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Weir PW

Software Requirements Specification

1. Introduction

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Description:	A suite of statistical and physical performance model tools for semiconductor process tuning. Functions as either a stand-alone analysis package or externally called module for use with OEM or as a process model engine for Advanced Process Control (APC) implementations. Weir PW provides an analysis enabler for the advanced control functions dictated by the needs of today's sub-wavelength, scanned lithography.

In keeping with an "open" architecture allowing the customer full access to all data, metrology derived from any source is imported and stored in Microsoft Excel™ workbooks. Data selection and culling provide manual and automated control of subsets highlighting scan or lens-slit behavior.

Tools are provided for metrology tool algorithm performance evaluation, variable covariance and automated calculation of precision contributors. Process models provide the ability to de-convolve the contributions of each sub-film to wafer-induced aberrations. Lens, mechanical and electro-optical interaction models provide characterization and equipment tuning parameters for lithography optimization.

Aerial image and process film interactions are directly evaluated and tuned to optimize production margins through enhanced characterization of image aberration and process settings of focus and exposure-dose.

1.1 Product Scope

Weir PW™, Weir PSFM and Weir DM are components of the Weir Wavefront Engineering Suite of process optimization tools. Weir PSFM provides advanced tools for aerial image wavefront plotting and focus uniformity modeling across the wafer and scanned image. Weir DM is an automation interface for Weir PW and Weir PSFM providing automated analysis encapsulation into control templates and data storage for trend charting of user-selected variables.

Weir PW™ addresses the need for an advanced suite of tools capable of importing and modeling any form of metrology used in semiconductor lithographic image evaluations. A single user interface provides statistical analysis of raw data as well as models for substrate, optics, and electro-mechanical scan image aberration measurement.

A recent paradigm shift in metrology techniques has seen the emergence of tools capable of simultaneously measuring multiple process variables through the use of empirical modeling of scattered intensity or ellipsometric broad-spectrum incident wavefronts. The physical point congruence of these variables provides unique opportunities for process optimization and a simultaneous liability of measured value susceptibility to the robustness of the tools conversion algorithms to process variations. Algorithm designs not capable of tracking the full bandwidth of process variations result in improper values and the erroneous evaluation of process control parameters in setup and ringing or run-away of APC loops.

Process performance optimization dictates a need for precise control and characterization of the perturbations of the manufactured image from their design ideals. Contained in this product are automated advanced tools for the evaluation of film uniformity and critical process feature quality including:

- ✍✍Statistic derivation for raw, modeled and residual data populations,
- ✍✍Across-lot, substrate and exposure-field spatial dependency mapping,
- ✍✍Topographic and underlying film uniformity and their relation to feature variation,
- ✍✍Production and process window optimization with the capability of:
  - ✍✍Removing individual tool and substrate contributed perturbations,
  - ✍✍Incorporating individual exposure tool lens signature aberrations in the centering the production process window and
  - ✍✍Performance matching of exposure tool, full-field process window signatures.
- ✍✍Automated evaluation of reticle-object to printed image fidelity often referred to as a Mask-Error Enhanced Functional analysis.
- ✍✍Automated tracking of empirically measured reticle values and device feature design criteria against lithographic image fidelity using empirical models that remove the individual signature aberrations of metrology and pattern generation tools.

The last two functions listed above define a tool-set for the performance characterization of all reticle enhancement techniques including optical proximity and off-axis illumination methods.

Exposure functional pattern generation tools and the metrology systems used in their performance evaluation are critical contributors to the accuracy of the process control sequence. Any tool addressing process optimization must be capable of deriving the contributions of these tools for both characterization and control purposes. Accuracy in process control dictates the need for removing the individual tool contributions from the composite behavior. Appropriate assignment of error budget contributions and sources therefore provides the ability to simultaneously monitor exposure tool tuning and optimize process centering to minimize design perturbations. Metrology and pattern-generation control functions included in Weir PW include:

- ✍✍Simulations of process performance resulting from pattern generation tool aberration correction.
- ✍✍Automated error-budget and lithographic subsystems precision calculations.
- ✍✍Metrology tool algorithm evaluation for accuracy and robustness
- ✍✍Performance models and variable covariance mapping tools for both metrology algorithm process performance characterizations.

