-level or layout pattern-dependent variation contributions.

The tool has been implemented using a CORBA-based client-server architecture. On the client side, a simple web-based client interface enables the user to specify raw data sources (files of parameter values at *x,y* locations on the wafer). The data are then transmitted to a remotely located server on the network which provides statistical decomposition services. Specific service requests are made using a CORBA IDL definition. The server process incorporates interpolation and trend extraction methods by wrapping Fortran interpolation code from netlib, as well as down-sampled moving average estimation approaches. Together, the CAD services and distributed architecture provide an appealing means for both IC technology and circuit designers to examine systematic wafer and die trends that may impact manufacturability or performance.

Distributed Design Tool Architecture

Progress has also been made on design tool implementations for distributed and collaborative circuit design. A prototype graphical user interface (GUI) for MAGIC (a VLSI layout editor developed at UC Berkeley) was developed in Java. This GUI runs within a Java-enabled web-browser, enabling circuit designers to access, share, view, and edit layout files via the World-Wide Web.

2.2.7 Publications

McIlrath, M. "LabNetwork." Presentation at Semiconductor Research Corporation (SRC) TechCon, Phoenix, Arizona, September 1996.

Conference Papers

Gower, A., D. Boning, and M. McIlrath. "Flexible, Distributed Architecture for Semiconductor Process Control and Experimentation." In *Open Architecture Control Systems and Standards.* Ed. F.M. Proctor. *Proc. SPIE* 2912: 146-158 (1997).

Kao, J., D.E. Troxel, and S. Kittipiyakul. "Internet Remote Microscope." In *Telemanipulator and Telepresence Technologies III.* Ed. M.R. Stein. *Proc. SPIE* 2901: 90-100 (1996).

Lohman, T., B. Murray, and V. Kanabar. "A Heterogeneous Distributed Database Architecture for University Integrated Circuit Manufacturing Research." *Proceedings of the Association of Information Systems 1996 Americas Conference*, Phoenix, Arizona, August 1996.

McIlrath, M., D.S. Boning, and D.E. Troxel. "Architecture for Distributed Design and Fabrication." In *Plug and Play Software for Agile Manufacturing.* Ed. B.L. Maia Goldstein, *Proc. SPIE* 2913: 134-147 (1997).

McIlrath, M., M.L. Heytens, and T.J. Lohman. "Gestalt-class: a Persistent, Multi-user CLOS Application Environment." *Proceedings of the Dynamic Objects Workshop (DOW-96)*, Boston, Massachusetts, May 1996.

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[5] B.D. Knowlton, C.V. Thompson, and J.J. Clement, "Simulation of the Effects of Grain Structure and Grain Growth on Electromigration and the Reliability of Interconnects," *J. Appl. Phys.*, forthcoming.

[6] B.E. Stine, D.S. Boning, and J.E. Chung, "Analysis and Decomposition of Spatial Variation in Integrated Circuit Processes and Devices," *IEEE Trans. Semicond. Manufact.* 10(1): 24-41 (1997).

Theses

Kittipiyakul, S. *Automated Remote Microscope for Inspection of Integrated Circuits.* S.M. thesis. Dept. of Electr. Eng. and Comput. Sci., MIT, 1996.

Wright, C. *Information Networking for Distributed Semiconductor Technology Development.* M. Eng. thesis., Dept. of Electr. Eng. and Comput. Sci., MIT, 1996.

2.3 Design and Operation of Manufacturing Systems

Sponsor

Leaders for Manufacturing Program

Project Staff

Joseph E. Nemec, Stanley B. Gershwin, Professor Donald E. Troxel

2.3.1 Scheduling Language for Manufacturing Systems

We have proposed the syntax and supporting structure of a language that allows a programmer to devise and implement scheduling policies for manufacturing systems. In the course of the description of the language, we have defined various methods of representing a factory, including the equipment and personnel in the factory, the process flows of parts and constraints on the production of parts. We take an object-oriented approach to the definitions of the various components of the factory model. With the factory well-defined, we have then described the structure and syntax of a language that allows for the implementation of scheduling policies, such as Kanban and CONWIP. A running example of a five-machine production line has been used to illustrate the constructs defined. Finally, we have described the structure of a scheduler based on the constructs developed that takes a real-time control perspective.

2.3.2 Thesis

Nemec, J.E. *A Quantity Scheduling Language for Manufacturing Systems.* S.M. thesis, Operations Research Center, MIT, 1997.