SEMATECH QUALIFICATION PLAN GUIDELINES FOR ENGINEERING

SEMATECH
Technology Transfer 92061182B-GEN

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Abstract: This document is the latest revision of the SEMATECH Qualification Plan Guidelines for Engineering. The guidelines are designed to characterize process performance and equipment and improve reliability. It provides a method for experimentation and improvement. The plan is used to understand, quantify, and improve the functionality of a tool or process while reducing variability. It provides process engineers, hardware development engineers, and their managers a basic understanding of the various elements in a development methodology that emphasizes quality, completeness, and decision-making with statistically valid data. This revision differs from the previous version as follows: 1) A reliability improvement methodology based on Motorola's IRONMAN procedure has been added. 2) The guidelines are no longer classified SEMATECH Confidential because references to particular suppliers or pieces of equipment have been deleted while still retaining useful illustrative examples. 3) An appendix has been added that outlines the additional steps a member company might add to the SEMATECH Qualification Plan to achieve a full "Production Use Readiness Qualification." The steps are useful because the plan focuses primarily on product or process characterization and/or improvement issues, and not on factory installation and maintenance issues.

Keywords: Passive Data Collection, Design of Experiments, Marathon Runs, Process Integration, Gauge Capability, Process Optimization, IRONMAN Testing, Equipment Reliability

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1 EXECUTIVE SUMMARY

The SEMATECH Qualification Plan (Qual Plan) is a guideline for characterizing process performance and equipment and improving reliability. It provides a method for experimentation and improvement. The Qual Plan is used to understand, quantify, and improve the functionality of a tool or process while reducing variability.

The Qual Plan is composed of three stages, with the second stage having two subsections—tool or process optimization (IIA) and reliability improvement (IIB).

Stage I: Project Baseline

The first stage is to ensure the stability and/or functionality of the tool or process. When the project goal is directed towards reliability improvement, a tool functionality demonstration may suffice; otherwise, Stage I establishes the baseline performance or functionality of the tool or process.

Stage I contains the following:

- 1Q: Plan Project
    - This determines project scope, requirements, schedule, cost, resources (including wafers needed), timeline, and tool acceptance. Reliability improvement projects often require off-shift operation support and supplier software and hardware support.
- 2Q: Gauge Studies
    - This identifies precision, accuracy, and sources of variation for measurement systems.
- 3Q: Passive Data Collection (PDC) or Functionality Demo
    - This establishes the baseline performance of the tool or process and explore relationships between input and output parameters over a pre-determined time for projects with performance improvement object. For projects directed towards reliability improvement, the capability of the tool to meet functionality requirements is determined.
- 4Q: Stage I Review
    - Here the statistical activities and plans for Stages IIA or IIB and Stage III are reviewed. Stage IIB will follow next when the project goal is reliability improvement, or when the PDC data indicates reliability improvement is necessary. Otherwise, Stage IIA follows.

Stage IIA: Process Optimization

This stage of the Qual Plan concentrates on optimizing the process**.** Stage IIA contains the following:

- 5A: Active Process Development
    - Input parameters systematically analyzed to identify the key ones. In addition, active process development is used to achieve stability when the Stage I PDC review indicates a lack of stability.
- 6A: Process Optimization

  - Designed experiments are performed to identify an optimized process window.
- 7A: Verify Stability
  - PDC is performed to establish stability of new settings and estimate reliability parameters.
- 8A: Stage IIA Review
  - Continuation to Stage III is determined by process and equipment results.

Stage IIB: Equipment Reliability Improvement

This stage of the Qual Plan focuses on planning and carrying out reliability improvement testing following the IRONMAN methodology.

- 5B: Prepare for IRONMAN
  - Equipment is cycled at night and engineering work based on root cause analysis of failures is carried out during the day. Resources needed to drive hardware and software improvements must be committed. This includes manpower, off-shift support, cycling wafers, cross-functional review teams, and ongoing data collection and analysis. Reliability testing is most effectively done at the supplier factory and all commitments and tracking logistics must be in place prior to the start.
- 6B: Passive Cycle Debug
  - This cycle of testing is done without the complexity of wafer processing added. The goal is to efficiently fix wafer handling problems before tackling the complexities of active processing.
- 7B: Active Cycle Debug
  - This testing is done mostly in a “production-like” mode. Reliability growth takes place as hardware and software problems uncovered during the testing are analyzed and fixed at a root cause level.
- 8B: Stage IIB Review
  - Metrics tracked during passive and active cycle debug must indicate the statement of work (SOW) reliability goals have been met before proceed to final confirmation during the Stage III marathon.

Stage III: Manufacturability and Competitiveness Demonstration

The third stage of a Qual Plan focuses on operating the tool in a manufacturing environment. This stage generates utilization statistics as specified in the SEMI E10 Guidelines (Appendix B), during a marathon run of the tool. The marathon includes enough time to generate statistically valid data. Stage III contains the following:

- 9Q: Plan for Marathon
  - This ensures resource requirements are available and support systems are in place.
- 10Q: Marathon
  - This determines manufacturability of tool or process in manufacturing environment.
- 11Q: Project Close-Out

  - Project resources are reallocated or accounted for. All contracts have been acted upon or updated and the future of the tool or deliverables has been decided.
- 12Q: Final Report
  - The project is reviewed and a final document is published.

The following lists provide some outcomes of a Qual Plan.

The following is identified:

- Key input and output parameters of the process and equipment
- Major sources of variation for each key output variable
- Significant interactions between variables
- Effects of key input variations on the distributions of the key outputs
- Opportunities for improvement (e.g., optimization of key output variables)
- Key variables to monitor and initial control limits for control system implementation
- Major modes of failure and root cause solutions

The following is determined:

- Repeatability and stability of metrology tools and systems
- Process capability, stability, and variability determined for each of the key output variables
- Load recommendations, test wafer locations (batch), and sample size requirements for the control system
- Reliability numerics
- Cost of ownership estimate

The following is developed:

- A troubleshooting guide for the control system
- Information transfer of a system’s qualification process
- Maintenance/repair procedures and frequencies
- Optimum process operating windows
- Technology insertion with users of information

A typical team for performing a qualification requires knowledge in the following categories:

- Project management
- Equipment development
- Process development
- Manufacturing operations
- Statistics
- Technology transfer
- Environment, safety, and health

- Reliability (Hardware and Software)

The time necessary to perform a qualification on a tool depends significantly upon the maturity of the tool under investigation. For example, a development project typically spends more time in Stage IIA than an improvement project does. On the other hand, improvement projects may perform designed experiments during Stage III to establish optimal utilization statistics.

It is very important that both customers and suppliers agree on realistic goals and objectives before the project plan is developed. The criteria for a project's success should be defined before execution begins.

Because of resource or time constraints, a tool or process often meets many, but not all, of the goals and objectives of a project. The methodology of the SEMATECH Qual Plan does not provide a checklist of items required before qualification is declared. The organization using the Qual Plan methodology must develop its own checklist of requirements.

2 SEMATECH QUALIFICATION PLAN INTRODUCTION

2.1 Document Scope

This document provides process engineers, hardware development engineers, and their managers a basic understanding of the various elements in a development methodology that emphasizes quality, completeness, and decision-making with statistically-valid data. This methodology is known as the SEMATECH Qual Plan (see Figure 1). The document is written in a generic format to enable member companies to use this methodology. This document will be updated periodically to reflect any changes that occur to the qualification methodology. A glossary, index, and three appendices are included. Appendix A describes additional steps a member company might take in qualifying a tool for fab use, Appendix B contains the SEMI E10 Guidelines, and Appendix C lists the SEMATECH training available to support the Qual Plan.

This document is NOT a process/hardware development procedure. Although the document emphasizes definitions and requirements and includes examples for several elements, it cannot replace formal statistical analysis, engineering training, or competent management. Although the document does not address project management, it fundamentally assumes a commitment to Managing by Data and the Total Quality process.

The examples in this document apply specifically to semiconductor equipment and processes and concentrate on the necessary statistical methods for proper interpretation of results. The fundamentals of the methodology also apply to other manufacturing industries.

For more information on applying the Qual Plan methodology, contact a member of the Statistical Methods group at SEMATECH.

2.2 SEMATECH Qualification Plan

The SEMATECH Qual Plan is a guideline for efficient, effective characterization of equipment and process performance and hardware and software reliability. It provides a method for experimentation and improvement. The Qual Plan is used to understand, describe, quantify, and improve the variability, functionality, and reliability of a particular piece of equipment or process.

The SEMATECH Qual Plan evolved from the Burn-in Methodology developed by Intel Corporation. Before these plans were used, new and upgraded equipment and processes underwent varying degrees of testing—from rigorous statistical tests and improvement efforts to limited acceptance testing that consisted of "production-ready" status upon installation. This kind of non-rigorous characterization often leads to months attempting to achieve equipment stabilization. The current version of the plan also incorporates and documents a methodology for hardware and software reliability improvement based on the Motorola’s IRONMAN approach.

The Qual Plan is useful for characterizing new or existing tools, conversions, or line requalifications. This qualification methodology applies to any type of manufacturing characterization and improvement program for equipment or processes. As an example, a subset of the Qual Plan formed the basis for the SEMATECH 200 mm conversion of wafer processing equipment.

The Qual Plan demands the practice of sound statistical methods to establish a baseline for a tool or process. The methodology operates in a cost-effective manner, using minimal resources to perform statistically valid data collection activities to produce a cost-effective tool or process.

The terms "qualification" and "characterization" are frequently used interchangeably. However, the two terms are very different. Qualification implies a wider base of activities than a characterization (Stages I, IIA, IIB and III). A SEMATECH Qual Plan qualification includes describing the tool or process performance, comparing the tool or process to a pre-defined set of goals and specifications, and stressing the tool or process in a manufacturing environment. In addition, from an ultimate user's point of view, qualification means readying the equipment to perform in an integrated manufacturing environment, which includes the additional steps described in Appendix A..

Characterization refers to the **subset** of the qualification activities involved in describing the performance of the tool or process (Stages I and IIA). Characterization often occurs in a non-manufacturing environment. Characterization is only a small part of the qualification procedure.

The following are some outcomes of a Qual Plan:

Identification of

- Key input and output parameters of the process and equipment
- Major sources of variation for each key output variable
- Significant interactions between variables
- Effects of key input variations on the distributions of the key outputs
- Opportunities for improvement of output variables as well as reliability
- Key variables to monitor and initial control limits for control system implementation
- Major modes of failure and their root causes and solutions

Determination of

- Repeatability and stability of metrology tools and systems
- Process capability, stability, and variability determined for each of the key output variables
- Load recommendations, test wafer locations (batch), and sample size requirements for the control system
- Reliability numerics
- Cost of ownership estimate

Development of

- A troubleshooting guide for the control system
- Information transfer of a system's qualification process
- Maintenance/repair procedures and frequencies
- Optimum process operating windows
- Technology insertion with users of information

SEMATECH QUALIFICATION PLAN

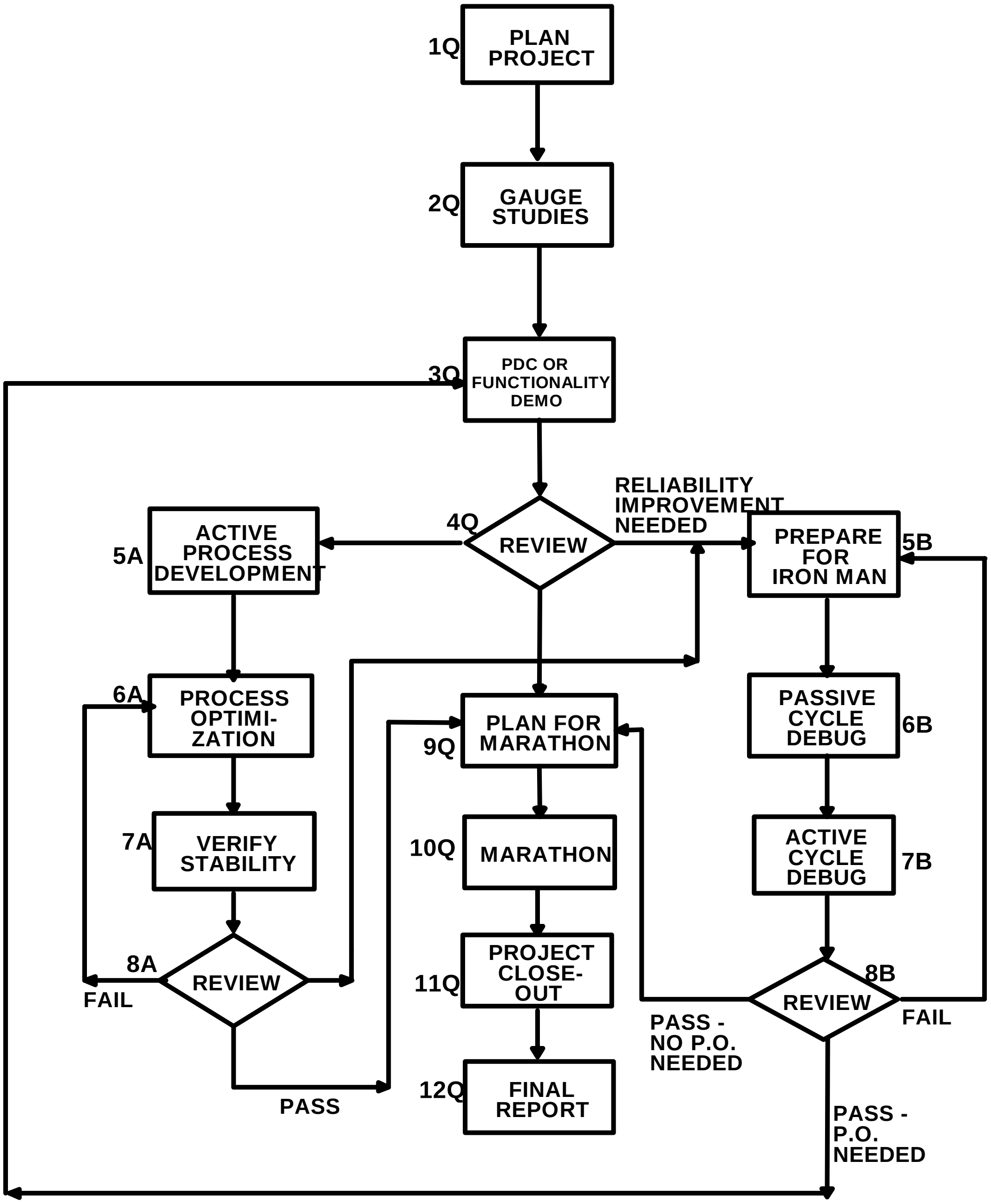

Figure 1 Qualification Plan Flowchart

3 QUAL PLAN PREREQUISITES

To implement the Qual Plan effectively, investigators must first explore considerations of personnel allocation, appropriate training, statistical expertise, beta-site facility capabilities, technical goals, and requirements of the project. This section discusses important topics that need to be addressed before developing a Qual Plan.

3.1 Customer Requirements

Planning and reviewing the goals of the project must involve the customers as customers define if the project was a success.

The customer's needs must be understood before the project is defined. For every project there are multiple customers, usually the end users of the equipment and the equipment supplier.

A typical team for performing a qualification requires knowledge in the following categories:

- Project management
- Equipment development
- Process development
- Manufacturing operations
- Statistics
- Technology transfer
- Environment, safety, and health
- Reliability

The core team usually meets regularly to discuss experimental plans, give updates, and plan future activities. Meetings involving the complete project team are held as necessary. Formal reviews occur periodically during the qualification.

If the team knowledge is deficient in any of the categories listed above, then selected team members receive training in the categories not covered. Courses include the following:

- Team member skills
- Problem solving
- Project management
- Statistical methods
- Hardware and software reliability
- Cost of Ownership (COO)
- Software-specific training
- Project tool and metrology system specifics

Classes are available through SEMATECH, universities, member companies, and the private sector. Information on classes available through SEMATECH can be obtained through the SE*MATECH Learning Resource Guide* published by the Organizational Learning and Performance Technology department (Technology Transfer document # 92061162D-TRG). For further information on SEMATECH training, see Appendix C.

The time necessary to perform a qualification on a tool depends significantly upon the maturity of the tool under investigation.

Different projects require varying amounts of time spent in the stages of the Qual Plan. A development project typically spends more time in Stage IIA than an improvement project does. On the other hand, improvement projects may perform designed experiments during Stage III to establish optimal utilization statistics.

While execution of most of the elements of a Qual Plan depends upon the information received during the previous element, there are also often opportunities for concurrently carrying out reliability improvement activities (Stage IIB) while switching back and forth from process optimization activities (Stage IIA). Note, however, that significant design changes incorporated to improve reliability will generally require reconfirming the optimal process windows discovered in Stage IIA.

The customers and supplier must agree on realistic goals and objectives before the project plan is developed. What constitutes a project's success must be defined before execution begins.

Because of resource or time constraints, a tool or process often meets many, but not all, of the goals and objectives of a project. The methodology of the SEMATECH Qual Plan does not provide a checklist of items required before qualification is declared. The organization using the Qual Plan methodology must develop its own checklist of requirements.

The safety work necessary for a qualification precedes the installation of the tool or process (Plan the Project). One of the tasks of the team is to receive and process the safety information provided by the supplier. The required safety information from the supplier includes industrial hygiene, equipment safety, and environmental impact reports.

The data and analysis generated from these reports facilitate the development of a procedure to correctly install the equipment at the customer's site. The safety information provided to the customer is updated with information gained during the execution of a qualification.

SEMATECH QUALIFICATION PLAN: STAGE I

Establish Project Baseline

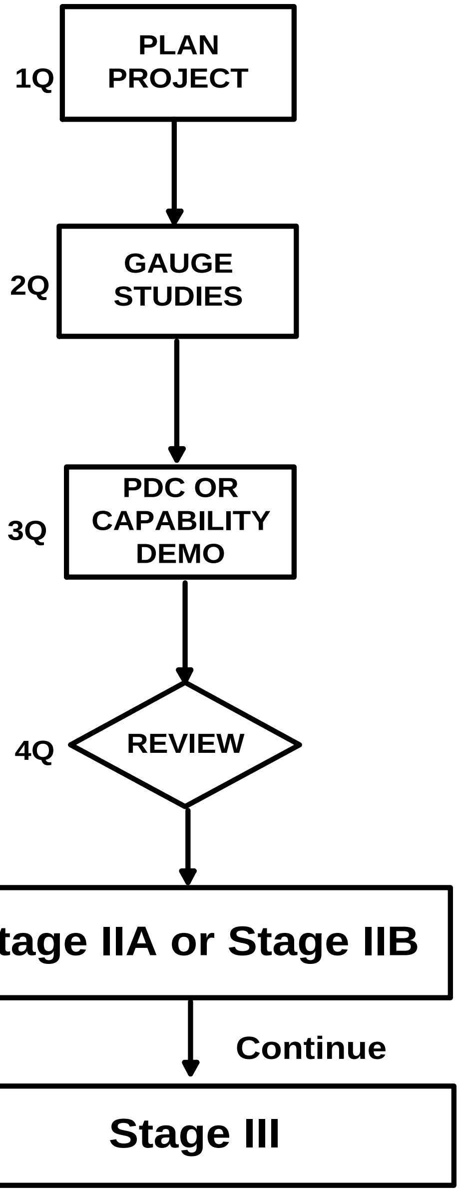

Figure 2 Flowchart of Stage I

4 STAGE I: PROJECT BASELINE

This stage contains four possible elements. The focus of Stage I is to create a project baseline to gauge expected improvements.

The first stage of a Qual Plan quantifies the stability and functionality of the tool or process.

4.1 Plan Project (1Q)

Project management has great impact on the efficiency of the Qual Plan. Planning will help predict potential problems and provide a framework for decisions if problems occur. Failure to complete planning before the project begins can allow problems that occur during the execution to affect the final results and timeline. The review process in the Qual Plan may require updating the project plan, but creation of its basic framework occurs here.

During this element, the team members and customers solidify the goals of the project. One project can have many goals. These goals should specifically state the metrics used and the basis for comparisons. Proper planning clearly defines specification metrics, establishes the methods of data collection, and defines the method of data reporting. Baseline metrics are developed to determine the success of the qualification.

Establishing an initial sampling plan allows an estimation of resources required. The sampling plan may change during the execution of the Qual Plan as the team develops a better understanding of the variability of the tool or process.

Accurate estimates of the quantity of material and data that the facility and team can produce over a fixed time period are generated. Artificially minimizing sampling can reduce the technical quality of the qualification while artificially maximizing sampling can reduce the capability to support the qualification.

A checklist of activities to complete and information to gather before continuing is often helpful. Typical items to include are:

- Contract acceptance from supplier
- Pre-ship check and initial acceptance at qualification site
- Correct software/hardware interfaces are present and functional
- Safety of tool accepted
- Allocation of required resources
- Cost of ownership estimate

For additional information on cost of ownership, refer to the Technology Transfer document *Cost of Ownership Model*, #91020473B-GEN.

Team members may need to attend training classes to prepare for qualification activities. Section 3.2 lists the knowledge categories necessary to perform a qualification.

Completion of training is not necessary at this point; training activities may continue throughout the duration of the project. However, training on the tool, metrology system, and related software should begin at this step.

4.2 Gauge Studies (2Q)

The objectives of a gauge capability study are to determine whether the metrology tool is stable, estimate the accuracy and precision of the metrology system, and establish control systems for the metrology system.

A metrology system includes the measurement tool and all the procedures used to make measurements on that measurement tool. The study consists of statistically-planned activities that identify and quantify the major sources of variability in the measurement process.

For additional information on gauge studies, refer to the Technology Transfer document *Introduction to Measurement Capability Analysis* #91090709A-ENG. For information on gauge studies for automated wafer measurement tools refer to *Evaluating Automated Wafer Measurement Instruments* #94112638A-XFR.

4.2.1 Preparation/Execution

- The project team identifies the following components of the execution plan:
- Input and output parameters to monitor
- Possible sources of variation for measurement system
- Sampling plan
- Analysis plan
- Staffing assignments to specific tasks.