1.2 Perspective

The Weir PW™ product incorporates a suite of tools for the analysis, control and design of the semiconductor lithographic process. Each module can be used separately or in conjunction with others, sharing a common interface, design and feel for the user. The product provides the most accurate analysis in the industry because of its ability to incorporate and differentiate the contributions of all sources of image perturbation.

The suite applies proprietary in-house developed “smart” modeling tools that recursively adapt to the data population and objective of the analysis. The result of which is seen in the accuracy of derivation of production control surfaces that eliminate the ringing and run-off of typical advanced process control modules. Both control and analytical functions are accuracy enhanced by the product’ s ability to include automated or manual culling of poor metrology.

Weir PW provides an open system of access and versatility for the user. Any form of metrology data can be easily imported into Weir PW. Data is stored in Microsoft Excel™ worksheets for easy access and customization.

1.3 The Customer

The Weir PW product provides valuable information and setup tools for the process, lithography, reticle design and exposure tool engineer.

Device designers finally have a tool for the easy measurement of image enhancement techniques such as OPC and RET structures.

Pattern generation tool vendors can benefit from the ability of the software to derived modeled sources of aberrations during assembly and maintenance. The software uniquely eliminate the sources of over- or under-correction during tuning commonly experienced by other competitive offerings through proprietary surface modeling techniques and the ability to remove process and substrate contributions.

Metrology tool vendors and production engineer benefit from the ability to automatically derive error-budget and component precision sources. Automated tools for deriving measured feature variation with process drift are critical for the development of measurement algorithms.

The semiconductor process engineer can easily center the exposure and dose, optimized for each exposure tool in the facility. Process development and tuning cycles are shortened since metrology, exposure tool and substrate contributions are easily removed from the sequence providing a clear understanding of the true response of the process. As a consequence of this, the sources of these aberrations can be clearly modeled and assigned. Thus directing the engineering efforts of the engineer to the greatest contributors of process variation whether they be substrate flatness, film uniformity, grain, reflectivity response or spin and puddle processing before of after exposure.

To the process engineer, the ability to characterize the collinear behavior of process variables enhances the speed and accuracy of process design. The benefits of all of these capabilities are inherent to control accuracy when Weir PW is used as a parameter-modeling engine in an Advance Process Control sequencer.

The “Stepper”, “Scanner” or exposure-tool engineer of each facility can employ the accuracy of the analysis to control in-line production behavior of the systems to optimize process performance of feature size and reduce re-work levels. Equipment maintenance periods are reduced by the software’ s ability to identify and provide the corrections needed. Maintenance frequency can be reduced by regular production use of the modeling software resulting in the ability to identify sub-assembly drift and component failures.

2. Description

2.1 Objectives

- ✍✍Provide industry customized proprietary methods of adaptive data modeling for error-budget, control surface, and characterization of tools and the semiconductor process.
- ✍✍Provide automated methods of improving analysis accuracy with the user ability to manually enhance or over-ride.
- ✍✍Discriminate between pure errors and the systematic contributions of the process and tools.
- ✍✍Substrate and film uniformity model mapping.
- ✍✍Field-based perturbation analysis for aerial, average and location sensitive situations.
- ✍✍Modeled control-surface analysis for exposure tool tuning parameters such as slit aberrations, tilt, bow and nonlinear errors.
- ✍✍Provide a software toolset for the calculation of optimum focus and exposure-dose of a semiconductor device reticle.
- ✍✍Calculate the process window size based upon the user’ s selection of the operating focus /exposure-dose and the constraining functional limits of device critical features.
- ✍✍Supply visualization for data and performance using advanced graphics and data plots.

2.2 Supporting Functions

- ✍✍Data import from any industry standard metrology vendor format
- ✍✍An open data storage format.
- ✍✍Data conversion into a Weir PW standard format for storage.
- ✍✍Tools for specifying setup, scan, exposure and focus layout of the raw data focus-exposure matrix.
- ✍✍Tools for manual specification of critical feature target and threshold size.

- ✍✍Provide metrology-technology specialized tools to measure and de-convolve focus and exposure-dose variation across the exposure field during test and production.

2.3 Background

The semiconductor production cycle can embody as many as forty (40) layers during manufacture. Each layer must be patterned to contain the various gates, sources and drains of every active transistor and capacitor in the final design. All of these physical elements must also be connected and linked to the outside world before the final product is functional. Patterns are first generated in each layer using a step-and-repeat (stepper) camera that exposes a product reticle at each grid site on the wafer stage. Newer designs, requiring greater resolution and smaller device geometries are typically exposed using a scanning-slit aperture (Scanner) to increase the effective Numeric Aperture (NA) and thereby enhance resolution locally.

The components of the devices fabricated to constitute a fully functional Integrated Circuit (IC) design each exhibit specific requirements for their size, composition and placement if they are to operate within specification. The scope of pattern sizes can vary from a millimeter or more down to just a few ten' s of nanometers in size. Tolerances of variation for the feature size are typically +/- one-quarter (¼) the design specification of each element.

Problems occur when attempting to simultaneously, accurately image isolated features and those in close proximity to other small or large structures. The effective dose varies for each element because of the exposure proximity effects and scatter of the actinic radiation from nearby structures that can add to the local dose level. The objective of the process engineer in these situations is to select an exposure-dose that enables both small and large features to be properly sized as specified in the product design specification.

3.2.1 Basic contributors to device feature size and shape errors

Semiconductor device manufacture depends upon process yield. However, profitability and competitive strength rely on the replication of design feature integrity and size to insure device speed and performance to design criteria. Perturbations in critical feature characteristics such as size, profile and regularity degrade element performance. It is therefore critical to understand the sources of degradation and tune the tool and process sequence to maximize the fidelity of the final product to the design criteria.

Ideally, feature size errors result from improper centering of the exposure-dose and focus process "window", thereby allowing normal process variation to exceed the process specification for some portion of the production population. However, today' s commercial offerings concentrate on calculation accuracy based solely upon the type of feature – via, line or space. These techniques completely neglect the incidental influence previous substrate film uniformity, wafer flatness, reticle-platen and wafer-stage tilt. Systematic errors contributed by the lens-slit aberrations of each exposure tool as well as each tools unique behavioral contribution to scan linearity, pitch and roll.

The substrate and exposure tool interactions seen as imaging errors resulting from wafer leveling, autofocus, slit scan direction and field tilt aberrations are also ignored in competitive products as are the contributions of the metrology tool. Many occasions arise where the robustness of the metrology recipe or algorithm do not properly extend beyond normal process and equipment drift. When applied in control loop sensitive situations such as a feedback or feed-forward process control, these variations result in an overall loss of process stability and even catastrophic, uncontrolled drift and that results in the latest yield-bust, frequently attributed to "unknown" causes.

A process analytical tool should therefore be designed to include consideration of the various sources of actual -- process inherent – and perceived – metrology inherent -- systematic errors. Process control demands dictate that any tool must have the ability to determine and quantify the contributions of each error source. Control sequences need to eliminate the sample-significant contributions such as previous layer film non-uniformity to their calculation of production values.

3.2.2 Reticle object contributions to feature size variation

A final contribution frequently ignored by today' s semiconductor industry is the role of the pattern reticle' s variation to the variations seen in the wafer-imaged device. The reticle' s image is far from being a true and absolute replication of the features described in the design of the device. Here too variations extend from processing, etching and substrate variations. Final image size can be systematically perturbed by reticle surface bow engendered by the substrate, etching process or even mounting on the platen of the exposure tool.

Individual features across the reticle can vary smoothly and systematically due to non-linear, tilted or poorly sized image exposures. Abrupt changes in size and integrity frequently result from scan-boundary overlaps and address alias snaps. Rather than a smooth systematic transition of reticle features, these boundaries signify anomaly in the local feature and frequently the restart of a intraField systematic scan aberration.