A gauge study occurs in three phases. First the necessity of calibrating the tool is explored, then repeatability of the measurement tool is estimated, and finally the reproducibility of the measurement system is evaluated.

A sampling plan includes the number, frequency, and types of measurements to take during the gauge study. Estimating accuracy requires a sample size of at least 16 replications. Estimating the repeatability of the metrology tool requires a sample size of at least 30 independent replications. The sources of variation to be explored determine the type and number of measurements used to estimate reproducibility.

If the project involves more than one type of product (e.g., different film types or thicknesses), then a separate gauge study for each type of product is performed. The gauge study is performed on standards or artifacts of each product type, if possible. If standards do not exist, the gauge study should still be carried out. A reference product can be created and used throughout the project. The final report should state the origin of the products tested.

The team identifies possible sources of variability that can affect the measurements. Examples of sources of variability are operator-to-operator variability and time. A repeatability study does not explore any sources of variation, while a reproducibility experiment exposes the metrology system to all relevant sources of variability.

The first phase of a gauge study identifies any need to calibrate the measurement tool. If a standard is available, the team determines gauge accuracy using repeated measurements. If a standard is not available, direct accuracy is not possible. However, measuring a reference product allows tool drift (relative accuracy) to be tracked.

Repeated measurements (30 minimum) over a short time interval using a standard or reference product provide estimates of the repeatability and short-term stability of the measurement tool. To minimize the contributions of external sources of variability, a single site is measured each time, with minimum manipulation of the object being measured. If the study requires measuring multiple sites several times, then the analysis must group the replicates by site to allow the standard deviation to be estimated properly. The magnitude of the standard deviation determines whether to continue the study, to repair the measurement tool, or to replace the tool.

A reproducibility experiment includes all likely sources of variation in the measurement system. The number and types of these sources guide the design of the sampling plan used to capture the variability of the system. The sampling plan should capture information concerning all of the chosen sources of variation. Adherence to this sampling plan is crucial for data integrity.

4.2.2 Analysis/Decisions

The measurement data are summarized to determine whether the tool needs calibration, and a 95% confidence interval for the observed bias is calculated. The bias is the standard value minus the mean of the measurements taken. If zero is within the confidence interval, a calibration is unnecessary. The tool should be calibrated only if the mean of the data is sufficiently far away from the standard value. Unnecessary calibration adds variation to the process.

Summary statistics generated from the initial data estimate repeatability. A comparison of the repeatability of the tool to process specifications determines whether the magnitude is acceptable. A trend plot of the initial 30 readings estimates the stability of the tool.

A trend chart of the data resulting from the reproducibility experiment estimates the stability of the measurement system. If the measurement system is stable, the variance components are calculated and analyzed. The total variance of the measurement system (precision) is compared to a measure of the variation in the process. When reporting the precision of the measurement system, the number of standard deviations is cited. The precision-to-tolerance ratio (P/T) is then calculated, using the precision of the measurement system and the process specifications.

The decisions made during a gauge study include the following:

- The tool needs calibration (yes/no).
- The metrology tool is stable (yes/no).
- The measurement system is stable (yes/no).
- The total error is acceptable (yes/no).
- The components of the total error are understood (yes/no).

If the total error is unacceptable, the team must decide how to proceed. The project can continue with the current measurement system with revised sampling plans, a new measurement system can be identified, or the project goals can be modified to take into account the actual measurement capability.

4.2.3 Documentation

The following outline details information to be included in a report of a gauge study.

General information

- Goals of the study
- Equipment model number, options, configuration, software release
- Source for standards, manufacturer’s certification of the standards
- Any issues or special factors that limit the scope/applicability of the study

Data collection method

Accuracy statement

- Pre-calibration bias (with 95% confidence interval)
- Linearity graph (before calibration) if multiple products were measured

Precision statement

- Repeatability
  - Numeric value (with confidence interval)
  - Trend plot of the data
  - Explanation of any patterns in the trend plot
- Reproducibility
  - Sources of variability investigated and those found to be significant
  - Components of variation table/graph
  - Boxplots of sources
  - P/T ratio, including specifications

Comparison of metrology tools

- Comparative studies with a 95% confidence interval of the differences for bias and precision

Long-term stability

- Control chart
- Reaction plans for out-of-control situations

Decisions and reasons to use an unstable system or one with a high P/T value (if applicable)

4.3 Passive Data Collection (PDC) or Functionality Demo (#Q)

If a significant reliability improvement effort is planned for the tool, then a functionality demonstration before starting the IRONMAN will often replace a rigorous PDC.

A PDC is a “baseline” characterization of a tool or process prior to beginning optimization activities. The PDC accumulates information for a finite time period without process or equipment adjustments (tweaks). Normal maintenance procedures are allowed, but should be documented. Optimization or active process development will occur later (Section 5.1 or 5.2). Analysis of the data determines stability, capability, sampling efficiency, and relationships among variables.

A PDC can begin after a gauge capability study has been started. However, the analysis of results cannot begin until the data analysis and interpretation of the gauge study has been completed. If the data from the gauge study show an unstable system, then the PDC must be repeated (or the products remeasured) after the metrology system has been stabilized.

The objectives of a PDC are to determine the capability of a tool's performance, to estimate the sources of variability in the process, and/or to set the direction of future experimentation.

For additional information on passive data collection, refer to *Passive Data Collection* (Technology Transfer #91090684A-ENG).

4.3.1 Preparation/Execution

- The project team identifies the following components of the execution plan:
- Input and output parameters to monitor
- Possible sources of variability for each response
- Sampling plan that captures the most likely sources of variability
- Data analysis plan
- Staffing assignments for specific tasks
- Format for a logbook to record unusual events that occur during processing.

The sample size for a PDC must include at least 30 complete independent replications. A replication captures all the variability inherent to an equipment event. For example: in a vertical furnace evaluation, a replication may be a complete furnace load; in a stepper evaluation, a replication may be a single wafer.

During the first PDC, intentional over-sampling is recommended, such as using 11 wafers per load instead of three or measuring 49 sites on a wafer instead of 13. This data (from over-sampling) permits informed choices about reducing sampling efforts on subsequent data collection activities. The number of input parameters monitored during sampling should be as large as practical. This is to promote understanding of which input parameters drive the equipment response.

Process or equipment alterations from the normal operating procedures are not allowed during a PDC.

The team measures the product on the appropriate measurement systems and collects the resulting data, including the input parameter values. Detailed documentation during the execution of a PDC can help explain patterns or anomalies discovered during the analysis.

If a problem occurs during a PDC, stop the PDC, determine the problem, correct the problem, and then start a new PDC effort.

4.3.2 Analysis/Decisions

Trend plots estimate the stability and capability of the equipment or process. Statistical analysis identifies relationships between variables. Analysis of variance components establish sources of variability and their relative contributions to the total variability in the system. This analysis often suggests opportunities for process improvements.

If the PDC used a relatively large sample size, the analysis may also suggest an appropriate reduced sampling plan for future work. Some of the decisions resulting from a PDC are as follows:

- The process is stable (yes/no).
- The equipment is stable (yes/no).
- Reasons for instability have been identified (yes/no).

If the answers to these questions are "no," further work may need to be done before proceeding with the next stage of the Qual Plan.

4.3.3 Documentation

The following outline details information to be included in a report of a PDC.

- Description
    - Goals of the study
    - Input and output parameters that were measured
    - Sampling plan
    - Process settings used
    - Equipment configuration
    - Repairs/unplanned events logged during PDC execution
- Stability and capability
    - Trend charts
    - Explanations of special causes of variation
    - Histogram(s)
    - Cpk with confidence intervals
    - Conclusions
- Relationships between process variables
    - Graphical displays (boxplots, scatter plots, etc.)
    - Analysis of statistical significance
    - Autocorrelations/cross-correlations in time
    - Improved sampling plan development
- Variance component analysis
    - Table of percentages
    - Graphical display
- PDC conclusions
- Recommendations for further investigations

4.4 Stage I Review

The Stage I review assesses the outcomes of the project during Stage I. Often this is the first time management and the complete project team look at the tool's performance. Two major areas require evaluation: results of the gauge study and PDC or functionality demonstration, and plans for future activities.

The recommended items to review from Stage I are as follows:

- Quantitative results and decisions from the gauge capability study
- Quantitative results and decisions from the PDC or functionality demo
- Tool performance during the PDC or functionality demo, including anticipated or unexpected hardware or software reliability issues
- Requirements for incoming material, process tolerance, resource allocation

Plans presented and discussed during the review should include the following:

- Resources required to complete Stage IIA and/or IIB
- Updated qualification schedule and budget
- Required buy-in from management and project customers to support dependencies

Next activities: Additional PDC activity or functionality demonstrations

- Continuation to Stage IIA or Stage IIB
- Cancellation of project

Stage I data may lead to additional unplanned effort for two reasons: either the process was unstable during the PDC or the tool hardware/software reliability was unacceptable. These two observations require different corrective action steps—Active Process Development as a part of Stage IIA to achieve process stability, or a branch to STAGE IIB to conduct an IRONMAN reliability improvement test.

4.5 Stage I Case Studies

4.5.1 Gauge Study: Particle Counter

This example is a subset of a gauge study performed on a particle measurement tool during SEMATECH's 200 mm conversion. The subset contained here is on an 8" particle measurement tool.

Metrics	Wafer used to measure
Sensitivity	0.212 µm Polystyrene Latex Sphere (PSL) 6" wafer
Count	
Accuracy	Etch Pit 6" relative standard wafer
Repeatability	0.364 µm and 1.035 µm PSL 8" wafers
Reproducibility	0.364 µm and 1.035 µm PSL 8" wafers
Mean Size	
Repeatability	0.364 µm and 1.035 µm PSL 8" wafers
Reproducibility	0.364 µm and 1.035 µm PSL 8" wafers

The sensitivity of the tool is the ability to see particles at 0.2 µm.

4.5.2 Wafer Information

All wafers are from VLSI Standards, Inc. The 0.364 µm and 1.035 µm wafers are 8" wafers. The 0.212 µm wafer and Etch Pit relative standard wafer are 6" wafers because 8" wafers of these types were unavailable.

Mean size is measured in µm². For a PSL diameter of 0.364 µm, the mean size should be 0.235 µm². For a PSL diameter of 1.035 µm, the mean size should be 1.30 µm².

The particle measurement tool was calibrated on the 0.364 µm PSL wafer. This may affect the sizing accuracy of the other PSL sizes.

4.5.3 Procedure

Sensitivity and count accuracy were measured 16 times on the respective wafers.

Repeatability data (for both count and mean size) was gathered by measuring both the 0.364 µm and the 1.035 µm wafers 40 times consecutively while cycling the wafers. Reproducibility data (for both count and mean size) were gathered by measuring both wafers twice a shift until 40 data points were gathered.

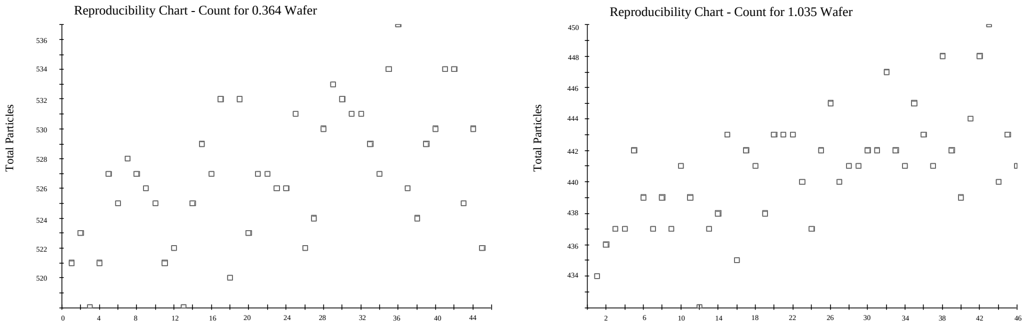

Figure 3 Reproducibility Trend Charts - Count

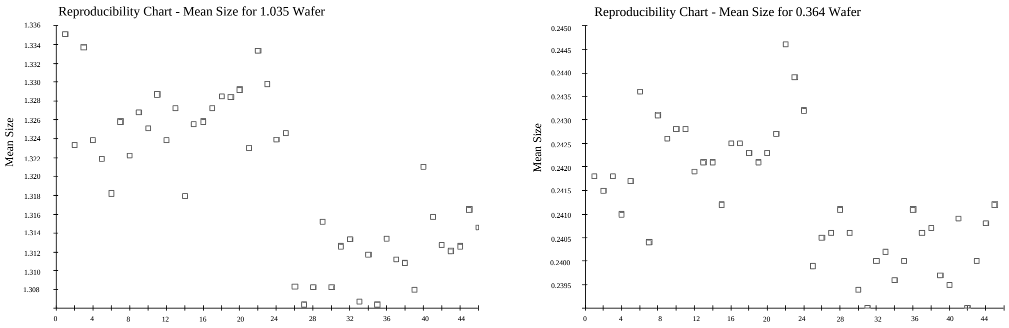

Figure 4 Reproducibility Trend Charts - Mean Size

Trend charts for the reproducibility data for the 0.364 µm and 1.035 µm are attached as Figure 3 for the count and Figure 4 for the mean size.

Process Metrics	Mean	Stdev
Sensitivity (0.212 µm)	0.0139	0.0001
Count Repeatability		
0.364 µm	527.95	3.42
1.035 µm	437.5	2.38
Count Reproducibility		
0.364 µm	526.91	4.55
1.035 µm	440.8	3.68
Mean Size Repeatability		
0.364 µm	0.242 µm²	0.0008
1.035 µm	1.32 µm²	0.0083
Mean Size Reproducibility		
0.364 µm	0.241 µm²	0.0014
1.035 µm	1.33 µm²	0.0046

4.5.4 Conclusions

This gauge study was not performed for a specific EIP or JDP. Thus P/T ratios for the measurement system were not immediately available. However, P/T ratios can be calculated from the information above for given process specifications. For example, if the process specification for particle counts is ±30, then the P/T ratio for the 1.035 µm is 37% and the P/T ratio for the 0.364 µm is 46%. This P/T ratio would have been unacceptable and a decision would need to be made on how to proceed.

4.5.5 Gauge Study: Thickness Measurement Tool

Overview

The purpose of the gauge capability study (or measurement capability study) is to identify and possibly reduce the sources of variation in the measurement system. The thickness measurement tool was the main metrology tool used in the characterization and development phase of the amorphous silicon etch process. The gauge capability study was performed on the optical film measurement tool to ensure its repeatability and reliability for measuring etch rates and selectivities.

Method of Study

The thickness measurement tool was used to measure the thickness of amorphous silicon and silicon oxide to provide etch rate, uniformity, and selectivity data. When it was discovered that the tool would produce anomalous readings when measuring certain thicknesses of etched amorphous silicon, the tool supplier provided a software upgrade that provided acceptable performance. Through the performance of the gauge study, it was determined that the measurement tool was capable of providing measurements of each of the films of interest without introducing excessive variation due to the measurement tool.

The methodology used for the gauge study of the thickness measurement tool is detailed in the following sections.

Standard Preparation

The samples chosen for the gauge study were representative of the films of interest for the duration of the project.

A 1000 Å thick oxide sample was prepared by etching an amorphous silicon wafer down to the thermal oxide underlayer. Wafers treated in a similar manner would be used to determine the selectivity of a silicon etch to underlying silicon oxide.

An 8000 Å silicon oxide wafer was prepared by etching an aluminum monitor wafer down to the underlying thermal oxide layer. Wafers treated in a similar manner would be used to determine the selectivity of the aluminum etch to the underlying oxide layer.

These were not NIST-traceable standards, but were wafers that had been measured repeatedly using an ellipsometer.

The thicker amorphous silicon "standard" was approximately 3500 Å of silicon deposited at 560°C on ≈1000 Å thermal oxide. The amorphous silicon was then implanted with 6E15/cm^2, 30 keV phosphorous. The implant was **not** activated. The thinner artifact wafer was prepared in the same manner and then etched back in a plasma etcher.

Determination of Tolerances

One of the performance goals for the project is within-wafer etch rate nonuniformity of 3% (3σ). The expected amorphous silicon etch rate is 3000 Å/minute; for a typical etch rate test of 30 seconds duration, 1500 Å will be removed. The target 1σ uniformity of the etch delta (1500 Å * 1%) is 15 Å. Therefore, the tolerance for measurement of amorphous silicon was ± 15 Å. For silicon oxide film measurements, the tolerance can be calculated from the etch selectivity goal of 90:1. With an expected etch rate of amorphous silicon of 3000 Å/min, a 90:1

selectivity to the underlying oxide would give an oxide etch rate of 33.3 Å/min. For an etch time of 60 seconds to determine the oxide etch rate, the expected delta (and tolerance of measurement) of 33.3 Å was used for the determination of measurement capability.

Repeatability

For each film, the wafer was loaded onto the stage and the centerpoint was measured 30 consecutive times without moving the stage between each measurement. This test would give an estimation of the variability inherent in the tool separated from the variability caused by wafer handling.

Reproducibility

For each "standard" wafer, 15 replications of a 40-point (for the 1000 Å oxide and both amorphous silicon samples) or a 30 point (for the 8000 Å oxide sample) contour map were taken over a short period of time, with the wafer unloaded and reloaded between each replication.

Stability/Control

The standards were checked regularly during the timeframe of the process development to identify out-of-control conditions and the need for tool maintenance.

Gauge Study Results

Repeatability

8000 Å Oxide: The standard deviation for the oxide standard was determined to be 0.235 Å for the 30-point test. The tolerance of the measurement was 33.3 Å; the P/T ratio was calculated to be 4.23%.

1000 Å Oxide: The standard deviation of the 30-point measurement test on the 1000 Å oxide sample was 0.194 Å. The tolerance of the measurement was 33.3 Å; the P/T ratio was 3.49%.

Amorphous Silicon (3260 Å): The standard deviation for the "as deposited" amorphous silicon artifact wafer was determined to be 0.179 Å. The tolerance of measurement was ±15 Å; the P/T ratio is calculated to be 3.58%.

Amorphous Silicon (1866 Å): The standard deviation for the 30-point test of the partially etched amorphous silicon film was 0.253 Å. The tolerance of the measurement was ±15 Å; the P/T ratio was 5.06%.

Reproducibility

The 7750 Å oxide sample was found to have a day-to-day contribution to the variability of the tool of 0.630 Å (1σ), and no contribution due to run-to-run variability. Almost all of the variability of the measurements was determined to be site-to-site variation. The pooled standard deviation of the individual sites was determined to be 1.311 Å. The measurement tolerance was 33.3 Å; the P/T ratio was 23.62%.

The pooled standard deviation for the 1000 Å oxide measurements was determined to be 0.567 Å. The measurement tolerance for this film was 33.3 Å; the P/T ratio was calculated to be 10.22%. The day-to-day variation of the tool was found to be 0.555 Å (1σ). No contribution from run-to-run variation was found.

The pooled standard deviation of the 40-point measurements of the as-deposited amorphous silicon film was determined to be 0.4148 Å. The measurement tolerance was ±15 Å; the P/T ratio for the tool is calculated to be 8.30%. The day-to-day variation was 0.090 Å (1σ), with no contribution due to run-to-run variation.

For the etched amorphous silicon standard, the pooled standard deviation was determined to be 0.649 Å. The measurement tolerance was ±15 Å; the P/T ratio is calculated to be 12.98%. Day-to-day variation was calculated to be 0.226 Å (1σ). There was no contribution due to run-to-run variation.

Stability/Control

For a 1000 Å thermal oxide film and an as-deposited amorphous silicon film, respectively, no major trends are apparent in the data, but small shifts in the sample mean were caused by replacing the lamp. The magnitude of the shifts were small enough that they could be ignored during the designed experiment phase, but should be accounted for if a lamp were to be replaced during a PDC.

Analysis

The target value for the repeatability of a measurement tool as determined above is a value less than 5%. If the basic repeatability is greater than 5%, then the tool may be fundamentally inadequate and large measurement noise may mask the true results. Since the amount of operator interaction with the measurement tool is minimal, the total measurement error is expected to be only slightly greater than the repeatability component. For the short-term intrinsic repeatability test, the tool appears capable of measuring both thicknesses of silicon oxide as well as the amorphous silicon.

The reproducibility of the film thickness measurement tool for both of the amorphous silicon standards and the oxide standards had P/T ratios that were < 30%. The tool was capable of providing reliable measurements for films near these thicknesses. The 30% value for P/T has been chosen for the small effect a measurement error of this magnitude would have on the observed process capability (C_{pk}).

During the course of the process development, it was determined that certain thicknesses of amorphous silicon could not be measured due to "dropouts" or erroneous zero readings. An upgrade to the software was provided by the tool supplier to specifically address the problems associated with measuring amorphous silicon.

4.5.6 Passive Data Collection: Furnace Sampling Plan

This case study is an example of the results from a PDC and shows the importance of “over-sampling.”

Each batch of material that passes through a furnace to grow or deposit a film on wafers typically involves 50 to 150 wafers. Selecting the correct sampling plan to isolate the sources of variability in such a process is not always obvious. In this example, each furnace run could accommodate 150 wafers. The sampling plan chosen places a monitor wafer at each end of the batch and one in the middle position. Several sites on each wafer were measured, and the sources of variability from run-to-run, wafer-to-wafer, and within-wafer (site-to-site) were calculated. Figure 5 is the boxplot of the data: 10 batches of wafers, 3 wafers per batch, and 9 measurements per wafer. The variance components analysis indicated the major contributor to variation within this process was within-wafer variation (82% of the total variation). The short-term estimate of capability for this process is relatively good:Cp ≈ 1.22.