The replication behavior of reticle features varies as a function of the feature' s size proximity to the resolution limits of the exposure tool. Neighborhood packing density and even orientation contribute to the variations seen. These variations are compounded when they are convolved against the aberrations of the exposure tool and it' s inherent changes in effective illumination, partial coherence and even numeric aperture across the exposure field.

Analysis of any set of process signatures must therefore include the ability to compare the final image variation to the signatures characterized across the fixed-reticle. These reticle-sourced aberrations, while significant, are frequently overpowered by the contributions of the process and substrate discussed in the previous section. The analysis must therefore be capable of removing the contributions of the process to properly identify those of the reticle. Current industry publications of reticle pattern fidelity and Mask Enhance Error Functions (MEEF) do not address the influence of the process and exposure systematic errors. Their estimation of MEEF contributions are therefore inflated to the point that it is impossible to model their behavior, thereby adding to the mystique of the mask-maker' s task.

One complicating factor is the influence of Reticle Enhancement Techniques (RET) on final image behavior. Their analysis is complicated by the sub-resolution interaction of the out-rigger figures with the actinic wavelength. Final image analysis from printed images of these techniques should therefore be performed against the simulation derived reticle data rather than direct measurement of mask features.

3.2.3 Centering Exposure-dose and Focus to optimize process margins

Feature size is a function of both the exposure-dose and the focus of the exposure tool. Feature sizes vary as a 2^{nd} order function of the error in focus. Optimum focus of an isolated feature will also be different than that of a feature located within a dense grouping of similar features. Therefore, the engineer must select a nominal operating point that will enable all features to be correctly focused and to receive the optimum dose for size control.

Functional dose and optimum focus will drift during the production sequence as characteristics such as film composition, thickness, photoresist batch and illumination sources age. In addition, focus and exposure are not fixed over the pattern field of the stepper or scanner. Optimum focus will vary according to the aberrations present in the optical stack (lens) and the frequency loading of features on the device. Dose and focus can vary in a scanner due to non-uniformity of the scan-plane and accelerations of the slit at the start or end of each scan.

Optimum focus and dose must be determined during production on a periodic basis depending upon the requirements of the device design and the capabilities of the exposure tool. When the capabilities of the exposure tool greatly exceed the needs of the device, then the process margin of operation is said to be great. Conversely, when the device needs are very close to the capabilities of the equipment set, then the process margin will be very small or even non-existent.

Production situations with large process margins will require only occasional optimization of the focus and dose. These optimizations typically are conducted on a monthly basis and at the introduction of a new photoresist batch or device design.

When the requirements of the device are very close to the capabilities of the exposure tool, the need for checking and adjusting the correct setting of focus and dose increases in frequency. In demanding environments, the settings should be performed for each individual device and exposure tool in the facility because of unique variations in lens aberrations and dose inherent in each tool.

The optimum dose for each feature is obtained by plotting the measured feature size as a function of the exposure dose. Feature size will typically be a linear function of the dose. Optimum dose will vary according to the relative size of the feature, it' s orientation, the density of adjacent features and it' s location within the exposure field.

Optimum focus is obtained by plotting the size of the feature against the focus-setting of the exposure tool. Focus will exhibit a 2^{nd} order or quadratic change in feature size as a function of the distance from optimum focus. Best focus for the feature is therefore located at the point at which the first derivative of the curve is zero.

Ideally, focus should be determined at the optimum dose and conversely, dose must be set at optimum focus. Since this is difficult to achieve without a series of iterations, the engineer typically exposure a regular array of images into a focus-exposure matrix (FEM) of values. The Critical Dimension (CD) value of the feature is then plotted as a contour function of the focus and exposure-dose. The target value of the feature determines the unique focus and dose setting for the process and tool.

The set of focus-dose settings that satisfy the specified tolerance of feature size variations defines the process-window of acceptable settings for the device. The range of focus values encompassed by this window is defined as the depth-of-focus (DoF) for the process. Similarly, the range of acceptable exposure-dose values defines the exposure latitude.