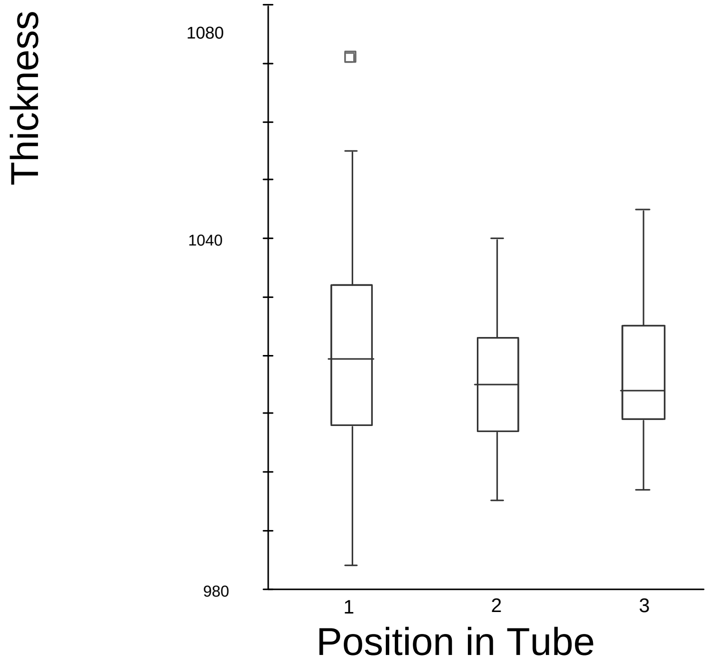

Figure 5 **Boxplot of Initial Sampling Plan**

After discussion, the team decided to increase the number of wafers per run to provide a better estimate of within-run or wafer-to-wafer variability. The second PDC used 11 wafers per run and produced the boxplot in Figure 6. When the variance components for this data were calculated, the major contributor to variation within this process was wafer-to-wafer variation (73% of the total). The contribution from within-wafer dropped to 27% of the total variation. The short-term capability of the process was recalculated and dropped to less than 1 (Cp ≈ 0.743). Given the performance of this system, the fewest wafers that one should use in characterizing it is five or more spaced appropriately within the tube.

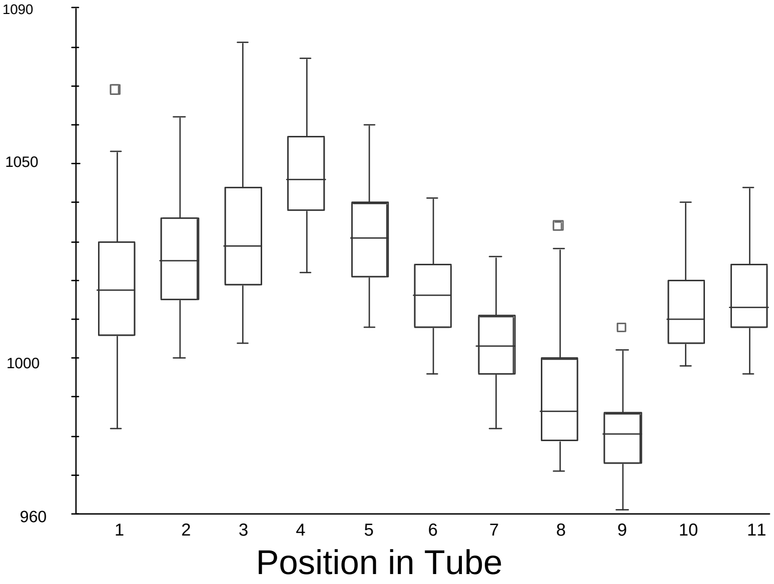

Figure 6 **Boxplot of Second Sampling Plan**

4.5.7 Passive Data Collection: Etch

This case study is an example of how a PDC can expose subtle hardware problems and instabilities.

Figure 7 shows the (normalized) etch rate results from a PDC on a new tool. The tool had passed its site acceptance test without issues. The only change made was the addition of a small chamber heater on part of the chamber that had never shown problems on the older generation tool.

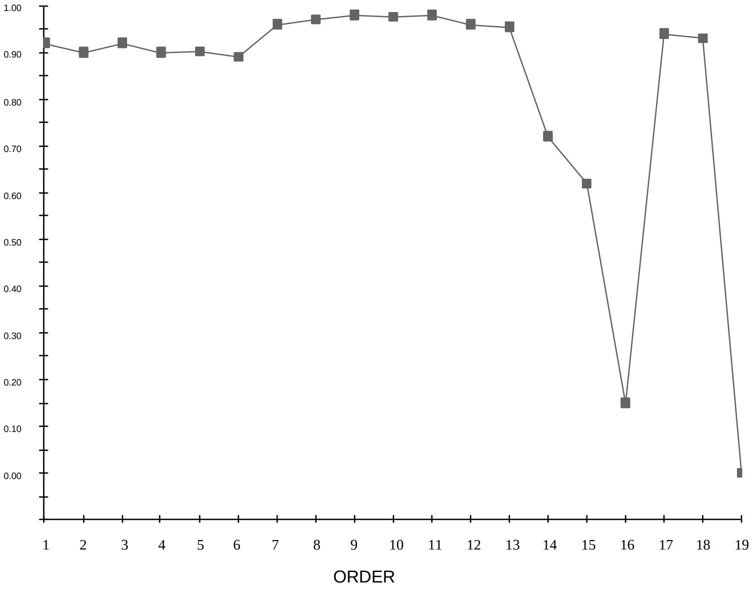

Figure 7 **Initial PDC**

The PDC was executed as a series of sets of wafers, one of which was an etch rate monitor. These wafers were measured after a timed etch; normally several wafers were saved and measured at one time. During the test, a problem was noticed with the etch rate, especially apparent at run 16 (the etch essentially stopped completely). It was determined that a switch had tripped on the gas feed line.

It was assumed that the gas feed had been compromised with purge gas. The line was then purged for an extended time and the flow controller calibrations were checked (but not changed according to PDC rules). The PDC was restarted the next morning.

Runs 17 and 18 etched normally, but run 19 showed the complete etch stoppage again. However, no facilities issues had occurred. Lacking an assignable cause, the PDC was abandoned and the chamber opened for inspection. A failed seal was observed near the new heater. It was concluded that the design of the new generation tool was more sensitive to heat, which caused failure.

The heater was removed and another PDC was run (Figure 8). The etch was now stable. A subsequent test with the heater showed the recurrence of the failure within ten wafers. This verified the design problem, which was then corrected.

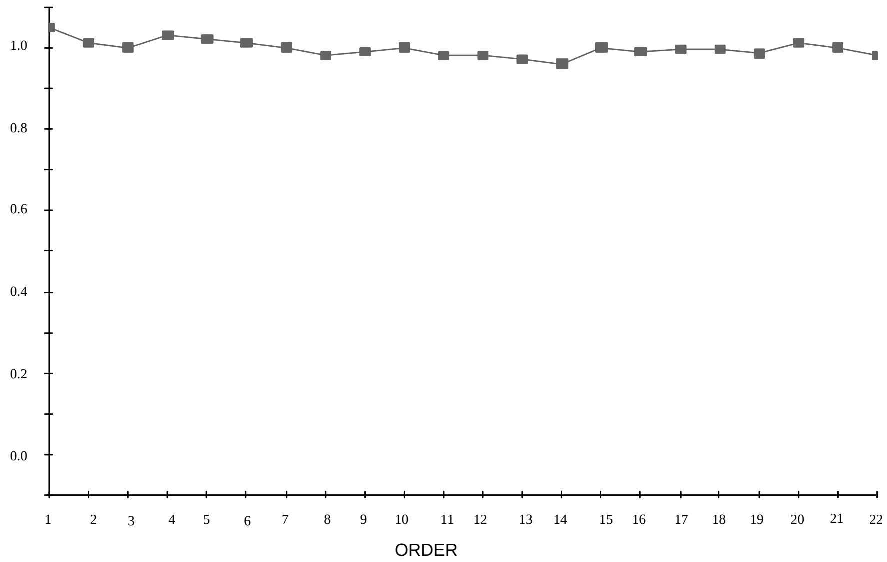

Figure 8 PDC After Hardware Correction

QUAL PLAN STAGE IIA

Process/Tool Optimization

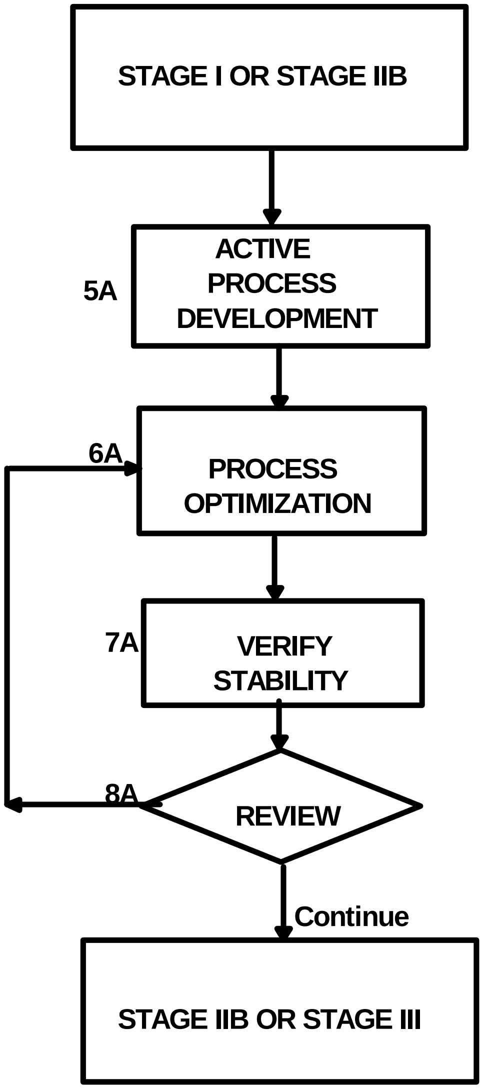

Figure 9 Flowchart of Stage IIA

5 STAGE IIA: PROCESS OPTIMIZATION

This stage explores and then optimizes the process recipe determined during the passive data collection in Stage I. Stage IIA contains four elements, three of which (6A, 7A, and 8A) may require several iterations depending upon the difficulty in finding a stable, optimal process.

At the end of Stage I, the review in Step 4Q will have established whether or not stability has been achieved. If stability exists, we proceed directly towards process optimization by using active process development to first determine the key input factors that affect the responses. If instability exists, active process development is again used to determine the key input factors affecting stability, but a mini-PDC needs to be done to demonstrate stability before proceeding to process optimization.

Process optimization is achieved most efficiently through the use of Design of Experiments (DOE). DOE methodology uses a series of experimental designs that manipulate several process inputs simultaneously to deliberately perturb a process in order to develop cause-and-effect relationships between process inputs and outputs.

A sequential experimental design strategy provides the most efficient use of resources as complete optimization of a process in a single stage is often resource-intensive. Screening experiments are used to determine the few significant input factors and explore possible two-factor interactions between the input factors. Response surface designs are then used to explore the effects of these remaining significant input factors on the responses.

The level of knowledge the project team has about a process dictates the type of experiment first used. Screening designs are used when the team has limited knowledge of the process and the process has many input variables with unknown or uncertain influences. Initial screening designs assume the relationships between inputs and outputs are linear rather than curvilinear. These designs can detect curvature in a response, but cannot estimate it. Screening designs can explore many input factors. It is important to include all potentially significant factors in the initial screening design. It is rare that a design would include more than 20 factors; such a large design would be unwieldy. The final number of treatment combinations depends upon the information desired.

Response surface designs are used when the project team has moderate to considerable knowledge about the process and previous experiments have defined a relatively few important input variables and possible two-factor interactions among these input variables. Response surface designs are applied when previous experiments have detected statistically significant curvilinear relationships between one or more of the process inputs and one or more of the process outputs. These designs should usually be restricted to no more than five input factors because of the large number of treatment combinations required to estimate curvature.

For additional information on experimental design, refer to *Design of Experiments* (Technology Transfer #91120781A-ENG).

5.1 Active Process Development (5A)

If the process tool has demonstrated stability we proceed directly towards process optimization by using active process development to establish the input factors that influence the responses to be optimized. If the process tool has demonstrated an unstable process with acceptable hardware reliability, a method for obtaining stable results must be determined. Again active process development will be used to determine the input factors that affect stability.

This stage of process development typically involves investigating the effects of a possibly large number of factors on several responses. Establishing cause-and-effect relationships between the variation of an input variable and a change in process outputs is the primary objective. The most efficient way to establish these relationships is through designed experiments. Active process development may also include purely engineering activities used to reach stability, such as refining the quality of consumables.

5.1.1 Preparation/Execution

The project team identifies the following components of the execution plan:

- Input factors and the ranges of their settings
- Likely interactions among the input factors
- Responses to measure
- A sampling plan (number of replications to include, etc.)
- Restrictions on the execution of the experiment
- Staffing assignments for specific tasks
- A plan for the analysis of experimental data
- Decisions based on results

The team generates or acquires updates on:

- Time frame for the experiment (includes analysis and documentation)
- Project cost
- Metrology system stability

Particularly in this early stage, electing to omit a number of process inputs to reduce the number of experiments necessary is unwise and may contribute to overlooking important relationships. As many input variables as practical are included. A design matrix is used that allows isolation of the main effects of the investigated inputs as well as the estimation of likely interactions. The types of experimental designs used here are called screening experiments.

Screening experiments generally use two levels of input factors: low and high, with added centerpoints. Several types of screening designs exist: factorial, fractional-factorial, and D-optimal. The type of design chosen depends upon the number of input factors, results required, and tool constraints. D-optimal designs are suitable when tool constraints on input factors prevent some combinations of those inputs. However, D-optimal designs are not as straightforward to design and analyze as factorial and fractional-factorial designs.

A correct sampling plan will include sufficient monitor wafers per batch to detect and measure the variation among wafers. The number of points taken per wafer must be sufficient to estimate the within-wafer variance component.

Active process development may involve many input factors. Therefore, attempting to quantify possible non-linear relationships between factor settings and outputs is premature. At this stage, the experimental design is used only to detect the existence of such non-linearities. Complete characterization of the process is deferred to later experiments (See Section 5.2, 6A: Process Optimization.).

It is important that the project team follow the experimental design and execute all the treatment combinations in the order presented in the experimental worksheet.

5.1.2 Analysis/Decisions

A detailed description of the analysis of designed experiments is beyond the scope of this document. For a more detailed description on designed experiments see the bibliography.

In general, the analysis should include suitable graphical methods as well as multiple regression analysis. The analyst should graph the data obtained using a variety of graph types (such as histograms, box plots, scatter plots, and trend plots) to detect unusual or maverick observations and to identify possible cause-and-effect relationships between input and output parameters. Properly designed scatter plots (two-way interaction plots) help identify interactions between inputs that affect an output. Multiple regression analysis quantifies the relationships and identifies statistically important input variables (and likely interactions among them) that the team can exploit to improve the process output or to decrease the process output variability.

The analysis should reveal some opportunities for improvements in the process by changing certain input settings. The changes observed in the process must have both engineering and statistical significance. Process changes must be analyzed for impact on established safety systems or environmental controls. An additional PDC (Step 3Q) at the new input settings is run to confirm predictions.

Some of the decisions made from the results of this element include the following:

- The process or equipment has achieved stability (yes/no).
- The correct input factors and their ranges were explored (yes/no).
- The project should continue to Stage IIA: 6A (yes/no).

5.1.3 Documentation

The following outline presents the content requirements for an active process development report.

Description
    Goals of the study
    Input factors and ranges explored
    Responses measured
Experimental method
    Design matrix
    Data collection methods
Results of experiment
    Model accepted for each response

Graphical display of results

Conclusions and future activities

5.2 Process Optimization (6A)

Step 5A determined which input factors were significant, established the interactions among them, and checked for any curvilinear effects. However, the designs used could only detect such curvature and not estimate it. It is the purpose of Step 6A to determine the process optimum.

5.2.1 Preparation/Execution

The project team identifies the following components of the execution plan:

- Experimental strategy: optimization (goals of experiment)
- Response variables of interest
- Input factors and range of settings
- Number of replications to include
- Restrictions on the execution of experiment
- Staffing assignments for specific tasks
- Plan for analysis of experiment
- Decisions based on results
- The team acquires updates on:
- Time frame for the experiment (includes analysis and documentation)
- Project cost
- Sampling plan
- Metrology system stability

Experiments to model curvature require a response surface design. These designs require three to five levels of each input variable and are able to quantify any curvilinear relationships between inputs and outputs detected in the screening experiments. Response surface design matrices include Central Composite, Box-Behnken, and D-optimal designs.

Again, D-optimal designs are most suitable when tool constraints on input factors prevent some combinations of those inputs.

5.2.2 Analysis/Decisions

As mentioned previously, a detailed description of the analysis of designed experiments is beyond the scope of this document. For a more detailed description of designed experiments see the references listed in the bibliography.

As before, the analysis should include suitable graphical methods as well as multiple regression analysis. Graphical diagnostic tools are invaluable for assessing the quality of the regression model obtained. The statistical analysis will identify significant inputs, their two factor interactions, and any quadratic terms (curvilinear effects) if appropriate for the design matrix. Graphical methods expedite the interpretation and exploitation of the final regression models obtained from response surface designs.

Contour plots are particularly useful for defining a process window in which several critical responses have acceptable values and stability to minor changes in process inputs. Several replications at the predicted process optimum confirm the values of the actual responses under those conditions and allow more refined estimates of confidence intervals for those responses.

Some of the decisions made during this element are as follows:

- The qualification is monitoring the correct inputs and responses (yes/no).
- The process window has acceptable width at acceptable performance (yes/no).
- The qualification requires further activities to improve performance (yes/no).
- Environmental, health, and safety factors have been evaluated (yes/no).
- The project is ready to continue to the next element (yes/no).

5.2.3 Documentation

The following outline lists the information to be included in a report of a designed experiment from Step 6A.

- Fixed factors during each experiment or across experiments
- Experimental objective and strategy
    - Factors, responses, and compromises
- Stability
    - Metrology
    - Process under investigation
- Impact on upstream and downstream processes
- Analysis
    - Interaction plots
    - Cube plots
    - Model
    - Fit of model
    - Contour Plots
    - Decisions
- Process window verification
- Conclusions and future activities

5.3 Verify Stability (7A)

This element involves a PDC on the optimized recipe developed in the previous element. Other results often gathered from this element are the estimation of utilization capability, update of the Cost of Ownership (COO) Model, and creation of control systems for the tool or process.

The length of the PDC in this element may vary from project to project. Some projects require the 30 replications minimum, while others treat this step as preparation for the marathon and run a larger number of replications. In the second instance, this element becomes a mini-marathon.

The calculation of utilization capability statistics from the mini-marathon follows the SEMI E10-92 Guidelines (Appendix B).

A mini-marathon often has two phases. First the team performs adequate replications to assure feasibility of the process recipe. Then the team runs additional replications to obtain utilization information.

This element verifies that the process is stable and that the tool can run for an extended period. It also refines the estimate of COO and allows the team to gather information for the marathon.

For additional information on COO or PDC, refer to the Technology Transfer documents *Cost of Ownership Model* #91020473B-GEN and *Passive Data Collection* #91090684A-ENG.

5.3.1 Preparation/Execution

The project team identifies the following components of the execution plan:

- Set of input and output parameters to monitor
- Possible sources of variability that affect these parameters
- Sampling plan required to capture the variability of each parameter
- Subsystems and sub-subsystems identified for utilization statistics
- Unique failure modes
- Reaction plans for out of control situations

The process is run as a PDC at the optimal settings determined from the designed experiments. Information on the process, hardware and software is recorded during the PDC. To ensure data backup to the software systems document the necessary information in log books during the data collection.

5.3.2 Analysis/Decisions

To assure the computer systems are functioning as required, the data on the computer systems should be checked against the information in the log books.

The results of the mini-marathon are analyzed in two segments: process capability performance (the initial replications) and tool performance (the remainder). Process results are analyzed as a PDC. In addition, process results are used to establish a process control system by

- Identifying key responses to be tracked
- Verifying the sampling plan to be used in collecting process control data
- Establishing summary statistics to be charted, trial control limits, and methods for calculating control limits
- Using team expertise to develop a trial decision tree for taking action when an out-of-control condition is detected.

The equipment performance is analyzed according to SEMI E10 guidelines, using the utilization information gathered during the mini-marathon. Statistics on tool utilization, such as Reliability, Availability, and Maintainability (RAM), are calculated. Confidence intervals should also be calculated where appropriate. Other utilization statistics can be calculated using throughput information.

RAM statistics (hours or cycles or wafers):

- Mean time between failures (MTBF) or mean wafers between failures (MWBF)
- Mean time between assists (MTBA) or mean wafers between assists (MWBA)
- Equipment dependent uptime
- Supplier dependent uptime
- Operational uptime
- Mean time to repair (MTTR)
- Operational utilization
- Total utilization

The information gathered on the failure modes is summarized and displayed in graphical format. The failure frequency by type or reason down should be graphed on a Pareto chart. Summary statistics, such as subsystem failure average frequency and subsystem failure MTTR are calculated for each of the identified subsystems.

Calculate the cost of ownership based upon the statistics obtained during this element.

Some decisions made during this element include the following:

- The equipment and process met the goals stated in the project plan (yes/no).
- Further work is required to reduce or control variability (yes/no).
- The equipment or process is acceptable for continuing to Stage III (yes/no).
- The COO estimate is acceptable (yes/no).

5.3.3 Documentation

The documentation for this element follows the PDC format. Several sections are added to the PDC format to document tool performance.

Equipment utilization data

    Statistics
    Decisions

Pareto charts of failures and assists

    Discussion of failures
    Discussion of assists
    Decisions

Discussion of control system

Estimate of COO

Conclusions and future activities

5.4 Stage IIA (8A) Review

This review process determines whether the tool has shown acceptable reliability and assures that project customers are satisfied with the results of the optimized process. If the process results are not acceptable, then the optimization process must be repeated before continuing to Stage III. If the tool's reliability is not acceptable, needed improvements would be addressed according to the procedures in Stage IIB, as described in Section 6 .

5.5 Stage IIA Case Studies

5.5.1 Optimization: Low-Temperature Etch

Motivation

Oxide etching is the most common plasma etch step in a typical ultralarge-scale integration (ULSI) process flow. All of these etches rely on an energetic bombardment (physical etch) in order to remove the SiO_2 quickly, and on polymer formation on silicon, silicide, or polysilicon surfaces to provide adequate selectivity to base layers. As contacts become smaller and requirements for selectivity become stricter, many of these processes are forced to move to a region of process space "near the cliff." That is, the process uses such a highly polymerizing chemistry that process latitude for profiles becomes small. Another side-effect is that the polymer formation occurs also on chamber walls and other surfaces so that the number of wafers between chamber cleans becomes fewer.

The motivation for low-temperature oxide etching was to study whether the use of low temperatures in a standard oxide etcher would allow use of a less polymerizing chemistry while still maintaining high selectivity to photoresist and underlayers. The hope was that the low wafer temperature might enhance polymer formation on the wafer so that the walls and other surfaces could stay cleaner, allowing longer operation between cleans. The ultimate result would be lower COO. Results from other sources seemed to indicate promise for the technique.

Overview of Experiments

The oxide etch characterization was concerned primarily with the etching of contacts (first window etch). A total of two screening experiments and one Response Surface Methodology (RSM) experiment were performed. No "marathon" or other long-term passive data collection on the process was performed.

The purpose of the characterization was to determine the effect of low temperatures on etch rate, nonuniformity, selectivity (to both photoresist and silicon), and profile.

The first oxide screening experiment used CHF_3 and C_2F_6 as in a standard triode oxide etch, but at lower pressures, lower temperatures, and with extremely high fluorine concentrations (very nonpolymerizing chemistries). The second oxide screening experiment used a mix of various chemistries of $CHF_3/C_2F_6/O_2/Ar$ to seek higher silicon selectivity with less polymerizing chemistries. The oxide RSM experiment returned to the CHF_3/C_2F_6 chemistry, to avoid arcing problems in the prototype hardware.

Experimental Summaries

First Oxide Screening

The following tests using the standard room-temperature oxide etch, a series of tests (about six wafers in all) were performed at low temperatures at the supplier site before the tool was shipped to SEMATECH. These indicated considerable sloping of the contacts at very low temperatures, especially at higher pressures and higher CHF_3 concentrations.

The purpose of the first oxide screening was to determine the significant factors affecting low-temperature oxide etching using a fluorine-rich chemistry.

The first oxide screening was a Level IV resolution fractional-factorial design of 22 test cases (16 matrix corners and 6 centerpoints). The factors were chosen to explore a region of process space having low to no CHF_3, low pressures, and moderate powers. Note: It is more appropriate to use ratios of gases and total flow instead of raw amounts of individual gases in such experiments. This approach is used below and is described in more detail in Chapter 8 of *Design of Experiments Volume 1: Topics in Experimental Design*, Technology Transfer # 91120781A-ENG.

The responses were etch rate, nonuniformity, selectivity to both silicon and photoresist, and the profiles of contacts. The actual process parameters and settings were as follows:

	Process Parameter		**Settings**	
Abbr	Name	Low	Center	High
C2F6	Percent C_2F_6 in CHF_3	50	75	100
TF	Total Flow (sccm)	30	60	90
RF	RF Power (watts)	400	500	600
P	Pressure (mtorr)	60	130	200
TC	Chuck Temperature	-50	-30	-10

The results of the first oxide screening experiment were:

- The oxide etch rate (ranges from 3600 Å/min to 5400 Å/min) and nonuniformity (ranges from 4% to 11%) were unaffected by chuck temperature.
- The silicon selectivity (range from 2 to 6) was very low, with weak dependence on temperature but with a pressure-temperature interaction.
- The silicon selectivity increased strongly with the percentage of CHF_3. It was postulated that the choice of limits for the matrix was simply too fluorine-rich to obtain adequate polymer for selectivity, even though the high slopes of the profiles would have implied sufficient selectivity in a standard etch.
- The photoresist selectivity (range from 1 to 5) showed improvement with lower temperatures.
- The etch rate at the flat was slowest.
- The profile became more sloped (less vertical) with lower temperature, higher pressure, and lower flow. A more vertical profile was observed at the flat.

Second Oxide Screening

The purpose of the second oxide screening experiment was to seek a range of oxide etch chemistries that gave higher silicon selectivities at low temperatures, and to determine the best region of process space for the RSM experiment.

The experiment used different combinations of CHF_3, C_2F_6, O_2 and Ar. A Plackett-Burman design was chosen on 12 runs (no centerpoints), which provided essentially a Level III resolution screening design on eight factors. The only responses tested were oxide etch rate, oxide nonuniformity, amorphous silicon etch rate, and photoresist etch rate. The parameters and their settings were as follows:

	Process Parameter	**Settings**	
Abbr	Name	Low	High
TC	Chuck Temperature	-70	-10
AR	Ar:CHF_3 Ratio	1	2
C2F6	C_2F_6:CHF_3 Ratio	0	0.35
O2	O_2:CHF_3 Ratio	0	0.05
TF	Total Flow (sccm)	100	150
P	Pressure (mtorr)	100	200
RF	RF Power (watts)	400	600
C3	Power Split (C3 setting)	0	400

The results of the second oxide screening experiment included:

- The oxide etch rate (range from 2750 Å/min to 5250 Å/min) increased with decreasing temperature.
- The oxide nonuniformity (range from 5% to 16%) was dominated by pressure, improving with increasing pressure.
- The selectivity to photoresist (range from 2 to 30) increased at low temperatures and decreased with increasing oxygen.
- The selectivity to silicon (range from 3 to 55) increased with lower temperature, increased to a large extent with increasing CHF_3, and was mostly unaffected by argon dilution.
- The tests showed more work would be necessary to optimize profile, but regions were found with sufficient selectivities to allow “room to maneuver.”
- The addition of high dilutions of argon gas generated problems with arcing in the prototype hardware. The decision was made to return to $CHF_3C_2F_6$ chemistries for the oxide RSM experiment.

Oxide RSM

The oxide RSM experiment was run as 32 runs (16 matrix corners, 6 centerpoints, and 10 star points) on a CHF_3/C_2F_6 chemistry. Four wafers were etched at each case: a blanket oxide wafer for etch rate and nonuniformity, a patterned amorphous silicon wafer for silicon selectivity, a time-etched patterned oxide wafer for photoresist selectivity, and a patterned oxide wafer etched to endpoint and about 10% overetch for profile studies. A fifth wafer was planned for reactive ion etch (RIE) lag studies, but the resources were not available. In addition, a dummy silicon wafer was "ashed" between each wafer of each case in order to keep the chamber clean and consistent.

The process parameters and their settings were as follows:

Process Parameter		Settings				
Abbr	Name	Lo*	Lo	Ctr	Hi	Hi*
CHF3	Percent CHF_3 in C_2F_6	60	70	80	90	95
TFLO	Total Flow (sccm)	80	100	120	140	160
POW	RF Power (watts)	400	500	600	700	800
PR	Pressure (mtorr)	50	100	150	200	250
TEMP	Chuck Temperature	-70	-50	-30	-10	+10

The conclusions from the experiment were as follows:

- Good models were obtained for all responses.
- Photoresist selectivities were high, especially at lower temperatures.
- Silicon selectivities, although high at some points, were generally not as high as desired.
- Etch nonuniformities were higher than those of the standard triode oxide etcher, even at warm temperatures.
- Profiles become very sloped at low temperatures with the CHF_3/C_2F_6 chemistry, although lower pressures tend to partially restore slopes .

Conclusions

Oxide contact etching was studied in the temperature range from -70°C to -10°C using a predominately fluorocarbon (CHF_3/C_2F_6) chemistry. Improvements were seen in photoresist selectivity. In general, oxide etching at low temperatures seems to provide certain benefits, but additional work is needed to develop a manufacturable process. Responses such as photoresist selectivity, silicon selectivity, and profile angle could all be optimized individually, but meeting all requirements simultaneously in this prototype hardware with this chemistry proved elusive. Such optimization would have required changes to the hardware and the chemistry, which were beyond the scope of this project.

5.5.2 Verification: Low-Temperature Etch

Motivation and Overview

As part of the SEMATECH Qualification, a 120-hour "mini-marathon" was performed on the low-temperature polysilicon etch process on a prototype tool. The mini-marathon ran from Sunday night until Friday night. The process recipe was chosen before the RSM analysis was complete. For the screening centerpoint process, sufficient results had been gathered to imply statistical stability. However, the responses, requirements, and robustness of the process had not been optimized. The primary purpose of the mini-marathon was to test the performance of the chuck chiller and temperature monitors, not the polysilicon etch process.

Procedure

The mini-marathon was designed as a 120-hour nonstop use of the tool and process. Cassettes of 24 wafers each were processed through the centerpoint polysilicon etch process. One or two wafers per cassette were "critical" wafers. These critical wafers had implanted but inactivated 3500 Å thick amorphous silicon with patterned resist. The linewidths ranged from 0.4 mm to 0.8 mm. Following a ten-second breakthrough step, these wafers were etched to optical endpoint (using a 704 nm fluorine line) and given 10% overetch by time. Endpoint times were recorded for each critical wafer. The critical wafers were sampled (3 wafers per lot) for in-line scanning electron microscope (SEM) measurements of critical dimension (CD) (pre-etch and post-etch at the same locations, same wafers). Following the mini-marathon, all of the critical wafers completed the flow so that electrical test linewidth data could be gathered.

The remaining 22 or 23 wafers per cassette were blank silicon "dummies" (test wafers). These wafers received the same process as the critical wafers with a maximum time of 110 seconds. At the end of each cassette, the previous critical wafers were removed and the new critical wafers loaded into slots chosen by a random number generator. The noncritical blanks were reused. They were replaced with a fresh box of blanks at the start of each shift.

At the start of each shift, etch rate tests and particle tests (0.2 mm and larger) were recorded as trend charts, but not as control charts. Temperature data were monitored consistently at five-second intervals, recording chuck and wafer temperatures as well as radio frequency (RF) status. Files were uploaded to the host computer approximately once per shift.

Hardware Reliability During the Mini-marathon

The tool performed admirably. Equipment-dependent uptime was over 114.5 hours out of 120 hours, or better than 95%. Besides one "Down to Facilities" (the SF_6 supply was lost temporarily), there were 12 assists and four "downs." All twelve assists were traced to a single problem in the prototype handler software. This problem also accounted for one of the "downs" as the equipment engineer took time to test equipment alignment before concluding that the problem was indeed one of programming. A simple change in operating procedure then avoided the problem for the remainder of the mini-marathon.

Two failures were due to hardware problems unassociated with the cold chuck system. These parts were quickly replaced.

The final failure occurred in the probe electronics box where a reset was required to restart the flash lamp. Once it was noticed, the manufacturing technician quickly reset the box. No further problems were observed.

Note that no chiller or coolant-related failures were observed. In fact, none have been experienced during the more than five months that the chillers have been continuously operating since their installation at SEMATECH.

Temperature Results from the Mini-marathon

During the mini-marathon, the chuck temperature was recorded. There was one high outlier that corresponded to the probe electronics box error mentioned in the previous section. Although the box was easily reset, it had been some time before the failure was noticed. Since the heater controller takes its control signal from the probe and goes to full heat when that signal is lost, considerable heat was dumped into the electrode during the short time the probe was not operating.

The second observation is a slow upward drift over the week. It is unclear whether this drift represents a true drift in temperature, a change in the probe calibration, or simply normal statistical fluctuation (more data would be required to assign the cause). It is important to note that the entire drift was well under one degree.

Wafer temperatures were also monitored during the mini-marathon. The spike from the probe error was not apparent in the data gathered, which implies relatively few wafers were processed during the few minutes that the probe was off. High temperature on the second day of the mini-marathon corresponds to the facilities problem with SF_6 delivery. Since SF_6 was not flowing, the remaining argon etch presumably warmed the wafer more.

Process Results from the Mini-marathon

Polysilicon (amorphous silicon) etch rate and nonuniformity data were taken from two etch rate monitors run each shift during the mini-marathon. This data was plotted on trend charts and show a controlled process with mean etch rate of about 4000 Å/min and mean nonuniformity (1%) of 7%.

The critical wafers were measured for CD on the 0.4 mm (nominal) lines. Two methods were used. The in-line SEM measurements provided both pre- and post-etch linewidths, while the electrical testing provided equivalent linewidths based on the resistance of serpentine patterns.

In the SEM tests, a sample of 12 wafers (5 sites per wafer) were measured out of a total of 69 critical wafers. On the average, dense lines (lines in a grid) showed a CD growth of +0.03 mm, while isolated lines showed a larger CD growth of +0.09 mm.

Electrical testing was performed at 60 sites per wafer on all 69 critical wafers as well as 4 "control" wafers that had been etched in a standard room-temperature etcher. Bridging yields on the critical wafers were as high or higher than yields from the standard room-temperature etcher (since the growth of the dense lines was small, and the larger growth of the isolated lines does not affect bridging yield). Comparisons to the standard room-temperature etcher were based not only on results from the "control" wafers of these lots, but also on results from other lots.

It should be noted that the photolithography process for patterning these lines is also still in development, and that the linewidth variation (wafer-to-wafer and lot-to-lot) must be shared by both the etch and lithography processes.

Conclusions and Summary

The pre-marathon prototype, low-temperature etch tool performed reliably during its mini-marathon, with no failures to the chiller or cold chuck and only one reset of the temperature monitoring electronics. Temperature stability was very tight across the entire week at the setpoint of -120°C, as based on an analysis of the more than 30,000 temperature data points when RF was ON in the chamber. Process control was good, with small CD growth on dense lines, although isolated lines showed larger CD growth.

The following table shows the summary of hardware and process results for the polysilicon etch mini-marathon.

Hardware	**Results**
Total Time	120 Hrs.
Equipment - Dependent Uptime	> 95%
Total Wafers Etched	> 1500
Temperature Setpoint	-120° C
Electrode Temperature, Mean	-120.69° C
Electrode Temperature, Std. Dev. (1σ)	0.52° C
Wafer Temperature, Mean	-120.49° C
Wafer Temperature, Std. Dev. (1σ)	1.00° C
Process	4000 Å/min
Mean Etch Rate	
Mean Etch Nonuniformity (1σ%)	7%
SEM CD Growth (Post-Pre, Dense Lines)	+0.03 mm
SEM CD Growth (Post-Pre, Isolated Lines)	+0.09 mm
Electrical Linewidth, Isolated Mean	0.42 mm
Electrical Linewidth, Isolated 1σ	0.029 mm
Electrical Linewidth, Dense Mean	0.36 mm
Electrical Linewidth, Dense 1σ	0.046 mm

QUAL PLAN STAGE IIB

Equipment Reliability Improvement

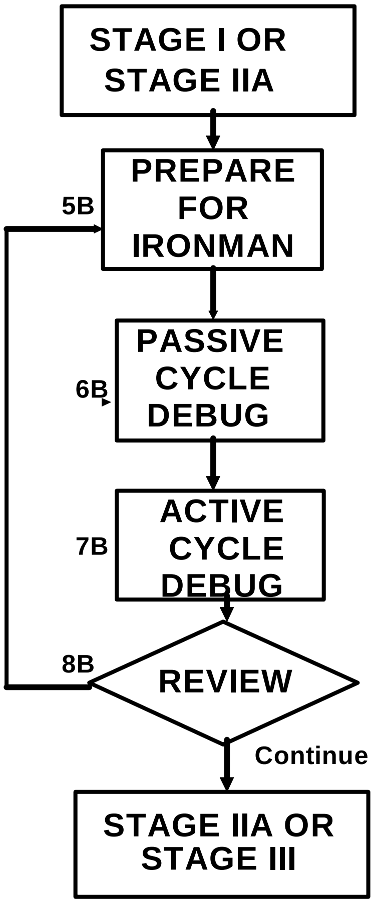

Figure 10 Flowchart of Stage IIB

6 STAGE IIB: EQUIPMENT RELIABILITY IMPROVEMENT

This stage focuses on improving equipment reliability. It may be performed independently or while Stage IIA is being performed. Stage IIB involves three elements that should be performed sequentially until the desired level of reliability is achieved. When an acceptable level of performance is achieved, then the project can proceed to Stage III.

The reliability performance of the equipment is established during the initial passive data collection or functionality demonstration (Stage 3Q). If the equipment did not achieve the desired level of performance, the decision should be made to work on improving the reliability of the equipment.

The methodology used for reliability improvement is an adaptation of the Motorola IRONMAN program. IRONMAN is a Motorola trademarked acronym meaning Improving Reliability Of New Machines At Night. In the simplest terms, the project is typically planned to cycle the equipment at night while engineering work on hardware, software or process development is completed during the day. Equipment failures are tracked with the use of a Failure Reporting, Analysis and Corrective Action (FRACAS) system and analyzed through the use of pareto analysis. Hardware and software improvements made during the IRONMAN should driven by the relative number of failures. The IRONMAN program may also be used to test equipment improvements and redesigned components for their impact on tool performance. The tool provides an alpha-site for these new components.

The reliability improvement activities may be conducted exclusively or may run concurrently with process development. If process optimization is performed while improving equipment reliability, care must be taken that hardware improvements do not affect the process performance.

Additional information on using the IRONMAN methodology can be found in *IRONMAN Methodology Manual*, Technology Transfer #94082509A-XFR.

6.1 Prepare For IRONMAN (5B)

Reliability goals should be included in the Statement of Work (SOW). The SOW for the project and forecasted resources should allow for reliability improvement. Alternatively, the SOW for the project should be re-negotiated as soon as the equipment reliability becomes an issue during the course of the project. The focus of the project shifts to reliability improvement.

Some of the factors to consider when negotiating the SOW are as follows:

- Manpower
- Off-shift operation
- Supplier hardware support
- Supplier software support
- Wafers - include cycling wafers in forecast
- Equipment architecture

The key to the IRONMAN is to cycle the tool at every possible opportunity. The project should be planned from the beginning to include the resources to run the IRONMAN. A commitment from the supplier will be required to ensure that improvements and design revisions will be made in an aggressive manner. The reliability testing should be performed at the supplier's factory to allow the most effective use of expert engineering and corrective action resources.

The IRONMAN should be run at the supplier's factory to ensure quick response time to failures, and to maximize the interaction with supplier engineers. The commitment of the supplier is necessary for the success of the project during Stage IIB. Design review during the IRONMAN is critical for the improvement of the equipment. Aggressive hardware and software design review should be performed during the reliability improvement activities. Hardware and software improvements are tested during the IRONMAN. A Failure Review Board (FRB) should be established to ensure closure on failures. The supplier must be committed to performing critical design reviews using the data generated in the IRONMAN to make design decisions.

A means of collecting data from the equipment will make the troubleshooting process more effective. Automated data collection of equipment and process parameters as the tool is cycled may simplify the process of root cause analysis when a failure occurs. A means of collecting data from the equipment will also make the root cause analysis of failures (troubleshooting) process more effective. A database collection system such as the SEMATECH Failure Reporting, Analysis and Corrective Action System (FRACAS) (TT# 94042332A-GEN) will simplify tracking tool failures and incidents.

Performance should be tracked daily, and communicated to the entire project team as well as supplier management. Tool performance should be reported daily in terms of wafers cycled for the day, mean wafers between failures (MWBF) or assists, and a list of incidents recorded during the day. The status of corrective actions put in place by the FRB should also be included.

6.2 Passive Cycle Debug (6B)

The passive cycle debug step of the process attempts to fix those problems that occur from handling the wafers. The IRONMAN process should start with stressing the wafer handling components of the tool without the complexity of wafer processing. This provides a cost effective way to eliminate simple handling problems without consuming wafers.

6.2.1 Preparation / Execution

The equipment should have wafers cycled through it, exercising only the wafer transport mechanisms. The focus of the passive cycle debug should be to concentrate on the performance of the equipment without the complication or expense of processing wafers.

The length of time spent on this activity will depend on the level of performance compared to some negotiated level of performance. It should be noted that mean time between failures (MTBF) may not be testable with any great confidence within the time allotted for the project. The length of time in which continuous cycling is performed may be highly variable as modifications to the equipment are being made, or failures are being diagnosed. In this case, MWBF may provide a better metric. Demonstrating 1000 wafers between interrupts with some level of confidence is a convenient goal. During this portion of the project, a means of tracking the data should be developed. The supplier should institute a FRB. The FRB is responsible for assigning owners and helping set schedules for the resolution of the failures recorded. All failures require root cause analysis and demonstrated corrective action by the FRB. The FRB shall also hold periodic design reviews.

6.2.2 Completion of Passive Cycle Debug

When the tool has met a pre-determined level of performance when cycling wafers, adding in the effects of wafer processing should be considered. The project should move to the next stage. The performance of the equipment as well as the action taken to meet the goal shall be published.

6.3 Active Cycle Debug (7B)

During the active cycle debug stage of the project, the stress of wafer processing is added to cycling wafers through the tool. The type of process used at this level should progress from an “inert” process at the beginning of the stage to a “production - like” process near the end of the stage. The “inert” process should be one that does not change the state of the wafer. The progression should be from a simple simulation of a process to a more complex process as the tool performance improves. For example, a plasma etch tool may be exercised with an argon or nitrogen plasma at first, and then the actual reactant gases could be used as performance improves.

6.3.1 Preparation / Execution

The focus of the active cycle debug stage is to stress all of the system components. The structure of the wafers and the process used during the cycling of the tool should be carefully considered. Since maximum benefit can be found by performing as many cycles as possible during the process, a short version of the wafer process should be used. The films on the wafers used may also have an effect on the performance of the tool. For example, if particle measurements are made as part of the IRONMAN, cycling wafers too many times in an etching process may cause a failure due to particles.

If all safety interlocks are in working condition, the equipment may be cycled unattended. This will help maximize the number of wafer cycles through the tool. If the equipment fails during this unattended period, the time to repair should not be included in the calculations.

The active cycle debug portion of the project should be used by the supplier to develop preventative maintenance (PM) procedures and estimate the PM schedule. Statistical Process Control (SPC) testing may be implemented at this level. SPC monitoring should be implemented to assure that the basic functionality has not been affected by hardware improvements. If Stage IIA is being run concurrently, this activity can be critical. SPC will help identify when process performance has been affected by modifications made to the equipment or software.