2.4 User Characteristics

User	Characteristics
Process Engineer	Engineer responsible for daily control and stability of the production process. This is a production function that requires periodic monitoring of the process. The process engineer will use the software to adjust production settings when new photoresist batches are installed and when equipment, wafer tracks and exposure-tools, are returned from maintenance.
Design or Device Engineer	Weir PW will be used as part of the design cycle of the device. Data derived from simulators such as ProLith (KLA-Tencor) and Solid C will be applied to determine the DoF and exposure latitude anticipated from the design. Production' s first lots will use the software to select the proper window coordinates based upon the modeling of empirical data. Wafer feature fidelity to reticle pattern variation can be modeled and derived independent of exposure tool and process influence. Individual exposure tools can be signature characterized and matched to enhance the production stability of critical device layers for both feature size and profile integrity.
Stepper Engineer	Weir PW directly calculates tool-tuning parameters such as focus offset, reticle platen tilt and substrate tilt. The software also calculates exposure-dose and focus optimization settings for each process layer and unique toolset contribution. Unique to Weir PW, the aberrations of the metrology and substrate can be removed from this calculation to insure true process fidelity. The tool engineer uses the Weir PW software to define and confirm the depth of focus as limited by the lens and optical train. Extensive use during initial acceptance of the tool will confirm the capabilities of the tool to meet the purchase specifications. Repairs and maintenance sequences will employ Weir PW to ensure the anticipated level of tool performance. Lens-slit base aberrations such as piston, tilt and higher-ordered bow can be directly measured from product or test wafers. Exposure tool scan-stability including pitch, roll and yaw can be estimated for the aerial image. Scan variation sensitivity to previous film uniformity can also be derived as can their response to the wafer location and edge-bead proximity.

2.5 Operating Environment

Weir PW is designed as a stand-alone executable, functional under Microsoft Windows NT, 2000 and XP.

Data will be acquired from any text, binary or Microsoft Excel formats. Vendor outputs are then standardized and stored into open Microsoft Excel workbooks. During an analysis, the intermediate data sets, model coefficients, estimations of accuracy and simulated response values for each data set is stored within the workbook and fully accessible by the user.

Data will enter the system from local disk storage, floppy, CD-rom or from remote nodes located across the Intranet.

Weir PW is designed as a stand-alone analytical tool providing full functionality and over-ride to the user. The software can also be called by external programs for periodic analyses of production data or as part of a parameter modeling engine in an advanced process control loop.

5.2.1 License Control

Weir PW employs software-only license control that keys to the disk and CPU of the system of installation. Transfer of the license from one computer to a second would require the user to return a license-removal code to TEA Systems confirming removal of the software. Updates for demonstration or permanent licenses are delivered using telephone, email or any other textual means. Weir PW supports only single-user licenses.

2.6 Operational Modes

Weir PW is a user-interactive application. The user can directly influence, tune and guide analysis decisions that will influence the positioning of the operating point of the production sequence in the process window.

The product image can be initiated as a stand-alone application from the user's "Start" menu or by sequence calling from a program external to the computer using windows-standard function calling conversions.

Data is stored in Microsoft Excel™ workbooks. Output can be printed or cut/pasted into other windows applications.

2.7 Typical Data Import Types

- CD-sem
- Electrical Linewidth Measurement
- KLA Tencor ProData and ProLith formats.
- Optical metrology tools
- Ellipsometric and scatter based metrology tools.
- Optical and ellipsometric overlay and registration tools.

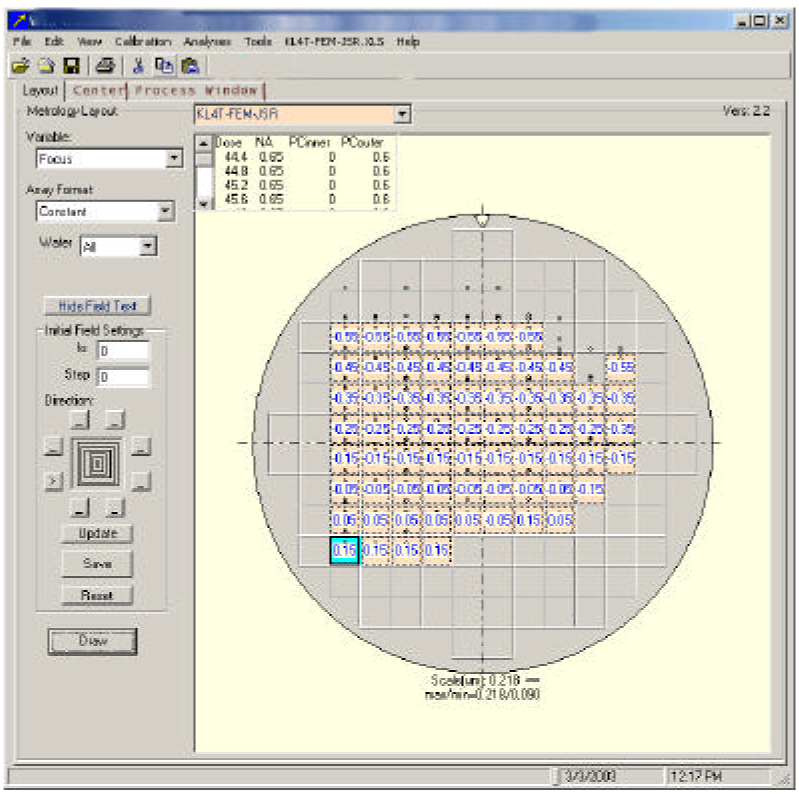

Figure 1: LithoWorks Layout Interface

3. User Interface

Data import and layout of the focus and dose matrix is performed using the interface shown in figure 1.

Analysis of the data is performed under the "process window" tab, shown in figure 2.

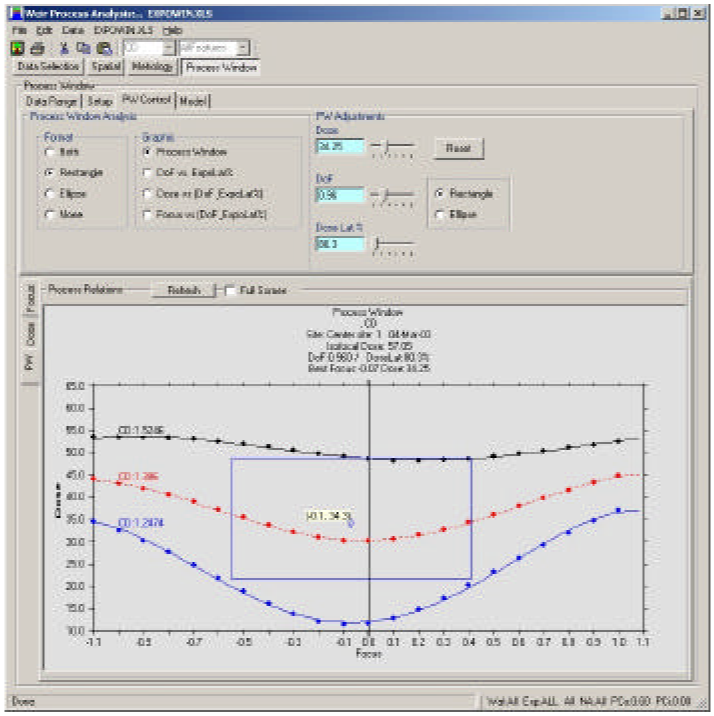

Figure 2: Process window calculation interface.

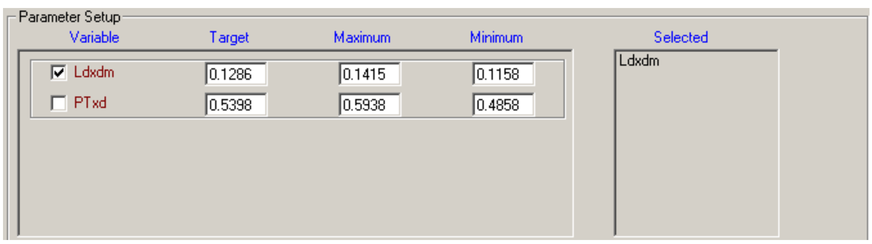

Figure 3: Target and control limit specification.