6.3.2 Completion of Active Cycle Debug

The active debug cycle section of the reliability program may end when the equipment achieves a predetermined level of performance. The program should then move to the Stage IIB Review. The program should also move to the review stage as soon as it becomes apparent that the desired level of performance will not be demonstrated within the allotted time or budget.

6.4 Stage IIB Review

As the project progresses through the IRONMAN process, it should become clear if the tool will meet the goals stated in the SOW. If the performance is far from the goal, or a large portion of the project time is spent in one of the earlier stages of the IRONMAN, then the project may need to be re-negotiated to address the issue of poor reliability performance.

The performance metrics generated during the reliability improvement stage of the project are not an accurate representation of the true performance in a manufacturing mode. This stems from limitations in the process and wafer types used as well as unknown acceleration factors. The key deliverable of Stage IIB should be characterized as a constantly improving failure rate. Completion of the reliability improvement stage does not provide the same information as the Marathon (Stage III) which provides a demonstration of both process and reliability performance.

6.5 Stage IIB Case Study

6.5.1 Introduction

A reliability improvement program using the IRONMAN methodology was applied to a plasma etch tool. The primary goals of the IRONMAN program were as follows:

- Measure the reliability performance of the plasma etch tool.
- Establish a system for problem identification and resolution.
- Implement solutions to identified reliability problems on the plasma etch tool and measure improvements.
- Perform regular process and system performance measurements for statistical process control.

6.5.2 IRONMAN Setup

The IRONMAN was arbitrarily divided into periods for the purpose of setting program milestones. All three IRONMAN periods were set up in the same basic manner as follows:

- Cycle daily on second and third shift.
- Use a two-step process with patterned Si wafers; run wafers six times each
- Record reliability information per E10-92 SEMI standard for Reliability, Availability, and Maintainability (RAM) definitions.

As the program progressed and more was learned about the tool, the etch process, and about how to employ the IRONMAN methodology at the manufacturer’s factory, the focus of each IRONMAN period underwent some modifications as follows:

IRONMAN 1

- Establish the IRONMAN methodology.
- Identify and rectify operator and facility problems that led to non-tool related failures
- Identify initial reliability problems with the tool and establish a methodology at the equipment manufacturer for the diagnosis, resolution, validation, and implementation of reliability problems (i.e. FRACAS).

IRONMAN 2

- Test hardware and software improvements that were identified and resolved from IRONMAN 1
- Implement specific software improvements that increased the throughput of the plasma etch tool.

- Move to unattended cycling over the weekend to increase the numbers of wafers through the tool and thus the cycles of learning.

IRONMAN 3

- Begin process-related SPC measurements using a standard process recipe.
- Test a major modification to the loadlock and transfer module vacuum and vent system aimed at particle improvement.
- Switch to cycling one chamber only. The second chamber is reserved for process development activity.

6.5.3 IRONMAN Results

Reliability Data:

Over 27,000 wafers (Figure 12) were cycled through the plasma etch tool in IRONMAN mode (an additional 2000 wafers were processed while IRONMAN 3 was on hold during PDC 2). Table 1 summarizes the results from all three IRONMAN periods.

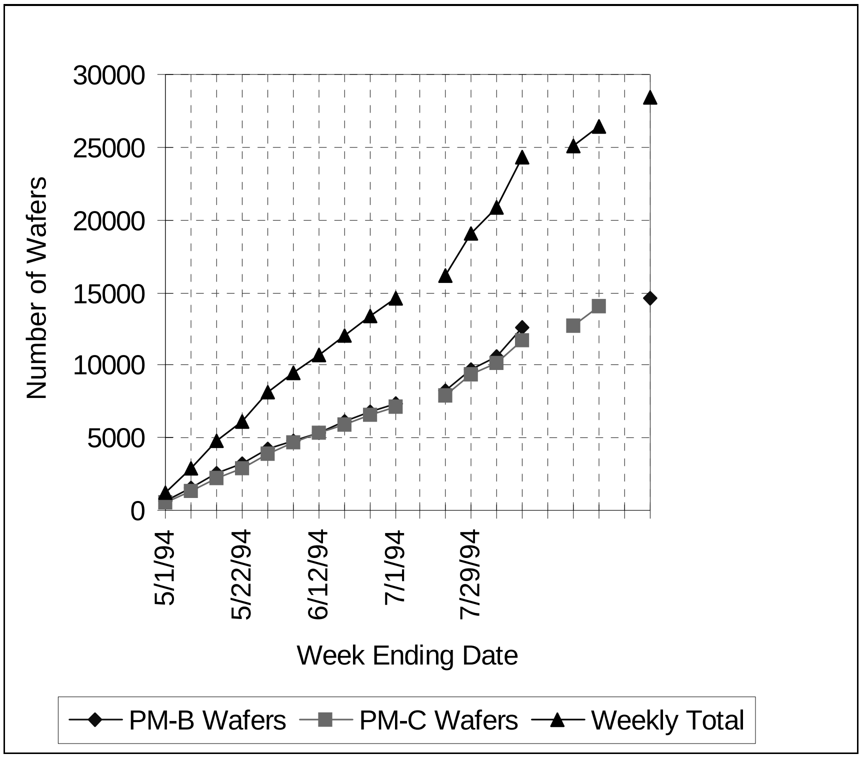

Figure 11 Cumulative Wafers Cycled

Table 1 IRONMAN Summary

	IRONMAN I (04/25 to 7/1)	IRONMAN II (7/6 to 7/12)	IRONMAN III (9/24 to ---)
Wafers Cycled	14559	9753	2104
System Productive Time *(hours)*	437	245	96.94
Total # of Tool Related Incidents	150	16	2
Total # of Non-Tool Related Incidents	20	1	0
Mean Wafers Between Interrupts (MWBI)	97	610	1052
MWBF (wafers)	310	1219	1052
MTBF (hours)	7	31	48
Throughput (1 module) (wafers/hour)	18	21	22
Operational Utilization	23%	33%	50%
MTTR (hours)	0.616	0.640	0.440

Listed below are the primary changes made between the IRONMAN periods which account for the improvements in equipment reliability:

IRONMAN 1 to IRONMAN 2

To address the problems uncovered during the IRONMAN, a cross functional FRB was established. This team used the Pareto analysis from the IRONMAN program and field data, to drive changes to the plasma etch tool polysilicon etcher. Regular meetings and corrective action programs were initiated with three original equipment manufacturers (OEMs) and a software action plan was developed.

Non-tool related incidents - During IRONMAN 1 the project team encountered several problems with the gas line installation at the equipment manufacturer’s factory clean room. These failures caused 16 of the 20 incidents recorded in IRONMAN 1. There were no facility failures during either IRONMAN 2 or 3. In addition, all of the operator induced failures were eliminated as the team gained experience in running the IRONMAN.

Power supply serial communication failure - A handshake problem between the RF power supplies and the process module computer accounted for 39% of the failures in IRONMAN 1. A change in the power supply firmware and the system software eliminated the problem. There have been no failures for either the source or bias power supplies nor the matchboxes in either IRONMAN 2 or 3.

IRONMAN 2 to IRONMAN 3

The plasma etcher system software (Table 2) summarizes the software problems identified and addressed during the IRONMAN periods. These problems accounted for 86 of 170 incidents in IRONMAN 1 (includes the power supply problem) and 9 of 17 incidents in IRONMAN 2. There were no software failures in IRONMAN 3.

Wafer map sensor - New design for the wafer map sensor on the cassette elevator in the vacuum loadlock was implemented. This sensor accounted for 14 of 170 failures in IRONMAN 1.

Table 2 Software Problems Identified During the IRONMAN

Incident #	Incident Description	Supplier Code	Sub-Assembly Code	Failures	Assists	FAILURE EVENT Identification (DATE)	Data Collection (Assign.+ Date of Notification)	Solution (Proposed Date)	Validation (Completion Date)
940426-01	Operator/Software Interface	**IH - Software + IH - Operator**	**SWAR**	**2**		26-Apr-94	Curr. -- SEG		
940426-02	Reboot Failure	**IH - Software**	**SWAR**	**1**		26-Apr-94			
940502-01	Wafer - Overheating caused wafer to melt cassette	**IH - Software**	**SWAR**	**2**		2-May-94	SEG	5-Aug	ver. 3.1.5 9/22/94
940502-02	Software - Screens Required Reloading	**IH - Software**	**SWAR**		**4**	2-May-94	SEG	5-Aug	ver. 3.1.5 9/22/94
940506-01	RF30 - "BAD READING" error flag	**RFPP + IH - Software**	**SOUR**		**61**	6-May-94	RFPP	14-Jun	28-Jun
940509-02	RF5 - Virtual error due software update delay	**IH - Software**	**SWAR**	**2**	**5**	9-May-94	SEG	June	8-Jul
940516-02	Unknown - Cascading messages prevented accurate logging	**IH-Software**	**SWAR**		**1**	16-May-94	SEG	5-Aug	ver. 3.1.5 9/22/94
940610-01	Chuck - Failed to unload wafer after processing	**IH - Controls + IH - Software**	**CHUK**	**1**		10-Jun-94			(ver 3.1.3)
940618-01	Bugs in lot processing software.	**IH - Software**	**WAFH**	**5**		18-Jun-94	18-Jun	5-Aug	ver. 3.1.5 9/22/94
940621-02	Load lock venting past atmosphere	**IH - Mechanical + IH - Software**	**VACV**	**1**		21-Jun-94	6/28 - S. Srinivasn & D. Katz	11-Jul	31-Jul
940622-01	Pressure interlock failure	**VAT + IH - Software**	**CHAM**		**1**	22-Jun-94	22-Jun		
940623-01	Error failed to appear on screen causing lock-up	**IH - Software**	**SWAR**	**1**		23-Jun-94	6/28 - SEG	22-Sep	ver. 3.1.5 9/22/94
940623-02	Could not save cassette definition	**IH - Software**	**SWAR**	**1**		23-Jun-94	6/28 - SEG		
940706-02	"INPUT BUFFER OVERFLOW, DATA LOST"	**IH - Software**	**SWAR**	**2**		6-Jul-94	6-Jul	5-Aug	
940713-01	Missed Error	**IH - Software + IH - Operator**	**SWAR**	**2**		13-Jul-94	13-Jul	5-Aug	ver. 3.1.5 9/22/94

These improvements have resulted in an improvement in MTBF from 7 hours to 48 hours and MWBI improvement from 97 to 1052 wafers. As the reliability of the system improves to a significant fraction of a week it becomes important to look at a longer period of time for the measurement of tool reliability. Figure 12 shows the 5 week rolling MWBI for the plasma etch tool during the IRONMAN runs (MWBI is shown rather than MTBF because the number of hours of IRONMAN run time fluctuates from week to week based on process and hardware development activities.). This chart shows a steady improvement in MWBI to > 500 wafers between incidents.

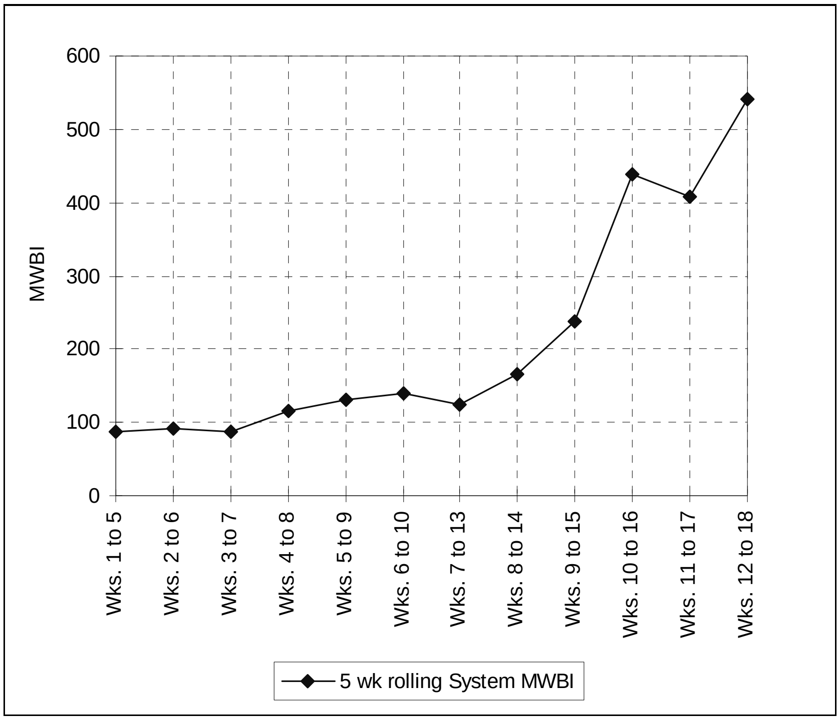

Figure 12 Five Week Rolling Average For MWBI

6.5.4 Electrostatic Chuck

All of the cycling during IRONMAN 2 and IRONMAN 3 was performed using electrostatic chucks (ESC’s). Two types of ESC's were used during IRONMAN testing, ESC “A” and ESC “B” were of different designs from different ESC suppliers. A software driver for these ESC's was developed in May, 1994 that turns off the ESC voltage prior to turning off the RF power supplies. ESC “A” was set up with a 4 second delay between the time when the voltage to the ESC is turned off and when the plasma is extinguished. With this setup >12,000 wafers have been cycled on one ESC and >2000 on a second with no clamp or declamp failures (the second ESC is currently still installed and running). However, ESC “B” exhibited some problems with declamp and can require delays in excess of 15 seconds to reliably declamp the wafer. This problem is still under investigation, but, in the mean time the ESC “A” design looks to be a highly reliable electrostatic clamp solution for use in plasma etch applications.

6.5.5 SPC Data

Beginning with IRONMAN 3, the project team started monitoring both system and process data to establish a baseline for SPC charts for the tool. Parameters currently measured include the following:

- Polysilicon etch rate (breakthrough and main etch)
- Polysilicon etch rate uniformity (breakthrough and main etch)
- Oxide etch rate (main etch)
- Oxide etch rate uniformity (main etch)
- Particle count (plasma off, loadlock and loadlock + process module)

- Base pressure
- Leakback

Polysilicon etch rate and uniformity results to date in IRONMAN 3 are shown in Figure 13 and Figure 14. Control limits will be added once sufficient data has been generated, the tool will be failed for the process being out of control.

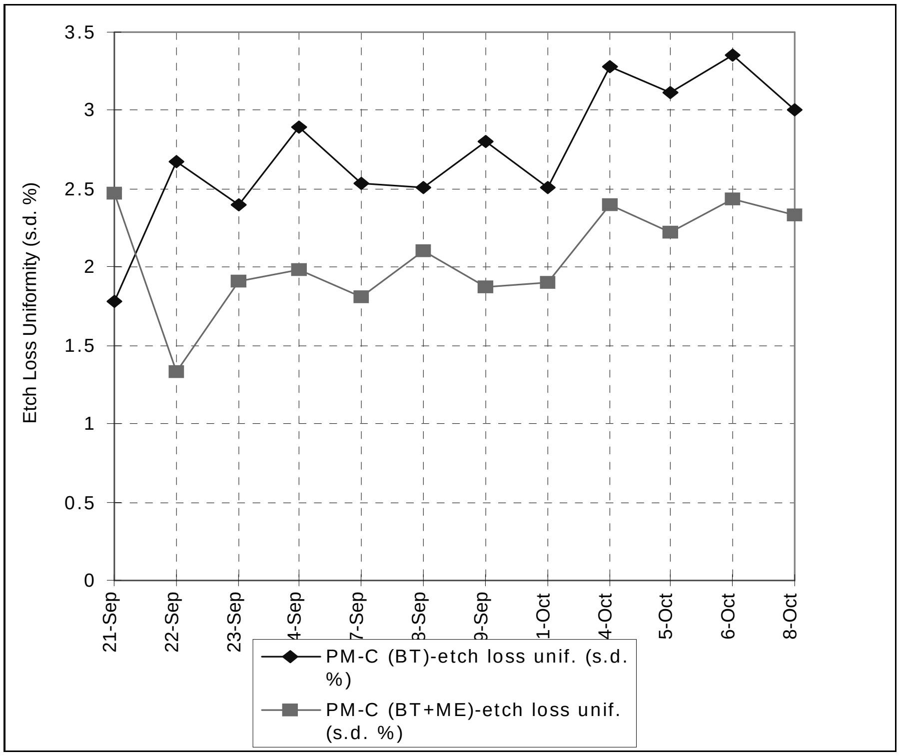

Figure 13 Etch Rate Trend Chart

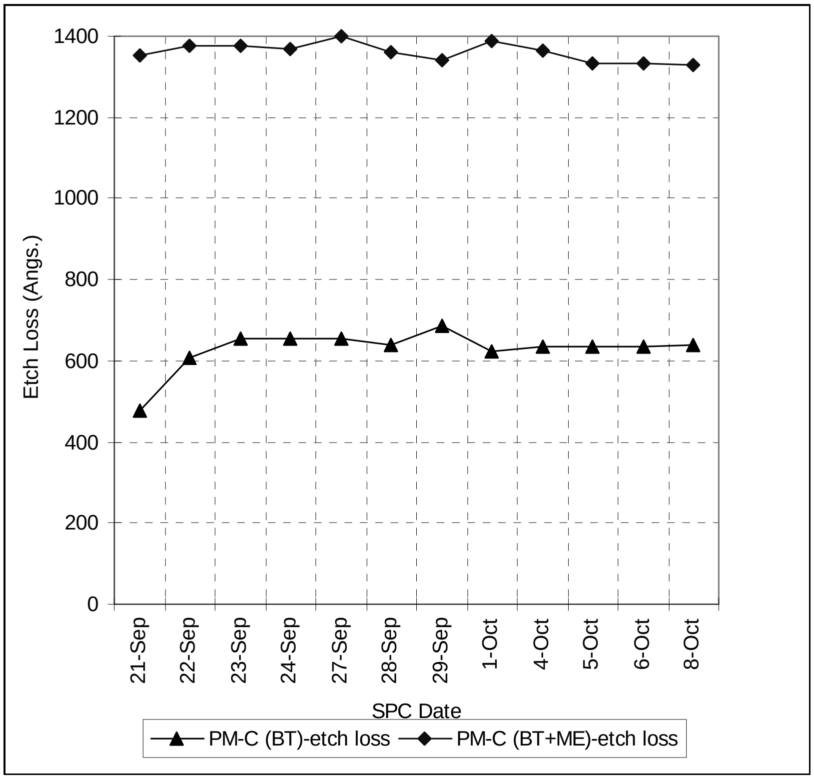

Figure 14 Etch Rate Uniformity Trend Chart

6.5.6 Particle Performance

One of the major changes to the tool made between IRONMAN 2 and 3 was a major redesign of the vacuum and vent system on the loadlocks and transfer chamber. The original design employed turbomolecular pumps in both the loadlocks and the transfer module to provide a staged vacuum level of $1x10^{-4}$ Torr in the loadlocks, $1x10^{-5}$ Torr in the transfer chamber and $1x10^{-7}$ Torr in the process chamber. The design did not provide for nitrogen purging of the loadlocks or transfer module. Data generated earlier in the year indicated that a continuous purge of the loadlocks into the transfer chamber could improve the particle performance on the tool. With this approach, the team did not feel that turbomolecular pumps were required on the loadlocks. The new design employs a mechanical pump to rough the loadlock to $1x10^{-2}$ Torr. The isolation valve to the backing pumps are then closed and the loadlocks are pumped through the transfer chamber turbomolecular pump with a continuous purge of 100 sccm of nitrogen.

Figure 15 shows the loadlock and process module particle performance before and after the change to the vacuum and vent hardware. This demonstrates not only an improvement in the loadlock particle performance, but a dramatic drop in process module particles even on a very dirty chamber (from almost 5000 adders before the purge to <30 adders after the purge addition, with no clean). This vacuum/vent/continuous purge scheme has been adopted as the standard hardware configuration for the plasma etch tool.

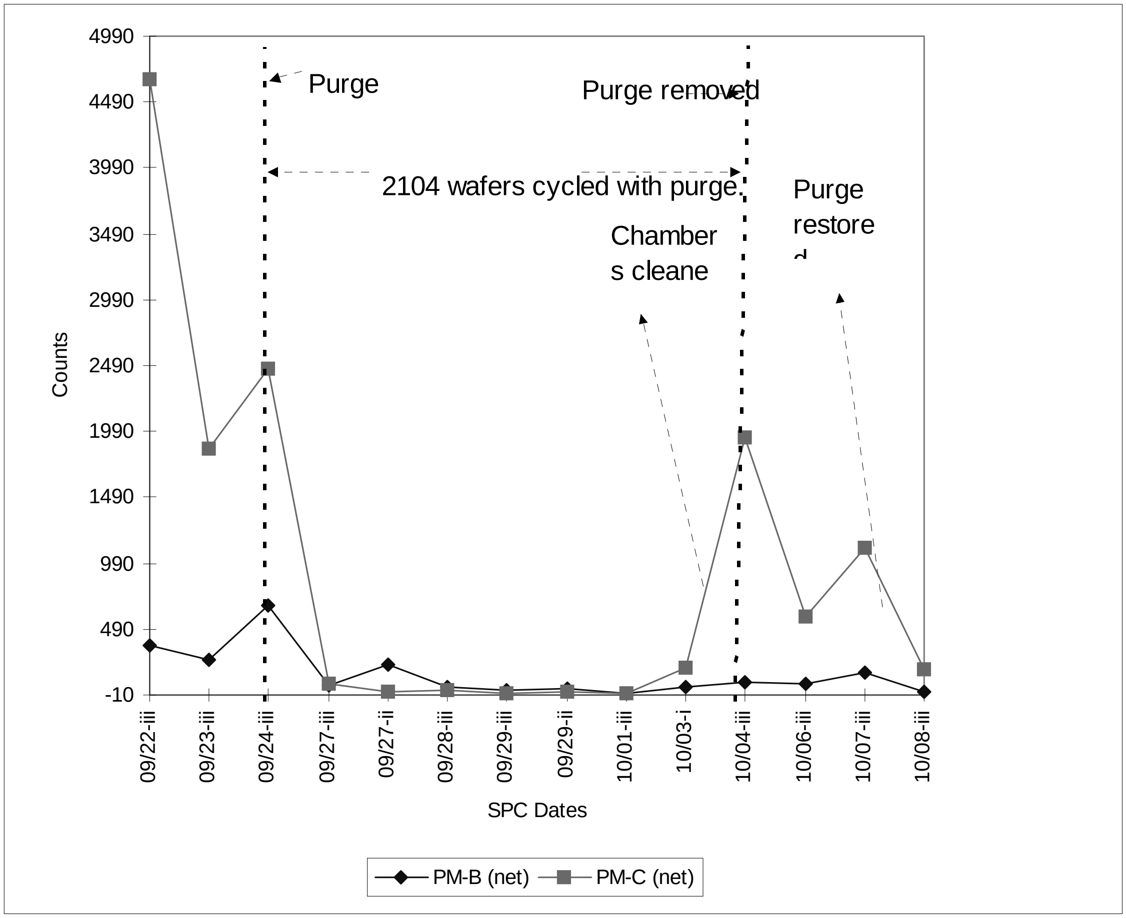

Figure 15 Loadlock Particle Performance

One concern at the start of IRONMAN 3 as the team started to collect process SPC data was to separate the effect of vacuum and vent hardware change on particle performance from the effect of switching from a change in the process chemistry. For this reason, IRONMAN 3 was started using the initial chemistry used for the other IRONMAN periods while the SPC data was collected with the new chemistry. The data in Figure 15 provided the team the information needed to test the new hardware configuration.