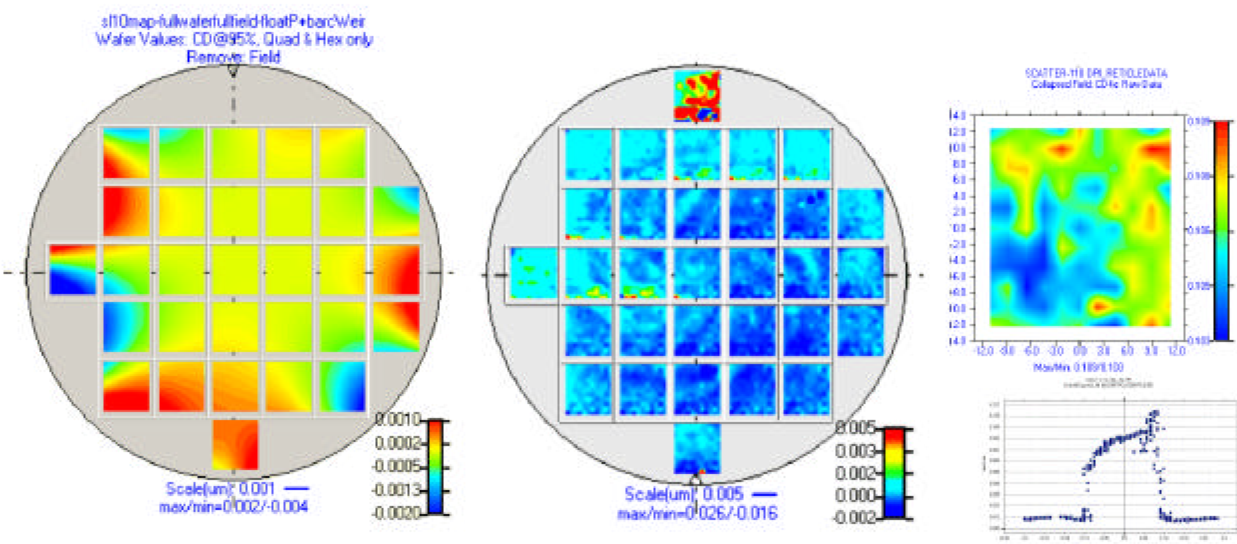

Figure 4: Spatial and metrology evaluations
Left: Substrate CD variation. ***Center***; Photoresist variation after substrate influence is removed. ***Right Top***: Average Field (Aerial) Image CD variation on a scanner . ***Right Bottom***: Scatter tool metrology algorithm limitation across the focus range.

Feature target and size limits are specified in the Data Setup window shown in figure 3. This window is accessed from a button-menu item.

A user-options interface will be provided for custom setting of:

- The default data import format
- Data directory location
- Graph colors

Feature variation for modeled wafer-systematic errors, film uniformity and field exposure variations are shown in figure 4.

4. Features

- Multiple sites per field
  - Point-and-click user mouse selection of sites
- Multiple features per calculation
- Across field signature derivation.
- Metrology covariance statistics and plotting
- Substrate, InterField and intraField models, statistics and visualization plots.
- Best Focus Calculation
  - Depth of focus determination.
  - Iso-focal point determination.
- Best Dose Calculation
  - Exposure latitude determination
- Process Window
  - Maximum rectangular or elliptical window
  - User-specified dose for depth of focus optimization
  - User-specified depth of focus for exposure latitude.
  - Calculation of Exposure-Focus curve for any number of process windows, field sites and features.
- Data culling
  - Automated, and by mouse-selection
- Mouse function
  - Point-and-click culling of data.
  - Point and click mouse selection of data for display, histogram or Cartesian plotting.
  - Editing of plots
  - Display of selected data points.
- Graphics
  - XY Cartesian, range, vector, histogram, contour, 3D of the substrate, field, sub-Field, scan and slit.

5. User Documentation

Documentation is provided as an adobe acrobat "pdf" file on CD-rom.

A hard-copy user manual is provided with every license.