6.5.7 Summary

More than 27,000 wafers were cycled through the equipment using the IRONMAN methodology. In that time there were significant advances in tool performance and reliability including the following:

- An increase in MWBI from ~100 wafers to > 1000 wafers
- An increase in MTBF from 7 hours to 48 hours
- Elimination of 10 out of 15 identified software defects (85 out of 92 total incidents)
- Elimination of 29 out of 42 identified hardware defects (62 out of 82 total incidents)
- Improvement in loadlock and chamber particle through the redesign of the loadlock and transfer module vacuum and vent system

The data generated from the IRONMAN program is being used to drive hardware improvements programs at the equipment manufacturer. All of the improvements demonstrated during the IRONMAN runs have been incorporated in the equipment manufacturer’s standard products.

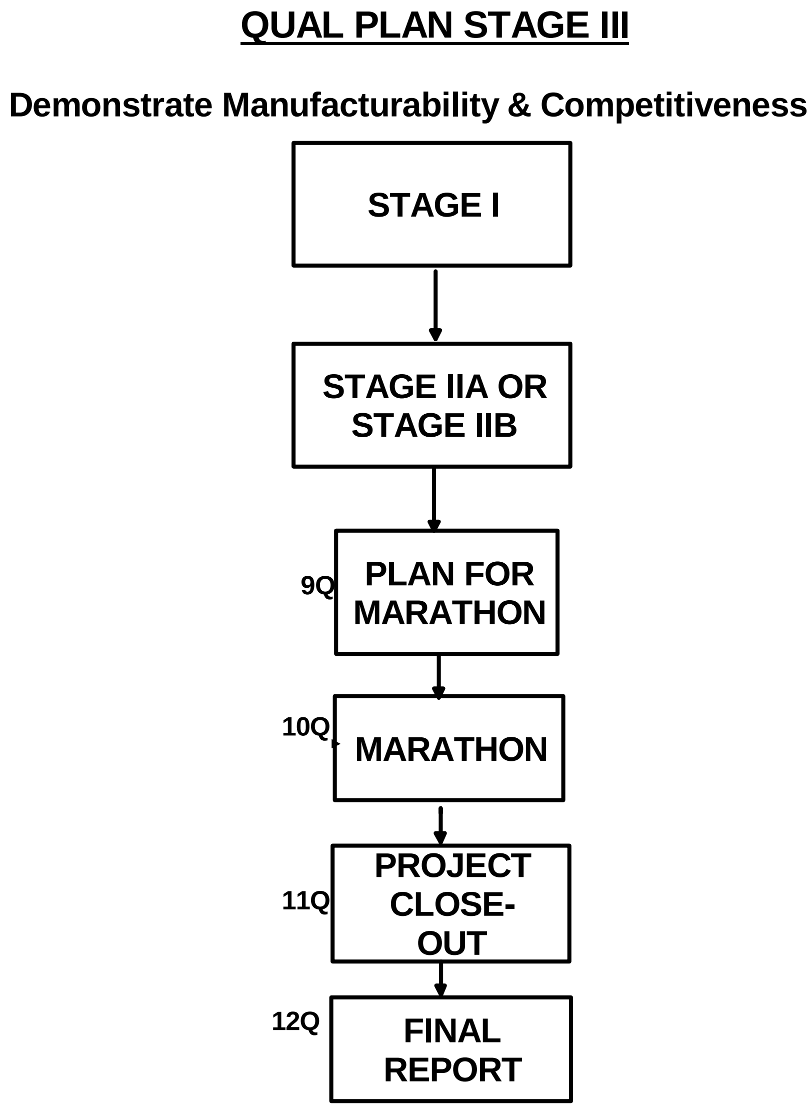

Figure 16 Flowchart of Stage III

7 STAGE III: MANUFACTURABILITY AND COMPETITIVENESS DEMONSTRATION

The third stage of a Qual Plan establishes the reliability, COO, and throughput of the tool. The information required for valid estimates is generated and the previous estimates are updated. These statistics are generated during simulation of a manufacturing environment, called a marathon run (24-hour/7-days a week). The type of information required determines the characteristics of the product used during the marathon.

7.1 Plan for Marathon (9Q)

This element finalizes decisions and verifies plans for Stage III before the marathon activities take place. It identifies potential problems and proposes solutions.

The three groups of activities in this section are reviewing and finalizing decisions, verifying support systems, and assuring allocation of required resources.

Plans and decisions include the following:

- Length of marathon – determined by statistical methods but subject to cost and resource constraints
- Type of wafers to use
- Maintenance plans defined, frequency determined, and schedules established
- Failure modes defined
- Equipment subsystems defined
- Conditions for aborting the marathon defined
- Detailed agreements on what is out of control
- Reaction plans to out-of-control situations
- Execution plan – when to run monitor wafers, when to use dummies, who does what, rework/reclaim plan, etc.

Support systems and commitments include the following:

- Commitment of 24-hour/7-day operation capability
- Engineering commitment for 24-hour/7-day operation
- Supplier commitment for resource support
- On-line control charts for all appropriate responses and metrology systems
- Measurement capacity and data analysis capability available
- Equipment utilization/failure reporting hardware links and software

Resources to be allocated include the following:

- Cost estimate and assumptions
- Training and certification of team members
- Logs generated to document reactions to excursions
- Adequate supply of test wafers – dummies as well as monitor wafers
- Required spare parts list generated and crucial spare parts on site.

A consistent approach to running the equipment and reacting to excursions or failures by all members of the equipment team must exist. Decisions and agreements should be documented.

7.1.1 Resource Review

Before proceeding to the marathon, (Stage 10Q), a resource review should be carried out. This review obtains management and project team approval before beginning the marathon. Such a review is crucial because the resources involved in a marathon are significant. Representatives from the customer and supplier will decide whether to continue the project into Stage 10Q based on the relation between project achievements and the cost of continuing and future benefits.

The team presents the decisions made, problems identified, support systems necessary, and resource allocations from Plan for Marathon, Stage 9Q.

7.1.2 Solution/Problem Assessment

If the marathon plans are rejected as a result of the resource review, a solution/problem assessment should occur. The activities during a solution/problem assessment focus on solving the problems identified during the resource review. These problems can come from sources such as resource or time constraints and tool performance.

If the project team resolves these problems, the project revisits the Plan for Marathon, Stage 9Q.

If the problems are not resolved, the project is usually canceled.

7.1.3 Project Cancellation

If the project is canceled, the project team focuses on documenting the achievements and failures of the project. If the project does not continue to the marathon, current tool performance is reported. The project continues to the Project Close-out (Stage 11Q) and Final Report (Stage 12Q).

7.2 Marathon (10Q)

The marathon or manufacturability demonstration identifies the maximum utilization possible for the given equipment downtime characteristics. The result should be independent of any given standard fab operation. The preparation for this effort is extensive, and the resources necessary to perform a marathon are significant.

The process and equipment must run continuously according to agreements in Section 7.1, with all the required support in place for the 24 hours-a-day, 7 days-a-week operation. The objective of this element is to determine the process and tool performance in a simulated manufacturing environment.

7.2.1 Preparation/Execution

The team and support members review the decisions and plans developed in Section 7.1. The execution of a marathon must simulate a manufacturing environment as closely as possible. Data collection must consistently follow the procedures detailed during Section 7.1. The team must record downtime accurately and classify it according to the decisions made during Section 7.1. Backup records may become extremely important to resolve classification issues correctly. Equipment software and computer records should be checked at regular intervals.

The team should detail operating procedures, responses, and activities permitted during the marathon. The marathon should include normal activities such as preventive maintenance (PM) and SPC or process adjustments that would be permitted in a normal mode of operation.

The project team must maintain constant communication to resolve problems quickly and must document any unplanned events and reactions in detail.

7.2.2 Analysis/Decisions

Backup records are compared to the main source of data collection. Discrepancies are investigated and the correct values are agreed upon. Utilization results are calculated and compared against program goals.

The team identifies specific subsystems and failure modes that impact reliability. Since reliability estimates from the marathon are the result of limited sampling, estimates for utilization statistics will have large confidence intervals that can make comparisons difficult.

The equipment performance is analyzed, according to SEMI E10 Guidelines, using the utilization information gathered during the marathon. The RAM statistics and their confidence intervals are then generated. Other utilization statistics, based on throughput, are also calculated. They are as follows:

- MTBF
- MTBA
- Equipment dependent uptime
- Supplier dependent uptime
- Operational uptime
- MTTR
- Operational utilization
- Total utilization

Complete a final Pareto analysis of the equipment and the subsystems and identify the reliability issues and their resolution. Examine the process performance during the marathon with respect to stability, capability, and the occurrence of out-of-control situations.

Equipment utilization capability is the upper bound on equipment utilization, given the reliability characteristics of the equipment. The Utilization Capability (UC) is determined for the equipment using the following formula.

$$\text{UC} = 1 - \left[\frac{\text{avg scheduled downtime / week} + \text{avg unscheduled downtime / week}}{\text{168 hours}} \right] \times 100$$

Assumptions are

•Standby time = 0

•Nonscheduled engineering time = 0

•Total time per week = 168 hours.

The COO parameters are determined and entered into the COO Model spreadsheet to calculate the final cost of ownership statistic.

The decisions from the marathon data are similar to those made during the mini-marathon. (See Section 5.3, 7A: Verify Stability.):

- The equipment and process met the goals stated in the project plan (yes/no). If no, which goals were not met and why.
- Further work needs to be done to improve tool or process performance (yes/no).

- The Cost of Ownership estimate is acceptable (yes/no).
- The dominant failure modes are identified (yes/no).
- Solutions for the failures can be implemented (yes/no).
- A second marathon should be performed (yes/no).

7.2.3 Documentation

Information that should be contained in a marathon report is listed below.

- Marathon plan
  - Sampling scheme
  - Timeline
  - Support systems
  - Control charts used and reaction plans
  - Other preparations
- Process performance
  - Graphical analysis
  - Data influences
  - Statistical analysis
  - Analysis of out-of-control conditions and their relationship to hardware/software reliability
- Tool performance
  - Pareto of failure modes
  - RAM statistics
  - Utilization statistics
- Cost of Ownership
  - Input parameters
  - Results
- Conclusions and Future Activities

7.3 Project Close-Out (11Q)

After the marathon stage has been completed, a project close-out review (Stage 11Q) discusses all three stages of the Qual Plan with emphasis on Stage III. Each program goal is compared against the results from the qualification. Unachieved goals are examined in detail to capture the most likely causes of failure. During this review, the customer and supplier will discuss whether the project was a success and may suggest future activities. Future activities might include additional studies, re-designs of equipment or process, or releases to manufacturing. If the project is to be closed out, emphasis moves to the final report/documentation stage (12Q) and all other phases of the project are closed.

7.4 Final Report (12Q)

Documentation of the qualification is an important function of the qualification team. Thorough and accurate reporting of the stages of the qualification activities provides timely and historic review.

Several types of readers must be considered when writing a report. Executive management and those individuals not directly associated with the project may wish to review the Executive Summary of a report. This section of the report is a "stand-alone" document. It should contain an overview of all of the key activities that the main report discusses, along with summarized tables showing the conclusion and final analysis of the project stage that the report is presenting.

End-user readers typically are more familiar with the technology being discussed, although this cannot be assumed. Therefore, the main body of the document should present adequate detail for this type of reader, such as greater discussion of experimental procedures, rationale for actions, and failure mechanisms. Main conclusions from the documentation sections of previous stages in the Qualification Plan should be included where relevant. Qualification document length should also be of consideration, however. Pertinent data presentation of graphs and charts, as well as photographs and analytical profiles should be limited to representative samples. Indirectly supporting material may be requested from the authors. A typical timeframe for documentation draft through publication, after completion of analysis, can be several weeks.

7.5 Stage III Case Studies

7.5.1 Qualification Report for a Stepper

Executive Summary

This report presents the qualification results of a prototype stepper. The report describes the results of a six week marathon test of the prototype system in a manufacturing environment. The report completes the evaluation of a particular system and established a baseline for continuous improvement. A follow up report on the commercial system was issued in 2Q92.

The prototype is a new generation stepper featuring wide field lenses at both I-line and DUV wavelengths, a high performance XYZ stage with local leveling, and a new system architecture with multi-tasking capability and a touch-screen user interface. Key performance specifications for the commercial system include the following:

• Resolution	0.50 mm
• Field Size	28.3 mm diameter
• Overlay	140 nm, matched systems
• Throughput	60 wafers per hour (WPH)
• Reliability	600 hours MTBF

Test Procedures

The prototype system has been qualified according to the Qual Plan with extended PDC, a six-week marathon test and continuous reliability data collection. The marathon test addressed four major areas: overlay on product levels, CD control with electrical monitors, productivity capability, and reliability in a manufacturing environment.

Six product levels were processed continuously and approximately five hours of tool monitor data was collected daily throughout the marathon. The test was extended to six weeks to evaluate software upgrades made after the fourth week.

Marathon Test Results

The overlay results of the system ranged from 150-350 nm (mean ± 3s) and were limited by the prototype stage, software quality and alignment mark optimization. CD control on 0.60 mm features was 50 nm (3 sigma) for the full 20 x 20 mm field. Contamination control was 1-3 particles per wafer pass (PWP).

Throughput on product levels ranged from 28-41 WPH dependent upon illuminator intensity and software revisions. System reliability was significantly impacted by software failures and assists. MTBF was 49 hours. MTBA was 0.8 hours, and MTTR was 4 hours.

As a result, utilization capability was 88% and productivity capability was 727 wafers per day (WPD).

Action Plans

The company has completed the engineering projects to address the lens and body shortfalls. A top priority effort is underway to correct and qualify the operating software. These projects have been incorporated into the commercial system now being installed at SEMATECH and are standard features of all commercial systems.

Conclusions

The prototype system has been an excellent vehicle for understanding technical strengths/weaknesses and developing the engineering teams. It was mutually acknowledged that the system performance would be limited by the level of the software and hardware at the start of the marathon test. This marathon test completes the evaluation of the system and establishes a baseline for continuous improvement.

Engineering projects to address the shortfalls have been completed and incorporated into the commercial system now being installed at SEMATECH. The objectives are to provide resolution for 0.5 mm applications with the lens, overlay performance better than 80 nm on product levels and productivity capability greater than 1000 WPD.

7.5.2 Vertical Thermal Reactor Equipment Improvement Program Final Report

Executive Summary

Introduction

This report details the Vertical Thermal Reactor Equipment Improvement Program (EIP) from its inception in 1990 through program completion in 1991. The program includes the furnace system modifications for an atmospheric pressure oxidation process system and a silicon nitride low-pressure chemical vapor deposition (LPCVD) process system.

Initial Baseline

In 1988, a member company installed 20 of the thermal reactor systems in their fab. This site was the largest installed base of these systems in the world, and this was a primary consideration in EIP site selection. The thermal reactor system met processing specifications such as thickness uniformity and particles. However, the system did not achieve the reliability, availability and maintainability (RAM) specifications. A baseline analysis of nine oxide and two nitride systems was conducted from May to July 1990. A summary of the results is shown in the following table.

Metric	**Oxide**	**Nitride**
Thickness Uniformity(all points ± 3s)	9.8%	6.7%
Particles per Wafer/150 mm at > 0.3 mm	0	32
Mean Productive Time Between Failure ($MTBF_p$) Hours	125	128
Mean Time To Repair (MTTR) Hours	12.6	17
Scheduled Downtime	7.3%	6.1%
Nitride Deposition before Required Tube Clean (mm)	NA	5.5 mm

Wafer breakage for both systems totaled 10 wafers per 10,000 processed. 90% of wafers broken occurred during one event. Calculations are per SEMI E10-90 specification. Oxide productive state = 24%; nitride = 21%. These baseline results do not meet what is required by SEMATECH member companies to remain competitive in integrated circuit manufacturing.

A summary of the goals for the EIP are presented in the following table.

Metric	**Oxide**	**Nitride**
Thickness Uniformity(all points ± 3s)	5%	5%
Particles/cm² at 0.3 mm	0.44	.088
Particles per wafer at 0.3 mm - 150 mm	6	12
Equipment Dependent Uptime	98%	95%
MTBFp Hours	750	500
MTTR Hours	5	5
Mean Productive Time Between Assist	167	167
Scheduled Downtime %	2%	4%
Nitride Deposition before Required Tube Clean (mm)	NA	20 mm

A team of engineers experienced with the 20 thermal reactor systems developed a comprehensive program to upgrade the thermal reactors. This team detailed 26 specific modifications. These 26 upgrades addressed all major and most minor shortfalls of the system and are outlined in the statement of work. These modifications were designed from March to October 1990. Initial testing of some of the upgrades was conducted on the systems during this time frame. In addition, a DOE was conducted on a 400 Å steam oxidation process and an 1100 Å nitride process. Optimal process windows were determined.

From October to December 1990, the two upgraded systems were manufactured. Twenty-one of the 26 SOW upgrades were finalized and tested in the marathon. Four upgrades were designed and will be available in future shipments (December 1991 forward). One item, the maintenance terminal, was not designed and will not be addressed.

In January 1991, the EIP site was transferred as a result of the decision by the member company to sell the old site. Two upgraded systems (one oxide and one nitride) shipped directly from the supplier to the new facility. The systems were installed in January and a startup and checkout was conducted over the following two months. This included testing of the upgrades in a complete system mode.

Extensive operator and technician training on the new model vertical furnace was completed. Gauge studies were conducted on three metrology tools to assure accuracy and precision of thickness and particle measurements.

Passive Data Collection

In April and May 1991, a 36-run passive data collection (PDC) was performed on the upgraded EIP oxide system. The 900° C, 400 Å oxide thickness uniformity (± 3s) was 3.9%. This was much improved from baseline uniformity of 9.8%, and exceeded the SOW goal of 5%. Analysis of variance results were 62% within-wafer, 30% wafer-to-wafer and 8% run-to-run. The average particle delta per wafer for size > 0.3 mm was -4.8 with a standard deviation of 7.8. Some runs showed a net particle gain, other a net particle reduction. Three runs were above the particle goal of six particles added per wafer.

A 25-run PDC was performed on the upgraded EIP nitride system. This study was conducted with the following process parameters:

- 150 mTorr pressure
- 3:1 ammonia (NH_3)/dichlorosilane (SiH_2Cl_2) ratio (190/65 sccm flow)
- 793°/782°/765° C for the three temperature zones.

The 1100 Å nitride film thickness uniformity was 4.4%. This was an improvement from the baseline pre-upgrade uniformity of 6.7% and exceeded the SOW goal of 5%. Analysis of variance results were 45% within-wafer, 54% wafer-to-wafer and 1% run-to-run. The process was not stable with large particle fluctuations observed. Several actions were taken that stabilized particle counts. These included:

- Opening the half gate during boat pull to prevent backstreaming of ammonium chloride
- Performing a semi-weekly PM to change boat and pedestal quartzware and clean the vacuum exhaust "S-tube"
- Applying heat tape to the vacuum exhaust port.

Marathon Results

Oxide

The oxide marathon was scheduled to be 42 days long. This would allow the $MTBF_p$ goal of 750 hours to be estimated with a 70% confidence level. The marathon length was extended to 51 days to make up for downtime associated with maintenance delay (down parts). A total of 275 runs were completed with 41,000 wafers processed.

The table below summarizes the oxide results for the marathon versus the SOW goal.

Metric	**Baseline**	**Goal**	**Marathon**
Thickness Uniformity (all points ± 3s)	9.8%	5%	4.3%
Particles > 0.3 mm per wafer 150 mm	0	6	-6.6
Equipment Dependent Uptime	90%	98%	98%
$MTBF_p$ Hours	125	750	914
MTTR (Eq. Dep.)	12.6	5	6
$MTBA_p$ (Hours)		167	34
Scheduled Downtime %	7.3%	2%	1%
Wafer Breakage per 10,000 wafers (combined Ox/Nit)	10	0.3	0

Because a marathon provides only a "snapshot" of actual machine reliability, using the conservative method of confidence levels, this is equivalent to the mean (productive) time between failures ($MTBF_p$) being 450 hours with a 70% confidence level.

Nitride

The nitride marathon was scheduled to be 28 days long. This would allow the $MTBF_p$ goal of 500 hours to be estimated with a 70% confidence level. The marathon length was extended to 38 days to make up for downtime associated with maintenance delay (down parts). A total of 196 runs were completed with 25,000 wafers processed.

Nitride particle counts varied throughout the marathon. After the PDC and subsequent hardware changes, particle counts stabilized on runs 68 - 120. During this period, the average particle delta at 0.3 mm was 17 particles/wafer, which did not meet the SOW goal of 12 particles/wafer, but was an improvement from the baseline of 32 particles/wafer. During the balance of the marathon, particle measurement system issues and residual acid in the quartz pedestal precluded meaningful particle data.

Two equipment dependent failures occurred during the marathon. One was due to a spike over-temperature thermocouple fault. While a definite cause for this is unknown, it was believed to be a loose thermocouple connection. The second failure was the runaway flow of nitrogen pressure control. This was a scrap event.

The cause for this is suspected to be a flaw in the newly designed gas interface board. This calculates to an actual $MTBF_p$ of 292 hours, compared to the SOW goal of 500 hours. Using the conservative methodology of confidence levels, this is equivalent to the $MTBF_p$ being 167 hours with 70% confidence. The following table summarizes the nitride results for the marathon versus the SOW goal.

Metric	Baseline	Goal	Marathon
Thickness Uniformity (all points ± 3s)	6.7%	5%	4.5%*
Particles > 0.3mm per wafer 150 mm	32	12	17**
Equipment Dependent Uptime	91%	95%	91%
$MTBF_p$ Hours	128	500	292
MTTR (Eq. Dep.)	17.0	5	9
$MTBA_p$ (Hours)		167	39
Scheduled Downtime %	6.1%	4%	5%
Wafer Breakage per 10,000 wafers (combined Ox/Nit)	10	0.3	0
Nitride Deposition before Required Tube Clean (mm)	5.5	20	>10

* 4.5 % uniformity is the assessed value which omits bottom wafer data for after run #120 due to improper installation of heat insulation collar. If this data is included, uniformity is 5.4%.

** Stable period of runs #68 - 120.

Experiments and Verification

The nitride RSM indicates that the selected process is robust with small process parameter changes having minimal effect on uniformity. However, the RSM did indicate that a lower center temperature and lower gas flow could improve uniformity further, although with a slight decrease in deposition rate.

A 19-run 150 Å gate oxide PDC was completed. The recipe used was a standard supplier process, with slightly modified push/pull steps. Uniformity (± 3s) was 3.9%, which exceeded the SOW goal of 5%. Analysis of variance results were 59% within-wafer, 32% wafer-to-wafer and 9% run-to-run.

Metallic contamination (Q_M) runs averaged 1.14E10 ions/cm^2 (goal = 1E10 ions/cm^2). Surface stat charge (Q_{SS}) runs averaged 4.38E10 charges per cm^2 (goal = 3E10 charges/cm^2). Gate Oxide Integrity (GOI) test results ranged from 13 to 20 MV/cm, exceeding the goal of 12 MV/cm.

Cost of Ownership

COO analysis was completed to compare the pre-upgrade baseline with the upgraded system. Due to the various RAM improvements (as demonstrated in the marathon), the 400 Å oxide cost was reduced from $2.05 to $1.23 per good wafer (100% functional probe yield). The major improvements in priority order were reduced wafer breakage, reduced defect density and reduced test wafer requirements. The 1100 Å nitride cost was reduced from $4.44 to $2.66 per good wafer. The major improvements in priority order are reduced defect density, reduced wafer breakage and reduced test wafer usage. These cost reductions represent net 40% reduction.

Conclusions

The highlights of the program were as follows:

- Design and execution of 26 EIP items
- Oxide and Nitride uniformity results
- Oxide and $MTBF_p$.

It is recommended that continued progress be made in the following areas:

- Nitride particle issues
- Nitride $MTBF_p$
- $MTBA_p$
- Lack of vendor spare parts during marathon.

8 GLOSSARY

The following abbreviations and terms are defined for your convenience.

8.1 Abbreviations

AFM	Atomic Force Microscope
CD	Critical Dimension
COO	Cost of Ownership
DOE	Design of Experiments
DUV	Deep Ultraviolet
EIP	Equipment Improvement Project
ES&H	Environmental Safety & Health
ESC	Electrostatic Chuck
FRACAS	Failure Reporting Analysis and Corrective Action System
FRB	Failure Review Board
FTAB	Focus Technical Advisory Board
GOI	Gate Oxide Integrity
IRONMAN	Improving Reliability of New Machines at Night
JDP	Joint Development Project
LPCVD	Low Pressure Chemical Vapor Deposition
MCA	Measurement Capability Analysis
MDL	Master Deliverable List
MSD	Manufacturing Systems Design
MTBA	Mean Time Between Assists
MTBA_p	Mean (productive) Time Between Assists
MTBF	Mean Time Between Failures
MTBF_p	Mean (productive) Time Between Failures
MTOL	Mean Time Off Line
MTTC	Mean Time To Clean
MTTR	Mean Time To Repair
MWBF	Mean Wafers Before Failure
OEM	Original Equipment Manufacturer
P/T	Precision to Tolerance ratio
PDC	Passive Data Collection

PM	Preventive Maintenance
PSL	Polystyrene Latex Sphere
PTAB	Project Technical Advisory Board
PWP	Per Wafer Pass
RAM	Reliability, Availability, and Maintainability
RIE	Reactive Ion Etch
RSM	Response Surface Methodology
SEM	Scanning Electron Microscope
SEMI E10	Guideline for Definition and Measurement of Equipment Reliability, Availability, and Maintainability
SOW	Statement of Work
SPC	Statistical Process Control
SQC	Statistical Quality Control
UC	Utilization Capability
USLI	Ultralarge-Scale Integration
WPD	Wafers Per Day
WPH	Wafers Per Hour

8.2 Terms

availability - The probability that the equipment will be in a condition to perform its intended function when required (see Appendix B)

accuracy - The deviation of a measurement from the true value (see bias)

artifact - A physical standard against which a parameter is measured (see standard)

assist - Any unplanned interruption or variance from specifications of equipment operation that requires human intervention of less than six minutes to correct (see Appendix B)

beta site - An external test site where concepts or equipment are proven. (A beta site test is typically performed after the alpha site test at the original site)

bias - The numerical value used to measure accuracy

calibration - Procedure to compare readings from a tool with a standard and then correct the tool for any tool deviations

capable - A process is capable when its metrics all fall within the specifications

capability indices - A measure of the relationship between the specification limits and the process capability (see Cpk)

characterization - The use of mathematical modeling, design of experiments, or statistical data evaluation to describe the characteristics of a process, environment, or product confidence interval - Upper and lower bounds about an estimate from a sample within which we are a certain percent confident that the true value (from the population) is located

confirmation run - A test to determine if the predictions from an experiment are valid (true) and reproducible

control limits - The upper and lower boundaries on a control chart of a measured response (such as particle adders or uniformity). They are determined by the natural variation of the response, NOT by specifications.

control chart - A graph of data with calculated control limits used to determine if a process is stable and in control

cost of ownership - The total cost of creating the end product (SEMATECH finds this metric very valuable in making equipment-related decisions)

covariate - An uncontrollable input factor, such as incoming material quality or environmental conditions

Cpk - A capability index, the average of the process minus the closest spec divided by three standard deviations (for a process with an average that is in between the two spec limits). A value of 1.00 implies that 99% of all values fall in process specifications, assuming a normal distribution model applies.

D-optimal design - An experimental design in which the runs are chosen by a software algorithm from a set of candidate runs (D-Optimal designs do not generally allow effects to be estimated completely independently of each other)

design of experiments - The planning of experiments to maximize the information gathered while minimizing cost, reducing experimental errors, and ensuring statistical validity of the results

downtime - The time when the equipment is not in a condition, or is not available, to perform its intended function (see Appendix B)

equipment improvement project (EIP) - An activity in which SEMATECH works with an external partner, usually a SEMI/SEMATECH equipment manufacturer, that improves existing manufacturing equipment to support phase requirements

execution plan - The execution plan includes the detailed project plans of the execution of the project (activities, milestones, schedule, resources)

experimental strategy - The procedure of conducting designed experiments to maximize information obtained (Screening experiments are used to identify the important factors; Response surface designs study the known important factors in greater detail)

factorial design - An experimental design in which all the possible combinations of the input factors are considered

failure - Any interruption or variance from the specifications of equipment operation requiring the replacement of a component (other than specified consumables) due to degradation or failure. Failures also include any assists that interrupt operation and take longer than six minutes to correct. (see Appendix B) failure modes - The categories of possible failures (Often expressed as a Pareto diagram indicating relative frequency of various causes)

fractional-factorial design - An experimental design in which a subset of the possible combinations of the input factors are considered

full-flow - In semiconductor manufacturing, the complete set of process steps required to produce a functional die

gauge study - A characterization performed on a measurement system to determine the size of the measurement error (also known as a measurement capability study)

independent replication - A natural repetition of a system or process that can be considered different from another repetition of a system or process in a largely random way. (An independent replication for a single wafer tool is usually a wafer. For a batch tool, an independent replication is a batch)

input parameters - Process or equipment parameters that can affect the process outputs, such as vacuum, temperature or pressure

interaction - An interaction is said to be present if the result of changing one factor in an experiment depends on the setting of another factor in the experiment

joint development project (JDP) - Those activities in which SEMATECH works with an external partner, usually a SEMI/SEMATECH equipment or materials supplier, to develop equipment, materials, and processes that support phase requirements or future generations of technology

maintainability - The probability that the equipment will be retained in, or restored to, a condition where it can perform its intended function, within a specified period of time (see Appendix B)

marathon - A SEMATECH Qualification Plan activity which simulates operating the tool in a manufacturing process continuously for an extended time

Master Deliverables List (MDL) - SEMATECH document (#89070086B-TC) that defines the scope, technical and manufacturability goals, schedule, and deliverables of each SEMATECH project

mean time between failures (MTBF) - The average time the equipment performed its intended function between failures (see Appendix B)

mean time between assists (MTBA) - The average time the equipment performed its intended function between assists. (see Appendix B)

mean time to repair (MTTR) - The average time to correct a failure and return the equipment to a conditions where it can perform its intended function (see Appendix B)

mean wafers between failures (MWBF) - The average number of wafers processed by the equipment between failures - sometimes a more meaningful measure of tool reliability than the average time between failures (see Appendix B)

mean wafers between incidents (MWBI) - The average number of wafers processed by the equipment between incidents - an incident includes both failures and assists (see Appendix B)

measurement capability analysis - A characterization performed on a measurement system to determine the size of the measurement error.

metric - Measurable output of a process or piece of equipment (Objectives are established for process or tool metrics)

metrology system - The system used to measure the wafers; includes not only the measurement tool but also all handling procedures

mini-marathon - A period of time when the tool is run 24 hours a day, 7 days a week to determine utilization statistics (A mini-marathon is run for a shorter time period than a marathon)

optimization - The process of continually improving the process or equipment to reach a defined goal

output parameters - The responses of interest in an activity, such as film thickness, overlay offset, or profile (see metric)

P/T - Precision to tolerance ratio, [6*(standard deviation of measurement distribution)/process tolerance]. A description of how much of the process specification window is being lost to measurement error.

passive data collection - An activity in which the behavior of a process, or piece of equipment, is sampled while running in a production mode (No equipment or process adjustments are allowed during data collection)

precision - The measure of natural variation of repeated measurements

process - A unique, finite course of events defined by purpose or effect, and achieved under given conditions

process window - The ranges within which the input factors of a process obtain the desired output

program - At SEMATECH, an open-ended or ongoing effort or combination of efforts which may include multiple projects

project - At SEMATECH, a unique venture comprised of interrelated activities with a definite beginning and end

project management - Dynamic project planning and facilitation from project start to completion that is based on pre-determined objectives (Decisions are based on resource dependencies and desired output)

qualification - A qualification is a study of a tool or process that includes performance characterization, comparison of that performance to a predefined set of goals and specifications, and stressing the tool or process in a manufacturing environment.

reference product - Product that is manufactured and used to establish stability of measurement systems (see gauge study, measurement capability analysis, artifact, standard)

regression - A statistical technique for creating a mathematical model to describe the outcome of a process in terms of its input parameters.

reliability - The probability that the equipment will perform its intended function, within stated conditions, for a specified period of time (see Appendix B) repeatability - The variation from the measurement tool when repeated measurements are made of the same parameter under absolutely identical conditions

reproducibility - The variation from the measurement system that results when different conditions are used to make the measurements

response cliffs - Dramatic changes in experimental responses due to relatively small changes in input factors

response surface designs - Experimental designs used to model curvature in responses (Designs use from 3 to 5 levels of input factors and are referred to as RSM designs).

sampling plan - The number, frequency, and types of measurements to take during data collection

screening experiments - Experiments used to identify the significant input factors for specified response parameters

SEMATECH Qualification Plan - A guideline for efficient, effective characterization and qualification of equipment or processes.

sources of variation - Components of a system that contribute to the overall variability of a process

SPC system - The system of control charts, reaction plans and monitoring procedures to establish and maintain control of a process

stability - A process is stable if it has constant process mean and controlled, predictable variation (see control limits, control chart)

Stage I - The first stage of a Qual Plan that establishes the baseline performance of the tool or process

Stage IIA - The second stage of a Qual Plan that concentrates on optimizing the process

Stage IIB - The second stage of a Qual Plan that concentrates on reliability improvement

Stage III - The third stage of a Qual Plan that focuses on operating the tool in a manufacturing environment

Stage IV - Production Use Readiness Qualification (not included as a part of the SEMATECH Qual. Plan but covered in Appendix A)

standard - A physical standard against which a parameter is measured (i.e., a test wafer used to measure drift) usually traceable to NIST [National Institute of Standards and technology].

Statement of Work (SOW) - A form of purchase specification used specifically for nonstandard requirements. (At SEMATECH, the principal document outlining the project requirements)

statistical process control (SPC) - The application of statistical techniques to control a process (Often the term "statistical quality control" is used interchangeably with "statistical process control")

statistical quality control (SQC) - The application of statistical techniques to control quality (strictly speaking, statistical quality control includes acceptance sampling as well as statistical process control.)

uptime - The amount of time during which the equipment is in a condition to perform its intended function (see Appendix B)

utilization capability - The equipment-dependent utilization, or upper bound independent of Fab-specific standard procedures (see Appendix B)

utilization statistics - The statistics that detail the utilization capability of the tool or process

variance components - The division of the total variance of a process into components due to specific causes

APPENDIX A
STAGE IV—PRODUCTION USE READINESS QUALIFICATION

A.1 Purpose

The ultimate aim of a tool and process qualification is to demonstrate that the tool is ready for routine and convenient use in a manufacturing environment. The body of this document concerned issues of process capability, process optimization, tool reliability and cost-of-ownership. However, this is not all that is involved in a full tool and process qualification. The tool must also be ready for installation and maintenance. The goal should be for the user to "plug in" the qualified tool and run it for production use.

This appendix contains the elements which must be completed to demonstrate that a tool is ready for installation and production use in a manufacturing facility. These elements include:

- Compliance to relevant standards
- Installation readiness
- Maintainability readiness

A.2 Method

Production readiness is accomplished and demonstrated as a team effort between the supplier and the customer. The cross-functional team includes equipment engineering, process engineering, maintenance engineering, production management, environmental, health and safety engineering, and facilities engineering members.

A.2.1 Form Team. The supplier and customer assemble a team which has the needed skills.

A.2.2 Document specific qualification requirements. The team documents the requirements that apply to the tool, using the general requirements (sections A.3, A.4 and A.5) as a guideline.

A.2.3 Develop work plan and schedule. The team publishes a work plan for assembling the required information.

A.2.4 Execute plan. The team executes the work plan.

A.2.5 Checkpoint review. When the work is completed, the results are reviewed and approved by the supplier and user management.

A.2.6 Publish results. The information is published by the supplier and made available to other customers.

A.3 General Requirements—Standards Compliance

Studies have shown that communications problems between the tool and host computer systems and resolution of safety problems cause significant delays in the installation of tools. Many of these problems can be avoided by compliance to appropriate standards. A fully qualified tool will demonstrate compliance to appropriate standards, including:

A.3.1. Host computer communications. The tool is fully compliant with SECS I (E-4), SECS II (E-5), and GEM (E-30) interface requirements. This is demonstrated using GEMVS for the acceptance test (GEMVS is offered and supported by LPA Software).

A.3.2 Safety. The tool complies with all relevant safety standards, including SEMI S2 and S3.

A.3.3 Other standards. The tool is compliant to other relevant standards. These are identified during the planning stage.

A.4 General Requirements—Installation Readiness

Complete preparation of a facility to receive a tool is essential to smooth and trouble free installation. The following information must be compiled to enable the facility to be prepared prior to the tool's arrival at the user's factory.

A.4.1 Physical layout diagrams

The physical layout of the tool is documented including the following information:

- Outline of the tool structure
- Height, width, and depth of tool
- Total weight of tool
- Size and weight of system components (information needed to transport components through the building)
- Location of physical supports
- Floor loading at the support points
- Door-swing and access panel space requirements

A.4.2 Facilities input requirements

The location of facilities input locations are shown on the physical layout diagrams, including the following information:

- Electrical connection points
- Control and data signal input/output connector points
- DI water connection points
- Cooling/heating water connection points
- Steam connection points
- Air conditioning connection points
- Compressed gas connection points
- Drain connection points
- Other connection points

A.4.3 Materials and energy consumption estimates

The materials and energy streams are estimated for a standard process. (The tool supplier and tool user identify the standard process during the planning stage.) The following are included:

- Electrical and/or other energy inputs are identified. The average and maximum values are specified.

- Cooling energy requirements are identified. The average and maximum values are identified. The values are given for both the amount going directly to a cooling system and that heat load released directly to the ambient air around the machine.
- Waste streams are identified by chemical composition and rate of production. Average and maximum rates of generation are shown.
- Consumables, such as pump oil, sputtering targets, process gasses and liquids, and cleaning materials are included, as well as structural components like o-rings etc.

A.5 General Requirements—Maintainability Readiness

Once a tool is installed, specific information is required to maintain the tool in a productive state.

A.5.1 Spare Parts

Spare parts are identified, including the following information:

- Spare parts list
- Order lead time for each item
- Min/Max reorder numbers for each item
- OEM cross referenced part numbers for each item
- Cost of each item
- Proposed user stocking strategy for each item

A.5.2 Hardware Documentation

Drawings required for tool maintenance include:

- Key component drawings
- Assembly diagrams
- Electrical drawings
- Plumbing logic diagrams
- Control (hydraulic, pneumatic, electrical, etc.) diagrams

A.5.3 Software Documentation

Software must be documented so that it can be maintained independently from the author programmer. The documentation includes the following:

- Annotated code
- Logic flow charts
- Register and I/O point index and cross-references

A.5.4 Preventive Maintenance

The PM procedures required to keep the tool working at the target MTBF and availability include:

- PM procedures
- PM schedules

A.5.5 Training

Documentation required for training operators and maintenance personnel includes:

- Theory and operation manuals
- Tutorial
- Trouble shooting guides
- Maintenance procedures

A.5.6 Change control and documentation

The supplier must demonstrate the ability to keep documentation up-to-date as field engineering changes are introduced. Soft copies of all documentation are provided to the user so that the user can also keep the documentation up-to-date as engineering changes are made. Two elements that demonstrate this are:

- Supplier documentation update and change control procedures and communication methods
- CAD based documentation using commonly available software

APPENDIX B
SEMI E10-92 Guidelines

GUIDELINE FOR DEFINITION AND MEASUREMENT OF EQUIPMENT RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM)

1. SCOPE

1.1 The primary intention of this document is to establish a basis for communication between users and suppliers of semiconductor equipment by providing guidelines for measuring the performance of that equipment in a manufacturing environment. The ultimate goal is to stimulate a spirit of cooperation and partnership among users and suppliers to promote improvement in equipment performance.

1.2 The body of this guideline is presented in two parts. The first part is Section 3 (Equipment States) which defines how equipment time is categorized. The second part is Section 4 (RAM Measurement) which defines how to measure equipment performance.

1.3 The document defines six basic equipment states into which all equipment conditions and periods of time must fall. The equipment states are determined by functional issues, independent of who performs the function.

1.4 The measurement of equipment reliability in this guideline, concentrates on the relationship of equipment failures to equipment usage, rather than the relationship of failures to total elapsed time. Productive time and equipment cycles are the indicators of equipment usage presented in this document.

1.5 Effective application of this guideline requires that users track equipment performance (RAM) with regard to time and/or equipment cycles. Supplier and user responsibility issues can only be monitored through the diligent use of an accurate tracking system.

2. SELECTED DEFINITIONS

assist - any unplanned interruption or variance from specifications of equipment operation which requires human intervention of less than six minutes to correct. After six minutes has elapsed, an assist becomes a failure. If intervention is required, but there is no interruption of operation within specifications, and no component is replaced, the action is an assist independent of its duration.

cluster tool - a manufacturing system made up of integrated processing modules mechanically linked together (the modules may or may not come from the same supplier). Effectively reporting RAM measurements requires users to track the performance of the total system and the individual modules.

cycle (equipment cycle) - one complete operational sequence (including product load and unload) of processing, manufacturing, or testing steps for an equipment system or subsystem. In single unit processing systems, the number of cycles equals the number of units processed. In batch systems, the number of cycles equals the number of batches processed.

downtime (equipment downtime) - the time when the equipment is not in a condition, or is not available, to perform its intended function. It does not include any portion of non-scheduled time.

failure (equipment failure) - any interruption or variance from the specifications of equipment operation requiring the replacement of a component (other than specified consumables) due to degradation or failure. Failures also include any assists that interrupt operation and take longer than six minutes. If unplanned corrective action is required (as in slow degradation that will cause a failure), and this action is scheduled for a later time (to avoid interruption of production), the event is logged as a failure at the time of corrective action.

maintenance - the act of sustaining equipment in a condition to perform its intended function. In this document maintenance refers to function, not organization. It includes adjustments, change of consumables, repair, PM, etc., no matter who performs the task.

non-scheduled time - a period when the equipment is not scheduled to be utilized in production. (see Section 3.7)

operations time - total time minus non-scheduled time (see Figure 1 in Section 3)

product - any unit which is intended to become a functional semiconductor device. This includes functional engineering devices.

ramp-down - the portion of a maintenance procedure required to prepare the equipment for hands-on work. It includes purging, cool-down, warm-up, etc. Ramp-down is only included in scheduled and unscheduled downtime.

ramp-up - the portion of a maintenance procedure required, after the hands-on work is completed, to return the equipment to a condition where it can perform its intended function. It includes pumpdown, warm-up, stabilization periods, initialization routines, etc. It does not include equipment or process test time. Ramp-up is only included in scheduled and unscheduled downtime.

shutdown - the time required to put the equipment in a safe condition when entering a non-scheduled state. It includes any procedures necessary to reach a safe condition. Shutdown is only included in non-scheduled time.

start-up - the time required for equipment to achieve a condition where it can perform its intended function, when leaving a non-scheduled state. It includes pumpdown, warm-up, cool-down, stabilization periods, initialization routines, etc. Start-up is only included in non-scheduled time.

support tool - a mechanical device that, although not part of a piece of equipment, is required by, and becomes integral with it during the course of normal operation (e.g. cassettes, wafer carriers, probe cards, etc.)

total time - all time (at the rate of 24 hrs/day, 7 days/week) during the period being measured. In order to have a valid representation of total time, all six basic equipment states must be accounted for and tracked accurately.

training (off-line) - the instruction of personnel in the operation and/or maintenance of equipment done outside of operations time. Off-line training is only included in non-scheduled time.

training (on-the-job) - the instruction of personnel in the operation and/or maintenance of equipment done during the course of normal work functions. On-the-job training typically does not interrupt operation or maintenance activities and can therefore be included in any equipment state (except standby and non-scheduled) without special categorization.

unit - any wafer, die, packaged device, or piece part thereof (includes product and non-product units)

uptime (equipment uptime) - the hours when the equipment is in a condition to perform its intended function. It includes productive, standby, and engineering time, and does not include any portion of non-scheduled time. (see Figure 1 in Section 3)

verification run - any unit or units (product or non-product) processed by the equipment to establish that it is performing its intended function within specifications.

3. EQUIPMENT STATES

3.1 To clearly measure certain aspects of equipment performance (RAM), this document defines six basic equipment states into which all equipment conditions and periods of time must fall.

The equipment states are determined by function, not by organization. Any given maintenance procedure, for example, is classified the same way no matter who performs it, an operator, a production technician, a maintenance technician, or a process engineer.

Figure 17 is a stack chart of the six basic equipment states. Key blocks of time are identified for use in equations given later in this document. These basic equipment states can be divided into as many sub-states as are required to achieve the equipment tracking resolution that a manufacturing operation desires.

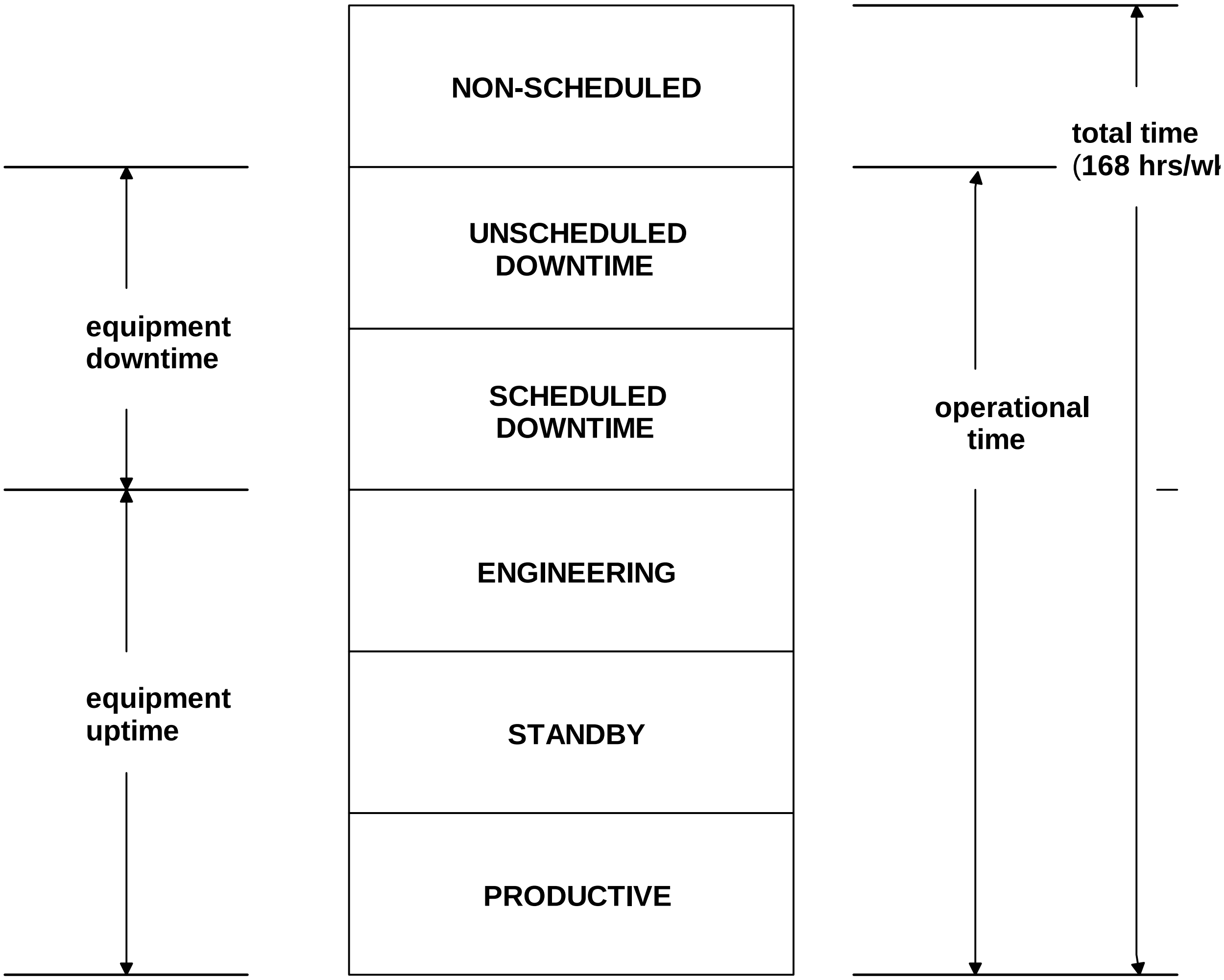

Figure 17 Equipment States Stack Chart

3.2 PRODUCTIVE STATE - a period of time (productive time) when the equipment is performing its intended function. It includes:

- Regular production (including loading and unloading of product)
- Work for third parties
- Rework
- Production test - verification runs other than those following a PM, setup, or repair procedure
- Engineering runs done in conjunction with production; may or may not be product units (e.g., split lots, and new applications)

3.3 STANDBY STATE - a period of time (standby time), other than non-scheduled time, when the equipment is in a condition to perform its intended function, chemicals and facilities are available, but it is not operated. It includes:

- No operator available (including breaks, lunches, and meetings)
- No product available (including no product due to lack of available support equipment, such as metrology tools)

- No support tools (e.g. cassettes, wafer carriers, probe cards, etc.)
- Waiting for results of production test
- In cluster tools: associated cluster module down

3.4 ENGINEERING STATE - a period of time (engineering time) when the equipment is in a condition to perform its intended function (no equipment or process problems exist), but is operated to conduct engineering experiments. It includes:

- Process engineering (e.g., process characterization)
- Equipment engineering (e.g., equipment evaluation)

3.5 SCHEDULED DOWNTIME STATE - a period of time (scheduled downtime) when the equipment is not available to perform its intended function due to planned downtime events

3.5.1 maintenance delay - a period during which the equipment cannot perform its intended function because it is waiting for either user or supplier personnel or parts (including consumables/chemicals) associated with maintenance. Maintenance delay may also be due to an administrative decision to leave the equipment down and postpone maintenance.

NOTE: Since this subject receives so much attention in supplier/user communications, it is important for users to accurately track how much delay time is associated with maintenance, and who is responsible for it. Supplier and user maintenance delay must therefore be tracked separately, each beginning at the point of notification that maintenance is required.

3.5.2 preventive maintenance - the sum of:

- preventive action - a predefined maintenance procedure (including equipment ramp-down and ramp-up), at scheduled intervals, designed to reduce the likelihood of equipment failure during operation
- equipment test - the operation of equipment to demonstrate equipment functionality (e.g. system reaches base pressure, wafers transfer without problem, gas flow is correct, plasma ignites, source reaches specified power, etc.)
- process test - verification runs, using non-product units, done after preventive action and equipment test

NOTE: Equipment suppliers are responsible for specifying a PM program to achieve a predetermined equipment performance level. Users are obligated to identify any deviation from the recommended program if they expect the supplier to meet or improve that performance level.

3.5.3 change of consumables/chemicals - the scheduled interruption of operation to replenish the raw materials of semiconductor processing. It includes changes of gas bottles, acids, targets, sources, etc., and any purging, cleaning, or flushing normally associated with those changes. It does not include delays in obtaining those consumables/chemicals.

3.5.4 setup - the sum of:

- conversion - the time required to complete an equipment alteration necessary to accommodate a change in process, product, package configuration, etc. (excluding modifications, rebuilds, and upgrades)

- equipment test - the operation of equipment to demonstrate equipment functionality (e.g. system reaches base pressure, wafers transfer without problem, gas flow is correct, plasma ignites, source reaches specified power, etc.)
- process test - verification runs, using non-product units, done after conversion and equipment test

NOTE: Equipment suppliers are responsible for providing procedures which achieve setup conversion and testing within predetermined specifications. Users are obligated to identify any deviation from the procedures if they expect the supplier to make setups fall within those specifications.

3.5.5 facilities-related downtime - a period of time when the equipment cannot perform its intended function solely as a result of out of specification facilities. Those facilities include:

- Environmental (e.g. temperature, humidity, vibration, particle count, etc.)
- House hookups (e.g. power, cooling water, house gases, exhaust, LN2, etc.)
- Communications links with other equipment or host computers

Any downtime created by 1,2, or 3 above shall be included in facilities-related downtime. For example, if, as a result of a scheduled fifteen minute power outage an otherwise unnecessary cryo pump regeneration is needed, all time required to return the equipment to a condition where it can perform its intended function is included in facilities-related downtime.

3.6 UNSCHEDULED DOWNTIME STATE - a period of time (unscheduled downtime) when the equipment is not in a condition to perform its intended function due to unplanned downtime events

3.6.1 maintenance delay - a period during which the equipment cannot perform its intended function because it is waiting for either user or supplier personnel or parts (including consumables/chemicals) associated with maintenance. Maintenance delay may also be due to an administrative decision to leave the equipment down and postpone maintenance.

NOTE: Since this subject receives so much attention in supplier/user communications, it is important to accurately track how much delay time is associated with maintenance, and who is responsible for it. Supplier and user maintenance delays must therefore be tracked separately, each beginning at the point of notification that maintenance is required.

3.6.2 repair - the sum of:

- diagnosis - the procedure of identifying the source of an equipment problem or failure
- corrective action - the maintenance procedure (including equipment ramp-down and ramp-up) employed to address an equipment problem or failure and return the equipment to a condition where it can perform its intended function. This includes maintenance to address equipment problems that were not severe enough to halt production, but required scheduling outside the regular PM program.
- equipment test - the operation of equipment to demonstrate equipment functionality (e.g. system reaches base pressure, wafers transfer without problem, gas flow is correct, plasma ignites, source reaches specified power, etc.)
- process test - verification runs, using non-product units, done after corrective action and equipment test

3.6.3 change of consumables/chemicals - the unscheduled interruption of operation to replenish the raw materials of semiconductor processing. It includes changes of gas bottles, acids, targets, sources, etc., and any purging, cleaning, or flushing normally associated with those changes. It does not include delays in obtaining these consumables/chemicals.

3.6.4 out-of-spec input - a period when the equipment cannot perform its intended function solely as a result of problems created by out of specification or faulty inputs. Those inputs include:

- Support tools (e.g. warped cassettes or wafer carriers, faulty probe cards, or reticles, etc.)
- Product (e.g. upstream process/product problems, warped wafers, contaminated wafers, warped lead frames, etc.)
- Test data (e.g. metrology tool out of calibration, misread charts, erroneous data interpretation/entry, etc.)
- Consumables/chemicals (e.g. contaminated acid, leaky target bond, degraded photo resist, degraded mold compound, etc.)

Any downtime created by 1,2,3, or 4 above shall be included in out of specification input downtime. For example, if, as a result of an intermittent probe card short, a prober/tester system is put down for repair, all downtime incurred prior to identifying that the problem is with the probe card is recategorized as out of specification input downtime. 3.6.5 facilities-related downtime - a period of time when the equipment cannot perform its intended function solely as a result of out of specification facilities. Those facilities include:

- Environmental (e.g. temperature, humidity, vibration, particle count, etc.)
- House hookups (e.g. power, cooling water, house gases, exhaust, LN2, etc.)
- Communications links with other equipment or host computers

Any downtime created by 1,2, or 3 above shall be included in facilities-related downtime. For example, if, as a result of a unscheduled fifteen minute power outage an otherwise unnecessary cryo pump regeneration is needed, all time required to return the equipment to a condition where it can perform its intended function is included in facilities-related downtime.

3.7 NON-SCHEDULED STATE - a period of time (non-scheduled time) when the equipment is not scheduled to be utilized in production, such as unworked shifts, weekends, and holidays (including shutdown and start-up).

If equipment is out of the production plan due to off-line training or an installation, modification, rebuild, or upgrade that cannot be accommodated by the regular PM schedule, its status is the non-scheduled state. This includes any qualification time required to bring the equipment to a condition where it can perform its intended function.

Any maintenance done to equipment during these periods cannot be counted in the non-scheduled state, since all maintenance must fall into either scheduled or unscheduled downtime (this includes automatic maintenance routines such as a programmed cryo pump regeneration).

By the same convention, any production or engineering work done during these periods must fall into either productive or engineering time (this includes unattended operation that may shut itself off "after hours").

4. RAM Measurement

4.1 Reliability, availability, and maintainability are measures of equipment performance which have been used widely in industry for decades. This section defines them for the semiconductor industry in a manner that is consistent with existing industrial standards. Along with the definitions for RAM are given indicators by which these measures can be quantified.

4.2 EQUIPMENT RELIABILITY - the probability that the equipment will perform its intended function, within stated conditions, for a specified period of time NOTE: This document defines time when the equipment is performing its intended function as the only appropriate time to consider in equipment reliability calculations. Two different methods of measuring this are presented - productive time and equipment cycles. Although the application of each appears to be the same, the results have notable differences. Productive time only considers what happens while making product (useful for manufacturing operation purposes). Equipment cycles take into account the wear and tear created by every machine cycle during all equipment states (useful for equipment reliability purposes).

4.2.1 $MTBF_p$ - Mean (Productive) Time Between Failures; the average time the equipment performed its intended function between failures; productive time divided by the number of failures during that time. Only productive time is included in this calculation. Failures that occur when attempt is made to change from any state to a productive state are included in this calculation. Using $MTBF_p$ therefore, requires that the user not only have the capability of capturing failure information, but also tracking and categorizing total time accurately.

$$MTBF_p = \frac{\text{productive time}}{\#\text{ of failures that occur during productive time}}$$

4.2.2 MCBF - Mean Cycles Between Failures; the average number of equipment cycles between failures; total equipment cycles divided by the number of failures during those cycles (includes both product and non-product cycles). This calculation transcends equipment states to include all cycles that the system, or subsystem, being considered experiences. It does not require tracking equipment states, only equipment cycles and equipment failures.

$$MCBF = \frac{\text{total equipment cycles}}{\#\text{ of failures}}$$

4.2.3 $MTBA_p$ - Mean (Productive) Time Between Assists; the average time the equipment performed its intended function between assists; productive time divided by the number of assists during that time. Only productive time is included in this calculation. Using $MTBA_p$, therefore, requires that the user not only have the capability of capturing assist information, but also of tracking and categorizing total time accurately.

$$MTBA_p = \frac{\text{productive time}}{\#\text{ of assists}}$$

4.2.4 MCBA - Mean Cycles Between Assists; the average number of equipment cycles between assists; total equipment cycles divided by the number of assists during those cycles (includes both product and non-product cycles). This calculation transcends equipment states to include all cycles that the system, or subsystem, being considered experiences. It does not require tracking equipment states, only equipment cycles and assists.

$$\text{MCBA} = \frac{\text{total equipment cycles}}{\#\ \text{of assists}}$$

4.3 EQUIPMENT AVAILABILITY - the probability that the equipment will be in a condition to perform its intended function when required.

4.3.1 equipment dependent uptime - the percent of time the equipment is in a condition to perform its intended function during the period of operations time minus the sum of all maintenance delay, out-of-spec input downtime, and facilities-related downtime. This calculation is intended to reflect equipment reliability and maintainability based solely on equipment merit.

$$\text{equipment-dependent uptime (\%)} = \frac{\text{equipment uptime x 100}}{\text{oper. time} - (\text{all maint. delay} + \text{out-of-spec input DT} + \text{fac-rel DT})}$$

4.3.2 supplier dependent uptime - the percent of time the equipment is in a condition to perform its intended function during the period of operations time minus the sum of user maintenance delay, out-of-spec input downtime, and facilities-related downtime. This calculation subtracts only user maintenance delay from the period, thereby taking into account supplier delays for parts and service. The intention is to provide an effective performance measurement for use in supplier service contracts.

$$\text{supplier-dependent uptime (\%)} = \frac{\text{equipment uptime x 100}}{\text{oper. time} - (\text{all maint. delay} + \text{out-of-spec input DT} + \text{fac-rel DT})}$$

4.3.3 operational uptime - the percent of time the equipment is in a condition to perform its intended function during the period of operations time. This calculation is intended to reflect overall operational performance for a piece of equipment.

$$\text{operational uptime (\%)} = \frac{\text{equipment uptime x 100}}{\text{operations time}}$$

4.4 EQUIPMENT MAINTAINABILITY - the probability that the equipment will be retained in, or restored to, a condition where it can perform its intended function, within a specified period of time.

4.4.1 MTTR - Mean Time To Repair; the average time to correct a failure and return the equipment to a condition where it can perform its intended function; the sum of all repair time (elapsed time not necessarily total man hours) incurred during a specified time period (including equipment and process test time, but not including maintenance delay), divided by the number of failures during that period.

$$\text{MTTR} = \frac{\text{total repair time}}{\#\ \text{of failures}}$$

4.4.2 MTOL - Mean Time Off Line; the average time to return the equipment to a condition where it can perform its intended function when downtime is incurred; the sum of all downtime (scheduled and unscheduled) during a specified time period, divided by the number of downtime incidents during that period.

$$\text{MTOL} = \frac{\text{total equipment downtime}}{\#\ \text{of downtime incidents}}$$

4.5 EQUIPMENT UTILIZATION - the percent of time the equipment is performing its intended function during a specified time period

NOTE: It is recognized that utilization calculations may not be useful in user/supplier negotiations, but are included in this document because they are important to equipment users, and therefore may be of interest to equipment suppliers.

4.5.1 operational utilization - the percent of productive time during operations time. This calculation is intended to be used for equipment utilization comparisons between operations with different work shift configurations since it does not include non-scheduled time.

$$\text{operational utilization (\%)} = \frac{\text{productive time x 100}}{\text{operations time}}$$

4.5.2 total utilization - the percent of productive time during total time. This calculation is intended to reflect bottom line equipment utilization.

$$\text{total utilization (\%)} = \frac{\text{productive time x 100}}{\text{total time}}$$

TOTAL TIME

OPERATIONS TIME

EQUIPMENT UPTIME

Productive time

- regular production
- work for 3rd party
- rework
- production test
- engineering runs

Standby Time

- no operator
- no product
- no support tool -
- waiting for production test results
- associated cluster module down

Engineering Time

- process experiments
- equipment experiments

EQUIPMENT DOWNTIME

Scheduled Downtime

- maintenance delay
- preventative maintenance
- change consumables/chemicals
- setup
- facilities-related

Unscheduled Downtime

- maintenance delay
- repair

change consumables/chemicals

- out-of-spec input
- facilities-related

Non-Scheduled Time

- unworked shifts, weekend, and holidays
- installation, modification, rebuild, or upgrade

- off-line training
- shutdown/start-up

Figure 18 E10-92 Summary of Time

APPENDIX C

SEMATECH CLASSES

SEMATECH offers a number of classes to assist in the execution of a Qualification Plan. Information on SEMATECH classes is available from the SEMATECH Organizational Learning and Performance Technology Department and "The SEMATECH Learning Resource Guide 1995," #92061162D-TRG.

There are numerous courses covering project management, team building, semiconductor processing, and environmental, health and safety issues. Courses specifically related to data collection and analysis and the Qualification Plan are listed below:

- Qualification Plan Overview
- Introduction to Statistical Methods with RS/1
- Statistical Methods with RS/1
- Introduction to Measurement Capability Analysis
- Passive Data Collection
- Design of Experiments Overview
- Design of Experiments
- Equipment Reliability Testing
- Failure Reporting, Analysis, and Corrective Action System (FRACAS)
- Reliability Analysis and Modeling Program (RAMP)
- Tactical Software Reliability
- Understanding and Using Cost of Ownership

REFERENCES/BIBLIOGRAPHY

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- *Evaluating Automated Wafer Measurement Instruments*: #94112638A-XFR
- *Failure Mode and Effects Analysis (FMEA)*: #92020963A-ENG
- *FRACAS*: #94042332A-GEN
- *Guidelines for Equipment Reliability*: #92031014A-GEN
- *Introduction to Measurement Capability Analysis*: #91090709A-ENG
- *IRONMAN Methodology Manual*: #94082509A-XFR
- *Passive Data Collection*: #91090684A-ENG
- *Project Management Guidelines*: #92041058A-GEN
- *Reliability Test Methods Toolkit*: #93091803A-TR

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